# ADVANCES IN ROAD SAFETY PLANNING

EDITED BY: Krzysztof Goniewicz, Frederick M. Burkle and Dorota Lasota
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# ADVANCES IN ROAD SAFETY PLANNING

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EDITORIAL
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# Editorial: Advances in Road Safety Planning

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**Keywords: road safety, traffic accidents, road traffic accident, traffic safety (TS), healthy transport**

## Editorial on the Research Topic

## Advances in Road Safety Planning

The concept of Healthy transport embraces many diverse areas, spanning from road safety, and traffic security, to environmental sustainability as well as human behavior and health.

The present collection includes papers that touch upon international experiences concerning traffic safety issues, and that address the relation between traffic safety and various factors that impact safety such as: road networks' engineering, management and control of the traffic system, planning and strategies, transportation systems, citizens' education, knowledge, and behavior.

Traffic Safety has been internationally recognized as a primary strategic goal in many societies (Najaf et al., 2017; Pauer, 2017). Traffic safety concept is not limited to the reduction of road accidents. Traffic safety should be considered as a national issue as it is strongly related to all aspects of life and has a close link with the protection and sustenance the natural environment (Pawłowski et al., 2019).

Increasing traffic safety is an important political and social goal. Road safety comprises the three pillars of "Engineering, Enforcement, and Education." Both public health and road safety teams have access to data and evidence. Sharing this can improve the effectiveness of actions and set evidence-based objectives. Joint evaluations can identify whether activities are having an impact across a broad range of health issues (Goniewicz et al., 2016; Najaf et al., 2018).

Promoting healthy and sustainable transport options prevents the negative effects of current transport patterns on human health, such as those caused by air pollution and physical inactivity. Cooperation among sectors and high-level political commitment are crucial to ensure that health issues are considered when transport policies are made (World Health Organization, 2020).

Taken together, the papers of our collection show research gaps in the many areas, but they also indicate solutions that can be implemented and contribute to improving security. Examples of efforts are presented in following articles: (i) Starkey and Charlton (ii) Khayesi (iii) Wang et al.. This depends upon the different perspectives of researchers and decision-makers.

Research conducted in many developed countries has confirmed that the number of fatalities and serious injuries resulting from road accidents could be reduced by applying an integrated approach to road safety (Mendoza et al., 2017; Marshall, 2018; Jamroz et al., 2019; Lasota et al., 2019, 2020). Such activities should be carried out within all facets of the road safety system, including transport, health care, supervision, law, and spatial planning.

After evaluating the effectiveness of actions aimed at improving road safety, it was concluded that many strategies and programs undertaken around the world contributed to the reduction of accidents and their consequences.

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In order to improve road safety and reduce the severity of injuries resulting from accidents, it is necessary to recognize the seriousness of road accidents as an urgent issue (Cassarino and Murphy, 2018). This requires cooperation among politicians, experts and practitioners from research and university centers dealing with road safety, road administration, emergency services, police and the media.

An essential tool for the effective prevention of injuries resulting from road accidents is the adoption of a systemic approach, which includes the following elements: problem identification, formulation of goals, preparation of programs and strategies, and monitoring the efficiency of the activities carried out (Yue et al., 2019).

Strategies and programs aimed at improving road safety should include the following actions: reduction of exposure to the hazards of accidents; prevention of accidents; reduction of injuries resulting from accidents; reduction of the effects of injuries through the improvement of post-treatment medical care (Goniewicz et al., 2016).

In order to improve road safety, it is necessary to strive for the change of legal provisions regarding the equipment of a car, and to intensify the educational activity in the field of first aid. As well as this, children of all ages should be exposed to intensive educational activities related to promoting road safety.

Undoubtedly there is still much research to be conducted in this area and the relevance of road safety is as great now as it ever was in addressing the challenges of sustainable and health. Nevertheless, only a solid assessment of costs and expected impacts can guide the design and implementation of a safe transport which represents an interplay between health and sustainable.

## AUTHOR CONTRIBUTIONS

KG: conceptualization. KG and DL: writing—original draft preparation. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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# Evaluation of Pedestrian Behavior on Mid-block Crosswalks: A Case Study in Fortaleza—Brazil

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In urban streets, pedestrians compete with vehicles for right-of-way. In some situations, it may be very challenging for pedestrians to deal with complex, sometimes hostile, traffic conflicts, especially in urban areas. This paper provides an exploratory analysis of pedestrian behavior on four types of mid-blocks crossing facilities in the city of Fortaleza, Brazil. The analysis was based on descriptive statistics and logistic regression models of variables related to signal control, facilities, and pedestrian characteristics and behavior. The models considered the following binary variables: (i) crossing vs. no crossing during pedestrian red phase; (ii) driver yielded vs. did not yield while pedestrian crossing; (iii) normal vs. aggressive/risked pedestrian behavior while crossing. A total of 2,400 crossings were considered in this study. The results show that, in general, the increase of traffic demand was related to easier crossings. Moreover, the presence of raised crosswalks increased in about 20 times the chances of a driver yielding to pedestrians in comparison to the marked-only crosswalk. In addition, the presence of mechanisms that facilitate pedestrian crossings such as raised crosswalks or traffic signals reduced the number of aggressive/risked crossings considerably.

**Keywords: pedestrian crossing, pedestrian facilities, pedestrian behavior, mid-block crosswalks, logistic regression models**

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## INTRODUCTION

Urban road infrastructure planners have traditionally maximized mobility and economic efficiency at the expense of safety, particularly for non-motorized road users. As motorization increases worldwide, walking has become more dangerous in many countries. Pedestrians accounts for 23% of all road traffic deaths, most of them in developing countries (World Health Organization, 2018). In many countries, mixed traffic makes pedestrians share the road with motor vehicles, forcing them to negotiate dangerous situations in fast-moving traffic. According to Elvik et al. (2009), ∼70% of the pedestrian crashes happen during crossing. Therefore, a key strategy for achieving a safe traffic system for pedestrians is to minimize the pedestrian-vehicle conflicts.

Crosswalks are the most essential and frequently used pedestrian facility to reduce the number of pedestrian-vehicles conflicts and therefore help reducing possible pedestrian fatalities in urban areas. There are different types of crosswalks that influence the pedestrian crossing process, which depend also on the available vehicle headways and on the pedestrian and driver behavior (Kadali and Vedagiri, 2016).

The literature shows that pedestrian crossing behavior is affected by demographic factors (e.g., age, gender), traffic characteristics (e.g., speed and flow), road environment (e.g., crossing walking distance, presence of traffic/pedestrian control devices and signals, road functional classification, vehicle volumes, weather, presence of crossing facilities), and subjective factors (e.g., perceptions and attitudes) (Bennett et al., 2002; Holland and Hill, 2007; Yannis et al., 2007; Harvad and Willis, 2012).

Econometric models, including discrete choice approaches founded on random utility theory, have been used to describe pedestrian behavior in urban streets (Cantillo et al., 2015). Earlier studies have proposed hierarchical logit models and multiple linear regressions to model pedestrian crossing behavior along an urban trip. A set of geometric and traffic characteristics as explanatory variables, such as walking and crossing distances, traffic volume, and the presence of crossing control devices have been used (Yannis et al., 2007; Zhou and Horrey, 2010). Li et al. (2013) pointed out that almost all pedestrians would speed up crossing the road at a crosswalk and adjust walking speed based on traffic gap.

The road infrastructure (i.e., number and width of lanes, the presence of pedestrian signals, marked areas, overpass, and medians) and trip purpose are two important factors affecting pedestrian crossing behavior (de Lavalette et al., 2009). Other factors are the traffic heterogeneity and signal programming, in the case of signalized intersections (Das et al., 2005).

Some studies suggest that pedestrian crossing behavior can vary according to age, gender, and whether the person is a driver (Cantillo et al., 2015). Usually, unobservable factors such as individual perceptions and attitudes are not considered in pedestrians crossing studies. Even though discrete choice models present good results, some of their assumptions are quite strong (Ortúzar and Willumsen, 2011). The inclusion of intangibles elements associated with pedestrians' perceptions and attitudes, expressed through latent variables, in discrete choice models could help to better understand how individuals behave. The main objective of this paper is to perform an analysis based on logistic regression models to analyze the pedestrian crossing behavior on four types of mid-block crossing facilities in the city of Fortaleza—Brazil.

# METHODS

This section is divided in two parts to explain the data collection and analysis, respectively.

## Data Collection

This study considered four pedestrian crossing types: (1) marked-only, (2) raised, (3) signalized, and (4) signalized with enforcement camera. The sites were selected considering the metropolitan area of Fortaleza City, Brazil (2.5 million inhabitants) from a list of sites based on the safety of the observers, type of control, traffic calming device, enforcement, and spatial coverage in the city.

After the evaluation of the potential sites, the selected locations are shown in **Table 1** and **Figure 1**. These sites are widely spread over the city of Fortaleza and traffic demand varies among the sites. It is important to note that this variability may mediate the results by representing different pedestrian and driver behaviors linked to a given site beyond the type of crosswalk. Considering the volume-capacity indicator as an explanatory variable was an approach to control for vehicular demands along the sites.

The data collection was conducted through direct field observations from June 12 to June 19, 2017. Each site was surveyed for 3 days (2 weekdays and 1 weekend day), from 7:30 a.m. to 12:30 p.m. and from 1:30 p.m. to 6:00 p.m. The observations were conducted by two observers: one observed the interaction between pedestrians and drivers and the other recorded the observations. In the beginning and in the end of each shift, the traffic volume was counted for a 15-min period to assess the vehicle demand level.

Each observation refers to the first pedestrian that arrived at the crosswalk, regardless if he/she will be joined by other pedestrians. For each observed crossing, the signal phase (if existed) was recorded. The characteristics of the pedestrian (sex and approximate age) and its behavior during the crossing (speed: walk/run; distraction: none/cell phone/headset/talking/other; and group size: alone/2 or more) were also recorded. The crossing behavior was classified into the following types:

1. Did not occur;
2. Normal crossing (when there is no conflict between pedestrian and vehicles);
3. Aggressive crossing (when the pedestrian behavior forces the vehicle to stop);
4. Risked crossing (when there is a conflict between the pedestrian the vehicle so that the vehicle needs to reduce its speed and/or the pedestrian needs to run).

The survey for sites 1 and 2 focused on the interaction between pedestrians and drivers during crossing. From the moment the pedestrian reached the crosswalk edge, the number of vehicles (by type: motorcycle, car/SUV, bus/minibus, and truck) that did not yield to him/her was observed. In cases that a driver yielded to the pedestrian, the vehicle type was noted.

The survey for sites 3 and 4 focused on the behavior of drivers and pedestrians during each signal phase, so the influence of signal phase on the crossing could be evaluated. During the pedestrian green, the number of vehicles that did not yield to pedestrians was recorded. During the pedestrian red, only the type of vehicle that stopped for the pedestrian (if any) was noted.

## Data Analysis

The data analysis is divided into two sections: (i) descriptive statistics and (ii) exploratory analysis. In the first section the data are represented in tables, so a general overview of the evaluated variables could be performed in the presented types of crosswalks. In the exploratory analysis, logistic regression models (LRM) were developed to explain the following binary response variables: (i) crossing vs. no crossing while pedestrian red phase in sites 3 and 4; (ii) driver yielded vs. did not yield while pedestrian crossing in sites 1 and 2; (iii) normal vs.

**TABLE 1 |** Selected sites—traffic volume and number of observations.

| Crosswalk type | Site address | Total traffic flow on all approaches (veh/h) | | #Observations | |
|---|---|---|---|---|---|
| | | Weekdays | Weekend | #Crossings | #Phases |
| 1 | Av. Francisco Sa, 6426 | 1,116 | 904 | 681 | – |
| 2 | Rua Barao de Aracati, 922 | 276 | 20 | 558 | – |
| 3 | Av. 13 de Maio, 2036 | 3,312 | 2,604 | 803 | 824 |
| 4 | Av. Frei Cirilo, 4314 | 1,284 | 916 | 358 | 402 |

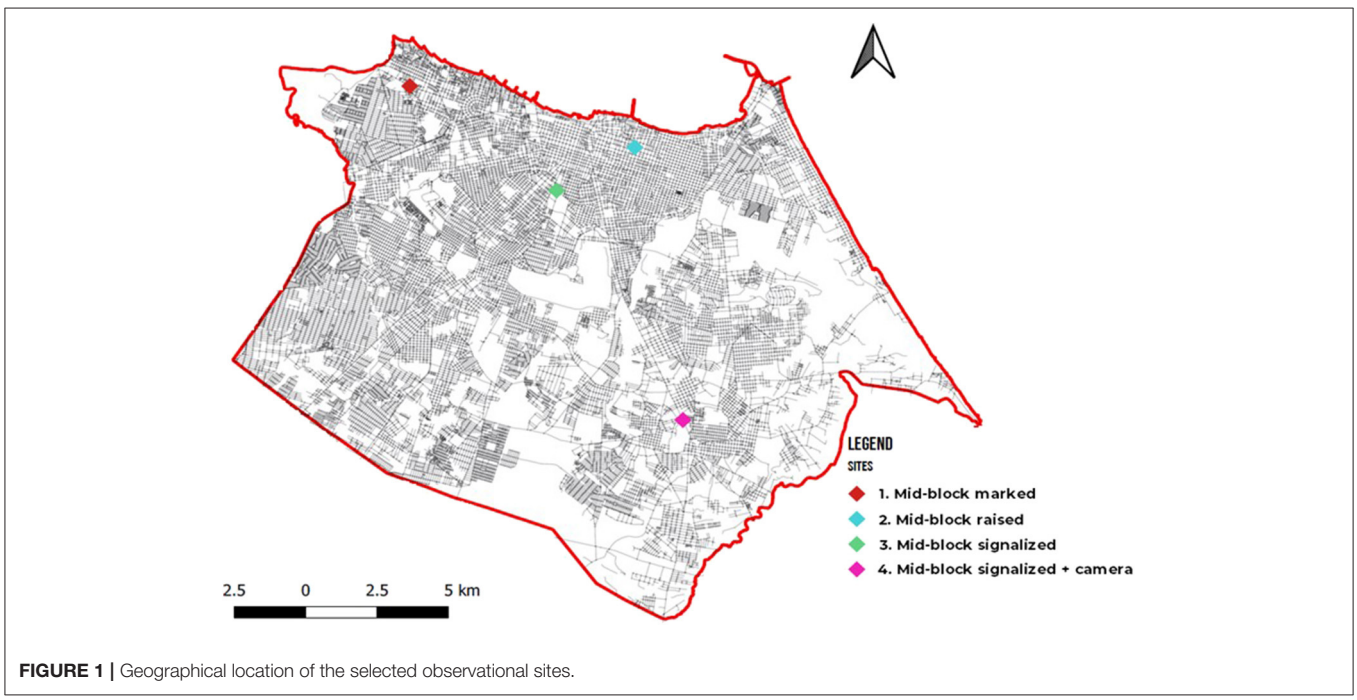


**FIGURE 1 |** Geographical location of the selected observational sites.

aggressive/risked pedestrian behavior while crossing in sites 1 and 2 and sites 3 and 4 during pedestrian red.

The type of crosswalk and the pedestrian/crossings characteristics were used as explanatory variables. A stepwise technique was employed to obtain the most significant factors ($p < 0.05$). Some statistics were implemented to interpret the results: (i) pseudo-$R^2$ based on the McFadden's $R^2$; (ii) Hosmer–Lemeshow test was used as the goodness-of-fit test, in which the predicted probabilities are divided into groups (commonly 10) and compared with the observed values applying the Pearson chi-square test; and (iii) odds ratio (OR) to estimate the influence of a variable in the response outcome value compared to a reference value.

Since the pedestrian crossing behavior may be influenced by vehicle demand and available gaps, it was decided to include the volume to capacity ratio (v/c) for each data interval. The vehicle capacity of each location was estimated by using VISSIM, one of the most widely used traffic simulation software packages. Some features that might impact the road capacity were inserted: number of lanes, signals cycle length and coordination, nearby bus stops, unsignalized intersections, and desired speed. The driver behavior parameters were kept at their default values.

# RESULTS

This section is divided into two parts. The first part presents a descriptive analysis of the data. The second part brings the results for the LRM.

## Descriptive Statistics

**Table 2** presents the descriptive statistics of the collected variables. The weather was recorded as light rain only in one of the survey shifts, so the influence of this variable cannot be measured.

In site 3, the percentage of teenagers was considerably higher than in the other crosswalks, as this crossing is located near an Educational Center, thus the incidence of running or distraction may be affected, if younger pedestrians are more likely to exhibit these types of behavior. **Table 2** also shows that v/c varies considerably among the sites, and since the behavior of pedestrians might be influenced by this variable, it was decided to account for it by including it as an explanatory variable.

**TABLE 2 |** Collected variables—descriptive statistics.

| Variable | Site | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Weather | | | | |
| 1: Dry/no rain | 92% | 100% | 100% | 100% |
| 2: Light rain/drizzle | 8% | 0% | 0% | 0% |
| Signal phase for Ped when He/She arrived | | | | |
| 1: Red for Pedestrian | – | – | 80% | 44% |
| 2: Green for Pedestrian | – | – | 20% | 56% |
| Crossed in | | | | |
| 1: Unmarked area | 58% | 50% | 4% | 14% |
| 2: Marked area | 42% | 50% | 96% | 86% |
| Pedestrian sex | | | | |
| 1: Male | 42% | 56% | 54% | 44% |
| 0: Female | 58% | 44% | 46% | 56% |
| Approximate pedestrian age range | | | | |
| 1: Child | 1% | 0% | 0% | 3% |
| 2: Teenager | 10% | 1% | 36% | 7% |
| 3: Adult | 77% | 76% | 55% | 73% |
| 4: Elderly | 12% | 23% | 9% | 17% |
| Number of people crossing | | | | |
| 1: Alone | 67% | 83% | 47% | 62% |
| 2: 2 or more | 33% | 17% | 53% | 38% |
| Estimated crossing speed | | | | |
| 1: Walk | 74% | 98% | 88% | 92% |
| 2: Run | 26% | 2% | 12% | 8% |
| Crossing distractions | | | | |
| 0: No | 91% | 93% | 87% | 96% |
| 1: Cell phone | 1% | 3% | 1% | 1% |
| 2: Headset | 0% | 0% | 2% | 0% |
| 3: Talking | 4% | 4% | 10% | 3% |
| 4: Other | 4% | 0% | 0% | 0% |
| Type of crossing | | | | |
| 0: Did not occur | 2% | 0% | 3% | 11% |
| 1: Normal | 52% | 92% | 74% | 82% |
| 2: Aggressive | 8% | 1% | 15% | 0% |
| 3: Risked | 38% | 6% | 8% | 7% |
| V/C | | | | |
| Minimum | 35% | 35% | 51% | 11% |
| 25° percentile | 43% | 37% | 81% | 20% |
| Median | 47% | 38% | 53% | 32% |
| 75° percentile | 50% | 47% | 90% | 34% |
| Maximum | 61% | 51% | 100% | 45% |

## Exploratory Analysis

In this section the results for the three LRM are presented. For models 1 and 3, which evaluate the pedestrian behavior, each observation relates to a pedestrian. For model 2, which focus on driver behavior, each observation consists of a driver yielding decision. **Table 3** presents the statistically significant variables and the results for each LRM developed.

The model assumption of little multicollinearity was verified. The variance inflation factor (VIF) was lower than 1.5 for all variables in all models. Regarding the Hosmer–Lemeshow test, there is no evidence of poor fit in any of the models ($p > 0.05$ for all of the models).

**TABLE 3 |** Logistic regression models results.

| Model | Variable | Variable category | Odds ratio |
|---|---|---|---|
| 1) Signalized mid-block: crossing occurrence during red phase for pedestrian<br>0: Did not happen<br>1: Happened<br>$N = 838$<br>McFadden $R^2$: 0.21<br>Hosmer–Lemeshow ($p$-value): 0.99 | V/C | 0–33% | Ref |
| | | 34–66% | 1.45 |
| | | 67–100% | 17.75** |
| | Age | Adult | Ref |
| | | Child | 0.06* |
| | | Teenager | 0.59 |
| | | Elderly | 0.78 |
| | Crossing area | Unmarked area | Ref |
| | | Marked area | 0.14** |
| 2) Unsignalized mid-block: driver yielding to pedestrian<br>0: Did not yield<br>1: Yielded<br>$N = 3{,}304$<br>McFadden $R^2$: 0.29<br>Hosmer-Lemeshow ($p$-value): 0.63 | V/C | 30–40% | Ref |
| | | 41–50% | 0.93 |
| | | 51–62% | 2.13* |
| | Group | Alone | Ref |
| | | More than 1 | 1.92** |
| | Crosswalk type | Marked-only | ref |
| | | Raised | 20.76** |
| | Crossing area | Unmarked area | Ref |
| | | Marked area | 7.15** |
| | Vehicle type | Car | Ref |
| | | Motorcycle | 0.63* |
| | | Bus | 1.74 |
| | | Truck | 2.09* |
| 3) All sites: type of crossing during red phase for pedestrian<br>0: normal crossing<br>1: aggressive/risked crossing<br>$N = 2{,}001$<br>McFadden $R^2$: 0.12<br>Hosmer-Lemeshow ($p$-value): 0.14 | Crosswalk type | Marked-only | ref |
| | | Raised | 0.09** |
| | | Signalized | 0.54** |
| | Sex | Female | ref |
| | | Male | 1.37** |
| | Crossing area | Unmarked area | Ref |
| | | Marked area | 0.58** |

*Significance level: (*) < 0.05; (**) < 0.01.*

The OR should be interpreted based on the comparison with the reference value. In model 1, for instance, the OR of 17.75 for the third category of v/c indicated that—holding other variables constant—the odds that $Y = 1$ (meaning crossing happened) is on average 17.75 times higher when the v/c is between 67 and 100% than when v/c is around 0–33%.

## DISCUSSION

Model 1 evaluates the crossing occurrence during red phase for pedestrian in the signalized sites. The presence of the camera enforcement in site 4 was not a significant variable. Regarding the v/c, it can be noticed that during conditions with increased vehicular demand crossings were more likely to happen (OR = 17.75). This finding might be associated with the saturated

traffic flow conditions specially where the signalized crossing is relatively close to other signalized intersections. In such conditions, vehicles may be subjected to frequent stops, allowing pedestrians to cross easier during the pedestrian red to save time and for convenience, according to pedestrian perception (Ren et al., 2011). Concerning the pedestrian age, the results from Model 1 show that children were more inclined to wait for the green for pedestrian than the other age categories (OR = 0.06). In respect to the crossing area, the pedestrians that attempted to perform the crossing in the marked area were also more likely to wait for the green for pedestrian that those who crossed in the unmarked area (OR = 0.14). This is probably related to the occurrence of large gaps in the traffic flow that motivates the pedestrian to cross before he/she reaches the crosswalk, without the need of the signal control to stop the vehicles.

Model 2 assesses the driver yielding to pedestrians in sites 1 and 2 based on characteristics of the pedestrians, the vehicle type and the crosswalk facility. Surprisingly, drivers tended to yield more for pedestrians when the v/c was higher (OR = 2.13). One may expect that in situations that there are fewer vehicles, drivers are more confident to yield to pedestrians, mainly because it would be less likely the occurrence of read-end crashes. One hypothesis for that result, however, is that in conditions with more traffic, the vehicular speed is usually lower, therefore drivers may be inclined to respect more the pedestrians. Referring to pedestrian group size, drivers tended to yield more when there were more than one person aiming to cross (OR = 1.92). This finding was also seen in Dommes et al. (2015).

With regards to the crossing facility, the presence of the raised crosswalk increased significantly the rate of driver yielding (OR = 20.76). This result is consistent with the work of Huang and Cynecki (2001), who observed an increase of ∼50% in the rate of yielding with the installation of both raised crosswalk and overhead flasher. This may be explained by fact that drivers must reduce the speed to pass through the raised facility and that the traffic environment around local 2 is quieter than in local 1.

Regarding the crossing area, the results demonstrate that drivers were more inclined to yield to pedestrians that were at the marked area than to ones that were at the unmarked area (OR = 7.15). Lastly, as for the vehicle type, motorcycles yielded less to pedestrians than cars did (OR = 0.63). This was somehow expected, since in the city of Fortaleza the motorcyclists usually drive more aggressively and faster than the other types of drivers do (Torres et al., 2018).

Model 3 evaluates the type of crossing (normal or aggressive/risked) around all locations. As the presence of camera enforcement was not significant for the model, sites 3 and 4 were grouped into one category: signalized sites. The v/c was not statistically significant. Concerning the crosswalk type, the raised site presented the fewest level of aggressive/risked crossing (OR = 0.09), followed by the signalized sites, which were safer than the marked-only site (OR = 0.54). Relative to pedestrian gender, it can be noted that males tended to perform more aggressive/risked crossings than females did (OR = 1.37). Finally, the crossings performed in the marked area were less risky than the ones in the unmarked area (OR = 0.58). This finding was also seen in Rosenbloom (2009) and Zhuang and Wu (2011), but it is not consolidated in the literature (Ren et al., 2011).

## CONCLUSION

This research evaluated the behavior of pedestrians when crossing four types of mid-block crosswalks in the city of Fortaleza-Brazil. Exploratory analyses were done by logistic regression models. The types of control (with or without camera enforcement), facilities (marked-only, raised or signalized), pedestrian age, gender and its behavior while crossing (speed, distraction, run/walk, and group size) and driver yielding to pedestrians were evaluated. The analyses focused on three aspects: (i) crossing vs. no crossing while pedestrian red phase in sites 3 and 4; (ii) driver yielded vs. did not yield while pedestrian crossing in sites 1 and 2; (iii) normal vs. aggressive/risked pedestrian behavior while crossing in sites 1 and 2, and sites 3 and 4 during pedestrian red.

In general, it was concluded that crossings during the pedestrian red phase in the signalized sites tended to happen more when the traffic demand high. Also, drivers yielded more to pedestrians in the unsignalized sites in medium to high traffic flow demand. Still regarding the driver yielding, it could be noted that the presence of the raised facility increased in about 20 times the number of drivers that yielded to pedestrians in comparison to the marked-only crosswalk. In relation to aggressive/risked crossings, it was shown that the existence of mechanisms that help pedestrian crossing, such as raised crosswalk or traffic signals, reduced considerably those types of undesirable crossings.

As limitations of the study, it is important to note that although the v/c was controlled, there may be differences in traffic volumes, as well as in demographic and socioeconomic characteristics surrounding the sites that may affect the results and create a confounding effect when comparing different types of crosswalks. In order to improve the comparison among sites, more observations and analyses controlling for these variables should be conducted. Finally, it is important to highlight that this study was conducted in only one city, so the results may not be generalized for other places.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## AUTHOR CONTRIBUTIONS

CT, LS, MC-N, and FC: study conception and design. CT, LS, MC-N, FC, AV-O, KA, AH, and AB: analysis and interpretation of results and draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Regulatory and Road Engineering Interventions for Preventing Road Traffic Injuries and Fatalities Among Vulnerable Road Users in Low- and Middle-Income Countries: A Systematic Review

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Low- and middle-income countries have the highest proportions of road accident fatalities among vulnerable road users. This review established the effectiveness of road engineering and the enforcement of traffic laws, and regulation interventions to prevent injury (fatal and non-fatal) to vulnerable road users from low- and middle-income countries. We searched the following databases up to Jan 04, 2018: PubMed; OvidSP Medline, OvidSP Embase, OvidSP Transport, Cochrane Injuries Group Specialized Register, Cochrane Central Register of Controlled Trials, and Proquest ERIC database. In addition, road safety organizations' databases and conference proceedings were hand searched to Jan 2018. Twenty-eight studies were matched to the study inclusion criteria of which we did not analyze six studies assessed as C grade for risk-of-bias. We estimated the effect-size of 18 studies. Four of the studies presented a unique outcome or a study design; it was not possible to calculate a standardized effect-size. The risk-of-bias rating of the studies included for effect-size analysis ranged between A and B grade. There was no evidence that road engineering interventions were effective for road traffic death counts, the number of injuries, and road accident casualty outcomes. While the enforcement of mandatory helmet law was ineffective in reducing road traffic death counts, intervention efforts proved effective in decreasing injuries. Enforcement of mandatory helmet law, automated-enforcement-system (camera), and pedestrian signal interventions were effective in increasing road users' compliance with road safety laws. Daytime running-headlight intervention reduced the number of road accident casualties. The quality of evidence for outcomes was ranked very low. Further research is needed to examine the effects of road engineering interventions on injury severity outcomes. Even though the evidence was of very low quality, traffic laws, and regulation interventions when combined with enforcement initiatives or with, other approaches proved effective in changing drivers' behaviors. Research on road engineering interventions combined with automated-enforcement-systems must be explored in an Low- and Middle-Income Country (LMIC) setting. The review found evidence gaps on the effects of segregation of vulnerable road users from motorized vehicles, changes in intersections, and bicycle infrastructure interventions.

**Keywords: enforcement, engineering, road safety, fatality, injury, motorcycle, pedestrian, LMIC**

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## INTRODUCTION

The UN Decade of Action for Road Safety 2011–2020 Sustainable Development Goals aimed to reduce road traffic deaths by 50% by 2020. While it has made some progress, the number of road traffic deaths and injuries remains high (World Health Organization, 2018). About half of the world's road traffic deaths occur among motorcyclists (23%), pedestrians (22%), and cyclists (5%) also known as "vulnerable road users" (World Health Organization, 2018). Road traffic deaths among vulnerable road users are a major public health problem in low- and middle-income countries (LMICs) where walking, cycling, and motorcycling are predominant transport modes. Pedestrians and cyclists were the largest group of victims of road fatalities in Bangladesh, at 44% (World Health Organization, 2013). In India, 78 and 53% of those killed on the roads in Mumbai and Delhi respectively were pedestrians (Mohan et al., 2009). Some studies have placed pedestrian fatalities in Mexico as high as 48% (Bartels et al., 2010). In Nairobi, Kenya, vulnerable road users accounted for 54% of all road fatalities (Kim and Dumitrescu, 2010). Pedestrians accounted for 43% of all road traffic fatalities in Ghana (World Health Organization, 2013).

Research has shown that traffic speed measures are essential to prevent road injuries among vulnerable road users (Elvik, 2001; Allsop, 2010; Wilson et al., 2010). Bicycle infrastructure reduces injury risks (Reynolds et al., 2009; Lusk et al., 2011; Harris et al., 2013), while regulatory and legislative interventions play a significant role in lessening the severity of injuries (Redelmeirier et al., 2003; Chisholm, 2008; Blanco et al., 2017). Although many LMICs have implemented road safety strategies, compliance and law enforcement are often limited. The common challenges for preventing road traffic injuries among vulnerable road users in LMICs include mixed road conditions, negative perceptions of road safety among non-motorized road users, non-use of helmets or use of non-standard helmets, alcohol, and speed (Vasconcellos, 2001; Nantulya and Reich, 2003). The new regulatory approach called the safe system approach, which focuses on the institutional level deployment of large-scale safety interventions, had a positive effect on road safety in high-income countries. Political will, leadership, active public sector participation, and full support of the private sector and civil societies are considered vital to move in the direction of a safe system approach (ITRAC, 2008; Wegman, 2017). From a public health perspective, the safe system approach framework has several benefits for examining key risk factors for vulnerable road users in LMICs. For instance, two-wheelers are used as the primary mode of transport in many LMICs. Research (International Transport Forum, 2015) shows that the mean age of motorcycle crash victims in LMICs is 25. Other studies have found that the chances of young motorcycle crash victims in the 17–19 years age group from a lower-income group is 2.5 times greater than their peers in higher socioeconomic groups (Huang and Lai, 2011; de Vasconcellos, 2013; International Transport Forum, 2015). The loss of life or disability causes a big economic burden on individuals and households from poorer backgrounds and has a direct negative effect on the national economy.

Nevertheless, institutional level reforms for road safety have received little attention in LMICs. Major barriers include under-reporting of road crash data as well as limited amount of disaggregated data on road crash fatalities, injuries and intermediate outcomes in crash databases, a lack of technical expertise, and a lack of coordination between agencies responsible for road safety management and amongst different levels of governments (International Transport Forum, 2016).

In the light of increasing road traffic deaths and low levels of public investments in road safety measures, international agencies began getting involved in improving road safety conditions in LMICs during the 1990's. World Bank's Global Road Safety Partnership (1999), World Bank's Global Road Safety Facility (2006), Bloomberg Philanthropies "Road Safety in 10 Countries Project—RS-10" (2009), and the United Nations General Assembly Resolution "Decade of Action for Road Safety (2011 to 2020)" (2011) aimed to implement road safety measures in collaboration with national stakeholders, non-governmental organizations, and academic institutions of LMICs. Because of increased sensitization of local and civic organizations, the establishment of national coordinating committees and road safety programs, and some improvements in systems for data collection and analysis, successful road safety intervention implementation practices have emerged (Bishai and Hyder, 2006; Esperato et al., 2012; Commission for Global Road Safety, 2013).

Published reviews on the effects of road infrastructure interventions have focused on interventions for road users in high-income settings (Perel et al., 2007). The lack of studies on road safety from LMICs in systematic reviews could be because of the focus on stand-alone road infrastructure interventions and inclusion criteria to include high-quality study designs only. Furthermore, many of the interventions examined in high-income settings are developed after considerable research and testing. In LMICs, the challenge is to transfer the knowledge gained in developed countries in a fraction of the time. In addition, the interventions need to be tested for cost and design effectiveness as well as the legal system for implementing road infrastructure interventions need to be developed to similar standards practiced in developed countries. LMICs should avoid repeating studies showing the effectiveness of road safety measures in high-income country settings because of contextual differences (Wegman, 2017).

In this context, a review of the evidence of road infrastructure interventions was conducted to provide a quantification of the effects of road safety interventions in LMICs. The review focused on the LMIC context, not the sophistication of the intervention. The findings of this review provide valuable, and contextually relevant, data for road safety policy making in LMIC settings.

The purpose of this review was to measure the effects of road engineering and enforcement of traffic laws and regulation interventions for the prevention of injury (fatal and non-fatal) to vulnerable (non-motorized and motorized two-wheel) road users in low- and middle-income countries. This review included randomized controlled trials and non-randomized study designs and the comparator was no intervention.

# METHODS

We reported this systematic review under the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) Statement (Moher et al., 2009) (**Table S1**). The protocol of the review was published in the Cochrane Database of Systematic Reviews (Gupta et al., 2015).

## Types of Studies

The review included randomized-controlled-trials (RCT) and non-randomized study designs: controlled before-and-after, uncontrolled before-and-after, interrupted time-series (ITS), and case-control.

Included studies compared changes in outcomes before and after the intervention implementation with or without a control group. For ITS, studies had a defined point in time when the intervention occurred and included data at least three time-points before and three time-points after the intervention. The intervention implementation was at the population level or the individual level, or both. Participants' selection was by the outcome; hence, outcome reporting was at the individual level.

This review did not include black spot identification studies and modeling studies.

## Types of Participants

In this review, "vulnerable road users" included all vulnerable road users —pedestrians, those using non-motorized means of transport (NMT), and those using motorized two-wheelers (motorcycles, mopeds, and light mopeds) inclusive of all ages in LMICs. The World Bank definition of NMT (World Bank, 1993) defines "vulnerable road user" by the amount of protection they have from other motorized traffic. Pedestrians, cyclists, and riders of two-wheelers are unprotected; hence, they are referred to as "vulnerable."

The World Bank definition of LMICs was used to classify low- and middle-income countries. As of July 1, 2018, low-income economies are those with a GNI per capita of $1005 or less; middle-income economies are those with a GNI per capita of more than $1006 but <$3,995.

## Types of Interventions

Three broad categories of interventions, road engineering, enforcement of traffic laws and regulation, and a combination of road engineering, and regulatory and legislative interventions were included. Alongside this, a combination of one or more of these interventions as well as with other approaches were considered.

Road engineering interventions are preventive measures involving engineering or structural changes to the road design that affect road user behavior. Road engineering interventions covered in the review comprise three sub-categories: (1) measures for reduction in vehicle-speed, (2) changes in intersections, and (3) segregation of non-motorized road users from motorized vehicles.

Enforcement of traffic laws and regulation interventions refers to setting up road safety rules and ensuring compliance from road users through legal enforcement. Regulation interventions focused on regulatory approaches that can affect large populations through law enforcement such as speed cameras, speed limits, speed zones, red-light enforcement cameras, use of daytime running-lights for two-wheelers, mandatory helmet law, traffic signal regulation, and stop signs.

A combination of road engineering and regulatory interventions includes segregated or on-road marked bicycle lanes involving specific road changes at junctions and intersections, bus rapid transit system with motorcycle lanes, pedestrian crossing, rumble strips on bus rapid transit system, and speed limit enforcement with speed reduction measures.

Comparisons: Comparison of intervention vs. no intervention.

## Types of Outcome Measures

This review studies reporting data on at least one of the following primary or secondary outcomes.

### Primary Outcomes

(1) Road traffic death counts; (2) Road traffic death rates expressed as rate per 100,000 inhabitants or rate per kilometer of road year; (3) Number or proportion of severe injuries (Injury Severity Score (ISS) > 17, Glasgow Coma Scale (GCS) 9 to 12) and moderate injuries (ISS 8 to 16, GCS 3 to 8); (4) Number or proportion of road accident casualty[1]; and, (5) Number or proportion of disabilities (severe [Glasgow Outcome Scale (GOS) = 4) and moderate (GOS = 3)].

### Secondary Outcomes

(1) Compliance; (2) Number or proportion of head-on collisions; (3) Number or proportion of rollovers; (4) Mean-vehicular-speed; and, (5) Mean cost of road crashes.

Outcome data on adverse impacts were extracted from all included studies, if available.

## Search Methods for Identification of Studies

Terms describing population and interventions were combined in the final search strategy. The final draft search strategy for bibliographic databases consisted of the following combinations: "Population and Intervention," "Population and Study type," and "Population and Outcomes." The search strategy was adapted for each database; for details, see search strategies for bibliographic databases (**Appendix 1**).

We searched the following bibliographic databases: PubMed; Ovid MEDLINE (1966–2018); EMBASE (1980–2018); ERIC (1966–2018); Cochrane Injuries Group Specialized Register; the Cochrane Central Register of Controlled Trials; TRANSPORT database [(combines records from Transport Research Information Service, International Road Research

[1]According to the Oxford dictionary, second definition of the "casualty" noun (hospital): "emergency room, the part of a hospital where people who are hurt in accident or suddenly become ill are taken for treatment." Included studies have extracted road traffic accident and injury outcome data from police reported road traffic accidents that either required medical assistance or were hospitalized. Thus, the "number or proportion of road accident casualty" defines the number or proportion of road traffic accidents.

Documentation, and TRANSDOC(1980–2018)]; World Bank Impact Evaluation Working Paper Series; Poverty Impact Evaluation database; Development Impact Evaluation (DIME) Database; JOLIS Library catalog; Latin-American and Caribbean Center on Health Sciences Information (LILACS) database; global Transport Knowledge Practice (gTKP); The Institute of Transportation Studies at the University of California; Monash University Accident Research Centre; TRANweb database; and Google Scholar.

In addition, we searched the following road safety organizations' databases: Transport Research Laboratory (TRL), Australian Road Research Board (ARRB), AMEND, African Development Bank (AfDB), Asian Development Bank (ADB), The African Community Access Program (AFCAP), Crash Modification Factors Clearing House, Central Road Research Institute (CRRI), Department for International Development (DFID), International Road Assessment Program (iRAP), International Road Federation (IRF), Global Road Safety Facility (GRSF), Global Road Safety Partnership (GRSP), EMBARQ -The World Resource Institute Center for Sustainable Transport (EMBARQ), Sub-Saharan Africa Transport Policy Program (SSATP), Transport Research and Injury Prevention Program (TRIPP), Organization of Economic Cooperation and Development (OECD), Road Engineering Association of Asia and Australia (REAAA), Road Traffic Injury Research Network (RTIRN).

Further to this, we checked reference lists of selected papers and we hand-searched conference proceedings. We have considered 1990 as a cut-off for the identification of studies analyzing road infrastructure interventions.

## Data Collection and Analysis

A team of two authors have screened the titles and abstracts and identified eligible studies independently. The full text of all eligible studies was obtained. Based on the study inclusion criteria, two authors conducted a full-text review for eligibility independently, and study inclusion differences were reconciled by a discussion between the two authors.

Full text of studies was screened in detail, and data from each study were extracted by one review author and checked by a second review author. Disagreements were resolved by discussion.

Where data were missing; we attempted to obtain the data from the authors. If we were unable to obtain missing data, we analyzed only the available data.

### Assessment of Risk of Bias in Included Studies

The quality of all studies (RCTs and non-randomized studies) were assessed using the Hamilton Assessment Tool (HAT) (Thomas, 1998). We proposed some modifications under the "Confounding" domain of the HAT tool to ensure that it is appropriate for studies of road infrastructure interventions. Please see the Hamilton Assessment Tool (**Appendix 2**).

Two independent review authors assessed the quality of all studies using the HAT tool. Each component was first assigned a global rating (Strong = 1, Moderate = 2, Weak = 3) indicating the overall potential for bias in each component. Each study was assigned an overall risk of bias assessment rating. The criteria for an overall risk of bias assessment rating of a study were as follows: studies with no weak ratings were assessed as A grade, studies with one or two weak ratings were assessed as B grade. And, studies having very serious (more than two weak ratings) on study design, confounders, and data collection methods used were excluded as C grade studies. Intervention integrity and analysis domain were not included in the assessment of the overall risk of bias ratings. Disagreements in the assessment of bias were resolved through discussion between the two review authors.

Based on the HAT tool, studies assessed with low risk of bias (that is two or more studies with an overall grade of A or B) were quantitatively synthesized using meta-analysis. We excluded C grade studies from meta-analysis and narrative synthesis.

### Measures of Treatment Effect

For uncontrolled before-and-after studies, we presented the dichotomous outcome data[2] using Odds Ratio (OR) with 95% confidence intervals (CI). For controlled before-and-after studies, we extracted the dichotomous outcome data for treatment and control sites and calculated the ratio of the differences in event rates before and after intervention in the treatment site by a corresponding difference in the control site.

For uncontrolled before-and-after studies, we presented the continuous outcome data[3] by calculating the mean difference with 95% CI. For continuous outcome data in controlled before-and-after studies, we calculated the difference in outcome data before and after intervention in the intervention site by the corresponding difference in the control site. We used mean differences (MDs) with 95% CI when the same scale was used and standardized mean differences (SMDs) with 95% CI when a different scale was used in studies. For time-series studies, we extracted the outcome data for calculating risk ratios (RR) using R software. The studies considered in this meta-analysis have road traffic death count or accident casualties as an outcome. The outcome being a count, a Poisson regression model was used to estimate the effects of intervention after adjusting for a linear trend in time.

We assessed statistical heterogeneity using the $Chi^2$ and $I^2$ statistics. A meta-analysis of effect sizes was conducted using a random-effects model.

### Unit of Analysis

Road engineering and legislative interventions were implemented to individual roads meeting pre-specified criteria or to all roads within a targeted community or a geographical

[2]In before-and-after studies with dichotomous outcome data, the individual study findings are displayed as "n/N," whereby: $n$ = the number of outcome events (e.g., fatality or helmet use compliance count) in the after intervention period (intervention group) or before intervention period (control group), and $N$ = the total number of outcome events in the interventions group or control group.

[3]In before-and-after studies with continuous outcome data, the individual study findings are given as "N" and "mean (SD)," whereby $N$ = the total number of outcome events (e.g., road accident causality or red-light running count) in the after intervention period (intervention group) or before intervention period (control group) and mean $SD$ = the arithmetic mean and standard deviation (SD) of the outcome measure in either the intervention or control group.

area. However, the reporting of outcomes was done at individual levels. In cases where a study had multiple intervention groups, data from all relevant intervention groups of the study were combined into a single group, and data from all relevant control groups were combined into a single control group.

### Data Synthesis

For data synthesis, studies were grouped by intervention categories: road engineering, enforcement of traffic laws and regulations, and a combination of road engineering and enforcement of traffic laws and regulations. Under these categories, studies were grouped by randomized and non-randomized study designs. The data from randomized and non-randomized studies were presented by (1) primary outcomes: road traffic death counts, number of injuries (moderate and severe), and number of road accident casualty; and (2) secondary outcome: compliance.

We did not synthesize data from road infrastructure and enforcement of traffic laws and regulations intervention categories together. We reported meta-analysis results of randomized control trials and non-randomized studies separately.

If there was extreme heterogeneity, we presented the effect sizes of those studies graphically using forest plots, and a narrative synthesis of the data were presented according to the ESRC guidance (Popay et al., 2006). All the data to be synthesized were predominantly quantitative; we found vote counting and developing a common rubric the most relevant for the synthesis at hand. The vote counting and a common rubric were developed by using two approaches: (1) using a tick mark where the effect of the intervention was positive and overall statistical significance, and (2) analyzing absolute measure of effect. Two software packages were used for meta-analysis. The RevMan was used for uncontrolled before-and-after and controlled before-and-after studies. Effect sizes for time-series studies were computed using R Statistical Software (**Appendix 3**) because RevMan is not suitable for meta-analyzing data for time-series studies.

### Sensitivity Analysis

Before making decisions about which studies should be included in the final syntheses, a sensitivity analysis was conducted to examine variation in reported effects by study characteristics. The key study characteristics used for sensitivity analysis were: in between-study heterogeneity, missing data, and the overall study quality grade assigned.

We considered a sensitivity analysis about the influence of small study effects on the result of the meta-analysis when there was evidence of between-study heterogeneity. We compared the fixed and random-effects estimates of the intervention effect. We performed a sensitivity analysis by excluding studies of the lowest quality.

We examined funnel plots and cumulative meta-analysis to assess the potential for publication bias in the included studies.

#### *GRADE and summary of findings tables*

A team of two authors was involved in conducting GRADE assessments. GRADE domains, risk-of-bias, indirectness, inconsistency, imprecision of results were primarily considered for assessing the quality of evidence.

### Patient and Public Involvement

The review did not involve any patients or the public.

## RESULTS

## Results of Search

The systematic search was conducted in January 2018. We identified 30,030 study records through database searching. Twenty-eight studies matched the study inclusion criteria; the search flow chart (**Figure 1**) details the search process.

## Included Studies

Twenty-eight studies matching study inclusion criteria were identified. Twenty-two studies were included for analysis and six studies were not analyzed because the outcome data did not qualify for analysis (**Figure 1**).

## Study Characteristics

Notably, 21 studies belonged to middle-income countries and one study belonged to low-income countries.

Study designs included one cluster randomized-control-trial (Sumner et al., 2014), one case-control (Quistberg et al., 2014), one controlled before-and-after (Liu et al., 2011), five time-series (Radin Umar et al., 1995a,b; Radin Umar, 2005; Espitia-Hardeman et al., 2008; Nadesan-Reddy and Knight, 2013) and 14 uncontrolled before-and-after studies (Panichaphongse et al., 1995; Chiu et al., 2000; Liberatti et al., 2001; Afukaar, 2003; Ichikawa et al., 2003; Bastos et al., 2005; Hoque et al., 2005; Bhatti et al., 2011; Antic et al., 2013; Lipovac et al., 2013; Nguyen Ha et al., 2013; Allyana et al., 2014; Van der Horst et al., 2016; Nhan et al., 2017).

There were seven studies on the impact of road engineering interventions (Radin Umar et al., 1995b; Afukaar, 2003; Hoque et al., 2005; Liu et al., 2011; Antic et al., 2013; Nadesan-Reddy and Knight, 2013; Van der Horst et al., 2016). Fourteen studies reported the impact of enforcement of traffic laws and regulation interventions (Panichaphongse et al., 1995; Radin Umar et al., 1995a; Chiu et al., 2000; Liberatti et al., 2001; Ichikawa et al., 2003; Bastos et al., 2005; Radin Umar, 2005; Espitia-Hardeman et al., 2008; Bhatti et al., 2011; Lipovac et al., 2013; Nguyen Ha et al., 2013; Allyana et al., 2014; Sumner et al., 2014; Nhan et al., 2017).

In addition, one study (Quistberg et al., 2014) included a combination of regulatory and road engineering interventions.

All studies examined one or more of the primary or secondary outcomes. Some studies reported only primary outcome measures: road traffic death counts, the number of injuries (moderate and severe), and the number of road accident casualty. Some studies reported only secondary outcome measures: compliance and mean-vehicular-speed.

One study (Allyana et al., 2014) presented outcome data for two sub-categories of enforcement of traffic laws and regulation interventions separately. Outcome data were extracted and assessed as they related to the sub-category automated-enforcement-system (camera)—red-light regulation

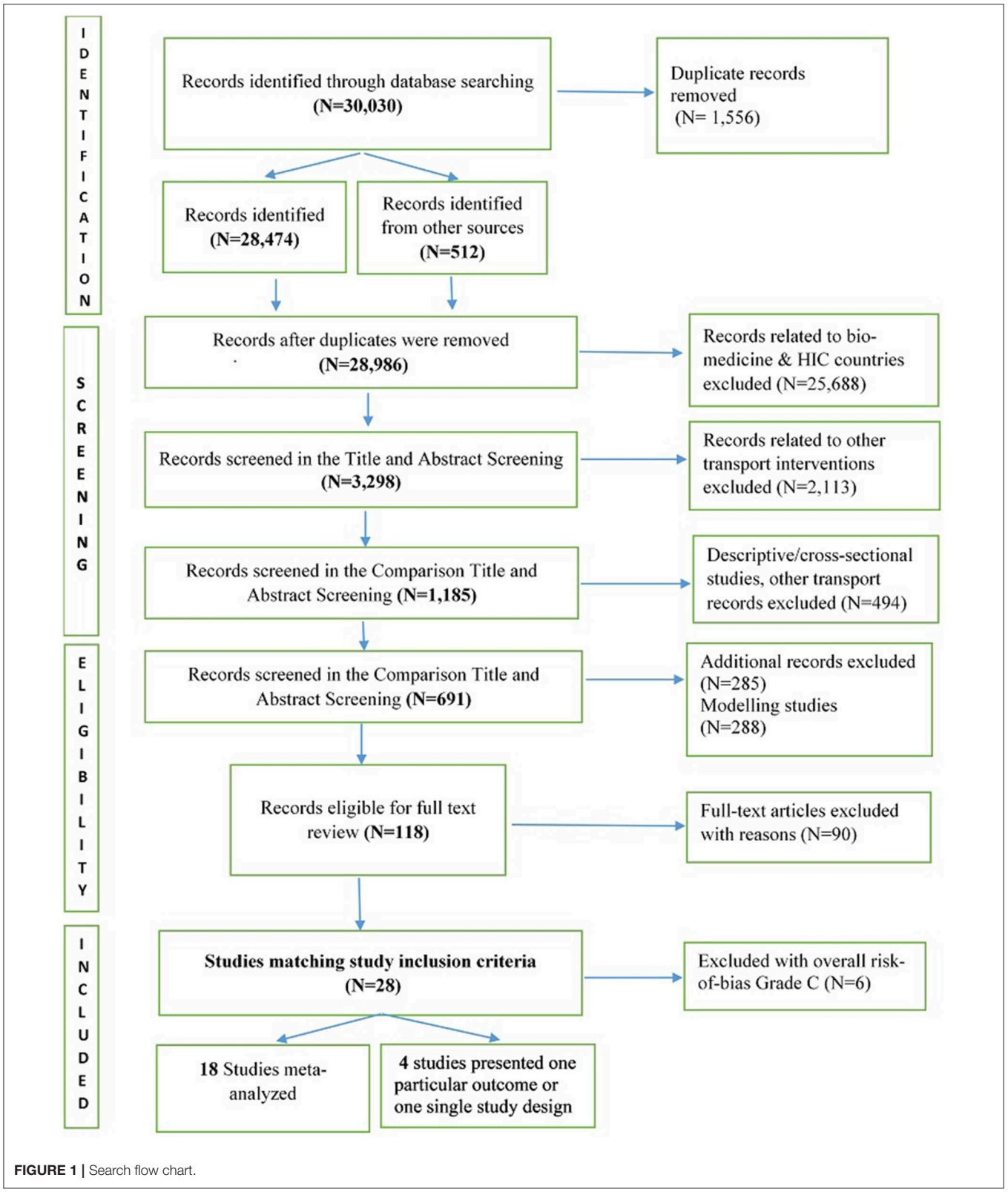


**FIGURE 1 |** Search flow chart.

into one group, and as they related to the sub-category automated-enforcement-system (camera)—speed limit into another group.

One study (Hoque et al., 2005) evaluated controlled before-and-after analysis of safety improvements at three black spots, and before-and-after analysis of road engineering safety measures

at two different site segments. Outcome data were extracted and assessed for the before-and-after analysis of road engineering safety measures only.

Included studies did not report the following primary and secondary outcome measures: moderate and severe disabilities (primary outcomes), the number, or proportion of rollovers, and mean cost of road crashes (secondary outcomes).

One study (Espitia-Hardeman et al., 2008) reported the outcome, the number of road traffic death rates expressed as the rate per 100,000 inhabitants. One before-and-after study (Afukaar, 2003), one case-control study (Quistberg et al., 2014), and one time-series study (Radin Umar et al., 1995b) reported the number of head-on collisions. One study (Nadesan-Reddy and Knight, 2013) reported pre-specified adverse outcome, increase in the collision between motor vehicles because of traffic calming measure speed humps. Because of an insufficient number of studies, we did not meta-analyze these outcome results.

For characteristics and the role of the funding source of studies analyzed, see the summary table of characteristics of studies included for meta-analysis (**Table 1**).

## Risk-of-Bias Assessment

The majority of the studies included in this review are observational and therefore subject to risk-of-bias in terms of making a causal inference of the effect of road safety interventions.

### Selection Bias

Intervention sites in almost all studies were somewhat or most likely to represent the target population. Based on HAT ratings, studies ranked between strong and moderate for selection bias.

### Study Design

Based on HAT ratings for study design criteria, one cluster RCT was rated strong for study design. Seven studies having time-series, controlled before-and-after, and case-control study designs were rated moderate. Time-series studies were short period time-series studies using monthly data extending at the most 1 year before and 1 year after the intervention. The controlled before-and-after study reported controlling for confounders by matching treatment and comparison sites on geographic characteristics of roads/location and the same period. The case-control study observed a short time-period for pedestrian and vehicle-flow, but the collision dates and data collection did not happen contemporaneously. However, the study explored the impact on the time difference and found no significant changes.

### Confounders

All before-and-after studies adequately controlled for some essential confounders related to road infrastructure interventions such as exposure effect (in traffic volume, area type, geometric design, and type of intersection) before and after the intervention implementation and outcome ascertainment (outcome reporting for non-motorized road users or having road traffic injuries only). For road engineering interventions, almost all studies were coded as at risk for regression-to-the-mean confounder, given that the selection of treatment sites for road improvement interventions is influenced by the high accident rates (Elvik, 2002).

### Data Collection

All studies described proper data collection methods. Overall, tools for primary and secondary outcome data were valid and reliable. All studies reported outcomes at the individual levels. Traffic laws enforcement intervention studies on motorized two-wheel road users reported outcomes for motorized two-wheel road users only.

### Overall Risk-of-Bias

The overall risk-of-bias using the HAT ratings for one cluster RCT (Sumner et al., 2014), five time-series studies (Radin Umar et al., 1995a,b; Radin Umar, 2005; Espitia-Hardeman et al., 2008; Nadesan-Reddy and Knight, 2013), one controlled before-and after-study (Liu et al., 2011), and one case-control study (Quistberg et al., 2014) provided the strongest assessment of the safety effects of road engineering and enforcement interventions compared to the rest of the included studies.

There were 14 studies (Panichaphongse et al., 1995; Chiu et al., 2000; Liberatti et al., 2001; Afukaar, 2003; Ichikawa et al., 2003; Bastos et al., 2005; Hoque et al., 2005; Bhatti et al., 2011; Antic et al., 2013; Lipovac et al., 2013; Nguyen Ha et al., 2013; Allyana et al., 2014; Van der Horst et al., 2016; Nhan et al., 2017) with a moderate risk-of-bias assessment. These studies used an uncontrolled before-and-after study design. In some uncontrolled before-and-after studies, the post-intervention period started soon after the intervention and included just one period before and one period after; therefore, studies controlled for general changes and change of traffic volume confounding variables.

We have excluded six studies that have overall risk-of-bias grade C because the outcome data did not qualify for analysis because of high risk-of-bias around study design, data collection, and confounders (Mutto et al., 2002; Passmore et al., 2010; Yuan et al., 2012; Wu et al., 2013; Yuan and Chen, 2013; Mousa et al., 2014).

**Table 2** provides an assessment of risk-of-bias and the overall risk-of-bias grade of A, B, and C.

## Effects of Interventions

Effect sizes were computed for 18 studies. Four studies (Liu et al., 2011; Antic et al., 2013; Quistberg et al., 2014; Sumner et al., 2014) presented one particular outcome or one single study design. The number of studies was not sufficient to calculate a standardized effect size.

### Road Engineering Intervention Compared to No Intervention

#### *Uncontrolled before-and-after studies*

Three uncontrolled before-and-after studies assessed primary outcomes: road traffic death counts, the number of injuries (moderate and severe), and the number of road accident casualty before and after road engineering interventions.

**TABLE 1 |** Characteristics of studies included for meta-analysis.

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **1. Afukaar, 2003** | **Uncontrolled before-and-after** | **Road engineering *(measures for reduction of vehicle speed)*** | |
| This study analyzed the police-reported crash and injury data on high-risk roads vulnerable to road accidents. The annualized average before the crash situation was compared with the average after intervention installation in order to ascertain the effectiveness of the measure. | | Rumble strips at Suhum Junction on the main Accra-Kumasi highway **[Sample size not available]**.<br>**Population:** Non-motorized road users at the Suhum Junction, Ghana. | Road traffic death counts;<br>Number of injuries;<br>Number of road accident casualty. |
| Primary study for data extraction; there was no funding source for this study. | | | |
| **2. Allyana, 2014** | **Uncontrolled Before and After** | **Enforcement of traffic laws and regulations *(automated-enforcement-system: cameras)*** | |
| **Speed limit study**: A comparison of speed limit violations before the intervention and after intervention periods was made to determine speed changes and speed limit compliance.<br>**Red light regulation study**: The red-light violations before speed camera installation were compared to those obtained after installation along with each individual approach of RLC on a lane-by-lane basis. | | The Malaysia Road Transport Rules 1997 prohibits red-signal crossing. The National Speed Limit Orders were implemented on 1 February 1989.<br>Speed limits enforcement **[Sample size: 31,580 vehicles observed]**; Red light enforcement of all vehicles **[Sample size 331,154 vehicles observed].**<br>**Population:** Motorized two-wheel road users on six locations in the Malaysia Peninsular. | Non-compliance–red light regulation;<br>Non-compliance–speed limit;<br>Mean-vehicular speed. |
| Primary study for data extraction; No funding source for this study. This study presented outcomes for two sub-categories of traffic laws enforcement and regulations. Outcome data were extracted and assessed as they related to the automated-enforcement-system (AES)—red-light compliance into one group, and the AES—speed-limit compliance into another group. | | | |
| **3. Antic, 2013** | **Uncontrolled before and after** | **Road engineering intervention *(measures for reduction of vehicle speed)*** | |
| In this study, vehicle speed measurements before speed bumps were installed and 1-day and 1-month after the installation were taken in order to determine the effects of speed bumps on the motor-vehicle speed at three locations on roads having a large number of pedestrian and other vulnerable road users. | | On each location, two-speed bumps, 50 m away from each other, were installed. **[Sample size: speed of 5,182 vehicles were observed]**.<br>**Population:** Non-motorized road users in Belgrade, Serbia. | Mean-vehicular-speed km/h. |
| Primary study for data extraction; this paper was supported by the Ministry of Science and Technological Development of the Republic of Serbia. | | | |
| **4. Bastos, 2005** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations (*mandatory helmet law)*** | |
| This study evaluated the enforcement of the Brazilian traffic code that mandates the use of helmets and seat belts of motorized road users in an urban setting. The data were obtained from the Integrated Service of Trauma and Emergency Care for the pre- and the post-intervention period. | | The Brazilian traffic code was established in January 1998 specifically to the mandatory use of helmets and seat belts for motorized road users. **[Sample size for helmet use: 6,298 motorcyclists]**.<br>**Population:** Motorcycle road users in Londrina, Brazil. | Compliance–mandatory helmet law. |
| Primary study for data extraction; Funding from CAPES (Coordenação de Aperfeic,oamento de Pessoal de Nível Superior). | | | |

*(Continued)*

**TABLE 1 |** Continued

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **5. Bhatti, 2011** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study evaluated the nationwide enforcement of National Highway Safety Ordinance 2000, which mandates helmet use and use of seat belts. A pre-enforcement awareness exercise was conducted between Dec. 2009 and Feb 2010. Seat belt and helmet wearing were observed on high-risk roads vulnerable to road accidents. | | The National Highway Safety Ordinance established in 2000 is specific to the mandatory helmet use for motorcycle road users and the mandatory seat belt use for drivers and front-seat occupants. [**Sample size: 742 motorcyclists; 295 pillion riders]**.<br>**Population:** Motorcycle road users on Karachi-Hala Highway, Pakistan. | Compliance–mandatory helmet law by motorcyclists and pillion riders. |
| Primary study for data extraction; No funding source for this study. | | | |
| **6. Chiu, 2000** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study evaluated the effect of motorcycle helmet law in an urban setting. Data on head injury were collected for the year before the intervention and after implementation of the helmet use law. The data were collected from 56 major teaching hospitals in Taiwan. Patients dead on arrival and non-hospitalized patients were excluded. | | The motorcycle helmet law was implemented in Taiwan, on June 1, 1997 **[Sample size: 8,795 cases of motorcycle-related head injuries]**.<br>**Population:** Motorcycle road users in Taiwan. | Road traffic death counts;<br>Number of injuries;<br>Compliance–mandatory helmet law. |
| Primary study for data extraction; This study was supported by grant NSC88-2314-B-038-132 from the National Science Council and grant DOH87-TD-1040 from the Department of Health, Taiwan | | | |
| **7. Espitia-Hardeman, 2008** | **Time-series** | **Enforcement of traffic laws and regulations (mandatory helmet law and mandatory use of reflective vests)** | |
| Time-series analysis was performed to assess the effects of motorcycle rider safety interventions in an urban community. The study had a defined point in time when the intervention occurred and included data at least three time points before and after the intervention. | | The enforcement of the mandatory helmet law was established in August 1996; the use of helmets for both drivers and passengers of motorcycles in November 1997; and the use of reflective vests in April 2001 **[Sample size: not available].**<br>**Population:** Motorcycle road users in Cali, Colombia. | Road traffic death counts. |
| Primary study for data extraction; there was no funding source for this study. | | | |
| **8. Hoque, 2005** | **Uncontrolled before-and-after** | **Road engineering (*changes at intersection; segregation of VRU from motorized road users)*** | |
| This study examined the effectiveness of road engineering interventions before and after the implementation of interventions on high-risk roads. This study consists of a controlled before-and-after analysis of road engineering interventions at three black spots and uncontrolled before-and-after analysis of road engineering interventions at two different site segments. Only the later was analyzed. | | The improvement measures included pavement widening, installation of a median barrier and other safety-related features, such as installation of pavement markings and signs and safety guard posts at the bridge approaches **[Sample size: not available]**.<br>**Population:** Non-motorized road users on the Dhaka-Arica Highway, Bangladesh. | Road traffic death counts;<br>Road accident casualty. |
| Primary study for data extraction; No funding source for this study. | | | |

*(Continued)*

**TABLE 1 |** Continued

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **9. Ichikawa, 2003** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study investigated the effect of the helmet act on increasing mandatory helmet use and reducing motorcycle-related deaths and injuries in a rural community in Thailand. Helmet use in a motorcycle accident was compared 2-years before and after enforcement of the helmet act. | | The helmet act for motorcyclists was enacted in Thailand in December 1994 and subsequently enforced at the regional level **[Sample size: 12,002 injured motorcyclists]**. **Population:** Motorcycle road users in northeast Thailand. | Road traffic death counts; Number of injuries; Compliance–mandatory helmet law. |
| Primary study for data extraction; No funding source for this study. | | | |
| **10. Liberatti, 2001** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study evaluated the enforcement of the Brazilian traffic code of January 1998 that mandates the use of helmets and seat belts among motorized road users in an urban setting. The data were obtained from the Integrated Service of Trauma and Emergency Care before and after periods. | | The enforcement of the Brazilian traffic code enacted in January 1998 is specific to the mandatory use of helmets and seat belts for motorized road users. **[Sample size for motorcycle victims: 747 in before period; 1090 in after-intervention period].** **Population:** Motorcycle road users in Londrina, Brazil. | Compliance–mandatory helmet law. |
| Primary study for data extraction; No funding source for this study. | | | |
| **11. Lipovac, 2013** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(red-light-running)*** | |
| This study investigated pedestrians' compliance with red-light regulation at traffic signals at two different pedestrian crossing in an urban setting. Pedestrian observance of traffic light signals before and after the pedestrian countdown intervention. | | The former Yugoslavia signed an international traffic Convention (Geneva, 1947), a signatory to the Vienna Convention (Vienna, 1968). A swinging red light constitutes a stop signal for road users. **[Sample size: 20,227 pedestrians].** **Population:** Non-motorized road users in Doboj city. | Compliance–running-red-light violation |
| Primary study for data extraction; No funding source for this study. | | | |
| **12. Liu, 2011** | **Controlled before-and-after** | **Road engineering intervention *(measures for reduction of vehicle speed)*** | |
| Controlled before-after and Empirical Bayesian (EB) methods were used to evaluate the effectiveness of transverse rumble strips at pedestrian crosswalks in a rural setting. At each treated site, point speed data were measured at 23 selected locations with different distances from pedestrian crosswalks. At each control site, speed data were measured at the pedestrian crosswalk as well as upstream and downstream control points. | | Raised rumble strips deployed on both approaches of a signalized pedestrian crosswalk on a rural road **[Sample size: For road crass 366 roadway segments; For speed 15,000speed observations].** **Population:** Non-motorized road users in Guangdong, China. | Number of road accidents casualty. |
| Primary study for data extraction; this research was funded by China's National Science and Technology, China's National Science Foundation, and Excellent Young Faculties Program, Southeast University. | | | |

*(Continued)*

**TABLE 1 |** Continued

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **13. Nadesan-Reddy, 2013** | **Time-series** | **Road engineering intervention *(measures for reduction of vehicle speed)*** | |
| This study assessed the vehicle and pedestrian-vehicle collision data on high-risk roads vulnerable to road accidents (school route) over a 5-year period following the implementation of speed humps. The study had a defined point in time when the intervention occurred and included data three-time points before and three-time points after the intervention. | | Traffic calming humps in the Chatsworth and KwaMashu residential areas of the eThekwini Municipality **[Sample size: Pre−5,911, Post−6,228].** **Population:** Non-motorized road users in the eThekwini province, South Africa. | Road traffic death counts; Number of injuries; Number of road accident casualty. |
| Primary study for data extraction; No funding source for this study. | | | |
| **14. Nhan, 2017** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study evaluated the effects of the Vietnamese Child Helmet Action Plan to mandate helmet use among school-going children passengers and adult drivers in an urban setting. The helmet use was measured by filmed observations of drivers and passengers as they arrived or left their schools. | | In Vietnam, the mandatory helmet use law for adult motorcycle drivers was introduced in 2007 **[Sample size: 124,366 motorcycle riders].** **Population:** Motorcycle road users in Ha Naoi, Da Nang, and Ho Chi Minh cities in Vietnam. | Compliance–mandatory helmet law. |
| Primary study for data extraction. No funding source for this study | | | |
| **15. Nguyen, 2013** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations *(mandatory helmet law)*** | |
| This study evaluated mandatory use of helmet among motorcycle drivers and pillion riders in three urban provinces in the Socialist Republic of Viet Nam, before and after the mandatory helmet law enforcement. | | The mandatory helmet law took effect in Vietnam on December 2007 **[Sample size: 665,428 motorcycle riders].** **Population:** Motorcycle road users in Yen Bai, Da Nang, and Binh Duong provinces in Vietnam. | Compliance–mandatory helmet law. |
| Primary study for data extraction; this study was funded by Bloomberg Philanthropies. | | | |
| **16. Panichaphongse, 1995** | **Uncontrolled before-and-after** | **Enforcement of traffic laws and regulations (*mandatory helmet law)*** | |
| This study compared the death rates two years before the helmet use decree and two years after its enforcement in an urban setting. The population included persons injured from MCA who were treated at Chulalongkorn Hospital and those who died because of MCA between 1991 and 1994. | | The mandatory use of helmet by motorcyclists and pillion riders law was promulgated on 16 Dec. 1992 in Bangkok Metropolitan area **[Sample size: 4,035 injured motorcycle accidents]**. **Population:** Motorcycle road users in Bangkok Metro area. | Road traffic death counts; Number of injuries; Number of road accident casualty. |
| Primary study for data extraction; this study was supported by the Bangkok General Hospital. | | | |

*(Continued)*

**TABLE 1 |** Continued

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **17. Quistberg, 2014** | **Case-control study** | **Combination of engineering and regulatory and legislative (*traffic enforcement)*** | |
| A matched case-control design was used where the units of study were crossing locations in an urban setting in Lima. 97 control sample collisions (weighted $N$ = 1,134) at intersections in Lima were randomly selected. Controls were pedestrian crossings in the proximity of matched case sites. | | Visible traffic signals, pedestrian signals, and signal timing **[Sample size: 97 control-matched sample collisions]**. **Population:** Non-motorized road users in Lima, Peru. | Number of accident casualty. |
| Primary study for data extraction; the study was funded by the Thomas Francis, Jr. Global Health Fellowship from the Department of Global Health, University of Washington. | | | |
| **18. Radin Umar, 1995a** | **Time-series** | **Enforcement of traffic laws and regulations *(conspicuity -use of daytime-running-headlights)*** | |
| This study presented a six months before-and-after analysis of the impact of running headlight. A nationwide daytime 'running-headlight' campaign was conducted, followed by an establishment of the daytime 'running-headlight' regulation. The study had a defined point in time when the intervention occurred and included monthly data at least three time points before and after the intervention. | | The running headlight regulation was established in September 1992 **[Sample size: 3,662 motorcycle accidents].** **Population:** Motorcycle road users in the Seremban and Shah Alam in Malaysia. | Number of road accident casualty. |
| Primary study for data extraction; there was no funding source for this study. | | | |
| **19. Radin Umar, 1995b** | **Time-series** | **Road engineering intervention *(segregation of vulnerable road users from motorized vehicles)*** | |
| This study presented an analysis of the impact of segregation of a motorcycle lane on high-risk roads vulnerable to road accidents. Accident data was extracted from the four-year pilot project data. The time series cumulative plot'2 of six months records before the intervention and after the intervention. The study had a defined point in time when the intervention occurred and included monthly-data at least three time points before and after the intervention. | | Motorcycles segregation from other traffic using an exclusive motorcycle lane **[Sample size: 4,319 motorcycle accidents].** **Population:** Motorcycle road users along Federal Highway F02, Shah Alam, Malaysia. | Number of road accident casualty; Number of injuries. |
| Primary study for data extraction; No funding source for this study. | | | |
| **20. Radin Umar, 2005** | **Time-series** | **Enforcement of traffic laws and regulations (*conspicuity -use of daytime-running- lights)*** | |
| This study evaluated the effect of the daytime-running-headlight regulation. A before and after evaluation of the safety intervention from the two-year accident series monthly data was conducted. The study had a defined point in time when the intervention occurred and included monthly data at least three time points before and after the intervention. | | The running headlight regulation was established in September 1992 **[Sample size: 4,865 motorcycle accidents].** **Population:** Motorcycle road users in the Seremban and Shah Alam, Malaysia. | Number of road accident casualty; Number of injuries. |
| Primary study for data extraction; there was no funding source for this study. | | | |

*(Continued)*

**TABLE 1** | Continued

| Short Title | Methods | Intervention | Outcomes |
|---|---|---|---|
| **21. Sumner, 2014** | **Cluster randomized-control-trial** | **Enforcement of traffic laws and regulations *(conspicuity measures)*** | |
| A cluster-randomized trial was conducted among 180 motorcyclist-taxi drivers in an urban city in northern Tanzania. Participants from the intervention arm (90) received a free reflective/fluorescent vest and participants form the control arm (82) did not receive free vests. | | The Transport Licensing (Motor Cycles and Tricycles) Regulations, 2010 mandates the use of reflective/fluorescent vests for motorcycle-taxi drivers in Moshi, Tanzania **[Sample size: 180 motor-cycle drivers].** **Population:** Motorcyclists in the Kilimanjaro region. | Compliance–motorcycle conspicuity. |
| Primary study for data extraction. | | | |
| **22. Van der Horst, 2016** | **Uncontrolled before-and-after** | **Road engineering intervention *(measures for reduction of vehicle speed)*** | |
| This before-and-after study used a combination of research methods to monitor and evaluate speed humps, rumble strips, and road markings on high-risk roads vulnerable road accidents on the N2 national highway. | | Speed management related road engineering interventions: speed humps, rumble strips, and road markings **[Sample size: Before: 5,966; After period: 5,964 traffic counts].** **Population:** Non-motorized road users on N2 highway in Bangladesh. | Number of road traffic accidents; Number of injuries; Road traffic death counts. |
| Primary study for data extraction. This study was funded by GRSF supported RTIRN small grants program. | | | |

*Primary outcomes.* Three studies (Afukaar, 2003; Hoque et al., 2005; Van der Horst et al., 2016) assessed road traffic death counts before and after road engineering interventions. There was no evidence that road engineering interventions were effective (OR 1.63; 95% CI 1.01–2.63; $I^2 = 0\%$) based on data from 948 people. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. See forest plot, primary outcome: changes in "road traffic death counts"after road engineering interventions (**Figure 2**). Three studies (Afukaar, 2003; Hoque et al., 2005; Van der Horst et al., 2016) assessed the number of injuries and found no difference in the odds of occurrence of injuries before and after road engineering interventions (OR 0.76, 95% CI 0.47–1.23; $I^2 = 36\%$) based on data from 948 people. The results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. See forest plot, primary outcome: changes in the number of "injuries" after road engineering interventions (**Figure 3**).

Two studies (Afukaar, 2003; Van der Horst et al., 2016) assessed the number of road accident casualties before and after road engineering interventions. There was no evidence that road engineering interventions were effective after a road treatment (OR, 2.31; 95% CI 0.57–9.35; $I^2 = 77\%$) based on data from 718 people. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality because heterogeneity was significant. See forest plot, primary outcome: changes in the number of "road accident casualty" after road engineering interventions (**Figure 4**).

*Secondary outcomes.* We assessed no secondary outcomes for road engineering interventions in before-and-after studies.

### *Time-series studies*

Two time-series studies were used to assess primary outcomes, road traffic death counts, and the number of road accident casualty before and after road engineering interventions.

*Primary outcomes.* One study (Nadesan-Reddy and Knight, 2013) reported road traffic death counts. However, because of an insufficient number of studies the outcome data for road traffic death counts were not assessed.

Two studies (Radin Umar et al., 1995b; Nadesan-Reddy and Knight, 2013) assessed the number of road accident casualty in percent change (-26.62, 95% CI−149.58 - 35.75;−111.80, 95% CI−492.97 - 24.34) based on data from 14,404 people involved in accidents after road engineering interventions. There was no difference in the occurrence of road accident casualty outcome before and after road engineering interventions. The outcome was downgraded as very low quality because of the high presence of heterogeneity. See forest plot, primary outcome: percent change in the number of "road accident casualty" after road engineering interventions (**Figure 5**).

*Secondary outcomes.* We assessed no secondary outcomes for road engineering interventions in time-series studies.

**TABLE 2 |** Assessment of risk-of-bias of studies included for analysis based on HAT.

| | Short title | Selection bias | Study design | Confounder | Data collection methods | Intervention integrity | Analysis of internal validity | Overall risk-of-bias | Grade |
|---|---|---|---|---|---|---|---|---|---|
| **Assessment of overall risk-of-bias** | | | | | | | | | |
| 1 | Afukaar, 2003 | Strong | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 2 | Allyana et al., 2014 | Moderate | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 3 | Antic et al., 2013 | Strong | Weak | Moderate | Strong | Strong | Strong | Moderate | B |
| 4 | Bastos et al., 2005 | Moderate | Weak | Moderate | Strong | Strong | Strong | Moderate | B |
| 5 | Bhatti et al., 2011 | Strong | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 6 | Chiu et al., 2000 | Strong | Weak | Moderate | Strong | Strong | Strong | Moderate | B |
| 7 | Espitia-Hardeman et al., 2008 | Moderate | Moderate | Moderate | Strong | Moderate | Strong | Strong | A |
| 8 | Hoque et al., 2005 | Strong | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 9 | Ichikawa et al., 2003 | Moderate | Weak | Moderate | Strong | Strong | Strong | Moderate | B |
| 10 | Liberatti et al., 2001 | Moderate | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 11 | Lipovac et al., 2013 | Strong | Weak | Strong | Strong | Strong | Strong | Moderate | B |
| 12 | Liu et al., 2011 | Strong | Moderate | Moderate | Strong | Strong | Strong | Strong | A |
| 13 | Nadesan-Reddy and Knight, 2013 | Moderate | Moderate | Moderate | Strong | Strong | Strong | Strong | A |
| 14 | Nhan et al., 2017 | Strong | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 15 | Nguyen Ha et al., 2013 | Strong | Weak | Moderate | Strong | Moderate | Moderate | Moderate | B |
| 16 | Panichaphongse et al., 1995 | Strong | Weak | Moderate | Strong | Moderate | Strong | Moderate | B |
| 17 | Quistberg et al., 2014 | Strong | Moderate | Strong | Strong | Moderate | Strong | Strong | A |
| 18 | Radin Umar et al., 1995a | Strong | Moderate | Moderate | Strong | Moderate | Strong | Strong | A |
| 19 | Radin Umar et al., 1995b | Strong | Moderate | Moderate | Strong | Moderate | Strong | Strong | A |
| 20 | Radin Umar, 2005 | Strong | Moderate | Moderate | Strong | Strong | Strong | Strong | A |
| 21 | Sumner et al., 2014 | Strong | Strong | Strong | Strong | Moderate | Strong | Strong | A |
| 22 | Van der Horst et al., 2016 | Strong | Weak | Strong | Strong | Moderate | Strong | Moderate | B |

**Assessment of confounding variables**

| | Short title | Q1–What was the basis for the selection of intervention sites -high accident frequencies or some other traffic rule? | Q2–Were the intervention and the control sites matched for geographic characteristics. | Q3–Were the intervention and control site matched for exposure effect? | Q4–Were the intervention and control site matched for trend effect? | Q5–Was there a sufficient passage of transitional period following the infrastructure construction? | Q6–Whether the study controlled for restricted participant selection? | Percentage of relevant confounders controlled or adjusted? | Potential for risk-of-bias |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Afukaar, 2003 | Very likely | Yes | Yes | No | Can't tell | Can't tell | 60–79% | Moderate |
| 2 | Allyana et al., 2014 | Very likely | Yes | Yes | No | N A | Yes | 60–79% | Moderate |
| 3 | Antic et al., 2013 | Not likely | Yes | Yes | No | Yes | Can't tell | 60–79% | Moderate |
| 4 | Bastos et al., 2005 | Not likely | Yes | Yes | Can't tell | N A | Yes | 60–79% | Moderate |
| 5 | Bhatti et al., 2011 | Very likely | Yes | Yes | No | N A | Yes | 60–79% | Moderate |

*(Continued)*

**TABLE 2 |** Continued

| | Short title | Q1–What was the basis for the selection of intervention sites -high accident frequencies or some other traffic rule? | Q2–Were the intervention and the control sites matched for geographic characteristics. | Q3–Were the intervention and control site matched for exposure effect? | Q4–Were the intervention and control site matched for trend effect? | Q5–Was there a sufficient passage of transitional period following the infrastructure construction? | Q6–Whether the study controlled for restricted participant selection? | Percentage of relevant confounders controlled or adjusted? | Potential for risk-of-bias |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Chiu et al., 2000 | Not likely | Yes | Yes | No | N A | Yes | 60–79% | Moderate |
| 7 | Espitia-Hardeman et al., 2008 | Very likely | Yes | Yes | Can't tell | N A | Yes | 60–79% | Moderate |
| 8 | Hoque et al., 2005 | Very likely | Yes | Yes | Yes | Can't tell | No | 60–79% | Moderate |
| 9 | Ichikawa et al., 2003 | Not likely | Yes | Yes | No | N A | Yes | 60–79% | Moderate |
| 10 | Liberatti et al., 2001 | Not likely | Yes | Yes | No | N A | Yes | 60–79% | Moderate |
| 11 | Lipovac et al., 2013 | Not likely | Yes | Yes | No | Can't tell | Yes | 80–100% | Low |
| 12 | Liu et al., 2011 | Not likely | Yes | Yes | No | Can't tell | Can't tell | 60–79% | Moderate |
| 13 | Nadesan-Reddy and Knight, 2013 | Very likely | Yes | Yes | Yes | Can't tell | Yes | 60–79% | Moderate |
| 14 | Nhan et al., 2017 | Not Likely | Yes | Can't tell | Can't tell | N A | Yes | 60–79% (some) | Moderate |
| 15 | Nguyen Ha et al., 2013 | Not likely | Yes | Yes | Can't tell | N A | Yes | 60–79% | Moderate |
| 16 | Panichaphongse et al., 1995 | Not likely | Yes | Yes | Can't tell | N A | Yes | 60–79% | Moderate |
| 17 | Quistberg et al., 2014 | Not likely | Yes | Yes | No | Yes | Yes | 80–100% | Low |
| 18 | Radin Umar et al., 1995a | Not likely | Yes | Can't tell | Can't tell | NA | Yes | 60–79% | Moderate |
| 19 | Radin Umar et al., 1995b | Very likely | Yes | Yes | Can't tell | No | Yes | 60–79% | Moderate |
| 20 | Radin Umar, 2005 | Not Likely | Yes | Yes | Can't tell | N A | Yes | 60–70% | Moderate |
| 21 | Sumner et al., 2014 | NA | NA | NA | NA | NA | Yes | 80–100% | Low |
| 22 | Van der Horst et al., 2016 | Not likely | Yes | Yes | Yes | Yes | Yes | 80–100% | Low |

**Explanations**

| | |
|---|---|
| Q1 | Regression-to-the-mean is typically observed at sites with high values for crash frequencies: If high accident frequencies then Very Likely; If other general traffic rules then Not Likely. |
| Q2 | If the treated facility is an intersection, the comparison site should be a similar intersection with respect to area type (commercial business district, urban, rural), intersection type (three-legged or four-legged), traffic control (signalized, two-way stop-controlled, etc.). |
| Q3 | For CBA, traffic volume and location matching, warm/cold weather months, daylight vs. dawn/night, traffic composition, enforcement level; In before and after, vehicular traffic volume and location matching, warm/cold weather months, daylight vs. dawn/night, traffic composition, enforcement level pre, and post. |
| Q4 | If the crash trend over a multi-year period shows a continuous increasing or a decreasing trend with little fluctuations in crash frequencies; If there is a sudden drop in the crash frequency after some improvements were made at the treatment site and the trend follows the after period trend. |
| Q5 | In Controlled Before and After, study which does not specify the time period over which outcome was reported, the question should be answered as Can't tell; In Before and After studies, if the intervention site was not given a 'sufficient' passage of transitional period following the infrastructure construction, the answer is No. In case-control studies, if the period between the intervention and outcomes is not the same for cases and controls, the answer is No |
| Q6 | Outcome ascertainment, so that all groups had the same value for the confounder, for example, restricting the study to two-wheel road users |
| Low risk-of-bias | For studies, if they control for 80–100% of the prespecified confounders using a transparent and rigorous method |
| Moderate risk-of- bias | For studies, if they control for 60–79% of the prespecified confounders, but have not used any transparent and rigorous method |
| High risk-of-bias | For studies with inadequate control for confounders |

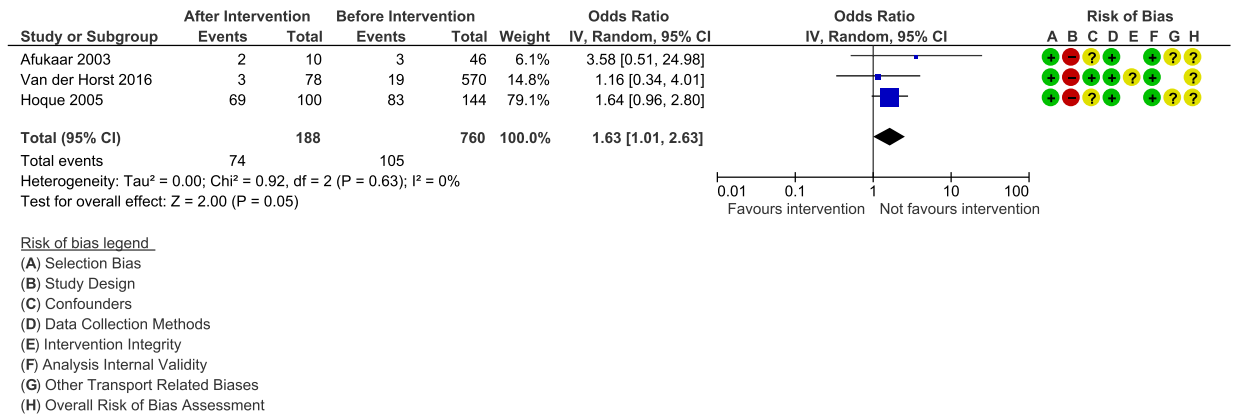


**FIGURE 2 |** Primary outcome: changes in 'road traffic death counts' after road engineering interventions.

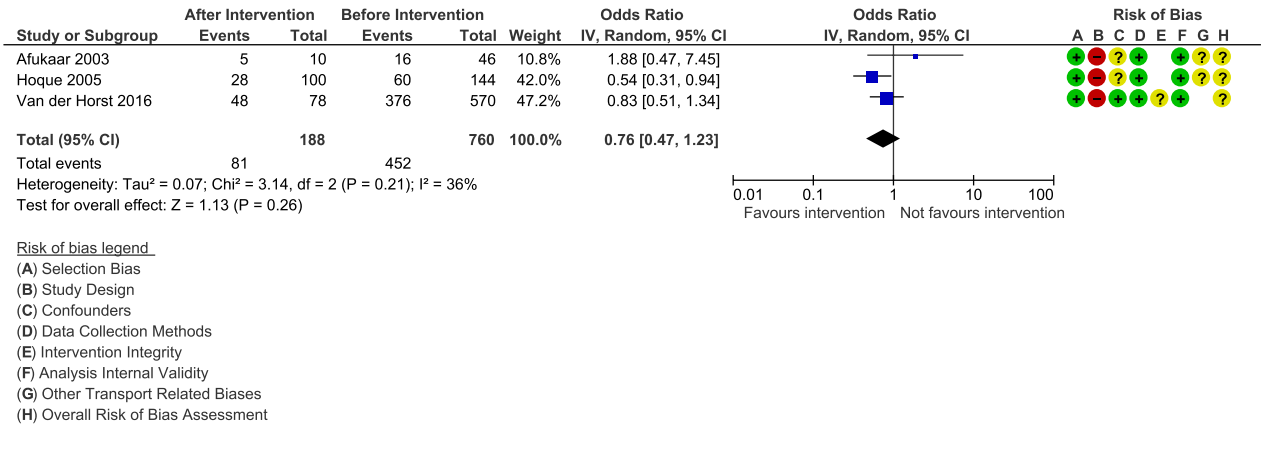


**FIGURE 3 |** Primary outcome: changes in the number of 'injuries' after road engineering interventions.

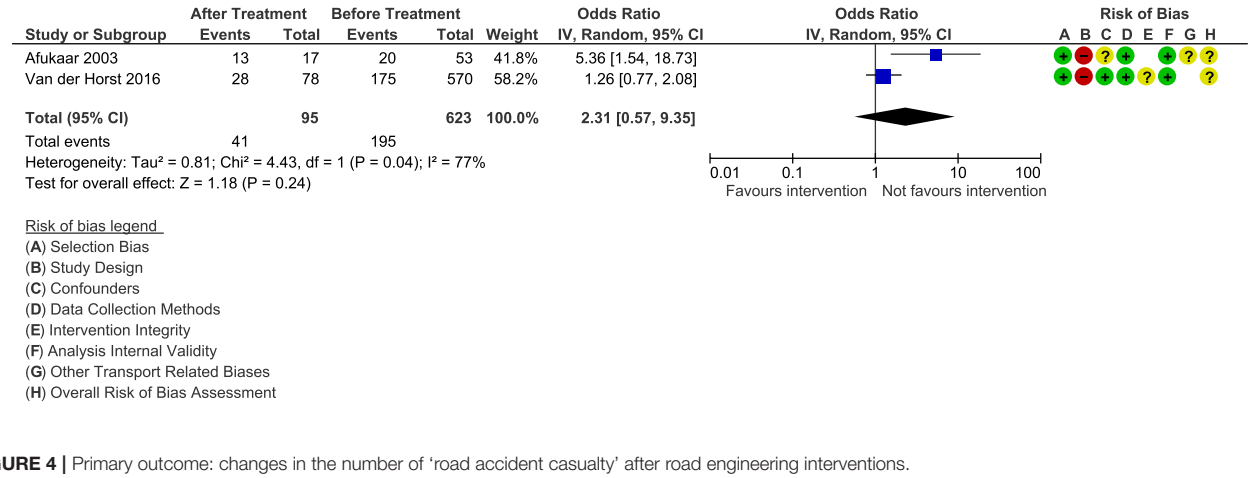


**FIGURE 4 |** Primary outcome: changes in the number of 'road accident casualty' after road engineering interventions.

*Vote counting and common rubric.* We could not develop the vote counting and common rubric for time-series studies.

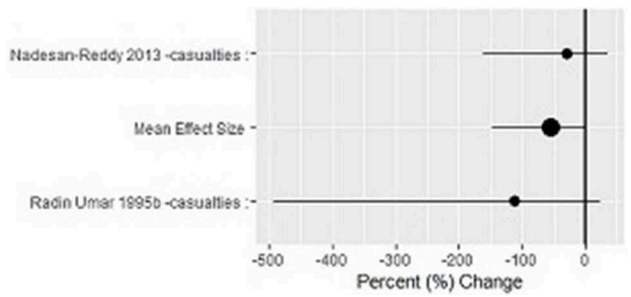


**FIGURE 5 |** Primary outcome: percent change in the number of 'road accident casualty' after road engineering interventions.

## Enforcement of Traffic Laws and Regulation Interventions Compared to no Intervention

### *Uncontrolled before-and-after studies*

Ten uncontrolled before-and-after studies assessed primary outcomes: road traffic death counts and the number of injuries (moderate and severe) and, secondary outcome, compliance before and after enforcement of traffic laws and regulation interventions.

*Primary outcomes.* Three studies (Panichaphongse et al., 1995; Chiu et al., 2000; Ichikawa et al., 2003) assessed road traffic death counts of motorcycle riders' road accidents before and after mandatory helmet law enforcement. There was no evidence that the mandatory helmet law enforcement was effective (OR 0.94, 95% CI 0.72–1.23; $I^2 = 68\%$) based on data from 35,710 people. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. Moderate heterogeneity was present. See forest plot, primary outcome:

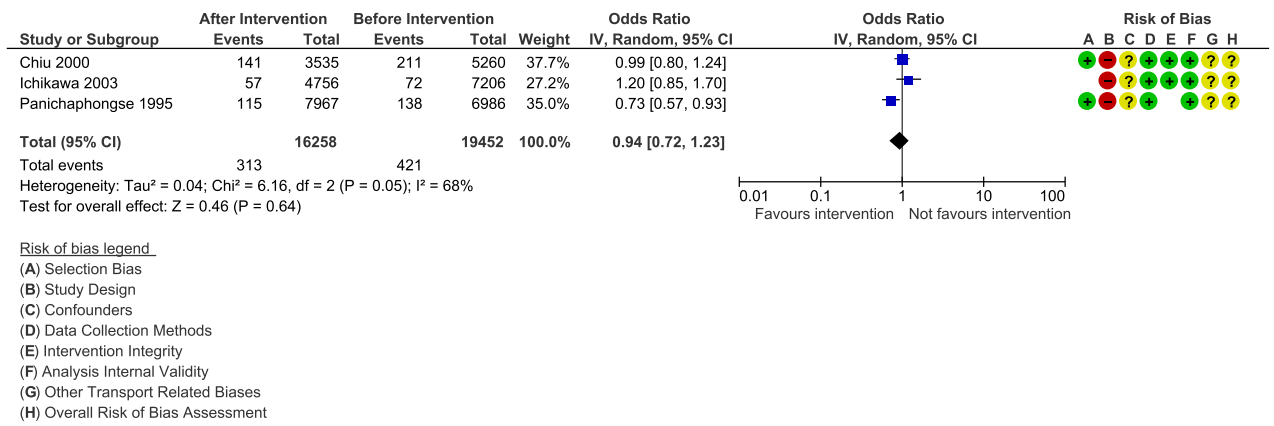


**FIGURE 6 |** Primary outcome: changes in 'road traffic death counts' after mandatory helmet law enforcement.

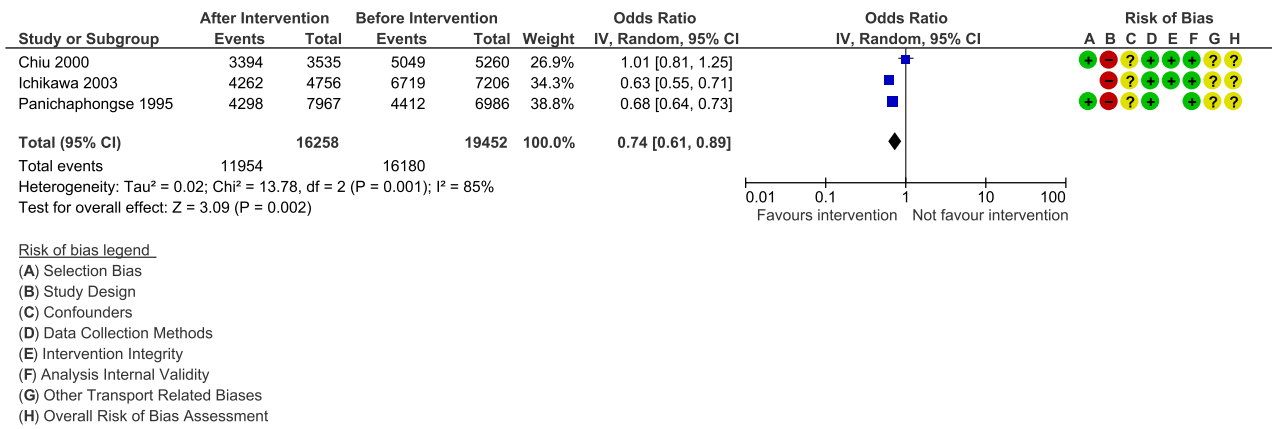


**FIGURE 7 |** Primary outcome: changes in the number of 'injuries' after mandatory helmet law enforcement.

**TABLE 3 |** Vote counting and the common rubric of enforcement of traffic laws and regulations.

| Uncontrolled before-and-after studies | Study name | Odds ratio (OR) | CI | Risk ratio | CI | Risk difference | *P*-value | Z-score | Voting count (OR) | The direction of intervention effect based on variations from the mean-effect- size |
|---|---|---|---|---|---|---|---|---|---|---|
| **Primary outcomes** | | | | | | | | | | |
| Road traffic death counts | Chiu et al., 2000 | 0.99 | 0.80,1.24 | 0.99 | 0.81, 1.23 | 0% | $P = 0.96$ | 0.05 | | Not favor intervention |
| | Ichikawa et al., 2003 | 1.20 | 0.85,1.70 | 1.20 | 0.85, 1.69 | 0% | $P = 0.30$ | 1.03 | | Not favor intervention |
| | Panichaphongse et al., 1995 | 0.73 | 0.57,0.93 | 0.73 | 0.57, 0.93 | 0% | $P = 0.01$ | 2.51 | √√ | Favors intervention |
| | **Mean effect size** | **0.94** | **0.72,1.23** | **0.96** | **0.83, 1.11** | | | | | |
| Number of injuries | Chiu et al., 2000 | 1.01 | 0.81,1.25 | 1.00 | 0.99, 1.01 | 0% | $P = 0.96$ | 0.05 | | Not favor intervention |
| | Ichikawa et al., 2003 | 0.63 | 0.55,0.71 | 0.96 | 0.95, 0.97 | −4% | $P < 0.00001$ | 7.03 | √√ | Favors intervention |
| | Panichaphongse et al., 1995 | 0.68 | 0.64,0.73 | 0.85 | 0.83, 0.88 | −9% | $P < 000001$ | 11.37 | √√ | Favors intervention |
| | **Mean effect size** | **0.74** | **0.61,0.89** | **0.94** | **0.88, 1.00** | | | | | |
| Number of moderate injuries | Chiu et al., 2000 | 0.96 | 0.83,1.10 | 0.96 | 0.84, 1.09 | 0% | $P = 0.54$ | 0.01 | | Not favor intervention |
| | Panichaphongse et al., 1995 | 0.73 | 0.69,0.78 | 0.84 | 0.81, 0.87 | −8% | $P < 0.00001$ | 0.62 | √√ | Favors intervention |
| | **Mean effect size** | **0.83** | **0.64,1.07** | **0.89** | **0.78, 1.00** | | | | | |
| **Secondary outcomes** | | | | | | | | | | |
| Helmet law - compliance among motorcycle road users | Bastos et al., 2005 | 10.31 | 8.65, 12.28 | 2.29 | 2.15, 2.45 | 49% | $P < 0.00001$ | 26.13 | √√ | Favors intervention |
| | Bhatti et al., 2011 | 1.49 | 1.11,1.99 | 1.19 | 1.05, 1.35 | 10% | $P = 0.008$ | 2.67 | √√ | Favors intervention |
| | Chiu et al., 2000 | 28.56 | 24.00, 33.98 | 15.85 | 13.51, 18.61 | 43% | $P < 0.00001$ | 33.82 | √√ | Favors intervention |
| | Ichikawa et al., 2003 | 6.17 | 5.42,7.03 | 5.01 | 4.45, 5.64 | 18% | $P < 0.00001$ | | √√ | Favors intervention |
| | Liberatti et al., 2001 | 4.31 | 3.44,5.40 | 2.12 | 1.88, 2.39 | 35% | $P < 0.00001$ | 12.67 | √√ | Favors intervention |
| | Nguyen Ha et al., 2013 | 20.89 | 20.27, 21.53 | 2.42 | 2.22, 2.25 | 52% | $P < 0.00001$ | 197.63 | √√ | Favors intervention |
| | Nhan et al., 2017 | 0.67 | 0.63,0.70 | 0.95 | 0.94, 0.96 | −5% | $P < 0.00001$ | 15.11 | √√ | Not favor intervention |
| | **Mean effect size** | **5.55** | **1.21, 25.55** | **2.36** | **1.69, 4.21** | | | | | |
| Red-light and speed limit violations | Allyana et al., 2014-speed limit violation | 0.15 | 0.14,0.16 | 0.24 | 0.22, 0.25 | −32% | <0.00001 | 60.11 | √√ | Favors intervention |
| | Allyana et al., 2014-red light-running | 0.50 | 0.48,0.52 | 0.51 | 0.49, 0.53 | −2% | <0.00001 | 33.48 | √√ | Favors intervention |
| | Lipovac et al., 2013 | 0.67 | 0.62,.73 | 0.75 | 0.71, 0.79 | −8% | <0.00001 | 9.94 | √√ | Favors intervention |
| | **Mean effect size** | **0.34** | **0.17,0.70** | **0.45** | **0.24, 0.83** | | | | | |

*Two ticks indicate (√√) statistically significant and No tick (blank) indicates–Not significant.*

changes in "road traffic death counts" after mandatory helmet law enforcement (**Figure 6**).

Three studies (Panichaphongse et al., 1995; Chiu et al., 2000; Ichikawa et al., 2003) assessed the number of injuries before and after motorcycle riders' road accidents. The number of injuries decreased after the mandatory helmet law enforcement (OR, 0.74; 95% CI 0.61–0.89; $I^2 = 85\%$) based on data from 35,710 people. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. The presence of statistically significant heterogeneity was observed. See forest plot, primary outcome: changes in the number of "injuries" after mandatory helmet law enforcement (**Figure 7**).

Two studies (Panichaphongse et al., 1995; Chiu et al., 2000) assessed the number of severe and moderate injuries of motorcycle riders before and after motorcycle road accidents. There was no evidence that the helmet law enforcement was effective for severe injuries (OR, 0.91; 95% CI 0.82–1.01; $I^2 = 32\%$) and moderate injuries (OR 0.83, 95% CI 0.64–1.07; $I^2 = 91\%$) based on data from 23,748 people.

The presence of heterogeneity for overall and moderate injuries was significant, and we developed the vote counting and common rubric.

*Vote counting and common rubric.* The mandatory helmet law enforcement did not have any effect on the absolute risk for road traffic death counts among motorcyclists. In two studies (Panichaphongse et al., 1995; Ichikawa et al., 2003), the absolute risk for the number of injuries among motorcyclists wearing helmets reduced by 4% and 9%, which was statistically significant. The number of moderate injury outcome for one study (Panichaphongse et al., 1995) stands out from other studies. This study showed a positive impact of the intervention; the absolute risk for the number of moderate injuries among motorcyclists wearing a helmet reduced by 8% and was statistically significant. For details, see vote counting and the common rubric of enforcement of traffic laws and regulations (**Table 3**).

*Secondary outcomes.* Seven studies (Chiu et al., 2000; Liberatti et al., 2001; Ichikawa et al., 2003; Bastos et al., 2005; Bhatti et al., 2011; Nguyen Ha et al., 2013; Nhan et al., 2017) assessed motorcycle road users' compliance with mandatory helmet law, and two studies assessed effects of automated-enforcement-system (camera) and pedestrian signal (Lipovac et al., 2013; Allyana et al., 2014).

Seven studies (Chiu et al., 2000; Liberatti et al., 2001; Ichikawa et al., 2003; Bastos et al., 2005; Bhatti et al., 2011; Nguyen Ha et al., 2013; Nhan et al., 2017) assessed motorcycle drivers compliance with helmet use after the mandatory helmet law enforcement (OR 5.55, 95% CI 1.21–25.55; $I^2 = 100\%$) based on data from 2,47,599 people. In places where a mandatory helmet law was enforced, there was five times more compliance among motorcyclists compared with when there was no mandatory helmet law enforcement. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. The presence of a considerable heterogeneity between the effect sizes for the seven studies included in the meta-analysis was statistically significant (P=0.00001). See forest plot, secondary outcome: changes in helmet use "compliance" after mandatory helmet law enforcement (**Figure 8**).

Two studies (Lipovac et al., 2013; Allyana et al., 2014) reported speed limit and red-light-running non-compliance (OR 0.37, 95% CI 0.16–0.86; $I^2 = 100\%$) based on 3,76,368 traffic volume and found that speed limit and red-light-running violations reduced by 63%. Results were analyzed using a random-effects model, and the outcome was downgraded to very low quality. See forest plot, secondary outcome: changes in "red light and speed limit non-compliance" after enforcement of traffic laws and regulations (**Figure 9**). Due to the presence of statistically significant heterogeneity ($I^2 = 100\%$), the vote counting and common rubric were also developed.

*Vote counting and common rubric.* Mandatory helmet law compliance among motorcyclists after the intervention period showed a statistically significant increase across individual studies. It was observed that compliance for helmet use among motorcyclists increased between 10 and 52%, in absolute terms. In one study (Nhan et al., 2017) however, compliance among motorcycle drivers decreased by 5% in absolute terms. The impact of traffic law enforcement on the speed limit and red-light-running violations showed positive and statistically significant effects across individual studies ($p < 0.00001$). The absolute risk for violations against speed limit decreased by 32% (Allyana et al., 2014), and red-light-running decreased by 2% (Allyana et al., 2014), and 8% (Lipovac et al., 2013). For details, see vote counting and the common rubric of enforcement of traffic laws and regulations (**Table 3**).

### *Time-series studies*

Three time-series studies assessed primary outcomes, road traffic death counts and the number of road accident casualty before and after enforcement of traffic laws and regulation interventions.

*Primary outcomes.* One study (Espitia-Hardeman et al., 2008) reported road traffic death-counts. Due to an insufficient number of studies, the outcome data for road traffic death counts were not assessed.

Two studies (Radin Umar et al., 1995a; Radin Umar, 2005) reported the number of road accident casualties in percent change (percent-change−51.06; 95% CI−228.64–30.56; percent-change −68.37; 95% CI−227.40–13.40) based on data from 5,083 people involved in accidents after the daytime running-headlight law enforcement. The mean effect size in percent change for road accident casualties declined by 38% after the law enforcement. The outcome was downgraded to low quality. See forest plot, primary outcome: percent change in the number of "road accident casualty" after daytime running-headlight regulation (**Figure 10**).

*Secondary outcomes.* We assessed no secondary outcomes for enforcement of traffic laws and regulation interventions in time-series studies.

*Vote counting and common rubric* . We could not develop the vote counting and common rubric for time-series studies.

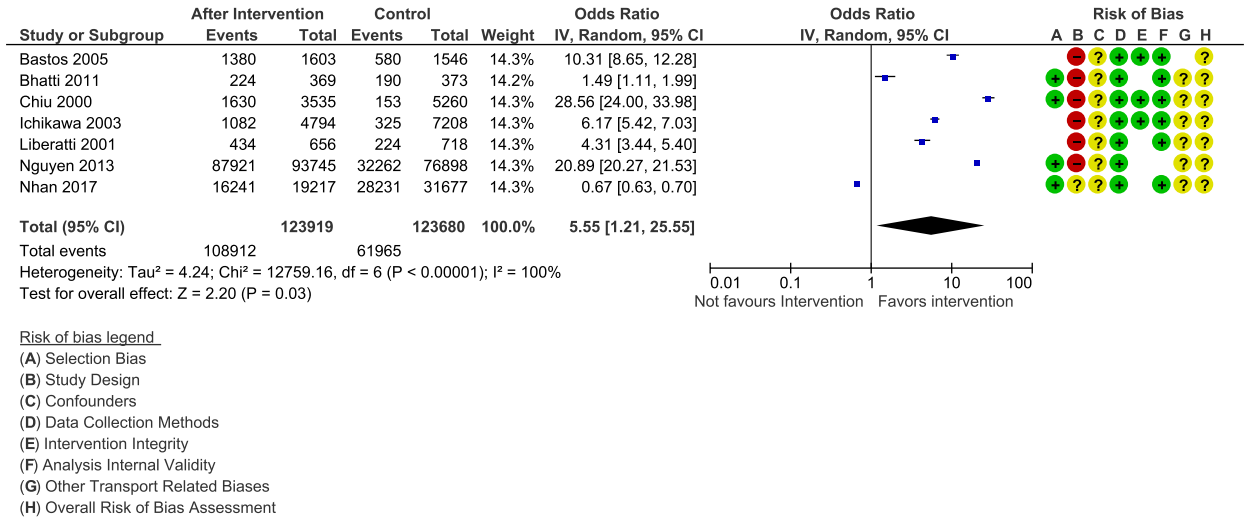


**FIGURE 8 |** Secondary outcome: changes in helmet use 'compliance' after mandatory helmet law enforcement.

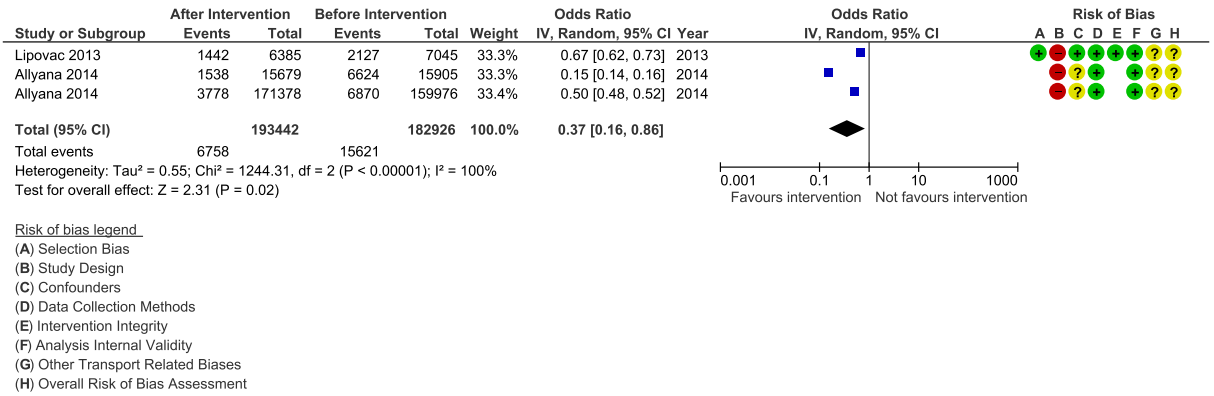


**FIGURE 9 |** Secondary outcome: changes in 'red light and speed limit non-compliance' after enforcement of traffic laws and regulations.

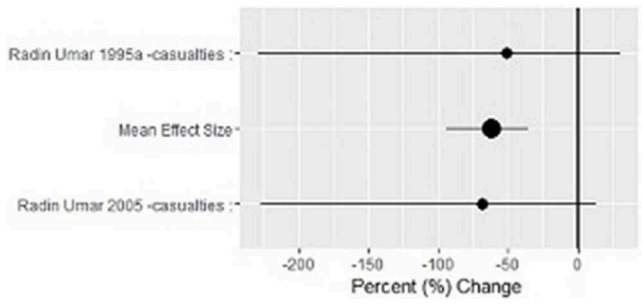


**FIGURE 10 |** Primary outcome: percent change in the number of 'road accident casualty' after daytime running-headlight regulation.

## Sensitivity Analysis

We compared the fixed and random effects' estimates of interventions after which we found that the overall estimates were slightly larger with the random-effects model, but the confidence intervals were identical for fixed and random effects. The overall effect was calculated using a random-effects model. The heterogeneity of studies was assessed by inspection of the forest plot, the confidence intervals of studies, and Chi² and $I^2$ statistics. The analysis under each intervention category was grouped by study design. It was not possible to separate very low-quality studies from high-quality studies due to a lack of sufficient studies or outcome data.

The publication bias was analyzed by examining funnel plots and cumulative meta-analysis. No publication bias was observed.

**TABLE 4 |** Summary of findings (GRADE) for road engineering interventions.

| **Population:** Vulnerable (non-motorized and motorized two-wheel) road users; **Settings:** Low- and middle-income countries<br>**Intervention:** Road engineering interventions. | | | | | |
|---|---|---|---|---|---|
| **Outcomes** | **Illustrative comparative risks* (95% CI)** | | **Relative effect (95% CI)** | **No of Participants (studies)** | **Quality of the evidence (GRADE)** |
| | **Assumed risk** | **Corresponding risk** | | | |
| | **Control** | **Road engineering** | | | |
| **Primary outcome–"road traffic death counts"** | **Study population** | | **OR 1.63** (1.01–2.63) | 948 (3 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,b,c] |
| | **138 per 1,000** | **207 per 1,000** (139–297) | | | |
| | **Moderate** | | | | |
| | **65 per 1,000** | **102 per 1,000** (66–155) | | | |
| **Primary outcome–"road accident injuries"** | **Study population** | | **OR 0.76** (0.47–1.23) | 948 (3 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,d,e] |
| | **595 per 1,000** | **527 per 1,000** (408–644) | | | |
| | **Moderate: Not available** | | | | |
| **Primary outcome–"road accident casualty"** | **Study population** | | **OR 2.31** (0.57–9.35) | 718 (2 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,f,g] |
| | **313 per 1,000** | **513 per 1,000** (206–810) | | | |
| | **Moderate** | | | | |
| | **180 per 1,000** | **336 per 1,000** (111–672) | | | |
| **Primary outcome–percent-change in the number of "road accident casualty"**[h] Follow-up: mean 1 years | **Study population** | | **Mean effect −56.02** (**–**147.68 to 1.716)[i] | 14,404 (2 studies) | ⊕ ⊖ ⊖⊖ **very low**[j,k] |
| | **213 per 1,000** | **−11,925 per 1,000** (-31,438–365) | | | |
| | **Moderate: Not available** | | | | |
| **Primary outcome–Percent-change in "road traffic death counts"**[h] Follow-up: mean 1 years | **Study population** | | **Percent-change −200.00** (1663.12–48.95)[l] | 12,139 (1 study) | ⊕ ⊖ ⊖⊖ **very low**[m] |
| | **121 per 1,000** | **−24,226 per 1,000** (1,000–1,000) | | | |
| | **Moderate: Not available** | | | | |

**The basis for the **assumed risk** (e.g., the median control group risk across studies) is provided in footnotes. The **corresponding risk** (and its 95% CI) is based on the assumed risk in the comparison group and the **relative effect** of the intervention (and its 95% CI). **CI,** confidence intervals; **OR,** odds ratio.*

*[a] Downgraded by one level. All included uncontrolled before-and-after studies were rated at high risk-of-bias for study design. The regression-to-the-mean confounding variable was not controlled in most studies.*

*[b] For all studies, effect estimates and CI overlap.*

*[c] Serious imprecision. The sample size and number of events does not meet "rule of thumb" (>76 events, >188 sample size). The 95% CI of the summary estimate includes both line-of-no-effect and potential appreciable benefits.*

*[d] There was an unexplained inconsistency that was supported by studies on either side of line-of-no-effect.*

*[e] Serious imprecision. Certainty in evidence lowered because of a small number of events (>149) leading to a wide CI in one study. The 95% CI of the summary estimate includes no effect.*

*[f] Serious inconsistency. Only two studies contributed effect estimates, the CI of individual studies was wide, presence of considerable heterogeneity ($I^2$ =77%, $p < 0.05$). Some heterogeneity was due to differences in country-specific population, road-environment, study size, and duration.*

*[g] Serious imprecision. The 95% CI includes no-effect and appreciable harm. The number of studies was small.*

*[h] For time-series data, the calculations of effect sizes were done using the statistical software R [1] (version 3.1.2).*

*[i] Two studies assessed the number of road accident casualty in percent-change (26.62, 95% CI −149.58 to 35.75; −111.80, 95% CI −492.97 to 24.34).The mean effect of road accident casualties declined by 44% in percent-change after road engineering intervention.*

*[j] Serious inconsistency. Unexplained inconsistency with effect estimates widely different and CI not overlapping. Some of the variations may be due to country-specific population, intervention sub-categories, road-environment, and study duration.*

*[k] Serious imprecision. The 95% CI includes both no effect and appreciable benefits.*

*[l] One study assessed road traffic death counts percent-change (−200.00, 95% CI −1663.12 to 48.95), based on 10,085 people involved in accidents after road engineering intervention.*

*[m] Wide confidence intervals.*

**TABLE 5 |** Summary of findings (GRADE) for traffic laws and regulation interventions.

| **Patient or population:** Vulnerable (non-motorized and motorized two-wheel) road users; **Settings:** Low- and middle-income countries<br>**Intervention:** Traffic law enforcement & regulation interventions | | | | | |
|---|---|---|---|---|---|
| **Outcomes** | **Illustrative comparative risks* (95% CI)** | | **Relative effect (95% CI)** | **No of Participants (studies)** | **Quality of the evidence (GRADE)** |
| | **Assumed risk** | **Corresponding risk** | | | |
| | **Control** | **Traffic laws and regulations** | | | |
| **Primary outcome–"road traffic death counts" among motorcycle road users** | **Study population** | | **OR 0.94** (0.72–1.23) | 35,710 (3 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,b,c] |
| | **22 per 1,000** | **20 per 1,000** (16–26) | | | |
| | **Moderate** | | | | |
| | **20 per 1,000** | **19 per 1,000** (14–24) | | | |
| **Primary Outcome–"number of injuries (moderate and severe)" among motorcycle road users** | **Study population** | | **OR 0.74** (0.61–0.89) | 35,710 (3 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,d] |
| | **832 per 1,000** | **785 per 1,000** (751–815) | | | |
| | **Moderate** | | | | |
| | **932 per 1,000** | **910 per 1,000** (893–924) | | | |
| **Primary outcome–percent-change in "road traffic death counts" among motorcycle road users**[e]<br>Follow-up: mean 1 years | **Study population: One study only** | | **Percent-change–500.65** (−1248.43 to 167.55)[f] | 0 (1 study) | ⊕ ⊖ ⊖⊖ **very low**[g] |
| | **Moderate: Not available** | | | | |
| **Primary outcome–percent-change in the number of "road accident casualty" among motorcycle road users**[e]<br>Follow-up: mean 6 months | **Study population** | | **Mean percent-change–62.122** (−94.495 to 35.138)[h] | 5,083 (2 studies) | ⊕ ⊖ ⊖⊖ **low**[i] |
| | **191 per 1,000** | **−11867 per 1,000** (−18051–1,000) | | | |
| | **Moderate: Not available** | | | | |
| **Secondary Outcome–"compliance" to mandatory helmet law among motorcycle road users** | **Study population** | | **OR 5.55** (1.21–25.55) | 24,7599 (7 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,j,k] |
| | **501 per 1,000** | **848 per 1,000** (549–962) | | | |
| | **Moderate: Not available** | | | | |
| **Secondary Outcome–"non-compliance" to red-light and speed limit** | **Study population** | | **OR 0.37** (0.16–0.86) | 37,6368 (3 studies) | ⊕ ⊖ ⊖⊖ **very low**[a,l,m] |
| | **86 per 1,000** | **34 per 1,000** (15–75) | | | |
| | **Moderate** | | | | |
| | **172 per 1,000** | **71 per 1,000** (32–152) | | | |

**The basis for the **assumed risk** (e.g., the median control group risk across studies) is provided in footnotes. The **corresponding risk** (and its 95% confidence interval) is based on the assumed risk in the comparison group and the **relative effect** of the intervention (and its 95% CI). **CI**, confidence intervals; **OR**, Odds ratio.*

[a] *Downgraded by one level. Included uncontrolled before-and-after studies were rated at high risk-of-bias for study design.*

[b] *Effect estimates of individual studies are closely aligned; CI is narrow enough for decision-making based on statistical analysis.*

[c] *Large sample size (>2,000 people in each arm) and narrow CI of the summary effect estimate.*

[d] *Serious inconsistency. $I^2$ of 85% ($p < 0.05$) indicate the presence of substantial heterogeneity. Some heterogeneity is due to differences in populations, data-collection duration, and study size.*

[e] *For time-series studies, the calculations of effect sizes were done using the statistical software R [1] (version 3.1.2).*

[f] *One study reported road traffic death counts based on data from 1,496 people involved in accidents after law enforcement.*

[g] *Serious indirectness. The population total sample size was inferred from other studies. The study included multiple interventions for the road safety of motorcycle road users.*

[h] *Two studies reported the number of road accident casualty (Percent-change −51.06, 95% CI −228.64 to 30.56; Percent-change −68.37, 95% CI −227.40 to 13.40).*

[i] *The 95% CI around the summary estimate for both studies include both (1) no-effect and (2) potential large effect.*

[j] *Serious inconsistency. Unexplained inconsistency supported by non-overlapping CI, a considerable level of statistically significant heterogeneity of effect estimates ($I^2$ =100%, $p < 0.05$). Some of the heterogeneity is due to differences in data collection duration and study size.*

[k] *Serious imprecision. The 95% CI is consistent with the possibility of appreciable benefits.*

[l] *Very serious unexplained inconsistency supported by statistically significant heterogeneity of effect estimates ($I^2 = 100\%$). Some of the heterogeneity is due to differences in populations, intervention sub-categories, and data collection size in included studies.*

[m] *Serious indirectness. Interventions included in the studies were of different sub-categories and used different population segments (motorcyclists and pedestrians).*

*GRADE quality of evidence*

We assessed the methodological quality of the included studies according to the GRADE system for rating the quality of evidence. We ranked the overall quality of evidence across all studies as very low quality. Please see, the summary of findings (GRADE) for road engineering interventions (**Table 4**) and the summary of findings (GRADE) for enforcement of traffic laws and regulations (**Table 5**).

## DISCUSSION

Road engineering interventions were not effective in reducing road traffic death counts, the number of injuries, and road accident casualty outcomes after road improvements. While the enforcement of mandatory helmet law was ineffective in reducing road traffic death counts, the intervention efforts proved effective in decreasing overall injuries and increasing helmet use compliance. Automated-enforcement-system (camera) and pedestrian signal interventions were effective in increasing road users' compliance to road safety measures. The daytime-running headlight intervention was effective in reducing road accident casualties.

Four studies presented either a unique outcome or a unique study design to measure enforcement of traffic laws and regulations and road engineering intervention outcome effects. In one study (Liu et al., 2011), the use of transverse rumble strips could reduce the incidence of crashes by 25%, on average. Another study (Antic et al., 2013) showed that the use of speed bumps of 5 and 7 cm height significantly contributed to the safety of vulnerable road users, especially the safety of pedestrians because mean-vehicle-speed was reduced by 79%. The findings of one study (Quistberg et al., 2014) showed that the signalization efforts were associated with an increased risk for pedestrian-vehicle collisions. One RCT (Sumner et al., 2014) found that the free distribution of reflective vests led to a statistically significant increase in vest usage among motorcycle riders; however, the absolute increase was modest.

This review included four non-randomized study designs. Because of methodological differences in study designs, the risk of bias in included studies ranged between A and B grade. Overall, all included studies had adequate information to individually meet the study inclusion criteria. The meta-analysis results assessed the presence of substantial heterogeneity for enforcement of traffic laws and regulation intervention studies. We expected some variations in between studies because of differences in sample size, data collection duration, and road environment. The summary effect estimates of studies showed inconsistency and impreciseness, which downsized the quality evidence of included studies as very low quality. The majority of the studies included in this review were uncontrolled before-and-after. It is difficult to perform controlled trials in the transport environment especially those meant for road improvements. In most studies, the post-intervention period started soon after the deployment of the intervention, and all studies included just one period before and one period after, therefore general changes and traffic volume confounders were most likely controlled. In addition, we attempted to minimize bias in the review process by searching a range of databases and not limiting the search by language. We also ensured that study identification and inclusion, data extraction, and risk-of-bias assessment were carried out by two review authors working independently or together.

This review has some limitations, which must be taken into account when interpreting our results. Given our broad approach to study inclusion criteria, we ended up with multiple types of study design, interventions, and outcomes. In addition, there were variations in between studies due to differences in sample size, duration of data collection, road environment, and macro-economic conditions in which the study was conducted. Almost all road engineering studies were found at the risk of regression-to-the-mean confounder given the fact that the selection of treatment sites for road safety intervention is largely influenced by the high frequency of accident rates. For time-series studies, the effect sizes were computed as the percent change. A drawback of this method is that it does not address the problem of autocorrelation and subsequently may result in reduced standard errors. Using ARIMA models may help evade the problem but fitting the ARIMA models requires larger datasets.

The findings of this review mirror the findings of the first systematic review of road traffic injury initiatives' effectiveness in LMICs (Staton et al., 2016). In this review, the first finding was that legislation interventions evaluated with the best outcomes when combined with strong enforcement initiatives or as part of a multifaceted approach. Second, road improvements may increase road traffic injuries. In our review, the evidence showed that enforcement of legislative interventions when combined with increased police surveillance, penalization for non-compliance, advocacy campaigns, and automated-enforcement-systems were more effective in changing drivers' behaviors when compared to stand-alone road engineering interventions. Because of police surveillance, the likelihood of being caught by the police and of being penalized force compliance behavior among road users in LMICs. It is also likely that road users become more aware of traffic safety because legislative enforcements are generally accompanied by awareness campaigns, as seen in some studies (Radin Umar et al., 1995a; Radin Umar, 2005; Bhatti et al., 2011; Nhan et al., 2017). For road engineering interventions, the results were uncertain on reducing the number of road traffic injuries and deaths. In one study (Mutto et al., 2002), because of the construction of an overpass (footbridge), pedestrian injuries increased, although there was a slight decline in fatalities. Since there was no police surveillance or a financial penalization for using roads to cross or any attempts to channel pedestrian traffic to the overpass, most of the pedestrians crossed by creating their own path at "convenient" points through traffic while risking life. Another research (Hijar et al., 2003) also found similar findings. Conversely, the findings of this review did not mirror the findings of reviews conducted in a high-income country setting. For instance, one review (Bunn et al., 2013) suggested that area-wide traffic calming measures may be a promising intervention for reducing the number of road traffic injuries and deaths. In another review (Liu

et al., 2008), researchers found that the motorcycle helmet reduced the risks of death and head injury in motorcyclists who crashed.

## CONCLUSION

Further research is needed to examine the effects of road engineering interventions on injury severity outcomes. Even though the evidence was of very low quality, traffic laws, and regulation interventions when combined with enforcement initiatives or with, other approaches proved effective in changing drivers' behaviors.

Future research on road engineering interventions combined with automated-enforcement-system must be explored in an LMIC setting. There is a need for high-quality study designs that use long-term observational periods at the start of the intervention and after the intervention implementation. This review found evidence gaps on the effects of segregation of vulnerable road users from motorized vehicles, bicycle infrastructure interventions, traffic-calming measures on pedestrian accidents.

## DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

## AUTHOR CONTRIBUTIONS

MG prepared the review article. SB read and approved the review article.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2020.00010/full#supplementary-material

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COMMUNITY CASE STUDY
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# Identifying Changes in Bicycle Accident Trends Using GIS and Time Series Information in the City of Zürich

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In order to be effective, road safety officers must have a complete overview of the accidents in their area of responsibility, including information pertaining to the location and severity of the accidents, and how the number of accidents are developing over time. Ideally, this information is stored in a Geographic Information System (GIS) enabled database, which helps to facilitate data processing and analysis, which enables improved understanding of the reasons for the accidents and the proposals of how to improve road safety. This paper presents a case study based on accident reports from the Zurich City Police. Using a joint GIS and time series analysis based on negative binomial regression, the data is analyzed to identify trends in accident development for several accident subgroups (e.g., bicycle accidents, senior citizen accidents, e-bike accidents) and specific locations. The subgroup of bicycle accidents will be discussed in more detail. The time series analysis is corrected for exposure (e.g., the increasing number of e-bikes) and forecasts the number of accidents which are likely to occur in the future. Significantly higher numbers of accidents than those expected serve as an early warning that further investigation, leading to possible interventions, is required. The case study shows that with this information, it is possible to identify both geographical areas and accident subgroups that have deviating patterns in accident numbers, and should be further investigated. For bicycle accidents, 4 out of 12 districts exceed the average accident trend by over 95% and 3 districts have an accident number that is over 10% higher than that district's forecast, with the highest being 33% above the already increasing accident trend. Other accident subgroups are presented in summary form. The results of the analysis allow consistent and automated analysis across all potential areas for improving road safety, helping to focus the efforts of road safety managers on those areas where their efforts are most effective.

**Keywords: GIS, time series, bicycle accidents, road safety, accident development**

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## 1. INTRODUCTION

Accident analysis is a fundamental part of road safety management. The likelihood of occurrence of road accidents and their severity are influenced by various factors, whose effects are sometimes difficult to determine due to interactions between them. The effects of these factors also change through space and time. The determination of the need for road safety improvement interventions

requires both a reliable data basis and suitable and effective methods for evaluating the data.

This paper shows how a joint GIS and time series analysis can be used to analyze the accident situation in a city. The first step is to correct the data for exposure (changes in number of vehicles and their specific mileage) to reflect changes in mobility behavior. The second step is to conduct a trend analysis to determine the accident situation and its significance. The results of these two steps are then used to detect geographically distributed irregularities in the accident situation and irregularities within the subgroups (e.g., bike accidents, senior citizen accidents, etc.) and thus can be used by road safety managers, to help them focus their accident prevention interventions on those areas where their efforts are most effective.

GIS based approaches provide valuable additional information by being able to detect areas with increased accident occurrences by statistical means and thus being able to extract spatial accident distribution models that provide further understanding of development of accident rates. This paper contributes to this approach by presenting a case study that uses a standard statistical model and standardized data, in order to have an overview on spatially distributed accident rate development, but also enables road safety officers with less in-depth statistical knowledge to get an overview on the accident development in their areas of responsibility and thus enables them to act in a focused way.

The data used in this work (all traffic accidents in the city of Zurich, Switzerland; from January 2004 to December 2018) was provided by the Department of Transport (DAV) of the city of Zurich. Zurich is the largest Swiss city with about 425,000 inhabitants and another 470,000 commuters (Stadt Zürich, 2018). The methodological insights gained are easily transferable to other cities.

The rest of this paper is structured as follows: First, a literature analysis is provided in section 2. The methodology is then explained (section 3), as well as how the methodology was used in the case study (section 4). Finally, the results and an outlook on possible future work are given in section 5.

## 2. LITERATURE

The literature section is divided into three parts: (1) an overview of previous work in this field, (2) legal foundations, which provide a framework for the investigation in Zurich, for example by requiring certain statistical methods for accident analysis, and (3) references to the statistical methods used in this paper.

GISs have proven to be invaluable tools for traffic safety studies. For example, Petch and Henson (2000) used GIS information to investigate child traffic casualties, taking into consideration the spatial differences in traffic, socio-economic factors, etc. on a district-based level; Steenberghen et al. (2004) used point pattern techniques to identify accident-prone areas and show the impact of traffic-calming measures. To further improve GIS-based traffic safety studies, specialized spatial-statistical methods were developed to also present the spatially distributed aspects of information. Li et al. (2007) presented a Bayesian approach to identify and rank road segments based on temporal patterns of crash risks, Aguero-Valverde (2013) presented multivariate spatial models that have their roots in disease mapping, Zeng and Huang (2014) presented a Bayesian spatial joint model for crash prediction for an urban road network, Deublein et al. (2015) used a Bayesian network model to predict accidents on Swiss highways, and Garcia de Soto et al. (2018) presented a model using artificial neural networks to predict accident frequency for the same task. However, all the above methods require in-depth statistical knowledge to perform the analyzes presented in the literature.

In Switzerland, road safety is an important political issue that has led to the development of a stringent road safety program (Schweizerischer Bundesrat, 2010), which comprises a set of regulations and standards concerning statistical methods that are used in road safety assessments. A benefit of these regulations is that they create nationwide comparability of accident situations, which is an important basis for systematic evaluation. An overview of the regulations is provided in **Table 1**.

The norm SN 641 711 (Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS), 2015) requires 6 key questions

**TABLE 1 |** Overview of Swiss legal regulations governing road traffic accident investigation.

| Identifier | Article | Version | Type | Name | Description |
|---|---|---|---|---|---|
| SR 741.01 | Art. 6a | 1 Jan 2019 | Law | Road traffic law | Safety of the road infrastructure (planning, accident analysis, road safety officer) |
| | Art. 89i-89n | | | | Introduction of a road accident information system (ISU), which combines and coordinates the collection and evaluation of accident data |
| SR 741.57 | | 1 Jan 2019 | Ordinance | Ordinance on the Road Traffic Accident Information System (ISUV) | Structure, purpose, organization, operation and use of the Road Traffic Accident Information System (ISU) |
| SR 741.11 | Art. 54-56 | 1 Feb 2019 | Ordinance | Ordinance on traffic rules | Mandatory accident report form to be filled in by the police |
| | Art. 56, Abs.1bis | | | | Obligation to compile standardized road accident statistics twice a year and to present the findings to the public |
| Bundesamt für Strassen (ASTRA) (2017) | - | 21 Dec 2017 | Instructions | Specialized Road Accident Application (VU) | Instructions for filling in the Accident Record Form (UAP) 2018 |
| SN 640 008 | - | 2000 | Standard | Road traffic accidents | Analysis of accident numbers, accident statistics, comparisons and trends |
| SN 641 711 | - | 2015 | Standard | Road traffic safety | Standard statistics |

to be answered about accidents: (1) How many, (2) where, (3) how, (4) when, (5) who, and (6) why. These questions are then divided further in total 26 "standard statistics" answering the questions. All of those should be answered using the statistical methods given in SN 640 008 (Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS), 2000). This norm pair has, however, been criticized as being too complicated because the given statistical methods (e.g., multivariate statistics for accident development) are tailored to experienced statisticians rather than road safety officers.

Based on the legal requirements, in particular the norm SN 641 711, and to find a compromise between statistical complexity and useability, the family of negative binomial (NB) regression models is chosen for this work as the basis for the statistical procedure. This family of regression models is based on the negative binomial distribution, but the models themselves slightly vary in their parametrizations. Hilbe (2011) summarizes the different models. The *NB2* model was selected as suggested in the VSS Research Report 1634 (Schweizerischer Verband der Strassen- und Verkehrsfachleute (VSS), 2018).

In summary, GIS combined with the use of advanced statistical methods provides valuable insight into accident situation development. However, this is mainly tailored to experienced statisticians with substantial in-depth knowledge. The normative prescribed statistical methods in Switzerland try to find a balance between complexity and usability, building on an excellent data basis framework for making assessing the accident situations in Swiss cities more accessible to less statistically experienced persons. Similar methods can also be transferred to cities in other countries, and might help increase the overall awareness about traffic accident situations in areas without dedicated traffic accident statisticians.

# 3. METHODOLOGY

This section describes the general methodology of this paper before applying it to the case study in section 4.

## 3.1. Data Correction

### 3.1.1. Exogeneity Correction

Accident records from Zurich show a sharp increase in the number of accidents between 2014 and 2016 (**Figure 1**). This increase, however, is principally because of the changed reporting of property damage accidents. Before 2015, minor property damage accidents[1] were not included in the accident records. From July 2015, however, all accidents (also including minor accidents) were recorded. This change lead to an increase of approximately 2,000 accidents per year. The data was adjusted to correct for the differences attributed to the different data collection methods. In the years following the change (i.e., 2016–2018), property damage accidents with the 2,000 smallest values were excluded. As the change took place in July 2015, i.e., mid year, only the 1,000 smallest property damage accidents were removed for 2015. This affected from 2015 to 2018 in total 366 or 6.4% of the bicycle accidents.

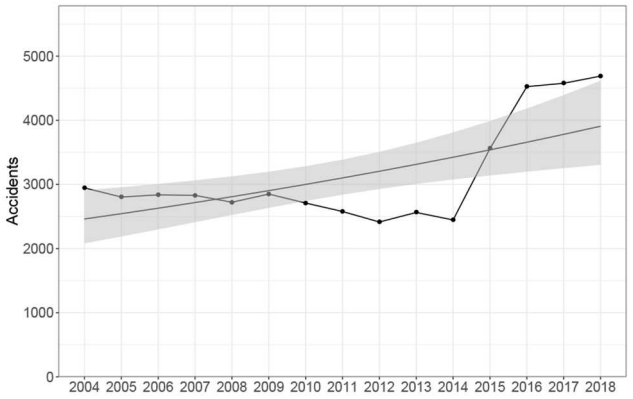


**FIGURE 1 |** Accident numbers from Zurich between 2004 and 2018.

### 3.1.2. Exposure Correction

As mobility behavior in the city of Zurich has changed over time (Federal Statistical Office Switzerland, 2018), so has the exposure to accidents. For example, there has been an increase of 50% in bicycle trips between 2012 and 2018, whereas the frequency of bicycle accidents has increased by over 70%.

Exposure correction must be integrated into the model calculation to adjust for the increase in exposure. For this purpose, an index of the traffic volume for each vehicle type is created from the data of the automated traffic counting stations within the city of Zurich, which is based on a weighted average of the average frequencies of each vehicle type per counting station. Additional index values were calculated based on the overall traffic development, allowing an index value to be available for the years before the commissioning of the automated traffic counting stations (Stadt Zürich Tiefbau- und Entsorgungsdepartement (TED), 2018).

The indexing is performed using an indexing Equation (Equation 1). The accident counts in year 2012 stay the same, but the counts of vehicles in the other years are adapted using this indexing equation to adjust for exposure.

$$r_{A,i} = \frac{n_{A,i}}{\eta_i} \tag{1}$$

with

$r_{A,i}$ . . . Accident rate in year $i$,
$n_{A,i}$ . . . Number of accidents in year $i$, and
$\eta_i$ . . . Index for year $i$ with base year 2012.

## 3.2. Trend Analysis

The statistical methods used are described in a Swiss norm (see **Table 1**), and are therefore only presented here in summary form. The basis of the calculation is the negative binomial distribution shown in Equation (2). The equation is presented in alternative

[1]Despite lacking a formal definition, *Dr. Wernher Brucks* (Head of Traffic Safety, City of Zurich Traffic Department) stated that the widely used definition of a minor property damage accident corresponds to an accident resulting in property damage of less than CHF 500.

parametrization with $r = 1/\alpha$, $p = 1/(1+\alpha\mu)$, and $(1-p) = \alpha\mu/(1+\alpha\mu)$; as shown in Hilbe (2011).

$$f(y \mid \mu, \alpha) = \binom{y_i + \frac{1}{\alpha} - 1}{\frac{1}{\alpha} - 1} \left(\frac{1}{1+\alpha\mu_i}\right)^{\frac{1}{\alpha}} \left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right)^{y_i} \quad (2)$$

with
$y \ldots$ response,
$\mu \ldots$ mean, and
$\alpha \ldots$ dispersion parameter.

The link function (a function that connects the predictor to the distribution function, and is also prescribed by the chosen statistical model) used in the calculation is shown in Equation (3).

$$\log(\mu) = \beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n \quad (3)$$

with
$\beta_n \ldots$ parameters, and
$X_n \ldots$ observations.

The negative binomial regression is performed using a generalized linear model in conjunction with an IRLS algorithm (Hilbe, 2011). The Pearson residuals are then calculated according to the procedure described in the Swiss norm. Values above 2 are defined as outliers and the corresponding observation points are marked for a more detailed analysis.

## 3.3. Unusual Accident Development

The results of the analysis can show areas with unusual accident development. For this, the accidents are divided into 12 different zones (corresponding to the districts of the city of Zurich). For these zones, a generalized linear model (GLM) is estimated using all but the last data point. Then, a 95% prediction range is estimated for this last data point using the bootstrap technique, to create several GLMs from the data.

Each GLM is created using a random sample from the empirical distribution, assuming the sample from the empirical distribution is correct and representative for the true distribution. This is done for $n = 1,000$ samples, in order to have 1,000 GLMs, that can then be used to infer the statistical parameters for the accident rate.

The prediction range is then an interval, where the last data point should lie within the range with 95% confidence (i.e., an interval provided by 95% of the several GLMs, given the previous data points. If the last data point is outside of this interval for a particular zone, the zone and data point are flagged, indicating an accident rate in the specific zone outside of 95% of the GLMs' forecasts, signifying unusual accident development.

# 4. CASE STUDY

This section presents the city of Zurich case study.

## 4.1. Overview

### 4.1.1. Data

This case study was conducted using accident data from the city of Zurich. It covers all road traffic accidents registered by the police in the area of the city of Zurich in the period from 01 January 2004 to 31 December 2018. Each observation corresponds to one accident. Several persons or objects may be involved in an accident. The accident data set contains 87 variables and 64,394 observations. In summary, the variables cover the following topics: accident location, date and time, weather, road type, and condition, means of transport involved, severity of the accident (fatalities, serious injuries, minor injuries, property damage), amount of property damage, main cause, type of accident, and whether children or elderly people were involved in the accident. For the model, the parameters for accident location and the accident timestamp are used directly, the other parameters are used to form subgroups.

### 4.1.2. Focus Area: Bike Accidents

For the sake of brevity, the results are presented here only for bicycle accidents. More results for other types of accidents can be found in Hermann (2019). From 2004 to 2018, 5,723 bicycle accidents were reported. These include 5,374 accidents with a classic bicycle, 109 accidents with at least one fast e-bike (up to 45 km/h) and 299 accidents with at least one slow e-bike (up to 25 km/h). 59 accidents involved both at least one e-bike and at least one classic bicycle. Of the 5,374 accidents, 11.2% resulted in property damage, 68.4% in minor injuries, 20.0% in severe injuries, and 0.4% in fatal injuries. For the following analysis, classic bicycles and e-bikes (fast and slow) are examined together, as they were only reported separately from 2012 on. Additionally, the vulnerability of the riders is comparable because of the low level of protection, and they are also treated similarly in legal terms. For this analysis, all accident outcomes are grouped together. As minor and major injuries make up over 88% of all accident outcomes, the analysis inherently focuses on those. Because of the fortunately low number of fatalities (approx. 1.6 per year), a sufficient sample size for district-wise evaluation is not available.

## 4.2. Trend Analysis

The trend analysis as well as the values used to assess unusual accident development are estimated for all types of bicycle accidents. The results are shown in **Figure 2**, where **Figure 2A** shows the raw data of the accidents and **Figure 2B** the results of the trend analysis with all corrections.

The two subfigures of **Figure 2** show the years 2007–2018 on the x-axis and either the accidents or the indexed accidents on the y-axis. The gray shaded area shows the 95% prediction interval for the GLMs (i.e., the area where 95% of the GLMs lie within) and the blue line shows 95% prediction range. Although both figures show an increasing trend in bicycle accidents (**Figure 2A**) respective indexed accident rate (**Figure 2B**), the differences are quite significant and underline the importance of correct exposure and exogeneity correction. The raw accident numbers (**Figure 2A**) show a significant trend of +10% per year, whereas the trend is only +2.3% per year when all of the corrections are applied (**Figure 2B**).

## 4.3. Unusual Accident Development

The discrepancies between the expected and actual values show that there is no abnormal increase in the number of expected

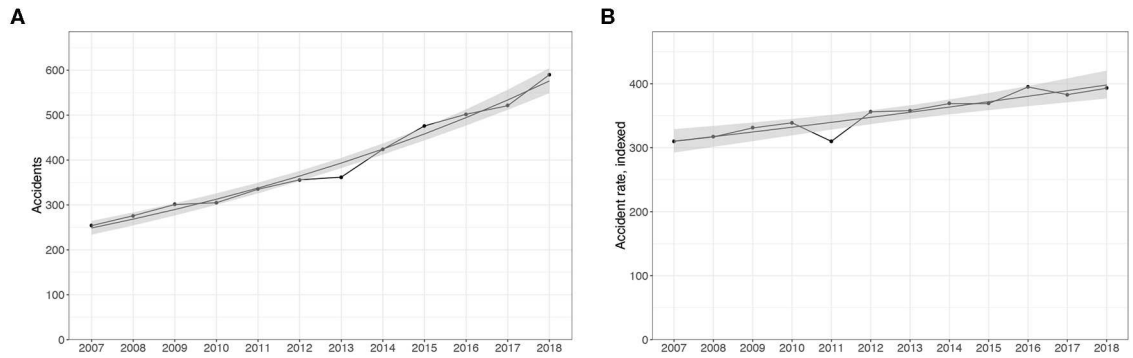


**FIGURE 2 |** Accident numbers without **(A)** and with **(B)** corrections.

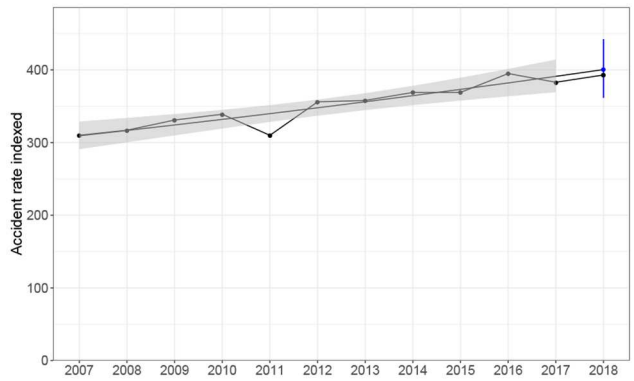


**FIGURE 3 |** 95% prediction range (blue) for bike accidents.

accidents in 2018 (**Figure 3**). This is indicated by the fact that the last data point lies within the blue bar, which represents the 95% prediction range for the next observation.

However, when looking at the spatially distributed data, more information emerges, as shown in the next section.

## 4.4. GIS-Analysis

The result are shown in compact form for the 12 city districts of the city of Zürich in **Figure 4**. Additionally, the graphs for each district are provided in the **Supplementary Material** to this paper.

All 12 districts are displayed with their outline and the trend in percent increase/decrease, and colored according to the trend analysis in **Figure 4A**. Dark green indicates a decreasing trend in exposure and exogeneity-corrected bicycle accident rate, light green indicates an increasing trend that is below the average trend of +2.3% for Zurich overall, orange indicates a trend above the average trend of +2.3%, but below +4%, and red indicates a trend of +4% or more.

**Figure 4B** shows the difference between the predicted accidents and the observed accidents, both color-coded and in numbers. Dark green indicates areas where the actual accident numbers are more than 10% below the predicted numbers, orange indicates areas where the actual accident numbers are between 0 and 10% higher than the predicted numbers, and red indicates areas where the actual accident numbers exceed the prediction by more than 10%.

It can be seen that the corrected accident rate trend in the city center is below average (0.8, 1.6, or −1.5% per year), while in the outer districts there is a tendency for increasing trends, which also extends across the city, just north of the city center.

In the difference of the prediction and actual accidents map, it can be seen that in the district with 4.5% increase (District 10, plot in the **Supplementary Material**), there is an additional 19% excess of accident numbers beyond the predicted numbers, signifying that the actual accident development is even higher than the already high increasing trend, although still within the 95% prediction interval from the early warning system.

In the district with the 5.5% increasing trend (District 9, plot in the **Supplementary Material**), there is, however, an unusual drop in accidents noticeable, as can be seen in the supplementary material, where all prediction plots for the districts are provided.

This shows an unusual accident development as well, although a desired one.

## 4.5. Conclusions

Significant deviations from predicted accident rates found in specific areas of a city demonstrate that processes or events are taking place that have not been considered in the initial model. This should give the road safety manager cause for concern, and should help him/her focus his/her efforts in understanding the accident situation. For example, presented with the results above, the road safety manager might want to reassess the exposure and check whether or not all relevant exogenous aspects are integrated into the initial model. Additionally, he/her might want to look at unexpected changes in traffic patterns that may cause the geographical distribution of the anomalies.

The case study shows that GIS and standardized time series accident information helps road safety managers understand their accident situation, and therefore, will help increase road safety.

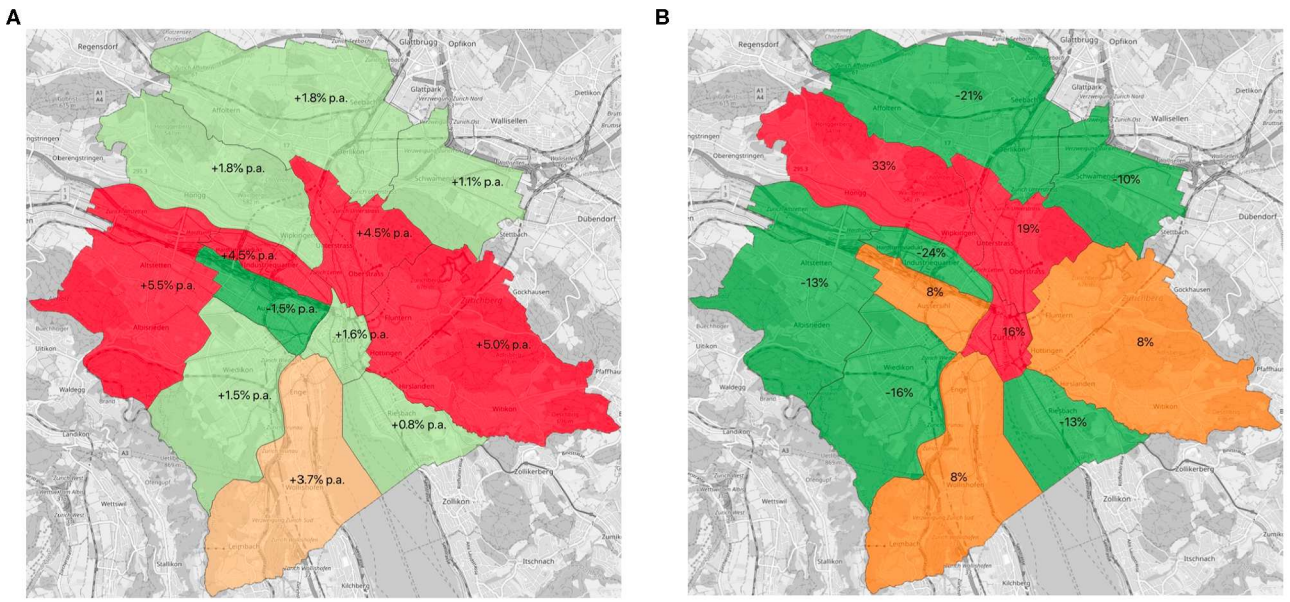


**FIGURE 4 |** GIS-based display of results; **(A)**: Accident trend, **(B)**: Difference of predicted and actual accidents.

## 5. SUMMARY AND OUTLOOK

Accidents result in property damage, injuries and deaths, and have indirect economic and societal impacts. It is advantageous to reduce them as much as possible. In this paper it is shown that through the use of GIS and time series information it is possible to identify both geographical areas and accident subgroups that show trends in accident numbers that deviate from those expected; something useful in focusing efforts to improve road safety. The results of the analysis allow consistent and automated identification of potential areas for improving road safety, helping to focus the efforts of road safety managers on those areas where their efforts are most effective.

Additionally, due to the use of standard models from statistics, road safety managers can easily add additional aspects (e.g., more detailed exposure correction from additional vehicle counting stations, traffic flow patterns,…) into the calculations and thus can improve the accuracy of the predictions and get more accurate results and a good basis for informed decisions (e.g., a split of E-bikes and normal bikes).

The case study presented showed an increase in bicycle accidents in the city of Zurich, and that a part of this increase was because of an increase in the number of bike trips, i.e., exposure. The time series analysis thus facilitates communication by being able to distinguish between a rise in accident numbers purely because of the higher number of bike trips and a rise in accident numbers because of other influences. This provides well-founded arguments for planning road safety interventions, if required. While this case study paper focuses on bicycle accidents, more in-depth analyzes of other accident groups can be found in Hermann (2019).

The insights gained through the analysis are not only useful in understanding the accident situation in the city of Zurich, but because of the standardized accident data collection and the standardization of the procedure on how to calculate the accident rate trend (i.e., the NB2 model) given in the norm, the same method can be used for all cities across Switzerland. By employing standard models from statistics, this method can also be used on an international scale with only minor adaptations if an appropriate data basis is available or can be built.

The results of the analysis apply specifically to the city of Zurich. Other cities facing similar challenges, however, can use the same method to improve their understanding of their accident situation.

## DATA AVAILABILITY STATEMENT

The data analyzed in this study were provided by the Traffic Department of the City of Zurich (Dienstabteilung Verkehr, Stadt Zürich) and cannot be made publicly available. Requests to access these data should be directed to Dr. Wernher Brucks, wernher.brucks@zuerich.ch.

## AUTHOR CONTRIBUTIONS

CK and JH contributed conception and design of the study. JH organized the database. CK and JH performed the statistical analysis and produced the result graphs and maps. CK wrote the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2020.00021/full#supplementary-material

**Supplementary Figure 1 |** Bike Accidents, District 1.

**Supplementary Figure 2 |** Bike Accidents, District 2.

**Supplementary Figure 3 |** Bike Accidents, District 3.

**Supplementary Figure 4 |** Bike Accidents, District 4.

**Supplementary Figure 5 |** Bike Accidents, District 5.

**Supplementary Figure 6 |** Bike Accidents, District 6.

**Supplementary Figure 7 |** Bike Accidents, District 7.

**Supplementary Figure 8 |** Bike Accidents, District 8.

**Supplementary Figure 9 |** Bike Accidents, District 9.

**Supplementary Figure 10 |** Bike Accidents, District 10.

**Supplementary Figure 11 |** Bike Accidents, District 11.

**Supplementary Figure 12 |** Bike Accidents, District 12.

**Supplementary Figure 13 |** Bike Accidents, Zurich (all districts).

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# In-Car Warnings of Emergency Vehicles Approaching: Effects on Car Drivers' Propensity to Give Way

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Emergency driving entails substantially higher risk rates than ordinary driving, and it is crucial that other road users notice the emergency vehicles on call. Sirens and emergency lights are used to warn and demand that other road users give way and provide safe passage, but accidents still occur. The purpose of this study was to test the effect of a broadcast hyper local Emergency Vehicle Approaching (EVA) message via RDS radio, noticing that an emergency vehicle on call is approaching and demands that others give way, on the propensity of individual drivers to give way. In two simulator experiments, a total of 90 car drivers participated. In Experiment 1, drivers were passed three times by an ambulance in traffic conditions where it was easy to detect the ambulance early, and two versions of EVA message were compared to a baseline condition without a broadcast message. In Experiment 2, drivers were passed only once by an ambulance and in traffic conditions that made it difficult to detect the ambulance early, and either received an EVA message, or no message. The results showed that EVA messaging made drivers give way earlier and learned to give way earlier even without an EVA message. The main finding was that EVA messaging was necessary for making inexperienced drivers give way to an approaching emergency vehicle on call. Most of them did not know that they are obliged to give way, and some did not notice the emergency vehicle before it passed them. In conclusion, the study suggests that EVA messaging to alert and instruct drivers how to give way properly is beneficial for traffic safety and for enabling time-efficient emergency transports.

**Keywords: emergency driving, warning messages, safety, transport efficiency, risk perception**

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## INTRODUCTION

Risk of accidents in connection with emergency driving (i.e., authorized driving in response to emergencies) have been more or less proportional to the increase of traffic and traffic density (Wilbur, 1997; Burke et al., 2001; Lundälv et al., 2010). Emergency driving entails risks, since the emergency vehicle (i.e., the vehicle designated and authorized to respond to emergencies) often drives significantly faster than the other vehicles (Saunders and Gough, 2003; Petzäll et al., 2011). Speed in itself, and speed differences between road users, are hazardous. Emergency vehicles on call, using sirens and warning lights, therefore have substantially higher accident rates than when

not being on call (Unterkofler and Schmiedel, 1994; Custalow and Gravitz, 2004; Bockting, 2007; Gormley et al., 2008; Pieper-Nagel and Wiegand, 2011; Abdelwanis, 2014). Further, the emergency driver often has a complex task to perform during driving (e.g., Albertsson and Sundström, 2011; Hsiao et al., 2018; Prohn and Herbig, 2020). For example, Finnish paramedics identify lack of education and training for emergency response driving as a main risk factor (Koski and Summanen, 2019). The emergency driver may need to communicate with colleagues and the dispatch, and to navigate. The situation in itself is also by definition stressful, since getting to and from an accident site (for ambulance drivers and firefighters) or crime site (for the Police) is potentially a matter of life or death. Emergency driving is further complicated by traffic intensity, which varies considerably depending on the site of the accident, where the emergency vehicle is in relation to the accident site but also because on actions taken by other road users, such as their reactions as they notice the warning lights and sirens (Vägverket, 2008). However, other road users often fail to observe the emergency vehicle although they use their blue emergency lights and sirens (Bylund et al., 1997). Traffic norms (i.e., how and why road users abide by laws and regulations, and interact) also may affect how inclined the road users are to identify an emergency on call and assist in providing safe passage for it (Alonso et al., 2017).

Traffic accidents involving an emergency vehicle on call and another vehicle can obviously to varying degree depend on the driver of the emergency vehicle and the driver of the other vehicle, respectively (Drucker et al., 2013). The emergency driver is obliged to use the warning systems of the vehicle to signal that the emergency vehicle is on call and demands all other road users to yield. The emergency driver also needs to drive such that the likelihood increases that the other road users detect that there is an emergency vehicle on call. This can be accomplished by not driving too much faster than the other traffic, placing the emergency vehicle more toward the middle of the road, and by not driving too near behind other vehicles. The emergency driver also needs to observe and adhere to maximum risk awareness, since speed is usually fast, margin of error is therefore small, and consequences of accidents are potentially fatal. The present paper is primarily about the *other* road users' behavior, however.

When an emergency vehicle approaches with sirens wailing and blue lights flashing, all other road users are obliged to yield and provide safe passage for the emergency vehicle. For the other road users to be able to follow the rule, two basic criteria must be fulfilled. First of all, they need to receive the information, that is, *detect and identify* that an emergency vehicle is approaching (e.g., "I see flashing blue lights and I hear sirens, so it must be an emergency vehicle on call, and it is coming my way"). Secondly, they need to *know the rule* in order to intentionally act correctly according to the information (e.g., "The emergency vehicle is on call and I am in its way, hence I need to yield safely and efficiently"). It may not be necessary for all road users to notice the emergency vehicle and know how to behave, since they may follow the good example of other road users. However, some road users do need to provide a good example, and rule knowledge is key to following rules. A restriction is that the road users also need to be in a state of mind such that they can *access the rule* and make correct decisions, and this is inhibited if they are startled or stressed, for instance if they notice the emergency vehicle very late.

Hence, the propensity to give way may depend on that the driver knows the rule, that is, that giving way is obligatory. Novel drivers (i.e., who have not had their driving license for very long) should be able to remember this rule from their driving education, provided that they learned and remember this rule among the great number of rules in the curriculum. On the other hand, an average novel driver has perhaps not experienced being passed by an emergency vehicle on call. The opposite applies for experienced drivers: they may have forgotten what was taught during their driving education, but they should several times have been passed by emergency vehicles on call.

The most common available warning systems are siren and emergency vehicle lighting (see e.g., Catchpole and Mckeown, 2007), both of which have limited reach and detectability. This is sometimes supplemented with broadcast calls over radio. A well-established technology for this is the Traffic Announcement (TA) features of the European Radio Data System (RDS). However, only a very small proportion of the recipients of such broadcast warnings are along the route of the emergency transport. In terms of signal detection theory (e.g., Green and Swets, 1966), most TA broadcasts are "false alarms" to the average driver. As a consequence, radio stations are reluctant to interrupt regular programming, and tend to select only the most critical cases (Wessman and Radio, personal communication, 2013). Recently, cellular mobile communication technology and collaborative intelligent transport services (C-ITS) begin to enable new ways of conveying traffic-related messages (e.g., Buchenscheit et al., 2009). Such messages can be adapted to the situation, traffic flow and individually directed only to those road users who are at risk of interfering with an emergency vehicle's route. Associated services are developed and demonstrated in the EU project NordicWay 2 (https://www.nordicway.net/), within which protocols and standards are developed for messages, issuing Emergency Vehicle Approaching (EVA) messages. Effects of C-ITS-based warning messages include a greater proportion of road users who react to the emergency vehicles, and a shorter mean response time (Lenné et al., 2008; Savolainen et al., 2010) as well as lower mean speed among the road users (Savolainen et al., 2010).

EVA messages can be defined as warnings that an emergency vehicle is approaching and demands that drivers ahead give way, and they target both self-driving and manually operated vehicles. The technology behind EVA messages is that the emergency vehicle that demands the traffic ahead of it to give way carries an FM radio transmitter that broadcasts the EVA message as a hyper local traffic warning via RDS (H&E Solutions, 2018) and on the TA frequency. The signal strength is proportional to difference in speed between the emergency vehicle and the traffic ahead of it, such that the message should not be received too far ahead in time, usually 10–15 s before the emergency vehicle passes. The EVA message is received in the radio and presented via the speakers. If available in the receiving car, the message is also presented in the dashboard screen (H&E Solutions, 2018).

There are several potential benefits of EVA messaging via RDS. First, it has the potential to reach the majority of road users in cars, since RDS has been included in the vast majority of car stereo devices for many years, and no additional technology in the receiving vehicle is needed. Second, almost all recipients of the message are along the route of the emergency vehicle, so there will be a small proportion of "false alarms" in terms of *not* being affected by the approaching emergency vehicle according to the alarm. Third, the alarm warning signal is amplified or augmented, and a greater number of road users can therefore earlier notice that there is an approaching emergency vehicle. Road users who are inattentive or have difficulty hearing the sirens approaching since they are listening to loud music on their car stereo will also be easier to notify. Fourth, those road users who do not know that they are obliged to give way and how to give way properly can be instructed. Fifth, and finally, the timing of the alarm signal can be adjusted in order for the road users to receive it with adequate timing—if the alarm signal is too early, they may treat it as a false alarm and therefore not give way.

*The general purpose* of the present paper was to test the effect of EVA messaging on individual drivers' propensity to give way to an emergency vehicle on call. Two simulator experiments were conducted to test and specify this effect with regard to how easy the emergency vehicle on call was to detect, and driving experience of the drivers who were to give way to the emergency vehicle on call.

# EXPERIMENT 1: EFFECTS WHEN THE EMERGENCY VEHICLE WAS VERY EASY TO DETECT

## Purpose

The purpose was to test the effect of EVA messaging on the propensity of a wide variety of drivers to give way to an ambulance on an emergency call, and when the drivers should have no difficulty detecting and identifying the ambulance at an early stage. Experiment 1 also served to explore and prepare for Experiment 2 by establishing if there were effects of EVA messaging, and by developing the methods.

## Method

### Participants

A total of $n = 22$ car drivers aged 19–57 years, $M = 29.3$ years, $SD = 12{,}3$ years, whereof 13 males and 9 females, participated. A valid driver's license for a private car (category B in Sweden) was required. They had had their driving licenses for 1–38 years, $M = 10.1$ years, $SD = 12.3$ years, and the recent year they varied between almost no driving at all to driving almost every day (1–5, $M = 3.04$, $SD = 1.55$) and between 10 and 40,000 km (see **Appendix**). Four drivers had extended driving licenses, for heavy trailer and truck (Swedish categories BE and C). All but four participants were recruited via e-mail lists to undergraduate courses at Linköping University, whereas the four oldest participants (aged over 50, and who also had most driving experience) were recruited via personal connections. They were rewarded with a cinema ticket each for their participation.

### Materials and Settings

A proprietary, small, car simulator without motion cueing was used. The only perceptual cues were from vision (i.e., the changing view of the surrounding environment when driving in it, including an inner rear-view mirror) and sound (i.e., from engine, other vehicles, tires and transmission, and air resistance). The visual cues were displayed on a 43-inch TV monitor placed 95 cm in front of the driver, thereby providing a field of view of about 90° horizontally and about 50° vertically. VTI's proprietary simulation software was used. The monitor's refresh rate was 60 Hz. The car stereo (emulating an RDS radio) was turned off, except for use of a "ping" sound to alert the driver when the EVA message was initiated in the instrument cluster (or in the instrument cluster as well as on the infotainment display in the center console). From the participant's position, the background noise sound pressure level (SPL) from ventilation and air conditioning was about 60 dBA, whereas the combined SPL from the background noise and the simulated driving at 80 kph was about 71 dBA. The SPL from the "ping" sound was about 68 dBA, which was considered to be well-audible for all potential participants. The SPL from the ambulance's siren increased proportionally to the distance. The sirens could be heard at about 60 dBA as soon as it appeared (i.e., was implemented in the simulation) 500 m behind the participant's car and increased to about 84 dBA when it was alongside the car.

More specifically, the EVA message was presented in two counterbalanced versions (EVA 1 and EVA 2, respectively). In EVA 1, only the instrument cluster was used. The EVA message was presented as a yellow triangle with a blue warning light and a text message stating "Utryckningsfordon på ingång! Var uppmärksam!" [Emergency vehicle approaching! Pay attention!]. As the ambulance closed in, further instructions were displayed regarding yielding and slowing down. In EVA 2, the EVA message was additionally presented on the infotainment display in the center console. The EVA message was received 50 s before the ambulance was estimated to catch up with the participant's car, based on the relative speed difference. In a control condition without EVA message (EVA 0) no EVA message and no "ping" sound was presented.

The driving scenario was a rural road, 3.5 m wide, with a roadside 2 m wide, marked by road-side markings 10 cm wide, 1 m long, and 2 m apart. The road center lines were 10 cm wide, 3 m long, and 9 m apart. Other traffic consisted of cars in the opposite direction, with an average of 20 s apart. No other vehicles in the same direction as the participant's car appeared in the scenario except an ambulance that closed in from 500 m behind, at a speed of 120% faster than the participant's own speed, but not slower than 80 kph. During takeover, the target lateral position of the ambulance was in the center of the opposite lane. The road was flat and relatively straight. There was not a lot of vegetation or buildings by the sides of the road, and the closest vegetation was 3 m from the edge of the roadside. Therefore, the ambulance could be heard and seen at a very far distance before it passed the participant driver.

### Procedure

The participants were first informed about the experiment according to the ethical guidelines by Vetenskapsrådet (n.d.)

whereupon written informed consent was received. An introduction to the simulator setup followed. The positions of the rear-view mirrors were pointed out, as was the fact that the car was equipped with an automatic transmission. The interfaces for receiving and acknowledging messages were also shown, but no specific information about what messages could be displayed was given.

The driving task began with a practice drive for 5 min. The instruction was to drive no faster than 30 kph and to look straight ahead for the first minute, to minimize the risk of simulator sickness, and then accelerate to the speed limit.

The test scenario took about 30 min to complete and was about 20,000 m long. An ambulance on an emergency call, with blue lights and sirens engaged, caught up with and passed the participant's car three times during the session (at about 3,000, 6,000, and 11,500 m from the start of the scenario). The scenario ended after the participant was passed by the ambulance for the third time, at about 20,000 m.

### Design

There were three experimental conditions of EVA Message: baseline with no EVA message (EVA 0), EVA message on the instrument cluster alone (EVA 1), and EVA message on the instrument cluster and on the infotainment display in the center console (EVA 2). The design was 3 × 2 × 2 (EVA Message × Interface Order × Baseline Order) split-plot factorial, with EVA Message and Interface Order within groups, and Baseline Order between groups.

EVA Message refers to the three experimental conditions (i.e., EVA 0, EVA 1, and EVA 3, respectively). Interface Order refers to the order that the EVA message was conveyed, such that in Interface Order 1, EVA 1 was presented first, whereas in Interface Order 2, EVA 2 was presented first. With regard to Baseline Order, Baseline Order 1 had the EVA 0 baseline condition first and then either of EVA 1 and EVA 2, whereas Baseline Order 2 had either EVA 1 or EVA 2 first, and finished with EVA 0.

There were three dependent variables. The first one was distance to the ambulance when giving way (i.e., when the participant's car was more than 3 m to the right from the road center line, which is approximately when the wheels on the right-hand side touch the road-side markings). The second one was lateral position when the ambulance was alongside the participant. The third one was speed when the ambulance was alongside the participant.

## RESULTS

A 3 × 2 × 2 (EVA Message × Interface Order × Baseline Order) split-plot factorial ANOVA was performed for each of the three dependent variables. With regard to the three levels of EVA Message, the present paper only focuses on the difference between no EVA message and presence of EVA message (i.e., EVA 0 vs. EVA 1 and EVA), but not between the two versions of the EVA message (i.e., EVA 1 vs. EVA 2).

For *distance to the ambulance when giving way*, there was a main effect of EVA Message, $F_{(2, 36)} = 6.47$, $MSE = 4383.58$, $p = 0.004$, $\eta_p^2 = 0.26$, such that the two versions of EVA 1 and EVA 2 caused the driver to give way earlier (i.e., at a greater distance before the ambulance caught up), see **Figure 1**. There was no main effect of neither Interface Order nor Baseline Order. However, there was an interaction effect between EVA Message and Baseline Order, $F_{(2, 36)} = 9.13$, $p = 0.001$, $\eta_p^2 = 0.34$. As can be seen in **Figure 1**, in Baseline Order 1 (when EVA 0 was the first condition and EVA 1 and EVA 2 followed) drivers did not give way as early when there was no EVA message, but then gave way much earlier. In Baseline Order 2, however, when EVA 1 and EVA 2 initialized the test and EVA 0 finished it, the drivers gave way about as early regardless of EVA Message, see **Figure 1**. Separate two-way ANOVAs (EVA Message × Interface Order) for each of the two Baseline Order groups confirmed this interpretation and specified that the main effect of EVA Message was due to the Baseline Order 1 group, $F_{(2, 18)} = 11.75$, $MSE = 5776.00$, $p = 0.001$, $\eta_p^2 = 0.57$. The Baseline Order 2 group had $F_{(2, 18)} = 0.18$, $MSE = 2991.15$, $p = 0.84$ (There was no main or interaction effect with regard to Interface Order for either Baseline Order group.).

For *lateral position when the ambulance was alongside the participant* and *speed when the ambulance was alongside the participant*, no effects were found (see **Figures 2**, **3**, respectively).

## DISCUSSION

EVA message had a significant effect on how early the drivers gave way, such that both interface versions made the drivers give way at much greater distances to the ambulance than when there was no EVA message. The results further reflect that since the road side was so wide, the view of the surroundings was so open, and since the traffic was so sparse, it sufficed to give way and proceed at a slightly lower speed. That is, the drivers probably considered that the ambulance could overtake without risk even though they did not stop by the road side. The interaction between EVA Message and Baseline Order reflects that after the EVA message had made them aware that giving way is expected, this behavior

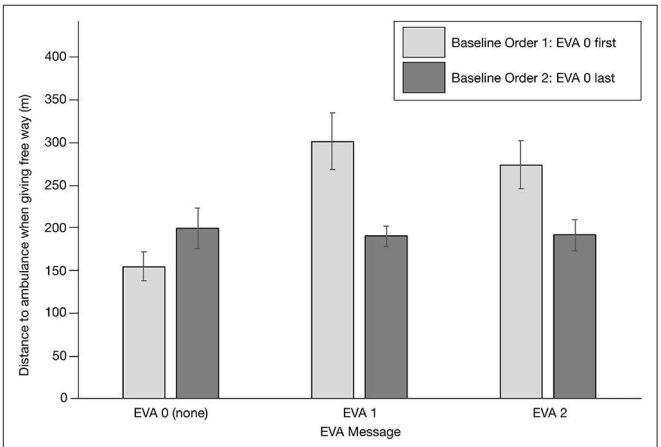


**FIGURE 1 |** Mean distance (± SE) to ambulance when giving way by exceeding 3 m lateral position from the road center line, by Baseline Order and EVA Message.

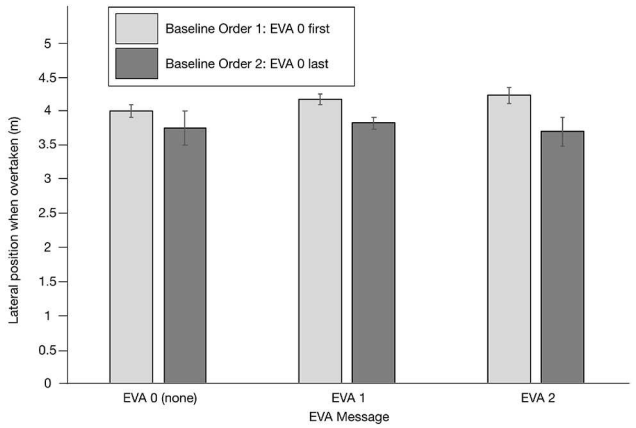


**FIGURE 2 |** Mean lateral position (± SE) to the right from the road center line when overtaken by the ambulance, by Baseline Order and EVA Message.

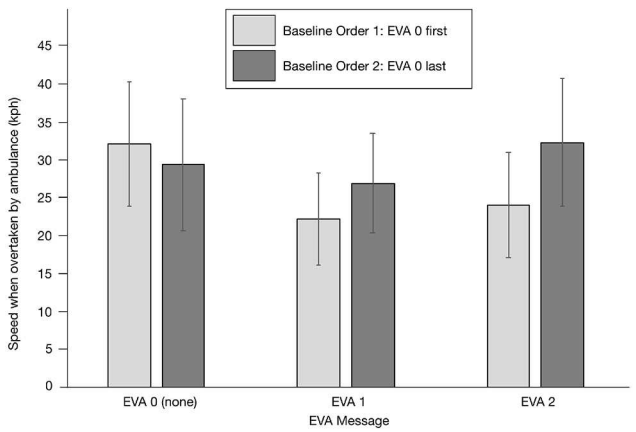


**FIGURE 3 |** Mean speed (± SE) when overtaken by the ambulance, by Baseline Order and EVA Message.

was maintained even if there was no EVA message—as long as the approaching emergency vehicle was detected, as it could easily be in this scenario.

The experimental design with EVA Message as a repeated measures variable was necessary to reveal interaction effects such as the one between EVA Message and Baseline Order, but it had the drawback that once the drivers had encountered the ambulance, they were primed such that their behavior might be affected in their next encounter. For example, some drivers might ponder about how they were taught to behave if an ambulance on emergency call closes in on them during their training for their driver's license, and then be better prepared to give way next time. That is, it is possible that the apparent large effect of the EVA message for the Baseline Order 1 group to some extent was a priming effect. Furthermore, driving experience as reflected in how long the drivers had had their driving licenses, their driving frequency and mileage for the recent year, had a large span. It may be expected that abundant driving experience is associated with better knowledge about how to behave when an emergency vehicle on call is approaching.

Experiment 2 was therefore designed to be a stronger test of how well-drivers with relatively little driving experience manage to give way to an emergency vehicle on call, with and without an EVA message broadcast to them, respectively, under a driving condition when the approaching emergency vehicle is difficult to detect early—and without a priming effect that spoils the naïve reaction when the emergency vehicle appears.

# EXPERIMENT 2: EFFECTS WHEN THE AMBULANCE WAS DIFFICULT TO DETECT

## Purpose

The purpose was to test the effect of EVA messaging on the propensity of drivers with relatively little driving experience to give way to an ambulance on an emergency call, when task demands and traffic conditions makes it difficult to detect and identify the approaching ambulance at an early stage.

## Method

### Participants

A total of $n = 68$ car drivers aged 20–30 years, $M = 22.0$ years, $SD = 1.9$ years, whereof 44 males and 24 females, participated. They were required to have a valid driver's license (Swedish category B) and had had them for 0–10 years, $M = 3,5$ years, $SD = 2,1$ years. Their self-rated mileage for the recent twelve months was 0–25,00 km, $M = 3705.1$ km, $SD = 5574.2$ km, and their self-rated driving frequency for the recent year was between more seldom than once a month and daily (1–5, see **Appendix**), $M = 2.4$, $SD = 0.92$. The participants were recruited via e-mail lists to undergraduate courses at Linköping University, and rewarded with a cinema ticket each for their participation. The experiment group which received an EVA message consisted of $n = 35$ participants, whilst the control group which received no EVA message had $n = 33$.

### Materials and Settings

The car simulator setup was the same as in Experiment 1, except for the monitor setup. In addition to the 43-inch front monitor, two 55-inch monitors were used to extent the field of view. They were placed at 45° angle from the front monitor at each side, resulting in about 180° field of view horizontally. The view included an inner rear-view mirror (as in Experiment 1) and side rear-view mirrors.

The driving scenario differed considerably as compared to Experiment 1. The roadside was relatively much narrower, 0.75 m, but there were parking pockets 80 m long and 3 m wide about 1,000 m apart. The road was also quite a lot more hilly and curvy, and there was vegetation as close as 1.75 m to the edges of the roadsides. Therefore, the ambulance closing in from behind could not be seen closer than a small fraction of the farthest possible spotting distance in Experiment 1. Further, one car and one delivery van closed in on the own car before the ambulance appeared, making it even more difficult to spot the ambulance by vision alone. Furthermore, sounds from the environment outside the car, including the sirens of the approaching ambulance, were

attenuated to mimic that the own car was soundproof as if it were a modern-day premium car. The background noise plus sound from the simulated driving at 80 kph was about 68 dBA. To make it even more difficult to hear the ambulance approaching, semi-loud music at about 69 dBA was played on the car stereo (Ministry, 1991), resulting in a combined SPL of about 73 dBA. When the ambulance was alongside the own car, the SPL from the sirens was about 80 dBA. The ambulance approaching from behind was therefore much more difficult to discriminate also by hearing as compared to in Experiment 1.

Meeting cars appeared about every 20 s. At 2,200 m from the start of the scenario, a car appeared 200 m ahead of the participant's car, whilst a car and a delivery van closed in from 180 and 150 m behind, respectively, and kept 25 behind the vehicle in front. The ambulance closed in on the participant's car from 500 m behind and passed the participant at about 3,250 m from the start of the scenario. The car behind gave way when the ambulance was 50 m behind it, whilst the delivery van gave way when the ambulance was 40 m behind it.

The ambulance closed in with a speed of 156% compared to the participant's car, with a minimum speed of 100 kph and a maximum speed of 160 kph. During takeover, the ambulance's target lateral position was in the center of the opposite lane.

The EVA message (to the experimental group, but not to the control group) was presented both with sound and in the instrument cluster, 14 s before the ambulance was estimated to pass the participant, based on the relative speed difference. In the audio system of the simulated car (emulating an RDS radio), the music faded and a male voice (at about 68 dBA) said "Varning! Utryckande fordon! Var god ge fri väg." [Attention! Emergency vehicle approaching! Please give way.]. Simultaneously, in the instrument cluster, a warning sign (i.e., a yellow warning triangle with a blue warning light) and a text message stated "Utryckningsfordon på ingång! Var uppmärksam!" [Emergency vehicle approaching! Pay attention!].

### Procedure

The participant was first informed about the experiment according to the ethical guidelines by Vetenskapsrådet (n.d.) whereupon written informed consent was received. The participant then filled out a questionnaire (see **Appendix**) regarding their age, sex, and driving experience.

Introduction to the simulator setup followed. Positions of the rear-view mirrors were pointed out, and the participant was told that the transmission was automatic.

The participant was told to drive as in real-life traffic, and to imagine being late to an important meeting but that it was utterly important not to exceed the speed limit since any offense during driving would lead to losing their driving license. In other words, the intention was to motivate the participant to keep to the speed limit as closely as possible. The participant was further told that the car had no cruise control, and that the hilly road therefore demanded active use of the throttle to avoid slowing down uphill, and to avoid speeding downhill. The driving task was thus intended to demand attention to speed keeping as well as to the traffic and surroundings.

To avoid risk of simulator sickness, the participant was told to start by driving no faster than 30 kph and to look straight ahead for the first minute, and then accelerate to the speed limit of 80 kph. The test scenario took about 6 min to complete and was about 4,000 m long. An ambulance under an emergency call, with blue lights and sirens engaged, caught up with and passed the participant's car at about 3,250 m from the start of the scenario (including the 1-min acclimatization to the simulator). The participant was then told to stop after the ambulance had taken over and increased its distance.

### Design

The design was between groups. Participants were randomized into either the control group with no EVA message (EVA 0) or into the experimental group with EVA message (EVA 1).

The dependent variables were the same as in Experiment 1: distance to the ambulance when giving way; lateral position when the ambulance was alongside the participant; and speed when the ambulance was alongside the participant.

## RESULTS

For each of the three dependent variables, a *t*-test for independent samples was used to test the effect of the EVA message. As can be seen in **Table 1**, the EVA message had a significant and large effect on all three measures. That is, the EVA message made drivers give way by moving to the right (in most cases by using a parking pocket), and by doing so also managing to get a lateral position farther to the right when the ambulance passed them. Further, the mean speed when being overtaken by the ambulance was slower.

Surprisingly, the distribution of drivers who did not give way was significantly heterogeneous by groups, $\chi^2(1, N = 68) = 17.99$, $p < 0.001$. That is, most (i.e., 24/37) participants who did not receive the EVA message (i.e., in EVA 0) did in fact *not* give way by moving to the right. In fact, most participants in the EVA 0 group said that they did not know whether or not they should give way. Further, eight of them failed to detect the ambulance until it had passed them.

Of those who did receive the EVA message (i.e., in EVA 1), all but four participants gave way (i.e., 31/35), most of whom used the parking pocket. A few of them missed the parking pocket but slowed down and moved far to the right. One of the four who failed to give way said that he did not hear what the audio instruction was.

**Table 2** presents additional analyses for speed and lateral position when being passed by the ambulance, for only those participants who fulfilled the criterion to give way by moving more than 3 m to the right from the road center line. As can be seen in **Table 2**, the results are similar to those in **Table 1** such that the effect of the EVA message remains at the same levels.

## DISCUSSION

Since a simple between-groups design was used, there could be no priming effects (i.e., both groups were naïve to the approaching emergency vehicle).

A strong and surprising finding was that the majority of the relatively inexperienced drivers did not know that they are supposed to give way to an emergency vehicle on call, and how to give way properly. This is to our knowledge a novel finding that

**TABLE 1 |** Descriptive statistics for the experimental and control groups, respectively, and inferential statistics for the differences.

| Measure | EVA 0 | | | EVA 1 | | | *t* | *p* | *d* |
|---|---|---|---|---|---|---|---|---|---|
| | *n* | *M* | *SD* | *n* | *M* | *SD* | | | |
| Distance, free way (m) | 13 | 22.98 | 24.59 | 31 | 83.63 | 70.21 | 3.02 | 0.004 | 1.00 |
| Speed (kph) | 33 | 71.72 | 12.41 | 35 | 31.11 | 22.64 | 9.24 | < 0.001 | 2.21 |
| Lateral position (m) | 33 | 2.56 | 0.67 | 35 | 4.22 | 1.25 | 6.87 | < 0.001 | 1.64 |

**TABLE 2 |** Descriptive statistics for the experimental and control groups, respectively, and inferential statistics for the differences, for only those participants who gave way by moving more than 3 m from the road center.

| Measure | EVA 0 | | | EVA 1 | | | *t* | *p* | *d* |
|---|---|---|---|---|---|---|---|---|---|
| | *n* | *M* | *SD* | *n* | *M* | *SD* | | | |
| Speed (kph) | 13 | 67.71 | 16.01 | 31 | 25.95 | 18.38 | 7.13 | <0.001 | 2.35 |
| Lateral position (m) | 13 | 3.15 | 0.46 | 31 | 4.45 | 1.12 | 5.47 | <0.001 | 1.33 |

probably reflects that giving way to emergency vehicles on call is generally not practiced during training for the driving license, and this would probably not be a good idea to try to implement in practice driving in real traffic. However, it would be a good idea to implement giving way to emergency vehicles on call—and other relatively rare traffic events that are critical to handle correctly and efficiently—in driving simulators during training for the driving license (c.f. Lindström and Thorslund, 2020). Grant (2010, 2017) studied drivers' psychological factors involved in their responses to emergency vehicles. Grant (2010) concluded that giving way to emergency vehicles seems to be lacking in driver education, and the present study supports this notion.

Eight participants in the control group that did not receive an EVA message failed to detect the ambulance until it had passed them, compared to no participant in the control group. It is likely that most of these eight did not look in the rear-view mirror, and that they were preoccupied with the driving task and keeping to the speed limit. Probably, they did not notice the sound of the siren because of this. The EVA message thereby was successful in alerting drivers to the ambulance.

Mainly due to the inexperienced drivers' lack of knowledge about how to handle when an emergency vehicle approaches, the EVA message had a significant and strong effect. The results suggest that the EVA message was crucial for making the drivers aware that an emergency vehicle on call was approaching, that they should give way, and how to give way properly.

## GENERAL DISCUSSION

EVA messaging was necessary for making inexperienced drivers give way to an approaching emergency vehicle on call (Experiment 2), since most of them did not know that they are obliged to give way. Others did not notice the emergency vehicle before it passed them. EVA messaging also made both inexperienced and experienced drivers give way much earlier (Experiment 1). Since drivers vary with regard to experience and attention to the surrounding traffic, the present study suggests that EVA messaging to alert and instruct drivers how to give way properly are beneficial for traffic safety and for enabling time-efficient emergency transports.

In real traffic, road users take notice of other road users' behavior and the traffic norms. This means that effects of EVA messaging may be both stronger and weaker in real traffic, depending on how well the road users identify the emergency vehicle on call and make a coordinated collective effort to provide safe and efficient passage for it (c.f. Alonso et al., 2017). If the traffic norms stipulate collective vigilance for emergency vehicles on call, and early and safe procedures to give way, the effects of EVA messaging should be smaller in comparison to if the traffic norms do not include consideration for emergency vehicles. In the latter case, EVA messaging should have the potential to redeem the norms by educating the road users on how to behave properly.

The theoretically potential benefits of EVA messaging should hypothetically result in measurable, significant and strong effects on how large proportion of road users who give way to an emergency vehicle on call, how early they on average give way, the proportion of road users who act irrationally, and the mean speed of the emergency vehicle. One of the greatest benefits with a simulator study such as this is that the driving scenario can be identical for all participants. One of the greatest drawbacks is that effects on actual traffic could not be studied. This means that the present study allows for strong tests of effects on a single road user at a time, but that the more complex effects in actual traffic (i.e., a greater group of road users) could not be tested. There are two suggestions for further research. Firstly, tests of effects in real-life traffic will require field experiments. Further, the unexpected finding that the majority of novel drivers did not know the rule about giving way to emergency vehicles on call should be followed up by a more extensive survey study in order to establish the proportion of drivers who do not know that they are required to give way and how to properly do so.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

BL planned, recruited participants, collected, processed and analyzed data, and wrote the manuscript. BT planned both experiments and assisted in all parts of the manuscript. HS helped plan Experiment 2 and wrote the article. DN planned, collected data, and assisted in writing parts of the manuscript pertaining to Experiment 1. JD helped plan and write Experiment 2.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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**Appendix**

Questionnaire: Demographics and driving experience (translated from Swedish)

Age: _____years

Sex: _____

What year did you get your driver's license (Category B)? _____

Do you have a license for any other category? ☐ No ☐ Yes, namely: _____

Are you a professional driver? ☐ No ☐ Yes

How often have you driven a car during the recent twelve months?

☐ Daily ☐ Most days of the week ☐ A few times a week

☐ A few times a month ☐ Less often

Approximately how far have you driven during the recent twelve months? _____ km

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# Built Environment Analysis for Road Traffic Crash Hotspots in Kigali, Rwanda

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**Introduction:** Road traffic injuries (RTIs) are a significant cause of morbidity and mortality in Rwanda. Investigations of the high risk areas for road traffic crashes (RTCs) are urgently needed to guide improvements in road safety. This study aims to identify RTC hotspots in Kigali, Rwanda, and to conduct a built environment analysis of these hotspots.

**Methods:** RTC and RTC-prone locations were collected from the Kigali Traffic Police and high frequency road users, and hotspots were identified through kernel density estimation. Built environment characteristics (BEA), including road design, road safety, pedestrian safety, and traffic density, were collected for each hotspot. BEA characteristics were associated with risk of RTC using logistic regression and BEA scores were calculated using principal component analysis. Patterns of BEA were identified through exploratory cluster analysis and associated with risk for RTC using logistic regression.

**Results:** 25 RTC hotspots were identified. High crash risk locations were less likely to have unpaved roads (21%, $p = 0.049$) and road narrowing (21%, $p = 0.049$). High crash risk locations were also more likely to have pedestrian walkways (100%, $p = 0.009$), factors aiding pedestrian crossing (100%, $p = 0.026$), and poor road surfaces (86%, $p = 0.005$). Cluster analysis showed that hotspots with fewer urban characteristics, including road safety features, motor vehicle density, and pedestrian safety features, have significantly decreased odds of being a high mortality risk hotspot than a hotspot with more urban characteristics (OR = 0.13, 95% CI 0.02–0.79).

**Conclusions:** RTC hotspots were in the city center with high motor vehicle density but did have road and pedestrian safety features, suggesting that speeding is a major cause of RTCs. Effective traffic calming measures and enforcement of road safety laws may reduce the burden of road traffic injuries in Kigali but additional analyses are recommended.

**Keywords: road, traffic, crash, injury, Rwanda, hotspot, built-environment, LMIC**

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## INTRODUCTION

Globally, road traffic crashes (RTCs) cause 1.35 million deaths and many other non-fatal road traffic injuries (RTIs) (World Health Organization, 2018). RTIs create a significant health and economic burden in low- and middle-income countries (LMICs). African countries have a particularly disproportionate burden of RTCs and RTIs. According to the World Health Organization (WHO), the countries in the African region have the highest per capita rate of road deaths in the world despite having a small fraction of the world's vehicles (World Health Organization, 2018).

Modeled estimates find that Rwanda has the highest road traffic fatality rate at 22 deaths per 100,000 and the highest burden of RTIs at 1,173 disability-adjusted life years per 100,000 population compared to other East African countries [Institute for Health Metrics and Evaluation (IHME), 2015]. The Rwandan National Police (RNP) reported 2,270 RTIs including 270 (11.9%) deaths in 2010. While total RTIs in 2010 were grossly the same as 2015 (2,187), fatalities rose to 351 (16.0%). (National Institutes of Statistics of Rwanda, 2017). Rwanda, like many LMICs, lacks a comprehensive RTC data system that links police and hospital records. This limitation is associated with high rates of RTC and RTI underreporting, raising concern that true numbers of RTIs and road deaths are much higher than reported. (Chandran et al., 2010; World Health Organization, 2018), Epidemiologic Reviews; Patel et al., 2016, BMC Public Health; (Samuel et al., 2012), Under-reporting of road traffic mortality in developing countries).

Urban Rwanda, Kigali Province, is densely populated at 2,535 residents per square kilometer, but the majority of the population lives in rural areas (National Institutes of Statistics of Rwanda, 2017). Kigali also contains 70% of the registered vehicles in Rwanda (National Institutes of Statistics of Rwanda, 2014). In 2011, 72% of all RTCs in Rwanda took place in Kigali (Asiimwe, 2011). Retrospective studies of hospital records indicate that RTIs accounted for 73.4% of all injury cases and 61.2% of fatal injuries in Kigali [(Petroze et al., 2014), Patterns of injury at two university teaching hospitals in Rwanda: Baseline injury epidemiology using the Rwanda injury registry; (Kim et al., 2016), World journal of surgery; (Enumah et al., 2016)]. Although there have been investigations on the epidemiology of RTIs, little is known about the geographic locations nor built environment characteristics of crash hotspots in Kigali [(Petroze et al., 2014; Kim et al., 2016), World journal of surgery; (Enumah et al., 2016; Patel et al., 2016), BMC Public Health].

In the past decade, geographic information systems (GIS) has emerged as a powerful tool to analyze the spatial and temporal patterns of RTCs [(Anderson, 2009), Kernel density estimation and K-means clustering to profile road accident hotspots; (Bíl et al., 2013), Identification of hazardous road locations of traffic accidents by means of kernel density estimation and cluster significance evaluation; (Plug et al., 2011), Spatial and temporal visualization techniques for crash analysis; (Xie and Yan, 2013), Detecting traffic accident clusters with network kernel density estimation and local spatial statistics: an integrated approach]. Improved understanding of the physical environment at RTC hotspots in Kigali may facilitate effective road safety initiatives to improve the built environment infrastructure and reduced RTI risk encountered by vulnerable road users [(Ewing and Dumbaugh, 2009), The built environment and traffic safety: a review of empirical evidence; (Schurman et al., 2009), Pedestrian injury and the built environment: an environmental scan of hotspots; (Miranda-Moreno et al., 2011), The link between built environment]. Therefore, this study aims to use spatial analysis to identify RTC hotspots in Kigali, Rwanda then apply built environment analysis to identify implementable interventions that may decrease the incidence and severity of RTIs at these RTC hotspots.

**Abbreviations:** ANOVA, analysis of variance; GIS, geographic information systems; LMICs, low- and middle-income countries; REDCap, research electronic data capture; RFTC, Rwanda Federation of Transport Cooperative; RTC, road traffic crash; RTI, road traffic injury; WHO, World Health Organization.

## METHODS

### Study Setting

The Republic of Rwanda is located in Eastern/Central Africa and has a population of nearly 13 million (**Figure 1**) (National Institutes of Statistics of Rwanda, 2017). Rwanda is the third most densely populated country in Africa and is undergoing rapid urbanization (National Institutes of Statistics of Rwanda, 2017). The province, and capital city of Kigali, is divided into three districts: Gasabo, Kicukiro, and Nyarugenge with a total population of more than 1.5 million inhabitants. (National Institutes of Statistics of Rwanda, 2014).

### Road Traffic Crashes Hotspot Identification

RTC hotspots were identified by combining retrospective police report data and a high road utilizers survey. Each of these RTC hotspot localization methods were previously validated and described in depth by Staton and Patel [(Staton et al., 2016), High road utilizers surveys compared to police data for road traffic crash hotspot localization in Rwanda and Sri Lanka; (Patel et al., 2016), BMC Public Health]. A summarized description is provided below.

### Retrospective Police Data

Data were collected from the standard police report form of all RTCs in Kigali that resulted in an injury. All accessible RTC reports between January 1 to December 31, 2013, were reviewed by trained data collectors in January, 2014. A total of 2,589 hand-written RTC reports were reviewed and tablet computers were used to record selected information in a secure Research Electronic Data Capture (REDCap) database hosted at Duke University. Information collected from police reports included crash logistics, locations of crash, involved persons, and injury. Geolocation of RTCs were determined by the address or description of location in the reports. If the precise location of the crash could not be determined it was noted during

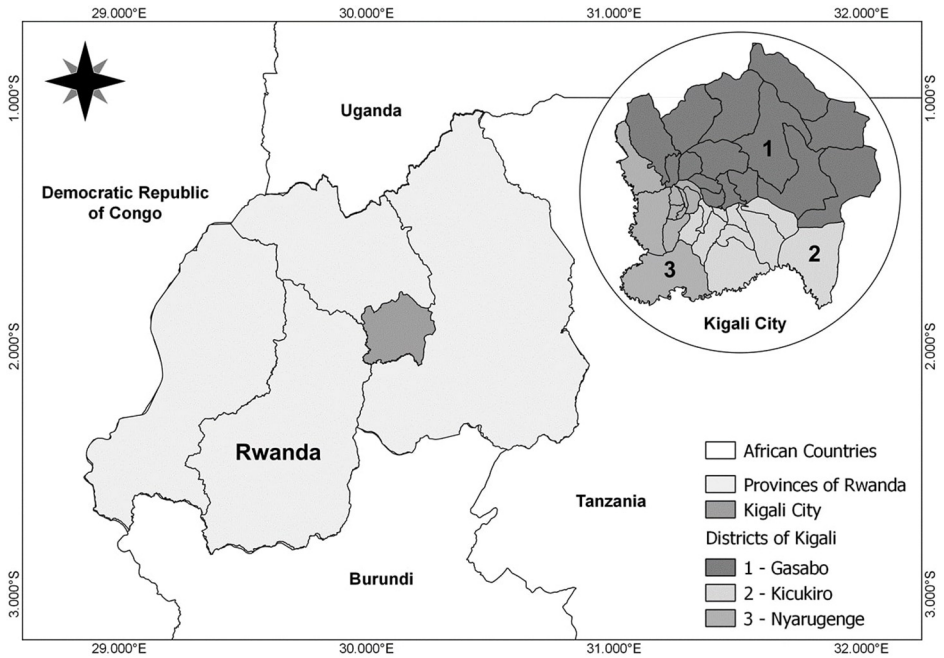


**FIGURE 1 |** Location of the Republic of Rwanda and the province of Kigali City.

data collection. An independent reviewer assessed the data for completion and inconsistency.

RTCs that had no reports in the Kigali Traffic Police office at the time of data collection were not part of the data analysis. The primary reasons for not having access to RTC reports include active case review by the judicial system, RTCs resolved without having filed official reports with the police, and misplaced reports [(Patel et al., 2016), BMC Public Health]. It was impossible to quantify the number of missing reports due to the limited information about RTCs outside of the police reports.

## Survey of Motorcycle Taxi Drivers

A brief, high road utilizer survey used in other settings where our research team works was adapted for Rwandan commercial motorcyclists [(Staton et al., 2016), High road utilizers surveys compared to police data for road traffic crash hotspot localization in Rwanda and Sri Lanka]. We ensured that respondents were high road utilizers by confirming their work history, the amount of time spent on roads, and their knowledge of the roads in Kigali City. Respondents were asked to identify locations with high RTC frequency and locations they perceived as high risk for RTCs, then to rate the severity of danger at each location on a scale from 0 to 100. The questionnaire was translated from English to the local language of Kinyarwanda, then back-translated to English to assure accuracy. Pilot-testing of the Kinyarwanda survey improved comprehension of questions, ease of use, and electronic data entry.

Between January 7–14th, 2014, 602 surveys were collected by trained, Kinyarwanda-speaking research assistants using tablet computers to record responses directly into REDCap. We aimed to make this sample representative of the entire commercial motorcyclist population by utilizing the formally designated national commercial motorcyclist association taxi stands in Kigali City. At each of these 43 stands, the first ten motorcyclists encountered who were parking awaiting a client were offered survey participation. An additional five motorcyclists circulating past the stand were stopped and offered participation. On average, the informed consent and survey required 10 min to complete. At the completion of the survey, motorcycle taxi drivers were compensated the average cost of a motorcycle taxi ride ($0.68USD). Completed survey data quality was checked by the research team and incomplete or inconsistent surveys were not included. Research staff familiar with Kigali city roads geolocated the survey-identified RTC hotspots with their corresponding levels of danger on a map by dropping a pin.

### RTC Hotspot Identification Through Spatial Analysis

Using the geolocation information collected from the police RTC reports and high road utilizer surveys, we identified RTC hotspots in Kigali City following a validated spatial analysis protocol [(Patel et al., 2016), BMC Public Health; (Staton et al., 2016), High road utilizers surveys compared to police data for road traffic crash hotspot localization in Rwanda and Sri Lanka; (Reardon et al., 2017), The epidemiology and hotspots of road traffic injuries in Moshi, Tanzania: an observational study]. Briefly, we used the Kernel Density Estimator to create a point density map of RTC locations using the heatmap plugin in the Quantum GIS software, version 2.4 [(Anderson, 2009), Accident Analysis & Prevention; (Bithell, 1990); Quantum GIS Development (Team, 2017)]. The Kernel estimator creates a

density raster by counting the number of points in a region of interest and creating a density map accounting for the frequency of points and the distance of each point to the region. The density mapping also accounts for the crash severity at each hotspot using the injury severity rating from the police RTC reports and the danger severity rating from the motorcycle taxi driver survey. We layered the RTC density raster over the map of Kigali City with district boundaries, national and district roads, and local road networks. The national and district road network vector data was created by the Rwanda Transport Development Agency in 2014 and the local road network vector data was created by the Rwanda Natural Resources Authority Lands and Mapping Department in 2010. These shapefiles are freely accessible from the Rwanda GeoPortal (Agency, 2016). Spatial data was also obtained from OpenStreetMap, a collaborative mapping project providing open-source spatial data under the Open Database License (OpenStreetMap contributors, 2015). To assess the risk for RTC relative to built environment characteristics, we classified each hotspot as "high" or "low" risk. These classifications were assessed according to the injury severity classification from the police database (grievous injuries requiring hospital care or deaths were high risk) or a self-reported evaluation from road users of the danger of a hotspot (scale of 0–10, 10 being the highest risk). Locations were considered high risk for RTC if they had at least one severity assessment above average.

## Built Environment Analysis of Crash Hotspots

### Built Environment Data Collection and Instrument

The RTC-dense regions yielded 25 specific locations at which we conducted built environment analyses (BEA). Since the geolocation data from the police and commercial motorcyclist surveys showed a high agreement (83.9% agreement and Cohen's Kappa 0.69-0.90), we selected BEA locations from police reports based on RTC frequency and severity of the associated injuries. [(Staton et al., 2016), High road utilizers surveys compared to police data for road traffic crash hotspot localization in Rwanda and Sri Lanka].

From March 17 to April 15, 2014, research staff trained to identify built environment characteristics visited each hotspot during day time and recorded data points from each location. Surveyed characteristics were grouped into 4 sections: road design (urbanicity, road hierarchy classification, intersections, number of lanes, auxiliary lanes, bus stops, bridges, curvature of road, and road visibility), road safety (pavement, surface condition, narrowing of road, road shoulder, police enforcement, speed bump, traffic light, traffic signs, and speed limit), pedestrian safety (pedestrian walkways, informal walkway, and factors aiding pedestrian crossing), and traffic density. Traffic density was measured at each hotspot by counting the number of cars, bikes, motorcycles, buses, and pedestrians that passed through the hotspot from all directions then was summed and divided by the number of directions to obtain a per minute average. If the hotspot occurs at an intersection, built environment characteristics were collected from all corners of the intersection. For each hotspot, the built environment survey was performed at least twice, with a 10-min interval between each repeat survey. Detailed descriptions of each built environment characteristic and the data dictionary used to construct our data collection form can be found in the Supplementary Material (**Table S1**).

All BEA data were aggregated using principal component analysis (PCA), built from a polychoric correlation matrix using a principal axis estimation approach. (Abdi and Williams, 2010) Further information on the methodology used to design the BEA instrument are described elsewhere [(Vissoci et al., 2018), Validation of a tool to conduct a Built Environment Analysis in a Low Income Country Setting]. Hotspots were labeled with the most frequently occurring built environment characteristics observed at the corners of intersections and over multiple observations. Overall traffic density for each hotspot was represented by the average traffic density over multiple observations. BEA was evaluated in 5 domains (Urban characteristics, rural characteristics, road safety, pedestrian safety and traffic density) in a standardized scale ranging from 0 to 100 (**Table 1**). A score of 0 in any given dimension refers to a low BEA score, referring to low characteristics of that given dimension for that hotspot area. Therefore, a low score in pedestrian safety would indicate that the area evaluated has fewer walkways, bus stops or sidewalks.

### Built Environment Data Analysis

Data were collected electronically using REDCap (Harris et al., 2009, Research electronic data capture [REDCap]—a metadata-driven methodology and workflow process for providing translational research informatics support) then hotspots were categorized into high and low crash risk and mortality risk locations. We calculated descriptive analysis for the BEA variables, including frequencies (absolute and relative) and medians (interquartile ranges). The distribution of built environment characteristics over crash risk was assessed using the chi-squared test of independence or Fisher's exact test where appropriate. Traffic densities were compared via Mann-Whitney U tests. All analyses were conducted with the R Language for Statistical Computing [(R Core Team, 2013), R: A language and environment for statistical computing].

K-means cluster analysis [(Lorr, 1983; Anderson, 2009), Accident Analysis & Prevention] was used to identify groups

**TABLE 1** | Built environmenti analysis domains and characteristics.

| BEA Domains | Characteristics |
|---|---|
| Rural roads | Multiple vs. single roads, presence of bridges, road surface conditions, presence of side road outside of the road, presence of auxiliary lanes. |
| Urban roads | Proportion of urban roads, number of intersections, highways vs. local streets, visibility. |
| Road safety | Presence of traffic lights, presence of road traffic signs, presence of speed limits, presence of speed bumps |
| Pedestrian safety | Presence of walkways, presence of bus stops, presence of pedestrian safe walking areas, pedestrian density in the road. |
| Traffic density | Density of cars, bus/trucks and motorcycles. |

of hotspots that share similar profiles of the BEA domains. Clustering models were fit using a Hartigan-Wong algorithm. Models with different clusters were tested and selection was conducted by minimizing the bayesian information criterion (BIC) and sum of squared values. Empirical validity was measured by comparing with real images of the locations [(Vissoci et al., 2018), Validation of a tool to conduct a Built Environment Analysis in a Low Income Country Setting] and expert opinion including local researchers and road users. Odds ratios were calculated to compare risks for high crash frequency and high morality by hotspot clusters. Analysis of variance (ANOVA) was used to compare the similarity of built environment characteristics among the clusters of hotspots.

# RESULTS

## Hotspots Identification

RTC locations recorded in the police database and locations at high risk for RTC as identified by commercial motorcyclist surveys were mapped (**Figures 2A,B**). Overall, we identified 12 RTC hotspots, mostly located in the city center, along the junction between Gasabo, Kicukiro, and Nyarugenge districts. All RTC hotspots were located at the intersection of major roads, four of which were roundabouts. Major roads on which crashes occur included KN 1 Rd, KN 2 Ave, KN 3 Rd, KN 5 Rd, KN 7 Rd, RN3, and RN15. Most regions are densely populated with some commercial buildings along major roads, while some are dense settlements along minor streets.

Of the 25 RTC hotspots where built environment characteristics were collected, 21 were located along national or district roads (**Figure 3**). We further classified the survey locations into 14 high crash risk and 11 low crash risk locations (**Figure 3A**), and 11 high mortality risk and 14 low mortality risk locations (**Figure 3B**). Survey locations that have both high crash risk and high mortality risk are the most dangerous areas because these locations are prone to both frequent and severe crashes. Of the 14 high crash risk sites, five (36%) were also high mortality crash sites. Four of these sites were located along KN 3 Rd and KN 5 Rd (RN3). Of the 11 low crash risk sites, six (55%) were high mortality crash sites. These locations were further away from the city center, along RN1, KN3 Rd, KG 15 Ave, KK 31 Ave, KG 7 Ave (RN3), and KG 11 Ave.

## Built Environment Characteristics of Hotspots

We collected information about 32 built environment characteristics on road design, road safety, traffic density, and pedestrian safety (**Table 1**). Most survey locations were on arterial or collector roads ($n = 21$; 84%), at intersections ($n = 20$; 80%), have two lanes ($n = 21$; 84%), and have auxiliary lanes (n = 14; 56%). Considering road safety characteristics, some locations also had bus stops and narrowing of the roads (both with $n = 10$; 40%), while more than half had inadequate visibility of the road ($n = 14$; 56%). Many roads were partially paved or dirt roads ($n = 10$, 40%) and had wet, flooded, slippery, or uneven surfaces ($n = 15$; 60%). While traffic signs ($n = 17$; 68%) and speed bumps ($n = 10$; 40%) were common; traffic lights ($n = 1$; 4%), the presence of marked speed limits (n = 5; 20%), and police enforcement ($n = 4$; 16%) were not. Over half of the surveyed locations had high traffic density ($n = 13$; 52%), with a higher median density of cars and motorcycles. Pedestrian walkways ($n = 20$; 80%), informal walkways ($n = 13$; 52%) and factors aiding pedestrians ($n = 21$; 84%) were common.

Road safety characteristics and pedestrian safety characteristics were associated with high crash risk. High crash risk hotspots were less likely to be partially paved or dirt roads (high crash risk $n = 3$ (21%), low crash risk $n = 7$ (64%), $p = 0.049$), less likely to have narrowing of road (high crash risk $n = 3$ (21%), low crash risk $n = 7$ (64%), $p = 0.049$), and more likely to have wet, flooded, slippery, or uneven road surfaces (high crash risk $n = 12$ (86%), low crash risk $n = 3$ (27%), $p = 0.005$). Pedestrian walkway and factors aiding pedestrian crossing, such as crosswalks, pedestrian traffic lights, and flower beds were more common in high crash risk locations (**Table 2**). As for high mortality risk; road-related bridges were present in higher fatal crash areas (mortality risk $n = 4$ (36%), low mortality risk $n = 0$ (0%), $p = 0.026$) (**Table 2**).

## Cluster Analysis of RTC Hotspots

We conducted cluster and principal component analysis to group hotspots into three clusters by road characteristics (urban or rural), road safety characteristics, motor vehicle density, and pedestrian safety characteristics (**Table 3**). Of the three clusters of hotspots, cluster A has the most urban road characteristics, road safety infrastructures, and traffic density. Cluster B hotspots have fewer urban road characteristics compared to cluster A, and the fewest road safety characteristics, lower motor vehicle density, and fewer pedestrian safety conditions. Cluster C hotspots are similar to cluster B; but with more road safety characteristics, greater motor vehicle density, and more pedestrian safety conditions. The three clusters of hotspots showed a similar degree of rural road characteristics but exhibited statistically significant differences in the levels of road safety conditions ($p < 0.0001$), motor vehicle density ($p = 0.0010$), and pedestrian safety conditions ($p = 0.0083$).

We calculated odds ratios for high crash risk and high mortality risk for clusters B and C hotspots using cluster A as the reference. Cluster B hotspots have a 0.16 times lower odds (95% CI 0.01–1.17) of being a high crash risk location and 1.37 times higher odds (95% CI 0.20–8.98) of being a high mortality risk location compared to cluster A hotspots. Cluster C hotspots have a 0.21 times lower odds (95% CI 0.02–1.32) of being a high crash risk location and 0.13 times lower odds (95% CI 0.02–0.79) of being a high mortality risk location compared to cluster A hotspots. **Figure 4** shows the locations of hotspots by built environment clusters.

# DISCUSSION

The objective of this study was to characterize the built environments related to road safety at RTC hotspots in Kigali, Rwanda, and to quantify the association between built environment characteristics, crash risk, and mortality risk. To our knowledge, this is one of the first studies integrating spatial

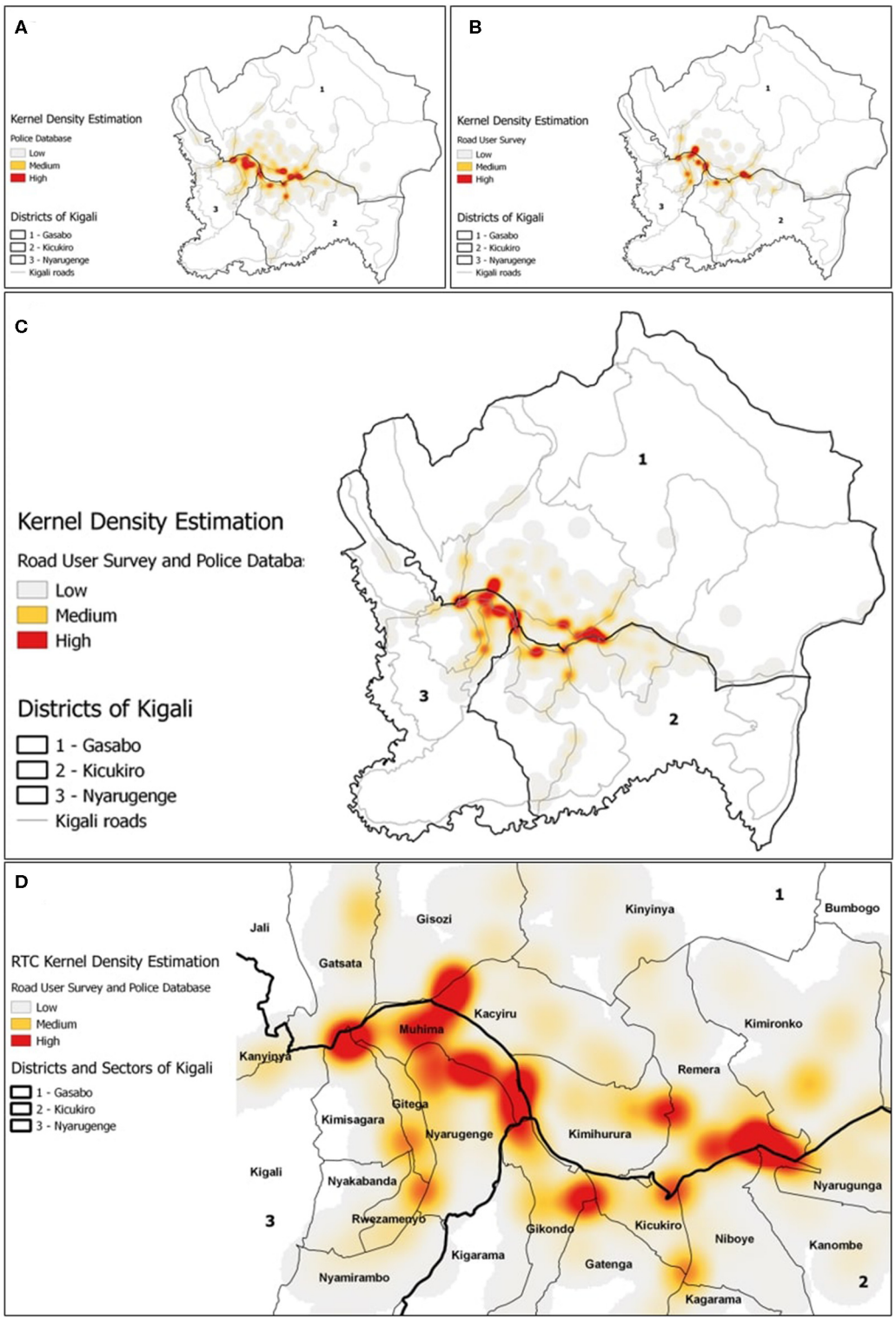


**FIGURE 2 |** Kernel density estimation of RTCs in Kigali, generated from RTC crash locations from police database **(A)**, crash-prone locations identified through the high frequency road user survey **(B)**, and the combined data from both methods **(C)**. RTC hotspots were overlaid with sector boundaries **(D)**. RTC density was classified into low, medium, and high density regions, as indicated by the heatmap.

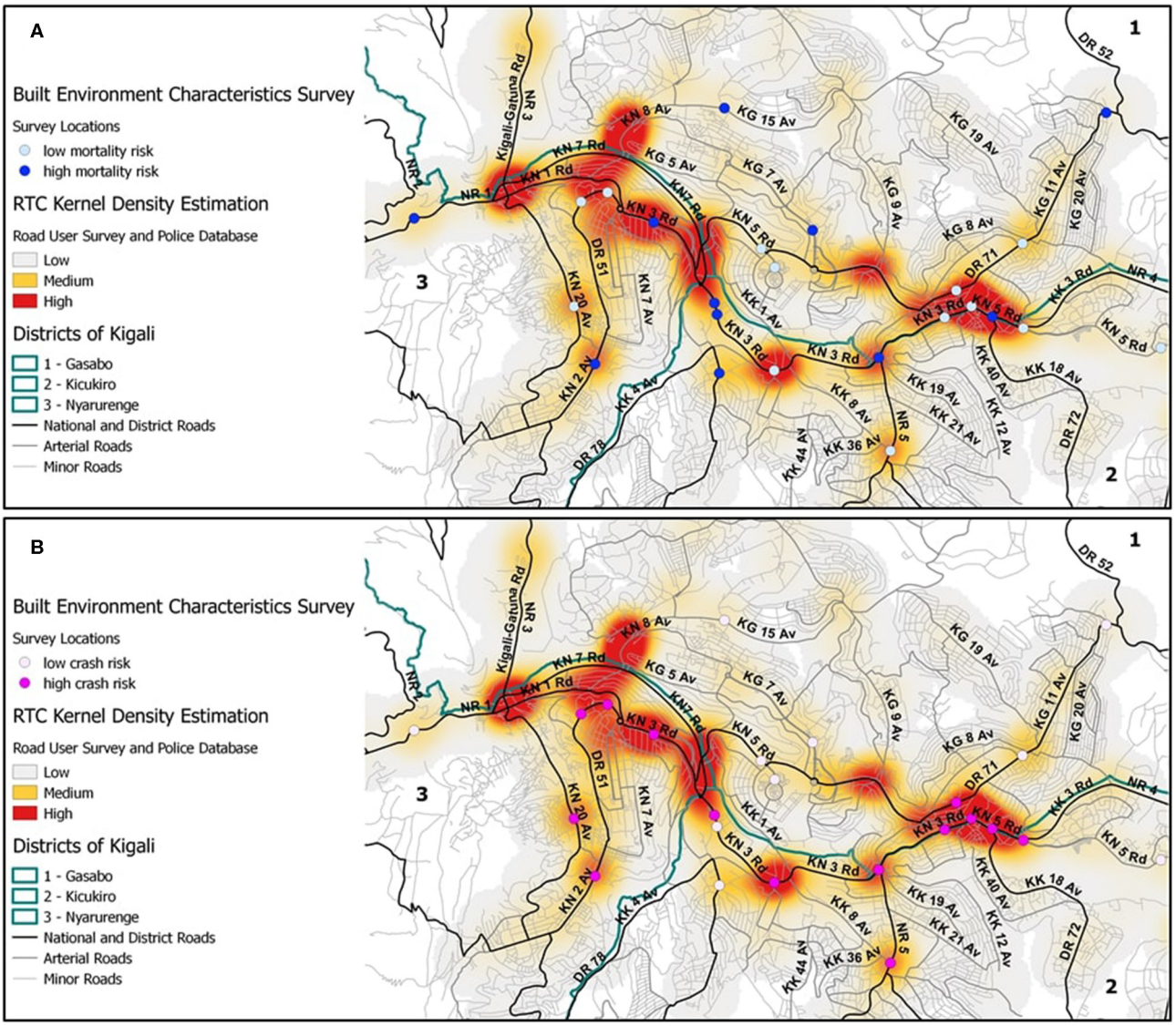


**FIGURE 3 |** Locations of the built environment characteristics survey, overlaid with the road network and the RTC kernel density estimation from the combined data from the police and high frequency road user survey. Survey locations were categorized into high and low crash risk sites **(A)** and mortality risk sites **(B)**. The green line depicts the borders of Gasabo, Kicukiro, and Nyarugenge districts.

analysis and built environment to investigate RTCs in LMICs, and is the first such study in Rwanda. It is also the first study that identifies RTC hotspots through a synthesis of crash locations from police reports and crash-prone locations as described by commercial motorcyclist surveys. Overall, we found that high crash risk locations have urban road characteristics such as paved roads, no narrowing of roads, pedestrian walkways, factors aiding pedestrian crossing, and wet, flooded, slippery, or uneven road surfaces. High mortality risk locations were mostly located in urban areas, at road junctions along national or district roads with high motor vehicle density, and have many road safety and pedestrian safety characteristics, suggesting that speeding is the primary cause of crash risk at these locations. Most crash hotspots were located in sectors that have some of the highest population densities in Kigali City (Rwanda Environment Management Authority, 2013). The majority of the land use in these sectors is residential, with a very small percentage being wetland, commercial areas, public facilities, and government facilities (Rwanda Environment Management Authority, 2013).

Our finding that 82% of fatal crashes occur at intersections suggests that reducing the heightened crash risk at road junctions is critical to decreasing RTCs. This is a trend reflected in other urban regions in China, India, Ethiopia, and Cameroon; though few cities have intersection crash rates as high as Kigali [(Tulu et al., 2017), Injury severity of pedestrians involved in road traffic crashes in Addis Ababa, Ethiopia; (Ponnaluri,

**TABLE 2 |** Description and association of built environment characteristics and crash risk and mortality risk classifications of road traffic hotspots in Kigali, Rwanda.

| BEA Characteristics | Total (*N* = 25) | Risk for a crash | | *p*-value | Risk of a fatal crash | | *p*-value |
|---|---|---|---|---|---|---|---|
| | | High (*n* = 14) | Low (*n* = 11) | | High (*n* = 11) | Low (*n* = 14) | |
| ***Road Design, N (%)*** | | | | | | | |
| **Road classification** | | | | | | | |
| Highway | 3 (12%) | 1 (7%) | 2 (18%) | 0.565 | 1 (9%) | 2 (14%) | 0.999 |
| Arterial St | 12 (48%) | 8 (57%) | 4 (36%) | 0.428 | 4 (36%) | 8 (57%) | 0.302 |
| Collector St | 9 (36%) | 5 (36%) | 4 (36%) | 0.999 | 6 (55%) | 3 (21%) | 0.115 |
| Local St | 2 (8%) | 0 (0%) | 2 (18%) | 0.183 | 1 (9%) | 1 (7%) | 0.999 |
| Presence of intersections | 20 (80%) | 11 (79%) | 9 (82%) | 0.999 | 9 (82%) | 11 (79%) | 0.999 |
| **Number of lanes (multiple or single lanes)** | | | | | | | |
| 2 lanes | 21 (84%) | 11 (79%) | 10 (91%) | 0.604 | 10 (91%) | 11 (79%) | 0.604 |
| 4 lanes | 3 (12%) | 3 (21%) | 0 (0%) | 0.230 | 1 (9.1%) | 2 (14%) | 0.999 |
| Presence of auxiliary lanes | 14 (56%) | 9 (64%) | 5 (45%) | 0.435 | 7 (64%) | 7 (50%) | 0.689 |
| Presence of bus stops | 10 (40%) | 7 (50%) | 3 (27%) | 0.414 | 5 (45%) | 5 (36%) | 0.697 |
| Presence of road-related bridges | 4 (16%) | 2 (14%) | 2 (18%) | 0.999 | 4 (36%) | 0 (0%) | 0.026* |
| **Road curvature** | | | | | | | |
| No curves | 17 (68%) | 10 (71%) | 7 (64%) | 0.999 | 7 (64%) | 10 (71%) | 0.999 |
| Hills | 1 (4%) | 1 (7%) | 0 (0%) | 0.999 | 1 (9%) | 0 (0%) | 0.440 |
| Horizontal curves | 7 (28%) | 3 (21%) | 4 (36%) | 0.656 | 3 (27%) | 4 (29%) | 0.999 |
| Inadequate visibility | 14 (56%) | 10 (71%) | 4 (36%) | 0.116 | 6 (55%) | 8 (57%) | 0.999 |
| ***Road Safety, N (%)*** | | | | | | | |
| Dirt road or partially paved road | 10 (40%) | 3 (21%) | 7 (64%) | 0.049* | 5 (45%) | 5 (36%) | 0.697 |
| Poor road surface (wet, flooded, slippery surface, holes) | 15 (60%) | 12 (86%) | 3 (27%) | 0.005** | 6 (55%) | 9 (64%) | 0.697 |
| Presence of narrowing of road | 10 (40%) | 3 (21%) | 7 (64%) | 0.049* | 3 (27%) | 7 (50%) | 0.414 |
| Presence of road shoulder | 6 (24%) | 3 (21%) | 3 (27%) | 0.999 | 2 (18%) | 4 (29%) | 0.661 |
| Police enforcement | 4 (16%) | 3 (21%) | 1 (9%) | 0.604 | 2 (18%) | 2 (14%) | 0.999 |
| Presence of speed bump | 10 (40%) | 7 (50%) | 3 (27%) | 0.414 | 6 (55%) | 4 (29%) | 0.241 |
| Presence of traffic light | 1 (4%) | 1 (7%) | 0 (0%) | 0.999 | 1 (9%) | 0 (0%) | 0.440 |
| Presence of traffic signs | 17 (68%) | 11 (79%) | 6 (55%) | 0.389 | 5 (45%) | 12 (86%) | 0.081 |
| Presence of speed limit | 5 (20%) | 3 (21%) | 2 (18%) | 0.999 | 3 (27%) | 2 (14%) | 0.623 |
| ***Traffic Density*** | | | | | | | |
| High traffic, n (%) | 13 (52%) | 8 (57%) | 5 (45%) | 0.561 | 6 (55%) | 7 (50%) | 0.821 |
| Car density, median (IQR) | 14 (9, 26) | 17 (10, 30) | 10 (5, 21) | 0.171 | 14 (10, 26) | 12 (9, 30) | 0.603 |
| Bike density, median (IQR) | 0 (0, 1) | 0 (0, 0) | 0 (0, 2) | 0.171 | 0 (0, 1) | 0 (0, 2) | 0.407 |
| Motorcycle density, median (IQR) | 9 (7, 14) | 9 (8, 16) | 9 (5, 14) | 0.338 | 9 (8, 14) | 9 (7, 15) | 0.701 |
| Bus density (big bus, taxi bus, and coasters), median (IQR) | 4 (3, 7) | 5 (4, 7) | 3 (1,9) | 0.338 | 4 (3, 7) | 4 (2, 9) | 0.827 |
| Pedestrian density, median (IQR) | 9 (4, 14) | 10 (6, 14) | 4 (2, 14) | 0.084 | 8 (4, 19) | 9 (4, 14) | 0.891 |
| ***Pedestrian Safety, N (%)*** | | | | | | | |
| Pedestrian pathway Walkway | 20 (80%) | 14 (100%) | 6 (55%) | 0.009** | 8 (73%) | 12 (86%) | 0.623 |
| Informal walkway | 13 (52%) | 5 (36%) | 8 (73%) | 0.111 | 5 (45%) | 8 (57%) | 0.695 |
| Factors aiding pedestrian crossing (crosswalks, pedestrian traffic light, flower bed, etc.) | 21 (84%) | 14 (100%) | 7 (64%) | 0.026* | 9 (82%) | 12 (86%) | 0.999 |

**Statistically significant at $p < 0.05$.*
***Statistically significant at $p < 0.01$.*

2012), Road traffic crashes and risk groups in India: Analysis, interpretations, and prevention strategies; (Bhatti et al., 2010), Situational factors associated with road traffic crashes: A case-control study on the Yaoundé-Douala road section, Cameroon; (Wang et al., 2015), Prevention of taxi accidents in Xi'an, China: What matters most?]. Similarly, many studies also report that poor road surfaces such as wet, flooded, slippery, or uneven road surfaces contribute to crashes; suggesting that improvements in road condition can reduce crashes due to uneven surfaces or weather-related crashes [(Bhatti et al., 2011), Burden and factors

**TABLE 3 |** Characteristics of built environment clusters and association with risk classification for RTC.

| | Cluster A ($n = 14$) Urban, dense sites with high infrastructure | Cluster B ($n = 2$) Low density, low infrastructure roads | Cluster C ($n = 9$) Sub-urban roads with some safety infrastructure | *p* |
|---|---|---|---|---|
| ***BEA charateristics*** | | | | |
| Urban characteristics, Mean (SD) | 87.62 (10.82) | 78.43 (17.57) | 76.62 (11.91) | 0.0862 |
| Rural characteristics, Mean (SD) | 65.65 (11.90) | 60.39 (11.87) | 62.44 (14.34) | 0.5897 |
| Built road safety, Mean (SD) | 70.71 (9.69) | 0 (0) | 35.14 (0.04) | <0.0001 |
| Road MV density, Mean (SD) | 46.90 (28.22) | 18.42 (12.20) | 23.88 (18.63) | 0.0010 |
| Built pedestrian safety, Mean (SD) | 17.94 (10.71) | 6.89 (7.57) | 11.17 (8.71) | 0.0083 |
| ***Association with risk classification*** | | | | |
| Risk area for crash, OR (CI 95%) | Ref | 0.16 (0.01-1.17) | 0.21 (0.02–1.32) | – |
| Risk area for mortality, OR (CI 95%) | Ref | 1.37 (0.20-8.98) | 0.13 (0.02–0.79)* | – |

associated with highway work-zone crashes, on a section of the Karachi-Hala Road, Pakistan; (Wang et al., 2015), Prevention of taxi accidents in Xi'an, China: What matters most?; (Matheka et al., 2015; Chen et al., 2016), Identification methods of key contributing factors in crashes with high numbers of fatalities and injuries in China]. Our data supports implementing road narrowing as a potential traffic calming measure to reduce crashes in Kigali. Road narrowing has been demonstrated as an effective road management technique to reduce traffic speed in high income countries, but very few studies have examined the impact of road narrowing in urban areas in low resource settings. One study in Iran showed that road narrowing caused 22,775 injuries and 4.23% of all fatalities in a year [(Lankarani et al., 2014), The impact of environmental factors on traffic accidents in Iran]. More built environment analyses need to be done to assess the impact of road narrowing on RTCs in densely populated areas in LMICs.

We found that roads with the highest mortality risk were in areas with the lowest motor vehicle density and the fewest road safety characteristics, followed by roads in areas with high motor vehicle density and more road safety characteristics. This suggests that exposure to fatal crash risk is impacted by both vehicular density and the number of road safety characteristics. However, in comparing built environment characteristics with respect to high and low mortality risks, the only difference we observed with statistical significance was the presence of road-related bridges. We did observe trends of increased numbers of speed bumps and the presence of speed limits in high mortality hotspots. This suggests that some infrastructure to decrease excessive speed is already in place, though these road safety infrastructures are severely lacking in most road traffic hotspots, marking an opportunity for the city of Kigali to intervene and reduce RTCs. Under-utilized resources to address excessive speed or intersection conflicts in Kigali may include speed limit signs, road traffic signs, police enforcement, speed bumps, and traffic lights.

We found that RTC hotspots identified from the police RTC database and the high frequency road user survey showed a high level of agreement. Supplementing the information collected from the police RTC reports with the road user survey reduces the impact of underreporting or bias in police records. While the extent of underreporting of RTCs in Kigali is unknown, this is a well-known issue in LMICs. Police records commonly miss from 50 to 80% of RTIs and road deaths observed in hospital or morgue data [(Periyasamy et al., 2013), Under reporting of road traffic injuries in the district of Kandy, Sri Lanka; (Chokotho et al., 2013), Assessing Quality of Existing Data Sources on Road Traffic Injuries (RTIs) and Their Utility in Informing Injury Prevention in the Western Cape Province, South Africa; (Qiu et al., 2015), Chinese Traffic Fatalities and Injuries in Police Reports, Hospital Records, and In-depth Records From One City; (Lateef, 2010), Estimation of fatalities due to road traffic crashes in Karachi, Pakistan, using capture-recapture method; (Bhalla et al., 2009), Building national estimates of the burden of road traffic injuries in developing countries from all available data sources: Iran; (Bhalla et al., 2017), Official government statistics of road traffic deaths in India under-represent pedestrians and motorized two wheeler riders; (Hatamabadi et al., 2011), Necessity of an integrated road traffic injuries surveillance system: A community-based study; (Matheka et al., 2015), Road traffic injuries in Kenya: A survey of commercial motorcycle drivers; (Salifu and Ackaah, 2012), Under-reporting of road traffic crash data in Ghana]. In addition to typical causes of underreporting, 15% of available police crash reports were excluded due to insufficient geolocation information, and could not be used for hotspot mapping. Finally, additional police reports were not included due to other unique local conditions such as the report being unavailable due to litigation in process. This condition could induce systematic biases, failing to capture some of the RTCs that resulted in loss of life and severe injuries. While there was good concordance generally between survey and crash report identified RTC hotspot locations, Incorporating the commercial motorcyclist survey allowed us to prospectively collect data prospectively from high road utilizers who are familiar with the crash-prone locations in the city. Police crash reports will, necessarily, fail to capture all of the near-miss crashes that symbolize perhaps the most potentially impactful sites at which interventions could reduce RTIs.

It has been suggested that effective, safe road systems must integrate the four E's of road safety - engineering, education, enforcement, and emergency medical services [(WHO, 2015),

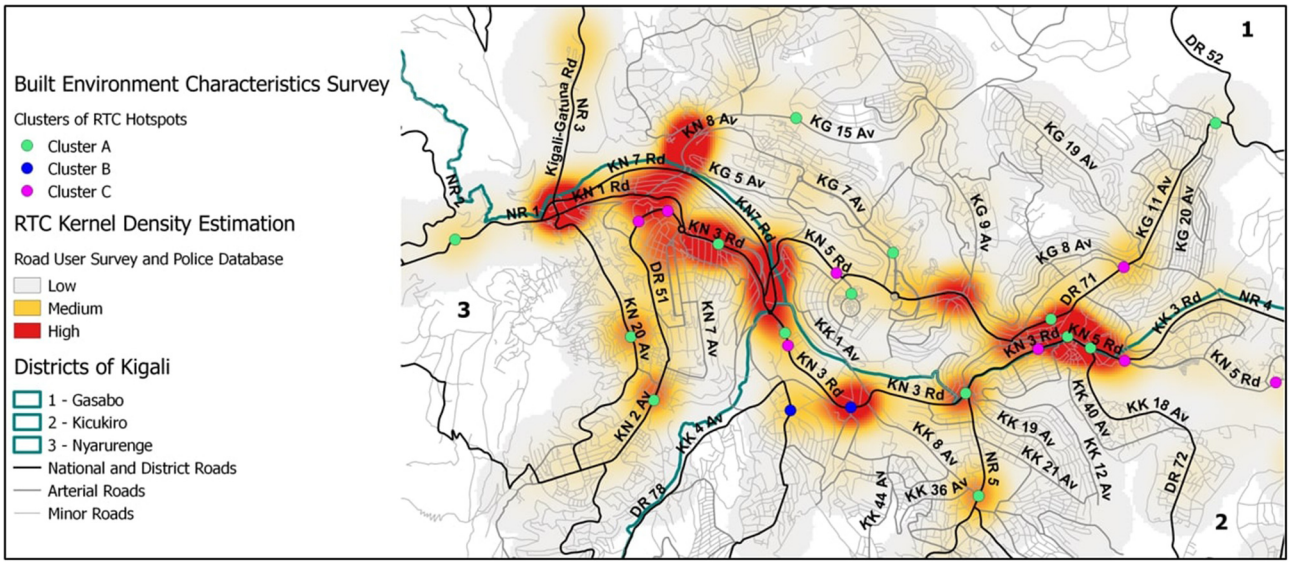


**FIGURE 4 |** Clustering of RTC hotspots, overlaid with the road network and the RTC kernel density estimation from the combined data from the police and high frequency road user survey. Cluster analysis was used to group RTC hotspots into three clusters based on road characteristics (urban or rural), road safety characteristics, motor vehicle density, and pedestrian safety characteristics at each location. Cluster A hotspots have primarily urban road characteristics with high built road safety conditions, high motor vehicle density, and high built pedestrian safety conditions. Cluster B hotspots have less urban road characteristics, few road safety characteristics, lower motor vehicle density, and less pedestrian safety conditions compared to Cluster A. Cluster C hotspots is similar to Cluster B, but with more road safety characteristics, higher motor vehicle density, and more pedestrian safety conditions.

Global status report on road safety 2015]. The government of Rwanda has instituted policies and investments in infrastructure to improve road safety conditions. Road user regulations are in place such as seatbelt laws, national speed limits, vehicle inspections, helmet laws, and national anti-drink-driving laws [(WHO, 2015), Global status report on road safety 2015]. The government also requires formal audits for new road construction projects and regular inspection of existing road networks [(WHO, 2015), Global status report on road safety 2015]. There are public awareness campaigns such as National Traffic Week and National Police Week targeting road safety education and the importance of observing road safe behaviors [(Mugisha, 2011), Motorcyclists laud traffic week; (Babijja, 2012), Traffic Week kicks off; (Times Reporter, 2017e), RNP launches campaign to promote road safety; (Times Reporter, 2017b), Police embarks on marking road accident hotspots]. Without question, Rwanda has made valiant efforts to improve the safety of the roads, especially in Kigali. However, a comprehensive, coordinated road safety action plan is notably missing from Rwandan road safety initiatives implemented thus far.

Previously, traffic law enforcement was a challenge due to the under-resourced police and corruption, but in the past decade the government has demonstrated a strong commitment to upholding road safety regulations. Examples include bolstering of the police workforce [(Rwanda National Police, 2013), Strategic Plan 2013-2018], cracking down on corruption [(Times Reporter, 2016d), Corruption is a human right violation, police say; (Gatera, 2013), Police blacklist 100 taxi-motorists; Times (Times Reporter, 2016b), Police partners with stakeholders to curb corruption; (Times Reporter, 2017d), Eight drivers arrested over bribery; (Times Reporter, 2017c), Police explain dismissal of 200 officers], and investing in technology and infrastructure to support law enforcement [(Times Reporter, 2016a), Police launch two more vehicle inspection lanes; (Times Reporter, 2016c), Police launch new highway traffic control mechanism; Times (Times Reporter, 2017a), How the new hi-tech traffic control devices work; (Iradukunda, 2017), Public transporters commit to fast track installation of speed governors]. The goal of this project was to identify RTC hotspots in Kigali through police records and high frequency road users, conduct built environment analysis of these hotspots, and suggest possible interventions to decrease RTCs at these locations. While this analysis highlights associations between built environment characteristics, crash risk, and mortality risk, this study cannot conclude any causal relationships. This study also does not investigate risky road use behaviors associated with built environment characteristics at these crash hotspots. Future studies should incorporate observations to investigate road user behavior such as traffic flow in roundabouts, drivers lane use behaviors, speed near intersections, and pedestrian road crossing behaviors [(Jha et al., 2017), Analysis of pedestrian movement on Delhi roads by using naturalistic observation techniques; (Hatfield and Murphy, 2007), The effects of mobile phone use on pedestrian crossing behavior at signalized and unsignalised intersections; (Johnson et al., 2010), Naturalistic Cycling Study: Identifying Risk Factors for On-Road Commuter Cyclists; (Eenink et al., 2014), UDRIVE: the European naturalistic driving study; (Perumal, 2014), Study

on pedestrian crossing behavior at signalized intersections]. Understanding risky road use behaviors can help assess the need for supplemental and improved safety infrastructure, while identifying critical needs in traffic law enforcement and road user behavior modification.

The results of this study should be considered in the context of its limitations. This study was a secondary analysis of crash reports from the Rwanda National Police. Reports were at times not accessible to our research team or did not have information sufficient for RTC geolocation and therefore were not included in the analysis. Possible reasons for the reports not being available include being requested for review by the judicial system or insurance companies. As described previously, police reports also have problems with under-reporting and incomplete reporting. It is impossible to determine whether the missing reports or incomplete reports were occurring at random. The RTC hotspot analysis also could not account for other confounding variables that impact crash risk, such as traffic volume, land use, and vehicle or pedestrian density approaching the hotspots. Another limitation of the study is the lack of built environment diversity among the surveyed hotspots. A majority of the surveyed hotspots were located in urban regions, resulting in similar built environment profiles. Future surveys of built environments of RTC hotspots in Kigali should be tailored to the characteristics, infrastructure, and crash risks associated with densely populated urban centers to further distinguish the built environment profiles of RTC hotspots in urban regions. Finally, the number of RTC hotspots is restricted given the size of the Kigali area. The small number of hotspots are an important limitation to the power of this analysis. To address this issue we included all RTCs in this analysis, aggregated as hotspots and providing the best scenario of BEA variability to our data analysis. In a similar tone, we could not perform subgroup analysis for pedestrians vs. non-pedestrians RTCs. This comparison would provide further clarity of the impact of built environment characteristics on RTCs and RTIs. However, it has been shown previously [(Patel et al., 2016), BMC Public Health] that the number of pedestrian related RTIs is too limited ($N = 257$) to identify unique hotspots for sequential analysis. Our approach of clustering the hotspots based on their built environment characteristics was chosen to provide an ecological perspective, and illustrate how hotspot characteristics differed when considering pedestrians and non-pedestrians based RTCs.

## CONCLUSIONS

This study presents a built environment analysis of RTC hotspots in Kigali, Rwanda. Most hotspots were located at intersections of national, district, and arterial roads. We found that characteristics such as paving of roads, road narrowing, slippery or uneven road surfaces are associated with greater crash risk. Pedestrian oriented built environment characteristics such as having crosswalks, pedestrian traffic lights, and informal pedestrian walkways were also associated with greater crash risk. Traffic calming measures such as speed limit signs, road traffic signs, police enforcement, speed bumps, and traffic lights may be under-utilized in Kigali. Although this study identifies potential interventions to reduce RTCs in Kigali, more extensive studies are needed to determine which interventions are most appropriate at each RTC hotspot. Improved geolocation data, attempts to link with hospital RTI reports and digitization of police crash reports could improve the accuracy and precision of conclusions that can be made from similar spatial analyses.

## DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are not publicly available due to the requirements of the ethics governing bodies, but are available from the corresponding author on reasonable request.

## ETHICS STATEMENT

This study was approved by the University Teaching Hospital of Kigali Ethical Committee; Rwandan National Ethics Committee; National Health Research Council of the Ministry of Health of Rwanda; and the Institutional Review Board of Duke University, in Durham, North Carolina. We obtained permission from the commissioner of the Rwanda National Police to collect the police RTC reports from the Kigali Traffic Police. We also obtained permission from the Rwanda Federation of Transport Cooperative (RFTC) to interview motorcycle taxi drivers. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

CS, SR, and EK conceived of the project. CS, SR, LA, and EK advised on the development of the project protocol. EK and SR managed data collection. DW, LA, and JN analyzed the data. JN, DW, and CS interpreted the data and created the first draft of the manuscript. All authors edited and approved of the final manuscript, EK completed extensive revisions after first reviews were received that were approved by authors.

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## SUPPLEMENTARY MATERIAL

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Older Drivers' Experience With Automated Vehicle Technology: Interim Analysis of a Demonstration Study

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Older adults (≥65 years) account for 20% of the US population but are over-represented in multiple-vehicle crashes. Automated vehicles (AVs) may hold safety benefits for older drivers, if they adopt this emerging technology. Therefore, this study is using a randomized, crossover design with *pre- and post-exposure surveys,* to quantify older drivers' perceptions, who were exposed to a simulator running in automated mode and riding in a highly automated shuttle (SAE Level 4). An interim analysis ($N = 69$) compares older drivers' perceptions before and after exposure to the automated simulator and automated shuttle. Early findings indicate that exposure to AV technology may positively affect older adults' perceptions to this emerging technology. In this study, older drivers' trust and perceived safety increased after being exposed to the driving simulator or automated shuttle compared to baseline. Older drivers' perceptions of *perceived usefulness* and *cost* of AVs, increased after being exposed to both modes of vehicle automation compared to baseline whereas their perceptions did not change after their first AV exposure (regardless of it was the simulator or shuttle). Exposing older adults to an automated simulator or on-road automated shuttle may promote older adults' acceptance and adoption of AVs.

**Keywords: automated shuttle, automated vehicles, driving simulation, survey, randomized experimental design, older drivers**

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## INTRODUCTION

The number of older adults (≥65 years) is nearing 20% of the US population, and Florida is leading the nation with 25% of its population being older adults (US Census Bureau, 2020). In 2017, there were almost 44 million licensed drivers aged 65 and older in the United States, a 63% increase from 1999 (Federal Highway Administration, 2018). Driving is an important mode of transportation for older adults that ensures mobility and independence and yields many health, community and societal benefits (Dickerson et al., 2014, 2017a,b). But older drivers are at an increased risk for multiple-vehicle crashes and deleterious crash-related effects (Karthaus and Falkenstein, 2016). According to American Automobile Association (AAA), since older drivers are more fragile, their fatality rates are 17 times higher than those between the ages of 25–64

years old (American Automobility Association Senior Driving, 2014). As the number of adults over 65 years of age increases in North America, strategies and countermeasures emerge as critical factors in preventing crashes involving drivers. Mitigation strategies, i.e., older driver screening, assessment, and intervention (Classen et al., 2012, 2014); enhanced vehicles with improved safety features (Charlton et al., 2002; Koppel et al., 2013; Bengler et al., 2014; Centers for Disease Control Prevention, 2015); enhanced infrastructure, such as protected left hand turn lanes or extended receiving lanes (Shechtman et al., 2007; Classen et al., 2009); and stringent policies, such as visual testing after age 89 before license re-issuing or in-person (vs. mail) renewal (Levy, 1995; Morrisey and Grabowski, 2005; Classen and Awadzi, 2008; Staplin and Freund, 2013), afford older drivers the opportunity to stay on the road—longer and safer, while they receive the health-related benefits of being actively engaged in their communities and participating in societal events. One emerging alternative transportation strategy for older drivers who are reducing driving or can no longer drive, is the use of automated modes of transportation. Such modes may include automated ride sharing, ride hailing, or on-demand services (i.e., paratransit), that could support the mobility and independence of older adults while reducing their crash risk on the road (Robertson et al., 2019).

The deployment of automated vehicles (AVs) is viewed by many as an emerging option that holds potential health and safety benefits for older drivers. Older drivers may benefit from the use of four distinct AV scenarios: automated public transport with fixed routes and schedules; automated on-demand public transport (i.e., automated shuttle); fleet-based shared AVs; and privately owned AVs (Faber and van Lierop, 2020). Both urban and peripheral areas may benefit from the availability of AVs due to increasing needs of accessibility (Faber and van Lierop, 2020). Older adults have a strong interest in using AVs in their daily life to overcome current mobility and accessibility barriers via on-demand booking and using feeder AVs for access and egress to other modes of transport (Faber and van Lierop, 2020). However, for such benefits to materialize, elderly transportation users would need to accept, trust, and adopt AV technology. Recent studies (Abraham et al., 2016, 2017; Hulse et al., 2018; Rovira et al., 2019) assessed older adults' perceptions of AV technology but were limited to soliciting input via surveys. Direct interactive experience in AVs in combination with surveys are a valuable alternative as they may more accurately reveal the perceptions of older drivers before and after "driving" the automated simulator or riding in the automated shuttle (Penmetsa et al., 2019). Simulators are already, quite ubiquitously, used to assess driving performance, or to provide interventions, in a much safer (than on-road) yet realistic environment (Campos et al., 2017). Driving simulators are also frequently used to expose research participants to vehicle automation (Kauffmann et al., 2018). However, it is unclear whether an automated simulator will influence drivers' perceptions of AVs and thus needs to be explored as this technology may be used to train users on how to use this technology and to potentially promote technology acceptance. Vehicle capabilities may be better understood if users are exposed to this technology via a driving simulator or on-road use rather than conventional alternatives (i.e., demonstration videos or a user manual).

Highly automated vehicles are now becoming a reality and are expected to have enormous safety, societal, and environmental benefits. Particularly, vehicle automation has the potential to prevent older driver crashes occurring due to age-related declines in function resulting in human error, enhance lifelong mobility, while also reducing pollution and non-recurrent congestion impacts because of crash reduction (National Highway Traffic Safety Administration, 2013, 2017). However, highly automated vehicles can be less safe than human drivers under certain circumstances (i.e., inclement weather). The Society of Automotive Engineers (Society of Automotive Engineers International, 2016) defined six levels of AVs, ranging from no automation (Level 0) to full automation (Level 5). The focus of this paper will be on highly AVs at the SAE Level 4, because that is the classification of the EasyMile EZ10, automated shuttle used in this study. In this study, older drivers were exposed to the automated shuttle and to the driving simulator which is a representation of a privately-owned or shared-use AV.

Recent studies have suggested that AVs should be safer than human drivers if individuals are to adopt and accept this technology (Waycaster et al., 2018; Shladover and Nowakowski, 2019). However, in the context of highly automated vehicles, which is the focus of this study, full acceptance and trust may lead to complacency and misuse of the system. As such, trust must be calibrated with the capabilities of the system to prevent distrust, overtrust, or overreliance (Kraus et al., 2019). The public will be less likely to accept AVs if they have the same risk level as human driving (Waycaster et al., 2018). Specifically, Liu et al. (2019) found that AVs should be four to five times as safe (i.e., 75–80% reduction in traffic fatalities) as human drivers, if they are to be tolerated and widely accepted (Liu et al., 2019). Although safety is a critical predictor, several other factors influence user perceptions and behavioral intentions (i.e., trust, perceived usefulness, ease of use). Advantages and disadvantages are anticipated to arise from the emergence of AVs. Benefits include improved mobility for the elderly and disabled (Yang and Coughlin, 2014) and the liberating of parking spaces for other land uses (Fagnant and Kockelman, 2015). The potential disadvantages include concerns relating to privacy, security, insurance, and liability, as well as job losses (Taeihagh and Lim, 2019). The extent to which these positive and negative outcomes eventuate will be highly dependent on user acceptance and adoption of this emerging technology. Recent AV consumer preference studies, specifically among older adults, indicate that trust and hesitation are barriers in adopting full vehicle automation (Reimer, 2014; Hartford, 2015; American Automobile Association, 2016). Faber and van Lierop (2020) conducted focus groups in which older adults voiced concerns related to cost, trust, control, and safety of AVs. A weakness of these studies is that older drivers were not exposed to "driving" an AV either in real-world format or via simulator technology. As such, only the perceptions, and not direct interactive experiences of these participants are measured, meaning that they do not allow us to fully understand adoption and acceptance practices of older adults who were

not exposed to the real life experience of driving or riding in an AV.

The scientific premise of this study is discussed in the next five points. (1) The number of older adults is nearing 20% of the population across the US. (2) Driving, a critical mode of transportation for older adults, yields many health, community and societal benefits but older drivers are at-risk for crashes and deleterious crash-related effects. (3) The deployment of automated shuttles and AVs are expected to have health and safety benefits for older drivers, positively impact the environment, and yield societal benefits (i.e., improved traffic flow). However, older drivers may not trust AVs and have additional concerns (i.e., perceived safety) about vehicle automation. (4) Interactive experiences in AV modes, in combination with surveys, may more accurately reveal the thoughts, beliefs, perceptions, or hesitations of older drivers before, during and after "driving" the automated simulator or the automated shuttle and (5) inform scientists and engineers of adjunctive strategies to enhance adoption practices among older drivers.

Thus, the purpose of this study is to quantify the perceptions of 69 older drivers, before and after "driving" in an interactive *high-fidelity Realtime Technologies Inc. (RTI) driving simulator* in Level 4 automated mode and riding in the *Transdev operated EasyMile EZ10, Level 4 automated shuttle* (Society of Automotive Engineers International, 2016). We expect that (1) drivers' perceptions (intention to use, trust, perceived usefulness, perceived ease of use, perceived safety, control and driving efficacy, cost, authority, and social influence), will improve after being exposed to "driving" the simulator and/or the automated shuttle and (2) the on-road experience in the shuttle may be a more positive experience compared to the driving simulator.

Information gained from such experiences will inform health care professionals, engineers, city managers, and transportation officials of opportunities and barriers to improve older drivers' interaction with AVs, facilitate their ease-of-use practices, and potentially empower them to adopt these technologies—and in so doing contribute to congestion mitigation and crash prevention—core components of a public health approach. Moreover, because Florida is a model state for older driver mobility issues (Classen and Awadzi, 2008), and Gainesville, Florida is an emerging "smart city" (Gonzalez, 2017), it is critical that scientists and engineers study and understand these adoption patterns of older drivers pertaining to automated technologies.

## MATERIALS AND METHODS

The University of Florida Institutional Review Board approved the study after a full board review. All participants provided informed consent for their enrollment into the study. This study used an experimental crossover-repeated measures design with a *pre-visit survey*, *intake surveys*, exposure to the automated mode driving simulator or the automated shuttle, *post-visit survey 1*, *crossover to simulator or automated shuttle*, and *post-visit survey 2*. Participants were recruited through the infrastructure and support of Oak Hammock and other residential communities, the older adult recruitment pool of UF's Institute for Mobility, Activity and Participation, and through UF's Institute on Aging. Participants received $25.00 for participation in the study.

Sixty-nine community dwelling drivers, 65 years of age or older, from North Central Florida, who had a valid driver's license and reported driving within the last 6 months were included in this study. Participants were excluded if they did not communicate in English or showed signs of cognitive impairment, i.e., scoring $\leq$26 on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Participant intake and assessment were conducted in the living areas of the Smart House in the Oak Hammock Residential Community (5100 S.W. 25th Blvd., Gainesville, FL; see **Figure 1**), which provided a comfortable atmosphere for participants and research personnel. The simulated driving assessments occurred in the simulator laboratory, located in the garage of the Smart House. The on-road

**FIGURE 1 |** The Smart House houses the project's high-fidelity driving simulator and serves as a site for testing.

experience in the automated shuttle occurred at a formerly used bus depot in Gainesville, FL.

## Equipment

### Realtime Technologies Inc. Driving Simulator

The RTI driving simulator is integrated in a full car cab with seven high definition visual channels, including three forward channels creating a 180° field of view, three backward channels with behind-car views accomplished with one rear screen (seen through the rearview mirror), two built-in LCD side mirrors, and one virtual dash display (LCD panel) within the car. The RTI system has a high fidelity graphic resolution, component modeling, steering feedback, spatialized audio with realistic engine, transmission, wind and tire noises, and an autopilot feature to turn the simulator into automated driving mode (see **Figure 1**). The *visual display* operates at a 60 Hz refresh rate to support smooth graphics projected on three flat screens with high intensity projectors. The system allows for experimental drives with changing environmental conditions, video recording of the driver's simulator session, and incorporation of rural, urban, and highway driving. The simulator operating system drives are created with a combination of ambient and scripted traffic that interacts realistically with other vehicles based on human behavior/decision models and real-time physics-based vehicle dynamics calculations.

The scenario for this study utilized a 5-min acclimation drive, to enhance adaptation to the driving simulation environment. We utilized the simulator sickness questionnaire (Brooks et al., 2010) to determine pre- and post-drive experiences related to simulator sickness. The 10-min automated drive (SAE Level 4) occurred in a low to moderate speed (15–35 mph) residential and suburban area with realistic road infrastructure, buildings, and ambient traffic with the system handling all aspects of the designated driving task. A control area situated at the rear of the vehicle overlooks the driver, vehicle and screens (see **Figure 2**) allowing the operator to control and monitor all aspects of the experiment. During the simulated scenario, a researcher was seated in the front passenger seat to assess simulator sickness via the motion sickness assessment questionnaire (MSAQ) (Brooks et al., 2010).

**FIGURE 2 |** RTI High Fidelity Simulator with control station.

### EasyMile EZ10 Automated Shuttle

This SAE Level 4 automated shuttle (see **Figure 3**) uses vision sensors, light detection, GPS tracking system, and ranging (LIDAR) to map its environment and to decide upon the best motion behavior at each instant. The EZ10 shuttle can drive automated on certain pre-mapped routes but is not yet able to drive on any road at any time. The shuttle does not have a steering wheel and can only be manually operated by a joystick remote control. The maximum speed of the vehicle is 25 miles per hour. The shuttle has six seats and six standing positions and can transport up to twelve passengers.

**FIGURE 3 |** Transdev: EasyMile EZ10 autonomous shuttle (SAE Level 4).

The shuttle route (see **Figure 4**) lasted about 10 min and took place in a deserted bus depot. During testing, participants remained seated while the shuttle operated at a low speed (≈15 miles per hour) without the presence of ambient traffic or road users. During segments of the route, the safety operator explained vehicle capabilities and features to the participants. The number of participants in the shuttle, during testing, ranged from two to six participants.

## Procedure

Each participant provided written informed consent, was screened for cognitive impairment using the MoCA, then completed pencil-and-paper surveys consisting of a demographic and medical history form, driving habits questionnaire (Owsley et al., 1999), technology acceptance model (Davis, 1989), technology readiness index 2.0 (Parasuraman and Colby, 2015), an autonomous vehicle user perception survey (AVUPS) (Mason et al., 2020). During participant intake, researchers explained that both the shuttle and simulator can drive automated pre-mapped routes but neither vehicle was able to drive on any road at any time. To minimize the effects of social interaction, participants were asked to remain silent while riding in the shuttle and in the driving simulator and to save their questions for after the experiment. Each participant ($N = 69$), was randomly assigned to complete the simulator ($n = 31$) or the automated shuttle ($n = 38$) drive, completed the AVUPS, cross-over to "drive" the modality not initially driven, and complete the AVUPS again. After riding in the shuttle or simulator, each participant completed the *Motion Sickness Assessment Questionnaire* (MSAQ).

### Simulator Sickness Protocol

Participants driving the simulator may be prone to developing simulator sickness. We implemented a simulator sickness protocol to mitigate the occurrence of simulator sickness (Brooks et al., 2010; Classen et al., 2011). These measures include: offering dietary recommendations prior to the drive; utilizing an acclimation protocol; employing a simulator sickness questionnaire; reducing the sensory incongruence between the visual, kinesthetic, and vestibular systems by removing visual clutter in the peripheral field, including engine sounds, and vibrations for vestibular sensation; supplying environmental adaptations (5 min acclimation drive, 10 min simulator drive, cool comfortable conditions at 72 degrees Fahrenheit, air circulating via fan; avoidance of complex sensory scenes (e.g., introduced "calmer" traffic scenes, with some vehicles, a few pedestrians, a few parked vehicle alongside the road, only necessary infrastructure, e.g., road marking, speed signs, and traffic lights); and determining/managing the extent of simulator sickness symptoms (Stern et al., 2017). All these strategies areproven to be successful in our previous older adult studies (Shechtman et al., 2007; Classen et al., 2011).

## Measures

### Demographic and Medical History Form

The demographic and medical history form was modified from the National Institute on Aging Clinical Research Toolbox and used to collect age, gender, race, education, relationship status, and employment data (US Department of Health & Human Services, 2019).

### Automated Vehicle User Perception Survey (Mason et al., 2020)

This AVUPS[1] was used to measure older drivers' perceptions of AVs before and after each exposure (simulator and shuttle). The survey consisted of 4 open-ended items, and 28 visual analog scale items—ranging from disagree to agree. The scale was a 100 mm horizontal line and participants placed a vertical dash to signify their level of agreement/disagreement for each item. Responses were treated as a continuous variable that ranged from 0 (negative perception of AVS) to 100 (positive perception of AVs). The survey items represent 11 dimensions including, experience with technology (3 items; e.g., "I use technology in my vehicle to make tasks easier for me"), intention to use (3 items; e.g., "I am open to the idea of using an AV"), trust (4 items; e.g., "I am suspicious of an AV"), perceived usefulness (5 items; e.g., "I believe AVs will allow me to stay active"), perceived ease of use (2 items; e.g., "It will require a lot of effort to figure out how to use an AV"), perceived safety (3 items; e.g., "I feel safe riding in an AV"), control/driving efficacy (3 items; e.g., "My driving abilities will decline due to relying on an AV"), cost (2 items; e.g., "I will be willing to pay more for an AV compared to what I would pay for a traditional car"), authority (1 item; "I would use an AV if National Highway Traffic Safety Administration deems them as being safe"), media (1 item; "Media portrays AVs in a positive way"), and social influence (1 item; "My family and friends will encourage/support me when I use an AV"). Both media and experience with technology, have been shown to influence users' perceptions of AVs (Talebian and Mishra, 2018) and AVUPS items were designed to assess users' experience with technology (i.e., not just AV technology) and the media they consumed, during a longitudinal study.

Item responses were averaged into their respective dimensions which produced dimension scores ranging from 0 (negative perceptions of AVs) to 100 (positive perceptions of AVs). The dimensions' internal consistency ranged from acceptable ($\alpha = 0.75$) to excellent ($\alpha = 0.91$). During scale development, the AVUPS content validity index (CVI) had a rating of 1.00, with 32 of 32 items rated ≥0.86 and a scale CVI of 0.96 (*mean* CVI of all items), indicating acceptable content validity (i.e., subject-matter experts indicated that the items in the survey are representative of users' perceptions of AVs). The scale is currently undergoing further reliability testing and factor analysis.

### Motion Sickness Assessment Questionnaire (Brooks et al., 2010)

The MSAQ questionnaire consisted of 4 items (sweaty, queasy, dizzy, nauseous) ranging from 0 (not at all) to 7 (severely). The survey was developed and validated for assessing simulator sickness symptoms.

[1]The *Automated Vehicle User Perception Survey* can be obtained from the corresponding author: justinmason@phhp.ufl.edu.

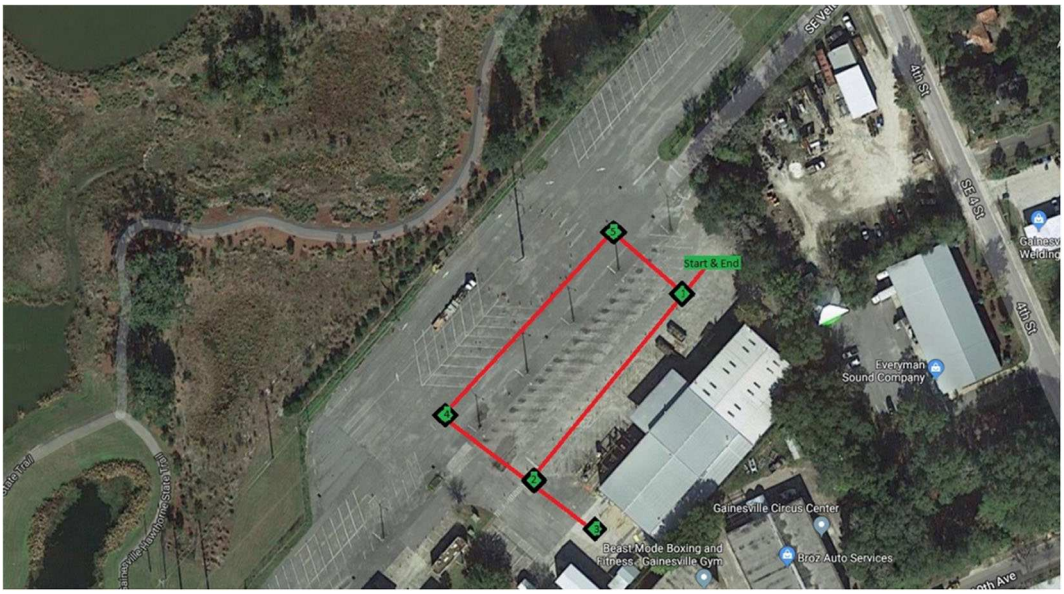


**FIGURE 4 |** Ten-minute route of the EasyMile EZ10 autonomous shuttle.

For the purposes of this interim analysis, we only focus on the demographic information, descriptive statistics of simulator and motion sickness, and all 11 domains from the AVUPS measured with a visual analog scale.

## Data Analysis

Descriptive statistics were conducted on participants' age, race, education, and employment status. A series of paired sample *t*-tests were performed on older drivers' simulator/motion sickness comparing baseline with post-simulator exposure as well as baseline with post-shuttle exposure. Continuous data are presented as mean and standard deviation (*SD*) whereas categorical data are presented as frequency (%). The 11 domains (previously described) of AVUPS were used as dependent variables and were assessed for normality to determine use of parametric vs. non-parametric analyses via visual examination (i.e., probability plots, histograms, stem, and leaf plots) and statistical tests (i.e., Fisher's skewness and kurtosis and Shapiro-Wilks tests). A one-way repeated measures ANOVA with three levels was conducted to assess differences between older drivers' perceptions at baseline, after exposure to the simulator, and after exposure to the automated shuttle. A one-way repeated measures ANOVA with three levels was performed to assess differences between older drivers' perceptions at baseline, after being exposed to one AV technology (i.e., post-exposure 1), and after being exposed to both AV technologies (i.e., post-exposure 2). *Post-hoc* tests (i.e., paired *t*-tests), were performed if repeated measures ANOVAs reached significance ($p < 0.05$). No adjustments were made for multiple comparisons (Rothman, 1990). Study data were collected and managed using Research Electronic Data Capture (REDCap) hosted at the UF (Harris et al., 2019). R Studios and R version 3.6.1 (R Core Team, 2019) were used for data collation and analyses. Significance level was set at $\alpha = 0.05$ with an accompanying 95% confidence level.

# RESULTS

A total of 69 participants (*mean age* = 74.64, *SD* = 6.17), consisting of 29 males (*mean age* = 77.03, *SD* = 5.42) and 40 females (*mean age* = 72.90, *SD* = 6.16) completed our study. Twenty females and 18 males were first exposed to the shuttle ($n = 38$), whereas 20 females and 11 males were first exposed to the simulator ($n = 31$). The racial distribution indicated that participants were self-identifying as 60 (87%) White, 6 (9%) Black, and 3 (4%) Other. The study participants demonstrated a high level of education as 73% had either a doctorate (26%), master's (28%) or bachelor's degree (19%); whereas 26% had an associate, some college or a technical school certification, and 1% had either a GED or high school education. Participants reported their current employment status, 58 (84%) retired, 10 (14.5%) working part-time, and 1 (1%) working full-time. All participants were able to complete their ride in the shuttle and driving simulator.

The paired-sample *t*-tests for simulator sickness revealed differences for queasy, dizzy, and nauseous after experiencing the driving simulator compared to baseline. Older drivers' ratings of feeling queasy, dizzy, and nauseous increased after riding in the simulator compared to baseline. The paired-sample *t*-tests for motion sickness revealed differences for feeling sweaty after riding in the automated shuttle compared to baseline. Older drivers' ratings of feeling sweaty decreased after riding in the automated shuttle. Motion sickness and simulator sickness results are displayed in **Table 1**.

**TABLE 1 |** Older drivers' simulator and motion sickness before and after being exposed to the automated shuttle and simulator.

| Dimensions | Pre-exposure | | Post-exposure | | Statistics | *P* |
|---|---|---|---|---|---|---|
| | *M* (SD) | Range | *M* (SD) | Range | | |
| **SIMULATOR** | | | | | | |
| Sweaty | 0.00 (0.00) | 0 | 0.19 (0.85) | 0–6 | $t_{(68)} = 1.85$ | 0.068 |
| Queasy | 0.04 (0.36) | 0–3 | 0.68 (1.31) | 0–7 | $t_{(68)} = 4.66$ | <0.001 |
| Dizzy | 0.04 (0.21) | 0–1 | 0.54 (1.20) | 0–5 | $t_{(68)} = 3.53$ | 0.001 |
| Nauseous | 0.01 (0.12) | 0–1 | 0.25 (0.78) | 0–5 | $t_{(68)} = 2.80$ | 0.007 |
| **SHUTTLE** | | | | | | |
| Sweaty | 0.49 (1.22) | 0–5 | 0.13 (0.66) | 0–5 | $t_{(68)} = 2.23$ | 0.029 |
| Queasy | 0.07 (0.60) | 0–5 | 0.00 (0.00) | 0 | $t_{(68)} = 1.00$ | 0.321 |
| Dizzy | 0.00 (0.00) | 0 | 0.00 (0.00) | 0 | | |
| Nauseous | 0.04 (0.27) | 0–2 | 0.04 (0.27) | 0–2 | $t_{(68)} = 0.00$ | 1.0 |

*The motion/simulator sickness questionnaire dimensions ranged from 0 to 7. Range is displayed as minimum to maximum.*

## Older Drivers' Perceptions Before, Post-shuttle, and Post-simulator

The repeated measures ANOVA revealed differences between exposure to AV technologies for drivers' *intention to use*, $F_{(2,136)} = 3.360$, $p = 0.038$, $\eta_p^2 = 0.047$, *trust*, $F_{(2,136)} = 13.565$, $p < 0.001$, $\eta_p^2 = 0.166$, *perceived usefulness*, $F_{(2,136)} = 5.018$, $p = 0.008$, $\eta_p^2 = 0.069$, *perceived safety*, $F_{(2,136)} = 11.140$, $p < 0.001$, $\eta_p^2 = 0.141$, and *control and driving efficacy*, $F_{(2,136)} = 3.724$, $p = 0.027$, $\eta_p^2 = 0.052$. However, older drivers' *intention to use* was not statistically significant after being exposed to the simulator ($p = 0.076$) and shuttle ($p = 1.00$) compared to baseline. Older drivers' *trust* was enhanced after being exposed to the simulator ($p = 0.013$) and shuttle ($p < 0.001$) compared to baseline. Older drivers' *perceived usefulness* ($p = 0.005$) was enhanced after the shuttle compared to baseline. Older drivers' *perceived safety* was enhanced after being exposed to the simulator ($p = 0.006$) and shuttle ($p < 0.001$) compared to baseline. Older drivers' *control and driving efficacy* were enhanced after riding in the shuttle compared to after the simulator ($p = 0.043$, Cohen's $d = 0.30$). The repeated measures ANOVA revealed no significant differences for older drivers' *experience with technology*, $F_{(1.8,123.5)} = 0.166$, $p = 0.827$, $\eta_p^2 = 0.002$, *perceived ease of use,* $F_{(2,136)} = 0.172$, $p = 0.842$, $\eta_p^2 = 0.003$, *cost*, $F_{(2,136)} = 2.838$, $p = 0.062$, $\eta_p^2 = 0.040$, *authority,* $F_{(2,136)} = 1.598$, $p = 0.206$, $\eta_p^2 = 0.023$, *media,* $F_{(2,136)} = 1.773$, $p = 0.174$, $\eta_p^2 = 0.025$, *or social influences*, $F_{(2,136)} = 1.364$, $p = 0.259$, $\eta_p^2 = 0.020$. **Table 2** indicates the descriptive statistics from the repeated measures ANOVA comparing older drivers' perceptions at baseline and after being exposed to the simulator and automated shuttle. The bar graphs (**Figure 5**) display descriptive trends for the AVUPS domains at baseline, after the shuttle, and after the simulator.

## Older Drivers' Perceptions Before, Post-exposure 1, and Post-exposure 2

The repeated measures ANOVA revealed differences between the number of exposures (i.e., baseline, post-exposure 1, post-exposure 2) to AV technologies for older drivers' *trust*, $F_{(2,136)} = 13.565$, $p < 0.001$, $\eta_p^2 = 0.168$, *perceived usefulness*, $F_{(2,136)} = 3.360$, $p = 0.038$, $\eta_p^2 = 0.057$, and *perceived safety*, $F_{(2,136)} = 13.565$, $p < 0.001$, $\eta^2 = 0.148$. Older drivers' *trust* was enhanced at post-exposure 1 ($p = 0.010$) and post-exposure 2 ($p < 0.001$) compared to baseline. *Older drivers' perceived usefulness* ($p = 0.028$) and *cost* ($p = 0.029$) increased after being exposed to both forms of AV technology. The repeated measures ANOVA revealed no significant differences for older drivers' *experience with technology*, $F_{(1.8,124.2)} = 0.074$, $p = 0.915$, $\eta_p^2 = 0.001$, *intention to use,* $F_{(2,136)} = 2.761$, $p = 0.067$, $\eta_p^2 = 0.039$, *perceived ease of use,* $F_{(2,136)} = 0.185$, $p = 0.832$, $\eta_p^2 = 0.003$, *control and driving efficacy,* $F_{(2,136)} = 0.332$, $p = 0.718$, $\eta_p^2 = 0.005$, *cost,* $F_{(2,136)} = 2.784$, $p = 0.065$, $\eta_p^2 = 0.039$, *authority,* $F_{(2,136)} = 1.200$, $p = 0.304$, $\eta_p^2 = 0.017$, *media,* $F_{(2,136)} = 0.837$, $p = 0.435$, $\eta_p^2 = 0.012$, *or social influences,* $F_{(2,136)} = 1.747$, $p = 0.178$, $\eta_p^2 = 0.025$. Older drivers' *perceived safety* increased at post-exposure 1 ($p = 0.013$) and post-exposure 2 ($p < 0.001$) compared to baseline. **Table 3** indicates the descriptive statistics from the repeated measures ANOVA comparing older drivers' perceptions at baseline, post-exposure 1, and post-exposure 2.

# DISCUSSION

This interim analysis was conducted to quantify the perceptions of 69 older drivers, who have been exposed to "driving" the interactive high-fidelity RTI driving simulator and riding in the Transdev manufactured EasyMile EZ10 automated shuttle.

We had two expectations: **Expectation 1**: Older drivers' perceptions in 9 of the 11 domains (all except for media and experience with technology) will change after being exposed to riding in the simulator and/or the automated shuttle. This was indeed the case for 3 of the 9 domains indicating older drivers' perceptions of AVs. Specifically, older drivers' trust and perceived safety increased after being exposed to either the simulator or shuttle whereas older drivers' perceived usefulness increased after begin exposed to the automated shuttle. Older drivers' trust and perceived safety increased after their first exposure to AVs (regardless of whether it was the simulator or shuttle) whereas trust, perceived safety,

**TABLE 2 |** Older drivers' perceptions at baseline, post-simulator, and post-shuttle.

| Dimensions | Baseline | Simulator | Shuttle | Cohen's *d* |
|---|---|---|---|---|
| Experience with technology | 78.2 (16.3) | 78.0 (18.0) | 79.1 (15.8) | 0.07 |
| Intention to use | 75.7 (18.8) | 80.6 (18.9) | 76.6 (18.0) | −0.22 |
| Trust | 64.1 (19.8) | 70.3 (18.5)* | 74.3 (16.6)* | 0.26 |
| Perceived usefulness | 75.5 (16.6) | 78.9 (19.8) | 81.5 (15.4)* | 0.15 |
| Perceived ease of use | 75.4 (19.8) | 76.6 (20.0) | 76.7 (19.3) | 0.01 |
| Perceived safety | 69.4 (19.9) | 76.6 (17.9)* | 78.74 (16.7)* | 0.13 |
| Control/Driving efficacy | 45.9 (18.8) | 44.5 (18.4) | 50.38 (20.2) | 0.30$^{\dagger}$ |
| Cost | 63.9 (21.8) | 67.1 (21.6) | 69.0 (19.0) | 0.09 |
| Authority | 76.5 (24.7) | 78.4 (22.9) | 81.0 (18.3) | 0.13 |
| Media | 60.0 (23.2) | 59.6 (24.2) | 64.6 (20.5) | 0.22 |
| Social Influence | 69.7 (25.1) | 70.8 (24.5) | 74.2 (19.3) | 0.16 |

*Cohen's d compares older drivers' perceptions after exposure to the simulator and automated shuttle. *$p < 0.05$ signifies differences compared to baseline. $^{\dagger}p < 0.05$ signifies differences of perceptions after the simulator compared to after the shuttle. Dimension scores range from 0 to 100.*

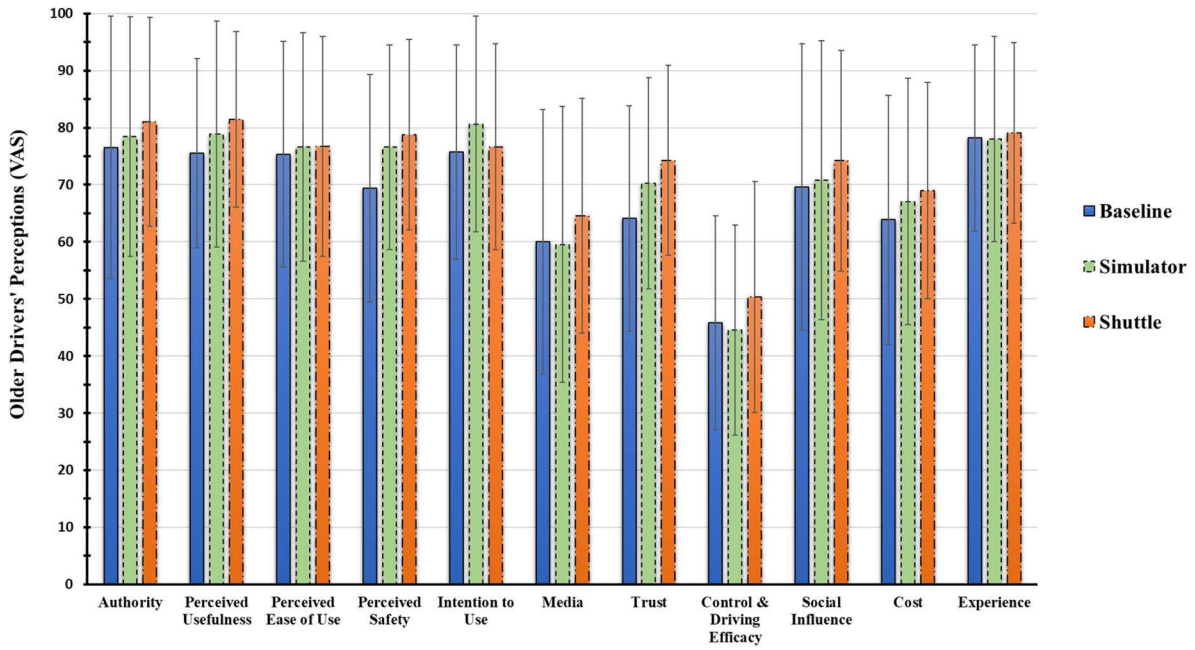


**FIGURE 5 |** Bar graph for older drivers' perception of AVs, via a visual analog scale, at baseline, post-simulator, and post-shuttle.

perceived usefulness, and cost increased after being exposed to both modes of AV technology. **Expectation 2:** The on-road experience in the automated shuttle may increase drivers' perceptions of AV technology compared to the driving simulator. Interestingly, when comparing perceptions after the simulator vs. after the shuttle, only *control and driving efficacy,* reached statistical significance. It is possible that older drivers' on-road experience was more realistic compared to the driving simulation, thus increasing their perceived control of AVs after riding in the automated shuttle. The on-board engineer, remote control to take over control of the automated shuttle, and accessible control panel may have influenced their sense of control.

Older drivers did not experience motion sickness in the automated shuttle, which may have influenced their perceptions compared to their experience in the driving simulator, resulting in increased simulator sickness severity. All participants completed the driving simulation, which suggests that feelings of simulator sickness were manageable. The lack of motion sickness experienced by older adults in the automated shuttle is promising for AV acceptance and adoption. Although, further investigation is required to discern differences between simulator sickness and motion sickness. Specifically, researchers should strive to develop congruent routes, settings, and vehicle speeds when comparing sickness that occurs due to vehicle automation or driving simulation. Another interesting finding is that the

**TABLE 3 |** Older drivers' perceptions at baseline, post-exposure 1, and post-exposure 2.

| Dimensions | Baseline | Post-exposure 1 | Post-exposure 2 | Cohen's *d* |
|---|---|---|---|---|
| Experience with technology | 78.2 (16.3) | 78.2 (18.0) | 78.9 (15.8) | 0.04 |
| Intention to use | 75.7 (18.8) | 77.0 (19.3) | 80.3 (17.7) | 0.18 |
| Trust | 64.1 (19.8) | 70.2 (19.7)* | 74.4 (15.3)* | 0.24 |
| Perceived usefulness | 75.5 (16.6) | 79.8 (18.2) | 80.6 (17.3)* | 0.05 |
| Perceived ease of use | 75.4 (19.8) | 76.5 (20.9) | 76.9 (18.4) | 0.02 |
| Perceived safety | 69.4 (19.9) | 76.1 (18.3)* | 79.2 (16.2)* | 0.18 |
| Control/Driving efficacy | 45.9 (18.8) | 47.3 (22.2) | 47.6 (16.5) | 0.02 |
| Cost | 63.9 (21.8) | 67.2 (19.6) | 68.9 (21.0)* | 0.09 |
| Authority | 76.5 (24.7) | 79.0 (20.4) | 80.4 (21.1) | 0.07 |
| Media | 60.0 (23.2) | 60.6 (23.3) | 63.6 (21.7) | 0.13 |
| Social influence | 70.0 (25.1) | 69.4 (25.0) | 74.3 (20.2) | 0.22 |

*Cohen's d compares older drivers' perceptions between their first (i.e., post-exposure 1) and second exposure (i.e., post-exposure 2) to automated vehicles. *$p < 0.05$ signifies differences compared to baseline. Dimension scores range from 0 to 100.*

older drivers' perceptions of *perceived usefulness* and *cost*, were enhanced after riding in both modes of vehicle automation compared to baseline whereas these perceptions did not change after their first AV exposure. One potential reason may be that the participants experience in the simulator and shuttle provided them with more thorough understanding of vehicle automation. Older drivers may need to be exposed to different modes of vehicle automation or be exposed to AVs on multiple occasions. However, these interpretations needs to occur with caution as Type 1 (i.e., due to multiple comparisons) and/or Type II error (i.e., inadequate power to detect a true difference) may be evident in this interim analysis that only accounts for the perceptions of 69 older drivers.

Descriptively, all 11 domains increased after being exposed to the automated shuttle compared to baseline (see **Figure 5**). Furthermore, participants reported more positive perceptions for 10 domains (all except for intention to use), after being exposed to the automated shuttle compared to the driving simulator. Older drivers' perceptions descriptively increased after their first exposure (i.e., regardless of it was the simulator or shuttle) to AV technology and continued to increase after being exposed to both modes of AV technology. Older drivers in the current study were exposed to the simulator and shuttle, which operated in very predictable conditions with a closed route, during clear environmental conditions, with clear road markings, and few interferences. Results from the current study align with similar studies where older drivers were exposed to a SAE Level 4 automated shuttle (Eden et al., 2017; Nordhoff et al., 2019) and a Level 4 driving simulator (Li et al., 2019) during ideal circumstances. However, as seen in findings from Walker et al. (2018), drivers that have negative interactions with AVs have decreased perceptions (i.e., trust) of AVs. Thus, drivers should be exposed to scenarios and routes that realistically portray automated system capabilities and limitations. Furthermore, the negative interactions with on-road vehicle automation may decrease perceptions of AVs at a greater magnitude than being exposed to driving simulation.

The results of this study align with findings from Penmetsa et al. (2019), indicating that as the public increasingly interacts with AVs, their attitudes toward the technology are more likely to be positive. Similar to Penmetsa et al. (2019), we recommend that policy makers provide opportunity for the public to interact with AVs. The interactive experience with AVs, ideally on public roads may increase the acceptance and adoption of AV technology. Numerous limitations in this study occurred due to the restrictions imposed by the federal government, which delayed our study timeline and required amendments to our research design and protocol. For example, the National Highway Traffic Safety Administration (NHTSA) issued a waiver approving pilot testing of participants, but the shuttle could not operate on public roads. As such, we modified our original plan—and operated the shuttle, not on a congruent road course to that in the simulator—but in a deserted bus depot, where there was no traffic, road users or road signs. The differences (i.e., shuttle speed, road-type, and traffic) between the shuttle route and simulator scenario must be noted as a limitation to this study. The physics experienced during driving simulation affects cognitive awareness that there would be no real consequences in the case of an adverse event, such as a crash. Moreover, the automated shuttle traveled at a restricted speed of 15 miles per hour, whereas the driving simulator scenario had speeds ranging from 15 to 35 miles per hour. Of course, this arrangement may have impacted the perceptions of the older drivers—and we may see a resulting effect following this arrangement. That means that the study may be prone to bias and an underestimation or overestimation of the actual effects of the exposure, especially pertaining to the experiences in the automated shuttle. Furthermore, the NHTSA waiver that was issued, expired after 6 months, and the study team is still awaiting permission to continue with the participant testing—hence the interim analysis. Lastly, in February 2020, NHTSA ordered a nationwide suspension affecting all 16 operating EZ10 automated shuttles. An EZ10 automated shuttle operating in Columbus, Ohio traveling 7 miles per hour made an emergency stop which caused a passenger to fall from their seat in a "minor incident"

(EasyMile, 2020). Finally, participants in our study were mainly white and highly educated, which may have caused sampling bias—as the views of minorities and less educated groups were not adequately represented.

This study is one of the first that actually presents data on user perceptions after participants have been exposed to *two forms* of vehicle automation (i.e., simulator and automated shuttle). The findings of this interim analysis suggest that the simulator, when programmed to run in the SAE Level 4 mode of autonomy, can be used to gauge user experiences of being exposed to autonomous technology. However, the participants' experiences showed a greater increase in perception pertaining to especially trust and *perceived* safety, when exposed to the automated shuttle. This suggest that the automated shuttle may be a superior mode of automation to influence user acceptance. However, the simulator may also influence users' perceptions and be a viable training device to provide specific scenarios that highlight capabilities and limitations of vehicle automation. For example, in cities where automated shuttles are not a reality yet, the autonomous simulator may be used as a reasonable substitute to gauge user experience and potential adoption of the AV technology.

Next steps for this project are to increase and balance (i.e., match for gender and age) the study sample size, by collecting and analyzing the perceptions of the total sample ($N = 106$). A robust analysis of the complete data set will include linear modeling as well as repeated measure ANOVAs to explore gender, age, and group by time (i.e., order) interactions. Additionally, we will analyze drivers' qualitative feedback, given in the four open ended questions of the AVUPS, to better understand their interactive experience pertaining to the acceptance and adoption of AVs. Information from this completed study will be used to develop strategies to further improve upon older driver adoption practices of AV, suggest practical hints to engineers for design elements, and provide information to shape city and state policies for regulatory purposes of AV deployment, adoption and use.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Florida Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

SC and VS: study conception and design. SC, JR, JW, and JM: develop driving simulation. JW and JM: data collection. JM and SC: analysis and interpretation of results. SC, JM, JW, and VS: draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Effects of Traffic Calming Measures on Mobility, Road Safety and Pavement Conditions on Abuakwa-Bibiani Highway

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Traffic calming measures (TCMs) have been widely adopted as the major speed control devices in Ghana. While initial evaluations have underscored their effectiveness, little research has been conducted to assess their characteristics relative to design guidelines as well as the negative externalities associated with their misapplications. The objectives of this research were to; (i) establish the characteristics of TCMs, and their implications on mobility; (ii) to establish essential speed parameters in communities where TCMs are deployed (iii) to establish pavement conditions abutting traffic calming measures and; (iv) to analyse the accident typology on the Abuakwa to Bibiani road. Firstly, a radar gun and android speed measuring device were used to unobtrusively measure vehicles' spot speeds and speed profiles, respectively, at different locations relative to the TCMs. Also, visual inspections were carried out to assess the pavement conditions surrounding the TCMs while a geodetic laser leveling instrument and a surveying staff were used to obtain the crown heights of the TCMs. Further, the accident typology on the candidate road were analyzed to establish how the TCMs are affecting road crashes. Vehicle speeds were generally lower than the posted speed limits in settlements which have TCMs. Nevertheless, the proportion of accident casualties being pedestrians despite lower speeds in settlements remains unacceptably high. Further, the collision typology on this highway were predominantly loss control and rear-end accidents suggesting that the TCMs are playing insidious roles in some of the crash types on this road. Pavement distresses such as depressions, cracks, rutting, raveling, potholes and deposit of debris were common in the vicinity of the TCMs. Our findings suggest that awareness creation among communities along the highway may be amenable to improving pedestrians' safety than relying on only engineering countermeasures. The predominant collision types; *loss control* and *rear-end* implies that the TCMs are inadvertently contributing to some accident types. For a long term and sustainable speed control, bypassing settlements, use of active dynamic speed bumps (smart or intelligent speed bumps); and a deterrence-based electronic enforcement such as the *Automatic Number Plate Recognition System* which uses the demerit points offer better alternatives on the highways.

**Keywords: traffic calming measures, speeding, speed bumps, speed humps, speed tables, enforcement**

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## BACKGROUND

Traffic calming is an important technique of speed control aimed to improve upon road safety. The term traffic calming may be defined as *the combination of physical measures that reduce the negative effects of motor vehicle use, alter motorists' behavior and improve conditions for non-motorized road users* (Hallmark et al., 2007, p. 3). Traffic calming devices such as speed bumps, speed humps and speed tables are common in Low-Middle Income Countries (LMICs) as well as many High Income Countries (HICs). For instance speed calming measures are used in the USA (Tester et al., 2004; Hallmark et al., 2007; Parkhill et al., 2007); Italy, (Galante et al., 2010); Lithuania (Jateikiene et al., 2016); Peru (Donroe et al., 2008); Egypt (Bekheet, 2014; Abdel-Wahed and Hashim, 2017); and Cameroun (Sobngwi-Tambekou et al., 2010). In many settings, traffic calming measures (TCMs) are predominantly used in residential streets. Conversely, these devices are used on highways, arterial roads and residential streets in Ghana, thereby presenting an ominous challenge to motorists and passengers.

The application of traffic calming procedures are necessitated in Ghana because of poor enforcement in a country where speeding is pervasive (Damsere-Derry et al., 2019). Along the inter-urban highways in settlements where traffic calming devices are absent, over 90% of vehicles exceed the posted speed limit of 50 km/h (Derry et al., 2007; Damsere-Derry et al., 2008). The situation has endangered pedestrians' life along inter-urban highways in Ghana, with pedestrian fatalities constituting over 40% of all road deaths in Ghana (Building Road Research Institute, 2018).

The predominant types of speed calming measures being used in Ghana include speed tables, speed humps and speed bumps. Unless otherwise stated, traffic or speed calming measures or devices in this context refer to speed bumps, speed humps and speed tables. A speed hump, table or bump is considered as a raised area in the road pavement extending transversely across the entire travel path (Parkhill et al., 2007). Characteristically, what distinguishes a speed bump from a hump or a table are their dimensions. Generally speed bumps, humps and tables have different designs and applicability. Speed tables are flat-topped with a height of 76–90 mm and a travel length (width) of 6.7 m (Parkhill et al., 2007). They are usually implemented on residential collectors and not used on emergency or bus transit routes. Marked speed tables for pedestrian crossing is referred to as "raised crosswalks." Though the Ghana Highway Authority (GHA) does not provide any guidelines for their implementation, speed tables are among the commonest traffic calming devices in Ghana. However, among the three devices being discussed here, speed bumps produce the most substantial discomfort to vehicle occupants when traversed upon at a higher speed and can cause damage to vehicle suspensions the most. Due to their abruptness, speed bumps use is restricted to parking lots and private roads (Parkhill et al., 2007).

The types of traffic calming measures used two decades ago in Ghana were characteristically smaller and shorter than what are being used today. They were made of asphaltic and thermoplastic materials and were respectively 10 and 5 cm high (Bawa, 2005). These diminutive TCMs are called rumble strips rather than the current speed bumps, humps and tables being used in Ghana today. Ostensibly, the earlier TCMs built in the late 1990s and early 2000s did not pose much challenge to pavements, motorists and passengers yet they alleviated pedestrians' injury risks.

The Ghana Highway Authority's design guideline specifies that for a circular hump and desired speed of 50 km/h, a maximum crown height of 7.5 cm is ideal and that any height beyond 10 cm may cause damage to vehicles (Ministry of Transport, 2007). Speed humps are typically implemented on residential and local roads (Parkhill et al., 2007) but in Ghana, they are deployed everywhere. The guidelines are usually based on the speed limit, community request, functional classification or traffic volume of the road. For example, the Department of Transportation in Virginia, USA bases implementation of traffic calming measures on Average Daily Traffic (ADT) >4,000 vehicles per day. Non-physical traffic calming measures such as education and enforcement are recommended where ADT is between 600 and 4,000 vehicles per day (Hallmark et al., 2007). Further, the Delaware Department of Transportation do not recommend speed humps for expressways, freeways, principal and minor arterials, and major collectors. Speed tables (raised crosswalks) are not recommended for freeways and principal arterial roads in that state. On lower road hierarchy, speed tables may be used when the ADT is <10,000 vehicles per day and the posted speed limit is <60 km/h (Hallmark et al., 2007, p. 61). It is therefore, not proper to allow local communities to build their own speed calming devices without any reference to specifications and traffic conditions.

Evaluation of traffic calming devices in Ghana has shown that these devices have life-saving potentials on pedestrian safety as they reduce vehicular speeds significantly (Bawa, 2005; Afukaar and Damsere-Derry, 2010; Damsere-Derry et al., 2019). People living in settlements without any traffic calming measures on the Ghanaian highways are two times more likely to die from vehicle-pedestrian collisions compared with people living in communities which have these devices (Damsere-Derry et al., 2019). Therefore, speed tables, humps and bumps are considered as *the crème de la crème* speed control countermeasures in Ghana. This is because perhaps, the road authorities have not tried other alternative speed calming measures. There has not also been any appraisal of the negative externalities of TCMs such as noise, platooning, safety for car occupants and health implications of vehicle occupants.

In view of their apparent effectiveness, every community along the highways in Ghana is clamoring for speed calming devices. When communities feel that their lives are endangered by speeding vehicles and their requests for traffic calming measures are not forthcoming, the people construct these devices by themselves (GNA, 2013, 2018; Anane-Amponsah, 2018; Ultimate FM, 2018).

In the wake of these challenges like platooning, noise, safety for vehicle occupants and damage to vehicles, some countries have developed alternative approaches of speed control. Firstly, active speed bump (Actibump) or smart traffic calming measures are being used as a better alternative to the traditional speed humps and tables. They are deployed on roads to contribute to

modern and sustainable urban development by using innovative traffic systems for human centered communities Endeva. (n.d). Actibump is an active dynamic speed bump which is activated only by vehicles exceeding the speed limit. Evaluation of these traffic calming devices indicated that not only are they capable of reducing speeds and pedestrian injuries but they also reduce noise and air pollution typically associated with traditional traffic calming measures (Nilsson, 2015; Al Haji et al., 2018). Secondly, deterrence-based countermeasures appears to bring about a more lasting behavior change (Ritchey and Nicholson-Crotty, 2011; Watson et al., 2013) than the physical devices that are merely perfunctory. However, in Ghana and many developing countries, enforcement by the police has failed to a large extent due to pervasive corruption (Starr FM, 2015; The Chronicle, 2015; Aburam Korankye, 2019). Mexico, which also records high level of corruption among the police has deployed smart speed bumps (Aburam Korankye, 2019).

Every road is built with a design life in mind. When the design life—the maximum number of years the road is expected to function elapses—the road is said to have reached its terminal condition. At this point, the road needs to be reconstructed or else deterioration will set in. However, certain natural, constructional and operational conditions like overloading, quality of the road pavements and environmental factors such as flood, poor drainage and temperature fluctuations can cause pavements to deteriorate prematurely (Hatmoko et al., 2019). In this research, it was assumed that conditions like overloading and environmental factors which can cause road pavements to deteriorate prematurely are constant for the entire road section investigated.

The objectives of this research were 4-fold: (i) Firstly, to establish the characteristics (i.e., density, spacing, heights, and traverse distances) of traffic calming devices relative to design guidelines and their suitability on trunk roads; (ii) secondly, to determine pavement conditions abutting traffic calming measures (iii) to establish speed parameters i.e., approach, speed on humps, speed between humps and operating speeds and; (iv) to establish the accident typology on the Abuakwa to Bibiani road in Ghana.

# METHODOLOGY

## Study Site and Period

The Abuakwa-Bibiani road is a section on the *Inter-Regional Road 5 (IR 5)*. It originates from Abuakwa in the Ashanti Region and stretches for 221 km to Osei-Kwadwokrom on the Ghana-Côte d'Ivoire border. The road section studied originates from Abuakwa (Km 0) to Bibiani roundabout (km 78.2). It is an important road linking one of the most important breadbaskets of Ghana, the Western North Region feeding a large marketing center, Kumasi and beyond. The road is a single carriageway for the entire length with an asphaltic pavement. It also has a lane width of about 3.5 m wide and an average shoulder width of 2.0 m. The road was constructed in 2004 and is in a fairly good motorable conditions except for a few localized potholes. Some of the road furniture is however damaged or missing in many places and require replacement. The road has many traffic calming devices in the settled sections. During the period 2013–2018 for which accident records were retrieved and analyzed, the TCMs on this road were typically speed bumps, speed tables and speed humps. They were made of pavement bricks, asphaltic and concrete materials and were either used alone or in conjunction with others. There were also illegal Traffic calming measures in some communities composed of sand, stones and logs. Field data such as vehicle speeds, road distresses counts and characteristics of speed bumps were taken in June and July, 2018.

## Approach

A 1-day reconnaissance survey was first carried out on the research road to familiarize researchers with prevailing conditions on site. The preliminary visit guided researchers on how to design the field sheets, identify the appropriate equipment and personnel that will be needed for the study. The initial site visit took place in May, 2018.

During the main site visit, visual inspection of pavement distresses and counts were carried out by the research team led by a Principal Highway Engineer. At each location, the team inspected the speed calming measures and their immediate surroundings to ascertain whether there were any visible pavement distresses such as rutting, raveling, evidence of patching, depressions, cracks, potholes etc. Also, the pavements surrounding the traffic calming measures were inspected to find out whether there were hazards like loose gravels and drainage problems evidenced by the accumulation of debris or water in the vicinity of the traffic calming devices. The differences between road distresses and hazards within the 1st and 10th m upstream and downstream within the TCMs vs. those within the 11th and 20th m upstream and downstream from the TCMs were determined.

In addition to visual inspections, field measurement was carried out to determine the basic characteristics of the speed calming devices. Physical measurements carried out included heights, widths, and intervening distances between speed calming measures within each settlement. Crown heights were measured with a geodetic laser leveling instrument and a surveying staff. Staff readings at the base and crowns of the speed calming devices were recorded from which the mean height was determined. These recordings were repeated at two (2) points along the devices and averaged. In relation to the widths (travel lengths), measurements were taken with a tape measure or a plumbed staff depending on convenience. A cyclometer was used to measure the intervening distances between the speed calming devices.

Where necessary (specifically, with the speed bumps) which were constructed in groups per location, an additional measurement representing the thickness, of each bump within the set was measured. The type, nature as well as the predominant materials of construction of each speed calming measure were also noted.

Three different types of spot speeds and the speed profile of each settlement were unobtrusively measured using radar speed guns and android speedometers, respectively. The procedure for the unobtrusive spot speed measurement have been described in detail in an earlier report (Derry et al., 2007) and summarized herein. By this procedure, the research vehicle was parked off

the traffic stream and researchers measured all the vehicles' spot speeds from within the research vehicle using handheld speed guns. This approach was adopted to prevent motorists from seeing that their speeds were being measured. The research vehicle also run through all the settlements as the lead vehicle and the android speedometer used to measure the speed profiles.

Firstly, spot speeds for various locations of the settlements i.e., approach speeds, speed on traffic calming devices and speed between the traffic calming devices were measured using radar guns. This was done to establish the impact of the devices on vehicle speeds, the manner motorists approach settlements as well as maneuver on the speed calming measures. Secondly, the operating speeds in the settlements, from gate to gate, were measured by an android supported speedometer.

## Accident Analysis

Five most recent years' (2013–2018) road crash statistics were retrieved and analyzed for the Abuakwa-Bibiani Highway. This data are stored in a software called the Microcomputer Accident Analysis Package (MAAP) which was developed by Transport Research Laboratory, UK. The key variables analyzed were collision types and road environments stratified by casualty injury severity.

## Settlements

The major settlements along the research route were Bibiani, Nkawie-Toase, and Nyinahin. These settlements are all district capitals. The remaining settlements were small villages; i.e., with population <5,000 inhabitants. Many of the vehicles which typically traverse the settlements are more likely to be inter-urban travelers rather than local traffic. Nkawie-Toase is about 11 km away from the start-point Abuakwa-Sunyani junction. It is a twain town which forms a conurbation with the Kumasi Metropolis. Nkawie-Toase and Nyinahin are both important farmers' markets where foodstuff vendors from Kumasi and neighboring cities buy their produce.

# RESULTS

## Observations

Generally, construction of the traffic calming measures was retrofitted into the existing pavement. It was observed that the construction materials were mainly asphaltic, concrete or pavement bricks or a combination of these. In total, 57% of the construction materials consisted of asphalt only, 33% concrete and pavement bricks, 7% concrete only, and 4% asphalt and concrete. Twenty-five illegally constructed speed bumps were present in some communities. The illegally constructed speed humps were usually made of lateritic and clay materials which lacked signage and posed hazard to motorists. The illegal devices also spread considerable amount of sand, gravels and stones on the roads. On some parts of the pavement, screws, bolts and nots fallen off from vehicles were common near speed bumps. These parts are suspected to have dropped off from vehicles which have low ground clearances due to constant crouching with traffic calming measures too high for their passing. It was also observed that the speed calming devices did not have reflective coating. Therefore, night-time travelers may not see them thereby posing danger to motorists.

## Characteristics of Traffic Calming Measures

### Density of Traffic Calming Measures on the Study Road

There were 75 "authorized" and 25 "unauthorized" speed calming measures along the 78.2 km stretch of road. Therefore, a density of 1.3 units of bumps per kilometer was typical on the research road.

### Heights of Traffic Calming Measures on the Study Road

The mean crown height of the "legal" traffic calming measures along the Abuakwa-Bibiani road was 9.9 cm high with the means ranging between 5 and 18 cm depending on type. Generally, as shown in **Table 1**, the mean crown height of 5–6 cm was typical of speed bump predominated settlements like Sepaase, Afari, and Mim while mean crown height of 10–18 cm was typical of speed humps or table dominated towns like Nkawie-Toase, Bibiani, Kwanfifi, Akorabukrom, and Anyinamso. In Nkawie-Toase township, the heights of the speed humps range between 14 and 25 cm. A one-sample mean comparison $t$-test shows that the mean for all the "authorized" traffic calming measures ($M = 9.9$cm, $SD = 5.95$); was significantly higher than the Ghana Highway Authority's recommended height of 7.5 cm, $t_{(74)} = 3.5$, $p = 0.0004$. Also, a one-sample mean comparison $t$-test shows that the mean speed humps at Nkawie ($M = 18.2$cm, $SD = 3.22$) and that of Bibiani ($M = 16.80$, $SD = 7.46$) were significantly higher than the GHA's recommended height of 7.5 cm, $t_{(12)} = 11.98$, $p < 0.0001$, and $t_{(4)} = 2.79$, $p = 0.0255$, respectively. It is important to stress that speed bumps are not supposed to be deployed on public roads. Due to their steep slopes and the discomfort they bring about to motorists, bumps are mainly recommended for parking lots and private roads. The fact that speed bumps are being used on arterial roads and highways in Ghana leaves much to be desired. In many cases, speed bumps were in duplicates, triplicates or quadruplicates rendering maneuvers on them uncomfortable and dangerous.

### Intervening Distances Between Traffic Calming Measures

The mean intervening distances between two successive speed calming measures along the research road was 222 m compared with 250 m as recommended by Ghana Highways Authority There were however variations between settlements. For instance, the least intervening distance of 100 m was measured at Mpasatia Junction and the maximum spacing of 453 m was measured at Anyinamso as shown in **Table 1**.

## Speed Distribution

### Mean Speed

As illustrated in **Table 2**, the mean vehicular speeds at the outskirts were generally lower than the recommended speed of 80 km/h and the posted speed limit of 50 km/h in settlements.

**TABLE 1 |** Characteristics of speed calming measures on Abuakwa-Bibiani road.

| Location | Mean distances and heights | | |
|---|---|---|---|
| | Spacing (m) | Width (m) | Height (cm) |
| Sepaase | 141.18 | 2.94 | 6.14 |
| Mim | 146.78 | 2.40 | 5.71 |
| Afari | 114.60 | 2.32 | 5.25 |
| Afari Hospital | 104.35 | 1.42 | 6.00 |
| Nkawie Toase | 163.69 | 3.75 | 18.19 |
| Mpasatia | 100.00 | 2.65 | 6.33 |
| Anyinamso | 453.00 | 3.75 | 14.00 |
| Serebuoso | 176.00 | 2.42 | 5.00 |
| Kentenkyire | 247.00 | 2.73 | 5.50 |
| Kwanfinfi | 340.00 | 2.80 | 16.50 |
| Nkrumah Nkwanta | 177.00 | 2.75 | 5.00 |
| Agogoso | 340.67 | 3.29 | 10.75 |
| Akentenso Nkwanta | 166.00 | 2.83 | 6.50 |
| Nyinahin | 234.88 | 2.86 | 8.67 |
| Akorabourkrom | 208.00 | 3.75 | 16.50 |
| Otaakrom | 248.00 | 3.75 | 11.33 |
| Baniekrom | 260.00 | 3.75 | 14.50 |
| Bibiani | 377.75 | 6.06 | 16.80 |
| Overall average | 222.16 | 3.12 | 9.93 |

This is potentially due to the spill over effects from nearby TCMs. In all, 1,656 spot speeds of vehicles were unobtrusively measured 60% of which occurred in settlements and the remaining 40% took place at the approaches of settlements. The mean approach speeds ranged between 50 and 70 km/h at the outskirt precincts of settlements along the highway. Contiguous settlements such as Otaakrom, Baniekrom, and Bibiani registered much lower mean approach speeds of 25–40 km/h.

The main reasons accounting for lower mean speeds at these locations were that on the Kumasi approach, there was a police checkpoint while on the Bibiani city approach, there was a roundabout and the town center where human activities were dense. The Kumasi approach to Agogoso and the Bibiani to Nkrumah Nkwanta approaches had recorded mean speeds $<$10 km/h since they were both situated at police checkpoints where vehicles had to come to a complete stop for police checks before moving forward.

### Speed on Traffic Calming Measures

Generally, many motorists came to a near or complete halt when they came upon traffic calming measures on the Abuakwa to Bibiani road. The mean speed on traffic calming measures generally range from 9 km/h to the highest of 27 km/h on speed calming measures. The predominant TCMs along the road corridor were speed bumps. Though speed bumps are smaller than humps and tables, their speed reducing capabilities are the most drastic. This is due to the unforgiving angles that speed bumps have on motorists compared to humps and tables, see **Table 2**.

### Speed Between Traffic Calming Measures

As shown in **Table 2**, the mean speed in between the TCMs in the settlements ranged from 20 to 47 km/h. These speeds are notably lower than the posted speed limit of 50 km/h and signify that vehicles and pedestrians can safely interact. However, the jolts experienced by motorists and passengers implies comfortability in mobility is compromised.

### Operating Speeds

Just like the spot speeds, the speed profiles along the settlements were considerably below 50 km/h, the speed limit specified for settlements along the research road. The only exception to this finding was Anyinamso where the operating speed was 55 km/h (see **Table 2**) because the spacing in that settlement was about half a kilometer apart.

## Pavement Defects

There was at least, one type of pavement distress in the vicinity of the traffic calming measures or another. In many instances, multiple pavement distresses were found at one location. **Table 3** illustrates the net counts of pavement distresses near the TCMs relative to their immediate surroundings. Specifically, the net road distresses and hazards within the 1st and 10th meter upstream and downstream within the TCMs vs. those between the 11th and 20th meter upstream and downstream from the TCMs were determined. In all locations, the number of road distresses and hazards near the TCMs were higher than those further away. The net road distresses are illustrated in **Table 3**.

As shown in **Table 3**, the single most prevalent pavement distress identified was raveling which constitute about 29% of all the road deteriorations identified followed by depression 20%. There were evidence of poor drainage problem and accumulation of soil and debris which constitute 18% of the pavement problems identified.

### Distribution of Accident Types and Severity Along Abuakwa-Bibiani Highway

As illustrated in **Table 4**, over 80% of all casualties emanated from rear end and ran off road collisions which all together resulted in over 43% of all fatalities during the period of research. Pedestrian collisions constituted over 14% of all injury related victims but 37% of all the road fatalities.

As shown in **Table 5**, over 90% of road accident casualties occurred in settlements; 82 and 11% occurring in village and urban settings, respectively. Further, 87 and 10% of all fatalities occurred in village and urban settings, respectively. It is important to stress here that these accidents occurred in settlements where the vehicle speeds were measured.

## DISCUSSION

The use of TCMs on the Abuakwa-Bibiani road is very widespread. In Ghana, communities usually request or construct these devices when their kinsmen are knocked down by motorists (Anane-Amponsah, 2018; Ultimate FM, 2018). At Taviefe-Avenya community in the Volta Region for instance, the youth erected unauthorized speed humps with sand, stones

**TABLE 2 |** Distributions of vehicle speeds on Abuakwa-Bibiani Highway.

| Location | Predominant TCM | No. of TCM | Operating speed | Speed distribution | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Bibiani approach | Kumasi approach | On hump | Between humps | 95% confidence interval |
| Sepaase ($n = 107$) | Bumps | 7 | 29.6 | 61.3 | 60.5 | 18.8 | 31.2 | 26.3–30.7 |
| Mim ($n = 112$) | Bumps | 7 | 21.2 | 64.1 | 63.0 | 16.2 | 26.9 | 16.2–24.0 |
| Afari (80) | Bumps | 4 | 25.2 | 57.0 | 69.8 | 20.8 | 29.0 | 22.3–26.1 |
| Afari Hospital ($n = 150$) | Bumps | 3 | 25.1 | 61.6 | 49.5 | 27.4 | 33.3 | 29.1–32.5 |
| Nkawie Toase ($n = 158$) | Humps | 13 | 28.7 | 51.0 | 54.7 | 17.8 | 31.6 | 23.5–27.9 |
| Mpasatia Junction ($n = 68$) | Bumps | 3 | 50.2 | 70.3 | 62.0 | 9.2 | 22.5 | 44.3–56.1 |
| Anyinamso ($n = 90$) | Humps | 3 | 54.5 | 59.3 | 52.8 | 10.1 | 40.8 | 43.0–50.6 |
| Serebuoso ($n = 74$) | Bumps | 3 | 28.7 | 61.8 | 60.3 | 11.2 | 46.0 | 49.0–57.0 |
| Kentenkyire ($n = 60$) | Bumps | 2 | 34.5 | 55.0 | 55.0 | 9.4 | 46.3 | 41.8–50.4 |
| Kwanfinfi ($n = 57$) | Bumps | 2 | 40.4 | 62.4 | 57.0 | 12.0 | 30.8 | 41.9–52.9 |
| Nkrumah Nkwanta ($n = 58$) | Bumps | 2 | 36.3 | – | 62.0 | 13.2 | 46.9 | 44.7–52.9 |
| Asibe Nkwanta ($n = 54$) | Bumps | 2 | 37.4 | 68.1 | 65.5 | 18.6 | 34.5 | 29.0–38.0 |
| Agogoso ($n = 80$) | Humps | 4 | 36.2 | 61.5 | – | 9.7 | 34.8 | 38.7–47.3 |
| Akentenso Nkwanta ($n = 56$) | Bumps | 2 | 36.2 | 68.5 | 68.7 | 14 | 31.7 | 43.6–50.0 |
| Nyinahin ($n = 150$) | Bumps | 9 | 37.8 | 57.5 | 67.5 | 11 | 37.2 | 43.6–50.0 |
| Akorabourkrom ($n = 54$) | Bumps | 2 | 48.9 | 47.6 | 48.3 | 9.6 | 35.1 | 37.9–45.9 |
| Otaakrom ($n = 68$) | Bumps | 3 | 48.2 | 51.6 | 37.3 | 9.4 | 38.4 | 37.1–43.3 |
| Baniekrom ($n = 60$) | Bumps | 2 | 29.1 | 39.5 | 33.8 | 13.2 | 19.8 | 16.2–24.0 |
| Bibiani ($n = 120$) | Speed tables | 5 | 28.5 | 25.5 | 25.3 | 9 | 35.6 | 26.3–30.7 |

**TABLE 3 |** Types of pavement distresses near traffic calming measures.

| Pavement defects | No. | Percentage |
|---|---|---|
| Debris accumulation | 45 | 18 |
| Patching | 38 | 15 |
| Potholes | 18 | 7 |
| Rutting | 3 | 1 |
| Depression | 51 | 20 |
| Cracks | 24 | 10 |
| Raveling/weathering | 72 | 29 |
| Total | 251 | 100 |

**TABLE 4 |** Distribution of casualty injury severity by collisions types on Abuakwa-Bibiani highway.

| Collision types | Casualty injury severity | | | | |
|---|---|---|---|---|---|
| | Fatal | Hospitalized | Minor | Total | Percent |
| Head On | 12 | 35 | 21 | 68 | 9.5 |
| Rear End | 22 | 66 | 57 | 145 | 20.3 |
| Ran Off Road | 18 | 117 | 308 | 443 | 62.0 |
| Hit Parked Vehicle | 2 | 6 | 13 | 21 | 2.9 |
| Hit Pedestrian | 34 | 45 | 18 | 97 | 13.6 |
| Side Swipe | 2 | 14 | 9 | 25 | 3.5 |
| Right Angle | 1 | 3 | 4 | 8 | 1.1 |
| Others | 2 | 2 | 3 | 7 | 1.0 |
| Total | 93 | 288 | 333 | 714 | 100.0 |

and logs after six pedestrians had died from vehicle collisions within 2 years (Anane-Amponsah, 2018). This practice is illegal and definitely poses road safety danger and may prematurely destroy the road pavement. However, when they are not built, pedestrians' life in the communities will be endangered. The question therefore is; why do the road authorities construct highways through settlements only for them to be interspersed with speed bumps, tables and humps? Bypassing settlements will ultimately reduce pedestrians' exposure and improve the liveability of settlements along trunk roads (Damsere-Derry et al., 2008, 2019).

Despite the considerable low speeds and high density of TCMs in the communities on Abuakwa-Bibiani road, pedestrian fatalities still constitute 34% of all casualty deaths and 14% of total casualty injuries. This implies that engineering interventions (TCMs) alone are not sufficient enough to improve pedestrians' safety. Behavioral changes among pedestrians is imperative to complement and minimize pedestrian casualties. This calls for intensive road safety education. One common characteristics of settlements along the research road is that road reservations have not been adhered to. The duality of purpose of the road serving as a *"local street"* and a highway is very evident. Buildings that were exclusively residential near the highway have been gentrified into stalls, shops and offices. Roadside trading along the highway is a common phenomenon which brings hawkers and buyers alike unto the road thereby increasing their exposure to vehicular collisions. Any policy aimed to prohibit

**TABLE 5 |** Casualty distribution by road environment on Abuakwa-Bibiani Highway.

| Road environment | Casualty injury severity | | | | |
|---|---|---|---|---|---|
| | Fatal | Hospitalized | Minor | Total | Percent |
| Urban | 9 | 19 | 50 | 78 | 10.9 |
| Village | 81 | 254 | 251 | 586 | 82.1 |
| Rural | 3 | 15 | 32 | 50 | 7.0 |
| Total | 93 | 288 | 333 | 714 | 100.0 |

trading along built-up areas along the highway will be a road safety benefit.

This research finds that the mean heights of the TCMs were significantly higher than the recommended GHA guidelines. In addition, other TCMs such as speed bumps were being misapplied on the highway. For, speed bumps are not recommended for highways (Parkhill et al., 2007). Nevertheless, the predominant type of TCMs on the Abuakwa-Bibiani Highway were speed bumps. This situation has exacerbated the safety of vehicle occupants as manifested in casualties from rear end and loss control collisions. There were also a number of unauthorized TCMs composing of sand, stones and logs along the highway. Many reports in Ghana have accentuated the impact of traffic calming measures (particularly unauthorized and inappropriate speed bumps) as the cause of road crashes in this country (GNA, 2013, 2018; David Kodjo, 2016; Aklorbortu, 2018; Afavi, 2020; Ghanaweb, 2020). As shown in **Table 5**, over 90% of casualty injuries occurred in either large towns or villages, and **Table 2** shows that the operating speeds in these settlements are low due to the traffic calming measures. For, it has been established that over 90% of motorists exceed the posted speed limit in communities which have no speed calming measures in Ghana (Damsere-Derry et al., 2008). It is therefore plausible to deduce that these traffic calming measures are associated with many of the loss control and rear end collisions. For rear end-collisions, leading vehicles which accost these devices abruptly may be forced to break instantaneously thus creating a conducive environment for closely following vehicles to hit their rears and motorists who cannot stand the unexpected jolts may ran off the road. Reflective paintings and proper signage are vital to alleviate these accident types. Importantly, these devices are not expected to be deployed on the highways though.

Another negative externality of TCMs on the road is the delays emanating from the slowing down effects from the speed bumps. Vehicles come to a complete or near halt when they come upon these devices. TCMs thus, impose two main constraints on transportation. Time dependent transportation services such as emergency responses are adversely affected by the slowing down effects of speed calming measures. Delays in the emergency response vehicles such as ambulances, or fire trucks to incidents may cause deaths, injuries and loss of property (Akowuah and Andoh, 2016; Radio Tamale, 2017; Al Haji et al., 2018; Anane-Amponsah, 2018). In fact, some of the negative impacts emanating from illegally constructed or poorly engineered speed calming measures are the very things they purport to prevent. For example, illegally and improperly constructed TCMs are known to be causing serious spinal injuries among passengers and motorists (Myjoyonline.com, 2016), road injuries, road traffic crash fatalities (David Kodjo, 2016; Aklorbortu, 2018; Afavi, 2020); and ailments such as waist pains, back pains and abdominal pains among drivers of emergency vehicles in Ghana (Akowuah and Andoh, 2016).

Various pavement distresses were also observed at the precincts of the traffic calming measures compared to their immediate surroundings. The construction and use of traffic calming measures appear to have initiated the road deteriorations. The practice of cutting the existing pavement to form the foundation of TCMs disturbs the pavements and set them forth for deterioration. Their construction (obviously not on a highway) should be considered when the road is being built to forestall the pavement destruction resulting from latter construction. Motorists' behaviors such as constant abrupt stops on the upstream and revving at the downstream of the traffic calming measures further weaken the pavement surfaces and accelerate their deteriorations. The rate of deterioration is aggravated when there is poor drainage near the calming devices thus leading to water and debris accumulation on the pavement. In particular, the dirt coating forces the asphalt binder to bond with dust rather than the aggregates thereby initiating raveling.

It is therefore recommended that better options of speed control that protect pedestrians as well as vehicle occupants and do not destroy the road pavement should be explored. Actibumps (active dynamic speed bump) or smart traffic calming measures are new innovations which have been tried and tested as better alternatives to conventional TCMs. Unlike the traditional TCMs which have no consideration for whether the driver is speeding or not, actibumps administer retributive justice to speed compliant motorists by punishing only those speeding. Actibumps' effectiveness has been reported in prior reports (Nilsson, 2015; Al Haji et al., 2018). Actibumps' use is recommended for Ghana as the types of TCMs currently being used are becoming a nuisance rather than road safety devices.

More importantly, deterrence-based countermeasures have been the best option to achieve a long lasting road safety compliance. The deterrence theory proposes that for enforcement practices to deter a proscribed behavior such as speeding, it should be a function of the perceived risk of detection, as well as the perceived certainty, severity and celerity of punishment (Watson et al., 2013). Deterrence-based enforcement has been the reason why speed control measures work effectively in High Income Countries (Ritchey and Nicholson-Crotty, 2011). Demerit points system which aims to disqualify motorists who incessantly violate traffic regulations is a deterrent-based enforcement which will improve motorists' speeding behavior in this country. Nevertheless, the current law enforcement particularly relating to road safety has been largely compromised due to the police overwhelming involvement in corrupt practices (Adu Gyamfi, 2015; Starr FM, 2015). This needs to be changed to ensure that deterrence-based countermeasures on speeding can be effective. The automatic number plate recognition method which uses the demerit point system of

speed enforcement will be a better alternative because this approach will forestall human interference and corrupt practices typically characterized with the manual police enforcement. In some developing countries where police enforcement is equally ridden with corruption, the non-Newtonian fluid speed bumps are used (Schwartz, 2009).

## CONCLUSION

In conclusion, speeding in settlements along the Abuakwa-Bibiani Highway has been successfully ameliorated by using the TCMs. Therefore, pedestrians' collisions attributable to speeding is somewhat alleviated. However, the current proportion of pedestrians' fatality of 34% is unacceptable for a road section with 1.3 TCMs per kilometer. In order to complement the current engineering interventions, road safety education which will inform pedestrians to limit their exposure on the highway may be highly beneficial. Pedestrians should be made aware that the risk of death and injuries is still present even when hit by vehicles traveling at the barest minimum speed. Also, the fact that TCMs are deployed on the highway presents ominous hazards to vehicle occupants. Densities and heights of TCMs on road also reduces efficient mobility and pose safety challenges to vehicle occupants. Therefore, it is recommended that settlements should be bypassed, electronic monitoring using the Automatic Number Plate Recognition techniques will minimize human interference and corruption issues which has ridden manual enforcement in Ghana. Demerit-point based enforcement will instill deterrence into motorists and cause motorists to comply with speed limits. Smart speed bumps (Actibumps) offer better alternatives to traditional TCMs which destroy the road pavements and vehicles.

It is also recommended that this research should be expanded to cover representative road networks in the country to present a comprehensive characterization of the negative externalities associated with the misapplication of TCMs. This may elicit alternative solutions that will improve safety for all road users i.e., pedestrians, passengers and drivers as well as comfort for vehicle occupants and protect road pavement deterioration.

## LIMITATIONS

This research was limited to only a 78.2 stretch out of 221 km long road. Therefore, findings reported herein may not necessarily reflect the entire road network or other roads in the country. Also, the study assumed that other factors such overloading, pavement quality and environmental conditions which could cause roads to deteriorate prematurely were constant for the entire road segment investigated. This may not necessarily be true for the entire road segment. This limitation was somewhat mitigated as equal lengths of the road sections adjoining the TCMs were used as controls for comparison.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

JD-D designed the research methodology and study design, conducted data analysis and literature review and drafted manuscript. RL led the field data collection and took part in peer review. DT assisted in literature review, took part in the field data collection and analysis. SB assisted in designing the study and took part in reconnaissance survey. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Cities

POLICY BRIEF
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# Policies and Interventions to Provide Safety for Pedestrians and Overcome the Systematic Biases Underlying the Failures

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Road transport is failing pedestrians more than other road users. For pedestrians, roads are not safe or improving: Globally pedestrian deaths have increased at nearly twice the rate of other road crash deaths (12.9% increase from 2013 to 2016, vs. a 6.6% increase for other road users). Pedestrians commonly lack safe crossings, safe speeds, and in many locations, footpaths. This paper briefly identifies successes and failures for pedestrian safety, reviews weaknesses, and limitations to actions for pedestrian safety, and identifies barriers to effective action. Barriers include current culture on road usage, victim blaming, under-estimation of the pedestrian crash death problem in particular, and other crash data issues. Advocacy, policies, and actions are recommended to overcome these barriers and to improve pedestrian safety.

**Keywords: pedestrian, speed, speed-crash risk relationship, safe system, road safety management, sustainability**

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## INTRODUCTION

Road crashes kill 1.35 million people and injure up to another 50 million each year (WHO, 2015, 2018). Over 90% of road crash deaths occur in Low- and Middle-income countries (LMICs) (WHO, 2018). Road safety is recognized in the United Nations (UN) Sustainable Development Goal (SDG) 3.6. with a target of halving road crash deaths by 2020. The UN also designated 2011–2020 as the UN Decade of Road Safety and developed the Global Plan for the Decade (WHO, 2011).

The ambitious targets set for the Decade of Action and the SDG target will not be met [Global Network for Road Safety Legislators, 2018; Job, 2018], except perhaps now through the dramatic reductions in road usage and thus risk exposure created by the coronavirus pandemic, COVID-19 (Carrington, 2020; Job, 2020). Nonetheless, there have been clear successes during the UN Decade including a stemming of the increase in road crash deaths. Pedestrian safety is a key limiting factor in the Decade, demanding more specific attention and funding.

Pedestrian safety and amenity are litmus tests of road transport sustainability in cities. Pedestrians are a vital part of the road transport system: for almost everyone road transport journeys begin and end with walking. Public transport via mass transit increases safety with appropriate buses providing dramatically lower rates of death per million passenger-kilometers than cars and especially motorcycles (Sustainable Mobility for All, 2017). Mass transit reduces greenhouse gas emissions (GHGs), increases transport efficiency, and allows for greater inclusion in the system than do less affordable private vehicles, especially in LMICs. Thus, public transport

is a vital part of the delivery of more sustainable transport (defined as safe, green, inclusive, efficient transport: Sustainable Mobility for All, 2017). Public transport requires more walking than private vehicle transport. Therefore, provision of safe public transport must include provisions of safe pedestrian facilities to allow people to walk at both ends of their public transit journey. In addition, walking is an active form of transport helping to address the epidemics of obesity and cardiovascular disease as well as other health issues. By replacing motorized vehicle travel, walking reduces fossil fuel use, GHGs, noise pollution itself a major cause of mental and physical ill-health (Job, 1996; WHO, 2011), and congestion.

## Global Pedestrain Safety Performance

Despite these visible values of pedestrian movement in sustainable transport, despite the urgent need for improvement based on transport being the only sector not to improve in GHGs (Sustainable Mobility for All, 2017), and despite the worsening global road safety situation (Wambulwa and Job, 2019) and the looming failure to meet the Sustainable Development Goal target of a 50% reduction in deaths (except possibly via the travel restrictions and other impacts of disaster of COVID-19: Job, 2020), safe pedestrian amenity is not being developed as might reasonably be expected. Rather, pedestrian safety is deteriorating at a faster rate than road safety for other road users: Analysis of data from the last two WHO (2015, 2018) reports, reveals that the increase in pedestrian deaths is almost double that of other crash deaths (12.9% increase vs. a 6.6% increase). The latest estimate amounts to 850 pedestrian deaths per day globally, and this is an underestimate (see later analysis). Pedestrians have nine times the risk of death of car occupants on a per km of travel basis (Sustainable Mobility for All, 2017).

High-income countries commonly are seeing worsening death rates for pedestrians while deaths for other road user groups decline. In the United States, from 2008 to 2018, pedestrian deaths increased by 41% while deaths for other road users decreased by a modest 7% - a problem which is at least receiving some media and research attention (Chong et al., 2018; Hu and Cicchino, 2018; Baker, 2019). In many high-income countries, pedestrians are an increasing percentage of road crash deaths: In France, pedestrians increased from 12% of road crash deaths in 2010 to 16% in 2016, in Germany the increase was from 13 to 15%, and in Australia 13 to 15% (WHO, 2015, 2018).

# SUCCESS IS POSSIBLE

The failure to reduce pedestrian deaths is not attributable to the absence of effective interventions. Many proven interventions exist, particularly within a safe system context. The safe system approach begins by admitting that humans will inevitably make mistakes and aiming to design, build, and operate a road transport system which accommodates those errors by limiting forces to those which the human body can withstand without causing death or major injury (Belin, 2016; Job, 2018). It has delivered major road safety successes (Carlsson, 2009; Mooren et al., 2011).

For pedestrians the evidence for the need for a safe system approach is compelling. Pedestrians (as well as cyclists and motorcyclists) are less protected than other road users with no surrounding metal shell or airbags, and thus require more accommodation within the safe system. Both drivers and pedestrians inevitably make mistakes which cause deaths and disabilities. Pedestrians include those more likely to make mistakes- children, those with dementia, those who are impaired by alcohol or drugs or distraction, or particular personalities and perhaps even particular socio-economic circumstances (Gorrie et al., 2008; Klaitman et al., 2018; Lucidi et al., 2019). Reliance on improving pedestrian and driver behavior will not deliver a safe system.

Examples of proven successes for pedestrians include basic elements such as provision of footpaths, yet iRAP surveys show that 80% of roads where pedestrians are present do not have usable footpaths (Turner and Smith, 2013). The "Pedestrian Manual" (Bartolomeos et al., 2013, p. 63–65) identifies 18 interventions which are proven to be effective for pedestrian safety, including: signals, footpaths, lighting, speed management through engineering (traffic calming; Job and Sakashita, 2016), and road narrowing (with relevant research in a middle income country showing relevance: Mukherjee and Mitra, 2019), effective laws and enforcement on speeding (Job and Sakashita, 2016), and on drink-driving (Job et al., 1997; Freethy, 2015), improved vehicle standards for pedestrian impacts, and improved post-crash response.

# PEDESTRIANS AND THE UN DECADE

## Effective Actions

The global road safety community and others have advocated strongly for safety of vulnerable road users, and pedestrians in particular [see the International Federation of Pedestrians (2019); Where the walk starts (2019) for advocacy and lists of pedestrian advocacy organizations]. The website of the Pedestrian Council of Australia (2019) begins with a systemic approach couched as: "Safety-Amenity-Access-Health." America Walks (2019) also provides a sound approach with tools for advocacy for systemic change. The International Road Assessment Program, the Global Road Safety Facility, and others have been strong advocates for pedestrian safety, noting the common absence of pedestrian sidewalks where pedestrians are present (iRAP, 2017; Wambulwa and Job, 2019), and the vital role of safe speeds for pedestrians (Job and Sakashita, 2016; Job, 2018). Evaluation of pedestrian risk, provision of footpaths, safe (and specifically speed-managed) crossing facilities, and safe speeds for pedestrians are all integral elements of the guidance for the World Bank's Environmental and Social Framework which recently added requirements covering road safety as part of these "safeguards" (World Bank, 2018, 2019).

Detailed manuals and other documents have been prepared to guide development of safety for pedestrians, including a pedestrian safety manual (Bartolomeos et al., 2013), the National Association of City Transportation Officials (NACTO) (2013) *Urban Street Design Guide*, and the *Safe and Sustainable* guide (Welle et al., 2018).

**FIGURE 1 |** Traffic calming: Narrowed lane and speed humps for a 20 km/h limit on a residential road in Switzerland, and speed tables either side of a pedestrian crossing in Senegal (Source: photos by the author).

**FIGURE 2 |** Speed humps installed by the community: a dirt speed hump in Africa and a rope speed hump in Latin America (Source: photos by the author).

Numerous countries have adopted more of the actions identified above for pedestrian safety including safe speed limits for pedestrians, speed managing infrastructure, and safer amenities for pedestrians to cross-roads (but note limitations of breadth in the next section). see **Figure 1** for an example of road narrowing, speed humps, and a 20 km/h speed limits for a residential street in Switzerland, and speed tables on approach to a pedestrian crossing in Senegal.

## Lack of Effective Action

Despite the advances noted above, the extent of adoption of strong safety policies and infrastructure has been quite limited, especially for pedestrian safety. The limited development of pedestrian safety is readily identified on our global road network almost anywhere. High speed road bisecting cities often are not designed for pedestrians to cross at all except at pedestrian bridges which, if they exist at all, are commonly over 2 km apart, forcing long walks to use them, and often only cater for the most able bodied people; Marked crossing are ignored by drivers in many countries; The vast majority of marked pedestrian crossing points are not supported by speed managing infrastructure in HICs or LMICs; Many points where pedestrians often cross do not have marked crossing [for examples, see Bartolomeos et al. (2013)]; in LMICs most locations where pedestrians walk do not have footpaths (Turner and Smith, 2013).

Speed is so inadequately managed that many people appreciate the relevance of speed to pedestrian safety, want speeds managed in their neighborhoods, and have acted directly to achieve this by installing their own speed humps (for examples see **Figure 2**).

# FACTORS UNDERLYING THE LACK OF ACTION FOR PEDESTRIAN SAFETY

Understanding of the factors behind the global systemic failure to effectively address pedestrian safety and amenity is vital to efforts to overcome the barriers to action and allow better safety improvement.

This systemic failure is, in part, due to many general challenges for road safety, which are only briefly described here, with pedestrian specific issues described in more detail. General challenges for road safety include profoundly the lack of political ownership of the issue. Road safety lacks political salience, which has never been more visible than during the novel coronavirus (COVID-19) outbreak which led to adoption of safer policies such as lower speed limits in order to free up hospital beds for COVID-19 cases. This gives visibility to the acknowledgment that existing speeds are causing serious injuries (and deaths) yet these are not being addressed for themselves until they risk limiting treatment of COVID-19 cases. Related to the lack of political buy-in for road safety, funding is inadequate for the size of the problem, and resources are wasted on ineffective actions (including broad school-based education on road safety and driver training) in place of sound evidence-based opportunities. Perhaps because education and training are recognized as effective in other arenas of life, they are broadly adopted in

road safety despite extensive credible recent and long-standing evidence for lack of effectiveness. A systematic Cochrane Library review of school-based driver training concluded that the results "provide no evidence that driver education reduces road crash involvement and suggest that it may lead to a modest but potentially important increase in the proportion of teenagers involved in traffic crashes." [Roberts and Kwan (2001); see also O'Neill (2020)]. Similarly, negative results have been shown for post-license driver training (Ker et al., 2003) and even motorcycle rider training (Kardamanidis et al., 2010; Ivers et al., 2016). There is one form of novice driver training which does appear to be effective (see Gregersen et al., 2003) which is being adopted in some HICs countries.

Nine key underlying factors of the failure to deliver safety particularly for pedestrians are described below.

First, *the growing benefits of passive safety of vehicles are primarily helping vehicle occupants not pedestrians*. Improvements attributable to stronger regulation and market forces driven by the New Car Assessment Program (Global NCAP) have led to great safety for vehicle occupants, whereas the safety improvement from these developments is much smaller for pedestrians. Although vehicle designs which reduces risk for pedestrians in the event of a crash exist and have been refined over many years (Chen et al., 2020), various high-income countries with otherwise strong vehicles standards for road safety have not regulated for vehicle pedestrian protection.

Second, *the benefits of autonomous braking systems rely on detection, and pedestrian detection may be less effective*. Autonomous braking offers the opportunity to save many deaths and injuries. However, the detection systems on which benefits depend can often miss pedestrians and thus the benefits for pedestrians predicted by advocates are an over-estimate (Combs et al., 2019). It is no coincidence that the first fatality involving an automated vehicle was a pedestrian.

Third, *the growth of 4-Wheel Drive and Sports Utility Vehicles (4WD and SUVs) is harmful for pedestrian safety*. In the United States, Australia, and other countries, the growth of these vehicles has outpaced the growth of cars. SUVs and 4WD vehicles have high fronts which cause more serious injuries to pedestrians in the event of a crash. Thus, the growth of these vehicles is a key cause of the lack of progress on pedestrian safety (Hu and Cicchino, 2018; Keall et al., 2018; Su, 2019).

Fourth, *e-mobility is taking footpaths putting pedestrians at risk*. There are challenges which appear to be increasing for the future of pedestrian safety, and the safety value of the smart city concept is questionable (Lytras and Visvizi, 2018). While forms of mobility such as e-scooters and e-bikes may reduce fossil fuel use and greenhouse gas emissions (depending on from which form of transport they draw customers), they are commonly used on footpaths even where this is not legal (Consumer Reports, 2019) and in some locations are allowed on footpaths legally and banned from roads (Haworth and Schramm, 2019). The use of these vehicles on footpaths erodes pedestrian amenity and compromises pedestrian safety, including crashes between these e-mobility devices and pedestrians (Sikka et al., 2019). More extensive consideration of the safety and amenity compromises of these mobility forms is urgently needed, perhaps including dedicated spaces for e-mobility.

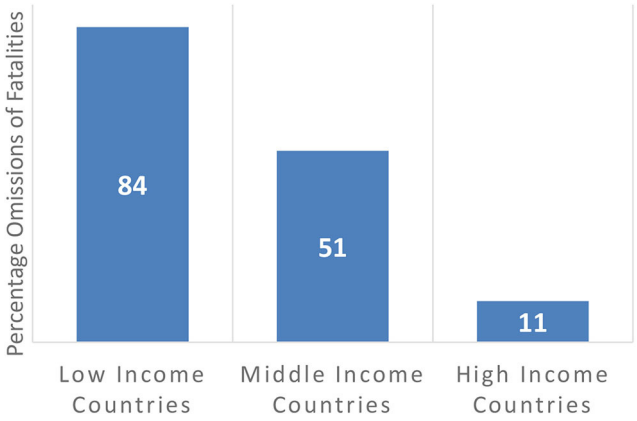


**FIGURE 3 |** Percentage of under-reporting of crash deaths in high, middle-, and low-income Countries compared with WHO estimates [Data from: Wambulwa and Job (2019)].

Fifth, *the extent of pedestrian death and injury is systemically under-estimated*. Under-reporting of deaths and injuries is extensive in many LMICs, as shown by the large discrepancies between official data for countries vs. both WHO estimates and Global Burden of Disease estimates of deaths (see **Figure 3**). The under-reporting of pedestrian crashes is a long-recognized problem (Morrison, 1992), and not yet solved. Most relevant to the current issue is that under-reporting of crashes is systematically biased by crash type, with crashes involving vulnerable road users including pedestrians being less likely to be reported than other crashes of similar severity (Dandona et al., 2008; Kira et al., 2016). Thus, not only is the extent of road crash trauma under-estimated in the official data of most countries, but also the contribution of pedestrian trauma is further systematically (though not necessarily deliberately) under-estimated. The real extent of the pedestrian safety problem is not visible to decision makers.

Sixth, *victim blaming at its worst for pedestrians,* often supported flawed crash data and victim-directed advice. Victim blaming, the tendency to blame those involved in crashes rather than the road system, sustains the old-school focus on road user behavior rather than adopting safe system principles to address the problem. Victim-blaming is well-recognized as a problem in road safety (Museru et al., 2002; Girasek, 2007), including for pedestrians in particular (Job, 2012). The tendency to victim-blaming is exacerbated for pedestrians by two factors. First, it is particularly difficult for police to determine fault in pedestrian crashes which results in systematic bias toward finding the pedestrian at fault. Police face an unenviable task when attending fatal or serious injury pedestrian crashes, if there are no uninvolved witnesses. Often, the pedestrian is dead or seriously injured and thus unable to provide their account of events, whereas the driver is likely to be uninjured and able to provide his/her account. The driver is unlikely to admit that he/she was

speeding or distracted, and likely to claim that the pedestrian darted out. While police may doubt the account, proving it wrong is deeply challenging, especially in countries which do not undertake detailed crash reconstruction. Without a detailed crash reconstruction which may uncover factors such as speeding the driver is unlikely to be charged (Job and Sakashita, 2016). Such crash reconstructions are rare in LMICs which suffer 93% of deaths globally. In these circumstances, pedestrian crash victims are systematically more likely to be seen as at fault. The crash data then invite a second problem: once the pedestrian is seen as mostly at fault, there is a tendency to jump to fix the pedestrians as a solution which drives advocacy for what pedestrians should do as the primary solution. For example, the NHTSA website on pedestrian safety starts with tips for pedestrians on how to be safe, then for drivers on how to drive safely for pedestrians but does not address how to advocate for systemic change, safe pedestrian amenities or lower speed limits (NHTSA, 2019) and a similarly problematic approach is adopted on the US (National Safety Council, 2020) website. These communications, of unknown value in behavior change, are deeply counter-productive to a safe system approach to pedestrian safety, by promoting views which facilitate political obfuscation of responsibility for providing a safe road system.

Seventh, *the focus on increased speed for economic improvement is misleading and costly especially to pedestrians*. Speed is a major determiner of road crashes, injuries, and deaths, with small changes in speed creating large changes in numbers of deaths and injuries (Job and Sakashita, 2016). Speeds can be effectively managed (Howard et al., 2008; Job and Sakashita, 2016). Critically, speeds of impact are a vital determiner of survivability for pedestrians, with risk elevating dramatically even at lower speeds. For example, a recent synthesis identified of a 5% risk of death at 30 km/h, increases to 13% for an impact speed of 40 km/h and 29% for 50 km/h (Hussain et al., 2019). Lower speeds are identified to protect pedestrians from serious injury (Jurewicz et al., 2016). However, commonly speed limit increases are sought on the basis of anticipated economic improvement through reduced costs of travel, and in cities on the basis of anticipated reductions in congestion. Both these expectations are refuted by the data: Increasing speeds increases other costs often not considered, including the costs of crashes, greenhouse gas emissions, vehicle maintenance, and air pollution. When all costs of speed are considered, economically ideal speeds even on open highways are typically substantially lower than the speed limits set and increasing speed limits harms the economy (Cameron, 2003; Elvik, 2009; Hosseinlou et al., 2015). Increases in speeds are shown not to help with congestion and may even make it worse (OECD, 2006), due to the longer headway drivers must leave as speeds increase. Some of the best road safety performing countries are applying 20 km/h speed limits in various residential streets (see **Figure 1** for an example from Switzerland).

Eight, the *road system is not designed to accommodate visibility challenges for pedestrians*. Pedestrians are inherently less visible than other road users because the human body is smaller than the human body plus any vehicle, even a bicycle. Thus, the angle subtended on the retina is smaller. This lower visibility of pedestrians is further compounded by two further factors. First, young child pedestrians are much smaller and especially shorter than adults meaning that they may not be as tall as a typical vehicle or other obstacles on the edge of the road which may obscure a driver's view of them. Second, pedestrians may be less likely to be seen by motorcycle riders moving faster than the rest of the traffic by lane filtering or lane splitting (riding between other vehicles in adjacent lanes), and the motorcycle may be less visible to pedestrians, especially small pedestrians.

Ninth, *pedestrians are not fully considered as part of the road transport system*. In many cities and countries roads are still considered to be for cars, with a prevailing view that pedestrians simply should not be on the roads. Direct evidence for the lack of consideration comes from the inclusion of driver waiting time in economic modeling for road policies and specific decisions such as signal phasing at intersections yet the absence of consideration of waiting time for pedestrians (Job, 2012). Thus, road policy in many high-income countries is determined with the astounding inconsistency that the time of a person waiting in a car has economic value, yet the time of the very same person waiting to cross the road has no economic value.

## DISCUSSION AND RECOMMENDATIONS

Pedestrians are at high risk of death and debilitating injury in road crashes. This paper identifies the neglect of pedestrian safety in the road transport system, despite clear evidence-based solutions, and proffers reasons for this. Strong progress for pedestrian safety depends not only on addressing the broad limiting factors of road safety delivery visible during the decade of action notably including inadequate funding and low political salience, but also depends on countering the identified specific barriers to effective delivery of pedestrian safety. Improvement may be facilitated by bold advocacy for fundamental culture change as well as incremental change. Seven areas of opportunity for change to improve pedestrian safety are suggested to both address the barriers to action and improve safety.

First, as an integral part of the safe system approach applied for pedestrians, managing speeds down is a vital safety intervention for pedestrians as well as all other road users. Speed managing infrastructure, such as speed humps, raised pedestrian crossings which deliver a 20-fold increase in the chance of drivers yielding for pedestrians (Torres et al., 2020), and well-designed roundabouts are the best systemic (and most sustainable) method for managing speeds in urban areas. The narrative for lower speeds must include correcting the mistaken impression that these will increase congestion and will increase total travel costs, as well as advocacy for safe system and demand for political accountability for road safety.

Second, improved data are required to overcome the systematic (though not deliberate) biases in crash reporting and thus data collection. Even if the deeper cultural and economic issues which may underlie under-reporting of pedestrian crashes in particular cannot be overcome, other interim solutions may improve the situation. For example, a dedicated field study in a specific area could determine the level of under-reporting (or the

real ratio of pedestrian to other crashes) and this could be applied as a correction factor to estimate the real extent of pedestrian deaths, injuries, and costs.

Third, strong advocacy and resistance to victim blaming is essential to generating appreciation of the need for safe infrastructure for pedestrians. This may usefully include correcting impressions of pedestrian error as the fundamental cause of pedestrian crashes and highlighting problems with police data on pedestrian crashes, while noting that this is not an attack on police but a recognition of the challenges they face with pedestrian crashes. Advocacy for the safe system approach is also valuable, including the promotion of a focus on the causes of injuries and how to avoid them, rather than a continuing often ineffective focus on causes of crashes *per se*. It is also important that advocacy for pedestrian safety and the roles of NGOs are not reduced to educating pedestrians to be safe, thus facilitating the victim blaming mentality. Instead, the strong promotion of safe system principles for pedestrian safety is required. Many system design interventions exist to improve pedestrian safety, as identified earlier.

Fourth, crash data may also be improved to address the systematic tendency to assign responsibility for a crash to the pedestrian. Stronger allowance for the cause of a crash being recorded as unknown combined with appropriate training may assist to reduce this data bias, allowing for better informed (less mis-informed) advocacy and safety solutions.

Fifth, provision of safe separate amenities for micro-mobility (e-scooters and e-bikes) rather forcing them to share roads with cars or footpaths with pedestrians will avoid the current trend to reduced amenity for pedestrians.

Sixth, road design and roadside furniture might valuably accommodate the visibility challenges of pedestrians, especially the young. Standards which improve visibility include the provision of raised platform crossings which raise the height of crossing pedestrians, curb extensions at crossings, removal of and prevention of roadside furniture such as signs and vegetation which may obscure a pedestrian from the view of an approaching driver, and prevention of parking on the approach side close to pedestrians crossing points.

Seventh, stronger inclusion of pedestrians as acknowledged legitimate road users is required. The old-school roads-are-for-cars mentality must be overcome; pedestrian waiting time must be considered in road design and operation decisions such as signal phasing; and usable pedestrian facilities such as footpaths and safe convenient crossing facilities must be a required standard for roads where pedestrians are present. Strong advocacy for this culture change by NGOs is vital.

With these changes we will move more effectively to address pedestrian safety and thus reap more of the ancillary sustainability benefits of walking and mass transit, including reducing obesity, greenhouse gasses, air pollutions, noise pollution, fossil fuel use, and improved inclusion.

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# Vulnerable Road Users or Vulnerable Transport Planning?

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The concept of vulnerable road users is widely used in transport and road safety discourse. The concept refers to walkers or pedestrians and cyclists (bicyclists and motorcyclists) who are easily injured and killed in a car-dominated road space. Who is really vulnerable: road users or transport planning? This paper subjects the concept of vulnerable road users to a critical analysis. It finds this concept wanting because research and practice show that the real vulnerability lies within transport planning that gives in to influences that are more focused on the needs of motorized transport. The paper proposes the concept of vulnerable transport planning to underscore the fact that transport planning often lacks inclusion and is influenced by forces that favour motor vehicles. This influence leads to omission and neglect of walkers, cyclists, children, persons living with disabilities, the elderly and highway-adjacent communities in transport and land-use planning. A focus on vulnerable transport planning directs research and practice to addressing the root cause of vulnerability rather than concentrating primarily on those affected by this vulnerability.

**Keywords: vulnerability, road users, walkers, cyclists, transport, planning, decision-making**

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## INTRODUCTION

The scientific and practice community continuously generates and promotes concepts and phrases to help in searching for solutions and raising the profile of an issue. Some of the concepts become widespread while others "die" off. In development, it has been observed that there is an impressive landscape of concept constructions, reconstructions and rebuttals (Darkoh and Khayesi, 2009). Chambers (2005, p. 186) describes this changing concept landscape in development as follows: "Additions to the common lexicon of development in the past two decades have been prolific. New words have been added faster than old have fallen into disuse. Some such as integrated, coordinated, planning, and socialism have peaked and passed into decline. Others in the eclectic and perhaps ephemeral language of postmodernism, such as deconstruction, narrative and meta-narrative, text and subtext, have largely languished in academic and literary backwaters. Others, such as equity and poverty, have been robust and resilient. Yet others, some old, some new, which have come close to the mainstream of much development discourse during the past two decades include: accountability, capabilities, civil society, consumer, decentralization, democracy, deprivation, diversity, empowerment, entitlement, environment, gender, globalization, governance, human rights, livelihood, market, ownership, participation, partnership, pluralism, process, stakeholder, sustainability, transparency, vulnerability, well-being."

While concepts and ideas are necessary to shape the world, they can easily reach a status where they are taken for granted (Peet, 2009). Researchers and practitioners sometimes become beholden to concepts and methods without deeply questioning their origin and relevance (Mees, 2009; Peet, 2009). For example, the concept of sustainable development, at the centre of national and international policy discourses, is in fact a contested concept, requiring continued discussion and operationalization by researchers and practitioners (Connelly, 2007; Purvis et al., 2019).

Transport and road safety literature refers to a certain section of road users—walkers and cyclists—as a vulnerable group (see for instance, Mohan, 1992; OECD, 1998; Peden, 2004; Constant and Lagarde, 2010; Institute for Road Safety Research, 2012; Goel et al., 2018; European Commission, 2020; European Transport Safety Council, 2020; PIARC, 2020). While the value of this term in pointing out the dangers that walkers and cyclists face in the road environment is appreciated, it is limited if it is not used along with an examination of the inherent structural neglect and bias of these road users in transport planning. If the term is not contextually applied, it could be used to reinforce the traditional view in road safety that places the sole responsibility of road traffic crashes on individual road users, overlooking other factors related to the design of roads or vehicles (Mohan, 1992; OECD, 1998; Peden, 2004; Institute for Road Safety Research, 2012; European Transport Safety Council, 2020). This way of looking at road safety could easily be used to justify the shifting of responsibility for key omissions and transgressions in transport planning from designers or planners to a group of road users. This paper subjects the concept of vulnerable road users to a critical analysis. It achieves this objective by tracing the origin and use of this concept in transport and road safety research, and then subjects it to a critical analysis within the context of the emergent evidence on where the vulnerability really lies.

## VULNERABILITY IN TRANSPORT AND ROAD SAFETY RESEARCH

Given the extensive use of the word vulnerability and the related words like adaptation and resilience in research and planning (Vogel et al., 2007), a valuable question to answer at this stage is: "What is vulnerability?". As explained by Luna (2018), the word "vulnerability" comes from the Latin *vulnerare*, which means to wound. This explains why vulnerability is commonly used to refer to possibility of being wounded. Essentially, it refers to the fragility of beings and things (Luna, 2018). Assessment and response to vulnerability takes into consideration exposure, susceptibility, resilience and solutions. For example, in the case of flooding, vulnerability arises out of a combination of several physical, social, economic, and ecological factors (Salami et al., 2017). Vulnerability occurs to individuals, ecosystems, institutions and communities at different geographical and administrative units.

Having provided the basic definition and clarification of vulnerability, I now turn to the use of this concept to refer to a group of road users. The question to answer at this stage is: "What is the origin and extent of the use of 'vulnerable road users' concept in transport research and practice?". Reference to unprotected road users, who later came to be generally referred to as vulnerable road users, first appeared in literature in the 1950s (Ptak, 2019). The concept continued to be used and clarified in the 1960s, 1970s, and 1980s as research continued into vehicle-pedestrian crashes, focusing on vehicle design for pedestrians, biomechanics of vehicle-pedestrian contact and legislation. Though the concept was increasingly used, scholars like Mohan (1992) argued that vulnerable road users had received less attention in research. The use of this concept has grown over the years and is widely used in publications, conferences, programmes and policies. It is widely accepted that vulnerable road users constitute a disproportionate share of people killed and injured in road traffic crashes at national and international levels (Mohan, 1992; OECD, 1998; Peden, 2004; Institute for Road Safety Research, 2012; European Commission, 2020; European Transport Safety Council, 2020). Analyses move between focusing on one specific category of these road users and merging two or three of them into one category (see for instance, Híjar et al., 2003; Goel et al., 2018).

There are briefings and guidance on the concept of vulnerable road users in form of factsheets, planning manuals, design manuals and position papers (Mohan, 1992; OECD, 1998; Peden, 2004; Institute for Road Safety Research, 2012; European Commission, 2020; PIARC, 2020). There are also sessions in some conferences that are dedicated to the theme of vulnerable road users. While preparing this paper, I conducted a basic search using Google search engine on 12 March 2020 on vulnerable road users, which yielded 53,200,000 hits, which reflected publications, policies, programmes, videos, images, maps and news items on this topic. It was not a systematic electronic database literature search as the interest was in getting a quick overview of the number of hits on vulnerable road users.

But what is meant by the term vulnerable road users? The literature defines them as (Mohan, 1992; OECD, 1998; Peden, 2004; Institute for Road Safety Research, 2012; European Commission, 2020; PIARC, 2020):

- Road users outside the car;
- Those most at risk in traffic; and
- Those unprotected by an outside shield.

Vulnerable road users commonly identified in literature are walkers, bicyclists and motorcyclists. With respect to demographic characteristics and capability, it is argued that some groups among walkers and cyclists are more vulnerable than others. Three groups commonly identified are children, people living with disability (specifically those who use wheel chairs) and older persons.

A logical question from the preceding description is if there is a comprehensive theory or conceptual model of vulnerable road users and vulnerability in transport research. Different theoretical aspects of vulnerable road users are evident in the literature. For example, the relationship between impact speed and pedestrian injury severity has been extensively studied, revisited and refined. Research in the 1990s that was cited extensively showed that pedestrians had a 90% chance of surviving car crashes at speeds of 30 km/h or lower, but less than a 50% chance of surviving impacts at 45 km/h (Pasanen, 1991). There has been a change in this knowledge largely due to the work of Rosén et al. (2011). After correcting sampling and statistical analysis errors in previous research, they found that an adult pedestrian has approximately a 20% risk of dying if struck by a car at 60 km/h (Rosén et al., 2011).

The biomechanics of vehicle-pedestrian crashes has also been conceptualized and studied. This research shows that most pedestrian–vehicle crashes involve frontal impacts. This research

has described fully the sequence of events in a frontal impact, with the starting point assumed to be a standing adult pedestrian who is struck by a car front. A diagram showing the contact points between the pedestrian and the car during a crash has been developed (Yang, 2005).

There has also been a theoretical and empirical analysis of the idea of safety in numbers. A key proponent of this concept is Jacobsen (2003) who argued, based on statistical analysis, that greater numbers of walkers and cyclists improve safety of these and other road users. Subsequent research by Bhatia and Wier (2011) has cautioned against the use of safety in numbers in transport policy and planning dialogue. This caution arises out of inadequate evidence to support a specific mechanism for the safety in numbers effect.

Research also draws attention to planning omissions and decision-making neglect that create vulnerability for walkers, bicyclists and motorcyclists (Vasconcellos, 2001). This issue is discussed in the next section. While this line of investigation sheds light on and alludes to real vulnerability, a political economy model of planning and decision-making in transport has not been at the centre of transport research, which is generally dominated by a positivist model of science (Khayesi et al., 2017). Changes taking place in transport research with respect to analysis of the political economy and governance systems are examined in the next section.

While there is sustained discourse on vulnerable road users, there is limited conceptual rigour in the analysis of vulnerability in the pioneering studies. While an effort has been made to develop and examine models of vehicle-pedestrian crashes and biomechanics, there is a need to critically look at where the real vulnerability lies. Several studies point out that vulnerability of walkers and cyclists largely comes from the way the transport system is approached and designed, highlighting that decision-making and practices favour motorized transport over walking and cycling (Burrington and Thiebach, 1995; Monheim, 2003; Mohan, 2008; Stone and Mees, 2010; Whitelegg, 2014; Legacy, 2016). However, some studies continue to refer to walkers and cyclists as vulnerable road users (see for instance, Constant and Lagarde, 2010). Even studies that refer to walkers and cyclists as vulnerable road users point out that deficiencies in road design, vehicle design and transport policies are key in increasing risk for these road users (Mohan, 1992; Tiwari, 2018; European Transport Safety Council, 2020). Why not call out transport planning as being vulnerable?

## REAL VULNERABILITY IN THE PRACTICE OF TRANSPORT PLANNING

In 1896 the coroner who examined the first reported pedestrian death of Ms Bridget Driscoll in the United Kingdom is quoted to have hoped that "such a thing would never happen again" (Wikipedia, 2020). One wishes the coroner's statement had become true. The reality is that this "thing"—death of a pedestrian or a road traffic collision—has happened time and again, several times, not only in the United Kingdom but in other countries as well. It has become a global challenge, with 23% pedestrian, 3% bicyclist and 28% motorized two- and three-wheeler deaths of the estimated 1.35 million road traffic deaths every year (World Health Organization, 2018).

An important contributor to "such a thing would never happen again" happening time and again is the neglect of walkers and cyclists in transport planning and decision-making (Monheim, 2003; Whitelegg, 2014; Soltani, 2017; Vasconcellos, 2017). For instance, after assessing urban transport planning in Brazil, noting the exceptional case of Curitiba, Vasconcellos (2017, p. 19) observes: "Nonmotorized transport modes have never been taken very seriously in Brazilian transportation planning. No city can claim to have a high-quality sidewalk network, and while bicycles are heavily used in smaller cities…they have never received proper attention." He indicates that there are only a few cities, especially in the south, that have invested in bicycle infrastructure (Vasconcellos, 2017). Soltani (2017) provides an in-depth assessment of urban transport planning in Iran. He describes how cities like Isfahan and Shinaz had public realms suitable for walking and socializing. He contrasts this nostalgic past with the modern Iranian cities that have been invaded by cars. He reports that walking is not formally recognized as a travel mode in most contemporary transportation masterplans in Iranian cities. Soltani (2017, p. 142) concludes his assessment by observing: "In recent decades, Iranian cities have relentlessly pursued policies in favour of car use. Car-oriented planning policies have shaped cities in which people need to drive tens of kilometres to reach their destinations. Urban life has become inconvenient for many people without a car."

Automobile dependent transport planning is a complex system consisting of ideas, practices, infrastructure, institutions and individuals. As explained by Urry (2004), automobility is a powerful complex constituted through technical and social interlinkages with other industries, car parts and accessories; petrol refining and distribution; road-building and maintenance; hotels, roadside service areas and motels; car sales and repair workshops; suburban house building; retailing and leisure complexes; advertising and marketing; urban design and planning; and various oil-rich nations. It is a self-producing system, leading to path-dependent lock-in for society (Urry, 2004). Growth in motor vehicles and related industries, which started in high-income countries, has spread to the rest of the world. Whereas the car confers accessibility benefits to individuals and society, it also dishes out costs such as pollution, congestion, crashes and urban sprawl (Ewing, 1997; Stead and Pojani, 2017). It is while planners and decision-makers attend to the needs of motorized transport that they neglect walkers and cyclists.

Neglect of walkers and cyclists in transport planning and decision-making occurs at several levels (Vasconcellos, 2001; Marden and Reardon, 2017):

- The baseline assessment and design stage which largely relies on the four-stage transport and landuse planning model and its extensions or improvements that focus on collecting and analyzing data related to motorized traffic with limited attention to travel behavior of walkers and cyclists.

- Political decision-making stage to allocate financial and human resources in which the transport researcher and planner are least involved, and prioritization is based on weighing several competing needs from transport and other sectors.
- Execution, monitoring and evaluation stage in which the omissions introduced at the assessment stage are realized if there is no intervention from the public consultation, and review within transport or pressure groups to correct the situation.

The transport researcher has relatively focused less on studying the reality of transport planning and decision-making, and has largely concentrated on quantitative aspects, which generate useful information (Marden and Reardon, 2017). However, the quantitative tradition, within the technical-rational model, does not provide insights into the dynamics of decision-making and how governance systems within and outside the transport sector shape and sustain the prevailing automobile dependent transport planning.

This situation has been steadily changing over the years, especially with the incorporation of the communicative turn and governance frameworks into transport research. This development is providing an understanding of how the process of transport planning, which seeks to determine, select and implement policies, plans and strategies to ensure movement of people and goods using different land, water and air modes of transport, works and is influenced by several decisions and stakeholders (Whitelegg, 2014; Legacy, 2016; Marden and Reardon, 2017). Examples are cited from this literature in the section that follows to illustrate vulnerability of transport planning.

Insightful examples of the neglect of walkers and cyclists in automobile-dependent transport planning have been investigated and published. For example, Mitullah and Opiyo (2017a) depict the absence of pedestrian paths and cyclist lanes on 18 road corridors in Nairobi, Kenya. While some corridors have facilities for walkers and cyclists, others do not. Overall, the type of infrastructure provided was not uniform and did not fully conform to design principles, coherence, attractivess and comfort. This type of situation is reported in several urban and rural areas in low- and middle-income countries. However, this situation is not limited to low- and middle-income countries. Several cities in the United States of America are described as having been built for the car and not for people on foot or bicycles (Jacobs, 1961). This reality is compounded by a lack of an efficient public transport system in several cities not only in the United States of America but also in Europe and Australia (Stone and Mees, 2010; Whitelegg, 2014).

An example of the influence behind the scenes that gives rise to the observed neglect is given in a study by Flyvbjerg (2002). He gives details about how regulations kept on changing for an environmental and traffic component in a project meant to preserve the character of the historical downtown area of Aalborg. The environment and traffic component sought to radically improve public transportation; enhance environmental protection, develop an integrated network of bike paths, pedestrian malls, and green spaces; and develop housing stock. Vehicle traffic was a major concern in the downtown project and the target was to reduce automobile traffic by one-third in the downtown area. Flyvbjerg (2002), through an in-depth scrutiny and interpretation of archival sources, found out that the chamber of industry and commerce was key in altering the traffic component. It achieved this influence by debriefing the project planning group in the company of the city council technical committee and the police. There are several ways through which automobile industry and related power holders leverage the planning and political systems to create conditions and make decisions favourable to motorized traffic at the expense of walking and cycling. Continued funding and approval of motorized transport and other mega infrastructure projects with overestimated costs is an example of how decision-making sustains automobile dependent transport planning (Cantarelli et al., 2010). Ignoring public inputs into debates and review of a proposed transport project and going ahead to approve its development by politicians is another way by which the powers that be hold transport planning captive to political influences (Legacy, 2016).

One of the effects of vulnerable transport planning is a decline in walking and cycling and an increase in car use, even for short-distance, largely attributed to inadequate attention being paid to walkers and cyclists. This situation partly contributes to health consequences, such as cardiovascular diseases, because of sedentary lifestyle. The vehicle is not the only cause but one of the contributors to sedentary lifestyle. A specific example of decline in walking and cycling is children independent mobility. This aspect refers to the freedom of children to get about in their local neighbourhood without adult supervision (Shaw et al., 2013).

A study conducted in 1990 revealed that, in England, between 1971 and 1990, there was a dramatic decline in children's independent mobility (Hillman et al., 1990). In 1971, 80% of 7 and 8-year-old English children surveyed were allowed to go to school without adult supervision. The study reported that by 1990, the figure had fallen to 9%. Over the same period, in Britain, although the volume of traffic nearly doubled, child fatalities on the roads nearly halved. These findings contrasted sharply with results of similar surveys that were also conducted in the then West Germany in 1990. It was found that German children in comparable areas had substantially higher levels of independent mobility, despite higher levels of car ownership. A follow-up study was conducted in 2010 (Shaw et al., 2013).

The key findings from the follow-up study are as follows (Shaw et al., 2013):

- There was substantial reduction in the independent mobility of primary school children in England since 1971: the proportion of children walking to school dropped from 81 to 63%, while the percentage being taken in cars increased nearly 4-fold (from 9% of primary school children to 34%) and the percentage of children using public transport or a school bus dropped from 9% to 3%.
- The number of English children accompanied by an adult on the journey home from school had increased in 2010 compared with 1971: 86% of the parents of primary school children surveyed in 1971 indicated that their children were allowed to travel home from school alone. This figure had

dropped markedly to 35% by 1990, and further dropped to 25% in 2010.

- Compared to England, in 2010, Germany had 51% points more primary school children allowed to come home from school alone, 30% points more were allowed to cross roads alone and 20% points more were allowed to use buses alone. The gap between England and Germany for the lisence to travel home from school alone also seems to have remained large.

The decline in the children independent mobility is attributed to several factors related to parents, children and the external environment. However, surveys of parents showed that their fear of traffic was the main reason for picking up both primary and secondary school children from school. Parents were concerned about the likelihood of their children being involved in road traffic crashes and this concern affected whether parents would grant their children licence or permission to cross roads (Shaw et al., 2013).

The preceding illustrative examples and a critique of transport planning reveals its vulnerability to consist of prioritizing needs of motorized traffic over walking and cycling in assessment, design, execution and monitoring of transport projects. It lends itself to influences and forces that take its focus away from prioritizing walking and cycling in transport infrastructure development as has been shown in the case of Aalborg city. This study does not go into developing indicators for measuring vulnerability of transport planning. Whereas it is an important aspect to address in concept development, the scope of this paper is in making the case for reframing vulnerability in transport and road safety planning. The theme on indicator development can form the focus of follow-up work.

## WHAT HAPPENS WHEN TRANSPORT PLANNING ADMITS AND CORRECTS ITS VULNERABILITY?

Through leveraging by advocacy groups, researchers, citizens, pedestrians and cyclists to overcome the "vulnerability" label, transport planning often wakes up to admit its vulnerability. For example, liveable streets and placemaking movements have been key in advocating for inclusive transport planning. Some scholars have had to make bold research-supported statements to show that walking and cycling are part of integrated or chain trips. For instance, Hillman and Whalley (1979) went as far as stating a basic principle as the title of their book *Walking is transport*. This emphasis on a basic principle is still relevant today for both walking and cycling for two main reasons. The first reason is because walking and cycling can be used as the only modes of transport for an entire trip for various purposes like going to school or going to work. The second is because these two modes of transport are key for a trip, especially at the beginning and end of a trip undertaken using motorized transport. This second reason is related to the concept of addressing the first and last mile challenge. This concept refers to the difficulty of accessibility and connectivity associated with the beginning or end of a trip between home and the bus stop or a farm and a market centre or a work place and a bus stop or a transport hub and final delivery point (Boarnet, 2017; European Environment Agency, 2020). This short distance, including the trip from home to the garage or parking lot for private car users, is generally not well catered for in transport planning. Ensuring safe, secure and accessible walking and cycling infrastructure and services contributes to easing transition from home or work place to public transport services.

Transport planning is not always on the defensive side. There are occasions and examples of when it admits its vulnerability. Positively, in some cases, transport planning acts to correct its omissions and neglect of walkers and cyclists in decision-making and infrastructure design. For example, the Netherlands, Denmark and Germany have over the years implemented integrated and self-reinforcing landuse and transport planning policies, consisting of provision of separate cycling facilities along heavily travelled roads and at intersections, traffic calming of most residential neighbourhoods, provision of ample bike parking facilities, integration with public transport, traffic education and training of both cyclists and motorists, and promotional cycling events (Pucher and Buehler, 2008; Whitelegg, 2014). This sustained and deliberative transport planning and decision-making effort has resulted in a high level of bicycle use in these three countries, compared with the United Kingdom and United Sates of America that had a small proportion of about 1% of trips by bicycle.

Pucher and Buehler (2017, p. 689) note: "Until recent decades, however, cycling was largely neglected by most European, North American and Australian transport planners and academics, not even considered a legitimate mode of transport, and thus excluded from most travel surveys and studies." This situation is changing following the adoption of cycling infrastructure, policies and programmes implemented in the Netherlands, Denmark, Germany and in other European cities. This policy change is reflected in increasing bicycle mode share as revealed in an analysis of data for 19 cities of Western Europe, North America and South America between 1990 and 2015 (Pucher and Buehler, 2017). While Copenhagen and Amsterdam still showed an increase over their existing high rates, 10% and 12%, respectively, countries that have had low rates showed significant increases, for example, Sevilla (6%) in Spain, Bogota (5%) in Colombia, Buenos Aires (3%) in Argentina and Portland in Oregon (5%) (Pucher and Buehler, 2017). Curitiba, Singapore and New York City have also taken steps related to legislation, infrastructure design and landuse planning to promote walking, cycling and public transport (Han, 2010; Khayesi and Amekudzi, 2011; Chen et al., 2013).

The city of Freiburg-im-Breisgau in Germany is cited as an example of proactive transport planning that has over the years taken transport and landuse planning decisions that have shifted travel from car dependence to other modes of transport (Roorda et al., 2011; Whitelegg, 2014). Examples of decisions and actions taken are development of a bicycle master plan, provision of bicycle parking spaces, pedestrianization of the old town centre, introduction of a 30 km/h speed zone on all residential streets and introduction of a low-cost-flat-rate monthly "environment ticket" for the region-wide bus service (Roorda et al., 2011). These decisions and actions have resulted in significant increase in walking, cycling and public transport trips (Whitelegg, 2016).

**FIGURE 1 |** Walking facilities in Cape Town, South Africa.

For example, in 2016, 29% of all trips was by walking, 34% by bicycle, 16% by public transport, 5% by car passenger and 16% by car driver (Whitelegg, 2016).

On the other hand, there are urban and rural areas in Africa with high levels of walking, but the transport planning and decision-making is yet to meaningfully tap into this encouraging situation. For example, walking is a key mode of transport in Nairobi, Dar es Salaam and Cape Town, constituting 73.7%, 70.3%, and 46.7%, respectively, of all trips undertaken in these cities (Vanderschuren and Jennings, 2017). Bicycle use makes up about 1% of all trips in these three cities in Africa. One would realistically expect that urban transport planning in Africa would prioritize these two modes that are at the centre of sustainable transport policy, but this is not the case. Though non-motorized transport strategies and policies have been developed for Nairobi, Dar es Salaam and Cape Town, their implementation has not been consistent (Jennings et al., 2017; Mitullah and Opiyo, 2017b). There are encouraging steps such as providing pedestrian paths and enforcing traffic laws in Accra, Lagos, Cape Town (**Figure 1**), Addis Ababa, Dar es Salaam and Nairobi but "coordination and strategic movement toward implementing a transformative NMT policy remains a hindrance" (Mitullah and Opiyo, 2017b, p. 202). Cities in Chile, like these African cities, have high levels of walking despite a transport policy that favours motorized traffic. A comprehensive review of literature by Herrmann-Lunecke et al. (2020) reveals the persistence of walking as the most important mode for daily trips in Santiago, constituting 34.5% of all trips. This mode of transport prevails among lower-middle income groups. This persistence is attributed to cultural, environmental, economic, and built environment factors, and not to proactive transport planning policy (Herrmann-Lunecke et al., 2020). The illustrative empirical findings from African and Chilean cities reveal the existence of a virtuous walking virus attributed to socio-economic and built environment factors, which needs to be sustained by a proactive transport planning approach, but this expectation is far from being seen as the authors cited have indicated.

An example of a road safety approach that admits that transport planning is vulnerable is the safe system framework. It advances the view that a change is needed in understanding and assigning responsibility in decision-making and constructing a safe transport system (Belin et al., 1997; International Transport Forum, 2016; Tiwari, 2018). It points out the importance of system designers in delivering a safe transport system. When transport planning fails to consider the needs of all road users and privileges motorized transport, then it is vulnerable in the sense that it is susceptible to rationality and forces that favour automobile dependent transport planning, excluding and neglecting some of the groups it is to serve. This framework argues for system designers to understand and cater for road users with varying physical or human capabilities. It also argues that road users have a responsibility to obey traffic rules. Thus, the decision-making in transport planning becomes vulnerable if it favours one mode of transport over other modes, paying inadequate attention to the tolerance of the human body to injury.

## CONCLUSION

We need to answer a key question as we conclude our learning journey in this study: "Who is truly vulnerable"? Given that it is transport planning that has generally neglected the needs of walkers and cyclists, then the real vulnerability is with this planning system. Hence, it is logical to be talking about vulnerable transport planning rather than vulnerable road users to direct efforts for solutions strategically at tackling the root cause of vulnerability. This study proposes and reinforces the idea that attention should be focused on vulnerability of transport planning instead of primarily beginning with road users, commonly referred to as vulnerable road users, who are essentially victims of neglect and omission in the planning of transport systems. Transport planning vulnerability is a pervasive phenomenon that is situated not only in transport planning decision-making but also in overall interaction of several economic, social, technological and political factors that contribute to automobile dependent transport planning. As we continue to reflect on where the real vulnerability lies, let us remember the words of Juliet to Romeo: "That which we call a rose, by any other name would smell as sweet" (Shakespeare, 2020).

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

## ETHICS STATEMENT

Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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# Preventable Trauma Deaths Rate (PTDR)—Analysis of Variables That Shape Its Value With Patterns of Errors Contributing to Trauma Mortality. Fifteen Years of Experience Based on the Example of a Polish Specialist Regional Hospital

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This analysis is based on a review of 224 out of 323 cases of trauma deaths in Regional Specialist Hospital of Grudziądz during the period of 2003–2017. In this study, we have described and systematized the most common situations resulting in severe personal injury. We then evaluated whether the diagnostic procedures and treatments that were employed were correct. From the objective statistical parameters described, we evaluate the level of quality of emergency medicine and the effectiveness of the integrated medical rescue system. Ultimately, the most significant component is PTDR (preventable trauma death rate). Inspiration for our research came from direct observation of our daily experiences in the ED where we derived great satisfaction from treating patients successfully. More importantly, however, we suffered the severe disappointments of failure that always and inevitably raised the same question: Have we done everything humanely possible to save this patient? In the daily struggle of saving lives, the question always remains: What could we have done differently? Better? More effectively? To answer this question, we have to examine our emergency procedures and activities. Were they correct and effective? This documentation not only shows us a statistical picture of the injuries sustained by trauma victims, but also presents a dynamic reconstruction of events as well as the pathophysiology of dying. When we view all this material as a complete picture, we see that it provides the opportunity to assess the accuracy of judgment, especially during the critical moments of diagnosis and subsequent treatment of the casualties. Not only did we describe the anatomic results of injuries, including rankings to proper regions of the body, we also reconstructed the pathophysiology of dying such as airway obstruction—suffocation, bleeding—exsanguination, or severe complications such as acute respiratory distress syndrome, pulmonary emboli, thrombosis of intracranial

vasculature, and fatal, irreversible organ damage. We checked operating procedures that had been done and those that should have been done to give the patient a chance for survival but were not due to wrong decisions. We have demonstrated that the element of time is critically important in diagnosing and implementing treatment of patients with major injuries; further, we have enumerated the potential complications, time errors, missed injury, and general mismanagement as professional risks for the emergency team: physicians, nurses, and paramedics. We have determined that almost half of all trauma deaths occur within the first 2 days following major injury, with most of those occurring within the first 6 h of hospitalization. The other deaths—"late deaths"—are the result of unsuccessful treatment or the development of complications in intensive care unit. In all hospital trauma deaths the leading causes are severity of brain injury (51%), exsanguination (31%), and asphyxiation (13%).

**Keywords: PTDR, TRISS, traumatic deaths, patterns of errors contributing to trauma mortality, polytrauma, timing and priorites in polytrauma patients, probability of survival of trauma patient**

## INTRODUCTION

A review of world literature concerning traumatology, injury prevention, and organization of treatment procedures of victims of serious accidents and fatalities due to trauma indicates that, at the beginning of the decade 2001–2010, ∼40 to 50% of accident fatalities brought to hospitals with signs of life could have probably been saved.

The results of this research demonstrated the need for creating a safer prehospital admission protocol, improving preparation of patients at the scene of the accident, and improving transport of patients to a reorganized network of hospitals, as well as refining hospital protocols to improve treatment of patients with severe multiple injuries.

Numerous educational and organizational programs have been implemented to create trauma centers and hospital networks cooperating together, as well as attempting to create a registry of accidents and a quality control system for evaluating the three phases of prehospital treatment, transport to hospital, and in-hospital care, that is, implementation of clinical procedures in the emergency department (ED) and in other specialized clinical departments.

Preventable trauma death rate (PTDR) was used as a measure for quality control to compare the effectiveness of various trauma systems operating in different areas and at different times.

Probability of survival is expressed by the indicator PTDR, which is based on the Trauma Revised Injury Severity Score (TRISS) methodology. This is calculated on the basis of the Injury Severity Score (ISS), indicator that describes the anatomical effects of trauma. Revised Trauma Score (RTS) describes physiological dysfunction and takes into account the patient's age and type of injury. This, in turn, is modified by an adjustment coefficient—coefficients B0–B3—and meets criteria for the objective quality indicators (Boyd et al., 1987; Champion et al., 1990; Nast-Kolb et al., 2006). "Coefficients B0–B3 are derived from the Major Trauma Outcome Study, a registry of several thousand trauma patients used to generate predictable adult death rates."

The purpose of this study is to analyze the dynamic changes that occur in PTDR and to describe irregularities that occur in diagnostic and therapeutic processes based on proprietary material collected by Dr. Władysław Biegański in Grudziądz Regional Specialist Hospital during the years 2003 to 2017.

Inspiration for our research came from direct observation of our daily clinical workflow in the ED, where we experienced satisfaction from our successes, as well as the bitterness of our failures and losses. Every time we lost a patient, it raised the same question: Did we do everything possible to save the patient?

This article investigates the most common mechanisms that cause serious injuries and carries out a retrospective analysis of the accuracy of diagnostic and therapeutic procedures that were implemented with regard to omissions and errors that have been committed, the degree of severity of the injuries, and the probability of survival of the trauma patients evaluated with respect to the relevant scales of posttraumatic AIS/ISS, RTS, and TRISS.

The period of early death is the time interval in which emergency medicine must perform. Execution must be swift, decisive, and accurate, consistent with the latest achievements in science and in the art of medicine to reduce mortality, morbidity, and suffering and the degree of disability due to injury. The level of emergency medical care and the efficiency of the emergency medical system itself are best evidenced by quality indicators. Of critical importance is the rate of avoidable deaths (Boyd et al., 1987; Champion et al., 1990; Esposito et al., 1995; Kunihiro, 2005; Chiara et al., 2006; Saltzherr et al., 2011; Kim et al., 2012; Seong et al., 2015; Jung et al., 2019).

**Abbreviations:** PTD, traumatic deaths to avoid; PTDR, the rate of posttraumatic deaths to avoid; AIS, ISS, RTS, commonly used in traumatology scales and indicators of the severity of injuries; TRISS calculation, scientific methodology for severe injuries, which allows calculation of Ps and PTDR using statistical methodology based on the collective, multicenter epidemiological studies of victims of serious accidents.

## MATERIALS AND METHODS

To answer this question, we have to analyze our emergency procedures and activities. Were they correct and effective? The most important information we have is what we have learned from the deaths of accident victims. This information not only shows us a statistical picture of the injuries sustained by trauma victims, but also provides a dynamic reconstruction of events, as well as the pathophysiology of dying. When all this material is viewed as a complete picture, it provides the opportunity to assess the accuracy of judgment, especially during the critical moments of diagnosis and treatment of the casualties. The study is based on a review of 224 of 323 cases of trauma deaths in Grudziądz Hospital during the years 2003 to 2017. The study includes only those patients for whom we have complete medical records, including autopsy examinations.

Not only the anatomic consequences of injuries have been described by assigning rankings to proper regions of the body, but also the pathophysiological changes they caused such as choking, bleeding, or severe complications such as acute respiratory distress syndrome (ARDS), thromboembolism, and fatal, irreversible organ damage.

Descriptions are provided of operating procedures that had been done, as well as those that definitely should have been done for patients in critical condition to increase their chances for survival. The study of autopsies provides a clear, kaleidoscopic image of major trauma patients and enables us to assess fairly the correctness of diagnostic and treatment processes.

The study defines the frequency of pneumothorax, hemopneumothorax, hematoma, and damage to the heart and major systemic vessels. It further emphasizes the importance of the reduction and stabilization of fractures of the pelvis in order to control retroperitoneal hemorrhage caused by these fractures.

In assessing the effectiveness of treatment of trauma patients, it is also important to take into consideration "the identified errors in the delivery of care," which are included in the following factors:

1) Time factor—delay in implementing ATLS due to delay in reaching out to accident victims or prolonged lapse of time between the occurrence of an accident until implementation of highly specialized procedures in the ED.
2) Failure to comply with standards of ED parallelism in diagnosis and treatment.
3) Irregularities/errors involving unresolved or delayed diagnosis of life-threatening conditions: airway obstruction, traumatic internal bleeding, intracranial hematoma, pneumothorax, and pericardial tamponade.
4) Irregularities/errors involving incomplete diagnosis related to oversight of a seriously injured organ at different stages of diagnosis and treatment, as well as the associated delays in commencing surgery: for emergency laparotomy or thoracotomy: emergency time greater than 2 h; for emergency craniotomy: emergency time greater than 4 h.
5) Lack of quick and efficient diagnostic procedures as well as using improper methods to transport patients safely within the hospital who are either unconscious or unstable.
6) Lack of decisiveness and competence among the treatment team in not applying the principle of more "aggressive treatment" for patients in critical condition.
7) Lack of proper coordination between the members of the "trauma team" and the absence of a decision-making leader.
8) Lack of an "on-call operating room," which is in constant readiness and designated exclusively for emergency procedures.
9) Lack or shortage of medical equipment and other necessary hospital services: laboratory diagnostics, imaging, blood bank.

The study employs the widely used TRISS methodology, based on RTS and Abbreviated Injury Scale/Injury Severity Score (AIS/ISS) to assess the probability of survival, Probability of survival of trauma patient (Ps), and PTDR, the rate of preventable trauma deaths.

TRISS formula removes subjective impact on the calculation of the rate of Ps and locates the deaths identified as definitely to avoid—DP ratio above 0.50 Ps; PP, possible to avoid between 0.25 and 0.5 Ps; and NP, unavoidable below 0.25 Ps. TRISS calculator simplifies complex mathematical calculations; DP, determination to avoid; PP, probably inevitable, unavoidable **NP**; **PDR**, definitions: *preventable death rate is the proportion of the deaths judged to be preventable if optimal trauma care has been delivered.*

**Trauma deaths defined as preventable need to meet three criteria**

1) The injuries produced by trauma and its sequelae must be survivable.
2) The care that has been delivered must be suboptimal when compared with standards.
3) The identified errors in the delivery of care have contributed directly or indirectly to the patient's outcome.

Traditionally, we use the following classification of deaths to avoid: DPD—definitely preventable death–definitely avoidable, if treatment of the injury is done by conventional methods in a facility with standard equipment. PPD—possible preventable death, death may be avoided if the injuries are severe but curable in the present state of medicine, provided that the patient goes immediately to a highly qualified treatment center having the highest standards of knowledge and art of medicine, where he/she receives appropriate treatment within a suitably short period of time. NP—non-preventable death, death is inevitable because of mortal injury, incurable in the present state of knowledge. This group includes each patient with a score of 6 on the AIS scale for even one of the six body regions; this injury is definitely fatal (Boyd et al., 1987; Champion et al., 1990; Bose and Tejwani, 2006; Chiara et al., 2006; Gao et al., 2006; Gruen et al., 2006; Shen et al., 2006; Stanescu et al., 2006; Seong et al., 2015).

We evaluated 71 variables including the mechanism of injury, the nature of the injuries, pathophysiological changes that they caused, and the time of the accident, as well as the time it takes for medical rescue operations and procedures of clinical emergency medicine to begin, errors in diagnostic and therapeutic procedures, survival, the leading causes of death, and early- and late-stage complications. The study used statistical analysis to examine the relationship of selected criteria among the patients who were observed.

The study uses statistical analysis to examine the dependence of PTDR on the observation time of patients as well as on other selected criteria.

The study of PTDR variability over time was calculated by specifying this parameter as a function of time. The PTDR (i) designates the PTDR calculated for the first (i) patients. This approach makes it possible to study the dynamics of PTDR changes over time. Comparison of PTDR in two predominant groups is accomplished by comparing PTDR changes within these groups. The statistical significance of PTDR decline (variance) is examined by testing the significance of the appropriate simple regression form: PTDR $= A\ t + B$, where $A$ and $B$ are coefficients determined on the basis of patient data; $t$ is observation time (in practice, this count represents the sequential order of patients). In the groups of patients analyzed, it was shown that $A < 0$. This means that PTDR decreases as observation time increases.

## RESULTS

The results of this study emphasize the key moments in the decision-making process of diagnosis and treatment and make it apparent that the art of healing is subject to adverse events, which are a part of the professional risks for physicians, nurses, and paramedics.

We have shown that pneumothorax and intracranial hematoma are dynamic processes that can appear at any stage of posttraumatic injury.

Nearly half of all trauma deaths occurred within the first 2 days following major injury, with most of those occurring during the first hours of hospitalization. The other "late deaths" are the result of complications during treatment in intensive care unit (ICU).

The primary causes of late deaths are mostly multiorgan failure (MOF) and sepsis. Autopsy studies have shown that pneumonia, as a result of ventilator-associated ARDS, accounts for 34% of trauma deaths, and thromboembolism accounts for 6% of trauma deaths.

In the material presented, other significant causes of death were early bleeding (30%) and asphyxiation (12%). However, the leading cause of all deaths in hospital was the severity of central nervous system (CNS) damage (50%).

Every fifth trepanation/craniotomy was performed too late, when raised intracranial pressure was present. In every seventh fatal accident, a laparotomy of the victim was necessary but overlooked and not done, or was done too late, resulting in significant damage.

In light of the autopsy findings, our persistent and prolonged struggle for survival of patients in the final stage of the disease who due to changes in venous sinus thrombosis and autolysis of the brain along with irreversible organ damage in the course of the MOF had no chance of survival turned out to be ineffective and doomed to failure.

In 33% of trauma deaths that occurred while patients were in hospital, severe brain injury as a result of high-energy impact contributed to the patients' demise.

In 66 patients with CNS injuries (40%), we found no fracture of the skull despite serious injury to the brain.

Pedestrians struck by cars were the largest group of fatalities. The fourth largest group was due to falls—from one-story or down a flight of stairs. Deaths due to criminal assault cover the eighth rank of victims. The most common combination of injuries was head, chest, legs, and pelvis injuries.

Quite often as many as 26% of deaths of injuries were attributable to hemopneumothorax or pleural hematoma with pulmonary contusion. Fourteen percent were for rupture of large systemic vessels and/or the heart. In every fifth patient, there was damage to abdominal organs. Pelvic fracture with retroperitoneal hematoma was found in one-sixth of the dead, but the stabilization of the fracture of the pelvis with associated retroperitoneal hemorrhage was performed sporadically. In one-fifth of the deceased, surgery was not performed or was not performed early enough.

Cranial trepanation or craniotomy was the most frequently performed surgery−108 treatments. This large number is a result of the enormous number of head traumas; CNS damage was found in 70% of fatalities. Respirotherapy subjects were 170 patients or 76%, and the majority of them died due to pulmonary complications: ARDS, pneumonitis, and pulmonary emboli. Intracranial hematoma was not recognized in 10 (4%) and pneumothorax in 13 (6.0%) patients.

In 4% of patients, autopsy revealed aspiration of gastric contents into the airways. In one-third of the deceased patients, rescue action and emergency procedures were delayed in excess of the golden hour; they relate to different stages in the chain of survival.

In 21% of mortalities, the source or intensity of bleeding site had been underestimated. Multiorgan failure and/or sepsis was the cause of every fourth trauma-related death. They were the primary cause of late death. Pleural drainage was as common a procedure as laparotomy (42 vs. 39 cases) and twice as frequently as fusion of the long bones. A thoracotomy was performed intermittently 4 cases (2%). However, it was indicated in 15% of cases if we include repair procedures that would have been done on an injured heart and major vessels. However, the patients were being delivered to the hospital in a moribund state, and the procedures were beyond the capabilities of a local hospital. In the majority of chest injury cases going to surgery, there was sufficient drainage of the pleural cavity.

Below we present results of our research in numbers and percentages (**Table 1**).

**Early and late deaths:** Early deaths <24 h: $n = 70$ (31%), >24 but <48 h: $n = 20$ (9%), late deaths >48 h: $n = 134$ (60%).

**Anatomical areas of the body with known injury:** head $n =$ 185 (83%), thorax $n = 102$ (46%), abdomen $n = 52$ (23%), limbs and pelvis $n = 67$ (30%), others $n = 12$ (5%).

**PTDR in period of 2003–2017:** period of 2003–2006 PTDR = 30/54 (55%), period of 2007–2010 PTDR = 19/56 (34%), period of 2011–2015 PTDR = 25/84 (30%), period of 2016–2017 PTDR = 7/30 (23%).

**Type of injuries:** only one region injuries $n = 105$ (47%), multiregion injuries $n = 119$ (53%).

**TABLE 1 |** Mechanism of injury.

| Traffic accident* | | | | | Fall from a standing position or a flight of stairs | Fall from a height | Criminal causes—homicide | Brain injury with cranial fracture | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Yes | No |
| a = 32 | b = 22 | c = 38 | d = 9 | e = 11 | 61 | 17 | 28 | 100 | 66 |
| 15% | 10% | 17% | 4% | 5% | 28% | 8% | 13% | 60% | 40% |

*a, car driver; b, passenger; c, pedestrian; d, motorcyclist; e, cyclist.

**Anatomical Effects of Injuries**

1. Fatal CNS damage, $n = 75$ (33%)
2. Ribs fracture without edema and/or pneumothorax, $n = 30$ (13%)
3. Multiple rib fracture with pneumothorax and hemothorax, $n = 59$ (26%)
4. Pulmonary contusion, $n = 60$ (27%)
5. Major systemic vessels and heart rupture 30 (14%)
6. Abdominal injuries 46, $n =$ (21%) (damage is usually found according to cited order: liver, spleen, mesenterium of small intestine, and the small intestine)
7. Pelvic fracture with retroperitoneal hematoma, $n = 38$ (17%)
8. Long-bones fracture, $n = 43$ (29%)
9. Spinal fracture, $n = 19$ (8%).

**Operative Strategies of Injured Patients**

1. Craniotomy/trepanation of the skull, $n = 108$ (48%)
2. Drain of pleural cavity, $n = 42$ (19%)
3. Thoracotomy, $n = 4$ (2%)
4. Laparotomy with corrective surgery, $n = 39$ (17%)
5. Fusion of long bones, $n = 16$ (8%)
6. No surgical procedure, $n = 49$ (25%)
7. Respirotherapy, $n = 170$ (76%).

**The Most Common Early Complications**

1. Bleeding, $n = 64$ (29%)
2. Asphyxiation, $n = 27$ (12%)
3. Irreversible trauma shock, $n = 64$ (29%)
4. Subtentorial and tonsillar herniation, $n = 76$ (34%).

**The Most Common Late Complications**

1. Suffocation due to pneumothorax and tension pneumothorax during respirotherapy, $n = 5$ (2%)
2. ARDS + pneumonia ventilator, $n = 76$ (34%)
3. Intracranial thrombosis and brain self-destruction, $n = 30$ (13%)
4. Neuroinfection accompanying CNS injury, $n = 10$ (4%)
5. MOF + sepsis, $n = 64$ (31%).
6. Pulmonary embolism, $n = 14$ (6%).

**Most Common and Most Serious Adverse Events**

1. Unrecognized pneumothorax, $n = 13$ (6.0%)
2. Unrecognized source or intensity of bleeding as well as underestimated, $n = 43$ (19%)
3. Aspiration of gastric contents into the respiratory tract, $n = 8$ (4%)
4. Late craniotomy (trepanation of skull), $n = 49$ (22%)
5. Late laparotomy or needed laparotomy was not done, $n = 27$ (12%)
6. Delay in rescue operations—exceeding the golden hour, $n = 73$ (33%)
7. Unrecognized intracranial hematoma, $n = 10$ (4%)
8. Injury beyond the capabilities of the local hospital, $n = 11$(4%).

**Leading Causes of Deaths**

1. Severity of CNS injury, $n = 115$ (51%)
2. Bleeding, $n = 62$ (31%)
3. Asphyxiation, $n = 28$ (13%)
4. Diagnostic errors—a failure to recognize significant damage or incorrect assessment of the severity and extent of damage, failure to recognize the serious complications in the course of treatment, $n = 46$ (20%)
5. Late complications during treatment in the ICU, $n = 103$ (46%).

## MONITORING THE EFFICIENCY OF THE STATE EMERGENCY MEDICAL SYSTEM IN TRAUMA USING PTDR

The PTDR analysis revealed a significant statistical decline in value during the period under consideration, indicating a substantial improvement in the merits of the State Emergency Medical System.

**Figure 1** shows the dependence of PTDR on the patient number and observation time using a simple regression to describe this relationship. In the initial phase, PTDR shows significant fluctuations, but after some time, these fluctuations decrease. The simple regression equation is: $\text{PTDR} = -0.00071\,t + 0.527406$. The relationship of the examined data is statistically significant at a significance level of $p < 0.0001$. The correlation coefficient is equal to $r = -0.70$.

A joint effort significantly improved the rate of preventable trauma deaths from 55% in 2003–2006, to 34% in 2007–2010, to 30% in 2011–2015, and 23% in 2016–2017.

The analysis of PTDR volatility demonstrated a statistically significant decline in its value during the specified time period,

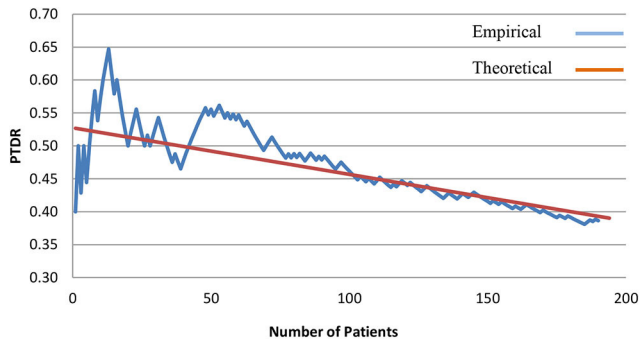


**FIGURE 1 |** The relationship between empirical and hypothetical PTDR from patient numbers.

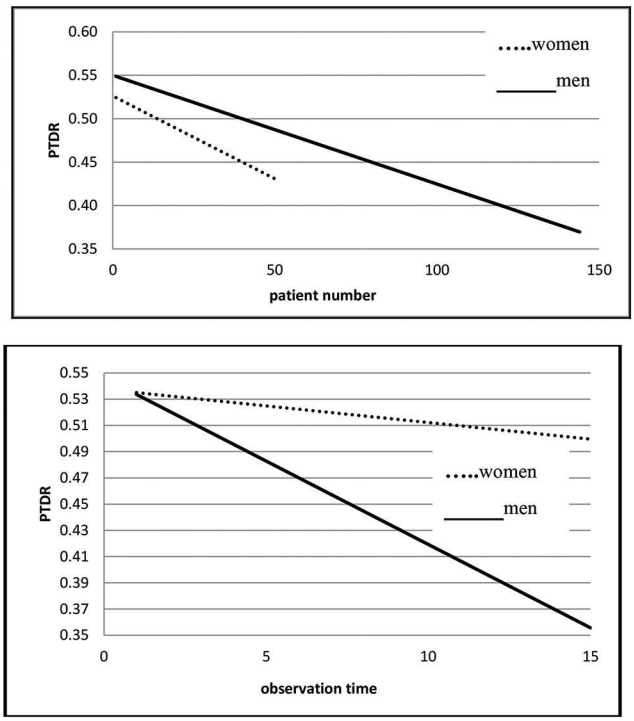


**FIGURE 2 |** PTDR relationship for women and men.

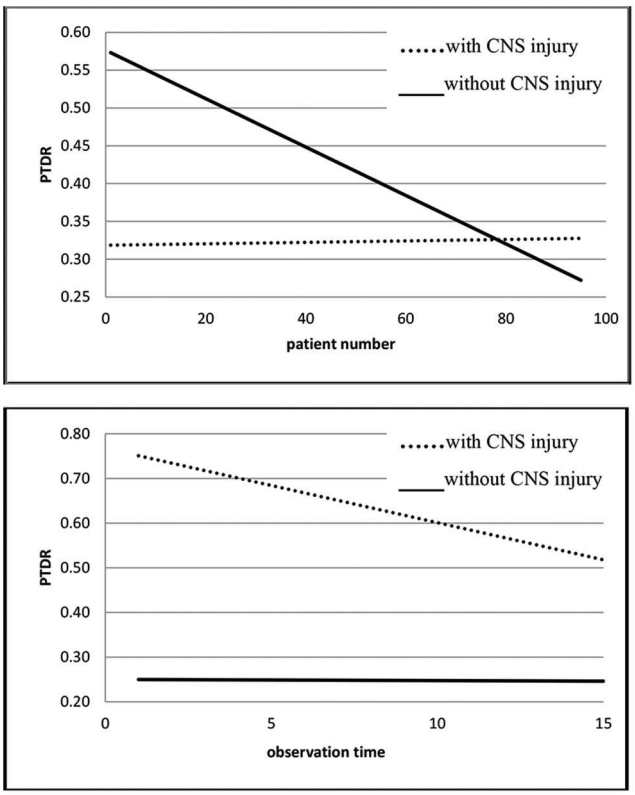


**FIGURE 3 |** The relationship of PTDR rates for patients with and without CNS injury.

indicating a substantial improvement in the quality of the PRM (State Emergency Medical) system. Progress in reducing the rate of avoidable trauma deaths during the study period is particularly evident among men in the subgroup classified as early deaths within the larger group including diagnostic errors and bleeding. The foregoing relationships were presented in the form of statistical models.

## PTDR Gender Dependence

The number of women (58) in the study is three times smaller than the number of men (166).

The decrease in PTDR is slightly higher for men than for women in the period studied. The simple regression as a model of decline for women is almost statistically insignificant ($p = 0.045$, $r = -0.28$), whereas for men, the linear model captures the nature of time dependence very well ($p < 0.0001$, $r = -0.68$). A decrease from 0.55 to 0.39 was noted in the study period.

**Figure 2** presents simple regression charts for gender.

### Comment

Men are, predominantly, the victims of traffic accidents and criminal activity—beatings. The decrease in PTDR is most evident in the group of people with multiple injuries associated with the above accidents. This group comprised mostly men.

## PTDR Variability Dependent on the Occurrence of CNS Injuries

For CNS = 1, the regression line is statistically constant ($p = 0.44$, $r = -0.08$). For CNS = 0, the decrease in PTDR is significant ($r = -0.78$, $p < 0.0001$), from 0.57 to 0.24 (0.26 in the model). **Figure 3** shows the PTDR waveform for CNS = 1 and CNS = 0.

### Comment

For patients with CNS injuries, PTDR is statistically stable throughout the study period. The causes for lack of progress in reducing the rate are complex.

Early deaths are typically the result of delayed rescue operations: calling the ambulance too late, delay in performing

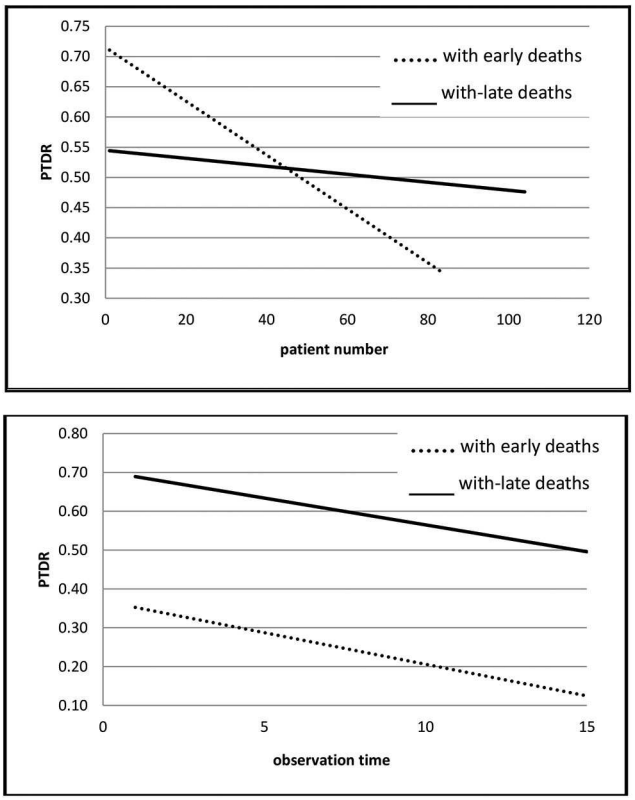


**FIGURE 4 |** PTDR relationship for patients with early and late deaths.

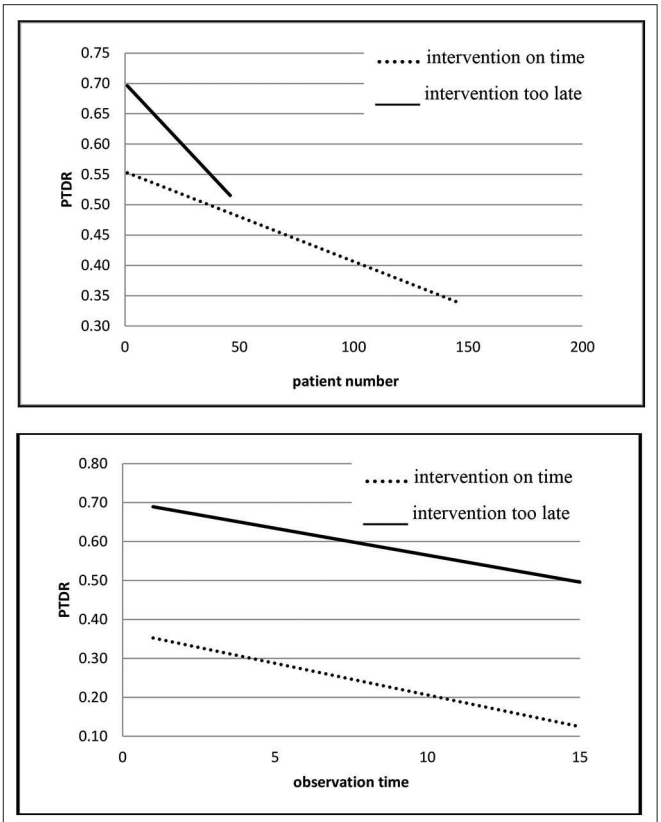


**FIGURE 5 |** PTDR relationship for patients in groups with and without too late intervention.

diagnostic and therapeutic clinical procedures such as computed tomography scan of the head, intubation and respiratory therapy, and surgery—skull trepanation/craniotomy. Previously, there was intussusception and debarking, resulting in death. This applies especially to people who were brutally beaten, under the influence of alcohol and psychoactive substances, as well as to older people, most often living alone in single-level homes who experience falls from a low height—often downstairs—and sustain head injuries.

In contrast, late deaths among ICU patients with CNS injuries are due to severe septic complications, neuroinfections, venous sinus thrombosis, and brain necrosis.

For patients with CNS injury, PTDR rate remains constant throughout the study period. Once again, causes for lack of progress in lowering the rate are complex.

## Early and Late Deaths

The decrease in PTDR for early deaths is significant ($p < 0.0001$, $r = -0.88$) and varies from 0.72 to 0.38 (0.35 in the model), whereas the decrease for late deaths is "minimally" significant ($p = 0.025$, $r = -0.22$). For late deaths, the decrease dropped from 0.54 to 0.4 (0.47 in the model).

**Figure 4** illustrates the course of simple regression for early and late deaths.

### Comment

The marginally significant decrease in the PTDR rate for late deaths in the ICU is related to numerous lethal complications that occur during ICU treatment that determine the patient's outcome. Patients who have received highly specialized medical assistance during emergency procedures in the early phase after an accident are more likely to survive than a patient treated in the ICU during the late phase in the presence of MOF.

This barely significant decrease in PTDR for late deaths in the ICU is due to numerous fatal complications. A patient is more likely to survive when receiving treatment during the early phase after an accident.

## Late Intervention

For both groups, late intervention and no intervention, a significant decrease in PTDR is observed. In the group with delayed intervention, there is a decrease from 0.7 to 0.54 (0.52 in the model) and is significant ($p < 0.0001$, $r = -0.59$).

**Figure 5** illustrates the course of the regression for instances of late intervention and interventions carried out without delay. In the group without late intervention, there is a decrease from 0.56 to 0.33 (0.34 in the model) and is also significant ($p < 0.0001$, $r = -0.26$).

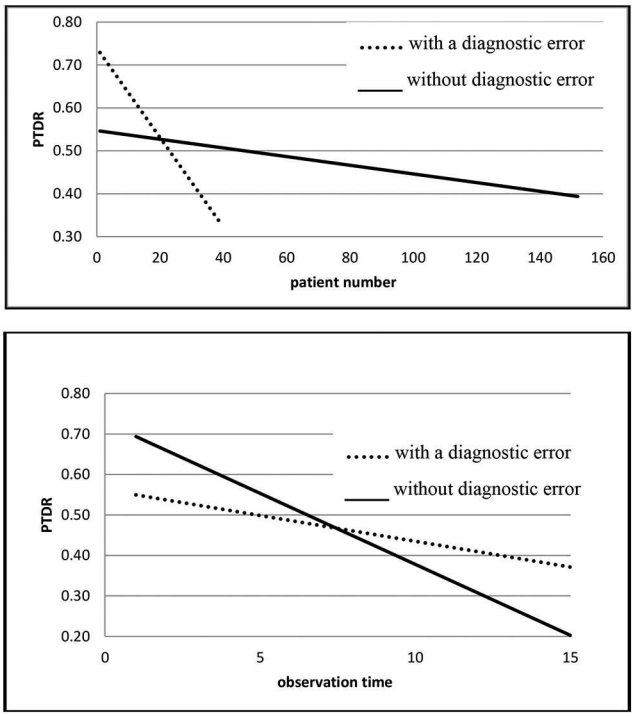


**FIGURE 6 |** PTDR relationship for patients in groups with and without diagnostic error.

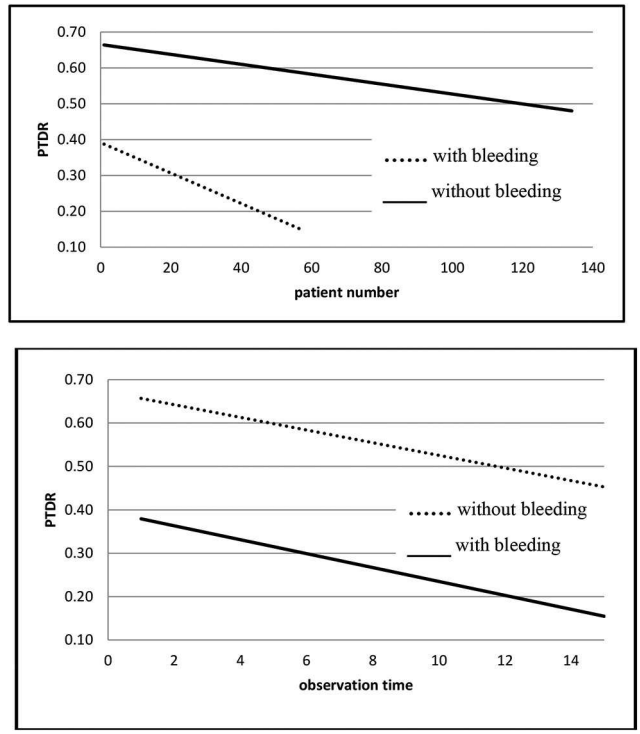


**FIGURE 7 |** PTDR relationship for patients in groups with and without bleeding (exsanquination).

### Comment

The late intervention group managed to lower PTDR by improving the performance of the trauma patient treatment system. However, the fact that there is a delay in transport, emergency medical operations and emergency medicine clinical procedures still determine the high terminal value of the indicator.

A lower PTDR rate was achieved by improving the performance of the system treating trauma patients in the late intervention group. Notwithstanding delays in transport, emergency medical activities, and clinical procedures, emergency medicine still continues ultimately to determine the high value of the indicator.

For quality, late intervention has been able to lower PTDR by improving the performance of the trauma patient treatment system.

## Diagnostic Errors

For both groups: with and without diagnostic errors, a significant decrease in PTDR was observed. In the group that had diagnostic errors, the decrease is significant ($p < 0.0001$, $r = -0.78$), from 0.76 to 0.33 (in the model 0.33), whereas in the group without diagnostic errors, a significant drop is also observed ($p < 0.0001$, $r = -0.66$), from 0.56 to 0.33 (0.39 on the model).

**Figure 6** illustrates the relationship between instances where errors were found and those where they were not found.

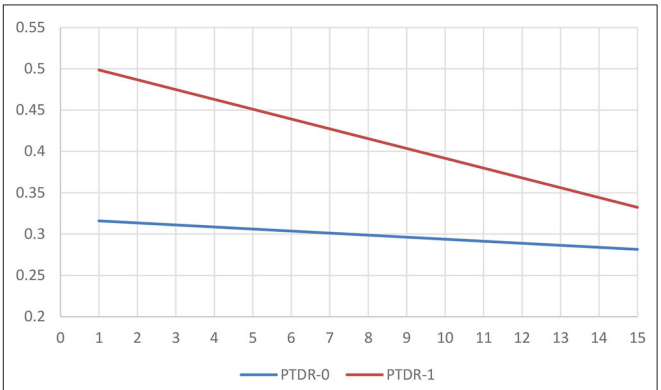


**FIGURE 8 |** Late complications.

### Comment

Where the cause of high PTDR was due to diagnostic errors, measures were taken to eliminate them by introducing new standards and procedures to achieve better results—a lower PTDR—rather than for cases where death was determined by factors other than errors.

## Bleeding

For both groups, bleeding and no bleeding, a significant decrease in PTDR is observed.

In the bleeding group, a significant decrease is observed ($p < 0.0001$, $r = -0.62$), from 0.4 to 0.2 (0.15 in the model), whereas in the non-bleeding group we have a significant decrease ($r = -0.56$, $p < 0.0001$), from 0.66 to 0.48 (0.48 in the model).

**Figure 7** contains graphs of PTDR showing the relationship between bleeding and absence of bleeding.

### Comment

Patients with bleeding showed a significant decrease in PTDR, down to 0.15, which clearly demonstrates the effectiveness of rescue efforts resulting from improvements in organizing the emergency medical and rescue system to save patients with bodily injuries and thereby providing still better opportunities for improving the effectiveness of emergency medicine. For the group of patients for whom the leading cause of death was not bleeding, the initial and final PTDR values still remain relatively high. This is due to the severity of organ damage, especially the CNS.

## Late Complications

### Comment

In the group of patients with late death due to complications during ICU treatment, a significant decrease in PTDR from 0.5 to 0.35 was obtained during the analyzed 15 years, which is evidence of increasingly more effective treatment of this group of extremely compromised patients.

# DISCUSSION

Where the system incorporating traumatology was implemented and trauma centers were established, PTDR was reduced from 30–50% to 10–20%, which resulted in a significant reduction in the number of fatalities and permanent disability (Iau et al., 1998; Kunihiro, 2005; Saltzherr et al., 2011; Sanddal et al., 2011; Kim et al., 2012; Park et al., 2017; Jung et al., 2019).

For hospitals annually treating only 50 to 100 patients with severe injuries (ISS > 15), PTDR still remains high in the 30 to 40% range. For hospitals treating more than 1,200 trauma patients a year, including at least 240 patients with severe injuries or more than 35 patients per surgeon per year, the rate is significantly reduced to 10 to 20% (Kunihiro, 2005).

Air transport of patients with severe injuries provides the opportunity to initiate advanced clinical procedures within 15 min, which considerably improves a patient's chances for survival. An assortment of "errors" that occur during the prehospital period that have an impact on PTDR are estimated to be ∼30%; those committed in the ED are 50%, and those related to failures in clinical treatment and hospital structure/organization are ∼40 to 50% (Kunihiro, 2005; Nast-Kolb et al., 2006; Pamerneckas et al., 2006; Salim et al., 2006; Sanddal et al., 2011; Park et al., 2017).

Mistakes that were made most frequently were related to delay in initiating BTLS and ATLS, prolonged transport of patients, unsafe transport of unconscious patients within the hospital, mistakes in providing for a patent airway for patients with chest injury, "careless" examination and assessment of patients, delay in ordering diagnostic imaging and laboratory tests due to overlooking significant injury, disregard for parallel diagnostics, and treatment of unstable patients and getting them to emergency surgery.

Diagnostic and treatment errors documented in the medical record play a significant role in describing the continuously high rate of avoidable trauma deaths—PTDR. They consist mainly of superficial patient assessment, underestimating the importance of gathering accurate information, underestimating the impact of serious injury, faulty interpretation of follow-up tests results, and incorrect preliminary diagnosis and delay in decisive treatment of the patient. Keep in mind the basic principle: "The more serious the injury, the more important it is to activate correct, decisive rescue procedures in the ED."

The simpler the pathophysiology of death, the faster the death. Fatal injuries leading to immediate deaths are the result of organ damage, primarily the brain, massive hemorrhage from major system vessels and/or the heart, and suffocation.

Early deaths are caused by intracranial hematoma, bleeding from torn intercostal artery, ruptured parenchyma of abdominal organs, torn mesentery of the intestine, and retroperitoneal bleeding caused by an unstable pelvic fracture.

The leading cause of late death, occurring in ICU, involves complications of a complex pathogenesis appearing as the result of the spread of systemic inflammatory response syndrome (SIRS) and MOF.

The most common diagnostic errors belong to misdiagnosis: posttraumatic intracranial hematoma, pneumothorax, or internal bleeding, or underestimating its severity. It has been shown that pneumothorax and cerebral hemorrhage are dynamic processes that appear to go through different stages in the development of the disease process.

An important role in reducing PTDR is played by the algorithm for the initial management of polytrauma patients. After the initial traumatic examination and Whole Body Computed Tomography (WBCT), the polytrauma patient should be immediately transferred to the operating theater or the ICU.

"Timing and priorities of operative interventions in polytrauma patients depending on the physiological status" (Keel M.). Compromised vital functions—lifesaving primary surgery, highly unstable/in extremis—damage control surgery, stable vital functions—delayed primary surgery—day 1. Hyperinflammation (SIRS)—second looks only! Days 2–4. Window of opportunity—scheduled definitive surgery 5–10 day. Recovery—secondary reconstructive surgery after 3 weeks (Keel et al., 2006).

All the preceding work cited has become part of the total experience of other international health centers—European, American, and Asian—and the results obtained are comparable to the documentation of other practitioners writing on these topics. The results cited above demonstrate that we are an integral and important part of global emergency medicine (Helling et al., 2005; Keel et al., 2006; Sampson et al., 2006; Shen et al., 2006; Stanescu et al., 2006; Saltzherr et al., 2011; Sanddal et al., 2011; Kim et al., 2012; Seong et al., 2015; Park et al., 2017; Jung et al., 2019).

## CONCLUSIONS

1. The introduction of the Act of the State Emergency Medical System and the system of treating trauma patients in Poland significantly influenced the reduction of avoidable traumatic deaths and thus increased survival in the group of patients who suffered severe trauma.
2. The decline in PTDR is modeled to varying degrees by specific variables, of which the most important are late intervention, diagnostic errors, bleeding, and severe CNS injury. Where the cause of high PTDR was due to diagnostic errors, measures were taken to eliminate them by introducing new standards and procedures to achieve better results—a lower PTDR—rather than for cases where death was determined by factors other than errors.
3. An important role in reducing PTDR is played by the algorithm for the initial management of polytrauma patients and timing. Patients who have received highly specialized medical assistance during emergency procedures in the early phase after an accident are more likely to survive than a patient treated in the ICU during the late phase in the presence of MOF.
4. Despite a significant improvement in the emergency medical system's operation, the number of errors made, expressed as an indicator of preventable traumatic deaths, is still high. In the years 2016–2017, PTDR amounted to 23%. The preceding obliges us to intensify our activities and look for more effective solutions, following the example of the world's leading trauma centers. There is an urgent need to build a trauma patient treatment system based on trauma centers and "network hospitals" cooperating with these centers.

## DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/supplementary material.

## AUTHOR CONTRIBUTIONS

AW collecting full medical records and developing a work concept. Determining the objectives of the work and developing the methodology for conducting it. Tracing world literature and writing a pioneering original work on PTDR and medical errors in the field of emergency medicine in Poland over a two-decade time perspective. JJ scientific consultant of the above work. RM collecting material in the form of medical documentation needed. TW statistical study of collected material. All authors contributed to the article and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Sustainable Cities

ORIGINAL RESEARCH
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# Safety Culture Among Car Drivers and Motorcycle Riders in Norway and Greece: Examining the Influence of Nationality, Region, and Transport Mode

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The aims of the study are to (1) compare the road safety behaviors among car drivers and motorcyclists in five different regions in Norway and Greece, (2) examine the factors influencing the road safety behaviors in these groups, and (3) examine the relationship between road safety behaviors and accident involvement. The study is based on survey answers from car drivers and motorcycle riders in two Greek and three Norwegian regions ($N$ = 1,212). Road safety culture (RSC) is defined as shared patterns of behavior and shared expectations to other road users. The results indicate shared national RSC among Norwegian riders and drivers in the three Norwegian regions. The results from the Greek sample indicate the importance of the regional level for RSC and a unique RSC on the studied Greek island. The data do not indicate that transport mode is important for road safety behaviors or RSC. Our analyses indicate that RSC is important as it is closely related to road safety behaviors, which in turn is related to accident involvement. This suggests that accidents may be reduced by influencing the RSC. To contribute to such efforts, we discuss how and where RSC is created and how it influences road safety behavior, based on our results.

**Keywords: road safety culture, motorcycle riders, car drivers, Norway, Greece**

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## INTRODUCTION

### Background

Road safety remains a health issue of international interest as it is still ranked among the 10 leading causes of deaths worldwide (WHO, 2018). The number of annual road traffic deaths has reached 1.35 million, while between 20 and 50 million people are non-fatally injured (WHO, 2018). The numbers of people killed or severely injured in road crashes have gradually been reduced in recent years as a result of traditional safety strategies focusing on safety behaviors, technology, and infrastructure (Elvik et al., 2009). It has been argued that additional reductions are contingent on developing new approaches to prevention, e.g., the safety culture approach (Ward et al., 2010; Nævestad and Bjørnskau, 2012; Edwards et al., 2014).

High-quality studies of safety culture interventions in organizations employing drivers at work, with pre- and post-measurements, and test and control groups have indicated up to 60% decrease in crash risk in the road sector (e.g., Gregersen et al., 1996). These studies focus, however, on the more established concept of organizational safety culture, which refers to the shared and safety relevant ways of thinking and acting that are recreated in social interaction within organizations (Nævestad, 2010). Previous studies also indicate that road safety culture (RSC) in sociocultural contexts that are not work organizations (nations, regions, communities, peer-groups), is important, as it influences road safety behaviors, which in turn influence drivers' accident involvement (cf. Nævestad et al., 2019a). Thus, by influencing RSC, we may be able to reduce road fatalities and injuries. We define RSC as shared patterns of behavior, shared norms prescribing certain road safety behaviors and thus, shared expectations regarding the behaviors of others (Nævestad et al., 2019a).

At the current stage, little is, however, known about how RSC comes about in the sociocultural contexts that are not work organizations. Non-professional road users are not culturally bonded through organizational units, e.g., with managers, policies, and systems aiming to facilitate safe behaviors (Nævestad and Bjørnskau, 2012; Edwards et al., 2014). It is important to examine the influence of different sociocultural contexts (e.g., country, community, and peer groups) on different road safety behaviors, as this knowledge may indicate both the socio-cultural mechanisms through which RSC influences the behaviors of non-professional road users, and thus at which analytical-level preventive measures should be directed.

One important way of developing such knowledge is to examine sociocultural groups with presumably different road safety behaviors and discuss influencing factors. To examine this, the present study compares road safety behaviors and RSC at three different levels: (1) country (Norway and Greece), (2) transport mode (car drivers and motorcycle riders), and (3) region/community (three regions in Norway and two in Greece).

The two countries were chosen for comparison as they have distinctly different road safety records. Norway had the lowest road mortality rate in Europe, with 20 road deaths per million inhabitants in 2018, while the corresponding mortality rate in Greece in 2017 was 64 (European Transport Safety Council, 2019). Several factors that could influence road safety culture are national (e.g., traffic rules, the police enforcing the rules, road user interaction, and infrastructure). Thus, it is not unreasonable to assume the existence of different national RSCs influencing road safety behaviors in these countries, shared by both car drivers and motorcycle riders across regions. In accordance with this, several shared aspects of national RSC among car drivers, bus drivers, and heavy goods vehicle (HGV) drivers in Norway and Greece were found in a previous study (cf. Nævestad et al., 2019a).

We compare two different groups of road users with distinctly different risk of accidents: car drivers and motorcycle riders. Research from Norway indicates that riders of heavy motorcycles have approximately six times higher risk of personal injury accidents than car drivers and that the risk is even higher for riders of light motorcycles (Bjørnskau, 2015). Existing research also indicates a higher risk among riders than drivers in Greece (up to 3.5 times depending on the driver's age) (Yannis et al., 2017). The higher risk has been attributed to riskier behaviors, like overspeeding (DaCoTA, 2012). As previous research has found such common behaviors across countries (DaCoTA, 2012), it is not unreasonable to expect the existence of common motorcycle behaviors and RSC, extending across countries and geographical communities, based on the unique experiences of motorcycle riders compared to, e.g., car drivers (e.g., higher physical vulnerability, higher accident risk, and the possible existence of a common motorcycle rider identity) (cf. Tunnicliff et al., 2011).

We also compare the importance of region/community for road safety behaviors and RSC (cf. Luria et al., 2014). Previous research indicates that road user interaction is a key process in which RSC is created, as road users continuously (re)create norms for behavior by behaving in certain ways, sanctioning unwanted behaviors, etc. (Özkan et al., 2006; Bjørnskau, 2017). Given the limited mobility patterns of most road users, we may expect these interaction processes to be relatively local, indicating the importance of community or region as an influence of road user behavior and RSC. Drivers and riders were therefore sampled from five regions. The drivers and riders in Greece were sampled from the capital Athens and a Greek island. The sampling was based on an assumption that the behaviors and RSC on an island could be different from that in the capital as an island is a geographically enclosed area and has many tourist drivers. It is a relatively big island with an extended road network. The drivers and the riders in Norway were sampled from the capital Oslo and two additional Norwegian counties, which were selected based on differences in accident risk and attitudes, as indicated in previous studies (Storesund Hesjevoll and Fyhri, 2017). The sampling in Norway was based on an assumption that the behaviors and RSC in these counties would be less safe than that in the capital, based on results from this previous research (Storesund Hesjevoll and Fyhri, 2017). Analogous results from USA, indicating differences between rural and urban RSC, have been reported by Rakauskas et al. (2009).

## Aims

The aims of this study are to (1) compare road safety behaviors among car drivers and motorcyclists in five different regions in Norway and Greece, (2) examine the factors influencing the road safety behaviors in these groups, and (3) examine the relationship between road safety behaviors and accident involvement.

# PREVIOUS RESEARCH

## Road Safety Behaviors in Norway and Greece

The present study compares two types of road safety behaviors.

*Overspeeding* is included as it is a crucial behavior influencing accident involvement and severity (Elvik et al., 2009). Previous studies indicate that motorcycles have a higher accident risk than cars and that this, to some extent, is related to a higher prevalence of risk taking behaviors like overspeeding (Bjørnskau

et al., 2012; DaCoTA, 2012). This indicates that this behavior is more prevalent among motorcycle riders than car drivers. Overspeeding also differs among car drivers from southern and northern European countries. Previous research comparing car drivers in northern and southern European countries find more self-reported overspeeding in Northern European countries than in Southern European countries (Özkan et al., 2006; Warner et al., 2011).

*Aggressive violations* are included as previous research indicates higher levels of aggressive driving in Southern European countries compared with Northern European countries. Warner et al. (2011) found a higher prevalence of aggressive violations (e.g., become angered and indicate hostility, sound the horn to indicate annoyance) in Greece and Turkey than in Sweden and Finland. Comparing the road safety behaviors in northern European and southern countries, Özkan et al. (2006) found that Greek drivers committed more aggressive violations than other nationalities, especially behaviors indicating their annoyance and hostility to other road users. Comparing the levels of aggressive behavior among motorcyclists and car drivers, Rowden et al. (2016) found, however, lower levels of aggression among motorcyclists, presumably as the relative lack of protection offered by motorcycles may cause riders to feel more vulnerable and therefore to be less aggressive when they are riding compared to when they are driving cars.

## Factors Influencing Road Safety Behaviors

### Demographic Variables

Previous research has indicated that violations (which seem to be the behavior most strongly related to accidents) seem to be more prevalent among young drivers and male drivers (Parker et al., 1998). Similar results have been found in studies of motorcycle riders (Bjørnskau et al., 2012; DaCoTA, 2012). The above-mentioned studies of driver behavior also indicate the importance of nationality for behavior (Özkan et al., 2006; Warner et al., 2011). The car drivers' education has also been found to influence road user behavior. Sucha et al. (2014) report of lower levels of "dangerous violations" and "dangerous errors" with increasing levels of education.

### Road Safety Culture

There are no commonly accepted definitions of road safety culture (Edwards et al., 2014). As noted, we define RSC as shared patterns of behavior, shared norms prescribing certain road safety behaviors, and thus shared expectations regarding the behaviors of others (Nævestad et al., 2019a). In the present study, shared norms prescribing certain road safety behaviors are operationalized as descriptive norms, which refer to individuals' perceptions of what other people (in the relevant reference group) actually do (Cialdini et al., 1991). Descriptive norms may influence behavior by providing information about what is normal in certain groups (Cialdini et al., 1991). Based on Cialdini et al. (1991), we may hypothesize that the mechanism explaining the relationship between RSC and road safety behaviors is a subtle social pressure to behave in accordance with "what is normal" in your primary reference group (cf. Nævestad et al., 2019a). Finally, it is also important to note that descriptive norms can also influence behavior through the false consensus bias, in which individuals overestimate the prevalence of risky behavior among their peers in order to justify their own behavior (Berkowitz, 2005).

In the present study, we examine three sources of RSC based on the unique factors influencing culture at three different analytical levels: (1) country, (2) transport mode, and (3) region/community.

#### *RSC at the national level*

Several factors may generate RSC at the national level. First, previous research indicates that road user interaction seems to be an important RSC as road users continuously (re)create norms for behavior by behaving in certain ways, sanctioning unwanted behaviors, etc. (Özkan et al., 2006; Bjørnskau, 2017). In this manner, norms for commonly accepted behaviors may be created. Second, the interaction of road users and road user behaviors can be influenced by infrastructure, e.g., road markings, the design of junctions, and road capacity (Özkan et al., 2006). Third, certain road safety behaviors and thus expectations to other road users can, to some extent, be "normalized" in formal driver training (Nævestad et al., 2019a). Finally, the perceived level of enforcement in a country is also a relevant factor (Özkan et al., 2006). Based on these four factors, we may expect different national RSCs among riders and drivers in Norway and Greece. The importance of safety culture at the national level has been indicated in a few previous studies from the road sector and also in studies from other sectors (cf. Luria et al., 2014).

#### *RSC at the regional level*

In the present study, we also examine the importance of region or community for RSC. As noted, we hypothesize that the interaction between road users is a crucial factor influencing RSC (cf. Özkan et al., 2006). Provided that most non-professional drivers usually drive within relatively limited regions on a daily basis, it is not unreasonable to expect that local community or regional RSC may form in some areas based on the interaction of road users in the area. This may especially apply on islands, which are relatively geographically enclosed areas. Regional RSC may also be influenced by other local or regional factors, e.g., the local authorities' focus on traffic safety, the level of enforcement in the region, and the type and the composition of road users in a region (e.g., a high proportion of old drivers and tourists). In accordance with these assumptions, Luria et al. (2014) identify a shared community safety climate based on geography. Rakauskas et al. (2009) find that rural drivers engage in riskier behavior, such as not wearing seatbelts, because they perceive the risks associated with such behaviors to be lower.

#### *RSC related to transport mode*

Finally, it is not unreasonable to expect the existence of common road safety behaviors and a common motorcycle RSC extending across countries. Motorcycles generally have a higher risk than cars, and this is often attributed to riskier behaviors, e.g., overspeeding (DaCoTA, 2012). This is also because cars and motorcycles are different in several respects: physical vulnerability (Rowden et al., 2016), accident risk (Bjørnskau,

2015; Yannis et al., 2017), and behaviors (Bjørnskau et al., 2012; DaCoTA, 2012). Moreover, previous research also indicates that motorcycle riding more often than car driving is related to identity and that those in the group with which one rides represent an important source of social influence (Tunnicliff et al., 2011).

## Factors Influencing Accident Involvement

### Car Drivers vs. Motorcycle Riders

Data from Norway indicate that heavy motorcycle (>500 ccm) riders have approximately six times higher risk of personal injury accidents than car drivers, while the risk of light motorcycles was even higher (Bjørnskau, 2015). The fatal accident risk of riders is also higher for riders than for drivers in Greece (Yannis et al., 2017).

### Road Safety Behavior

In a meta-study examining the relationship between car drivers' road safety behaviors and self-reported accidents, De Winter and Dodou (2010) found especially violations, but also errors, to be related to accidents. Warner et al. (2011) found a relationship between aggressive violations and accident involvement. Moreover, speeding appears to be a bigger problem for powered two-wheeler (PTW) crashes, compared to other modes (Strandroth and Person, 2005; DaCoTA, 2012). Strandroth and Person (2005) found that 40% of riders involved in fatal accidents had an excessive speed. Excessive speed was also related to road-racing replica motorcycles (sport motorcycles). This was also reported in Bjørnskau et al. (2012).

### Demographic Variables

Nationality is a crucial demographic variable influencing the accident risk of both car drivers and motorcycle riders. As noted, the road mortality rate in Greece was 3.2 times higher than that in Norway (European Transport Safety Council, 2019). Moreover, age is also an important variable influencing the accident risk for both riders and drivers (Bjørnskau et al., 2012; Yannis et al., 2017). The same applies to gender: male drivers have a higher risk of being involved in accidents than female drivers and riders (Bjørnskau et al., 2012; Yannis et al., 2017).

### Mileage

The number of kilometers driven each year is an important risk factor influencing the risk of being involved in an accident (Elvik et al., 2009). In this respect, it is important to remember that motorcycle riding largely is a seasonal activity in Norway, probably generating fewer kilometers per year than in Greece.

## Hypotheses Based on Previous Research

First, we expect road safety behaviors to vary according to nationality, indicating the influence of national factors on road safety behaviors (hypothesis 1). Based on this, we expect higher levels of overspeeding among Norwegian respondents and more aggressive violations among Greek respondents. Second, we expect the road safety behaviors to vary according to transport mode, indicating the influence of mode on road safety behaviors (hypothesis 2). This involved more overspeeding among riders and less aggressive violations among riders across countries. Third, we expect region/community to influence the road safety behaviors, especially on the Greek island, which in some respects is a geographically enclosed community (hypothesis 3). Finally, we expect that the drivers' and the riders' accident involvement will be related to their road safety behaviors (hypothesis 4).

# METHOD

## The Safe Culture Project

The study was conducted within the research project "Safety culture in private and professional transport: examining its influence on behaviors and implications for interventions," undertaken by the Institute of Transport Economics of Norway in cooperation with the National Technical University of Athens (NTUA). The results from this project focusing only on bus drivers in Norway and Greece have been presented in Nævestad et al. (2019b), and the results from both professional and private drivers in Norway and Greece have been presented in Nævestad et al. (2019a). The present study builds on and takes further a previous conference paper focusing only on riders and drivers in Greece (Nævestad et al., 2019c).

## Recruitment of Respondents

The study is based on survey answers from car drivers and motorcycle riders in Norway and Greece (cf. **Table 1**). The Norwegian car drivers were recruited through the Preference Database of the Norwegian Postal Service. In September 2017, e-mails with web-links to the survey were sent to people in three Norwegian counties, including the capital, Oslo. Counties were selected based on differences in accident risk and attitudes. Of the 45,452 people who received the e-mail, 6,727 people (14.8%) opened the e-mail and 645 (9.6%) completed the survey. The Norwegian motorcycle riders were recruited with the help of the Norwegian motorcycle union, which distributed the survey link to its members in Oslo and the two counties. To increase the response rates, the Norwegian respondents were informed that they could participate in a draw for a present card of 2,000 NOK, if they wanted to.

The Greek car drivers and motorcycle riders were recruited through a marketing research company in Greece, which was under the scientific supervision of researchers from the NTUA. The recruitment of drivers in Greece was also difficult; therefore, it was decided to approach candidates in person and further explain the scope of the survey. This helped eliminate their doubts and fears about confidentiality and the use of the information they would provide.

When comparing the motorcycle riders in Norway and Greece, it is important to note that PTWs, i.e., mopeds and motorcycles, are common in southern European countries. In comparison, motorcycle riding is generally a seasonal (summer) activity in Norway, which often is related to leisure (e.g., Bjørnskau et al., 2012). Based on this, we may expect that the purpose of the motorcycle trips in Norway and Greece often may be different (e.g., leisure vs. practical daily transport), that the average rider characteristics (e.g., age and gender) are different, and that the types of motorcycles are different (e.g., larger and more expensive motorcycles in Norway). To make

**TABLE 1 |** Distribution of drivers/riders in the five regions in Norway and Greece, including the proportion of males.

| Country | | | | Country and mode | | | |
|---|---|---|---|---|---|---|---|
| | *N* | % | Males | | *N* | % | Males |
| Norway | 733 | 61 | 66% | Car | 596 | 49 | 59% |
| | | | | Motorcycle (MC) | 137 | 11 | 94% |
| Greece | 479 | 39 | 72% | Car | 286 | 24 | 64% |
| | | | | MC | 193 | 16 | 85% |
| Total | 1,212 | 100 | 68% | | 1,212 | 100 | 68% |
| **Region** | | | | **Region and mode** | | | |
| Greek Island | 161 | 13 | 75% | Car | 87 | 7 | 62% |
| | | | | MC | 74 | 6 | 91% |
| Athens | 318 | 26 | 71% | Car | 199 | 16 | 65% |
| | | | | MC | 119 | 10 | 82% |
| Oslo | 563 | 46 | 66% | Car | 461 | 38 | 59% |
| | | | | MC | 102 | 8 | 97% |
| County 1 | 120 | 10 | 68% | Car | 91 | 8 | 64% |
| | | | | MC | 29 | 2 | 83% |
| County 2 | 50 | 4 | 56% | Car | 44 | 4 | 50% |
| | | | | MC | 6 | 1 | 100% |

the motorcycle rider samples as comparable as possible, we have only included motorcycle riders from both countries, not riders of PTWs in general (i.e., mopeds are not included).

## Survey Themes

### Background Variables

Both surveys among car drivers and motorcycle riders included questions on background variables like age, experience as a driver, gender, kilometers driven with a car or motorcycle in the last 2 years, how often the respondents drive/ride, and what kind of car or motorcycle they drive/ride, and the respondents' highest level of education.

In the present study, we use two elements to operationalize RSC related to country, region, or mode: (1) road safety behaviors and (2) descriptive norms. When these two elements vary according to country, the results are attributed to national RSC; when they vary according to region, it is attributed to regional RSC; and when they vary according to mode, it is attributed to a shared car or motorcycle RSC.

### Road Safety

Road safety behaviors are measured by means of six items taken from the Driver Behavior Questionnaire (DBQ). The DBQ answer alternatives have been changed from relative to absolute alternatives (e.g., question: "for every ten trips, how often do you …?," alternative answers: "never," "once or twice," "three or four times," "five or six times," "seven or eight times," "more than eight times but not always," and "always"). Two questions measure overspeeding: "disregard the speed limit on a residential road" and "Disregard the speed limit on a motorway road." These were combined into an index (Cronbach's Alpha: 0.498). Four questions measure aggressive violations: "sound your horn to indicate your annoyance to another road user," "become angered by a certain type of driver and indicate your hostility by whatever means you can," "become angered by another driver and give chase with the intention of giving him/her a piece of your mind," and "overtake a slow driver on the inside." These were combined into an aggressive violations index (Cronbach's Alpha: 0.804).

### Descriptive Norms

We measure the descriptive norms by means of seven questions. The respondents were asked: "when driving in my country, I expect the following behavior from other drivers:" (1) "that they sound their horn to indicate their annoyance to another road user," (2) "that they become angered by a certain type of driver and indicate their hostility by whatever means they can," (3) "that they overtake a slow driver on the inside," (4) "that they drive when they suspect they might be over the legal blood alcohol limit," (5) "that they drive without using a seatbelt," (6) "that they disregard the speed limit on a motorway road," and (7) "that they disregard the speed limit on a residential road." Five answer alternatives ranged between 1 (none–very few) and 5 (almost all/all). The seven items were combined into a descriptive norms index (Cronbach's Alpha: 0.897).

The descriptive norms index focuses on the national level, asking the respondents about expectations to other drivers when driving in their respective countries. We can, however, generally expect that the riders and the drivers primarily assess this based on their experiences with the drivers on their local roads in the regions where usually drive. Thus, we may assume that this index may capture regional differences in RSC. The scope of the respondents' daily geographical driving environment limits their experiences. This means, for instance, that the expectations of the riders/drivers on the island to "other road users in their country" largely are based on their experiences with local drivers from their island. The same applies to riders/drivers in the three Norwegian counties; two of them are 220 km apart in the south of Norway, and the third is in the north of Norway, at least 2,400 km away from the two other regions. However, if the scores on the descriptive index are common across national regions, we attribute it to national RSC. Furthermore, we also assume that the descriptive norms index may capture RSC related to mode as we use it to assess whether the motorcycle riders' expectations to car drivers are common across their respective regions or countries, because of their unique experiences as riders, or whether they share expectations with other car drivers in their region or nation (indicating that region or nations are more important sources of RSC).

### Safety Outcomes

We report the results for one question on the respondents' crash involvement while driving in the last 2 years, with four answer alternatives: (1) no, (2) yes, involving property damage, (3) yes, involving personal injuries, and (4) yes, involving fatal injuries.

## Analysis

When comparing the mean scores of the different groups, one-way ANOVA tests, which compare whether the mean scores are

equal (the null hypothesis) or (significantly) different, are used. Tukey *post-hoc* tests are conducted. Two regression analyses have been conducted. In the first analysis, the factors predicting the respondents' answers on the dependent variable aggressive violations are analyzed. Hierarchical linear regression analyses are used, where independent variables are included in successive steps. In the second regression analysis, the factors predicting the respondents' answers on a dependent variable (accident involvement) measuring accident involvement are analyzed. Logistic regression analysis is used in this analysis as the dependent variable has two values (no = 1 and yes = 2). The *B* values are presented, and they indicate whether the risk of accident involvement is reduced (negative *B* values) or increased (positive *B* values), when the independent variables increase with one value. Of course, it is impossible to conclude about causality as this is a cross-sectional and correlational study. The term "predict" is nevertheless used when the regression analyses are described.

# RESULTS

## Description of the Sample

**Table 1** provides details on the distribution of drivers/riders in the five regions in Norway and Greece, including the proportion of males.

**Table 1** indicates that nearly half of the sample is comprised of car drivers from Norway, while 39% of the sample is comprised of riders and drivers from Greece. The share of males is higher for motorcycle riders in both countries, but especially in Norway. Looking at the five regions included in the study, the share of males was highest on the Greek island (75%) and lowest in one of the Norwegian counties (County 2) (56%). Comparing modes, we see that the share of males generally is higher in the motorcycle samples.

**Table 2** provides details on the distribution of age groups among the drivers/riders in the five regions in Norway and Greece.

**Table 2** indicates that the respondents from Norway generally are older than the respondents from Greece. The differences between the age groups in Greece and Norway are statistically significant at the 1% level ($P = 0.001$). Looking at the five regions included in the study, the share of respondents over 46 years old was lowest on the Greek island (18%) and highest in Norwegian county 2 (60%). Comparing modes, we see that the age of Norwegian motorcycle riders generally is higher than the Greek riders. The share of Norwegian riders over 46 years old is over twice as high as in the Greek rider sample. The age of the Norwegian motorcycle riders is also higher than the car drivers in both countries.

The differences in the riders'/drivers' experience are in accordance with the age differences. Over half of the riders and the drivers in Norway had over 20 years of experience, while the corresponding shares in the Greek sample were 25 and 37%.

The three most prevalent motorcycle types in Norway were touring (44%), classic (18%), and other (18%). The three most prevalent motorcycle types in Greece were scooter (55%), classic (21%), and other (8%). The riders were also asked about the engine capacity of their motorcycles, and 98% of the Norwegian respondents answered over 500 ccm, while 77% of the Greek riders answered up to 500 ccm. The three most prevalent car types in the Norwegian sample were passenger car (50%), station wagon (29%), and suburban vehicle (SUV; 15%), while 90% of the drivers in the Greek sample drove passenger cars. The results on the respondents' highest level of education indicate that the share of respondents with at least 3–4 years of university/college education was 76% among the Norwegian drivers, 61% among the Norwegian riders, 54% among the Greek drivers, and 48% among the Greek riders.

Questions were also included about the drivers'/riders' accident involvement (property damage, personal injury, and fatal) in the course of the last 2 years. A proportion of 14% had been involved in an accident (at least property damage). This applies to 10% of the car drivers and 14% of the motorcyclists in Norway and 17% of the car drivers and 23% of the motorcyclists in Greece. A chi-square test indicate that the differences were statistically significant at the 1% level ($P = 0.001$).

**TABLE 2 |** Distribution of age groups among the drivers/riders in the five regions in Norway and Greece.

| Country | | | | Country and mode | | | |
|---|---|---|---|---|---|---|---|
| | <26 | 26–45 | >46 | | <26 | 26–45 | >46 |
| Norway | 6% | 45% | 49% | Car | 7% | 50% | 44% |
| | | | | Motorcycle (MC) | 3% | 25% | 72% |
| Greece | 9% | 55% | 37% | Car | 5% | 53% | 42% |
| | | | | MC | 14% | 57% | 29% |
| **Region** | | | | **Region and mode** | | | |
| Greek Island | 14% | 68% | 18% | Car | 9% | 67% | 24% |
| | | | | MC | 20% | 69% | 11% |
| Athens | 6% | 48% | 47% | Car | 3% | 47% | 50% |
| | | | | MC | 10% | 50% | 40% |
| Oslo | 6% | 48% | 47% | Car | 7% | 52% | 42% |
| | | | | MC | 2% | 28% | 70% |
| County 1 | 5% | 41% | 54% | Car | 6% | 48% | 46% |
| | | | | MC | 3% | 17% | 79% |
| County 2 | 14% | 26% | 60% | Car | 14% | 30% | 57% |
| | | | | MC | 17% | 0% | 83% |

## Road Safety Behaviors

The first aim of the study was to compare the road safety behaviors in the studied groups. Shared patterns of road safety behaviors is the first element in our definition of RSC. One-way ANOVAs were conducted to examine the effects of the key variables on road safety behaviors. We also conducted *post-hoc* tests (Tukey) to examine whether the differences between the groups' mean behavior scores were significantly different. This was done first, based on a variable with five values (i.e., region). We conducted a similar *post-hoc* test (Tukey) based on a variable with 10 values [five regions × car/motorcycle (MC)] to examine whether the means of drivers and riders within each region were

similar (i.e., not significantly different). Similarly, we conducted *post-hoc* tests based on a variable with four values to examine the means of riders and drivers within countries (two countries × car/MC). Finally, two-way ANOVAs were conducted to examine the interaction effects of country and mode on behaviors. **Table 3** shows the mean scores for overspeeding.

**Table 3** indicates relatively similar scores for Norwegian and Greek respondents on the overspeeding index. A one-way ANOVA was conducted to examine the effect of country on overspeeding. An analysis of variance showed that the effect of country on overspeeding was not significant [$F_{(1,1,210)} = 0.604$, $p = 0.437$].

A one-way ANOVA was conducted to examine the effect of transport mode on overspeeding. An analysis of variance showed that the effect of transport mode on overspeeding was not significant [$F_{(1,1,210)} = 2.361$, $p = 0.125$]. The mean score of drivers was 5.1 (SD: 3.1), while it was 5.4 for riders (SD: 2.9). A two-way ANOVA that examined the effect of country and mode on overspeeding was conducted (cf. hypothesis 1 and hypothesis 2). There was a statistically significant interaction between the effects of country and mode on overspeeding [$F_{(1,1,208)} = 5.011$, $p = 0.028$].

The variable country and mode was made to compare the scores for the modes within countries. In accordance with the observed interaction effect, a one-way ANOVA showed that the effect of country and mode on overspeeding was significant [$F_{(3,1,208)} = 2.865$, $p = 0.036$]. The Tukey *post-hoc* tests indicate that the mean score of riders in Norway (5.9 points) was significantly higher than that of drivers in Norway (5.1 points) at the 5% level ($P = 0.026$).

A one-way ANOVA was conducted to examine the effect of the variable region on overspeeding. The results indicate that the effect was significant [$F_{(4,1,207)} = 16.903$, $p = 0.001$]. The scores of the three Norwegian regions are relatively similar on the overspeeding index, while the score of Athens is the lowest among the regions and the score of the Greek Island is the highest. A Tukey *post-hoc* test, comparing the scores of the five regions, indicates that the score of the Greek island is significantly higher than those of the other four regions ($P = 0.001$), while the score of Athens is significantly lower than the scores of all other regions ($P = 0.001$), except county 2 (because of a low $N$ in this group).

The variable region and mode, with 10 values (riders vs. drivers × five regions), was made to the compare scores for the modes within regions. A one-way ANOVA was conducted to examine the effect of this variable on overspeeding, indicating that the effect was significant [$F_{(9,1,202)} = 9.100$, $p = 0.001$]. A Tukey *post-hoc* test indicates that the scores of riders and drivers within each region were not significantly different.

To conclude, we see regional differences in the Greek data (Athens vs. Greek island), indicating the importance of region as an influencing factor, and similar scores among the three Norwegian regions, indicating the importance of country. Finally, overspeeding is not significantly correlated with accident involvement and weakly correlated with descriptive norms (Pearson's $R$: 0.189) ($P = 0.001$).

**Table 4** shows the mean scores for aggressive violations in the five regions and in the two countries.

**Table 4** indicates higher scores among the Greek respondents on the aggressive violations index. A one-way ANOVA was conducted to examine the effect of country on aggressive violations, indicating a significant effect [$F_{(1,1,210)} = 170.492$, $p = 0.001$].

**TABLE 3 |** Mean scores for overspeeding (minimum: 2, maximum: 14) in the five regions and the two countries.

| Country | | | | Country and mode | | | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | ***N*** | | **Mean** | **SD** | ***N*** |
| Norway | 5.2 | 3.0 | 733 | Car | 5.1 | 3.0 | 596 |
| | | | | Motorcycle (MC) | 5.9 | 3.1 | 137 |
| Greece | 5.1 | 3.0 | 479 | Car | 5.1 | 3.2 | 286 |
| | | | | MC | 5.0 | 2.6 | 193 |
| **Region** | | | | **Region and mode** | | | |
| Greek Island | 6.6 | 3.3 | 161 | Car | 7 | 3.7 | 87 |
| | | | | MC | 6.2 | 2.6 | 74 |
| Athens | 4.3 | 2.6 | 318 | Car | 4.3 | 2.6 | 119 |
| | | | | MC | 4.3 | 2.4 | 199 |
| Oslo | 5.2 | 2.9 | 563 | Car | 5.1 | 2.9 | 461 |
| | | | | MC | 5.7 | 2.8 | 102 |
| County 1 | 5.2 | 3.4 | 120 | Car | 4.8 | 3.2 | 91 |
| | | | | MC | 6.4 | 3.9 | 29 |
| County 2 | 5.1 | 3.4 | 50 | Car | 4.9 | 3.2 | 44 |
| | | | | MC | 6.5 | 4.7 | 6 |

**TABLE 4 |** Mean scores for aggressive violations (minimum: 4, maximum: 28) in the five regions and the two countries.

| Country | | | | Country and mode | | | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | ***N*** | | **Mean** | **SD** | ***N*** |
| Norway | 5.5 | 1.8 | 733 | Car | 5.5 | 1.8 | 596 |
| | | | | Motorcycle (MC) | 5.2 | 1.5 | 137 |
| Greece | 8.0 | 4.7 | 479 | Car | 7.7 | 4.9 | 286 |
| | | | | MC | 8.4 | 4.3 | 193 |
| **Region** | | | | **Region and mode** | | | |
| Greek Island | 11.0 | 6.1 | 161 | Car | 10.7 | 6.8 | 87 |
| | | | | MC | 11.5 | 5.1 | 74 |
| Athens | 6.4 | 2.7 | 318 | Car | 6.4 | 2.1 | 119 |
| | | | | MC | 6.5 | 3.0 | 199 |
| Oslo | 5.6 | 1.8 | 563 | Car | 5.6 | 1.9 | 461 |
| | | | | MC | 5.4 | 1.7 | 102 |
| County 1 | 5.1 | 1.5 | 120 | Car | 5.2 | 1.6 | 91 |
| | | | | MC | 4.8 | 0.9 | 29 |
| County 2 | 5.1 | 1.5 | 50 | Car | 5.2 | 1.5 | 44 |
| | | | | MC | 4.3 | 0.5 | 6 |

A one-way ANOVA was conducted to examine the effect of transport mode on aggressive violations, indicating a significant effect [$F_{(1,1,210)} = 13.910$, $p = 0.001$]. The mean score of car drivers was 6.2 (SD: 3.3), while it was 7.1 (SD: 3.8) for motorcyclists. A two-way ANOVA that examined the interaction effect of country and mode on aggressive violations (cf. hypothesis 1 and hypothesis 2) was conducted, indicating a significant interaction effect [$F_{(1,1,208)} = 5.011$, $p = 0.025$].

The variable country and mode was made to compare the scores for the modes within countries. A one-way ANOVA was conducted to examine the effect of the variable country and mode on aggressive violations, indicating a significant effect [$F_{(3,1,208)} = 58.944$, $p = 0.001$]. A Tukey *post-hoc* comparison indicates that the scores of riders and drivers within each country are similar (i.e., differences are not statistically significant).

A one-way ANOVA was conducted to examine the effect of the variable region on aggressive violations. The results indicate that the effect was significant [$F_{(4,1,207)} = 117.249$, $p = 0.001$]. The Tukey *post-hoc* tests, comparing the scores of the five regions, indicate that the score of the Greek island is significantly higher than those of the other four regions ($P = 0.001$), while the score of Athens is significantly different than those of the other regions at the 1% level ($P = 0.001$), except county 2 which is significantly different at the 5% level ($P = 0.030$). The scores of the three Norwegian regions are not significantly different from each other.

The variable region and mode, with 10 values (riders vs. drivers × five regions), was made to compare the scores for the modes within regions. A one-way ANOVA was conducted to examine the effect of this variable on aggressive violations, indicating that the effect was significant [$F_{(9,1,202)} = 52.563$, $p = 0.001$. The Tukey *post-hoc* tests indicate that the scores of riders and drivers within each region were not significantly different.

To conclude, we see internal differences in the Greek data (Athens vs. Greek island), indicating the importance of region as an influencing factor, and similar scores among the regions in the Norwegian data, indicating the importance of country. Finally, aggressive violations are weakly correlated with accident involvement (Pearson's *R*: 0.104) ($P = 0.001$) and moderately correlated with national norms (Pearson's *R*: 0.387) ($P = 0.001$).

## Descriptive Norms

In addition to drawing inferences about RSC based on shared patterns of behavior, we also measure RSC by means of a sum score index comprised of seven questions measuring national descriptive norms (Cronbach's Alpha: 0.897) (min 7, max 49). Descriptive norms is the second element in our definition of RSC.

**Table 5** shows the results on the descriptive norms index for the different groups.

**Table 5** indicates generally higher scores on the descriptive norms index among drivers and riders in Greece. A one-way ANOVA was conducted to examine the effect of country on descriptive norms, indicating a significant effect [$F_{(1,1,210)} = 607.184$, $p = 0.001$]. This indicates that the Greek respondents generally expect more aggression and violations from other road users in their country than the Norwegian respondents.

A one-way ANOVA was conducted to examine the effect of transport mode on descriptive norms, indicating a significant effect [$F_{(1,1,210)} = 9.827$, $p = 0.002$]. The mean score of drivers was 13.3 (SD: 6.2), while it was 14.5 for riders (SD: 6.1). This result is, however, small compared to the national differences.

**TABLE 5 |** Descriptive norms index (minimum: 7, maximum: 49).

| Country | | | | Country and mode | | | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | ***N*** | | **Mean** | **SD** | ***N*** |
| Norway | 10.7 | 3.4 | 733 | Car | 10.7 | 3.6 | 596 |
| | | | | Motorcycle (MC) | 10.8 | 2.7 | 137 |
| Greece | 18.0 | 6.8 | 479 | Car | 18.6 | 7.1 | 286 |
| | | | | MC | 17.2 | 6.4 | 193 |
| **Region** | | | | **Region and mode** | | | |
| Greek Island | 21.8 | 5.8 | 161 | Car | 23.4 | 6.1 | 87 |
| | | | | MC | 19.9 | 4.6 | 74 |
| Athens | 16.2 | 6.6 | 318 | Car | 16.5 | 6.4 | 119 |
| | | | | MC | 15.5 | 6.8 | 199 |
| Oslo | 10.9 | 3.5 | 563 | Car | 10.9 | 3.7 | 461 |
| | | | | MC | 11.1 | 2.7 | 102 |
| County 1 | 10.1 | 2.9 | 120 | Car | 10.0 | 3.0 | 91 |
| | | | | MC | 10.2 | 2.5 | 29 |
| County 2 | 9.8 | 3.1 | 50 | Car | 10. | 3.2 | 44 |
| | | | | MC | 8 | 1.3 | 6 |

The variable country and mode was made to compare the scores for the modes within countries. A one-way ANOVA was conducted to examine the effect of this variable on descriptive norms, indicating a significant effect [$F_{(3,1,208)} = 206.629$, $p = 0.001$]. The Tukey *post-hoc* tests did not indicate significant differences between car drivers and motorcycle riders in Norway on the descriptive norms index, indicating that they expect the same level of aggression and violations from other drivers in their country (i.e., common descriptive norms). Comparing riders and drivers in Greece, we found that the score of the Greek drivers were somewhat higher than the riders. The difference was statistically significant at the 5% level ($P = 0.014$).

A one-way ANOVA was conducted to examine the effect of the variable region on descriptive norms. The results indicate that the effect was significant [$F_{(4,1,207)} = 209.499$, $p = 0.001$]. The score of the Greek island is about six points higher than that of Athens, while the scores of the three Norwegian regions are lower and fairly similar. A Tukey *post-hoc* test, comparing the scores of the five regions, indicates that the score of the Greek island is significantly higher than those of the other four regions ($P = 0.001$). This score of Athens on the descriptive norms index is also significantly different from those of the other four regions ($P = 0.001$). The mean score of Oslo is not significantly different from those of the two other Norwegian regions, indicating a shared national RCS among these regions.

The variable region and mode, with 10 values (riders vs. drivers × five regions), was made to compare the scores for the modes within regions. A one-way ANOVA was conducted to examine the effect of this variable on descriptive norms, indicating that the effect was significant [$F_{(9,1,202)} = 97.778$, $p =$

0.001]. The Tukey *post-hoc* tests indicate that the scores of riders and drivers within each region were not significantly different, with one exception. The score of car drivers on the Greek island (23.4) is significantly higher than that of motorcycle riders (19.9) at the 1% level ($P = 0.001$). This explains the significant difference between Greek riders and drivers at the national level.

To sum up, the results seem to indicate shared descriptive norms among the Norwegian respondents, while the descriptive norms in Greece seem to vary according to the regional level, as indicated by the higher scores among the respondents on the Greek island.

## Factors Influencing Road Safety Behaviors

In this section, we conduct regression analyses to examine the variables that predict road safety behaviors, in accordance with the second aim of the study. We only examine aggressive violations as this behavior was significantly related to accident involvement. **Table 6** shows the results of nine regression models with "aggressive violations" as the dependent variable.

**Table 6** indicates five main results. The first main result is that the Greek island is the variable with the strongest contribution to aggressive violations in the model. This indicates a higher prevalence of aggressive violations among drivers and riders on the island, also when we control for demographic variables. The contribution of age and education is reduced somewhat when island is included, indicating a correlation with these and the somewhat younger respondents with lower levels of education on the island. The contribution of island in the model indicates an "island effect," or an influence at the regional level in the data, in addition to the national differences. We dichotomized the region variable into Greek island (2) and other (1) based on the comparisons of means in **Table 4**, which showed higher levels of aggressive violations on the Greek island. Thus, the value "other" is comprised of the other four regions.

The second main result is that descriptive norms is the second most important variable that predicts the drivers' and the riders' tendency to commit aggressive violations. This means that the respondents who expect a higher level of aggressive behavior and violations among other drivers in their own country are more likely to be involved in aggressive violations themselves. As expected, this variable is strongly correlated with nationality, which ceases to contribute significantly when we include descriptive norms in step 4. Thus, it seems that the contribution of nationality is mediated through descriptive norms.

The third main result is that demographic background variables, like the respondents' gender, age, and education, also contribute significantly and negatively. Older drivers, female drivers, and drivers with higher levels of education commit lower levels of aggressive violations.

Fourth, motorcycle type does not contribute significantly in the model, but car type does. Motorcycle type was dichotomized into scooter (2) and other (1), based on comparisons of means indicating higher levels of aggressive violations among scooter riders. Car type was similarly dichotomized into SUV and pick-up (2) and other (1), based on comparisons of means. **Table 6** indicates that SUV and pick-up drivers seem to commit slightly more aggressive violations, controlling for the other variables.

Finally, the adjusted $R$ value is 0.354 in step 9, indicating that the model explains 35% of the variation in the dependent variable.

## Factors Influencing Accident Involvement

In this section, we examine the factors influencing accident involvement, in accordance with the third aim of the study. **Table 7** presents the exposure for the different groups, accident involvement, and accident risk, measured as accidents with at least property damage, per million kilometers driven. The numbers are based on self-reported data. As expected, the table indicates higher numbers of kilometers driven for drivers than for riders in both countries and more kilometers driven in for riders in Greece than in Norway, as motorcycle riding is more of a seasonal activity in Norway.

As expected, we see a higher risk for motorcycle riders and generally a higher risk for riders and drivers in Greece than in Norway. The accident risk on the island was 14.9 accidents per million kilometers for riders and 8.4 for drivers.

The table also includes incidents in the last 2 years. This refers to "near misses" in the last 2 years for riders, which is

**TABLE 6 |** Linear regression.

| Variables | Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7 | Step 8 | Step 9 |
|---|---|---|---|---|---|---|---|---|---|
| Gender | −0.127** | −0.161** | −0.130** | −0.122** | −0.118** | −0.109** | −0.103** | −0.105** | −0.101** |
| Age group | | −0.225** | −0.178** | −0.125** | −0.124** | −0.138** | −0.101** | −0.099** | −0.102** |
| Nationality | | | 0.318** | 0.097 | 0.093** | 0.068* | −0.012 | −0.019 | −0.012 |
| Descriptive norms | | | | 0.396** | 0.398** | 0.404** | 0.288** | 0.291** | 0.290** |
| Car–motorcycle (MC) | | | | | 0.017 | 0.012 | −0.009 | −0.021 | −0.011 |
| Education | | | | | | −0.107** | −0.082** | −0.081** | −0.081** |
| Greek island | | | | | | | 0.335** | 0.332** | 0.329** |
| MC type (other: 1, scooter: 2) | | | | | | | | 0.025 | 0.023 |
| Car type (other: 1, suburban vehicle: 2) | | | | | | | | | 0.047* |
| Adjusted $R^2$ | 0.016 | 0.066 | 0.164 | 0.266 | 0.266 | 0.277 | 0.351 | 0.352 | 0.354 |

*Dependent variable: "aggressive violations" (minimum = 4, maximum = 28). Standardized beta coefficients.*
**p < 0.05; **p < 0.01.*

**TABLE 7 |** Estimated million kilometers (km) driven in the last 2 years with car or motorcycle, including the share of respondents who answered that they had experienced an accident (minimum property damage) or incident in the last 2 years, and estimated risk of accidents with property damage based on self-reported numbers of kilometers and accidents.

| Group | Million kilometers | *N* | Accidents | Accident risk | Incidents |
|---|---|---|---|---|---|
| Car Norway | 13 | 596 | 57 | 4.4 | 140 |
| Motorcycle (MC) Norway | 2 | 137 | 19 | 11.9 | 79 |
| Car Greece | 6 | 286 | 49 | 7.9 | 56 |
| MC Greece | 3 | 193 | 44 | 14.3 | 79 |

defined as situations where the riders or others have had to brake and/or turn heavily to avoid a collision. For drivers, this refers to situations where they have dented or scratched their car or touched an object (e.g., a post, a wall, or another car while parking) in the last 2 years. A share of 24% of Norwegian car drivers and 58% of the Norwegian motorcycle riders had been involved in incidents, while 20% of the Greek drivers and 41% of the Greek riders had been involved in incidents.

A logistic regression analysis was conducted with accident involvement as the dependent variable. In this analysis, the accident involvement variable, which originally had four answer alternatives, was dichotomized (0 = accident and 1 = accident). The *B* values are presented and they indicate whether the risk of accident involvement is reduced (negative *B* values) or increased (positive *B* values), when the independent variables increase with one value. We include different independent variables step-wise in the analyses to be able to examine the isolated effect of the independent variables, i.e., when the other variables are held constant. **Table 8** shows the results of nine logistic regression models with accident involvement as the dependent variable.

**Table 8** indicates five main results. The first main result is that previous incidents is the variable with the strongest contribution to the riders' and the drivers' accident involvement. The contribution is negative as the experience of incidents ("yes") is coded as 0, while "no incidents" is coded as 1. Thus, we see a relationship between accidents and near-accidents in the data, which also is related to behaviors (i.e., aggressive violations). We discuss that further below.

The second main result is that nationality is the variable with the second strongest contribution to accident involvement, controlling for the other variables in the analysis. The value is negative, indicating that being Norwegian involves a lower risk of being involved in an accident, controlling for the other variables in the analyses.

Third, the analysis also indicates that motorcycle type is related to accident involvement. Classic MC contributes significantly and negatively, indicating a relationship with accident involvement, controlling for the other variables in the analyses.

Fourth, aggressive violations contribute significantly to the drivers' and the riders' accident involvement. This means that the more involved riders and drivers are involved in this type of behavior, the more likely they are to be involved in accidents. Aggressive violations cease, however, to contribute significantly to accident involvement in step 9, indicating a close relationship between aggressive violations and incident involvement, which also is strongly related to accident involvement.

Fifth, the analysis also indicates the importance of the car vs. MC dimension for accident involvement (in addition to the national dimension). This variable contributed significantly in steps 4–7, until classic MC was included in the analysis. Thus, the contribution of classic MC in steps 8 and 9 represents a higher accident risk of motorcycle riders.

The Nagelkerke $R^2$ indicates the amount of variance in the dependent variable that is explained by the independent variables in the models. In step 9, the Nagelkerke $R^2$ is 0.095, which indicates that the independent variables explain 10% of the variance in the respondents' accident involvement.

# CONCLUDING DISCUSSION

## Road Safety Behaviors Among Riders and Drivers

The first aim of the study was to compare the road safety behaviors among car drivers and motorcyclists in Norway and Greece. This was done to identify the shared patterns of behaviors in the studied groups (country, mode, and region), which make up the first element in our operationalization of RSC.

First, we expected the road safety behaviors to vary according to nationality (hypothesis 1), involving more overspeeding among the Norwegian respondents than among the Greeks and more aggressive violations among the Greek respondents than among the Norwegians (Özkan et al., 2006; Warner et al., 2011). The results only partly supported this hypothesis when it comes to overspeeding: the results only indicated significantly more overspeeding among riders in the Norwegian sample. Thus, our result is not in accordance with previous research, which indicates higher speed levels among car drivers in northern countries (Özkan et al., 2006; Warner et al., 2011).

The results supported hypothesis 1 concerning the importance of nationality when it comes to aggressive violations. In line with previous research (Özkan et al., 2006; Warner et al., 2011), we found higher levels of aggressive violations among both Greek drivers and riders compared with the Norwegians, and the scores were relatively similar for riders and drivers within countries.

Second, we expected the road safety behaviors to vary according to transport mode, indicating the influence of mode

**TABLE 8 |** Logistic regression.

| Variables | Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7 | Step 8 | Step 9 |
|---|---|---|---|---|---|---|---|---|---|
| Gender (female = 0, male = 1) | 0.219 | 0.257 | 0.190 | 0.096 | 0.085 | 0.045 | 0.045 | 0.025 | 0.077 |
| Age (>46 years = 2, Oth. = 1) | | 0.300* | 0.210 | 0.211 | 0.213 | 0.162 | 0.181 | 0.173 | 0.156 |
| Nationality (Greek = 0, Norwegian = 1) | | | −0.697*** | −0.619*** | −0.616*** | −0.522*** | −0.568*** | −0.553*** | −0.623*** |
| Car–motorcycle (MC) (MC = 0, car = 1) | | | | −0.365* | −0.380* | −0.379* | −0.389** | −0.258 | 0.038 |
| Mileage | | | | | 0.002 | 0.001 | 0.001 | 0.001 | 0.003 |
| Aggressive violations | | | | | | 0.037* | 0.046* | 0.045* | 0.036 |
| Greek island (= 0, other = 1) | | | | | | | 0.211 | 0.166 | −0.038 |
| Classic MC (= 0, other = 1) | | | | | | | | −0.567* | −0.569* |
| Incidents (yes: 1, no: 2) | | | | | | | | | −01.065*** |
| Nagelkerke $R^2$ | 0.002 | 0.007 | 0.032 | 0.037 | 0.037 | 0.041 | 0.042 | 0.046 | 0.095 |

*Dependent variable: accident involvement. B values (no accident: 0, accident: 1). *p < 0.1; **p < 0.05; ***p < 0.01.*

on road safety behaviors (hypothesis 2). Based on previous research, we expected higher levels of overspeeding among riders (Bjørnskau et al., 2012; DaCoTA, 2012). Our results only partly supported this hypothesis when it comes to overspeeding as we found significantly higher levels of overspeeding among the Norwegian riders, but not among the Greek riders. Based on Rowden et al. (2016), we expected lower levels of aggressive violations among motorcyclists, presumably as the relative lack of protection offered to motorcycles may cause the riders to feel more vulnerable and, therefore, to be less aggressive. Our results are not in accordance with this. We found similar levels of aggressive violations among both riders and drivers.

Third, we expected region/community to influence road safety behaviors, especially on the Greek island, which in some respects is a geographically enclosed community (hypothesis 3). Our results support this hypothesis when it comes to the Greek island, but not when it comes to the Norwegian regions. The results indicate that the riders and the drivers on the Greek island had the highest scores on the overspeeding index, also indicating the importance of region for overspeeding. They also had the highest scores on the aggressive violations index, indicating a higher prevalence of such behaviors among riders and drivers on the Greek island. These results indicate the importance of region for road safety behaviors, in accordance with hypothesis 3 and previous research (cf. Luria et al., 2014; Rakauskas et al., 2009).

## Factors Influencing Road Safety Behaviors

The second aim of the study was to examine the factors influencing the road safety behaviors in the different groups. We conducted regression analyses to examine this, focusing on the behaviors that were significantly correlated with accident involvement (aggressive violations).

### The Mediating Effect of Descriptive Norms

In accordance with results for the comparisons of means (and hypothesis 1), the regression analysis indicates the influence of nationality on aggressive violations. Nationality was an important predictor of aggressive violations until descriptive norms was included in the analysis. Comparing the means on the descriptive norms index, we found significantly higher scores among the Greek respondents than the Norwegian respondents and relatively similar scores among riders and drivers within countries. In Norway, we saw similar scores for both drivers and riders in the three Norwegian regions, indicating common descriptive norms among Norwegian respondents.

Descriptive norms refer to the individuals' perceptions of what other drivers in their country do (cf. Cialdini et al., 1991). In the regression analyses with aggressive violations as the dependent variable, the effect of nationality was mediated by descriptive norms as the contribution of nationality was removed when descriptive norms were included in the analysis (cf. steps 3 and 4, **Table 6**). Descriptive norms was the second most important variable influencing aggressive violations. Thus, our analyses indicate that descriptive norms is an essential variable in the analyses, providing an important explanation to the relationship between nationality and road safety behaviors. This is in accordance with previous research indicating that descriptive norms may influence behavior by providing information about what is normal and expected in certain groups (Cialdini et al., 1991).

### The Influence of Region in the Greek Sample

The regression analyses indicate that region (i.e., Greek island) was the most important predictor of aggressive violations. These results are in accordance with hypothesis 3, and previous research indicates the importance of the regional level or the community level as a source of RSC (Rakauskas et al., 2009; Luria et al., 2014). Our results seem to indicate an "island effect," with significantly different patterns of road safety behaviors and descriptive norms on the island. In the case of the Greek island, the data seem to indicate a unique regional RSC. The results indicate that riders and drivers from the Greek island stand out in several respects: they report of a higher prevalence of overspeeding and aggressive violations, and their scores on the descriptive norms index were significantly higher than those of the other studied groups. The latter indicate that they attribute higher levels of aggression and violations to other drivers on the island.

The descriptive norms index focuses on the national level, asking the respondents about their expectations to other drivers when driving in their respective countries. As noted, we can,

however, generally expect that riders and drivers primarily assess this based on their experiences with the drivers on their local roads and in the regions where they usually drive, and that the scope of the respondents' daily geographical driving environment limits their experiences. This means, for instance, that the expectations of riders/drivers on the island to "other road users in their country" largely are based on their experiences with local drivers from their island. Thus, it seems that we can also use this index to measure differences in regional RSCs. The correlation between the Greek island and the descriptive norms index is indicated by the reduction in the contribution of the latter variable (steps 6 and 7 in the linear regression analyses in **Table 6**), when the former variable is included. This is caused by the fact that the respondents on the Greek island expect more aggressive violations from other drivers (cf. **Table 5**).

### The Influence of the Car vs. the Motorcycle Dimension

Contrary to hypothesis 2, our results do not indicate that transport mode (car vs. motorcycle) is an important influence on road safety behaviors, even though cars and motorcycles are different in several respects: physical vulnerability and accident risk. This is contrary to previous research indicating lower levels of aggressive violations among riders (Rowden et al., 2016) and higher levels of overspeeding (Bjørnskau et al., 2012; DaCoTA, 2012). It should, however, be mentioned that we found higher levels of overspeeding among Norwegian riders. The little importance of mode in the material could also be due to the relatively different types of riders in the two countries, as noted in the section Recruitment of respondents. While motorcycle riding generally is a seasonal (summer) activity in Norway, which often is related to leisure (e.g., Bjørnskau et al., 2012), Greece has a higher ownership rate, and motorcycles and mopeds are used more for everyday transport. To make the samples more comparable, we only included motorcycles from both countries. We see, however, that almost all the Norwegian motorcycles (98%) had an engine capacity of over 500 ccm, while this only applied to 23% of the Greek respondents. We have also seen that the most prevalent motorcycle types differ in the two countries, with touring (44%) being the most prevalent in Norway, while it was scooter (55%) in Greece.

### The Influence of Demographic Variables

The regression analyses indicate that aggressive violations were influenced by demographic variables. In accordance with previous research (cf. Parker et al., 1998; Bjørnskau et al., 2012; DaCoTA, 2012), we found that female drivers and riders and older drivers and riders are less likely to be involved in unsafe behaviors. Finally, in accordance with previous research (Sucha et al., 2014), we also found lower levels of aggresive violations with increasing levels of education.

## Factors Influencing Accident Involvement

The third aim of the study was to examine the relationship between road safety behaviors and accident involvement. We examined the bivariate relationships between the studied road safety behaviors and accident involvement. Contrary to previous research, these analyses do not indicate a relationship between the riders' and the drivers' overspeeding and accident involvement (e.g., Bjørnskau et al., 2012; DaCoTA, 2012). Only aggressive violations were correlated with accident involvement. Based on results from the bivariate analyses, aggressive violations were included in the logistic regression analyses of variables that predict accident involvement. One of the main results of this analysis was that aggressive violations were related to the drivers' and the riders' accident involvement, in accordance with the results of Warner et al. (2011), who found this behavior to predict accident involvement in the Greek sample of car drivers. The results also indicate that this behavior was related to involvement in "traffic incidents," as aggressive violations ceased to contribute significantly when we included "traffic incidents." In accordance with previous research, the results also indicated a higher risk for motorcycle riders (Bjørnskau et al., 2012; Yannis et al., 2017) and Greek respondents (European Transport Safety Council, 2019).

## Questions for Future Research

In the introduction, we stressed that little is known about how RSC comes about in the sociocultural contexts that are not work organizations and that it is important to examine the influence of different sociocultural contexts on the different road safety behaviors. The purpose of this was to illuminate (1) the socio-cultural mechanisms through which RSC influences the behaviors of non-professional road users, (2) the analytical levels which preventive measures should be directed, and (3) the processes through which RSC are created.

### How RSC Influences Road Safety Behaviors

When it comes to the issue of how RSC influences the behaviors of non-professional road users, we hypothesize that it influences through descriptive norms, by providing information about what is normal and expected among other drivers in the country or the regions of the respondents (Cialdini et al., 1991). Thus, the mechanism explaining the relationship between descriptive norms and road safety behaviors is subtle social pressure to behave in accordance with "what is normal" among other drivers in these groups (cf. Nævestad et al., 2019a). Ward et al. (2010) assert that research on road safety culture often seems to lack an explanation of the theoretical link between safety culture and safety behaviors. Future research should examine further the importance and the potential of such subtle social pressure. Our research indicates that memberships in sociocultural groups constitutes an important influence on behaviors, which also is related to accident involvement. Thus, influencing the power of sociocultural ties could lead to reductions in accidents. We expand further on this below.

### The Analytical Levels Which Preventive Measures Should Be Directed

Second, when it comes to the analytical levels which preventive measures should be directed, we have examined the importance of three different levels that influence road safety behaviors in the present study: (1) country, (2) region, and (3) transport mode. Our analyses by and large indicate that, when it comes to facilitating RSC, nation and region are far more important than

transport mode, e.g., car vs. motorcycle. We have argued that the results indicate a Norwegian RSC shared by both riders and drivers across three regions. Additionally, the results indicate a unique regional RSC on the Greek island. Thus, our data indicate that measures to influence road safety behaviors and RSC should focus on geographical units (country and regions) rather than on specific groups of road users (e.g., car vs. motorcycle). The significance of geography for RSC was also indicated by Luria et al. (2014). These results require a discussion of the factors that influence national and regional RSC.

### The Processes Through Which RSC Are Created

First, previous research indicates that road user interaction seems to be an important source of RSC as road users continuously (re)create norms for behavior by behaving in certain ways, sanctioning unwanted behaviors, etc. (Özkan et al., 2006; Bjørnskau, 2017). In this manner, norms for commonly accepted behaviors may be created. We have, however, not examined interaction specifically, indicating the need for future research (cf. Bjørnskau, 2017). Second, the interaction of road users and road user behaviors can be influenced by infrastructure, e.g., road markings, the design of junctions, and road capacity (Özkan et al., 2006). We have not examined this in the present paper, and this should be an important issue for future research. Third, certain road safety behaviors and thus expectations to other road users can, to some extent, be "normalized" in formal driver training (Nævestad et al., 2019a). We have, however, not examined this specifically. Finally, the perceived level of enforcement in a country is also a relevant factor (Özkan et al., 2006). This should also be examined in future research.

The importance of region in the Greek data indicates the importance of local interaction processes in the daily (re)creation of RSC. This is also indicated by the similarities between riders and drivers within the studied regions. The most important thing that these groups have in common seem to be the roads that they share, where they continuously create and recreate RSC. When it comes to the Greek island, it should also be noted that regional RSC also may be influenced by the type and the composition of road users in a region (e.g., a high proportion of old drivers and tourists) (Nævestad et al., 2019a). These are important issues for future research that we have been unable to examine. Moreover, the perceived level of enforcement on the island may also influence behaviors and RSC (Özkan et al., 2006). The same applies to the local authorities' focus on traffic safety. These factors may be different on an island compared to the rest of the country. The same applies to infrastructure, e.g., road markings, the design of junctions, and road capacity (Özkan et al., 2006).

In the Norwegian sample, we found relatively similar descriptive norms and road safety behaviors across modes in the three studied regions. This could also be due to interaction, but in this context, it is important to note that county 2 is about 2,600 km apart from county 1 and 2,400 km apart from Oslo. Based on this, we should perhaps not expect the interaction between the road users from the different regions to be an important explanation of their common RSC and common road safety behaviors. Given the physical distance and the geographical limitations to direct road user interaction, we should perhaps expect other factors to be important when it comes to communicating national norms for "normal" behaviors in traffic. Such factors could, for instance, be formal and standardized driver training, police enforcement, media, and of course also by traveling to other parts of the country and interacting in the traffic there. The significance of all these factors should be examined in future research. This especially applies to the social processes that may induce changes in norms and road safety behaviors. Moreover, Luria et al. (2014) also discuss the possibilities of using safety culture interventions that have proven to be effective in organizations at the community level to improve community RSC. This is an important issue for future research. As noted, the safety culture intervention studied by Gregersen et al. (1996), which involved group discussions, involved a 60% reduction in the accident risk.

## Methodological Limitations

### Different Recruitment of Respondents in the Two Countries

The recruitment of respondents, motivational measures, and administration of the surveys were different in the two countries (cf. section Recruitment of Respondents). This is a potential methodological weakness of the study which is important to bear in mind when interpreting the results. The car drivers in Norway were recruited through the database of the postal service, they got survey links per e-mail, and they answered the survey online using their computers, tablets, etc. The motorcycle riders in Norway were recruited through the motorcycle union, and they answered online. The car drivers and motorcycle riders in Greece, on the other hand, were recruited through a marketing research company in Greece, which was under the scientific supervision of researchers from the NTUA. They answered the survey orally, in direct contact with the interviewers from the marketing research company. This approach was chosen to motivate the Greek respondents to participate. As the recruitment of drivers and riders in Greece was difficult, it was decided to approach candidates in person and explain the scope of the survey. This helped eliminate their doubts and fears about confidentiality and the use of the information they would provide. Similarly, as the recruitment of drivers and riders in Norway also was challenging, they were informed that they could participate in a draw for a present card of 2,000 NOK. The different ways of recruitment reflect different national opportunities for racing car driver and motorcycle rider respondents in different regions in the two countries. The different ways of administering the surveys and motivating the respondents were implemented to get as many as possible to participate. It is important to remember the different national answering contexts when interpreting the results. The respondents may, for instance, be more inhibited when answering surveys face to face than alone on their computer. This could potentially mean that the respondents who answer face to face under-report their own risk taking behavior. In the present study, we have, however, seen the opposite: the Greek respondents, especially those from the island, report of more aggressive violations and also the highest levels of overspeeding (on the Greek island). Thus, it does not

seem that this potential bias has had a significant influence on the answers. Moreover, in a recent Norwegian study of safety culture, which employed different answering techniques (web form and orally), we did not find significant differences between respondents answering the survey in different ways (Nævestad et al., 2018).

## The Representativity of the Samples

When interpreting the results by drawing inferences about differences in national and regional RSC in the countries, it is also important to remember that the national samples are relatively small and that the respondents may not be representative of the respective national populations of car drivers and motorcycle riders.

First, our comparisons of the respondents on key variables (**Tables 1**, **2**) indicate that the age and the sex compositions are slightly different in the national samples, with somewhat more women and more respondents in the oldest age category in the Norwegian sample. Although the potential confounding effects of these variables are tested in the regression analyses, that does not negate the fact that the samples are not "equal" with respect to demographic representation. Thus, we should take care when making conclusions about the different national RSCs based on the present study. Moreover, the response rate is low in the Norwegian samples of car drivers (about 10%), which also requires a check of the representativity of the national samples. Because of the recruitment technique employed for the Greek respondents, we are unfortunately unable to calculate the response rate in these samples. The challenges related to recruiting respondents in the two countries and the low response rate among the Norwegian car drivers warrant a discussion of whether the sample of respondents that chose to respond in the two countries is unbiased. With such a low response rate, there is a danger of systematic "self-recruitment" and "self-exclusion," meaning that only some groups chose to participate. This requires a comparison of our samples with official statistics to validate the sample data. We therefore obtained aggregated official data on car license and motorcycle license holders in Norway and Greece (cf. **Table 9**).

The data in **Table 9** show that there is a share of 51% males among Norwegian car license holders as compared to 59% in the survey (cf. **Table 1**). The corresponding share for car drivers in Greece was 66% as compared to 64% in the survey (cf. **Table 1**). This indicates that women are somewhat under-represented in the Norwegian car driver sample. The aggregated data for age groups in the two countries (cf. **Table 2**) are not totally comparable to the age groups applied in **Table 9**, but they indicate that the proportions of car drivers of 45 years and older are under-represented in the samples from both countries, but especially in the Greek sample. Drivers between 25 and 44 years are over-represented in both national samples. The data in **Table 9** indicate that the age groups in the Norwegian motorcycle driver sample is relatively comparable to the population of license holders, although the compared age categories are not entirely similar. When we compare the distribution of males and females in the Norwegian motorcycle rider sample (**Table 1**) and in the population (**Table 8**) of Norwegian motorcycle license holders, we see, however, that women are under-represented in our sample. There were no data on the education level of the car drivers or motorcycle license holders in the two countries. Unfortunately, the Greek motorcycle license data only refer to licenses issued between 2008 and 2017, that is why the percentage for older drivers is so low. It is unfortunately difficult to assess the representativity based on these data. Shares for sex are also missing in the Greek motorcycle license data.

**TABLE 9 |** Aggregated data on private car license holders and motorcycle license holders in Norway and Greece.

| Age group and sex | Car drivers | |
|---|---|---|
| | **Norway %** | **Greece %** |
| <25 | 8 | 5 |
| 25–44 | 34 | 34 |
| 45+ | 58 | 61 |
| Gender: M | 51 | 66 |
| | **Motorcycle riders** | |
| | **Norway %** | **Greece %** |
| <30 | 5 | 47 |
| 31–50 | 21 | 45 |
| >50 | 74 | 8 |
| Gender: M | 73 | – |

*Age groups and sex, Norway and Greece.*

Second, it should also be mentioned that the regions outside the capitals in both countries are strategically sampled based on the hypothesis about regional RSCs that might differ from those in the capital. This hypothesis was supported in the case of Greece, but not in the case of Norway. However, an argument indicating that our national samples nevertheless seem to reflect differences in national RSCs, shared by both motorcycle riders and car drivers in the two countries, is that the observed national differences are also in accordance with previous research, which reports more aggressive violations in southern countries (Özkan et al., 2006; Warner et al., 2011). These arguments indicate the validity of our conclusions about national RSC. Additionally, our main results about RSC are also in line with our other studies, which also includes professional drivers, e.g., bus drivers (Nævestad et al., 2019b), and HGV drivers in Norway and Greece (Nævestad et al., 2019a). Thus, our observations of national RSC in Norway and Greece are based on relatively similar reports from car drivers, motorcycle riders, bus drivers, and HGV drivers in Norway and Greece. These groups attribute fairly similar behaviors to other drivers in their respective countries. This indicates that we may draw conlcusions about different national RSC based on our study.

Finally, we also draw conclusions about the significance of regional RSC based on our data, and we have seen that the respondents on the Greek island differed from the other groups in several demographic respects. The share of respondents over 46 years old was, for instance, lowest on the Greek island (18%), while it was three times higher in the Norwegian county 2 (60%). We unfortunately lack data on the rider and the driver populations in the five regions, and we are therefore unable to evaluate the representativeness of the sampled riders and

**TABLE 10 |** Scores for behavior and descriptive norms for men aged between 26 and 45 years, with high school or 3–4 years of university education in the five regions.

| Regions | Overspeeding | | | Aggressive violations | | | Descriptive norms | | |
|---|---|---|---|---|---|---|---|---|---|
| | **M** | **SD** | ***N*** | **M** | **SD** | ***N*** | **M** | **SD** | ***N*** |
| Greek island | 6.7 | 2.7 | 73 | 12.3 | 5.8 | 73 | 21.8 | 5.7 | 73 |
| Athens | 4.7 | 2.4 | 71 | 7.1 | 3.1 | 71 | 15.2 | 6.9 | 71 |
| Oslo | 4.9 | 2.4 | 83 | 6.1 | 2.2 | 83 | 11.9 | 3.9 | 83 |
| County 1 | 4.8 | 2.6 | 22 | 5.8 | 2.2 | 22 | 10.9 | 3.3 | 22 |
| County 2 | 3 | 0 | 2 | 4.5 | 0.7 | 2 | 9.2 | 2.8 | 2 |

drivers in the regions. We control, however, for demographic characteristics (e.g., age, sex, and education) in the regression analyses, and these indicate an effect of Greek island, controlling for these variables. That indicates that our results concerning region is not caused by bias from demographic variables. Additionally, we see relatively similar reports from both riders and drivers from the island. Finally, we can also compare the scores for comparable groups by controlling for gender, age, and education. **Table 10** shows the mean scores for men aged between 26 and 45 years, with high school or 3–4 years of university education in the five regions.

The comparisons in **Table 10** indicate that the differences between the regions are maintained and relatively similar to those observed in **Tables 3**–**5**. Thus, the observed regional differences do not seem to be due to differences in the demographic compositions of the regional samples. This comparison is not the same as making an assessment of representativeness as we may assume that the populations of riders/drivers in the different regions may be different, and in several cases, this can be one of the explanations for different regional RSCs.

To conclude, the issue of representativeness is, however, always crucial, and as the present study has some deficiencies in this regard, more studies are required to arrive at robust conclusions. Thus, to further develop our knowledge about RSC and to obtain even more accurate results, we suggest that future research on this subject should cover larger samples of road users.

### False Consensus?

RSC is partly measured as descriptive norms. A potential critique that can be raised against the identification of the descriptive norms mechanism is that it also may influence behavior through the false consensus bias, which means that people overestimate the prevalence of risky behavior among others to justify their own behavior (Cialdini et al., 1991). However, the fact that we find that both car drivers and motorcycle riders independently of each other attribute approximately the same level of violations to other road users in their respective countries (and within the five studied regions) indicates that our results, to some extent, reflect differences in national (and regional) RSCs. Moreover, the descriptive norms scores do not follow directly the road safety behavior scores, e.g., for riders and drivers on the Greek island.

## CONCLUSION

The present study indicates that road users' memberships in different sociocultural groups is important for road safety as it influences the road safety behaviors of both drivers and riders, which in turn is related to accident involvement. We have found that geographical variables like country and region seem to be important for RSC, presumably as interaction between road users is a key process in which RSC is (re)created. Membership in such sociocultural groups seem to influence road safety behaviors through the road users' perceptions about the behaviors that are "normal" and expected in their country and on their local roads. Future research should examine how these important social impacts on behavior can be influenced in manners that lead to increased road safety.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by NSD. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

T-ON, AL, and GY have cooperated on the planning and design of the study, data collection in Norway and Greece, conceptual development, and interpretation of results. T-ON has conducted most of the analyses and writing of the draft, with substantial contributions from AL and GY. T-ON, AL, and GY are accountable for all aspects of the work. All authors contributed to the article and approved the submitted version.

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REVIEW
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# Aging, Obesity, and Motor Vehicle Collisions

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Aging and obesity are two key areas of research as risk factors leading to motor vehicle collisions (MVCs). However, only a few studies identified obese older drivers as an at-risk population of MVC (i.e., older than 65 years old with Body Mass Index >30 kg/m$^2$). This paper aims to review the literature related to aging, obesity, and MVCs. Extensive literature searches were conducted, and the results are presented in a narrative review of the literature, in order to discuss the risk for involvement in MVC as well as the solutions for this population. Extrinsic factors are components of the "built environment" that decrease road safety for this population and poor fit of the vehicle through their inappropriate design for this population. The intrinsic factors are the autonomy and the health status of the driver. Health status are challenges associated with obesity and aging that increase the prevalence of being part in a MVC and that increase risk of morbidity and mortality during or following a collision. Finally, some prevention strategies are presented for consideration. There is a need to inform public policy makers on the additional risk factors associated with aging and obesity for MVCs.

**Keywords: aging, obesity, motor vehicle collision, car design, prevention, mobility**

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## INTRODUCTION

Despite many safety improvements (e.g., air bags, electronic stability control) in the past decades, motor vehicle collisions (MVC) continue to be a large source of mortality worldwide (World Health Organization, 2013). Numerous studies identify major risk factors related to fatal and non-fatal MVC, including distracted driving (Fitch et al., 2014) and driving under the influence of drugs or alcohol (Ogden and Moskowitz, 2004). With much of the focus in the literature on these two intrinsic risk factors, the role of personal characteristics seems overlooked. While there is relatively little information about aging and obesity, they have been separately identified as risk factors of MVC (Eby et al., 2009; Desapriya et al., 2011).

Older individuals are the fastest growing segment of the driving population. According to the National Highway Traffic Safety Administration report (NHTSA, 2017), there were 40 million licensed drivers 65 and older in the United States which was a 33% increase compared to the statistics of 2006. Also, by the year 2030, 70 million individuals in the U.S.A. will be over age 65 and 90% of them will be licensed to drive. Considering that it is well-known that some aspects of normal aging affect driving capacity (e.g., slower reaction time, reduction of visual acuity), pathological

aging represents a higher incidence of MVC (Turcotte, 2012; Desapriya et al., 2014). However, a lack of consensus persists in the available literature regarding whether older drivers are involved in increased numbers of MVC because of factors related to aging, or if the difference might be due to a low driving distance bias (Langford et al., 2008). Although low driving distances may mitigate that older drivers may pose to other road users, a large body of literature supports the increased MVC risk for older drivers.

As a population, we are not just aging, but we are also getting heavier. As of 2014, the World Health Organization (WHO) estimated that at least 600 million adults worldwide are obese (World Health Organization, 2018a). The prevalence of obesity throughout the world is well-documented and, it is universally recognized as an important issue that has an impact on several areas of our daily lives (Finucane et al., 2011). Sedentary behaviors, poor dietary habits, and genetic predisposition are among some of the factors associated with this increase in obesity (Chaput et al., 2014). Obesity is a well-established risk factor for a number of common chronic diseases (e.g., diabetes, and obstructive sleep apnea). As pathological aging is, health issues related to the obesity have negative consequences by increasing the driver's risks of MVC (Zhu et al., 2010; Jehle et al., 2012).

A novel hypothesis, and one that is central to the current article, is that obesity and aging have a synergistic effect on risk for MVC and severity of outcomes. That is, it is our contention that older obese drivers are a population at an increased risk for MVCs when compared to obese only or elderly only drivers. This paper focuses on the synergistic aspects of aging and obesity and how this leads to a potential increased risk for involvement in a MVC as well as the consequences following the MVC. The aim of this paper is to provide a narrative review of the current literature on the combined effect of aging and obesity on road safety. Through this review, it is our intention to provide a summary of the evidence of the concurrent issues of aging and obesity as a contribution toward evidence-based public policy decisions, to increase awareness and to initiate a discussion to identify possible solutions.

## METHODS

For this narrative review, searches were conducted on Pubmed, ISI Web of Knowledge and Google scholar as they encompass a wide array of scientific areas as well as the most relevant peer-reviewed publications (Falagas et al., 2008). This methodology is scientifically transparent, replicable, and useful to generate an in-depth analysis of the scientific literature (Sackett et al., 1997). To select the most relevant scientific articles to include in this narrative review, the inclusion and exclusion criteria were defined prior to the search:

- Original articles written in English or in French and published in peer-reviewed journals;
- Published or in press between January 1990 and December 2017.
- Search terms were aging AND obesity AND driving.
- Articles were excluded if the sample presented drivers with no specific mentions of their age (ex. Mean age, age distribution) or their weight and/or body mass index.

Titles and abstracts of papers were scanned independently by two of the authors to identify relevant articles to retrieve for full text analysis. In cases where the papers seemed potentially eligible, but no abstract was available, the full text of the paper was retrieved. Disagreements between authors led to a deeper joint analysis of the paper; and a decision was then made regarding its inclusion. Full texts were independently reviewed for inclusion by the same two authors. Twelve articles were found ($N = 12$), but only one was directly related to aging, obesity and driving ($N = 1$) (Frank et al., 2010). The list of retrieved articles was then reviewed to identify additional published papers.

By using an approach adapted from Sackett et al. (1997), identified papers were also categorized using a standardized value system to grade biomedical practices according to the following system: Level I: Systematic reviews, meta-analyses, randomized controlled trials; Level II: Two groups, non-randomized studies (e.g., cohort, case control); Level III: One group, non-randomized (e.g., before and after, pre-test and post-test); Level IV: Descriptive studies including analysis of outcomes (e.g., single-subject design, case series); and Level V: Case reports and expert opinions including narrative literature reviews and consensus statements. In this case, the paper identified was classified as a Level II. Using such an approach while conducting a review provides a scheme of references for the practitioners interested in using these results in their practicum. Evidence-based practices are built on the assumption that scientific evidence of the effectiveness of an intervention can be deemed more or less strong and valid according to a hierarchy of research designs, the assessment of the quality of the research, or both.

Reference measurements standards were used to characterize the evaluated population. Elderly individuals were characterized as age 65 and older since it is "the golden age." Other articles made associations between the evolution of a particular phenomenon and advancing age even if <65. The measure for obesity is the body mass index (BMI) as described by WHO (World Health Organization, 2018a). BMI is calculated as weight in kilograms divided by height in meters squared. A BMI $\geq$ 30 kg/m$^2$ is considered obesity.

The presentation of the information will be based on the approach of Wang and Carr (2004) where they have identified three factors for collisions related to optimizing solutions in road safety: the environment, the vehicle and the driver. In this case, the extrinsic factors are the environment and the vehicle since they heighten indirectly the risk of MVC. The intrinsic factor is the driver that is considered as the proximal element that contributes to MVC (**Figure 1**). Finally, prevention strategies and research directions are presented for each factor mentioned.

## DISCUSSION

### Extrinsic Risk Factors

#### Environment

Prior to discussing the consequences of aging and obesity on driving, a brief discussion of our modern environment [some

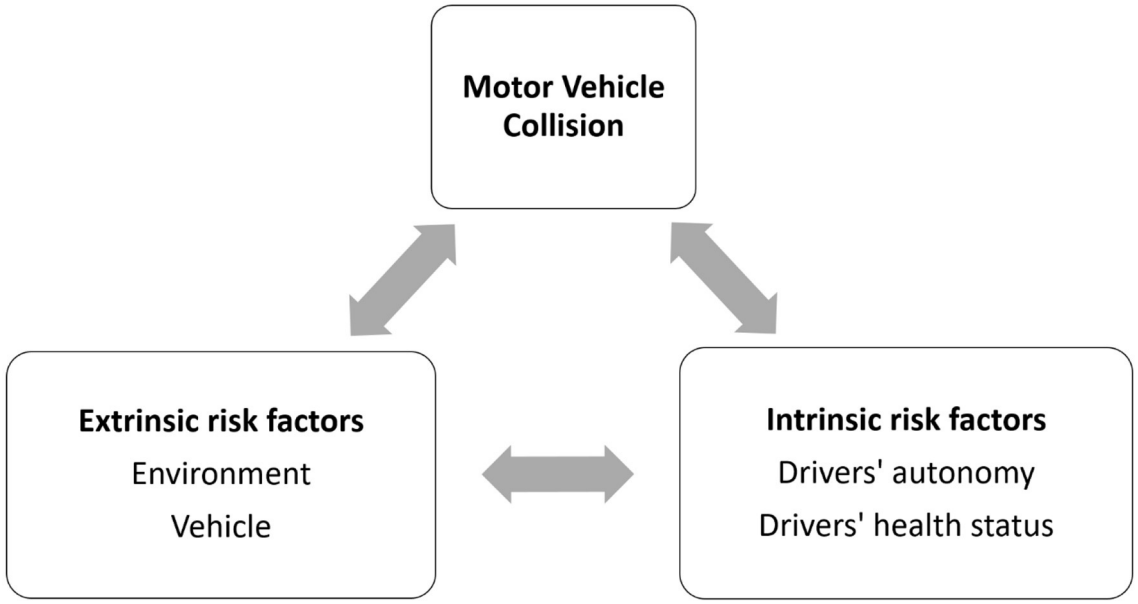


**FIGURE 1 |** Mapping of the association between MVC (motor vehicle collision), extrinsic (environment, vehicle), and intrinsic (drivers' autonomy and health status: pre, during and post-MVC) risk factors found in the literature.

have termed it an obesogenic environment (Kirk et al., 2010)] and how it contributes in a manner that the elderly population tend to use passive mode of transportation, and subsequently how it favors obesity. Tackling the complexities of urban design is beyond the scope of this literature review.

Worldwide, there is increasing urbanization and a typical characteristic of any larger city is that the center is often the economic hub of the region and a major site of employment. Despite the attempt to increase sustainable living quarters in cities (Cooper et al., 2009) many individuals purchase homes on the outskirts of the urban center and commit to a daily commute (Coughlin, 2009), therefore producing a "built environment" favoring longer distances to travel and less physical activity. These are barriers for an aging population who could use active mode of transportation and thus promote passive transportation (Zhao and Kaestner, 2010). Driving is considered as a light physical activity (Ainsworth et al., 2011) reducing the energy expenditure contributory to obesity with more time spent in the vehicle (Hill and Peters, 1998). There exist a relationship between time spent driving and obesity. Each hour spent in a car has been associated with a 6% increase in the likelihood of obesity and each 0.8 km (half-mile) walked (daily) reduced the odds of obesity by 5% (Frank et al., 2004).

Urban and suburban sprawl was measured in most studies and whatever the sample used, people in more sprawled neighborhoods are heavier than those in neighborhoods that are concentrated. Consequently we spent more time behind the wheel and certainly not creating an optimal environment to diminish the impact of the obesity (Maibach et al., 2009; Guo and Gandavarapu, 2010; Tranter, 2010).

## Vehicles

This section is dedicated to view the characteristics of a vehicle which has an impact on the aging obese population. It is in the interest of researchers to explore the design elements of a car in order to adapt or modify it to several type of population to decrease the risk of injury during MVC. The major constraints of the present car design and fit will be discussed.

With the population getting older and heavier, several studies were completed in order to see the effectiveness of the seat belt for obese occupants on the road (Lamielle et al., 2006). The seat belt, composed of a lap belt crossing the hip bone and a belt crossing from the hip to the center of the chest to the shoulder appears problematic for them. For the older drivers, there is an elevated percentage of non-seatbelt users as for obese and overweight drivers. For the aging population, the seat belt seems to be effective but in certain body regions, there are higher risks of injuries for these individuals compared to younger adults due to the position of the restraint system on more fragile structures of the older adult's anatomy. It has also been reported that an increase in body weight was related to a decrease in seat belt usage when compared to normal weight individuals (Schlundt et al., 2007) as well as seatbelt use has been found to be lowest in morbidly obese occupants (i.e., BMI $>$ 40 kg/m$^2$) (Moran et al., 2001; Viano et al., 2008). This trend was present for all age groups except in the 18–24 years old group. Unfortunately, no information is provided to explain these associations.

Furthermore, the seat belt design seems to be effective but have certain risk due to the seat belt positioning issues. Reed et al. (2012) evaluated the belt fit of 54 men and women, forty-eight percent of whom were obese. Their results showed that an increase in BMI of 10 kg/m$^2$ was associated with a lap belt

positioned further forward and higher relative to the anterior-superior iliac spines of the pelvis (of 43 mm and of 21 mm, respectively). Each 10 kg/m$^2$ increase in BMI was associated with an increase in lap belt webbing length (of 130 mm). This increased length of seatbelt introduces slack in the seat belt system by routing the belt further away from the skeleton and might increase body excursions and contacts with the binnacle of the car. Taking both aging and obese population in consideration, the seat belt design is a risk factor since it is not adapted their anatomy, which subsequently elevates their injury and mortality risk.

Furthermore, current car design follow national standards, such as the Canadian Motor Vehicle Safety Standards or the US Federal Motor Vehicle Safety regulations and New Car Assessment Program. Yet, the 50th percentile male Hybrid III crash test dummy has a mass of ∼78 kg and a stature of ∼1.75 m (corresponding to a BMI of ∼25.4 kg/m$^2$). The Hybrid III 95th large male crash test dummy weighs 101.15 kg and measures 1.88 m (corresponding to a BMI of ∼28.6 kg/m$^2$). Despite of differences between dummies' weights and heights (50th−95th percentile male), it is very hard to extend the behavior of these dummies to heavier individuals since the two dummies do not represent obese individuals at all (Moran et al., 2002). If the regulations do not take into account the different needs for the obese population, current car design standards might be causing more injuries for this population.

Taking both aging and obese population in consideration, the seat belt design is an important risk factor since it is not adapted to the fragile anatomy of old and the excess weight of obese individuals, which subsequently elevates their injury risk.

## Intrinsic Risk Factors

### Driver

This section is dedicated to examine the MVC components of older obese drivers. Two elements will be discussed here, the way of thinking of the driver' autonomy and their health issues related to MVC.

#### *Autonomy*

In general, it appears that older people are infrequent public transportation users, and they rely mainly on their privately owned vehicles (Dobbs, 2008). With aging, this is problematic, as shifting from an independent source of transportation to a dependent source of transportation can be challenging for ones sense of autonomy (Edwards et al., 2009). This is recognized as one of the significant factors that prevent older adults to acknowledge when should be the correct time to change from an independent to a dependent mode of transportation. Drivers' autonomy contributes to the use of automobile as the primary method of transportation which does not promote active transportation methods that are positively associated with better health status (Edwards et al., 2009).

#### *Health status*

Numerous health problems associated with aging related illness or conditions have been traditionally linked to MVC. The premise of this section is that the aging and obese driver has increased risk of involvement in an MVC. We will dissect the potential causes or associations for this assumption by using a model inspired by the Haddon's matrix (Haddon, 1972; Runyan, 1998). This matrix provides a framework to structure the presentation of the impact of aging and obesity on MVC. This section will be presented as follows: initial health status (pre-MVC), risk of injury (during-MVC) and injury recovery (post-MVC).

*Initial health status (pre-MVC).* Changes in vision, cognitive processing and physical function associated to aging are thought to be partially responsible for the high rates of MVC among older drivers. Decline in visual function is part of the normal aging process. Reading signs, judging the speed of vehicles and adjusting to darkness are common problems for older drivers (Kline et al., 1992). The reduction of the useful field of view seems to be one of the best predictor of MVCs among older drivers (Owsley et al., 1998; Wood and Owsley, 2014). Cognitive functions important for driving have been identified as attention, memory, perceptual abilities and information processing speed (Colsher and Wallace, 1991), all of which frequently pose problems for older adults. Due to the types of MVC in which older drivers are usually involved [i.e., MVCs with other vehicles at intersections (Preusser et al., 1998)] it is suggested that these events are primarily linked to a decline in cognitive functions (Anstey et al., 2005). Also, it is reported that older people are more prone to having excessive daytime sleepiness independently of having sleep apnea (Bixler et al., 2005). Reduction in grip and muscle strength and endurance, flexibility and motor speed are also age-related factors that may impair driving (Anstey et al., 2005). For example, reduced neck rotation diminishes the driver's ability to turn its head to detect possible peripheral obstacles in complex driving situations.

Obesity is often associated with increased prevalence of obstructive sleep apnea and hypopnea (OSAH) (Smith and Phillips, 2011; Xie et al., 2011), which is in turn, is associated with increased daytime sleepiness (Braeckman et al., 2011) and thought to be a major risk factor for MVC (Papadakaki et al., 2008). Mulgrew et al. (2008) showed that compared to a control group, patients with mild, moderate and severe OSAH had a higher rate of MVC with personal injury. These results are similar to those of other studies that linked OSAH and the risk of being involved in a MVC (Cummings et al., 2001; Ellen et al., 2006; Tregear et al., 2009). OSAH is under recognized by most primary care physicians in the United States; an estimated 80% of Americans with OSAH are not diagnosed (Young et al., 1997). Studies have showed that even obese persons without OSAH can still show signs of daytime sleepiness (Magee et al., 2010). There is even a stronger relationship that people with obesity (independently of having apnea) had excessive daytime sleepiness compared to people with sleep disordered breathing (Bixler et al., 2005).

Furthermore, eye diseases (ex. Glaucoma and cataracts) are related to greater incidence in aging and obese populations (Cheung and Wong, 2007). These alterations compromise vision and thus, safe driving. Diabetes is another comorbidity commonly seen within aging and obese individuals that can

increase risk in driving impairment (Winer and Sowers, 2004). Variations in blood sugar may increase the following symptoms that can increase risk of MVC: sleepiness, confusion, diminished alertness, alteration of vision (blurred vision, vision loss, or diabetic retinopathy) and nerve damage that may cause pain or sensory loss in the hands, legs and feet (Canadian Association of Occupational Therapists, 2009). Cox et al. (2000) advance that diabetes can heighten the risk of driving impairment, mostly with hypoglycemia.

*Risk of injury (during-MVC).* It is important to make the distinction between fragility (i.e., increased risk of injury) and frailty (i.e., reduced capacity to recover from an injury). Regarding aging, one of the biggest issues for older drivers involved in a collision is their increased fragility in comparison with younger drivers (Rockwood and Mitnitski, 2007; Kent, 2010). When considering all body regions, injuries to the thoracic cavity are greatest for older drivers (Kent et al., 2005; Jingwen et al., 2012). There is also an increased risk of thoracic injuries for obese individuals (Boulanger et al., 1992; Cormier, 2008). Risks of incurring a serious or fatal injury are also higher in older individuals (Lyman et al., 2002); after 65 years old the fatality risk increases by ∼3% per year (Frampton et al., 2012).

The possible reasons for this increased fragility are the natural changes in the musculoskeletal system related to aging (i.e., sarcopenia, osteoporosis). The loss of muscle mass and strength (Brooks and Faulkner, 1994) decrease the traction force provided by the tendon on the bone and therefore, reducing the bone mineral density (Hannan et al., 2000). This reduces the capacity to absorb the kinetic energy during the impact (i.e., MVC), and potentially producing more severe injuries. In addition, some studies came to the conclusion that aging with obesity is a risk factor for diminished bone density and the mechanisms for the regulation of bone density could be altered (Villareal et al., 2004). This could elevate the risk of fractures during MVC.

As for obesity, several studies, using different guidelines, have come to similar conclusions concerning the risk of serious and fatal injuries during MVC for obese individuals. Viano et al. (2008) concluded that obesity influences the risk of serious and fatal injury in MVC by conducting a matched paired analysis carried out between normal weight and obese individuals taken from a National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) field data set (1993–2004). Their results showed that obese occupants (drivers and/or passengers) had 54–61% higher risk of injury compared to a normal weight occupant. Moreover, the matched pairs' analysis showed that obese drivers had higher risk of fatality and serious injury than drivers with normal BMI (97 and 17%, respectively) as well as obese passengers (32 and 40%, respectively). Using NASS-CDS data from 2003 to 2007, Ma et al. (2011) looked at the association between non-fatal MVC injuries and obesity. Their results showed that obese male drivers were at greater risk for non-fatal injuries than non-obese male drivers. This effect was not observed for female drivers, perhaps due to differences in body weight distribution as hypothesized by the authors. This difference has also been presented as the "cushion effect" (Arbabi et al., 2003; Wang et al., 2003). However, there is currently no way of characterizing body weight distribution in any road safety data set. Possibly showing the influence of the cushion effect, Jehle et al. (2012) evaluated 155,584 fatalities from the Fatality Analysis Reporting System's (FARS) database for the year 2000–2005. Results showed that the adjusted risk of mortality from the lowest to the highest in comparison with normal BMI was: 1st overweight, 2nd obese class I, 3rd normal BMI, 4th underweight, 5th obese class II obese, and 6th obese class III. This result shows that perhaps overweight and obese class I individuals could be advantaged by the "cushion effect."

Other studies observed the body region impairs by injury as well as the pattern of injury among obese individuals. Zhu et al. (2010) created computer models based on 10,941 individuals from a NASS-CDS field data set (2001–2005) implied in frontal collisions, and created MVC simulations. According to their modelization, obese men had a higher risk of serious injury and more particularly to the upper body, such as the head, neck, thorax, and spine (i.e., cervical, thoracic, and lumbar) compared to normal weight individuals. Overall, men were more at risk of serious injury than women in every region (except for extremities and abdominal region). Similarly, Rupp et al. (2013) used the Abbreviated Injury Scale (AIS) to evaluate the effects of BMI on the risk of serious-to-fatal injury (≥3 or AIS 3+) to different body regions for adults in frontal, nearside, far side, and rollover MVCs. Their results showed that increased BMI increased the risk of lower-extremity injury in frontal MVCs, increased risk of upper-extremity injury in frontal and nearside MVCs, and increased risk of spine injury in frontal MVCs. Interestingly, there was a decreased risk of lower-extremity injury in nearside impacts for that same group. It was estimated that if no occupants in frontal collision were obese, 7% fewer occupants would sustain AIS 3+ upper-extremity injuries, 8% fewer occupants would sustain AIS 3+ lower-extremity injuries, and 28% fewer occupants would sustain AIS 3+ spine injuries. Recent literature reviews on the impact of obesity on driving came to the same conclusion (Desapriya et al., 2011; Lavallière et al., 2012).

### *Injury recovery (post-MVC)*

In addition to their increased fragility, older people tend to take longer to recover from an injury than their younger counterparts. Nagy et al. (2000) compared data from 85 older trauma patients (≥65 years old) to younger patients (15–40 years old) with similar injuries. Their results showed that older patients had a longer hospital stay (6.9 ± 9.1 vs. 4.3 ± 5.7 days) and spent more days at the intensive care unit (7.3 ± 9.2 vs. 3.4 ± 3.2 days) than younger patients. Older individuals also have increased mortality from complications in the hospital (i.e., days following the surgery) than their younger counterparts (Perdue et al., 1998). Occupants aged over 80 years old were more likely to die from their injuries after an MVC than 65–79 years old occupants (Bansal et al., 2009).

Obesity has also been associated with mortality and complications following surgical procedures in trauma settings (Glance et al., 2014). As an example, following knee arthroplasty of 15,321 patients, age and diabetes were showed as independent predictors of mortality whereas a BMI greater than ≥40 kg/m$^2$ was an independent predictor of post-operative complications

(OR = 1.47; 95% CI = 1.09–1.98) (Belmont et al., 2014). However, it is impossible to identify whether it's the accident or the surgery that caused mortality or complications because no information concerning the cause is mentioned in the FARS database.

Newell et al. (2007) investigated the relationship between BMI and outcomes in blunt injured patients. Their results showed that, when compared to normal BMI, morbid obesity was associated with increased morbidity (e.g., acute respiratory failure, multisystem organ failure) but not with increase mortality (OR 0.81, 95% CI, 0.35–1.86). Neville et al. (2004) also reported that obesity is an independent predictor of mortality following severe blunt trauma. It appears that following a MVC, it is possible that both surgery and post-surgery recovery are affected by aging and obesity (and their related co-morbidities). One comorbidity, commonly seen in aging obese, that can create complications is diabetes. Diabetes can compromise many steps of the wound healing process that increases the healing time and can contribute to ulcer formation (Blakytny and Jude, 2006).

## PREVENTION STRATEGIES: WHAT ARE THE SOLUTIONS

This section is dedicated to possible interventions proposed by the literature and public organizations to decrease the risks of the aging and obese populations to be involved in a MVC. Considering that the driver has a direct impact on the prevalence and risks during and post-MVC, the presented paper identify strategies to improve the health issues of the driver (intrinsic factor), their vehicle and its environment by optimizing the extrinsic factors for safety.

### Environment

There are several characteristics of the built environment that could be improved in order to satisfy the needs for the aging obese individuals. It is important to promote "age-friendly" environment and several organizations have responded to the present issues for the elderly population. Recent initiatives by the WHO have put forward "Age-friendly Cities and Communities" (World Health Organization, 2018b). Two of the main concerns of this network are 1) outdoor spaces and buildings, and 2) transportation. This initiative aims to help cities and communities make changes to best suit the needs of older people and promote active aging. Similarly, the Beverly Foundation (Beverly Foundation, 2001) identified the "5 A's" to senior-friendly transportation: availability (transportation services are provided to seniors when required), acceptability (service quality acceptable and adapted to seniors; clean and well-maintained vehicles), accessibility (provide "door-to-door" and "door-through-door" transportation), adaptability (can make multiple stops or different routes, better crossing signs for pedestrians and accommodate wheelchairs and walkers) and affordability (cost of transportation is affordable). The 5 A's reflect the general needs of the elderly population and these solution paths should be considered with close attention.

For obese individuals as of for older, an optimal environment should be designed and constructed in such a way as to promote physical activity, healthy habits and active modes of transportation (ex. access to bicycles and docking stations) to facilitate prevention. These types of strategies appear to be successful at encouraging individuals to adopt more active lifestyles which have been shown to decrease obesity rates and improve health status. While conducting the literature review, only one reference addressed the topics of neighborhood design, physical activity, obesity and older individuals. This study, conducted by Frank et al. (2010), found that an increased walkability score in a neighborhood was associated with increased levels of walking, although the amount of walking was less than the daily minimum requirements of physical activity guidelines (Garber et al., 2011). This suggests that a neighborhood design that only focuses on improving walkability is insufficient as a strategy to promote activity levels to those suggested in national guidelines. Despite the small quantity of physical activity through walking, there exist positive associations between walkability distance and beneficial health outcomes.

After looking at the issues raised by aging and obesity, there are two ways of responding to optimize the environment 1) adapt the road infrastructure 2) promote active transportation. For the first point, there are several recommendations, such as increasing the visibility of the road signs (bigger size, and elevated luminance) and decrease speed limits in strategic places could be possible measures (Cooper et al., 2009). For the second point, safe walking paths (lit and with minimal risk of fall elements), better road crossing systems, are some of the possible changes that could be proposed (Spence et al., 2009). Considering both population's characteristics and needs more carefully, promoting active transportation is possibly the best solution due to the increased risk of MVC for these people (even with environmental changes) and promoting a healthy lifestyle to aging obese individuals.

### Vehicle

Considering the increasing worldwide prevalence of aging and obesity for the next decades, better adapted vehicle designs are needed shortly. Some components of the vehicle fit can improve comfort of the occupants, but also decrease the risk of injuries during MVC. The designs that can be adjusted to the individual's anthropometric measures can facilitate the ingress/egress and the comfort while driving (Wang and Carr, 2004). Additional handles to ease ingress and egress of vehicle, belt extension options, steering wheel size options, and telescopic steering column are all options that car dealerships should offer to their clients. For a decreased risk of injury during a MVC, there is a need for new intelligent safety restraining systems that can adjust to heavy weights and integrated seat belt systems that improve the fit. Also, new protection elements, such as dual-stage airbags to decrease the initial impact of the air-bag, increase protection near the feet by putting additional airbags and have active head restraint system in order to prevent injuries to the neck (Wang et al., 2003).

Although new technology is being developed or emerged progressively in order to give the driver feedback on driving

capabilities (physical and cognitive). For example, advanced state detection systems can detect state of under-arousal (e.g., drowsiness) and over-arousal (e.g., detecting overload in compromised individuals) through physiological measures (i.e., reduced visual scanning, and percent of eye closure). This feedback system would particularly be helpful among individual with sleepiness symptoms (Reimer et al., 2009). On top of these technologies aimed at the state of the driver, other developments have been made in order to alert the driver of incoming risky/adverse event (i.e., forward collision warning) or mitigate (i.e., autonomous emergency braking). Reports from the Insurance Institute for Highway Safety (IIHS) (IIHS, 2012) have shown that these technologies are effective at reducing the number of MVC and the severity of them.

However, when it comes to vehicle selection, most of the auto industry is focused on selling cars to young drivers. Strangely, people aged 25 are less prone to buy a new car than the one aged 65 and older. Manufacturers know that not a single driver will buy a vehicle if it is advertised as the "older drivers' vehicle" or model (Yoon et al., 2009). Other studies have looked at the vehicle selection of older drivers. Vrkljan and Anaby (2011) asked drivers of 18 years and older, to rank the importance of eight vehicle features (storage, mileage, safety, price, comfort, performance, design, and reliability). Indifferently of age, safety, and reliability were the most highly rated and seemed to be even more important among older drivers (Koppel et al., 2013). Although older drivers seem to rank safety as number one feature, this might not be their priority when they are at the car dealership (Zhan et al., 2013). While drivers rely on technologies (e.g., braking systems and air bags) rather than collision test and collision worthiness to ask about vehicle safety, it might be important to emphasis on all safety characteristics by increasing the vulgarization of: "what are the safety characteristics and why are they important for my own safety" (Koppel et al., 2013).

Nothing is known about the vehicle buying decisions of people with greater BMI's, it is suggested that they are buying bigger vehicles for their increased interior space. It would be interesting to investigate the factors that lead to purchase of a certain type of vehicle in more detail. For example, the security issue as well as "comfort." If a vehicle is perceived as being more comfortable, what are some of the specific characteristics that lead the driver to describe the vehicle as comfortable? Moreover, these bigger vehicles are also recognized for their higher safety in MVC mitigation, which might underestimate the actual implication of obesity in the mortality rate.

### Driver

Concerning the possible prevention programs, there should be a combination of better screenings and interventions in order to decrease risk of MVC for certain populations, such as aging and obese individuals (Viamonte et al., 2006). Tests should be administered regularly in order to detect the drivers that do not have the abilities to drive. Another efficient method was used by Ontario (Canada), where drivers who had medical issues, such as alcoholism, dementia, sleep disorders, diabetes, and epilepsy were given medical warnings on a 3 years period to. This prevention program reduced by 45% annual collision rates for this population and 41% annual collision rates for people with diabetes compared to the statistics of the period before medical warnings were implemented (Redelmeier et al., 2012).

After having detected these individuals, interventions can be made in order to regain the right to drive. For instance, seeing a health specialist in order to improve the health issues that influence the driving skills is the first step to take. They could suggest different alternative solutions like specific medical treatments, specific trainings, and educate aging obese to regain the license. To improve one's ability to drive safely, specific training seems to be an effective strategy to develop certain qualities of aging obese individuals to decrease the risk on the road.

Finally, education toward some medical conditions commonly associated with aging and obesity, like diabetes, could prevent driving impairment by recognizing the signs of a possible risk of driving mishap and how to deal with the medical issue in certain situations (Craik, 2011). Furthermore, older obese individuals should be educated concerning their behavior toward the definition of autonomy. It has been shown that healthy aging is associated with the adaptability of the person to accomplish daily activities and to be aware of its limitations (Hansen-Kyle, 2005). This means that older obese individuals who take the road with poor fitness to drive would be considered less autonomous than using alternative methods of transportation. It is important to expose the danger of this attitude for their health and safety and the one of other road users.

## LIMITATIONS

It is often mentioned as being difficult for researchers to differentiate between lean and fat mass for individuals in database usage as well as making sure BMI is a clear indicator of obesity. Another approach, suggested in cardiovascular diseases prevention, indicates that the best way of diagnosing the risk would be with a waistline measurement (Despres, 2009). Therefore, it is suggested that waist circumference might be a better alternative when evaluating the impact of weight in car collisions (Arbabi et al., 2003). Unfortunately, there is no dataset, to our knowledge, that includes such information. As a result, most of the literature uses a surrogate measure, BMI, and this is a limitation in the research. Additionally, many studies adjust for age in their statistical analysis thus removing any age indicators in statistical results. Moreover, most of the studies used age as a confounding factor and therefore diluted the results that were of interest for the current review. Furthermore, a limitation of this study is the lack of studies conducted on obese and aging individuals as one type of population. Most of the literature used in this article is conducted on only obese or aging individuals. With this limitation, it is difficult to document the impact of the interaction of both conditions on the risk of MVC. Moreover, often associated with aging and obesity, there is a multitude of health conditions and medications usage associated to them that could alter driving capacities and therefore increases risk of being involved in a MVC. These health conditions and their

associated medications could not be covered in the current narrative review. Finally, a probable limitation of this narrative review includes the search process itself, which may not have allowed the identification of all studies showing the effects of age and obesity on motor vehicle collisions. The use of additional databases, such as CINAHL, PsychInfo, and ERIC might have led to slightly different results (Falagas et al., 2008) as well as other search terms.

## CONCLUSION

The baby boomers represent a new generation on its own as consumers (Coughlin, 2009). They have experienced mobility, new technology and a growing trend in improvement in every field. While aging, they expect to continue this type of lifestyle and they will ask more from the industries. Also, many of them are aging, and not necessarily in a healthy way, while others are aging obese. Aging obese individuals are facing many challenges, and one of them is that their vehicle are not properly designed for them. Certainly, an approach of interest for car manufacturers would be to aim a universal design, it is a moving target however and that will be hard to fulfill, since the discrepancy in the anthropometry of drivers is getting more spread out. Therefore, we do have to raise awareness of manufacturers and designers to develop adapted vehicle in the future.

## AUTHOR CONTRIBUTIONS

ML, MT, FL, MB, and GH contributed equally to this manuscript. All authors contributed to the article and approved the submitted version.

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# Convolutional Neural Network for Driving Maneuver Identification Based on Inertial Measurement Unit (IMU) and Global Positioning System (GPS)

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Identification and translation of different driving maneuver are some of the key elements to analysis driving risky behavior. However, the major obstacles to maneuver identification are the wide variety of styles of driving maneuver which are performed during driving. The objective in this contribution through the paper is to automatic identification of driver maneuver e.g., driving in roundabouts, left and right turns, breaks, etc. based on Inertia Measurement Unit (IMU) and Global Positioning System (GPS). Here, several machine learning (ML) algorithms i.e., Artificial Neural Network (ANN), Convolutional Neural Network (CNN), K-nearest neighbor (k-NN), Hidden Markov Model (HMM), Random Forest (RF), and Support Vector Machine (SVM) have been applied for automatic feature extraction and classification on the IMU and GPS data sets collected through a Naturalistic Driving Studies (NDS) under an H2020 project called SimuSafe[1]. The CNN is further compared with HMM, RF, ANN, k-NN and SVM to observe the ability to identify a car maneuver through roundabouts. According to the results, CNN outperforms (i.e., average $F_1$-score of 0.88 both roundabout and not roundabout) among the other ML classifiers and RF presents better correlation than CNN, i.e., $MCC = -0.022$.

**Keywords: convolutional neural network, driving maneuver, inertial measurement unit, global positioning system, machine learning**

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## INTRODUCTION

Since the number of vehicles and road traffic users are increasing rapidly, the number of accidents is also increasing. In everyday life, car drivers are involved in several driving maneuver e.g., driving in roundabouts, left and right turns, breaks, etc. while they are driving, and risky maneuver are also causing accidents (Gerdes, 2006). Thus, road traffic safety issues are increasingly important for research and development for governments and vehicles manufacture. The European Commission is aiming to reduce the number of road accidents with the vision to achieve zero road fatalities in EU (KPMG, 2012; Fagnant and Kockelman, 2013). To meet this objective and to improve the traffic safety and efficiency, it is necessary to understand the wide variety of styles for driving maneuver which promotes initiatives to conduct researches to reduce the rate of road accidents

[1]http://simusafe.eu/

and to improve road safety. Again, understanding the driving maneuver can help us to build models of drivers to improve Advanced Driver Assistance Systems (ADASs), vehicle safety, and privacy and help to detect risky driving styles (Zardosht et al., 2018).

"SimuSafe: Simulation of behavioral aspects for safer transport" is a project funded by the European Union, H2020, where one of the main objectives is to create a realistic behavioral model such that researchers will be able to conduct research and collect data not available in real-world circumstances (Ahmed et al., 2017). Under the SimuSafe project, Naturalistic Driving Studies (NDS) have been conducted to examine a real traffic situation by observing the drivers driving maneuver like accidents and near misses, crashes, etc. (Barnard et al., 2016; Muronga, 2017; Feng, 2019). As NDS data are collected along with a large time frame this makes the time-consuming, tedious and impractical task of identifying maneuver manually by a human. Thus, this challenge has inspired the need to research and develop an automated system that capable of identifying potential maneuver i.e., roundabouts reliably. Several research studies have been found in the literature that aim for identification of basic events, e.g., identify whether a car is accelerated, braked, made a left/right/U-turns, or any risky driving maneuver, e.g., sharp turning (Di Lecce and Calabrese, 2009; Johnson and Trivedi, 2011; Van Ly et al., 2013; Zheng and Hansen, 2016; Hernández Sánchez et al., 2018; Ouyang et al., 2018; Ma et al., 2019), however, the identification of roundabouts is not as common (Zhao et al., 2017; Altarabichi et al., 2019).

The main challenge in this study is to determine the best Machine Learning (ML) algorithm for identifying driving maneuver i.e., roundabouts from the NDS based on the sensory data from IMU and GPS by investigating several ML algorithms. This paper presents an automatic driving maneuver e.g., driving in roundabouts, left and right turns, breaks, etc. identification system. Here, the study determines Convolutional Neural Network (CNN) as a best ML algorithm to identify driving maneuver based on Inertia Measurement Unit (IMU) and Global Positioning System (GPS) data collected through the NDS in SimuSafe. The proposed system is also compared and evaluated with different ML algorithms e.g., Hidden Markov Model (HMM), Random Forest (RF), Artificial Neural Network (ANN), K-nearest neighbor (k-NN) and Support Vector Machine (SVM) to observe the capability of detecting driving maneuver, specifically the driving maneuver for navigating a roundabout. The NDS data are collected using 16 volunteers over a period of 3 months in two different countries through naturalistic driving, i.e., the drivers were not controlled and restricted to a predetermined path. Here, the test cars were equipped with GPS and IMU, and the IMU consists of an accelerometer and a gyroscope. Thus, the test vehicular sensors are used to capture different aspects of driving dynamics and motion to identify roundabout as a driving maneuver.

## BACKGROUND AND RELATED WORK

ML is a subset of AI focuses on developing computer programs capable of learning from experience (Fernandes de Mello and Antonelli Ponti, 2018). According to –Tom Mitchell, "a computer program is said to learn from experience E with respect to some class of tasks T and performance measure P if its performance at tasks in T, as measured by P, improves with experience E" (Robert, 2014). *Supervised classification* problems involve an input space (i.e., the instances of $\chi$) and an output space (e.g., the labeling of $\Upsilon$). An unknown target function $f : \chi \rightarrow \Upsilon$ defines the functional relationship between the input space and output space. As mentioned above, a dataset $D$ exists containing input-output pairs $(\chi_1, \Upsilon_1), \ldots\ldots, (\chi_n, \Upsilon_n)$ drawn as an independent and identical distribution (i.i.d) from an unknown underlying distribution $P(\chi, \Upsilon)$. The goal is to find a function $g : \chi \rightarrow \Upsilon$ that can approximate the solution of $f$ with minimum errors. The function $g : \chi \rightarrow \Upsilon$ is called a classifier (Friedman et al., 2001). Supervised learning is applicable when the given set of data has a known output for the specified inputs. Several supervised ML algorithms i.e., CNN, ANN, HMM, RF, k-NN, and SVM.

The *HMM* is a supervised learning algorithm, widely used for classification and pattern recognition. It has been used in the field of voice recognition to determine the phrase or word and in the context of natural language processing (NLP), i.e., part-of-speech tagging and noun-phrase chunking (Rabiner, 1989). HMM is built on the assumption that only the results of the actions of states are observable, states are not directly observable, they make observations, which are weighted by their probability. By considering all the possible order of states, and the probability of their actions, the order of states that has the highest probability is selected as the final one. Two models are currently considered namely, Discrete Hidden Markov Models (DHMMs) and Continuous Hidden Markov Models (CHMMs) (Attal et al., 2013; Yiyan et al., 2017).

*k-NN* is a non-parametric simplistic ML algorithm. It does not need to fit the data, which makes it flexible in the sense that k-NN is a memory-based algorithm which uses the observations in the training set to find the most similar properties of the test dataset (Breiman, 2001). In other words, k-NN classifies an unseen instance using the observations that have closest match similarity ($k$-number nearest neighbors) to it. In the statistical settings, k-NN does not make any assumptions about the underlying joint probability density, rather uses the data to estimate the density. In k-NN, a distance function e.g., the Euclidean distance function is often used to find the $k$ most similar instances. Then methods like majority voting is used on the $k$-neighbor instaces that indicates most commonly occurring classification to make the final classification. The bias-variance trade-off of k-NN depends of the selection of $k$, i.e., the number of nearest neighbors to be considered. As the value of $k$ gets larger the estimation smoothed out more. Since k-NN is based on a distance function, it is straightforward to explain the nearest-neighbor model when predicting a new unseen data. However, it may be difficult to explain what inherent knowledge the model has learned.

*ANN* is a method that is vaguely inspired by the biological nervous system, i.e., neurons in a brain. It is composed of interconnected elements called neurons that work in unity to solve specific problems (Basheer and Hajmeer, 2000; Drew and Monson, 2000; Zhang, 2000). The neurons are connected through links, and numerical weight is assigned to each neuron. This weight represents the strength or importance of each neuron input and repeated adjustment of the weights are performed

to learn from the input. Various types of neural networks are described in Basheer and Hajmeer (2000), and one of the most popular network architectures is the multilayer feedforward neural network methods using backpropagation to adapt/learn the weights and biases of the nodes. Such networks consist of an input layer that represents the input variables to the problem, an output layer consisting of nodes representing the dependent variables or the classification label, and one or more hidden layers that contain nodes to help capturing the nonlinearity of the data. The error is computed at the output layer and propagates backwards from the output layer to the hidden layer, then hidden layer to the input layer.

*CNN* is the most common approach that uses deep learning that applies neural network architectures with more than one hidden layer, i.e., if there are multiple hidden layers, it is referred to as a Deep Neural Network (DNN). One of the most popular types of deep neural networks is known as *CNN* and commonly used for pattern recognition and image processing, such as street sign recognition and pedestrian detection (Gerdes, 2006; Zhao et al., 2017). Like a typical neural network, a CNN consists of an input layer, a combination of convolutional and pooling layers, i.e., has neurons with weights and biases. The model learns these values during the training process, and it continually updates them with each new training example. However, in the case of CNNs, the weight and bias values are the same for all the hidden neurons in a given layer. The advantages of using CNN is that it requires less or no prepossessing (Al-luhaibi et al., 2018), a graphical representation can be seen in **Figure 1**.

*RF* is a popular ensemble algorithm in ML that consists of a series of randomized decision trees, where every tree is built using a random split selection (Breiman, 2001). Each decision tree is trained using bootstrap data samples, where bootstrapping is the process of creating samples with replacement. During the bootstrapping process, not all the data are selected for training; the selected data are referred to as out-of-bag data, and these out-of-bag data are used to find the generalization error or the out-of-bag error. The trees will each have a random bias, to not overfit the data. During the tree-generation process, for the *k-th* tree, a random vector $\upsilon_k$ is generated, which is drawn from the same data distribution but independent of previous random vectors $\upsilon_1, \ldots\ldots, \upsilon_{k-1}$. For the given training dataset, the tree grows using the random vectors $\upsilon_k$ and creates a predictor $h(\chi, X_k, \upsilon_k)$, where $\chi$ is the input data, $X_k$ is the bootstrap sample, and $\upsilon_k$ consists of several number of independent random variables $m$ between 1 and $K$. Different generalizations can be achieved by varying the number of variables; it is recommended to start the search from $m = [\log_2 K + 1]$ or $m = \sqrt{K}$ (Breiman, 1996, 2001). After generating a large number of trees, the output is the majority vote of all these decision trees. The important aspects of a random forest are that as the forest grows by adding more trees, it will converge to a limiting value that reduces the risk of overfitting and does not assume feature independence. RF is implemented using bagging, which is the process of bootstrapping the data plus using aggregation to make a decision. Thus, from a given input, the algorithm selects the most common class from the collection of trees to be the best choice (Vapnik, 1992; Ho, 1995).

*SVM* is used for separating and classifying data into different distinct classes by finding the hyperplane that not only minimizes the empirical classification error but also maximizes the geometric margin of the classification (Vapnik, 1992; Guyon et al., 2002). SVM maps the original data points in the input space to a high dimensional feature space, making the classification problem simpler. Hence, SVM is suitable for classification problems with redundant datasets (Ertel, 2018). Consider an n-class classification problem with a training data set $\{\chi_i, \Upsilon_i\}_{i=1}^n$, where $\chi_i \in \mathbb{R}^d$ is the input vector, and $\Upsilon_i$ is the corresponding class label. The SVM maps the d-dimensional input vector space to a $d_h$-dimensional feature space and learns the separating hyperplane $\langle w, \chi \rangle + b = 0, b \in \mathbb{R}$ that maximizes the margin distance $\frac{2}{\|w\|_2^2}$, where $w$ is a weight vector, and $b$ is the bias. The SVM classifier obtains a new label $\hat{\Upsilon}$ for the test vector by evaluating Equation (1):

$$\hat{\Upsilon} = \sum_{i=1}^{N} w_i.K(\chi, \chi_i) + b \tag{1}$$

where $N$ is the number of support vectors, $w_i$ are the weights, b is the bias that is maximized during training and $K$ is the kernel function.

An overview of different ML approaches in driving maneuver identification with a result analysis of the related work is presented in **Table 1**. As can be seen accelerometer, gyroscope,

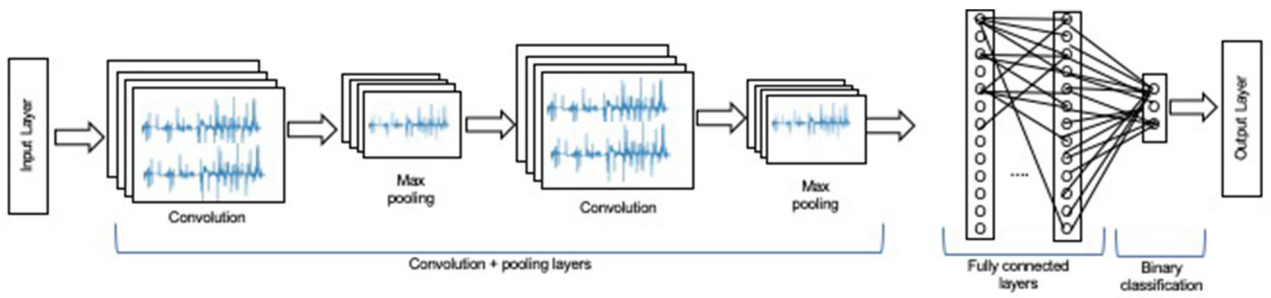


**FIGURE 1 |** A graphical representation of CNN is presented.

**TABLE 1 |** Some related articles based on ML algorithms, parameters, sensors, etc.

| Algorithms | Device, sensors, parameters | Classes | Comments | Articles |
|---|---|---|---|---|
| SVM, Topological Anomaly Detection | Smartphone with Accelerometer, Gyroscope, and GPS are used for vehicle | 4 classes for Driver Behavior rank from A to D | Average results were reliable | Zheng and Hansen, 2016 |
| Dynamic Time Warping | Smartphone with Accelerometer, Gyroscope, Magnetometer, and GPS are used for vehicle | 12 classes, Turns, Aggressive Turns, U-Turns, Aggressive U-turns, Aggressive acceleration, Aggressive Braking, Swerve, Device Removal, Excessive Speed | Very limited training sets with more classes, results were average | Johnson and Trivedi, 2011 |
| K-means, SVM | IMU sensor with Accelerometer in lateral axis from car CANbus | 10 different classes in Acceleration, Breaking, Turns, combinations | Results were not good; 65% accuracy is achieved by SVM | Van Ly et al., 2013 |
| Random forest, C-SVC, IBk, JRip, J48, Naïve Bayes | Smartphone with Gyroscope used for vehicle | 5 classes with turns, U-turns, lane changes | Random forest achieved 98% accuracy on an average | Ouyang et al., 2018 |
| Gaussian mixture model (GMM), Partial least squares regression (PLS), Support Vector Regression (SVR), Wavelet | Smartphone with Accelerometer and Gyroscope used for vehicle | 2 classes, Aggressive and not Aggressive behavior | With single parameters GMM and SVR are provided better classification than multiple parameters with GMM and PLS | Ma et al., 2019 |
| ANN | GPS and Biaxial Accelerometer used for vehicle | 6 classes with Acceleration/Deacceleration, Turns/NotTurns, Overtaking/NotOvertaking | The ANN achieved 88% accuracy with 4 hidden layers and 200 epochs | Di Lecce and Calabrese, 2009 |
| Principle Component Analysis (PCA), CNN, Recurrent Neural Network (RNN) | Smartphone with Accelerometer used for vehicle | 4 classes with Acceleration, Breaking, Turn, and Others | Achieved 90% accuracy by PCA based on longitudinal and lateral component | Hernández Sánchez et al., 2018 |
| SVM | Sensors with powertrain, steering, GPS, and Odometer | 2 classes for stop and start | SVM achieved 95% in prediction | Zhao et al., 2017 |
| HMM | Smartphone with Accelerometer and GPS are used on human movement analysis | 5 classes with Stop, Walk, Run, Bicycle, Motorcycle (MC) | Stop, walk, MC were identified, but overlapping with run and bicycle | Waga et al., 2012 |
| ANN, RF, k-NN, Logistic Regression (LR) and SVM | IMU devices mounted in vehicle | 2 classes roundabouts and others | ANN model outperforms other classifiers achieving 81% F1 score for roundabout identification | Altarabichi et al., 2019 |
| RF, SVM and ANN | 3-D accelerometer/gyroscope sensors mounted on motorcycles | 5 classes with left turn (LT), right turn (RT), straight line (SL), roundabout (RA), and stop (ST), | Random Forest method performs most consistently through the different data sets and scores best | Larose, 2005 |

magnetometer is commonly used as IMU together with GPS. These parameters are gathered through smart phones, car CANbus, and other specific devices. Again, commonly used ML algorithms are ANN, RF, k-NN, LR, and SVM. Here, all of them are supervised ML algorithms, which includes classes between two and twelve, e.g., stop and start maneuver, and turns, aggressive turns, U-turns, aggressive U-turns, aggressive acceleration, aggressive braking, swerve, device removal, excessive Speed. It was also observed that several of the research has identified maneuver with a higher accuracy i.e., more than 90% accuracy. For example, the authors in Zheng and Hansen (2016) applied SVM, and Topology anomaly detection for driver behavior based on accelerometer, gyroscope and GPS through smart phone. Again, in our previous work (Altarabichi et al., 2019) and (Larose, 2005), several ML algorithms such as ANN, RF, k-NN, LR, SVM have been applied in IMU and 3-D sensors that had been mounted in a car and motorcycle to classify roundabouts, left turns, right turns, straights, and stops. Unsupervised ML such as PCA, CNN and RNN have also been applied on accelerometer data collected from the car to classify accelerations, breakings, and turns as presented in Hernández Sánchez et al. (2018). Different anomaly detection algorithms were compared by Ma et al. (2019) to detect aggressive behavior of the drivers using motion data from an accelerometer and gyroscope data that are collected by a smartphone mounted in a vehicle. The algorithms have used in the report are Gaussian Mixture Model (GMM), Partial Least Squares Regression (PLSR), Wavelet, and SVR. SVR is a regression version of SVM. Their results have shown that the algorithms are promising for detecting aggressive driving when using both the accelerometer and gyroscope, compared to when using either of the sensors

**FIGURE 2 |** Example of roundabout labeled by GPS data.

independently. The GMM got a $F_1$-score of 0.76 and SVR got 0.73.

## MATERIALS AND METHODS

The data used in this study are obtained through the SIMUSAFE project using timestamped sensor data that corresponds to NDS trips. There are 16 volunteers and the data are collected between May and August 2018. The data had been collected from cars equipped with sensors, e.g., the IMU and GPS.

Inertial measurement unit (IMU) is required within SIMUSAFE DAS because such measurements available on-board in vehicles are not standardized. Thus, myAHRS+ is used as exact unit because of its guaranteed compatibility with ODROID DCP. Another important advantage is the availability of a driver (BSD license) for ROS distribution used in SIMUSAFE DCP. The IMU requires calibration due to installation position, because measurements in host vehicle coordinate system are required. Similarly, a USB GPS module named "Ublox G7020-KT" is used because of cost and being distributed over ODROID website, thus ensuring compatibility and support of the SIMUSAFE DCP. The GPS unit readings are handled by DCP system that uses a gpsd service. Such system was found not to provide a PPS signal and therefore DCP clock is synchronized over network rather than via GPS. The roundabout entries from the smart camera were used to label the datasets to find out whether they are roundabout or not. The GPS is used to collect the longitudinal and latitudinal coordinates. Since the supervised learning requires data to be labeled, all the GPS points were plotted on a map as presented in **Figure 2**. Two types of feature extractions have been conducted, (1) window-based feature extraction and (2) maneuver-based feature extraction. Here, the fixed window-based feature extraction is more common, widely used traditional approach where the sample size can be increased and decreased based on the size of the window and also, calculation time is very less. As the window size is always same for all the feature, the feature value is stable. On the other hand, the maneuver-based is a new way to test the approach, proposed by Pilko et al. (2014) and Gonzalez et al. (2017), here the concept of dividing the driving process in a roundabout into three stages: entrance, driving within the roundabout and exit maneuvers. To account for this maneuvers sequence, each dataset instance is built using a rolling window with three maneuvers as a window size. Thus, the sample size is decreased and also feature value is not stable and window size is different for each feature as it is depending on the combination of a sequence entrance -> in the roundabout -> exit. Moreover, the computation time is also very high then the other method and as the sample size it less no possibility to used CNN.

**TABLE 2 |** IMU sensor signals with corresponding parameters.

| No. | Signal | Description | Parameters |
|---|---|---|---|
| 1. | RollRateExtSns | Vehicle roll rate | Roll |
| 2. | RollExtSns | Roll angle of vehicle chassis | |
| 3. | PitchRateExtSns | Vehicle pitch rate | Pitch |
| 4. | PitchExtSns | Pitch angle of vehicle chassis | |
| 5. | YawRateExtSns | Vehicle yaw angle | Yaw |
| 6. | LongAccelExtSns | Longitudinal acceleration | Acceleration |
| 7. | VertAccelExtSns | Vertical acceleration | |
| 8. | LatAccelExtSns | Lateral acceleration | |

In *window-based feature extraction*, the roundabout detection model is developed to use IMU sensor data for the purpose of classification, eight signals are utilized from IMU sensory data as observed in **Table 2**. The IMU sensors collected data in the form of acceleration in the longitude, lateral, and vertical direction, pitch, roll values, and yaw rate. The longitude axis was aligned with the direction of the car face, and the vertical axis was placed perpendicular to the road (Altarabichi et al., 2019). The filtered and labeled data set contains 76306 data points, of which 847 are labeled as roundabouts. The calculated median time to travel through a roundabout, in the data set, is 8 s, with the average time being slightly longer. The data are windowed, windowing gives information before and after a given point and therefore aids the classification of longer lasting maneuver.

In *maneuver-based feature extraction*, the data are resampled with 14 to 1 Hz to reduce signal noise, and a Gaussian rolling window is applied to smoothen the resampled signals. The YawRateExtSns is selected as a base signal to establish the start and end time of driving maneuvers. The integral of YawRateExtSns readings between start and end time is calculated to measure the corresponding Yaw angle of the performed maneuver. The time series of sensor readings that represent driving trip is transformed accordingly into a sequence of maneuvers performed by the vehicle. Driving

maneuvers are presented by eight time-domain features that correspond to the mean value of each of the eight IMU signals throughout the maneuver. A ninth feature is added that corresponds to the calculated Yaw angle, and a feature that corresponds to the duration of the maneuver in seconds is added to total of 10 features per maneuver. This approach generated a training data set that consist of 22111 instances. GPS signals were used to label 249 roundabouts occurrences manually according to the map images of the driving trips (Altarabichi et al., 2019).

With *window-based features,* the CNN, HMM, RF, and SVM have been applied to classify maneuver. In our previous work (Altarabichi et al., 2019), the class imbalance in the dataset is addressed by performing validation assigning a weight to roundabout class {1, 2, 4, 8, 16, 99}, however, the results were not satisfactory. Thus, the paper focuses both on assigning a weight to roundabout class and the stratified sampling on the imbalance data set for the machine learning modeling. Through *CNN*, to account for the unbalanced representation of classes, roundabouts are given a class-weight of 4 : 1. The data were windowed and split into a training and a test set using stratified sampling. The stratified split makes sure both the sets had the same class representation. The CNN is trained using the 10-fold cross-validation. The model with the lowest categorical cross-entropy validation loss is used for the evaluation of the test data set. The implementation of the CNN algorithm is conducted using Python Deep Learning library Keras[2], here, the parameters are presented in **Tables 3**, **4**. For *HMM*, the models are created with the 4 states and trained using the Baum-Welsh algorithm (Li and Jain, 2009). Here, the number of the states are determined through manual testing by evaluating the accuracy. To avoid getting stuck in a local optimum, different initialization is used. The models with different initialization are compared based on the log probability of the training data, and the best one is selected. Also, windowing is used on the testing data with a window size of 7 and a stride of 1. The window size is determined manually by evaluating the accuracy. The implementation is conducted through the hidden Markov model module simplehmm.py provided with the **Febrl** system is a modified re-implementation of LogiLab's Python HMM module[3]. The evaluation is done using 10-fold cross validation based on the IMU signals, to get an average accuracy and to prevent the accuracy from being biased. For *RF*, the hyperparameters are selected based on the directed grid search with cross-validation. The data are windowed, standardized, and 10-fold cross validation is used here. The parameters are window size =9, estimators=100, criterion = entropy, class weight = balanced, max features = sqrt, min sample split = 25 and min samples leaf = 1 through the python programming and using scikit-learn library[4]. For *k-NN*, classifier k=1 is considered while using Python Scikit-learn package library[4]. Here, import the KNeighborsClassifier module is used to construct the model together with fit() function as training and predict() function as test. For the dataset splitting the function train_test_split() is used with 3 parameters features, target, and test_set size. For *SVM*, different kernel function has been used such as Radial Basis Function (RBF), sigmoid and polynomial. To find hyperparameters, grid search is used on arbitrarily selected parameters with a large range on a limited data set. Grid search could have been used as a key tool to find suitable parameters for different classification models.

With *maneuver-based features*, the generated dataset is used to train several classifiers including the ANN, RF, k-NN, and SVM. The Python Deep Learning library Keras[2] is used for the implementation of ANN with using two fully connected layers with 128 neurons in each layer and a dropout=0.05. While the other ML algorithm is applied using scikit-learn library[4] in Python. Here, a hyperparameters optimization is performed using a grid search to tune different classifier parameters. For the k-NN classifier (k=1), while the RF (n_estimators=41, min_samples_leaf=2, bootstrap=False, max_features=sqrt), the SVM (kernel=rbf, class_weight=balanced) as define in (Altarabichi et al., 2019).

**TABLE 3 |** Parameters used in CNN.

| SL | Parameters | Values |
|---|---|---|
| 1. | Window size | 9 |
| 2. | Batch size | 256 |
| 3. | Epochs | 1000 |
| 4. | Class weights | 4:1 |
| 5. | Test size | 25% |
| 6. | Early stop | 80 |
| 7. | Dropout rate | 50% |
| 8. | Convolutional filters 1 | 300 |
| 9. | Convolutional filters 2 | 100 |
| 10. | Convolutional kernel size | 2 |
| 11. | Pooling size | 2 |

**TABLE 4 |** CNN layers with their output size.

| SL | Layer | Output values |
|---|---|---|
| 1. | Input | (9, 10) |
| 2. | Convolutional 1D | (8, 300) |
| 3. | Average pooling | (4, 300) |
| 4. | Convolutional 1D | (3, 100) |
| 5. | Flatten | 300 |
| 6. | Dropout | 300 |
| 7. | Dense | 40 |
| 8. | Dense | 2 |

## Experimental Works

The main objective of this experimental work is to observe several ML algorithms and their classification accuracy as a performance.

[2]https://keras.io/

[3]http://users.cecs.anu.edu.au/~Peter.Christen/Febrl/febrl-0.3/febrldoc-0.3/node25.html

[4]https://scikit-learn.org/stable/

Here, the roundabout classification is considered where 10-folds cross validation (CV) is applied.

## Considering Window-Based Features

The feature sets identified using window-based approach are used in 10-folds cross validation, where ML algorithms, CNN, HMM, RF and SVM are used. An average value for precision, recall and $F_1$-score are calculated considering both the roundabout and not/others classes and the results are presented in **Table 5**.

As can be observed form **Table 5**, the CNN and RF both achieved the highest $F_1$-score which is 88%, where highest precision is observed for RF, i.e., 92% and highest recall is observed by CNN, i.e., 87%. In CNN, the model achieved best training accuracy with improvements by trained the model for first 30 epochs whereas the validation-loss reached the lowest point in epoch 47. The comparison between the implemented ML algorithms considering $F_1$-score is presented in **Figure 3**, where both CNN and RF shows the highest score compare to other methods.

The confusion matrixes both for the CNN and RF are presented in **Table 6**. Here, we consider the topmost $F_1$-scores achieved by the ML algorithms i.e., CNN and RF.

As can be observed from **Table 6**, the highest precision achieved for roundabout is 83% by RF and highest recall achieved for the roundabout is 74% by CNN. A Matthews Correlation Coefficient (MCC) is also calculated for CNN and RF to compare the algorithm defined in terms of True Positive (TP), True Negative (TN), False Positive (FP) and False Negative (FN) and the formula can be express as follows in eq2 (Boughorbel et al., 2017), the MCC results are presented in **Table 7**.

$$MCC = \frac{TP * TN - FP * FN}{\sqrt{(TP + FP) * (TP + FN) * (TN + FP) * (TN + FN)}} \quad (2)$$

## Considering Maneuver-Based Features

The ML approaches are again tested with maneuver-based features, that is the created models are validated using 10-folds cross validation. Here, instead of CNN, ANN is applied to compare with the rest of the ML algorithms, i.e., SVM, RF, and k-NN. An average value for precision, recall and $F_1$-score are calculated considering both the roundabout and not/others classes and the results are presented in **Table 8**.

As can be seen from the table, ANN algorithm achieved the highest $F_1$-score on an average of roundabout and not/others classes i.e., 81% with similar precision and recall, i.e., 81% $\cong$ 82%. While, the k-NN algorithm achieved 2nd highest $F_1$-score which is 80% with 82% precision and 79% recall. The comparison between the implemented ML algorithms considering $F_1$-score presented in **Figure 4**, where both ANN shows the highest score compare to other methods and 2nd highest score was by k-NN.

**TABLE 5 |** Average classification results on both roundabout and not/others classes using several ML algorithms.

| No. | ML algorithms | Precision | Recall | $F_1$-score |
|---|---|---|---|---|
| 1. | CNN | 0.90 | 0.87 | 0.88 |
| 2. | HMM | 0.52 | 0.81 | 0.48 |
| 3. | RF | 0.92 | 0.84 | 0.88 |
| 4. | SVM | 0.85 | 0.76 | 0.80 |
| 5. | k-NN | 0.78 | 0.80 | 0.77 |

**TABLE 6 |** Confusion matrixes for CNN and RF.

| ML algorithms | | Predicted class | | Recall |
|---|---|---|---|---|
| **CNN** | | **Roundabout** | **Not/other** | |
| True class | Roundabout | 625 | 222 | 0.74 |
| | Not/Other | 161 | 75298 | 1.00 |
| Precision | 0.80 | 1 | | |
| **RF** | | **Roundabout** | **Other** | **Recall** |
| True class | Roundabout | 575 | 272 | 0.68 |
| | Not/Other | 115 | 75344 | 1.00 |
| Precision | | 0.83 | 1 | |

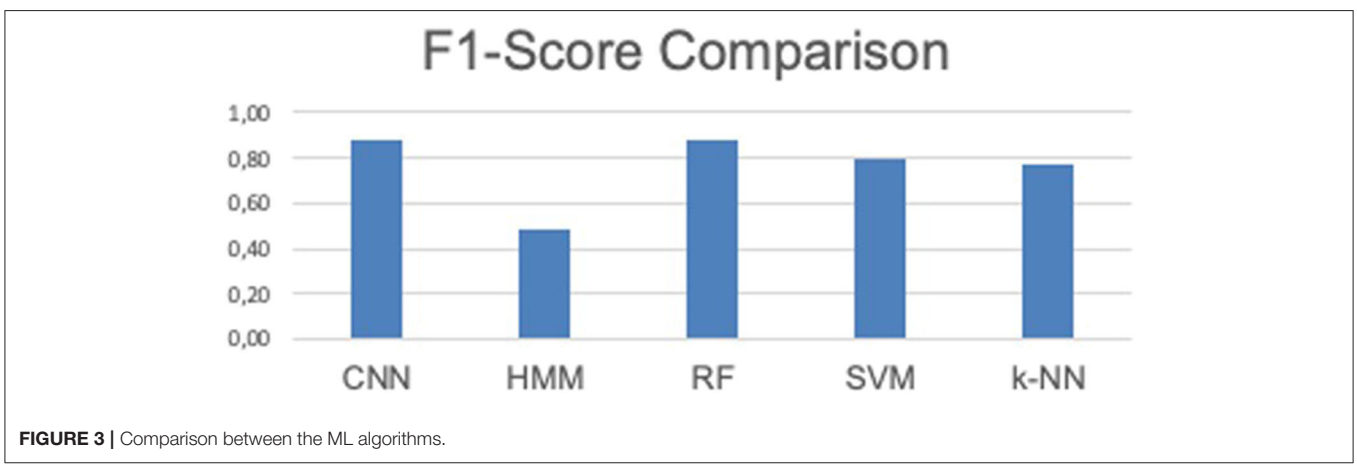


**FIGURE 3 |** Comparison between the ML algorithms.

**TABLE 7 |** MCC value on both roundabout and not/others classes using CNN and RF algorithms.

| | CNN | RF |
|---|---|---|
| TP | 625 | 575 |
| TN | 222 | 272 |
| FP | 75298 | 75344 |
| FN | 161 | 115 |
| TP*TN-FP*FN | −11984228 | −8508160 |
| (TP+FN) | 786 | 690 |
| (TP+FP) | 75923 | 75919 |
| (TN+FP) | 75520 | 75616 |
| (TN+FN) | 383 | 387 |
| √(TP+FP)*(TP+FN)*(TN+FP)*(TN+FN) | 41545915 | 39152736 |
| MCC | −0.28 | −0.22 |

**TABLE 8 |** Average classification results on both roundabout and not/others classes using several ML algorithms.

| No. | ML algorithms | Precision | Recall | $F_1$-score |
|---|---|---|---|---|
| 1. | ANN | 0.85 | 0.88 | 0.85 |
| 2. | RF | 0.94 | 0.60 | 0.73 |
| 4. | SVM | 0.91 | 0.67 | 0.77 |
| 5. | k-NN | 0.83 | 0.86 | 0.82 |

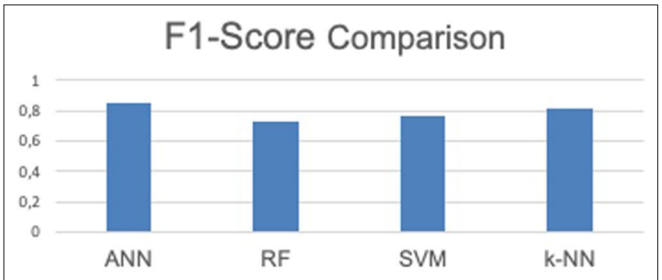


**FIGURE 4 |** Comparison between the ML algorithms.

**TABLE 9 |** Confusion matrixes for ANN and k-NN.

| ML algorithms | | Predicted Class | | Recall |
|---|---|---|---|---|
| ANN | | Roundabout | Not/Other | |
| True class | Roundabout | 193 | 56 | 0.78 |
| | Not/Other | 78 | 21784 | 1 |
| Precision | 0.71 | 1 | | |
| k-NN | | Roundabout | Other | Recall |
| True class | Roundabout | 180 | 69 | 0.72 |
| | Not/Other | 90 | 21772 | 1.00 |
| Precision | | 0.67 | 1 | |

The confusion matrixes both for the ANN and k-NN are presented in **Table 9**. Here, we consider the topmost $F_1$-scores achieved by the ML algorithms i.e., ANN and k-NN.

**TABLE 10 |** MCC value on both roundabout and not/others classes using ANN and k-NN algorithms.

| | ANN | k-NN |
|---|---|---|
| TP | 193 | 180 |
| TN | 56 | 69 |
| FP | 21784 | 21772 |
| FN | 78 | 90 |
| TP*TN-FP*FN | −1688344 | −1947060 |
| (TP+FN) | 271 | 270 |
| (TP+FP) | 21977 | 21952 |
| (TN+FP) | 21840 | 21841 |
| (TN+FN) | 134 | 159 |
| √((TP+FP)*(TP+FN)*(TN+FP)*(TN+FN)) | 4174914 | 4536843 |
| MCC | −0.40 | −0.43 |

As can be observed from **Table 9**, both the highest precision and recall are i.e., 71 and 78%. achieved for the roundabout using the ANN algorithm. Similar to the Window-based Features, MCC is calculated and presented in **Table 10**.

## Comparison Between the Features

A comparison between the windows-based features and the maneuver-based features with their classification results are presented in **Figure 5**. Here, maximum $F_1$-*Score* and Maximum *MCC* value is considered out of several machine learning algorithms as presented earlier. As can be seen form the figure, both considering $F_1$-*Score* and *MCC* the windows-based features achieved the heights score in classification.

# SUMMARY AND DISCUSSION

To achieve the goal of the project that is to create a realistic behavioral model the Naturalistic Driving Studies (NDS) has been performed to examine a real traffic situation by observing the drivers driving maneuver like roundabout. A total 16 volunteers are selected randomly and participated between May and August 2018. However, in window-based, labeled data set contains 76306 instances, of which 847 are labeled as roundabouts, and in maneuver-based it was 22111 instances with 249 roundabouts. As the study focuses on the roundabout identification not any individual's performance, thus the total sample size out of these 16 volunteers are enough for investigate several ML algorithms. To reduce the impractical task of identifying the maneuver manually by a human, this paper proposed a CNN to identify driving maneuver. Here, the collected IMU sensory data sets are used for the feature extraction, and both window-based and maneuver-based features are considered. And the GPS sensory data is used to label the data sets as the roundabout and not/others classes. Several ML algorithms including the CNN is investigated, and the other algorithms are: HMM, RF, ANN, k-NN, and SVM. A 10-fold

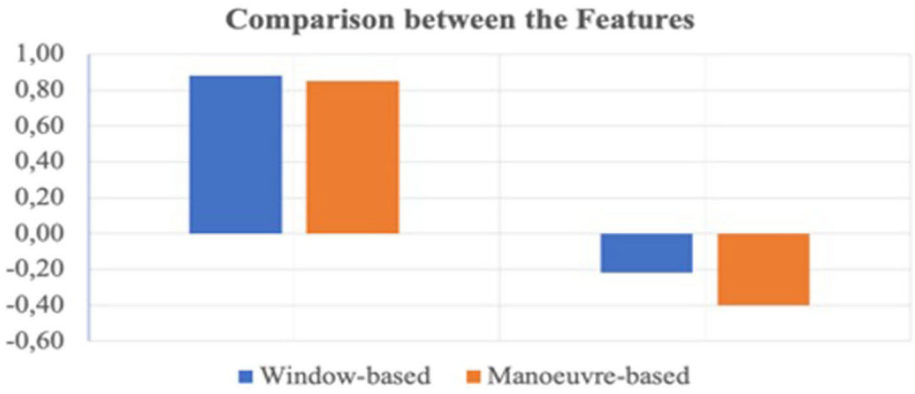


**FIGURE 5 |** Comparison between the extracted features with Maximum $F_1$-Score and *MCC*.

cross validation is conducted and precision, recall and $F_1$-Score are calculated both for the roundabout and not/others classes and using window-based and maneuver-based feature sets. According to the results, CNN and RF achieved the best average $F_1$-Score i.e., 88% as an overall classification accuracy. However, while considering MCC, it shows RF shows the best correlation, i.e., −0.22, the reason of the imbalanced samples may affect the results where the study is about Very high TN to very low TP.

CNN methods seem to be the best option for the classification; however, it requires huge amount of data, thus using window-based features 76306 instances are used for generating the model. This also valid for ANN where only two connected hidden layers is used with 22111 instances. A manual inspection is also conducted on one driver data set, that is by plotting GPS data to observe the accuracy by the CNN model. It was observed that the CNN model classified nearly all roundabouts and major false positives false negatives are occurred because of they are either at start or end of the roundabout. The model also classifies some of the S-shaped road curves as roundabouts as observed. It was also found that there are some instances those can be said as "rare instance" of false positive, here, the geometry of the road is similar to a roundabout, e.g., entrance and exit to the highway. Again, some of the roundabout are so small that the driver just drives their car straight without any turning or a standard right turn are also identified as false negative. While labeling the data set, poor GPS data are also affected and make hard for manual task of labeling all the roundabout without any error. More narrow experiments could be conducted to explore the miss-classification at the starting point and the exit of roundabouts.

As a conclusion CNN could be used as a suitable method to classify roundabout, and RF could be the next suitable choice as it has higher precision than CNN. Also, the 88% $F_1$-Score shows satisfactory performance with an unbalance data set, but, the MCC value recommend to use RF. However, the observation shows better performance while using the window-based feature set extracted through CNN than the manuover-based features extracted in a sequence entrance -> in the roundabout -> exit.

CNN is considered to be the best classifier as the Recall of the algorithm is 87% i.e., the sensitivity of the roundabout is the fraction of the total amount of relevant instances that were actually retrieved. As the number of the roundabout classes are very less compare to other classes it may increase with CNN if the number of the sample increased and the dataset become balanced. Again, in maneuver-based features extraction ANN outperforms with 88% recall whereas RF was only 60%. Note, that ANN is a part of CNN with less network layer can used while there are not enough data samples. Also, However, none of other ML algorithms such as HMM, SVM, k-NN and ANN are unable to achieve satisfactory performance while identifying the driving manuover. Again, as the data set is collected through a Naturalistic Driving Studies (NDS) under a project called SimuSafe, around 20% data were affected due to sensor changes its positions. That is either or both the IMU and the GPS sensors are not faulty but while using it on the car the position of the sensor was change which was not notice until the data collection period is over. Thus, several of the instances are found with irregularities in either IMU or GPS or both as the mounted sensors are misplaced, which should be validate in future study with providing information to the user to correctly mounted sensors. More control and simulated studies are ongoing, e.g., in cycle 2, the test will be conducted in simulator environment and also in the truck. Thus, the data set can be more uniformly labeled and finally, a more balanced data set can be achieved. Then the study could be replicated using the more extensive data sets with the more uniform positioning of the IMU-sensor in the vehicle to minimize discrepancies. Three models i.e., CNN, RF, and ANN are implemented into a car's CAN for real manuover identification both in practical life-data collection and in simulators. Again, these will be tested in cycle 2 in SimuSafe, which is now suspended due to Corona predicament. SimuSafe aims to have bigger study using 400+ participants throughout of Europe (Sweden, Spain, Italy, France and UK) considering both controlled and simulated environment which is ongoing.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because data sets are not open and published yet by the Project. Requests to access the datasets should be directed to Marteyn van Gasteren, marteyn.vangasteren@itcl.es.

## AUTHOR CONTRIBUTIONS

MA initiate the paper, he wrote the most of the chapter of the manuscripts excepts introduction and discussion. SB wrote the introduction and discussion of the paper and also reviewed the whole manuscript. All authors contributed to the article and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Drivers Use of In-Vehicle Information Systems and Perceptions of Their Effects on Driving

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In recent years the number of cars on the road with manufacturer installed in-vehicle information systems (IVIS) has increased dramatically, and with smartphones connecting directly to these systems drivers can access a wide range of applications on the move. Some IVIS features are designed to improve safety (e.g., speed and collision warnings) but access via an IVIS to all apps on a smartphone has the potential to distract drivers and increase crash risk. We undertook this study to find out what IVIS features and apps drivers use and to ask about their effects on driving. An online survey completed by 1,017 drivers (50% female, 16–85 years) revealed the most common activity drivers engaged in was listening to music, followed by listening to directions. Fewer than half of the drivers reported conversing on a hands-free phone and 25% reported texting/sending emails or using social media. Frequency of engagement in secondary tasks decreased with age. Using hand-held mobiles was rated as having the greatest negative impact on driving, with drivers attempting to mitigate the risk by carrying out the activity in slow moving traffic or at traffic lights. Females rated the risk of most of the secondary tasks as greater than males. Almost half of the sample had access to speed warnings systems but only a small proportion had experience of lane departure, dangerous curve or intersection warning systems. Of those with access to driver safety systems, 50–70% never used them despite rating the system as useful and as having safety benefits. As the number of vehicles with manufacturer installed IVIS continues to increase on the road, drivers' engagement with them while driving is also likely to increase. To address this, there is a need for a multi-agency approach to educate drivers on the safe use of these systems and apps in their vehicles. Incentives for drivers to use the safety-related features may also be worth considering.

**Keywords: distraction, app, driver safety, mobile phone, secondary task, speed advisory**

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## INTRODUCTION

In-vehicle information systems (IVIS), whether supplied with a vehicle by the manufacturer, or added later by drivers by means of apps on their smart phones, have become relatively commonplace in the vehicles on our roads. The reason for this is because these IVIS offer a large number of benefits for drivers. For example, navigation systems allow drivers to easily find locations in unfamiliar cities, and the provision of real-time traffic information allows drivers to take alternate routes to minimize journey times. Other IVIS, such as those that provide speed warnings, or lane

departure warnings have even more direct safety benefits. Speed is a key factor in the severity and risk of crashes (Aarts and Van Schagen, 2006; Elvik, 2013), and apps designed to warn drivers when they exceed the speed limit have the potential to provide significant safety benefits (Várhelyi, 2002; Carsten, 2012; Starkey and Charlton, 2020). Some speed-related IVIS [known as intelligent speed assist (ISA) systems] can directly intervene to reduce the speed the vehicle is traveling by increasing the resistance in the accelerator, or capping the maximum speed depending on the posted speed limit (Várhelyi, 2002; Carsten, 2012). Eco-driving system operate in a similar way, and provide information to drivers about their speed and rate of acceleration to reduce the amount of fuel used (Barkenbus, 2010; Kircher et al., 2014). ISAs offering real-time visual and auditory speeding alerts may be particularly beneficial for roads with temporary speed reductions (e.g., during roadworks; Whitmire et al., 2011). Despite the potential safety benefits, reports suggest that drivers only engage ISAs for half of the journey time (Jamson, 2006), and those who enjoy speeding were least likely to use them (Lai et al., 2010).

Whilst IVIS have the potential to improve driver safety, they also have the potential to distract the driver and encourage them to engage in secondary tasks, increasing the probability of a crash. Distraction or inattention has been identified as a factor in at least 12% of crashes worldwide (Beanland et al., 2012; Ministry of Transport, 2016; Sagberg and Sundfør, 2016). In Norway from 2011 to 2015 mobile phone use was identified as a causative factor in 7–14% of all inattention-related fatal crashes; using an ICT system (including GPS, laptop, tablet video camera, backing camera) was linked to 4% of crashes, interaction with passengers 1–3%, adjusting the radio 3%, and eating and/or drinking were linked to 2%. Overall, in-vehicle distractions excluding mobile phones were linked to 8% of fatal crashes suggesting that further exploration of in-vehicle distraction is warranted (Sundfør et al., 2019). In terms of IVIS specifically, findings from the 100-car naturalistic study revealed that interaction with IVIS increased crash risk 4.6-fold (Dingus et al., 2016), and a recent meta-analysis (based on research prior to 2012) found IVIS to be linked to 1.66% of all crashes (Ziakopoulos et al., 2019).

Engagement in secondary tasks whilst driving is relatively common. Data from naturalistic and observational studies report that drivers are engaged in secondary tasks between 14 and 38% of the time (Metz et al., 2014; Huemer et al., 2018; Sagberg et al., 2019). The most commonly observed secondary task was using a mobile phone (1–10% of drivers). However, findings from surveys and interviews suggest the rates are much higher with 30–50% of drivers reporting using a mobile phone (talking messaging, navigation etc.). Over 30% reported adjusting the radio, selecting music, eating or drinking and almost 10% reported adjusting in-vehicle equipment (Jamson, 2013; Sagberg and Sundfør, 2016; Sagberg et al., 2019). Women reported significantly less frequent engagement in secondary activities compared to men, and engagement in all four types of distraction (inattention and traffic-related distraction, common secondary tasks, telephone calls, risky secondary tasks) decreased with age (Sagberg and Sundfør, 2016). A recent systematic review of observational studies of secondary task engagement whilst driving reported that 98% of studies found that age was linked to cell phone use. In 56% of the studies, the younger drivers had the highest prevalence of cell phone use (greater than the middle-aged or older drivers), and in 51% of studies, the oldest drivers showed the least cell phone use (Huemer et al., 2018). In contrast, a survey of nomadic device use across 27 EU states found that middle-aged drivers were more likely to using a phone when driving compared with older drivers (Jamson, 2013). Drivers appeared to recognize there is risk associated with mobile phone use; drivers rated sending and receiving messages as having the greatest risk, and talking on the phone the least. Only a small proportion of drivers (5%) reported any incident of dangerous driving due to using their phone, but 25% reported that they had observed dangerous driving by others as a result of mobile phone use. Overall, female respondents reported the risk of secondary activities as being greater than did the males (Sagberg and Sundfør, 2016).

In terms of manufacturer installed IVIS, interviews with Australian drivers revealed that the most commonly used features were GPS (75%), playing music (via Bluetooth or inbuilt apps) (25%), and making and taking calls (15%) (Oviedo-Trespalacios et al., 2019). Few participants used the IVIS for texting due to difficulties with the voice recognition software (a task that has been shown to be cognitively demanding, particularly for older drivers) (Strayer et al., 2016). In terms of the risks associated with IVIS, participants reported that the IVIS often malfunctioned leading drivers to interact with their phone to fix the problem. Over 50% of the participants acknowledged that the IVIS might be distracting and increase risk, but the majority thought it was easy to use the system safely.

Together these studies highlight that carrying out other activities and using various devices while driving is relatively common. As noted earlier, there has been a large increase in recent years in the number and types of apps that are now available for use on a smart phone while driving, and an increasing number of cars have manufacturer installed IVIS. Importantly, an increasing number of these apps/systems have been designed to improve driver safety (e.g., collision warning and speed advisory systems) rather than distract the driver, but we have very limited information about drivers' use of these types of apps or IVIS features. Our study was designed to address this gap, and aimed to find out the types of in-car information systems and entertainment systems that people use whilst driving, including their experience with safety-related apps and features. We were also interested in exploring drivers' perceptions of the risks associated with the secondary tasks and the strategies they used to minimize any negative effects.

Specifically, the current study surveyed drivers to identify: (1) the range of in-vehicle applications and information systems drivers currently use, by age and gender, (2) the prevalence and frequency of their use, (3) drivers' attitudes regarding the safety of IVIS use, (4) any negative effects of using them on their own or others driving, and (5) any strategies or techniques drivers used to minimize negative effects.

# METHODS

## Participants

Our aim was to recruit a stratified convenience sample of ∼1,000 participants comprised of similar numbers of males and females across four age groups (16–24, 25–44, 45–64, and 65 years and over) to ensure the findings included the views of a wide range of drivers in New Zealand. Data collection ceased once the target sample size was reached. A digital data collection company (Research Now) was contracted to recruit participants from across New Zealand to complete the online survey during April and May 2017. A series of mass email invitations to complete the online questionnaire were sent to 22,992 Research Now panel members. Of these, 1,784 followed the link to read the introductory information about the survey, 1,610 consented to take part, and 1,506 met the four eligibility criteria (21 were excluded as they were not permanent New Zealand residents, 2 did not have a good understanding of English, 2 were under16 years of age and 79 had not driven a car in the last month) and began the survey. Incomplete responses were removed leaving a final sample of 1,017 (sampling error = ±3.07% at 95% CI).

**Table 1** summarizes the demographic characteristics of the sample. As can be seen in the table, respondents' ages ranged from 16 to 85 years, and the majority of respondents identified as being New Zealand European. Those in the younger age groups identified with a more diverse range of ethnic groups compared with the oldest group of respondents. In terms of driving experience, most respondents held a full license and as expected, the older groups had been licensed drivers for longer than the younger age groups. The distance driven by respondents in a typical week varied greatly, with the youngest and oldest drivers reporting driving the shortest distances. The greatest proportion of drivers involved in a crash were aged 25–44 years, closely followed by those aged 16–24 years. The fewest crashes were reported by those in the 45–64 years aged group. Those aged 25–44 were most likely to have been pulled over by the police

**TABLE 1 |** Demographic characteristics and driving history of the sample.

| | Age group | | | | Overall |
|---|---|---|---|---|---|
| | **16–24 years (*n* = 227)** | **25–44 years (*n* = 260)** | **45–64 years (*n* = 261)** | **65+ years (*n* = 269)** | ***N* = 1017** |
| Male (*n*, %) | 111 (48.90) | 127 (48.85) | 131 (50.19) | 139 (51.67) | 508 (49.95) |
| Mean age (SD) | 20.74 (2.70) | 34.71 (6.21) | 55.20 (5.85) | 71.45 (4.64) | 45.57 (19.85) |
| **Ethnicity (*n*, %)**[a] | | | | | |
| NZ European | 176 (77.53) | 156 (60.00) | 200 (76.63) | 245 (91.08) | 777 (76.40) |
| Māori | 20 (8.81) | 17 (6.54) | 7 (2.68) | 2 (0.74) | 46 (4.52) |
| Pacific Island | 10 (4.41) | 7 (2.69) | 1 (0.38) | 0 (0) | 18 (1.77) |
| Chinese | 20 (8.81) | 19 (7.31) | 7 (2.68) | 0 (0) | 46 (4.52) |
| Indian | 9 (3.96) | 22 (8.46) | 7 (2.68) | 3 (1.11) | 41 (4.00) |
| Other | 24 (10.57) | 58 (22.31) | 45 (17.24) | 20 (7.43) | 144 (14.16) |
| **Income** | | | | | |
| <$20,000 | 36 (15.86) | 9 (3.46) | 16 (6.13) | 5 (1.86) | 66 (6.48) |
| 21–40,000 | 33 (14.53) | 19 (7.31) | 22 (8.43) | 91 (33.83) | 165 (16.22) |
| 41–60,000 | 30 (13.22) | 30 (11.54) | 32 (12.26) | 75 (27.88) | 167 (16.42) |
| 61–80,000 | 27 (11.89) | 33 (12.69) | 40 (15.32) | 42 (15.61) | 142 (13.96) |
| 81–100,000 | 29 (12.78) | 33 (12.69) | 47 (18.01) | 22 (8.17) | 131 (12.88) |
| $100,000+ | 42 (18.50) | 114 (43.84) | 86 (32.95) | 17 (6.32) | 259 (15.63) |
| Refused | 30 (13.22) | 21 (8.08) | 17 (6.51) | 17 (6.32) | 85 (8.36) |
| **License type (*n*, %)** | | | | | |
| Learners | 55 (24.2) | 5 (1.92) | 0 (0) | 0 (0) | 60 (5.90) |
| Restricted | 62 (27.31) | 29 (11.15) | 5 (1.92) | 2 (0.74) | 98 (9.64) |
| Full | 108 (47.58) | 224 (85.15) | 256 (98.08) | 267 (99.26) | 855 (84.07) |
| Years licensed (mean, SD, range) | 3.78 (2.61) 1–10 | 14.61 (7.76) 1–30 | 36.16 (8.76) 3–50 | 47.51 (7.02) 2–50 | 26.38 (18.47) 1–50 |
| Km driven per week (mean, SD, range) | 111.08 (172.73) 0–1,000 | 187.50 (213.65) 0–2,000 | 245.82 (342.76) 6–3,000 | 158.40 (151.99) 0–1000 | 178.20 (238.86) 0–3,000 |
| Crash in the last year (*n*, %, range) | 31 (13.66) 1–9 | 37 (14.23) 1–9 | 12 (4.60) 1–4 | 21 (7.81) 1–2 | 101 (9.93) |
| Pulled over for using phone (*n*, %) | 10 (4.4) | 18 (6.9) | 5 (1.9) | 0 | 33 (3.2) |
| Number of licensed drivers in NZ | 444,545 | 1,252,228 | 1,153,370 | 534,252 | 3,384,395 |
| Percent of licensed drivers sampled | 0.05 | 0.02 | 0.02 | 0.05 | 0.03 |

[a]*Note that the totals may exceed 100% as respondents could select more than one ethnicity.*

for using a mobile phone, followed by those in the youngest age group. The percentage of licensed drivers in NZ who completed the questionnaire ranged from 0.02 to 0.05% depending on the age group.

## Procedure and Questionnaire Design

The study received approval (#17:25) from the School of Psychology Research and Ethics Committee at the University of Waikato. As described above, a digital data collection company, Research Now, notified their panel members by email of the opportunity to participate in the survey. The email contained a web link which potential respondents could use to access the survey. Upon activating the web link the potential respondents were provided with a short overview of the purpose of the research, followed by a request to provide consent and complete the eligibility questions. Eligible respondents were directed to the remaining questions in the survey, while ineligible respondents received a message that explained they were not eligible for the current study, and thanked them for their interest. On completion of the survey respondents were given the opportunity to provide their email address if they wanted to receive a summary of the research findings, and they were thanked for taking part.

The questionnaire was designed to investigate drivers' use of IVIS applications such as navigation devices and advisory systems. A set of 14 behaviors and events (**Table 2**) linked to the use of IVIS and related systems was developed based on existing literature (e.g., Jamson, 2013), and supplemented by advice from the broader research team and the project steering group. We also developed a list of possible effects that the behavior or event could produce (e.g., speed up or slow down unintentionally) and countermeasures that could be used by drivers to minimize these effects (e.g., I pull over and stop; **Table 2**).

After providing consent, and completing the eligibility questions, respondents were asked to rate how each of the 14 IVIS behaviors and events would affect *an average person's driving* (from −3 very impaired to +3 very improved). Following that, they were asked how frequently *they personally engaged* in each of the 14 IVIS behaviors (or how often each event occurred) while they were driving (not applicable, never, seldom, sometimes, often, or usually). For responses other than not applicable or never, the respondents were asked what effects this had on their driving from the list of outcomes (**Table 2**), selecting as many as applied to them. The outcomes question was followed by a question asking what, if anything, they did to minimize the effects, again by selecting as many as applied from the list of countermeasures (**Table 2**). In each case, respondents had the option to provide details of "other" effects the behavior or event had on their driving and "other" ways they minimized these effects. They were then asked to rate how much each behavior or event altered their ability to drive safely, from −3 (very impaired) to +3 (very improved).

Respondents were then asked whether they had ever used a speed advisory system, and if so which type (a system that informs them of the speed limit, a system that warns them if they go over the speed limit or the limit they have set manually, or one that limits the speed of their vehicle). They were also asked to rate the likely safety benefits (from 1 definitely not safer, to 7 definitely safer) of four speed-related systems (from Warner et al., 2010); (1) an information system that shows the current speed limit, (2) an advisory system that shows the current speed limit and warns the driver with a flashing light and sound if the speed limit is exceeded, (3) a supportive system that shows the current speed limit and exerts a counter-force on the accelerator at speeds over the speed limit (it is harder to push the accelerator if you are going over the speed limit), and (4) an intervening system that shows the current speed limit and interacts with the vehicle to prevent you exceeding the speed limit. After rating the likely safety benefits they were asked to indicate whether they would like each system installed in their car (from 1 definitely not, to 7 definitely). The final section of the questionnaire asked for demographic and driving history information, including length of licensure, distance driven each week, crash history, mobile phone offenses, age, and ethnicity.

**TABLE 2 |** The behaviors and events, possible outcomes, and countermeasures used in the online questionnaire.

| Behavior or event | Outcomes | Countermeasures |
|---|---|---|
| • A conversation on a hands-free mobile phone<br>• Texting/sending emails/posting on social media<br>• Browsing/reading social media<br>• Use the internet via your smartphone<br>• Take pictures with your phone or camera when driving<br>• Listening to music with the car audio system<br>• Selecting music/play lists via your smartphone<br>• Entering your destination on a navigation system/app<br>• Looking at the map on a navigation system/app<br>• Listening to directions from a navigation system/app<br>• Using a manufacturer installed display (e.g., to select a radio station)<br>• Getting a warning from a lane departure warning system<br>• Getting a warning from a speed advisory system<br>• Getting a warning from a curve or dangerous intersection warning system | • I slow down or speed up unintentionally<br>• My lane keeping becomes unstable (I weave in my lane)<br>• It impairs my ability to scan the road ahead (e.g., for curves, intersections)<br>• I drive too close to the car in front<br>• My reaction to changing traffic situations is slower or delayed<br>• Sometimes I don't notice pedestrians and cyclists<br>• Sometimes I have to stop suddenly at intersections or crossings<br>• Sometimes I don't notice traffic signs or signals<br>• None of the above<br>• Other<br>• None | • I pull over and stop<br>• I slow down intentionally to maintain safety<br>• I concentrate more on driving to ensure I stay in my lane<br>• I pay special attention so that I can monitor traffic effectively<br>• I turn it off if it becomes distracting or annoying<br>• I only do this in slow moving traffic (e.g., in a traffic queue)<br>• I use it on a straight and clear road<br>• I ask my passenger to use it instead of me<br>• None of the above<br>• Other<br>• None |

## Analyses

To provide an overall indication of IVIS prevalence, respondents' responses to the questions about the frequency of each behavior/event while driving were recoded to indicate whether or not the event occurred. We also calculated the total number of activities that each respondent engaged in and the frequency of engagement in each behavior/event. All subsequent analyses focused on the drivers who reported engaging in or experiencing each event (therefore the sample sizes for each behavior or event differ). Where the variables were categorical, and the data were frequency counts, we used the Chi square test of independence for the analyses. For continuous variables (e.g., safety ratings) we used either between groups or repeated measures analysis of variance (Anova) as appropriate (Field, 2018).

The next part of the analysis examined the drivers' perceptions of the effects of engaging in the target activity. More detailed analyses were conducted to examine the characteristics of the respondents (i.e., age and gender) reporting that each activity/experience had no effect on their driving. After this, we explored the techniques drivers used to minimize any negative effects of engaging in each behavior or event, and explored the characteristics (age and gender) of the drivers who reported making no changes to their driving.

To assess the overall effect of each behavior or event on driving safety, a series of 2 × 4 Anovas were conducted to determine the influence of age and gender on the ratings. A series of repeated-measures Anovas were then conducted to compare the ratings of how much an *average driver's safety* would be affected by engaging in each behavior/event to the ratings of how much the *driver's own safety* would be affected. The final section of the analyses focuses on the respondents' ratings of the likely safety benefits and likelihood of installation of the four speed information systems.

# RESULTS

## Prevalence

The percentage of drivers who reported carrying out each activity or experiencing the event while driving is shown in **Figure 1**. As shown, almost all drivers (96%) listened to music with the car audio system. The next most common was listening to directions from a navigation system (64%), followed by using a manufacturer installed display (56%) and looking at a map on a navigation system (54%). Fewer than half of the respondents reported talking on a hands-free phone (47%), approximately a third (31%) entered a destination on a navigation system, and fewer than a quarter of the respondents reported sending texts, emails, or using social media. Few respondents read social media (8%), used the internet via their phone when driving (15%) or experienced lane departure (10%) or curve warnings (9%). The rates for men and women were similar for the majority of the activities/events; however, there was a significant association between gender and reporting having received warnings from speed [$X^2_{(1)} = 4.65$, $p = 0.031$] and curve advisories ($X^2 = 2.17$, $p = 0.023$) with men more likely to have received warnings than women. The total number of IVIS behaviors and events reported were similar for men ($M = 4.86$, $SD = 2.78$, range = 0–14) and women ($M = 4.81$, $SD = 0.11$, range = 0–14). An independent samples $t$-test confirmed this difference was not statistically significant, $t_{(1, 015)} = 0.31$, $p = 0.76$.

**Table 3** shows the prevalence of each IVIS behavior or event across the four age groups. There were statistically significant associations between age group and the prevalence of each behavior or event for almost all items (apart from lane departure warnings and curve/intersection warnings). The prevalence of listening to music using the in-vehicle audio, listening to directions, using the manufacturer installed display and experiencing speed advisory warnings increased with age. In contrast, selecting playlists on a phone, texting, emailing

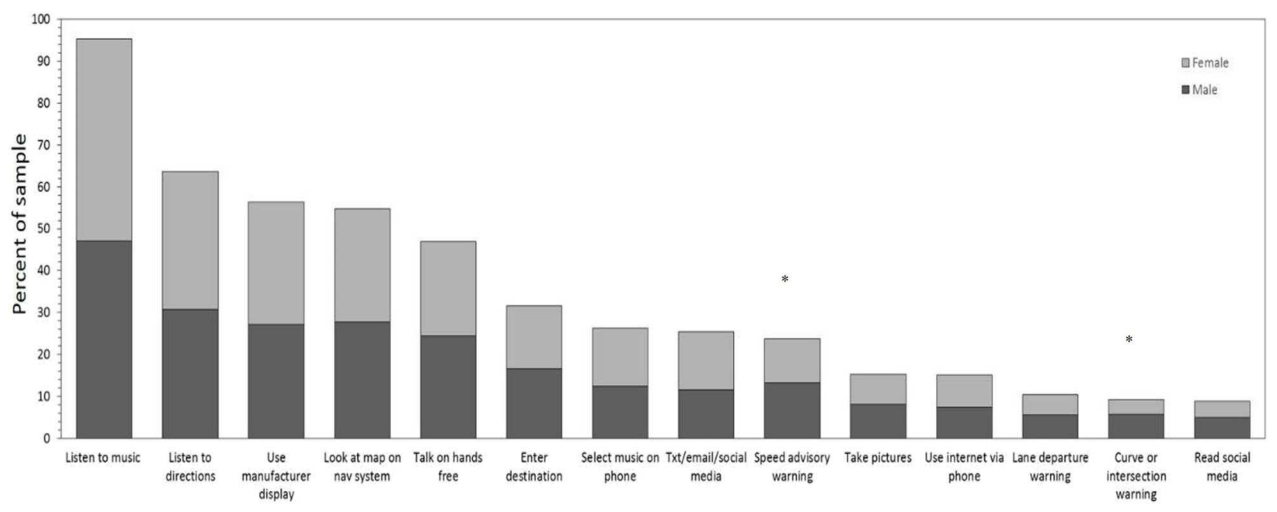


**FIGURE 1 |** The percentage of male and female drivers reporting engaging in each activity or experiencing each event while driving (*indicates significant difference) ($p < 0.05$) between males and females.

**TABLE 3 |** The number and percentage of the total sample engaging in each IVIS behavior or event while driving for each age group.

| | 16–24 years ($n = 227$) | 25–44 years ($n = 260$) | 45–64 years ($n = 261$) | >65 years ($n = 269$) | Chi$^2$ ($df = 3$) | Total ($n = 1017$) |
|---|---|---|---|---|---|---|
| | *n* (%) | *n* (%) | *n* (%) | *n* (%) | | *n* (%) |
| Listen to music | 208 (20.5) | 244 (24.0) | 258 (25.4) | 260 (25.6) | 16.8** | 970 (95.4) |
| Listen to directions | 121 (11.9) | 171 (16.8) | 180 (17.7) | 176 (17.3) | 14.6** | 648 (63.7) |
| Use manufacturer display | 109 (10,7) | 136 (13.4) | 161 (15.8) | 167 (16.4) | 14.7** | 573 (56.3) |
| Look at map on GPS | 116 (11.4) | 174 (17.1) | 148 (14.6) | 120 (11.8) | 28.4** | 558 (54.9) |
| Talk on hands free | 117 (11.5) | 159 (15.6) | 134 (13.2) | 67 (6.6) | 77.5** | 477 (46.9) |
| Enter destination | 82 (8.1) | 115 (11.3) | 71 (7.0) | 54 (5.3) | 40.2** | 322 (31.7) |
| Select music on phone | 122 (12.0) | 94 (9.2) | 35 (3.4) | 17 (1.7) | 178.8** | 268 (26.4) |
| Text/email/social media | 94 (9.2) | 106 (10.4) | 43 (4.2) | 16 (1.6) | 127.6** | 259 (25.5) |
| Speed advisory warning | 35 (3.4) | 50 (4.9) | 75 (7.4) | 81 (8.0) | 21.3** | 241 (23.7) |
| Take pictures | 53 (5.2) | 60 (5.9) | 22 (2.2) | 21 (2.1) | 44.6** | 156 (15.3) |
| Use internet via phone | 63 (6.2) | 71 (7.0) | 16 (1.6) | 4 (0.4) | 113.6** | 154 (15.4) |
| Lane departure warning | 16 (1.6) | 28 (2.8) | 34 (3.3) | 28 (2.8) | 4.7 | 106 (10.4) |
| Curve/intersection warning | 27 (2.7) | 23 (2.3) | 19 (1.9) | 26 (2.6) | 3.1 | 95 (9.3) |
| Read social media | 40 (3.9) | 40 (3.9) | 7 (0.7) | 3 (0.3) | 67.7** | 90 (8.9) |
| Total | 1,203 (24.5) | 1,471 (29.9) | 1,203 (24.5) | 1,040 (21.2) | | 4917 |

** *Significant association ($X^2$) between age and prevalence ($p < 0.001$).*

or using social media, taking pictures on a phone, using the internet on a phone, and reading social media tended to decrease with age. For the remaining behaviors (looking at a map on a navigation device, talking hands free on the phone, and entering a destination on a navigation system), prevalence was lowest in the youngest (16–24 years) and oldest age groups (>65 years). The total activities reported by age group showed a decrease with age (16–24 years $M = 5.30$, $SD = 2.97$; 25–44 years $M = 5.66$, $SD = 2.95$; 45–64 years $M = 4.61$, $SD = 1.98$; >65 years $M = 3.87$, $SD = 1.97$). A one-way Anova confirmed this difference was statistically significant [$F_{(3,\ 1,013)} = 25.40$, $p < 0.001$ $\eta_p^2 = 0.07$]. Bonferroni corrected *post-hoc* tests indicated that the youngest group (16–24 years) and the 25–44 years group carried out significantly more activities compared with those over 45 years (all $p$'s $< 0.05$). The oldest group (>65 years) carried out significantly fewer activities compared with all other age groups (all $p$'s $< 0.01$).

## Frequency of Engagement in Each IVIS Behavior/Event

Listening to music via the in-vehicle audio system was the most common activity, carried out *often* or *usually* for 75% of respondents with an in-vehicle audio system (see **Table 4**). The mean rating for frequency of use (never = 0 to often = 4), was also the highest for listening to music. Listening to directions, using the manufacturer-installed display, looking at maps on a navigation system, and talking on a hands-free phone, were reported as occurring *seldom*, or *sometimes*, although fewer than 40% of drivers reported *never* engaging in these activities. For almost all the other IVIS activities (apart from receiving speed advisory warnings) at least 60% of the drivers reported never having engaged in the behavior or experiencing the event even though they had the opportunity to do so (shown in the lower portion of **Table 4**). For those that did engage in these IVIS activities, the majority of drivers indicated that they *seldom* did so.

The list of IVIS behaviors and events included those that are legal (e.g., talking on a hands-free phone), those that are illegal in NZ (e.g., texting), and those that are designed to improve driver safety, many of which are only available in new vehicles (e.g., lane departure warnings). The majority of respondents reported having access to a smart phone, but fewer than half of the drivers in the sample reported having access to technology to improve driver safety such as speed advisory systems, lane departure warnings and curve or intersection warnings. Of those with access, over half (52%) had received speed advisory warnings (most commonly *seldom* or *sometimes*), and only a quarter had received warnings from lane departure or curve and intersection warning systems. In contrast, over 60% of drivers reporting talking on a hands-free phone while driving. A much smaller proportion of drivers reported sending texts (26%), using the internet (16%), or accessing social media (9%) when driving (albeit this amount of drivers is high given their potential implications for safety).

## The Effects of Engaging in IVIS Behaviors and Events

Drivers who reported engaging in each behavior (or experiencing each event) were asked to indicate how it affected their driving from a range of 10 options, by selecting as many options as applied to them. **Table 5** summarizes the participants' responses by each behavior/event and overall (bottom line of **Table 5**). Overall, over 50% of the reported instances of various in vehicle activities were judged by respondents to have no effect on their driving. The next most frequently reported effects of IVIS activities (∼20% of the reports) were slowed reactions to changing traffic situations, slowing down or speeding up unintentionally, and impairments in scanning the road ahead, while fewer than 10% of the effects were reported to adversely affect lane keeping, ability to notice traffic signals and signs

**TABLE 4 |** The frequency of engagement in each IVIS behavior or event (for those with access to the device/equipment) and the mean rating for frequency of use.

| | Never | Seldom | Some-times | Often | Usually | Mean rating (SD) | Total |
|---|---|---|---|---|---|---|---|
| | *n* (%) | *n* (%) | *n* (%) | *n* (%) | *n* (%) | | *n* |
| Listen to music | 39 (3.9) | 43 (4.3) | 142 (14.1) | 277 (27.5) | 508 (50.3) | 3.2 (1.1) | 1009 |
| Listen to directions | 190 (22.7) | 229 (27.3) | 282 (33.7) | 104 (12.4) | 33 (3.9) | 1.5 (1.1) | 838 |
| Use manufacturer display | 295 (34.0) | 194 (22.4) | 210 (24.2) | 82 (9.4) | 87 (10.0) | 1.4 (1.3) | 868 |
| Look at map on GPS | 306 (35.4) | 248 (28.7) | 234 (27.1) | 61 (7.1) | 15 (1.7) | 1.1 (1.0) | 864 |
| Talk on hands free | 292 (38.0) | 234 (30.4) | 174 (22.6) | 56 (7.3) | 13 (1.7) | 1.0 (1.0) | 769 |
| Enter destination | 532 (62.3) | 190 (22.2) | 103 (12.1) | 22 (2.6) | 7 (0.8) | 0.6 (0.9) | 854 |
| Select music on phone | 667 (71.3) | 127 (13.6) | 97 (10.4) | 30 (3.2) | 14 (1.5) | 0.5 (0.9) | 935 |
| Text/email/social media | 735 (73.9) | 172 (17.3) | 65 (6.5) | 15 (1.5) | 7 (0.7) | 0.4 (0.7) | 994 |
| Speed advisory warning | 221 (47.8) | 118 (25.5) | 96 (20.8) | 17 (3.7) | 10 (2.2) | 0.9 (1.0) | 462 |
| Take pictures | 849 (84.5) | 124 (12.3) | 21 (2.1) | 5 (0.5) | 6 (0.6) | 0.2 (0.6) | 1005 |
| Use internet via phone | 791 (83.7) | 111 (11.7) | 32 (3.4) | 5 (0.5) | 6 (0.6) | 0.2 (0.6) | 945 |
| Lane departure warning | 332 (75.8) | 59 (13.5) | 31 (7.1) | 11 (2.5) | 5 (1.1) | 0.4 (0.8) | 438 |
| Curve/intersection warning | 259 (73.2) | 48 (13.6) | 31 (8.8) | 10 (2.8) | 6 (1.7) | 0.5 (0.9) | 354 |
| Read social media | 887 (90.8) | 60 (6.1) | 15 (1.5) | 8 (0.8) | 7 (0.7) | 0.1 (0.5) | 977 |

*Data are presented as number and percentage of those with access and mean (SD).*

**TABLE 5 |** The effects of engaging in each IVIS behavior or event.

| | Total (*n*) | None (%) | Slow reaction (%) | Alter speed (%) | Poor scanning (%) | Weave (%) | Miss signals (%) | Stop abruptly (%) | Miss peds/ bike (%) | Drive too close (%) | Other (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Listen to music | 970 | 82.9 | 6.4 | 5.5 | 1.8 | 1.6 | 3.1 | 2.4 | 2.3 | 2.0 | 1.8 |
| Listen to directions | 648 | 75.8 | 11.7 | 7.4 | 4.8 | 3.4 | 5.4 | 4.3 | 2.9 | 1.7 | 2.0 |
| Use manufacturer display | 573 | 56.7 | 22.2 | 13.4 | 17.5 | 8.6 | 5.6 | 5.4 | 5.6 | 3.1 | 0.9 |
| Look at map on GPS | 558 | 36.4 | 34.2 | 20.3 | 27.8 | 12.7 | 11.1 | 9.0 | 8.8 | 6.6 | 1.6 |
| Talk on hands free | 477 | 39.0 | 35.8 | 27.3 | 17.0 | 8.6 | 13.4 | 8.6 | 10.3 | 6.3 | 1.5 |
| Enter destination | 322 | 34.2 | 38.2 | 24.8 | 31.4 | 19.9 | 14.0 | 13.7 | 12.4 | 9.6 | 1.6 |
| Select music on phone | 268 | 30.6 | 32.1 | 23.1 | 31.0 | 23.1 | 11.6 | 11.6 | 12.3 | 11.2 | 1.1 |
| Text/email/social media | 259 | 8.1 | 56.0 | 37.5 | 52.1 | 35.9 | 20.5 | 24.7 | 16.2 | 15.8 | 1.2 |
| Speed advisory warning | 241 | 56.4 | 5.4 | 29.5 | 4.6 | 2.9 | 3.3 | 3.3 | 2.1 | 3.3 | 5.4 |
| Take pictures | 156 | 17.9 | 34.6 | 29.5 | 42.3 | 23.1 | 19.2 | 17.3 | 16.7 | 14.1 | 1.3 |
| Use internet via phone | 154 | 15.6 | 47.4 | 35.1 | 35.1 | 25.3 | 20.1 | 18.2 | 18.8 | 18.8 | 3.2 |
| Lane departure warning | 106 | 54.7 | 16.0 | 22.6 | 12.3 | 11.3 | 4.7 | 6.6 | 7.5 | 5.7 | 0.9 |
| Curve/intersection warning | 95 | 47.4 | 8.4 | 32.6 | 10.5 | 6.3 | 4.2 | 7.4 | 8.4 | 5.3 | 4.2 |
| Read social media | 90 | 12.2 | 42.2 | 34.4 | 50.0 | 26.7 | 26.7 | 28.9 | 21.1 | 24.4 | 1.1 |
| Grand total | 4,917 | 51.3 | 24.1 | 18.6 | 18.3 | 11.0 | 9.2 | 8.4 | 7.7 | 6.3 | 1.8 |

*Data is presented as a percentage of the total number of times the behavior or event occurred.*

leading to sudden stops at intersections or crossings, impaired ability to notice pedestrians and cyclists, and driving too close to the car in front.

Looking at each activity individually, the majority of respondents indicated that listening to music and listening to navigation directions had no effect on their driving. A small proportion of respondents indicated that listening might slow their reaction to changing traffic situations and lead to unintentional changes in speed. Activities rated as having the greatest effect on driving involved the use of a hand-held mobile phone (texting/sending emails, reading social media, using the internet, and taking pictures). Slowed reaction to changing traffic was the most commonly identified effect, but respondents identified hand-held phone use as affecting driving behavior in nearly every possible way (from the list provided). In contrast, having a conversation on a hands-free mobile was rated as having no effect by 40% of users, the remaining respondents most frequently indicated it would lead to slowed reactions to changing

traffic, unintentional alterations in speed, impaired ability to scan the road ahead and failure to notice traffic signs of signals. Approximately a third of respondents using IVIS systems for navigation rated entering a destination and looking at a map on a navigation system or app, as having no effect on driving. The most frequently identified effects were slowed reactions to other traffic, unintentionally altering speed and poor scanning of the road ahead. Receiving warnings regarding speed, curves or lane position were reported to have no effect by approximately half of the respondents who used these types of systems. Around a third of users indicated that receiving a warning would lead them to alter their speed.

Given the possible negative consequences of driver distraction on safety, follow-up analyses were conducted to examine the characteristics (age and gender) of the drivers reporting that each behavior or event had no effect on their driving to determine if this was related to driver experience. The proportion of drivers in each age group (**Table 6**) reporting that they believed the activity had no effect was significantly different for listening to music via the car audio, the three activities relating to navigation, taking pictures and having a conversation on a hands-free phone. The proportion of those reporting no effect from listening to music, listening to directions, looking at a map, and taking pictures increased with age (i.e., the youngest drivers were more likely to report that the behavior or experience affected their driving). In contrast, the middle age groups had the highest proportion of users reporting no effects of a conversation on a hands-free phone (around 40%) and the lowest proportion of those rating entering a destination into a navigation system as having no effect.

We also compared the proportion of males and females rating each of the activities or experiences as having no effect. There were no significant associations between gender and ratings of no effect for all except one of the items. The proportion of men rating looking at a map on a navigation system as having no effect was significantly higher than the proportion of females providing the same rating (males 45.0%, females = 27.5%; $X^2_{(1)} = 18.46, p < 0.001$).

## Strategies to Minimize the Effects of IVIS Use

Drivers were also asked to indicate how they mitigated any effects of the behaviors they engaged in or the events they experienced. **Table 7** presents the countermeasures reported by each behavior/event and overall. The most frequently reported countermeasures were to ask the passenger to carry out the activity (exceeding the use of no countermeasures). Other commonly reported strategies (>20%) were to slow down intentionally, concentrate more on driving to maintain lane position, pay special attention to monitor traffic effectively, and pull over and stop.

Unsurprisingly, listening to music was associated with the fewest reported countermeasures, and was most commonly dealt with by turning the music off. For activities involving a hand-held mobile, or interacting with a navigation device, the most commonly endorsed countermeasures were to ask the passenger to carry out the activity or use the device, to pull over and stop, or to use in slow traffic. Drivers indicated that they used a range of different countermeasures when having a conversation on a hands-free phone including asking their passenger to take the call, concentrating more, paying special attention to traffic and pulling over, suggesting they were aware of the possible negative effects on their driving.

Additional analyses to examine the use of countermeasures by gender and age, revealed significant associations between age group and use of no countermeasures for listening to music, listening to directions and looking at a map on a navigation device (**Table 8**). The middle age groups (25–44 and 45–64 years) reported proportionally less use of countermeasures

**TABLE 6 |** The number and percentage of respondents in each age group engaging in each IVIS behavior or event reporting that it had no effect on their driving.

| | 16–24 years | 25–44 years | 45–64 years | >65 years | Chi$^2$ ($df = 3$) | Total |
|---|---|---|---|---|---|---|
| | *n* (%) | *n* (%) | *n* (%) | *n* (%) | | *n* (%) |
| Listen to music | 154 (74.0) | 192 (78.7) | 224 (86.8) | 234 (90.0) | 26.60** | 804 (82.9) |
| Listen to directions | 83 (68.6) | 124 (72.5) | 136 (75.6) | 148 (84.1) | 11.02* | 491 (75.8) |
| Use manufacturer display | 56 (51.4) | 72 (52.9) | 93 (57.8) | 104 (62.3) | 4.23 | 325 (56.7) |
| Look at map on GPS | 35 (30.2) | 57 (32.8) | 54 (36.5) | 57 (47.5) | 9.33* | 203 (36.4) |
| Talk on hands free | 30 (25.6) | 69 (43.4) | 53 (39.6) | 34 (20.7) | 13.97** | 186 (39.0) |
| Enter destination | 28 (34.1) | 28 (24.3) | 28 (39.4) | 26 (48.1) | 10.50* | 110 (34.2) |
| Select music on phone | 35 (28.7) | 28 (29.8) | 10 (28.6) | 9 (52.9) | 4.30 | 82 (30.6) |
| Text/email/social media | 5 (5.3) | 13 (12.3) | 1 (2.3) | 2 (12.5) | 5.78 | 21 (8.1) |
| Speed advisory warning | 16 (45.7) | 25 (50.0) | 46 (61.3) | 49 (60.5) | 3.75 | 136 (56.4) |
| Take pictures | 5 (9.4) | 11 (18.3) | 3 (13.6) | 9 (42.9) | 11.74** | 28 (17.9) |
| Use internet via phone | 11 (17.5) | 7 (9.9) | 5 (31.3) | 1 (25.0) | 5.19 | 24 (15.6) |
| Lane departure warning | 5 (31.3) | 11 (39.3) | 21 (61.8) | 21 (75.0) | 11.58 | 58 (54.7) |
| Curve/intersection warning | 12 (44.4) | 7 (30.4) | 9 (47.4) | 17 (65.4) | 6.12 | 45 (47.4) |
| Read social media | 6 (15.0) | 4 (10.0) | 1 (14.3) | 0 | 0.9 | 11 (12.2) |
| Grand total | 481 (19.1) | 648 (25.7) | 684 (27.1) | 711 (28.2) | | 2524 |

*$p < 0.05$, **$p < 0.01$.

**TABLE 7 |** Countermeasures used for each behavior or event.

| | Total (*n*) | None (%) | Ask other (%) | Slow down (%) | Concentrate (%) | Pay attention (%) | Pull over (%) | Turn off (%) | Slow traffic (%) | Clear road (%) | Other (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Listen to music | 970 | 50.3 | 11.8 | 3.8 | 14.8 | 14.0 | 1.4 | 29.2 | 2.6 | 4.4 | 1.5 |
| Listen to directions | 648 | 39.7 | 21.1 | 19.8 | 20.8 | 26.4 | 8.5 | 13.1 | 4.5 | 2.8 | 0.8 |
| Use manufacturer display | 573 | 27.9 | 32.5 | 22.9 | 19.7 | 20.9 | 11.7 | 19.4 | 17.8 | 16.8 | 2.3 |
| Look at map on GPS | 558 | 14.5 | 39.1 | 34.2 | 24.9 | 26.5 | 31.0 | 10.4 | 17.7 | 12.9 | 3.4 |
| Talk on hands free | 477 | 10.7 | 31.0 | 27.0 | 37.7 | 33.1 | 38.2 | 18.2 | 15.3 | 14.3 | 0.8 |
| Enter destination | 322 | 8.4 | 42.9 | 28.3 | 16.5 | 16.8 | 53.1 | 8.7 | 22.7 | 17.1 | 2.2 |
| Select music on phone | 268 | 11.9 | 45.9 | 27.6 | 22.4 | 17.9 | 20.1 | 16.4 | 26.1 | 19.8 | 1.1 |
| Text/email/social media | 259 | 3.9 | 43.2 | 26.3 | 27.8 | 19.7 | 43.6 | 20.5 | 47.1 | 25.9 | 2.7 |
| Speed advisory warning | 241 | 23.7 | 2.9 | 55.2 | 16.2 | 24.9 | 3.7 | 6.6 | 4.6 | 2.9 | 1.7 |
| Take pictures | 156 | 4.5 | 39.7 | 37.2 | 28.2 | 21.8 | 44.2 | 12.8 | 35.3 | 28.2 | 1.3 |
| Use internet via phone | 154 | 7.8 | 41.6 | 27.3 | 24.0 | 20.8 | 44.2 | 24.0 | 36.4 | 24.0 | 0.6 |
| Lane departure warning | 106 | 24.5 | 5.7 | 27.4 | 42.5 | 36.8 | 5.7 | 8.5 | 7.5 | 7.5 | 0.9 |
| Curve/intersection warning | 95 | 22.1 | 4.2 | 51.6 | 30.5 | 29.5 | 10.5 | 8.4 | 4.2 | 6.3 | 0.0 |
| Read social media | 90 | 5.6 | 28.9 | 24.4 | 18.9 | 26.7 | 32.2 | 32.2 | 41.1 | 22.2 | 2.2 |
| Grand total | 4,917 | 25.1 | 27.4 | 24.0 | 22.5 | 22.4 | 20.7 | 17.7 | 15.5 | 12.1 | 1.7 |

*Data are presented as the percentage of the total occurrences of each behavior/event.*

when listening to music compared with the youngest and oldest age groups. Those aged 25–44 years were also less likely than the other age groups to take action to minimize the effects of listening to directions from a navigation device or when looking at a map on a navigation device.

In terms of gender differences, a greater proportion of males than females used no countermeasures when listening to music via the in-vehicle audio [males = 56.2%, females = 46.5%; $X^2_{(1)} = 5.66$, $p < 0.05$], when selecting a playlist on their phone [males = 16.7%, females = 7.7%; $X^2_{(1)} = 5.05$, $p < 0.05$], and when looking at a map on a navigation system [males = 19.5%, females = 9.4%; $X^2_{(1)} = 11.43$, $p < 0.01$].

## Ratings of Impairment for Each Behavior or Event

Respondents were asked to rate how much they thought their *own driving* overall would be affected by engaging in the IVIS activities (from −3 very impaired to +3 very improved), as well as rating how much *an average person's driving* would be affected by each activity. A summary of the effects of each IVIS behavior/event on the respondents' own driving safety by age group is provided in **Table 9**. As shown in the "total" column in **Table 9**, texting/sending emails/posting on social media were rated as producing the greatest impairment, followed by selecting music or a playlist on your phone, entering a destination and looking at a map on a navigation system. Activities or events most likely to improve safety included getting a warning from a curve or dangerous intersection warning system, a speed advisory system or a lane departure warning. Activities which were most often identified as being the least safe (texting/sending emails/posting on social media) were the ones most often associated with respondents taking countermeasures (**Table 7**). Conversely, the activities rated as being quite safe (e.g., listening to music or directions) were least likely to be associated with countermeasures.

We conducted a series of 2 × 4 Anovas to determine if there were significant differences in driving safety ratings by age and gender. There were no statistically significant interactions between age and gender for any of the behaviors or events. **Table 9** shows the ratings by age group for each item, as well as Anova statistics associated with the main effect of age. As can be seen in the table there were significant differences across the age groups for listening to music via the car audio system, using the manufacturer installed display, looking at a map on a navigation system, having a conversation on a hands-free phone, selecting a playlist on a phone and taking pictures. Bonferroni corrected *post-hoc* tests revealed that the two oldest age groups rated listening to music as having a more negative effect on their driving safety compared with those aged 16–24 years. For using an in-vehicle display, having a conversation on a hands-free phone, selecting a playlist and taking pictures, those aged 45–64 years thought their driving was significantly more negatively affected compared with those aged 25–44 years who carried out the same activity. The

**TABLE 8 |** The number and percentage of respondents in each age group engaging in each IVIS behavior or event reporting that they used no countermeasures.

| | 16–24 years *n* (%) | 25–44 years *n* (%) | 45–64 years *n* (%) | >65 years *n* (%) | Chi$^2$ (*df* = 3) | Total (*n* = 1,017) *n* (%) |
|---|---|---|---|---|---|---|
| Listen to music | 87 (41.8) | 148 (60.7) | 143 (55.4) | 110 (42.3) | 25.80** | 488 (50.3) |
| Listen to directions | 49 (40.5) | 84 (49.1) | 73 (40.6) | 51 (29.0) | 14.89** | 257 (39.7) |
| Use manufacturer display | 34 (31.2) | 46 (33.8) | 46 (28.6) | 34 (20.4) | 7.71 | 160 (27.9) |
| Look at map on GPS | 15 (12.9) | 36 (20.7) | 18 (12.2) | 12 (10.0) | 8.21* | 81 (14.5) |
| Talk on hands free | 9 (7.7) | 20 (12.6) | 18 (13.4) | 4 (6.0) | 4.31 | 51 (10.7) |
| Enter destination | 10 (12.2) | 8 (7.0) | 5 (7.0) | 4 (7.4) | 2.09 | 27 (8.4) |
| Select music on phone | 13 (10.7) | 14 (14.9) | 2 (5.7) | 3 (17.6) | 2.79 | 32 (11.9) |
| Text/email/social media | 2 (2.1) | 8 (7.5) | 0 | 0 | 7.01 | 10 (3.9) |
| Speed advisory warning | 5 (14.3) | 17 (34.0) | 18 (25.0) | 17 (21.0) | 4.99 | 57 (23.7) |
| Take pictures | 3 (5.7) | 3 (5.0) | 1 (4.5) | 0 | 1.19 | 7 (4.5) |
| Use internet via phone | 4 (6.3) | 5 (7.0) | 3 (18.8) | 0 | 3.25 | 12 (7.8) |
| Lane departure warning | 5 (31.3) | 9 (32.1) | 5 (14.7) | 7 (0.3) | 3.04 | 26 (24.5) |
| Curve/intersection warning | 3 (11.1) | 6 (26.1) | 5 (26.3) | 7 (26.9) | 2.65 | 21 (22.1) |
| Read social media | 3 (7.5) | 1 (2.5) | 1 (14.3) | 0 | 2.19 | 5 (5.6) |
| Grand total | 242 (19.6) | 405 (32.8) | 338 (27.4) | 249 (20.2) | | 1234 |

*$p < 0.05$, **$p < 0.01$.

**TABLE 9 |** The mean and standard deviation of the driving safety ratings by age group for the respondents engaging in each IVIS behavior or event (ratings were from −3 very impaired to +3 very improved).

| | 16–24 years (*n* = 227) | 25–44 years (*n* = 260) | 45–64 years (*n* = 261) | >65 years (*n* = 269) | Anova (age) | Total (*n* = 1017) |
|---|---|---|---|---|---|---|
| | Mean (*SD*) | Mean (*SD*) | Mean (*SD*) | Mean (*SD*) | | Mean (*SD*) |
| Listen to music | 0.2 (0.9) | 0.2 (1.0) | 0 (0.6)[a] | 0[a] (0.6) | $F_{(3, 962)} = 5.0$** | 0.1 (0.8) |
| Listen to directions | 0.2 (1.2) | 0.1 (1.1) | −0.1 (1.0) | 0 (0.8) | $F_{(3, 640)} = 2.4$ | 0 (1.0) |
| Use manufacturer display | −0.3 (1.0) | −0.3 (1.0) | −0.6 (0.9)[b] | −0.5 (0.8) | $F_{(3, 565)} = 4.4$** | −0.4 (0.9) |
| Look at map on GPS | −0.6 (1.2) | −0.6 (1.2) | −0.9 (1.0) | −0.7 (1.1) | $F_{(3, 550)} = 3.1$* | −0.7 (1.1) |
| Talk on hands free | −0.2 (1.2) | −0.4 (1.1) | −0.7 (0.9)[a,b] | −0.6 (0.8) | $F_{(3, 469)} = 6.1$** | −0.5 (1.0) |
| Enter destination | −0.6 (1.3) | −0.7 (1.4) | −1.1 (1.2) | −0.7 (1.2) | $F_{(3, 314)} = 2.6$ | −0.8 (1.3) |
| Select music on phone | −0.7 (1.1) | 0.6 (1.3) | −1.3 (1.1)[b] | −1.3 (1.4) | $F_{(3, 260)} = 4.1$** | −0.8 (1.2) |
| Text/email/social media | −1.3 (1.4) | −1.4 (1.6) | −1.8 (1.2) | −2.1 (1.0) | $F_{(3, 251)} = 2.2$ | −1.5 (1.4) |
| Speed advisory warning | 0.6 (1.5) | 0.8 (1.2) | 0.7 (1.3) | 0.7 (0.9) | $F_{(3, 233)} = 0.3$ | 0.7 (1.2) |
| Take pictures | −1.0 (1.5) | −0.6 (1.6) | −1.7 (1.0)[b] | −1.2 (0.9) | $F_{(3, 148)} = 3.5$* | −1.0 (1.4) |
| Use internet via phone | −0.9 (1.4) | −0.9 (1.8) | −1.4 (1.7) | −1.8 (1.3) | $F_{(3, 146)} = 0.8$ | −0.9 (1.7) |
| Lane departure warning | 0.3 (1.5) | 0.2 (1.2) | 0.1 (1.2) | 0.2 (0.9) | $F_{(3, 98)} = 0.1$ | 0.2 (1.2) |
| Curve/intersection warning | 0.9 (1.3) | 0.9 (1.3) | 0.5 (1.3) | 0.8 (0.7) | $F_{(3, 87)} = 0.5$ | 0.8 (1.2) |
| Read social media | −0.7 (1.8) | −0.8 (1.8) | −0.7 (1.9) | −1.0 (2.6) | $F_{(3, 82)} = 0.2$ | −0.8 (1.8) |
| Total | −0.3 (0.6) | −0.2 (0.7) | −0.6 (0.8) | −0.6 (0.9) | | −0.4 (0.7) |

[a] *Significantly different from the 16–24 year group.*
[b] *Significantly different from the 25–44 year group ($p < 0.05$, Bonferroni corrected post-hoc). *$p < 0.05$, **$p < 0.01$.*

45–64 years group also rated having a conversation on a hands-free phone as having a greater negative effect on their driving safety compared with the youngest respondents (16–24 years).

There were also significant differences between men and women's ratings of the effects of listening to directions from a navigation system, using a manufacturer installed display, looking at a map on a navigation system, entering a destination on a navigation system, selecting a playlist on a phone, and texting/email/ posting on social media (**Table 10**). In each case, women rated the activity as having a significantly more negative effect on their driving safety compared with men.

In the next set of analyses we compared the respondents' ratings of how much an average person's driving would be affected by engaging in each IVIS behavior or event, to the ratings of how much their own driving would be affected (from −3 very impaired to +3 very improved). These data are presented in **Figure 2**. As can be seen in the figure, listening to directions, listening to music via the in-vehicle audio, receiving warnings from lane departure, speed advisory, and curve/dangerous

**TABLE 10 |** The mean and standard deviation of the driving safety ratings by gender for the respondents engaging in each IVIS behavior or event (ratings were from −3 very impaired to +3 very improved).

| | Male ($n = 508$) Mean | Female ($n = 509$) Mean | Anova (gender) | Total ($n = 1017$) Mean |
|---|---|---|---|---|
| Listen to music | 0.1 (0.9) | 0.1 (0.7) | $F_{(1, 962)} = 3.3$ | 0.1 (0.8) |
| Listen to directions | 0.1 (1.0) | −0.1 (0.9) | $F_{(1, 640)} = 5.4^{*}$ | 0 (1.0) |
| Use manufacturer display | −0.3 (1.0) | −0.5 (0.7) | $F_{(1, 565)} = 6.8^{**}$ | −0.4 (0.9) |
| Look at map on GPS | −0.4 (1.2) | −1.0 (0.9) | $F_{(1, 550)} = 31.2^{**}$ | −0.7 (1.1) |
| Talk on hands free | −0.4 (1.1) | −0.6 (0.9) | $F_{(1, 469)} = 2.6$ | −0.5 (1.0) |
| Enter destination | −0.5 (1.5) | −1.0 (1.1) | $F_{(1, 314)} = 7.5^{**}$ | −0.8 (1.3) |
| Select music on phone | −0.5 (1.4) | −1.0 (1.0) | $F_{(1, 260)} = 5.9^{*}$ | −0.8 (1.2) |
| Text/email/social media | −1.1 (1.6) | −1.8 (1.2) | $F_{(1, 251)} = 5.8^{*}$ | −1.5 (1.4) |
| Speed advisory warning | 0.8 (1.2) | 0.6 (1.2) | $F_{(1, 233)} = 1.6$ | 0.7 (1.2) |
| Take pictures | −0.8 (1.7) | −1.1 (1.1) | $F_{(1, 148)} = 0.2$ | −1.0 (1.4) |
| Use internet via phone | −0.8 (1.9) | −1.1 (1.4) | $F_{(1, 146)} = 0.1$ | −0.9 (1.7) |
| Lane departure warning | 0.3 (1.3) | 0.1 (1.0) | $F_{(1, 98)} = 0.2$ | 0.2 (1.2) |
| Curve/intersection warning | 0.9 (1.3) | 0.5 (1.0) | $F_{(1, 87)} = 3.6$ | 0.8 (1.2) |
| Read social media | −0.3 (1.8) | −1.4 (1.6) | $F_{(1, 82)} = 1.0$ | −0.8 (1.8) |
| Total | −0.2 (0.6) | −0.6 (0.7) | | −0.4 (0.7) |

*$p < 0.05$, **$p < 0.01$.

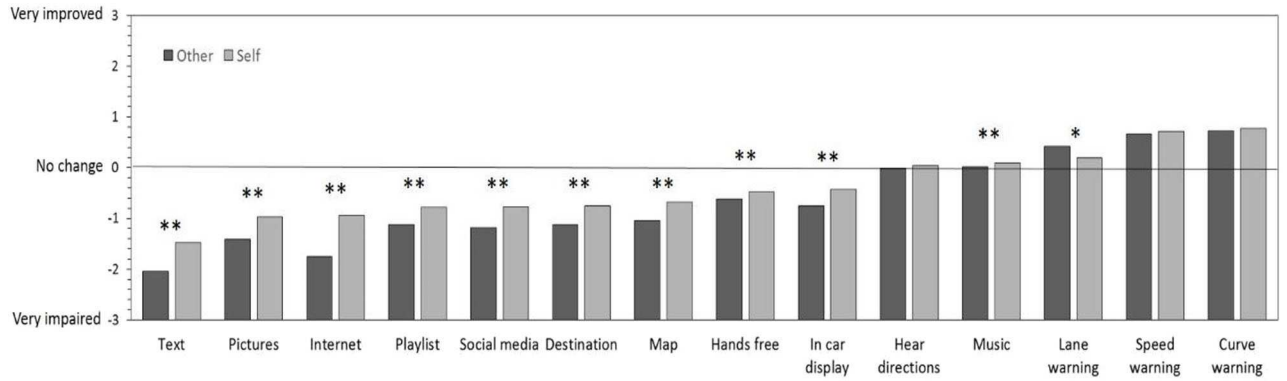


**FIGURE 2 |** Overall ratings of the effects of each activity on driving safety for the respondents (self) and other drivers (data is presented as the mean rating for all drivers engaging in each activity) (**$p < 0.01$, *$p < 0.05$ other vs. self-rating).

intersection systems were rated as improving driving safety overall (the mean ratings were above zero). All other behaviors and experiences (nine of the 14 activities) were rated as leading to driving impairment rather than improvement, with texting/sending emails and posting on social media receiving the lowest ratings (i.e., leading to the greatest impairment). With regard to ratings of their own and others' driving safety, respondents generally rated each behavior or experience as having a more negative effect on the average driver compared with the effects on their own driving, with only one exception. Receiving a warning from a lane departure warning system was rated as leading to a greater improvement in the driving safety of the average driver compared with themselves. To determine if the ratings of the effects of the activities differed from zero we conducted a series of one-sided *t*-tests for the self and other ratings. For the ratings of other drivers, all ratings were significantly different to zero (all $ps < 0.001$) apart from listening to music with the car audio system ($p = 1.00$). For the ratings of their own driving, all ratings were significantly different from zero (all $ps < 0.001$) apart from listening to directions ($p = 0.27$) and receiving a lane departure warning ($p = 0.08$).

To determine if differences in the driving safety ratings between themselves and other drivers were statistically significant a series of repeated measures Anovas were undertaken (note: the sample size for each analysis differed because we only included drivers who engaged in each of the behaviors/experiences themselves). Analyses revealed that respondents rated other drivers as significantly more impaired than themselves when texting/ emailing/posting on social media [$F_{(1, 258)} = 79.9$, $p < 0.001$, $\eta_p^2 = 0.24$], taking pictures with a phone or camera [$F_{(1, 155)} = 18.8$, $p < 0.001$, $\eta_p^2 = 0.10$], using the internet via

a smartphone [$F_{(1, 153)} = 61.2$, $p < 0.001$, $\eta_p^2 = 0.30$], selecting music or playlist on a phone [$F_{(1, 321)} = 27.5$, $p < 0.001$, $\eta_p^2 = 0.08$], browsing social media [$F_{(1, 89)} = 10.0$, $p = 0.002$, $\eta_p^2 = 0.10$], entering a destination [$F_{(1, 321)} = 27.5$, $p < 0.001$, $\eta_p^2 = 0.08$], and looking at a map on a navigation device [$F_{(1, 557)} = 60.5$, $p < 0.001$, $\eta_p^2 = 0.10$], having a conversation on a hands-free phone [$F_{(1, 476)} = 9.5$, $p = .002$, $\eta_p^2 = 0.02$], using a manufacturer installed display [$F_{(1, 572)} = 67.1$, $p < 0.001$, $\eta_p^2 = 0.10$] and listening to music via the in-vehicle audio [$F_{(1, 969)} = 9.8$, $p = 0.002$, $\eta_p^2 = 0.01$]. They also rated lane departure warnings as improving driver safety to a significantly greater extent for other drivers compared with themselves [$F_{(1, 105)} = 4.1$, $p = 0.04$. $\eta_p^2 = 0.04$]. There were no statistically significant differences between self and other ratings for listening to directions [$F_{(1, 647)} = 1.4$, $p = 0.20$, $\eta_p^2 < 0.01$], or receiving warnings from a speed advisory [$F_{(1, 240)} = 0.3$, $p = 0.60$, $\eta_p^2 < 0.01$], or curve and dangerous intersection warning system [$F_{(1, 94)} = 0.1$, $p = 0.70$, $\eta_p^2 < 0.01$].

## Safety Benefits of Speed Advisory Systems

Finally respondents were asked to rate the likely safety benefits (from 1 definitely not safer to 7 definitely safer) of four speed information systems (an information system, advisory system, supportive system, and intervening system) and to indicate if they would like them installed in their car (from 1 definitely not to 7 definitely). As shown in **Figure 3** respondents rated the information and advisory systems as most likely to improve safety and they were generally willing to have these types of systems installed in their cars. In contrast, although the respondents thought the supportive and intervening systems would improve safety, they were unlikely to have them installed in their cars. A series of bivariate correlations revealed that the perceived safety benefit showed significant strong positive correlations for each of the four systems (information system $r = 0.58$; advisory system $r = 0.70$; supportive system $r = 0.68$, intervening system $r = 0.70$, all $ps < 0.001$, $N = 1016$).

# DISCUSSION

The survey was conducted to identify the range of in-vehicle applications and information systems currently used by drivers, the prevalence and frequency of their use, the effects of their use on driving and to explore any strategies or techniques drivers use to minimize any negative consequences. Our study clearly demonstrates the wide variety of secondary tasks drivers engage in. As reported in previous studies, the most common were listening to music, using navigation systems, and conversing on a hands-free phone. Only a small proportion of the sample had experience with a lane departure warning system or dangerous curve and intersection warning systems. Overall, the prevalence for each activity was similar for men and women, but varied by age, with a general decrease in engagement in each activity/behavior with age, as reported in previous research (e.g., Jamson, 2013; Sagberg and Sundfør, 2016). Interestingly though, rates of texting, talking on a hands-free phone, and using a navigation device was highest in the 25–44 years group, possibly because of employment and family-related demands. The two middle age groups reported using fewer countermeasures compared to the youngest and oldest drivers, but the two oldest age-groups rated the activities as having the greatest overall negative impact on driving safety. Whilst using a hand-held mobile was rated as most likely to have negative effects, a small but significant proportion of drivers still engaged with a hand-held phone, despite legislation banning their use for over 10 years in NZ. Generally males rated the activities as having less of an impact on their driving compared with the female drivers, as in previous research (Sagberg and Sundfør, 2016). Interestingly, drivers rated almost all the activities or events as having a more negative impact on an average driver compared to their own driving, similar to Jamson (2013) and Sagberg and Sundfør (2016). This effect, known as the self-enhancement bias is a well-documented effect where drivers rate their own safety and skill better than that of other drivers and their crash risk as lower (e.g., Delhomme, 1991; Walton and Bathurst, 1998; Harré and Sibley, 2007).

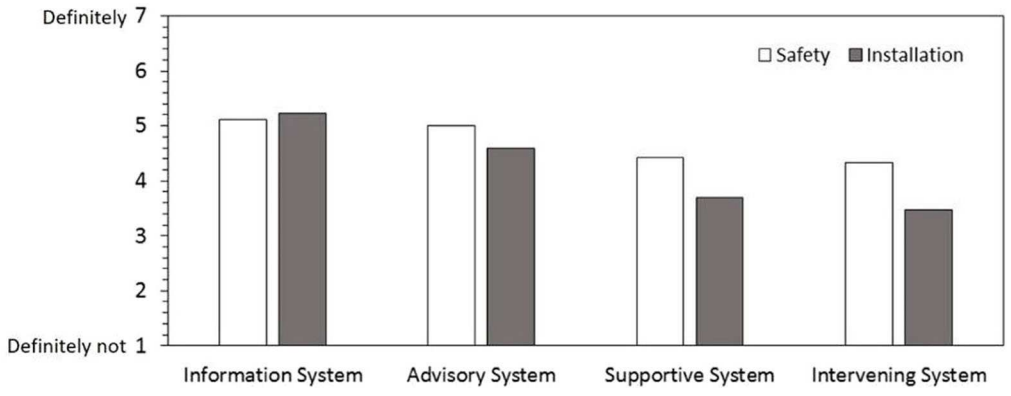


**FIGURE 3 |** Ratings of the safety benefits and likelihood of installation (from 1 = definitely not, to 7 = definitely) of four speed information systems.

These findings raise some interesting and contradictory issues. Although drivers acknowledge that interacting with IVIS systems are likely to negatively impact driving safety, they are still willing to engage in these activities. This may be partly because whilst they are aware of the negative impacts of driving whilst distracted from education campaigns and, in the case of hand-held mobile phones legislation, they have carried out these tasks or activities many times without any adverse consequences. This combined with the self-enhancement bias described previously may go some way to explaining drivers' willingness to continue to engage in distracting activities.

There is, however, evidence that drivers have access to, and some are willing to engage with driver safety related apps. Whilst only a small proportion of drivers in the current study had experience of curve advisory or lane departure warnings, almost half of the sample had access to an ISA, with around half of those (approximately one quarter of the total sample) reporting they had received speed-related warnings. The relatively high proportion of drivers with access to an ISA is encouraging, although the greatest challenge will be encouraging drivers to use them. Overall the results show that relatively few drivers use safety-oriented IVIS, and even when they have access to the systems 50–70% of drivers never use them. In fact the number of drivers reporting using a speed advisory system is the same as that reporting texting/email/social media while driving.

In interpreting the findings from this study, it should be borne in mind that that the participants recruited for this study were a convenience sample stratified across gender and age groups which places some limits on how far one can generalize the findings. In addition, the study used self-report data, and there is the possibility that respondents were not completely honest with their answers or that may have interpreted the response options differently. The strength of the study include a relatively large sample size from a wide age range.

In conclusion, use of safety orientated IVIS is low, and without incentives or education it is likely to remain low despite drivers beliefs that they have safety benefits. Given the range of secondary activities drivers engage in, despite some of them being illegal, it is even more important that we encourage drivers to use safety related apps when available. The rapid pace of technological change may mean that many drivers do not know how to use the manufacturer installed systems safely so a multi-agency approach is warranted to educate drivers. This could include car manufacturers, car rental companies, businesses with company cars, and we all as government agencies. Incentives for drivers to use the safety related features may also be worth considering.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the participants did not provide consent for the data to be shared. Requests to access the datasets should be directed to nstarkey@waikato.ac.nz.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by School of Psychology Ethics Committee, University of Waikato, Hamilton, New Zealand. The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

NS and SC contributed to the study design, data collection, data analysis, drafting and revision of the manuscript, and approved the final version of the manuscript for publication. All authors who meet authorship criteria are listed, and certify that they have participated sufficiently to take public responsibility for the content in the submitted work, including participation in the concept, design, analysis, writing, or revision of the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Does Urban Security Modulate Transportation Choices and Travel Behavior of Citizens? A National Study in the Dominican Republic

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**Introduction:** Traditionally, the scientific literature on urban and transportation dynamics addresses many topics, but the security-related outcomes of users remain a pending issue, especially in emerging countries and their cities. Nevertheless, recent evidence suggests that, especially in developing countries, security issues may influence people's decision-making in the choice of transport means, daily urban-trip patterns and road behaviors of users.

**Objective:** The purpose of this study was to explore the relationships between the perceived security (in both urban environments and public transport systems) and the daily-travel behavior and trip patterns of the Dominican Republic population.

**Methods:** This cross-sectional study, performed in 2019, analyzed data collected from 1,026 inhabitants from different cities of the Dominican Republic (54% females and 46% males), who completed a survey on security issues, travel behaviors and transportation-related habits.

**Results:** The results of this research suggest that demographic factors, such as age, education, and city/town size, and the safety perceived in the urban environment play a significant role in the choice of transportation modes, as well as in the participants' experience as victims of crime-related incidents (either witnessing or suffering crime episodes on public transport or city streets) during urban trips performed over the last 5 years.

**Conclusion:** Overall, the results of this study suggest that perceived safety, in both urban environments and public transport systems, is a relevant issue affecting the daily transport-related patterns and behavioral choices of the Dominican Republic's population. The results of this research might contribute to the strengthening of transport security planning, considering factors that are not traditionally kept in mind for policymaking in transportation dynamics.

**Keywords: Dominican Republic, travel behavior, perceived security, urban security, transportation security**

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## INTRODUCTION

As it is already well-known that many factors could be -either directly or indirectly- related to people's decision making on transportation means, the literature seems to be properly scoped on many crucial facets such as health, safety, and service-related settings (Herman et al., 1959; Syed et al., 2013; Muro-Rodríguez et al., 2017): however, further key issues -such as the user's perceived security- are still considerably understudied in many regions, especially among those presenting several shortcomings and emerging needs in this matter. This is the case of the so-called emerging countries and their cities, in which aspects such as social gaps, developmental trends, and new social challenges might be affecting the way in which the daily movements of the population take place (Zhang et al., 2005). Hence, many studies endorse the hypothesis that exploring specific factors affecting travel behaviors of the population might allow for the strengthening of a safer and more inclusive mobility, through the establishment of adequate strategies and measures to promote safer and more sustainable transport modes (Schneider, 2013).

From a psychosocial perspective, transport dynamics have been traditionally associated with factors related to cost-benefit balances and planned behaviors (Cantarella and Cascetta, 1995). However, balance models are only useful under the assumption of representativeness, existence, uniqueness and stability. Therefore, more dynamic models of transportation-related issues may be also addressed following both the deterministic and stochastic approaches (Sánchez-Flores and De Palma, 2013). This way, throughout the years, other explicative factors playing a role in the choice of a transport modes have been studied. Thus, environmental concerns, international growth, the development of the internet and new technologies are three of the most studied elements in this field (Waller et al., 2008). Moreover, some other research has developed theories to explain the choices of habitual transport modes, mainly taking into account elements related to awareness and availability, cost and convenience, enjoyment of the use, habits, and basic safety (Schneider, 2013).

In this sense, the relation between the security level of the urban environment and the choice of (e.g.,) commuting routes, trip schedules and transport modes has already been empirically endorsed through various studies performed in other countries (Alm and Lindberg, 2002; Lai and Chen, 2011). People tend to choose transport modes that they perceive as safer (Beirão and Cabral, 2007). Therefore, it is interesting to research the relation between transport mode and road safety elements, such as the traffic accidents in which the road user has been involved. In this sense pedestrians, cyclists, and motorcycle users are the most vulnerable users, since they are much less protected on the road (Kim et al., 2007). It is interesting that, despite this situation of vulnerability, cyclists perceive a lower risk of crashing with cars, if compared with what drivers perceive in the same situation (Chaurand and Delhomme, 2013). The existing positive relation between perceived safety and risky driving is also clear, and it is based on the excessive confidence of experimented drivers, which has an impact on traffic accidents (Ho et al., 2015; Ho and Widaningrum, 2016); however, many similar relationships are still unexplored among non-motorized users, such as pedestrians and public transportation passengers.

The present research proposes, in addition, that the security (both objective and perceived) of citizens can play an important role in the choice of transport modes and in the traffic accidents suffered by users. Urban safety is a complex phenomenon that is developed from different perspectives (Arriagada and Godoy, 2000). In general terms, it is understood as the concern for both quality of life and human dignity (ILPES, 1997). From another perspective (which we adopt in this research), citizens' perception of security is characterized by the enjoyment of one's daily potential activities, without fears of (e.g.,) being assaulted, suffering an aggression, as well as to walk along the streets without being afraid of robbery attempts (PNUD, 1998). This concept is tightly related to public order, personal safety/security and the overall safety of the population (Vidales, 2012). We must highlight not only that citizens' safety and security is objectively important, but also that researchers need to consider subjective perceptions to holistically understand how they affect the individual's well-being at different levels (Vidales, 2012).

This way, this research attempts to establish a relation between the choice of transport modes of citizens, road safety, and the perceived urban security in the Dominican Republic. This is a country located in Central America, with more than 10.5 million of inhabitants, and it counts on various types of public and private transport systems.

Data from the National Survey on Mobility from 2019 expose that, although more than 60% of the population has a private vehicle, motorcycles (that are cheaper and more accessible for the general population) constitute the majority of them, and cars are less frequently found. Furthermore, the use of public transport for daily movements is quite frequent: only as a figure, it is estimated that more than a half of commuting trips are performed on public transport, which is frequently used by more than 58% of the population (INTRANT, 2020). In this regard, the most used transport modes are public buses ("guagua"), and either formal or informal moto-taxis ("motoconchos"). On the other hand, the most valued public vehicle is the subway, even though it is less used, especially because (among other reasons) it is only available in the most urbanized zones of the country (INTRANT, 2020).

Additionally, if factors such as the low average income and social inequality are considered, the improvement of the current public transportation modes, that are expected to continue to experience a massive and increasing use during the following years, results crucial for daily life dynamics of Dominicans (Carneiro and Sirtaine, 2017; INTRANT, 2020). Nevertheless, and although public transportation has proven to be essential in the Dominican Republic, many residents face daily security-related challenges that can potentially affect their welfare: according the National Mobility Survey from 2019, safety is the most relevant concern of private vehicle users, while the perception of danger in the streets and transportation means is predominant among people who do not own a vehicle (INTRANT, 2020); this substantial gap provides clues of this factor influencing the choice of transport modes, an aspect that we aim at researching in this study.

## Objective of the Study

The main objective of this research was to study the relationships between the perceived security (in both urban environments and public transport systems) and the daily-travel behavior and trip patterns among the Dominican Republic population. Moreover, we studied differences in three sociodemographic variables: age, level of education, and city/town size, as well as the percentage of individuals who have witnessed/suffered security threats while performing urban trips.

# METHODS AND MATERIALS

## Participants

This cross-sectional study analyzed the data gathered from 1,026 inhabitants from different cities of the Dominican Republic, who completed a questionnaire on safety and other issues related to transportation in the year 2019. Approximately 54% of them were females and 46% males. The mean age was $M = 31.88$ ($SD = 13.45$) years. Further demographic features of the study sample are shown in **Table 1**.

## Design, Procedure and Instruments

This study used an observational cross-sectional method. The sample design was performed by means of a simple random sampling proportional to age, sex, and region of the Dominican population. The minimum sample size was initially established at about $n = 660$ subjects, if a margin error for the general data of 5% is considered, with a confidence interval of 95% in the least favorable case of $p = q = 50\%$. However, this study achieved an even wider sample size, composed of 1,026 participants. Some comparisons of key demographic features between the study sample and the populational data are shown in **Table 2**.

The data were gathered through a street-conducted questionnaire, that retrieved a convenience sample based on the accessibility to the population. The average duration of the survey was 15 min, and it was carried out anonymously, to protect the participants' identity. It is worth highlighting that the data were used for statistical research purposes only, and participation was voluntary and anonymous. The inclusion/exclusion criteria were: (1) being over 18 years old, and (2) regularly (at least once a week) performing urban trips in one's cities, regardless of their duration and geographical coverage. To answer the survey, participants were informed about the basic principles of privacy, personal data treatment and confidentiality. Participants' consent was required by researchers. The total of discarded (incomplete or unclear forms) surveys was 41.

In order to achieve the purpose of our study, participants were asked about the following variables.

### Sociodemographic Features

Participants were asked about their: sex/gender, age, educational level, current occupation, size of the city/town of residence.

### Daily Travel Patterns

Once the participants were socio-demographically characterized, they were asked about the most frequent transportation means used for their daily movements; the average duration (measured in minutes) of their commuting trips (i.e., trips performed to/from work or studies center, in case of students); the frequency of public transport use; and the main reason for performing their usual urban trips.

### Perceived Security Assessment

Additionally, they were asked to rate, in a 1–5 scale (being 1 = totally unsafe and 5 = totally safe) the security they perceived in their (a) urban environment (city/town of residence), and (b) the public transportation system available in their city or town.

### Experiences of Direct Victimization or Crime-Witnessing

Finally, participants were inquired about their past experiences (in a time frame of 5 years before the survey), asking if: (a) they had witnessed (although not suffered) an unsafe incident (i.e., theft attempts) in the city's street or public transport system; and (b) if they had suffered (regardless of witnessing or not any other attempt affecting third parties), at least once, a theft attempt while circulating within any of these two environments. Furthermore, and in case the participants positively responded to one of the previous questions, they were asked whether they modified their travel behavior as a consequence of this(these) experience(s) of victimization, providing a list of six different possible behaviors commonly adopted after suffering an on-trip victimization (i.e., Changing my mode/route of transportation; avoiding traveling alone; avoiding walking/using public transport when it is very crowded; avoiding walking/using public transport when it is very empty; modifying my travel schedules; staying on permanent alert).

## Ethics

For this study, the Research Ethics Committee for Social Science in Health of the University Research Institute on Traffic and Road Safety (INTRAS) at the University of Valencia was consulted, and it granted the research's accordance with the principles stated in the Declaration of Helsinki for research with human subjects, since no personal data were involved, the participants' responses were treated with total anonymity and the risk level was determined as "very low" (IRB number HE0001251019). All participants gave us their consent to participate in the study after a careful reading of the Informed Consent form, in which the study aim, and all the aforementioned considerations were explained by the research staff.

## Data Processing

First of all, we carried out an exhaustive data curation, in order to enhance the basic aspects of the data that were to be analyzed. Once the data was clean and properly labeled (41 incomplete surveys were discarded), basic descriptive analyses of the study sample were performed in order to characterize the participants of the study according to their demographic features and urban-travel patterns. Correlational analyses were performed through Spearman's *rho* or $r_s$, in order to determine the measures of association between the main study variables.

**TABLE 1 |** Demographic data of the sample and transportation-related indicators.

| Feature | Category | Frequency | Percentage |
|---|---|---|---|
| Gender | Female | 553 | 53.9 |
| | Male | 473 | 46.1 |
| Educational level | Primary studies or lower | 47 | 4.6 |
| | Secondary-high school | 318 | 31.0 |
| | Technical studies | 84 | 8.2 |
| | University studies | 486 | 47.4 |
| | Post-graduate studies | 91 | 8.9 |
| Occupation | Student | 473 | 46.1 |
| | Employed | 410 | 40.0 |
| | Self-employed (autonomous) | 83 | 8.1 |
| | Unemployed | 19 | 1.9 |
| | Retired | 5 | 0.5 |
| | Householding | 16 | 1.6 |
| | Other | 20 | 1.9 |
| City/town size (population density) | <5,000 inhab. | 40 | 3.9 |
| | 5,000 to 10,000 inhab. | 129 | 12.6 |
| | 10,000 to 50,000 inhab. | 74 | 7.2 |
| | 50,000 to 100,000 inhab. | 68 | 6.6 |
| | 100,000 to 200,000 inhab. | 74 | 7.2 |
| | >200,000 inhab. | 641 | 62.5 |
| Main reason for performing urban movements | Daily commuting | 640 | 62.4 |
| | Short trip to a specific point | 87 | 8.5 |
| | Leisure ("go for a walk") | 95 | 80.1 |
| | Exercise or fitness | 113 | 11.0 |
| | Housework (groceries shopping, picking up children…) | 91 | 8.9 |
| Most frequently used transport means for urban movements | Massive transport system (bus, metro, tram…) | 603 | 58.8 |
| | Taxi, Uber, or similar | 47 | 4.6 |
| | Private car | 225 | 21.9 |
| | Motorcycle | 47 | 4.6 |
| | Bicycle | 4 | 0.4 |
| | By walking | 57 | 5.6 |
| | Other | 43 | 4.2 |
| Witnessed (although not suffered) >1 theft attempt during their urban movements (last 5 years) | Yes | 172 | 16.7 |
| | No | 854 | 83.3 |
| Suffered (regardless of witnessing) >1 theft attempt during their urban movements (last 5 years). | Yes | 563 | 54.8 |
| | No | 463 | 46.2 |

This test ($r_s$) offers more accuracy for bivariate correlation's estimation when using both ordinal and scalar variables than Pearson's $r$ (Liu et al., 2016). Mean comparisons (One-way ANOVAs) were performed for comparing the scores given to numerical variables according to sex/gender, education, and city/town size. Finally, categorical analyses with Chi-square ($X^2$) tests were used to establish relationships and differences between pairs of non-numerical variables. All statistical analyses were carried out using the Statistical Package for the Social Sciences (IBM SPSS Statistics), Version 23.0 (IBM Corporation, Armonk, NY, USA).

# RESULTS

## Descriptive Findings and Correlational Analyses

Apart from the data presented in the socio-demographic characterization of the sample, in **Table 3** the means (M) and standard deviations (SD) of the main study variables are summarized. In short, it was found that the average duration of daily commuting trips of Dominican citizens was 75 min, and their mean number of public transport trips per week was close to 6, that is equivalent to three roundtrips a week. Furthermore,

the average level of security perceived in the streets of their cities was 2.35 out of five, while the security perceived in the available public transport systems was 2.52 out of five.

In a second step, the ordinal and continuous variables included in the study were analyzed through Spearman's ($r_s$) bivariate tests, finding interesting correlations between some pairs of them. Concretely:

- The age of Dominican citizens was negatively correlated to their number of trips performed by public transport in a week.
- The educational level was positively correlated to their daily commuting length, their weekly number of trips performed by public transport, and to the security perceived in the urban environment (i.e., city streets).
- The city/town size (population density) was negatively correlated to the level of security attributed to both city streets and public transportation systems. In other words, Dominicans from smaller cities/towns perceive their urban environments and public transport systems as more secure, if compared to inhabitants of larger/denser towns or cities. Also, the population density is positively correlated to the citizens' weekly number of trips performed by means of public transport.
- The length of daily commuting trips (performed between home and/or the work/study place) was positively associated with the number of times that citizens used the public transport in a week. Also, the longer the daily commuting trips, the lower security level is perceived in both city streets and public transportation systems, and vice-versa (negative correlation).
- The number of weekly public transport-based trips was negatively associated with the level of security perceived in the urban environment and the security perceived in the public transport systems.
- Finally, a positive correlation between the levels of security perceived in the urban environment and the public transportation systems was also found. In other words, a person perceiving more security in the city streets tends to perceive a higher level of security on the public transport too, and vice versa.

**TABLE 2 |** Demographic comparisons between the sample features and country-based data.

| Variable | Category | Study sample (%) | Dominican republic census[a] (%) |
|---|---|---|---|
| Sex | Male | 46.1 | 50.17 |
| | Female | 53.9 | 49.83 |
| | ≤24 | 43,8 | 49.43 |
| Age group | 25–34 | 21.2 | 15.67 |
| | 35–50 | 16.7 | 18.17 |
| | >50 | 18.3 | 10.51 |
| Habitat | Urban (>50,000 inhabitants) | 76.3 | 74.25 |
| | Rural (<50,000 inhabitants) | 23.7 | 25.75 |

[a]*Data obtained from SICEN (http://sicen.one.gob.do/).*

## Mean Comparisons

One-way Analyses of Variance (ANOVA) allowed us to determine the existence of a set of significant group differences between categories or groups, according to the three key demographic factors addressed in this study. In the case of citizens' sex, males perceive both city streets and public transport systems as safer than females. In addition, no significant differences in terms of weekly public transport use or daily commuting length were found.

As for Dominican citizens' educational level, significant differences were found in the case of all four contrasted variables, except for perceived security in urban environments, and the perceived security of both streets and public transport systems was tendentially higher for subjects with lower educational levels. Finally, and in what concerns e.g., city/town size intervals, it was found that inhabitants of mid-size towns (5,000 to 50,000 inhabitants) tendentially perceive transport systems as safer than citizens living in either small or large cities.

*Post-hoc* (Tukey) tests showed only slightly significant differences between specific levels (groups) for the variables tested with two or more categories (i.e., education and city size); this suggests a considerable homogeneity of the data across subjects when they are categorized by educational level and city/town size, as shown in **Table 4**. Specifically, for what

**TABLE 3 |** Descriptive statistics and bivariate (Spearman's $r_s$) correlations between study variables.

| Variable | | Mean | SD | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Age | 31.88 | 13.45 | −0.012 | 0.046* | −0.031 | −0.221** | −0.026 | −0.026 |
| 2 | Educational level[a] | – | – | – | 0.107** | 0.063** | 0.046* | 0.049* | 0.015 |
| 3 | City/town size[a] | – | – | | – | 0.042 | 0.161** | −0.106** | −0.067** |
| 4 | Daily Commuting Length (min.) | 74.93 | 51.20 | | | – | 0.200** | −0.167** | −0.165** |
| 5 | Public Transport trips a week | 5.68 | 3.75 | | | | – | −0.174** | −0.112** |
| 6 | Perceived Security (City streets)[b] | 2.35 | 1.23 | | | | | – | 0.632** |
| 7 | Perceived Security (Public transport)[b] | 2.52 | 1.24 | | | | | | – |

[a]*Processed as a categorical (ordinal) variable;* [b]*Scale 1–5; *Correlation is significant at 0.05 level (2-tailed); **Correlation is significant at 0.01 level (2-tailed). Gray values represents the statistical correlation is not significant.*

**TABLE 4 |** Inter-group descriptive data (above) and mean comparisons (ANOVA; below) for security perception and urban trip-related factors according to sex, educational level, and city/town size interval (factors).

| Study variable | Category | Mean | SD | Std. error |
|---|---|---|---|---|
| **Factor 1: Sex** | | | | |
| Perceived security (City Streets) | Female | 2.20 | 1.21 | 0.05 |
| | Male | 2.52 | 1.24 | 0.06 |
| Perceived security (Public Transport) | Female | 2.42 | 1.23 | 0.05 |
| | Male | 2.63 | 1.25 | 0.06 |
| Public transport trips a week | Female | 5.81 | 3.69 | 0.16 |
| | Male | 5.53 | 3.82 | 0.18 |
| Daily commuting length (min.) | Female | 82.80 | 70.19 | 3.31 |
| | Male | 77.86 | 57.24 | 2.92 |
| **Factor 2: Educational level** | | | | |
| Perceived security (City Streets) | Primary studies or lower | 2.57 | 1.45 | 0.22 |
| | Secondary-high school | 2.40 | 1.28 | 0.07 |
| | Technical studies | 2.46 | 1.25 | 0.14 |
| | University studies | 2.33 | 1.21 | 0.06 |
| | Post-graduate university studies | 2.10 | 1.10 | 0.12 |
| Perceived security (Public Transport) | Primary studies or lower | 2.82 | 1.44 | 0.22 |
| | Secondary-high school | 2.62 | 1.30 | 0.07 |
| | Technical studies | 2.61 | 1.34 | 0.15 |
| | University studies | 2.47 | 1.16 | 0.05 |
| | Post-graduate university studies | 2.23 | 1.19 | 0.13 |
| Public Transport trips a week | Primary studies or lower | 7.09 | 3.47 | 0.52 |
| | Secondary-high school | 5.50 | 3.56 | 0.20 |
| | Technical studies | 5.75 | 3.58 | 0.39 |
| | University studies | 6.07 | 3.75 | 0.17 |
| | Post-graduate university studies | 3.47 | 3.92 | 0.41 |
| Daily commuting length (min.) | Primary studies or lower | 65.92 | 53.47 | 8.67 |
| | Secondary-high school | 74.85 | 62.99 | 4.07 |
| | Technical studies | 80.29 | 84.58 | 1.41 |
| | University studies | 84.54 | 65.49 | 3.26 |
| | Post-graduate university studies | 83.17 | 48.88 | 5.33 |
| **Factor 3: City/town size** | | | | |
| Perceived security (City Streets) | <5,000 inhab. | 2.30 | 1.36 | 0.22 |
| | 5,000 to 10,000 inhab. | 2.50 | 1.29 | 0.11 |
| | 10,000 to 50,000 inhab. | 2.51 | 1.26 | 0.15 |
| | 50,000 to 100,000 inhab. | 2.54 | 1.22 | 0.15 |
| | 100,000 to 200,000 inhab. | 2.47 | 1.13 | 0.13 |
| | >200,000 inhab. | 2.27 | 1.22 | 0.05 |
| Perceived security (Public transport) | <5,000 inhab. | 2.63 | 1.39 | 0.22 |
| | 5,000 to 10,000 inhab. | 2.81 | 1.26 | 0.11 |
| | 10,000 to 50,000 inhab. | 2.76 | 1.32 | 0.15 |
| | 50,000 to 100,000 inhab. | 2.63 | 1.13 | 0.14 |
| | 100,000 to 200,000 inhab. | 2.50 | 1.02 | 0.12 |
| | >200,000 inhab. | 2.42 | 1.25 | 0.05 |
| Public transport trips a week | <5,000 inhab. | 5.75 | 4.11 | 0.65 |
| | 5,000 to 10,000 inhab. | 5.33 | 3.58 | 0.32 |
| | 10,000 to 50,000 inhab. | 5.53 | 3.48 | 0.41 |
| | 50,000 to 100,000 inhab. | 5.69 | 3.69 | 0.45 |
| | 100,000 to 200,000 inhab. | 5.28 | 4.03 | 0.47 |
| | >200,000 inhab. | 5.81 | 3.77 | 0.15 |
| Daily commuting length (min.) | <5,000 inhab. | 67.59 | 42.82 | 7.95 |
| | 5,000 to 10,000 inhab. | 73.33 | 65.56 | 6.59 |
| | 10,000 to 50,000 inhab. | 71.73 | 55.21 | 7.19 |
| | 50,000 to 100,000 inhab. | 85.85 | 78.30 | 1.76 |
| | 100,000 to 200,000 inhab. | 82.50 | 57.05 | 7.49 |
| | >200,000 inhab. | 82.78 | 65.55 | 2.83 |

| ANOVA | $F^a$ | $df^b$ | $Sig^c$ |
|---|---|---|---|
| **Factor 1: Sex** | | | |
| Perceived security (City Streets) | 17.150 | 1, 1,024 | <0.001 |
| Perceived security (Public Transport System) | 7.261 | | <0.01 |
| Public transport trips a week | 1.428 | | 0.232 |
| Daily commuting length (min.) | 0.764 | | 0.382 |
| **Factor 2: Educational level** | | | |
| Perceived security (City Streets) | 1.327 | 5, 1,020 | <0.250 |

*(Continued)*

**TABLE 4 |** Continued

| ANOVA | $F^a$ | df[b] | Sig[c] |
|---|---|---|---|
| Perceived security (Public Transport System) | 2.402 | | <0.05 |
| Public transport trips a week | 123.255 | | <0.001 |
| Daily commuting length (min.) | 933.65 | | <0.01 |
| **Factor 3: City/town size interval** | | | |
| Perceived security (City Streets) | 1.701 | 5, 1,020 | 0.132 |
| Perceived security (Public Transport System) | 3.012 | | <0.01 |
| Public transport trips a week | 0.567 | | 0.725 |
| Daily commuting length (min.) | 0.776 | | 0.567 |

[a]*Result of the F (One-way ANOVA) test;* [b]*Degrees of freedom;* [c]*p-value.*

concerns educational levels, no *post-hoc* differences were found for the perceived security, neither in urban environments nor in public transport systems. *post-hoc* differences for educational levels were only found in (i) the number of public transport trips performed a weeks, in which individuals with higher (post-graduate) educational levels performing significantly fewer trips than citizens with lower educational levels (primary to university studies). They were also found (ii) between individuals with secondary and university (graduate) studies, the latter having significantly longer commuting trips. As for city/town size, it was found that inhabitants from largest cities (>200,000 inhabitants) perceive significantly less security in transport systems than those living in small towns (5,000–10,000 inhabitants).

## Categorical Analysis

In addition to analyzing demographic factors, this study aimed to determine how urban safety issues may influence the travel behavior of participants. Hence, we analyzed the travel-related behavioral changes reported by: (i) 172 (16.7% of the sample; 45% females and 55% males; non-significant $X^2$ test for gender differences) participants who had witnessed theft attempts during the previous 5 years (either in the public transport or in the city's streets while commuting) without suffering them directly, and (ii) 563 (54.8% of the sample; 52% females, 48% males; non-significant $X^2$ test for gender differences) participants who reported that they had suffered at least one theft attempt (regardless of whether they had witnessed or not theft attempts affecting third parties) during the previous 5 years, as shown in **Table 5**.

Regarding the first case (participants witnessing theft attempts, although not suffering them), it was found that, after beholding an on-travel, theft-related security issue, participants did not significantly modify their routes, nor the transport means used for their movements [significant at $X^2_{(1)} = 5.886$, $p < 0.05$]. The most frequent behavioral pattern reported as a response to beholding theft attempts or similar incidents affecting other users (but not them) is rather being in a permanent state of alert (60.5%) while traveling.

As for the second case, 54.9% of participants who suffered at least one on-travel theft attempt decided to modify their habitual daily transportation means or routes; for instance, by shifting from bus to taxi, or by choosing a different route for performing the same trip [significant at $X^2_{(1)} = 33.970$, $p < 0.001$]. Furthermore, other main actions taken by participants affected by theft attempts were: being permanently alert while traveling (55.8%), avoiding traveling alone (40%) and avoiding walking/using public transport when it is very empty (36.1%).

# DISCUSSION

The core aim of this research was to study the relationships between the security perceived in both urban environments and public transport systems, as well as the daily-travel behavior and patterns of the Dominican Republic's population. The results of this research suggest that demographic factors and urban travel patterns, as well as the perceived urban security, play an important role in the choice of transportation modes and other travel patterns of the Dominican population.

Particularly, the results of the current research have shown how, overall, Dominican citizen's perception of the public transportation security constitutes a pending issue for both public administrations and transport systems, especially if we consider that these outcomes are coherent with the ones gathered by the National Survey on Mobility of 2019 (INTRANT, 2020). The aforementioned survey also highlighted some interesting points on the "worst valued" elements of public transportation, that were: comfort, hygiene, and, once again, users' security.

Furthermore, previous studies carried out in the region (i.e., other Latin American countries), for instance in Ecuador (Núñez et al., 2018), Argentina (Pereyra et al., 2018) and Colombia (Cámara de Comercio de Bogotá, 2018) have coherently documented similar trends: in short, all of them suggest that even though citizens do not present a high level of dissatisfaction with public transportation, many of them report having frequently found themselves in situations of unsafety or harassment during their urban trips. Therefore, it is indeed surprising to find such a high use of this transport mode among Dominican citizens. One reasonable assumption in this regard is that, due to -as it is mentioned in the introduction- the several economic and social disparities present in the country (Carneiro and Sirtaine, 2017), the great majority of Dominicans might find the most accessible and affordable option for their daily urban trips in public transportation (INTRANT, 2020); one of the reasons is that, for instance, the economic investment represented by buying and maintaining a private vehicle remains challenging for a very low-income population that predominantly works under a lack of job security (Carneiro and Sirtaine, 2017).

The results of the present study show that the more security is perceived in the streets, the fewer trips are performed by public transportation. In this sense, there are studies demonstrating that

**TABLE 5 |** Travel actions taken by study participants after witnessing or suffering a theft attempt in city streets and/or public transport.

| Action | Yes | | No | |
|---|---|---|---|---|
| | Frequency | Percentage | Frequency | Percentage |
| **(i) Witnessing theft attempts** | | | | |
| Changing my mode/route of transportation | 53 | 30.8 | 119 | 69.2 |
| Avoiding traveling alone | 47 | 27.3 | 125 | 72.7 |
| Avoiding walking/using public transport when it is very crowded | 33 | 19.2 | 139 | 80.8 |
| Avoiding walking/using public transport when it is very empty | 50 | 29.1 | 122 | 70.9 |
| Modifying my travel schedules | 40 | 23.3 | 132 | 76.7 |
| Staying on permanent alert | 104 | 60.5 | 68 | 39.5 |
| **(ii) Suffering theft attempts** | | | | |
| Changing my mode/route of transportation | 309 | 54.9 | 254 | 45.1 |
| Avoiding traveling alone | 225 | 40.0 | 338 | 60.0 |
| Avoiding walking/using public transport when it is very crowded | 157 | 27.9 | 406 | 71.1 |
| Avoiding walking/using public transport when it is very empty | 203 | 36.1 | 360 | 63.9 |
| Modifying my travel schedules | 167 | 29.7 | 396 | 70.3 |
| Staying on permanent alert | 314 | 55.8 | 249 | 44.2 |

the perception of security in a certain area encourages people to move on foot or to use a bike (Dennis et al., 2019; Nostikasari et al., 2019). Therefore, it is logical that these people will diminish their use of public transportation. Also, a positive relation was detected between the perception of security in the streets and the perception of security in public transportation. In this sense, it is remarkable that the longer the trips performed by public transport, the lower is the perception of their security. This could be related to the fact that spending more time on these vehicles increases the probability of experiencing a dangerous situation, either personally or as a witness.

In this sense, it is also expectable that females may perceive public transportation means as less secure than males, since they are the ones using it the most, especially if the typical gender-gaps of emerging countries are kept in mind (Núñez et al., 2018; Pereyra et al., 2018). In this regard, there is empirical evidence on women using public transportation in violent areas who usually display more fear or concern, even in locations in which males are those getting more involved in violent accidents and/or security incidents (Quiñones et al., 2018). To this we must add that Latin American public transport systems present a high incidence of harassment, mostly affecting women, as observed in many other locations in the region (Gardner et al., 2017; Orozco-Fontalvo et al., 2019). Accordingly, this set of differences between men and women are highlighted in several researches, with females always standing out as the most frequent victims of harassment-related incidents (Ibarra and Castro, 2016; Falú, 2017; Orozco-Fontalvo et al., 2019).

Complementarily, other differential factor are age and city/town density. In regard to the first one, this study found that older people perceive more security flaws and shortcomings in public transportation, as observed, for instance, in a recent study carried out in Peru (Huamani et al., 2019). As for the second factor, there is a tendency to develop a lower perception of security if the size of the town of residence is bigger. It is important to distinguish whether such a perception is adjusted to the real data on crime or, on the other hand, if it is a false/biased perception, which may take place more frequently in urban environments (Prieto and Richard, 2016).

Lastly, and in regard to those citizens witnessing and/or suffering threatening situations during urban trips, the most frequently performed behavioral action was increasing the level of alert. From a psychological perspective, it makes sense to assume that the increase of anxiety and alert levels are among the most common responses after facing hazardous situations, potentially implying behavioral, physical, cognitive and emotional consequences (Muggah and de Boer, 2019). The present study also points out that "changing route" or "avoiding traveling alone" are relatively frequent behaviors. Also, it is remarkable that, for what concerns these situations, there are few public transport users who actually avoided using the transportation systems or vehicles when it is almost empty (this is a difficult factor to control if, for instance, work schedules are inflexible and end too late), in comparison with avoiding it when it is crowded. In this regard, similar studies have especially focused on the relationship between isolated public transport environments and higher levels of anxiety and lower levels of perceived security (Davidson et al., 2016; Orozco-Fontalvo et al., 2019).

## CONCLUSION

The results of this study suggest that perceived security, both in urban environments and public transport systems, is a relevant issue that affects the daily and transport-related patterns and behavioral choices of the Dominican Republic population, and it constitutes a core issue to address in transport planning. Furthermore, and although there are no differences in terms of witnessing or suffering a crime-attempt, there are significant

gender-based differences in the security perception of these two environments: women perceive a higher lack of security in both scenarios.

This research establishes a starting point for the elaboration of adequate strategies aimed at strengthening the promotion of safer and more sustainable public transportation means and urban environments, considering the income-state and the high demand of public transportation among most of the population in the Dominican Republic, as well as in other countries of the region with similar income-related and demographic characteristics.

### Limitations of the Study

Although our sample size was considerably large and representative of the Dominican population, and all statistical parameters were accurately and positively tested during the data analysis, some key technical issues must be acknowledged as potential sources of bias. First, this study is based on self-reports, placing its results within the spectrum of the common method biases, often observed in research with cross-sectional designs (Cossman and Rader, 2011; Simundić, 2013). These sources of bias may range from social desirability to lack of sincerity and acquiescence bias. Also, if we consider that the survey addressed a set of topics embodied in the current social discussions, several social concerns related to factors such as poverty, inequalities, and lack of safety may emerge, as observed in previous studies dealing with topics perceived as sensitive by the population, such as crime, fear of crime, and victimization (Sutton and Farrall, 2005; Derksen, 2012). In short, this kind of topics are usually stigmatized, and therefore still tend to affect study outputs, although the anonymity of participation and the scientific value of the data were clearly guaranteed prior to the individual's partaking in the study. Finally, there are two technical issues that should be acknowledged as limitations of this study as well: (i) The sampling procedure was not probabilistic, but rather based on the willingness to participate showed by individuals interviewed by the research staff on the city streets. This could therefore bias the study outcomes, to a certain extent (e.g., what about the perception of individuals who hardly go out, or non-respondents' profiles?); (ii) For assessing perceived security both in urban locations and public transport systems, single item-based variables were used. In this regard, for further studies it is suggestible to use multi-item scales for measuring critical issues such as security perceptions, that may allow researchers to retrieve more specific information on these issues. Performing complementary procedures, such as testing questionnaire reliability, is also highly advisable.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, under reasonable request.

## ETHICS STATEMENT

The study design and protocol were reviewed and approved by the RESEARCH ETHICS COMMITTEE of the University Research Institute on Traffic and Road Safety at the University of Valencia (IRB HE0001251019).

## AUTHOR CONTRIBUTIONS

All authors contributed to the design of the study and also wrote the final manuscript. FA drew up the study design with the help of SU, the rest of the authors also contributed. MF and SU were in charge of the data revision. CE also drafted the manuscript. FA performed the statistical analysis. All authors read and approved the final manuscript.

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# Evaluating Impacts of a Leading Pedestrian Signal on Pedestrian Crossing Conditions at Signalized Urban Intersections: A Field Study

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Signalized intersections appear among urban locations with a high frequency of pedestrian injury. Due to the need to move large traffic volumes, a shared vehicle-pedestrian green phase is generally applied for turning vehicles and crossing pedestrians at intersections on busy urban roads. The shared green relies on a driver's ability to yield to crossing pedestrians which, if it fails, may increase the risk of pedestrian injury. A solution suggested for improving pedestrian safety in such situations is to provide a leading pedestrian signal, i.e., the pedestrian green appears earlier than the vehicle green, forcing vehicles to give priority to the pedestrians already on the crossing. A field-study was conducted at two intersections in Tel-Aviv, Israel, to examine the impact of such a measure on pedestrian crossing conditions. The pedestrian green phase was brought forward by 3 s. The study analyzed changes in road user behaviors, in the crosswalk area, in the after period when the measure was activated compared to the before period. The results showed that following the measure's application, the percentage of traffic lights' cycles with giving-right-of-way to all pedestrians, at the beginning of green, increased to 97–100% for pedestrians crossing from the sidewalk and to 94–99% for those who crossed from the road median. In addition, improvements were observed in the provision of pedestrian right-of-way during the whole green phase. The measure did not affect the rate of vehicle-pedestrian conflicts due to low conflict occurrence at the study sites. Overall, the findings indicated positive changes in pedestrian crossing conditions, following the introduction of a leading pedestrian green. The increase in giving-right-of-way to pedestrians by turning vehicles is expected to contribute to improved pedestrian safety while crossing at signalized intersections.

**Keywords: pedestrian safety, signalized intersection, shared vehicle-pedestrian green, leading pedestrian signal, field observations, giving-right-of-way**

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## INTRODUCTION

Walking is a basic mode of urban transport in various societies, with well-established health and environmental benefits stemming from increased physical activity and reduced air pollution [World Health Organisation (WHO), 2010, 2013]. As urban density increases in many countries [International Association of Public Transport (UITP), 2015], a growing number of authorities have begun to implement policies to stimulate walking as an essential component of sustainable

urban development. However, pedestrian injury is still one of major safety problems throughout the world, where pedestrians account for 23% of the total fatalities in road crashes in the world [World Health Organisation (WHO), 2018], and represent 40% of total fatalities and 25% of serious injuries on urban roads in Europe [European Transport Safety Council (ETSC), 2019].

In Israel, pedestrian injury is one of the leading road safety problems over the last decades, since pedestrians usually present about a third of the annual fatalities and serious injuries in the country (Gitelman et al., 2012; Sharon, 2017). Most pedestrians (87%) are killed or seriously injured on urban roads (Sharon, 2017). The scope and constancy of the pedestrian safety problem, in Israel, strengthen the need for efforts to promote interventions to improve pedestrian safety. Moreover, the plans of sustainable urban development that discourage private car use and encourage walking (as well as public transport use and cycling) raise additional safety concerns since the existing urban environment is not ready yet for safe walking [Stoker et al., 2015; European Transport Safety Council (ETSC), 2019].

International experience emphasizes the role of infrastructure-related measures for reducing pedestrian injury because such measures provide an immediate and long-term effect [Huang and Cynecki, 2001; Ewing and Dumbaugh, 2009; Zegeer and Bushell, 2012; World Health Organisation (WHO), 2013; Mead et al., 2014]. Among other measures, providing signalized pedestrian crosswalks was reported to be effective in increasing pedestrian safety (Harkey and Zegeer, 2004; Elvik et al., 2009).

Signalized crosswalks, including those at signalized intersections, are supposed to serve as a safe place for pedestrians to cross, since they implement a principle of time-separation between vehicle and pedestrian movements. However, signalized intersections appear to be among urban locations with a high frequency of pedestrian crashes. According to recent estimates, on urban roads in Israel, seven percent of the fatal or serious pedestrian injuries occurred on signalized crosswalks (Sharon, 2017). Gitelman et al. (2012) examined infrastructure characteristics at urban locations with a higher frequency of pedestrian crashes, in Israel, and found that pedestrian crossings at signalized intersections represented the largest group, over a fifth of the sites examined. The vast majority of such intersections were situated on busy urban streets, with heavy traffic volumes and pedestrian activities. Due to the need to move large traffic volumes through the intersection, on an urban road, a shared vehicle-pedestrian green phase is generally applied for turning vehicles and crossing pedestrians. This feature was overrepresented at the signalized intersections with pedestrian crashes in the cities (Gitelman et al., 2012). It should be noted in this context that among other reasons for pedestrian-involving crashes at signalized intersections can be non-compliance with red lights by crossing pedestrians, insufficient length of green signals for completing the road crossing by pedestrians, etc. (Harkey and Zegeer, 2004; Elvik et al., 2009; Koh et al., 2014; Duduta et al., 2015).

According to the design guidelines for traffic signals (Guidelines, 1981), a right turn can be planned as a common green light for the turning vehicles and for pedestrians who cross the road at the adjacent crosswalk—**Figure 1**. In this case, both vehicles turning right and crossing pedestrians simultaneously receive green lights, while a blinking yellow sign indicates that the drivers should give priority to crossing pedestrians. The need for using shared green light is related to the traffic aspects of the intersection and typically refers to the lack of possibility to provide a separate green phase for pedestrians due to capacity constraints. A shared green light for turns at intersections can also be met in other countries (e.g., Koh et al., 2014).

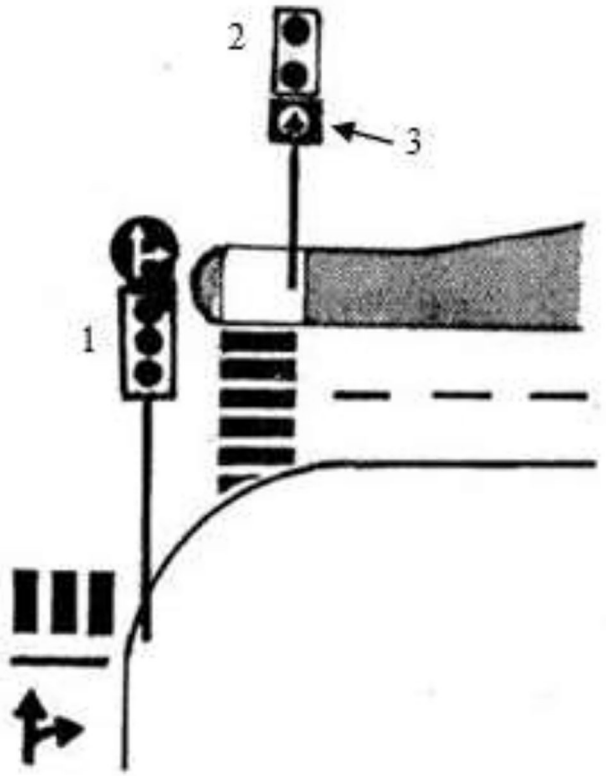


**FIGURE 1 |** Typical setting of shared green phase for turning vehicles and crossing pedestrians, at a signalized intersection, based on Guidelines (1981). 1, traffic lights for turning vehicles; 2, traffic lights for crossing pedestrians; 3, blinking yellow sign "give priority to crossing pedestrians".

The shared green light relies on a driver's ability to notice and yield to the crossing pedestrians which, if it fails, may increase the risk of pedestrian injury. A solution suggested in the professional literature for improving pedestrian safety in this situation is to provide a leading pedestrian signal, i.e., the pedestrian green appears earlier than the vehicle green, enabling pedestrians to begin crossing in advance of right turning vehicles and hence forcing vehicles to give priority to the crossing pedestrians [Harkey and Zegeer, 2004; National Cooperative Highway Research Program (NCHRP), 2004; Gitelman et al., 2012].

Literature findings with regard to the safety impacts of shared pedestrian green with right-turning vehicles at intersections are not numerous. Elvik et al. (2009) summarized the international experience regarding the safety impacts of various changes in the traffic lights at intersections and found that the shared

green for pedestrians and vehicles was associated with an 8% increase in pedestrian-involving crashes and a 12% decrease in the vehicle-only crashes (both changes are close to significant). Conversely, the separate pedestrian green was associated with a significant decrease in both pedestrian and vehicle crashes, at 30 and 18%, respectively (Elvik et al., 2009). Concerning an earlier appearance of pedestrian green light in the shared situation, no crash estimates were reported.

Previous research in the USA indicated that a leading pedestrian signal in the shared green with turning vehicles has a potential to improve pedestrian safety, which is reflected in reduced vehicle-pedestrian conflicts and better giving-way to pedestrians by vehicles in the crosswalk area. For example, Van Houten et al. (2000) reported on a study conducted at three urban intersections, when the pedestrian green was changed to start 3 s earlier than the turning vehicles' green. They found a 95% reduction in the odds of vehicle-pedestrian conflicts for pedestrians who started crossing at the beginning of their green, while the odds of the incidence of pedestrians yielding the right-of-way to turning vehicles decreased by 60%. Harkey and Zegeer (2004) described field studies conducted at one intersection in Orlando and at three intersections in Petersburg, Florida, where pedestrian green was changed to appear four or 3 s earlier than the right-turning vehicles' green. In both cases, in after-before comparisons, a decrease in the number of vehicle-pedestrian conflicts was observed.

Being aware of a high presence of signalized intersections in Israeli cities and associated pedestrian safety problems, a field study was initiated aiming to explore the impacts of a leading pedestrian signal, on pedestrian crossing conditions at signalized intersections. As indicated above, previous research on the subject was scarce but generally reported a positive safety potential of the measure. In addition, international experience shows [Ekman and Hyden, 1999; Harkey and Zegeer, 2004; World Health Organisation (WHO), 2013; Mead et al., 2014] that safety-related impacts of an infrastructure measure may vary depending on the local conditions. Thus, the examination of impacts of a leading pedestrian signal was undertaken aiming to contribute both to the local practice of planning traffic lights at urban intersections and to the international knowledge with regard to the safety impacts of this infrastructure measure.

## METHODS

This section is divided into two parts to explain the study framework and selecting the study sites, and data collection and analysis' methods, respectively.

### The Study Framework and Selection of the Study Sites

The measure considered in this study was the introduction of a leading pedestrian signal—an earlier appearance of pedestrian green signal in shared green for right-turning vehicles and crossing pedestrians, at an urban intersection (see **Figure 1**). The pedestrian green was brought forward by 3 s relative to the co-occurring green light for the turning vehicles. After the initial 3 s of pedestrian green only, there was a shared green both for vehicles and pedestrians. The selection of 3 s for a leading pedestrian signal in this study was based on the experience of previous studies on the topic (Van Houten et al., 2000; Harkey and Zegeer, 2004) and also accounting for the fact that the longer the advanced time the more harmful it can be for the intersection capacity. In addition, Van Houten et al. (2000) indicated that 3 s are appropriate as a start-up time for crossing pedestrians of any age.

The purpose of the study was to examine the influence of the measure on pedestrian crossing conditions, whereas the later are estimated in terms of road user behaviors related to pedestrian safety. An after-before design was applied, where behavior indicators were estimated and compared at the study sites, in the after period when the measure was activated with the same indicators in the before period. Such a design is common in observational studies for estimating safety-related impacts of road infrastructure measures, including those with a focus on pedestrian safety (Van Houten et al., 1999, 2000; Harkey and Zegeer, 2004; Ewing and Dumbaugh, 2009; Gitelman et al., 2017).

The selection of road user behaviors for the current study was based on the experience of previous studies on the topic (Van Houten et al., 2000; Harkey and Zegeer, 2004) and also on the studies which examined pedestrian behaviors at signalized intersections, in general (Gitelman, 2014; Koh et al., 2014; Dommes et al., 2015). The road user behaviors examined in the current study included: giving-right-of-way to pedestrians by turning vehicles during the shared green, vehicle-pedestrian conflicts' occurrence in the crossing area, and crossing on red by pedestrians.

Road user behaviors were to be collected by means of field observations. At each site, three rounds of observations were planned: *before*—prior to application of the measure; *after1*—a week after the activation of the measure to examine its immediate impact; *after2*—about 2 months after the activation, to examine the behavior changes in the long term. The two rounds of after observations were applied to examine the effect of the measure immediately after its activation and after a certain "adaptation" period of the road users to the new situation.

The study intended to examine the measure in a large city with a common use of shared vehicle-pedestrian green for right-turning vehicle movements at signalized intersections. An agreement for co-operation was attained with the traffic engineering department of the Tel Aviv-Yafo municipality. Tel Aviv-Yafo is one of the biggest Israeli cities, with about 450,000 inhabitants and a high concentration of employment centers, including business, administrative, industrial and commercial activities. Due to heavy commuter traffic which enters the city daily, both by car and by public transport, "the active population" of the city is more than twice as high as the number of its inhabitants (Troitsky, 2018).

The requirements for the study sites were defined as follows: (1) It should be a signalized intersection with a signalized pedestrian crossing having a shared green light for pedestrians and turning vehicles, and situated in the city center; (2) The traffic volumes for turning vehicles in the shared green should not be high, about 200 vehicles per hour (in non-rush hours);

(3) The volumes of crossing pedestrians at the crosswalk with shared green should be medium-high, with at least 30 crossings per hour in the daytime. The requirements were based on the characteristics of the city and also accounted for the local guidelines of planning traffic lights, i.e., avoiding the use of shared green at sites with high volumes of turning vehicles. The third requirement related to the need to observe crossing pedestrians at the study sites (i.e., not to select sites with rare crossing pedestrians). Similar boundaries for the intensity of pedestrian activity were applied in other local studies, e.g., Gitelman et al. (2017).

A list of intersections with shared green lights was received from the city traffic department and consequently examined by the study team through preliminary field surveys. The introduction of the advanced pedestrian signal required a refitting of the traffic lights' program at the intersection that should be performed by a traffic engineer. Due to logistic and budget constraints, it was agreed among all the bodies involved (the municipality, the study commissioner and the study team) to apply the change at two sites. Thus, two intersections were selected for the study, both situated in the heart of employment activities of the city and in the proximity to public transport routes. The study sites were:

Site 1 (Levinsky—Lavander) is a four-legged intersection between a dual-carriageway collector road and a single-carriageway secondary road, situated in the vicinity of the central bus station and on a walking route that connects a railway station and the central bus station. A shared vehicle-pedestrian green was found and the advanced pedestrian signal was consequently applied on one leg of the intersection. **Figure 2**, *a* presents the crosswalk included in the study;

Site 2 (Hamasger—Ben Avigdor) is a three-legged intersection, on a dual-carriageway collector road, which crosses the old industrial area of the city having multiple business, administrative and commercial activities and a variety of bus routes. A shared vehicle-pedestrian green was found for vehicles turning right from the secondary to the main road and the advanced pedestrian signal was applied on this leg. **Figure 2**, *b* presents the crosswalk included in the study, in this site.

Due to the diversity of traffic arrangements at the city intersections and an overload of city streets with various signs (e.g., business and property signs, advertisements, traffic signs), additional signs concerning the change in the traffic lights were not installed at the study sites.

## Data Collection and Analysis

At each site, road user behaviors were collected using video-recordings of the crosswalk area, where the camera view covered the crosswalk, the sidewalk and the median next to the crosswalk, the turning vehicles near the crosswalk and the traffic lights for vehicles and for pedestrians. The duration of video-recording, in each period of observations, was about 10 h in a weekday (mostly, between 11 a.m. and 9 p.m.), including 6–7 h of daytime and 2–4 h of evening hours. This way, the observations included hours with both higher and lower vehicle traffic and with more pedestrian activities. The video-recordings were conducted on July 28, 2011 (before), November 24, 2011 (after1) and February 2, 2012 (after2), at both study sites. All days were with sunny and clear weather.

Using the video-records, the data were coded manually, using pre-defined forms and rules. First, hourly traffic volumes of the turning vehicles were produced by means of vehicle counting for each quarter of an hour and converting the values into average hourly estimates. Second, each traffic lights' cycle was identified by the beginning of pedestrian green, and for each cycle were documented: the cycle start time (hour-minutes-seconds); the numbers of pedestrians who started to cross from the sidewalk and from the median; whether there was a vehicle near the stop line for turning right. Third, if at the beginning of the green (in the first 3 s) there were a turning vehicle and at least one crossing pedestrian, then for that cycle it was indicated whether the first vehicle gave priority to all pedestrians coming from the sidewalk (yes/no) and to all pedestrians coming from the median (yes/no). In addition, the amount of pedestrians who started to cross in the first 3 s was counted, including their subdivision according to gender and major age groups (children, adults, elderly).

Further, concerning each traffic lights' cycle were documented: the duration of the whole green (in seconds); the number of pedestrians who crossed on green from the sidewalk, of them those who did not receive priority from the vehicles and those who experienced a conflict with the vehicle; similar numbers were counted for pedestrians who crossed on green from the median; the duration of the red light (in seconds) and the number of pedestrians who started crossing on red. A conflict was defined as a sudden change in the speed and/or the direction of walking by a pedestrian or of travel by the vehicle in order to avoid a collision. Such a definition is common in observational studies of pedestrian-vehicle interactions at crossing facilities (Van Houten et al., 1999; Ewing and Dumbaugh, 2009; Gitelman et al., 2017).

Using the total data records produced for a site, a set of behavioral indicators was estimated, for each period of observations, including: (1) Percent of cycles with giving-right-of-way by the turning vehicles, to all pedestrians who crossed from the sidewalk, in the first 3 s of green; (2) Percent of cycles with giving-right-of-way by the turning vehicles, to all pedestrians who crossed from the median, in the first 3 s of green; (3) Percent of pedestrians who were yielded by turning vehicles, during the whole green light, among the pedestrians who crossed from the sidewalk; (4) Percent of pedestrians who were yielded by turning vehicles, during the whole green light, among the pedestrians who crossed from the median; (5) Percent of conflicts between pedestrians and vehicles in the crosswalk area, during the whole green light, among the pedestrians who crossed from the sidewalk; (6) Percent of vehicle-pedestrian conflicts in the crosswalk area, during the whole green light, among the pedestrians who crossed from the median; (7) Average number of pedestrians who crossed on red, per a traffic lights' cycle.

The behavior indicators were estimated separately for daytime and evening hours. In addition, to characterize the extent of relevance of the topic examined, we estimated the percent of cases when there was a vehicle turning right at the intersection, out of the total number of traffic light cycles observed.

The significance of differences between the behavior indicators in the periods after the activation of advanced

**FIGURE 2 |** Crosswalks with shared green for right-turning vehicles and crossing pedestrians that were included in the study: **(A)**—site 1, **(B)**—site 2.

pedestrian signal vs. the before period was examined using a $z$-test for proportions and a $t$-test for average values (Jekel et al., 2007). The difference was judged as significant when $p < 0.05$ was obtained. In addition, odds ratios and their 95% confidence intervals were estimated for the indicators of giving-right-of-way to pedestrians by turning vehicles when the advanced pedestrian signal is present.

Furthermore, binary logistic regression models were developed to explain the main behavior indicators—the probability of giving-right-of-way to all crossing pedestrians by turning vehicles, in the first 3 s of green. Four explanatory models were fitted—separate models for both sites and for pedestrians who crossed from the sidewalk and from the median. Among the explanatory variables in the models were examined: the study period (before, after1, after2); the number of crossing pedestrians at the beginning of green which were divided into three categories (1, 2-3 or more than 3 pedestrians), and the time period (day or evening hours). Weather conditions were not included in the data since all observations took place in nice weather conditions (sunny days, no rain). The observation units in the model datasets were traffic lights' cycles when both turning vehicles and crossing pedestrians were present at the beginning of the pedestrian green. The models were fitted using the Logistic procedure of Statistical Analysis Software (SAS 9.4). In the models' development, the need for interactions of the third and second order, between the explanatory variables, was examined but found not significant and thus the models were fitted without interactions between the variables. Each model fit was examined using a convergence criterion, Likelihood Ratio, Score and Wald criteria (which should be significant, $p < 0.05$); a Max-rescaled R-Square value was estimated for each model which indicates the amount of information gained when including the predictors into the model in comparison with the "null" model. Type 3 tests of effects showed the significance of the model variables ($p < 0.05$ indicates a significant impact). Using the models, adjusted odds ratios (OR), with 95% Wald confidence intervals, were estimated to show the impacts of the explanatory variables' values on the response variable.

# RESULTS

In this section we present the background characteristics of the study sites and the detailed results of observations at both sites, during daytime hours. Explanatory models for the probability of giving-right-of-way to crossing pedestrians by turning vehicles, at the beginning of green, are also presented. The next section will discuss the summary changes in behavior indicators, at the study sites.

## Background Characteristics of the Study Sites

**Table 1** provides estimates of vehicle traffic and pedestrian volumes, at the study sites, in terms of the mean and standard deviation of the hourly volume of turning vehicles and the mean number of crossing pedestrians, per traffic light cycle, in various study periods. (To note, the traffic lights' cycle length was 90 s at site 1 and about 125 s at site 2). It can be seen that, across various periods of observations, the level of vehicle traffic was relatively stable at the study sites in daytime hours but was more variable in evening hours. The average numbers of crossing pedestrians were quite consistent, both in day and evening hours. The percent of cycles with presence of turning vehicles was slightly over half at site 1 and more substantial at site 2. In most cases, the average hourly numbers of turning vehicles were around 200 which corresponds to a low level of traffic volumes on urban roads. The amount of crossing pedestrians was high at site 1 and suited to a medium level at site 2. Given both lower numbers of turning vehicles and fewer crossing pedestrians in evening hours at site 2, some observational samples were small thus limiting the after-before comparisons.

The majority of pedestrians observed were adults (aged 19–64) while the shares of children (up to the age of 18) and elderly people (aged 65+) were minor, <10% each. Such a result was expected since both sites belong to industrial and business areas of the city. The share of female pedestrians was less than half at site 1 and close to half at site 2. In general, the study sites reflected various conditions with regard to the volume and the composition of crossing pedestrians.

**TABLE 1 |** Study sites, with estimates of vehicle and pedestrian volumes, in various study periods, and characteristics of crossing pedestrians.

**a—Vehicle traffic.**

| Study site | Average number of turning vehicles, per hour (standard deviation) | | | % of traffic light cycles with turning vehicles (total number of cycles observed) | | |
|---|---|---|---|---|---|---|
| | Before | After1 | After2 | Before | After1 | After2 |
| Site 1, day hours | 219 (34) | 196 (35) | 198 (48) | 62% (285) | 52% (208) | 54% (247) |
| Site 1, evening hours | 144 (36) | 195 (35) | 207 (68) | 52% (126) | 51% (163) | 54% (176) |
| Site 2, day hours | 234 (25) | 272 (42) | 233 (25) | 96% (220) | 64% (150) | 80% (184) |
| Site 2, evening hours | 170 (35) | 110 (25) | 202 (48) | 82% (72) | 67% (84) | 87% (124) |

**b—Pedestrian traffic.**

| Study site | Among pedestrians crossing from the sidewalk | | | | | Among pedestrians crossing from the median | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No of cycles when crossing pedestrians and turning vehicles were present[#] (average number of crossing pedestrians per cycle) | | | Gender: % of males | Age: % of adults | No of cycles when crossing pedestrians and turning vehicles were present[#] (average number of crossing pedestrians per cycle) | | | Gender: % of males | Age: % of adults |
| | Before | After1 | After2 | * | * | Before | After1 | After2 | * | * |
| Site 1, day hours | 164 (4.5) | 98 (4.3) | 121 (3.8) | 57–67% | 87–96% | 172 (7.1) | 104 (7.4) | 129 (7.3) | 53–65% | 87–98% |
| Site 1, evening hours | 55 (3.6) | 80 (6.1) | 88 (5.0) | 64–67% | 87–98% | 63 (6.1) | 82 (7.3) | 89 (7.2) | 61–63% | 86–99% |
| Site 2, day hours | 119 (1.8) | 46 (1.7) | 96 (1.6) | 51–63% | 87–92% | 153 (2.8) | 57 (2.8) | 117 (2.3) | 53–63% | 84–96% |
| Site 2, evening hours | 10** (1.3) | 8** (1.3) | 33 (1.6) | 46–54% | 70–98% | 9** (2.1) | 18 (2.3) | 48 (2.1) | 47–56% | 95–100% |

[#]*At the beginning of pedestrian green.* [*]*Range, across the three periods.*
***Small sample: up to 10 cycles observed with both movements.*

## Behavior Changes at Site 1, in Day Hours

**Table 2** shows the behavior indicators estimated for site 1, in day hours, in each period of observations, including the results of statistical comparisons between the periods. The activation of advanced pedestrian signal was associated with a significant increase in the share of cases when the turning vehicle gave priority to all pedestrians who crossed at the beginning of green, both from the sidewalk and from the median. The percent of cycles where all pedestrians who started crossing in the first 3 s received the right-of-way increased from 89 to 99% for those who crossed from the sidewalk, and from 86 to 98% for those who crossed from the median. This means that giving-right-of-way to pedestrians at the beginning of green was improved substantially while the frequency of the situation when a crossing pedestrian is interrupted by a turning vehicle was minimized to 1–2%.

However, among the pedestrians who crossed during the entire green, the percentage of those who received priority from the turning vehicles did not change consistently: for pedestrians who crossed from the sidewalk, the share of those who received the right-of-way increased by 4% immediately after the introduction of the advanced green but reduced to the previous level after 2 months. For pedestrians crossing from the median, a general increase in the percent of giving-right-of-way was observed following the measure's activation, by 4–6%, but the improvement was moderated after 2 months.

Conflicts between pedestrians and vehicles in the crossing area were rare (between 0 and 3 events per round of observations), both before and after the application of change in the traffic lights; the changes in conflict occurrence were insignificant. Similarly, the average number of pedestrians crossing on red did not change substantially between the periods: it was and remained about 1 pedestrian, per cycle.

## Behavior Changes at Site 2, in Day Hours

**Table 3** presents the behavior indicators observed, in various periods, at site 2 and the results of their comparisons. The impacts of the advanced pedestrian signal were more positive and consistent at this site indicating a substantial increase in giving the priority to crossing pedestrians at the beginning of green, by 16–23%, with no moderation in the effect after 2 months of activation. The frequency of cases when a crossing pedestrian was not respected by a turning vehicle was minimized to 2–4%. In addition, in the longer after period, an improvement was observed in the share of giving-right-of-way to pedestrians during the whole green phase, both for those crossing from the sidewalk and from the median. The increase was remarkable for pedestrians crossing from the median, by 19%.

Similar to site 1, vehicle-pedestrian conflicts in the crosswalk area were rare (between 0 and 2 events per round of observations), and their frequency did not change significantly between the study periods. The average number of pedestrians

**TABLE 2 |** Behavior indicators at site 1, day hours, in each observation period, and the results of statistical comparisons between the periods.

| Behavior Indicator | Behavior indicator values (No of observations) | | | Statistical differences between periods | | |
|---|---|---|---|---|---|---|
| | Before | After1 | After2 | After1 vs. Before | After2 vs. Before | After2 vs. After1 |
| % of giving-right-of-way by the turning vehicles to all pedestrians who crossed from the sidewalk, in the first 3 s of green | 89% (164[a]) | 99% (98) | 99% (121) | I, $p < 0.001$, OR 12.0, CI 1.6–91.1 | I, $p < 0.001$, OR 14.8, CI 1.9–112.4 | ns, $p = 0.88$, OR 1.2, CI 0.1–20.0 |
| % of giving-right-of-way by the turning vehicles to all pedestrians who crossed from the median, in the first 3 s of green | 86% (172[a]) | 99% (104) | 98% (129) | I, $p < 0.001$, OR 16.7, CI 2.2–125.4 | I, $p < 0.001$, OR 10.3, CI 2.4–44.4 | ns, $p = 0.68$, OR 0.6, CI 0.1–6.9 |
| % of giving-right-of-way to pedestrians, during the whole green, among the pedestrians who crossed from the sidewalk | 90% (1597[b]) | 94% (1055) | 88% (1234) | I, $p < 0.001$, OR 1.8, CI 1.3–2.4 | ns, $p = 0.26$, OR 0.9, CI 0.7–1.1 | D, $p < 0.001$, OR 0.5, CI 0.4–0.7 |
| % of giving-right-of-way to pedestrians, during the whole green, among the pedestrians who crossed from the median | 93% (1676[b]) | 99% (1091) | 97% (1270) | I, $p < 0.001$, OR 7.1, CI 3.9–12.9 | I, $p < 0.001$, OR 2.9, CI 2.0–4.2 | D, $p < 0.01$, OR 0.4, CI 0.2–0.8 |
| % of conflicts between pedestrians and vehicles in the crossing area, during the whole green, among the pedestrians who crossed from the sidewalk | 0.13% (1597[b]) | 0.28% (1055) | 0.16% (1234) | ns, $p$ =0.39 | ns, $p = 0.80$ | ns, $p = 0.54$ |
| % of conflicts between pedestrians and vehicles in the crossing area, during the whole green, among the pedestrians who crossed from the median | 0% (1676[b]) | 0.18% (1091) | 0.08% (1270) | ns, p = 0.16 | ns, $p = 0.32$ | ns, $p = 0.49$ |
| Average number of pedestrians who crossed on red, per traffic lights' cycle, ± sd | 0.91 ± 0.86 (285[c]) | 1.05 ± 0.51 (208) | 0.98 ± 0.52 (247) | I, $p < 0.05$ | ns, $p = 0.28$ | ns, $p = 0.13$ |

[a] *Number of traffic light cycles with turning vehicles and crossing pedestrians.*
[b] *Total number of pedestrians who crossed on green.* [c] *Total number of traffic light cycles.*
*I, increase; D, decrease; ns, no change; OR, odds ratio; CI, 95% confidence interval.*

crossing on red was low, about 1 pedestrian per two traffic light cycles, and generally did not change after the activation of advanced pedestrian signal.

## Explanatory Models

**Table 4** shows results of the explanatory models fitted to the probability of giving-right-of-way to all crossing pedestrians at the beginning of green, accounting for the study period (before or after the activation of advanced pedestrian signal), the number of crossing pedestrians at the beginning of the green light and the time of day. All four models converged and were significant; the Max-rescaled R-Square values were 0.22–0.28 for models of site 1, and 0.14–0.16 for models of site 2. In all the models, a significant impact of advanced pedestrian signal was found. The adjusted OR for the probability of giving-right-of-way to crossing pedestrians at the beginning of green, after 2 months of the activation of the signal change compared to before period, was 23.7 for pedestrians crossing from the sidewalk and 10.3 for those crossing from the median, at site 1, and 8.7 and 8.5, respectively, at site 2. The time of day (day vs. evening hours) did not have a significant impact on the behavior examined, in all models. The number of crossing pedestrians did not have a significant impact on the response variable in the models, except for the case of pedestrians crossing from the median at site 1, where a lower number of crossing pedestrians (one or 2–3 only) was associated with a lower probability of giving-right-of-way by turning vehicles compared to 3+ crossing pedestrians (OR of 0.11 and 0.32, respectively).

# DISCUSSION

**Table 5** presents a summary of changes observed in road user behaviors following the application of an advanced pedestrian signal at the study sites, both in day and evening hours, with a focus on the impacts in a long-term. At both sites, there was a consistent improvement in giving-right-of-way to pedestrians by the vehicles, in first 3 s of their green, both in day and evening hours and for crossing from both sides of the road. Following the activation of the advanced pedestrian green, the percentage of cycles where all pedestrians received priority at the beginning of the green increased to 97–100% for those who crossed from the sidewalks and to 94–99% for those who crossed from the median; the increase was significant in most cases (except for the case of evening hours at site 2 where the number of cycles with crossing pedestrians was small in the before period). The general regression models for both sites found a significant increase in giving-right-of-way to pedestrians at the beginning of green, following the measure's application, for pedestrians

**TABLE 3 |** Behavior indicators at site 2, day hours, in each observation period, and the results of statistical comparisons between the periods.

| Behavior Indicator | Behavior indicator values (No of observations) | | | Statistical differences between periods | | |
|---|---|---|---|---|---|---|
| | Before | After1 | After2 | After1 vs. Before | After2 vs. Before | After2 vs. After1 |
| % of giving-right-of-way by the turning vehicles to all pedestrians who crossed from the sidewalk, in the first 3 s of green | 82% (119[a]) | 96% (46) | 98% (96) | I, $p < 0.01$, OR 4.7, CI 1.1–21.0 | I, $p < 0.001$, OR 10.1, CI 2.3–44.1 | ns, $p = 0.50$, OR 2.1, CI 0.3–15.7 |
| % of giving-right-of-way by the turning vehicles to all pedestrians who crossed from the median, in the first 3 s of green | 73% (153[a]) | 91% (57) | 96% (117) | I, $p < 0.01$, OR 3.8, CI 1.4–10.2 | I, $p < 0.001$, OR 8.2, CI 3.1–21.5 | ns, $p = 0.28$, OR 2.1, CI 0.6–7.8 |
| % of giving-right-of-way to pedestrians, during the whole green, among the pedestrians who crossed from the sidewalk | 88% (285[b]) | 93% (68) | 94% (319) | ns, $p = 0.18$, OR 1.8, CI 0.7–4.7 | I, $p < 0.01$, OR 2.3, CI 1.3–4.2 | ns, $p = 0.62$, OR 1.3, CI 0.5–3.7 |
| % of giving-right-of-way to pedestrians, during the whole green, among the pedestrians who crossed from the median | 76% (445[b]) | 100% (41) | 95% (336) | I, $p < 0.001$* | I, $p < 0.001$, OR 6.2, CI 3.6–10.7 | D, $p < 0.001$* |
| % of conflicts between pedestrians and vehicles in the crossing area, during the whole green, among the pedestrians who crossed from the sidewalk | 0.70% (285[b]) | 2.9% (68) | 0.63% (319) | ns, $p = 0.29$ | ns, $p = 0.91$ | ns, $p = 0.27$ |
| % of conflicts between pedestrians and vehicles in the crossing area, during the whole green, among the pedestrians who crossed from the median | 0.22% (445[b]) | 0% (41) | 0.30% (336) | ns, $p = 0.32$ | ns, $p = 0.85$ | ns, $p = 0.32$ |
| Average number of pedestrians who crossed on red, per traffic lights' cycle, ± sd | 0.55 ± 1.13 (220[c]) | 0.35 ± 0.84 (150) | 0.62 ± 1.01 (184) | ns, $p = 0.07$ | ns, $p = 0.52$ | I, $p < 0.05$ |

[a] *Number of traffic light cycles with turning vehicles and crossing pedestrians.*
[b] *Total number of pedestrians who crossed on green.* [c] *Total number of traffic light cycles.*
*I, increase; D, decrease; ns, no change; OR, odds ratio; CI, 95% confidence interval.*
**OR is not applicable due to 100% of giving-right-of-way to pedestrians in after1 period.*

crossing from any side of the crosswalk, both in day and evening hours. The impact of the measure was substantial, with the adjusted odds ratios (in a long-term) over 10 at site 1 and over 8 at site 2.

Concerning the giving-right-of-way to pedestrians during the whole green, following the activation of the measure, the changes were inconsistent for pedestrians who crossed from sidewalks, while for pedestrians crossing from the median, a consistent improvement was observed. Such a difference in the effect can be related to a lower conspicuity of pedestrians coming from the sidewalks, for turning vehicles. The level of yielding to pedestrians by the vehicles, in the after period, was 90% and greater, at all sites, which is comparable with the rates reported in the US study (Van Houten et al., 2000).

The effect of the advanced pedestrian green on giving priority to crossing pedestrians was stronger at site 2, where medium volumes of crossing pedestrians were observed compared to high volumes at site 1. Based on the observations at site 2, it can be stated that fewer crossing pedestrians are associated with lower initial rates of giving them the right-of-way during the shared green, both at the beginning of the green light and during the whole green phase. The introduction of an advanced pedestrian signal enables pedestrians to start walking while vehicles are still waiting thus providing actual priority for crossing pedestrians, which is particularly important for single pedestrians compared to groups because the former are more frequently disregarded by the vehicles (Dommes et al., 2015). Similarly, in the current study, one of the models for predicting giving-right-of-way for pedestrians at the beginning of green found a lower probability of yielding to single pedestrians or small groups compared to a larger number of pedestrians.

The rate of conflicts was close to zero before the application of the measure and remained similar after the application. Unlike previous studies (Van Houten et al., 2000; Harkey and Zegeer, 2004), the current study could not show an effect of the advanced pedestrian green on conflict occurrence in the crossing area due to the scarcity of this problem at the observational sites. For example, Van Houten et al. (2000) reported the average conflict rates of 2.1–3.3 per 100 pedestrians in baseline conditions and of 0.1–0.2 per 100 pedestrians after the introduction of a leading pedestrian green. The current study values were between the above boundaries. The higher frequency of conflicts in the

**TABLE 4 |** Logistic regression models for the probability of giving-right-of-way to crossing pedestrians by turning vehicles, in the first 3 s of green.

| Variable | Variable category | Estimate | Standard error | Pr > ChiSq | Odds ratio | 95% Wald Confidence Limits | |
|---|---|---|---|---|---|---|---|
| **a–At site 1, for pedestrians crossing from the sidewalk.** | | | | | | | |
| Intercept | | 2.79 | 0.55 | <.0001 | | | |
| Study period* | After1 | 2.91 | 1.03 | 0.0047 | 18.38 | 2.44 | 138.32 |
| | After2 | 3.17 | 1.03 | 0.0021 | 23.70 | 3.15 | 178.04 |
| | Before | 0 | . | . | Ref. | | |
| No of crossing pedestrians | 1 | −0.97 | 0.56 | 0.0805 | 0.38 | 0.13 | 1.13 |
| | 2–3 | −0.23 | 0.49 | 0.6342 | 0.79 | 0.31 | 2.06 |
| | over 3 | 0 | . | . | Ref. | | |
| Time of day | Day hours | −0.52 | 0.53 | 0.3283 | 0.60 | 0.21 | 1.68 |
| | Evening hours | 0 | . | . | Ref. | | |
| **b–At site 1, for pedestrians crossing from the median.** | | | | | | | |
| Intercept | | 2.73 | 0.44 | <.0001 | | | |
| Study period* | After1 | 3.27 | 1.03 | 0.0014 | 26.32 | 3.52 | 196.80 |
| | After2 | 2.32 | 0.62 | 0.0002 | 10.13 | 3.01 | 34.16 |
| | Before | 0 | . | . | Ref. | | |
| No of crossing pedestrians* | 1 | −2.22 | 0.49 | <.0001 | 0.11 | 0.04 | 0.29 |
| | 2-3 | −1.14 | 0.43 | 0.0081 | 0.32 | 0.14 | 0.74 |
| | over 3 | 0 | . | . | Ref. | | |
| Time of day | Day hours | −0.35 | 0.43 | 0.4089 | 0.70 | 0.30 | 1.63 |
| | Evening hours | 0 | . | . | Ref. | | |
| **c–At site 2, for pedestrians crossing from the sidewalk.** | | | | | | | |
| Intercept | | 1.59 | 1.02 | 0.1195 | | | |
| Study period* | After1 | 1.25 | 0.64 | 0.0519 | 3.48 | 0.99 | 12.24 |
| | After2 | 2.16 | 0.64 | 0.0007 | 8.70 | 2.48 | 30.52 |
| | Before | 0 | . | . | Ref. | | |
| No of crossing pedestrians | 1 | −0.17 | 0.81 | 0.8354 | 0.85 | 0.17 | 4.14 |
| | 2-3 | 0.25 | 0.85 | 0.7719 | 1.28 | 0.24 | 6.84 |
| | over 3 | 0 | . | . | Ref. | | |
| Time of day | Day hours | 0.01 | 0.67 | 0.9903 | 1.01 | 0.27 | 3.73 |
| | Evening hours | 0 | . | . | Ref. | | |
| **d–At site 2, for pedestrians crossing from the median.** | | | | | | | |
| Intercept | | 0.78 | 0.54 | 0.1521 | | | |
| Study period* | After1 | 1.25 | 0.43 | 0.0036 | 3.50 | 1.51 | 8.15 |
| | After2 | 2.14 | 0.43 | <.0001 | 8.47 | 3.65 | 19.63 |
| | Before | 0 | . | . | Ref. | | |
| No of crossing pedestrians | 1 | −0.12 | 0.43 | 0.7822 | 0.89 | 0.38 | 2.07 |
| | 2-3 | −0.49 | 0.38 | 0.1963 | 0.61 | 0.29 | 1.29 |
| | over 3 | 0 | . | . | Ref. | | |
| Time of day | Day hours | 0.51 | 0.44 | 0.2497 | 1.67 | 0.70 | 3.97 |
| | Evening hours | 0 | . | . | Ref. | | |

***(a)*** *N = 606. Max-rescaled R-Square=0.218. *Significant variable, $p < 0.001$.*
***(b)*** *N = 639. Max-rescaled R-Square = 0.284. *Significant variable, $p < 0.0001$.*
***(c)*** *N = 312. Max-rescaled R-Square = 0.136. *Significant variable, $p < 0.01$.*
***(d)*** *N = 402. Max-rescaled R-Square = 0.157. *Significant variable, $p < 0.0001$.*

**TABLE 5 |** Summary of changes in behavior indicators at the study sites, following the application of advanced pedestrian green.

| Behavior Indicator | Site 1, day hours | Site 1, evening hours | Site 2, day hours | Site 2, evening hours |
|---|---|---|---|---|
| % of giving-right-of-way to pedestrians crossing from the sidewalk, in the first 3 s of green | I, from 89 to 99% | I, from 91 to 100% | I, from 82 to 98% | ns*, from 90 to 97% |
| % of giving-right-of-way to pedestrians crossing from the median, in the first 3 s of green | I, from 86 to 98% | I, from 87 to 99% | I, from 73 to 96% | ns*, from 67 to 94% |
| % of giving-right-of-way to pedestrians crossing from the sidewalk, during the whole green | ns, 88–90% | D, from 91 to 85% | I, from 88 to 94% | ns*, 94–95% |
| % of giving-right-of-way to pedestrians crossing from the median, during the whole green | I, from 93 to 97% | I, from 96 to 99% | I, from 76 to 95% | ns*, from 81 to 89% |
| % of conflicts between vehicles and pedestrians crossing from the sidewalk, during the whole green | ns, 0.1–0.2% | ns, 0–0.1% | ns, 0.6–0.7% | ns*, 0% |
| % of conflicts between vehicles and pedestrians crossing from the median, during the whole green | ns, 0–0.1% | ns, 0–0.2% | ns, 0.2–0.3% | ns*, 0% |
| Average number of pedestrians who crossed on red, per cycle | ns, 0.9–1 | I, from 0.6 to 0.9 | ns, 0.6 | I, from 0.4 to 0.8 |

*I, increase; D, decrease. Results reported in this table are based on the comparison of after2 vs. before periods. I/D indicates a statistically significant change, with $p < 0.05$; ns, not significant. *Small sample in before period ($N < 30$).*

initial conditions in the US study can be related to the higher number of lanes at the pedestrian crosswalks examined (four compared to two in the current study) and also to the fact that both left- and right-vehicle turns were allowed concurrently with pedestrian green while in the current study the shared green was for right-turning vehicles only. In spite of the lack of impact on vehicle-pedestrian conflicts, the consistent and significant increases in giving-right-of-way to pedestrians, in the current study sites, definitely support the improvement in pedestrian crossing conditions, following the introduction of advanced pedestrian green.

Despite the improvement of pedestrian crossing conditions during the green light, the number of pedestrians who crossed on red did not decrease and even an increase was observed in evening hours, at both sites (see **Table 5**). The phenomenon of pedestrians crossing on red at signalized intersections is well known in the road safety literature (Gitelman, 2014; Koh et al., 2014; Dommes et al., 2015). The intention to cross on red typically increases with a longer waiting time for pedestrians (Duduta et al., 2015) and, in particular, when sufficient gaps appear in the vehicle traffic on the road. Both explanations are relevant to the current study intersections. The gaps in vehicle traffic are more expected in the evening hours; indeed, a slight increase in the rate of pedestrians crossing on red was observed in evening hours in this study. In general, the study findings indicated that advanced pedestrian green probably cannot contribute to improving the compliance with red lights by crossing pedestrians.

Overall, the changes observed in road user behaviors following the activation of an advanced pedestrian signal in shared vehicle-pedestrian green were positive, particularly with regard to giving-right-of-way to pedestrians, and hence, they can be associated with a safety improvement of pedestrian crossing conditions at the signalized intersections. This measure may provide safety benefits in busy urban areas where, due to the need to move high volumes of vehicle traffic at signalized intersections, shared green light was applied for turning vehicles and crossing pedestrians. The study demonstrated the benefits of the measure under the conditions of relatively low volumes of turning vehicles (about 200 vehicles per hour) and medium to high volumes of crossing pedestrians.

The limitations of the current study are related to the limited number of sites where the measure was applied that led to small observational samples in some cases. Further follow-up studies of the measure at intersections with different combinations of vehicle and pedestrian volumes and various urban environment conditions would contribute to a better understanding of its effects on pedestrian safety. Possible impacts of demographic and socio-economic characteristics of crossing pedestrians and of various vehicle types should be also considered in this context.

The definition of conflict adopted in the current study—an abrupt vehicle braking and pedestrian stop or taking an evasive action to avoid a collision, followed the experience of previous research on the topic (Van Houten et al., 1999, 2000; Ewing and Dumbaugh, 2009). However, it was based on a visual recognition by an observer and thus may suffer from a subjective interpretation. Due to small numbers of conflicts observed in this study, a formal conflict analysis technique with measures like time-to-collision and post-encroachment time (e.g., Laureshyn et al., 2010) was not applied. Future research with automated video-analysis and formal traffic conflict analysis techniques would be useful for better understanding of conflict occurrences at signalized intersections, including a quantification of the effect of advanced pedestrian green on conflict occurrence under Israeli conditions. As evident from the results of the current study and Van Houten et al. (2000), substantial samples of crossing pedestrians should be observed in order to pronounce the impact of the measure on conflict rates.

## CONCLUSION

This study examined the impacts of a leading pedestrian signal—an earlier appearance of the pedestrian green signal in shared green for right-turning vehicles and crossing pedestrians—on pedestrian crossing conditions at urban intersections. The findings indicated the increase in giving-right-of-way to pedestrians by turning vehicles which is expected to contribute to improved pedestrian safety while crossing at signalized intersections. The effect of the measure may be stronger at intersections with a lower initial level of giving-the-right-of-way to pedestrians and higher rates of vehicle-pedestrian conflicts, during the shared green.

Being aware of pedestrian safety problems in urban areas and in line with sustainable urban development, infrastructure measures which improve pedestrian safety should be promoted throughout the cities (Stoker et al., 2015; European Transport Safety Council (ETSC), 2019). At busy signalized intersections, when separate pedestrian green is inapplicable due to capacity reasons, the application of advance pedestrian signal should be considered as a rule. To promote safe walking in the cities, accounting for pedestrian needs should become one of the basic principles in planning traffic lights at signalized intersections, especially in areas with high pedestrian presence.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## AUTHOR CONTRIBUTIONS

VG: study conception and design. RC: coordination with external bodies, data collection. FP: data analyses. VG: interpretation of results and draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Built Environmental Correlates of Cycling Accidents Involving Fatalities and Serious Injuries in London, UK

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**Introduction:** Approximately 2,552 individuals were killed or seriously injured through cycling accidents in the Greater London Area between 2010 and 2015. The purpose of this study is to investigate a wide range of built environmental correlates of cycling accidents resulting in KSI so that we can identify potential areas for targeted interventions.

**Methods:** We performed a cross-sectional analysis to examine the association between serious cycling injuries (2010-15), using road segment as the unit of analysis, and a wide range of built environmental characteristics. Multilevel models were used to account for potential spatial clustering.

**Results:** Serious cycling injuries were independently associated with higher commercial and residential densities, higher distance to speed camera, higher bus, car, and 2-wheeled (motorcycle and moped) traffic, and higher density of alcohol outlets. Greenspace was associated with decreased odds of injuries up to the 3rd quartile, but roads adjacent to the highest levels of green space (4th quartile) had increased odds of injuries. Findings from our study point to the potential of urban planning interventions to reduce serious cycling injuries (e.g., speed cameras, improving safety near alcohol outlets and in parks, and recreational areas, etc.). Further research using quasi-experimental approaches is required to evaluate whether the implementation of interventions leads to injury reductions.

**Keywords: injuries, built environment, urban planning, transportation, cycling**

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## 1. INTRODUCTION

Policies to promote cycling has been taken up as a priority investment area for urban transformation across many local governments in Europe and North America. The benefits of cycling are well-documented in the public health literature: a review to assess the health impact of cycling found consistent evidence of a positive dose-response gradient between the amount of cycling and cardiovascular fitness for observational and intervention studies (Oja et al., 2011). However, cyclists also have an increased exposure to road accidents (De Hartog et al., 2010), and research to investigate the environmental determinants of cycling accidents can help to maximize the benefits of cycling by addressing risks associated with injuries.

Prior studies have investigated various types of built environmental correlates of cycling injuries, and have studied the relative levels of risk associated with (1) various route and intersection types (e.g., major streets, local roads, roundabouts, and signalized vs. non-signalized intersections)

(Reynolds et al., 2009; Zahabi et al., 2011; Teschke et al., 2012; Hollingworth et al., 2015; Kaplan and Giacomo Prato, 2015; Polders et al., 2015), (2) presence and types of cycling infrastructures (e.g., on-road shared cycling routes, marked bike lanes, separated cycle paths via barrier, etc.) (Reynolds et al., 2009; Teschke et al., 2012; Pedroso et al., 2016; Pucher and Buehler, 2016), (3) land uses (e.g., density of retail establishments, residential/population density, industrial density, and proximity to parks) (Wedagama et al., 2006; Zahabi et al., 2011; Romanow et al., 2012; Kaplan and Giacomo Prato, 2015; Chen and Shen, 2016), (4) environmental factors affecting levels of visibility (e.g., slope, street lighting, and sinuosity) (Zahabi et al., 2011; Dozza and Werneke, 2014; Chen and Shen, 2016), and (5) traffic volume and proportion of cyclists to total traffic (Vandenbulcke et al., 2009; Jacobsen, 2015; Kaplan and Giacomo Prato, 2015; Elvik and Bjørnskau, 2017).

Some consistent patterns are emerging from this literature. A review of 23 studies investigating the association between transportation infrastructure and on-road cycling accidents (Reynolds et al., 2009) have identified a range of risk factors including multi-lane roundabouts, multi-use trails, and major roads (as compared to minor roads), while purpose-built cycling infrastructure including on-road bike routes and marked bike lanes have a significant protective effect. With regards to risk factors related to land use, some studies have found that commercial density, proximity to city-center, and industrial land use are associated with cycling accidents (Wedagama et al., 2006; Kaplan and Giacomo Prato, 2015); while another study found that the presence of parks, land use mix, and residential density had no influence on cycling injuries (Robinson, 2005). Lastly, a meta-analysis of 26 studies found consistent evidence that a high proportion of cyclists to total traffic had a protective effect (Elvik and Bjørnskau, 2017).

The purpose of this paper is to extend the literature on built environmental determinants of cycling accidents through an exploratory and descriptive study focusing on the associations between KSI risk and a full range of built environmental factors—including factors that were previously understudied or unique to the London context. Our study is intended to support London's Vision Zero Action Plan (Transport for London, 2018b) to eliminate road accidents leading to deaths and serious injuries. By quantifying the risk of a wide range of built environmental features associated with KSI, our study is aimed at identifying built environments for targeted interventions. In the next section, we outline some unique risk factors in the London context.

In cities across the UK, the rapidly growing market for on-demand food and cargo deliveries (where many workers rely on motorized 2-wheeled vehicles, i.e., motorcycles and mopeds) has prompted agencies, including Transport for London and the European Agency for Safety and Health at work, to call for additional studies to investigate the potential risks associated with using 2-wheeled motor vehicles, and risks posed to other road users (Baverstock et al., 2007; European Union OSHA, 2010; Transport for London, 2018a). In 2014, 9% of injuries to pedestrians on London's roads involved a motorcycle, which is surprisingly high considering the low modal share of motorcycles (Greater London Authority, 2016). In the UK, individuals aged 17 and above may obtain a provisional motorcycle license through a one-day compulsory basic training (with no practical or theoretical examination requirements) to ride a 2-wheeled motor vehicle up to 125 cc on public roads. Existing drivers (with any valid driver's license) are allowed to ride mopeds with a maximum speed of 50 km/h (UK Government). While the UK graduated motorcycle licensing pathway requires multiple tests toward riding larger capacity and faster motorcycles, Transport for London have noted the paucity of research related to the impact of growing demand for 2-wheeled motor vehicles given the relatively low barrier to become a beginner rider in the context of the growing demand for food and parcel delivery jobs. Since cyclists and motorcyclists often share the same physical space on the road (e.g., cycling lanes), there is a need to clarify the level of association between increased motorcycle traffic and KSI cycling accidents.

While a growing body of literature finds that speed cameras are associated with reductions in motor vehicle speeds and collisions (Delaney et al., 2005; Tay, 2010; De Pauw et al., 2014), no prior studies have addressed its association with cycling accidents. Moreover, the use of speed cameras is controversial and generally suffers from low public acceptance (Centre for Disease Control and Prevention, 2019). Opponents have argued that cameras invade privacy, are unable to denote when moderate speeding might be a safer option, or they question the reliability of the camera equipment (Delaney et al., 2005). In many jurisdictions, these arguments have led to government action to abolish the use of speed cameras (Associated Press, 2019; Bellefontaine and Riebe, 2019). Given the controversies around speed camera technology and the pervasiveness of speed cameras in the London context, it is important to generate evidence of its impact on cyclist KSI, which may help to inform current political debates.

Finally, given that public alcohol consumption is legal in England, the impact of pubs and bars on local levels of overcrowding (exacerbated by outdoor smoking) and anti-social behaviors is a salient concern in many London neighborhoods, and a potential risk factor for cycling accidents. While a growing number of cross-sectional and panel studies have noted the elevated independent risk associated with alcohol outlet density and motor vehicle accidents at the neighborhood level, relatively fewer studies have studied the association of alcohol outlets and cycling accidents, and none in the highly urbanized London context with its unique pubs and drinking culture.

To address these policy relevant concerns, we developed our descriptive/exploratory study to address the following research question: what is the cross-sectional association between the risk of KSI cycling accidents and built environmental risk factors? These risk factors include commercial density, green space density, population density, road type, traffic volume by vehicle type, cyclist numbers, cyclist as a proportion of total traffic, proximity to speed cameras, and proximity to alcohol outlets.

# 2. METHODS

## 2.1. Dependent Variable: KSI Cycling Accidents

Cycling accidents data for the years 2010-2015 were obtained from Transport for London and included reports of 2552 KSI cycling accidents. Transport for London manages its traffic and accidents data through the ACCSTATS database, which is updated through the UK national Police accidents records. We used road segments (obtained from the Ordnance Survey) as the unit of analysis in our study, and covered a total of $n$ = 233,549 road segments across the Greater London Area (excluding motorways/highways without any cycling traffic). Unlike minor accidents, KSI accidents are almost always represented in official statistics since police and ambulatory services are involved. Since KSI accidents are rare events, i.e., over the period of 2010-2015, the majority of road segments did not have any KSI accidents (98.9%) with only 1.03% with 1 accident, and 0.07% associated with 2 or more accidents, we have created a binary outcome variable (i.e., no accidents vs. at least one KSI accident).

## 2.2. Independent Variables: Built Environmental Predictors

To capture the complexity of the urban built environment, we examine the effects of a wide range of built environmental and socio-environmental characteristics, which include land use (i.e., green space and commercial density), alcohol establishments, proximity to speed cameras, population density, road type (e.g., dual carriageway, single carriageway, roundabouts, slip roads, traffic island link, traffic island link at junction), traffic volume (separate for motorcycle, car, large/heavy goods vehicles, and cyclists), and the proportion of cycle traffic to motor traffic. Sample characteristics and cross-tabulations with KSI cycling accidents is summarized in **Table 1**.

Given that the relationship between greenspace and cycling accidents has been examined in previous studies (Maas et al., 2008), it was included in our statistical model. Greenspace data was obtained from Greenspace Information for Greater London. We calculated the proportion of greenspace within 750 m of each road segment, which corresponds to the average 10-min walking distance and is considered an appropriate distance for examining land use density (Staricco and Vitale Brovarone, 2018). When we examined the relationship between greenspace and cycling KSIs graphically, we found that the relationship was potentially non-linear, and thus quartiles were used (instead a continuous variable) in our statistical model. Commercial density was obtained from the Ordnance Survey Points of Interest and were summed within a 750 m buffer of the road segment. Quartiles were also used to represent this data to detect potential non-linear effects. Data for alcohol outlets (i.e., any location that serves or sells alcohol) came from OpenStreetMap data, and were summed in the 750 m buffer of each road segment.

Traffic flow data were accessed from the Department for Transport for average annual traffic between 2000 and 2010 and were based on traffic monitoring points. London has 2791 traffic count points and an additional 300 automatic traffic counters. Annual traffic based on a wide time interval was used to ensure seasonality effects would be accounted for in the model (e.g., winter vs. summer traffic, occasional and rare sports events, etc.). Based on Euclidean distance the counts from the nearest traffic monitoring point were assigned to road segments based on the type of road and was divided based on vehicle type. Traffic flows are defined as the million vehicle kilometers traveled on a road in a year and using a year's worth of data helps smooth many temporal variations in traffic. This method of estimating traffic flow has been validated and used in other studies in road accident research.

Using Department for Transport data, network distance was also used to calculate proximity to the nearest speed camera (for the year 2014) based on the centroid of each road segment. Population density was calculated for each individual LSOA based on the 2011 Census, and was joined to the road segments. For road segments that are on the boundaries of two LSOAs, the average population density was calculated.

## 2.3. Statistical Method

To account for spatial dependence (e.g., road segments are clustered into neighborhoods that may be affected by a common set of neighborhood attributes such as land use, population density, or traffic volume), multilevel modeling is used to account for the spatial autocorrelation of KSI. In our multilevel model, our level 1 units (233,549 road segments) are nested within level-2 groups (neighborhoods proxied by 4671 UK census LSOAs for the Greater London Area), and random intercepts are included that allow each neighborhood context to vary (Larsen and Merlo, 2005). Borough fixed effects (k-1 dummy variables representing the 32 London Boroughs) is included to account for between-neighborhood spatial autocorrelation. This method was chosen since London boroughs have control over many aspects of their local transport planning strategy (e.g., parking fines and rules for bus lanes) and the regional fixed-effect can adjust for these similarities across adjacent LSOAs within the same local government. The fixed-effect coefficients also have the added benefit of estimating the relative odds of KSI associated with cycling in each borough. Given that the dependent variable has a binomial distribution, where probability of getting one or more KSI accident can be modeled using multilevel logistic regression (through a logit link function) summarized as:

$$log[\frac{p_{ij}}{1-p_{ij}}] = (\beta_0 + u_{0j}) + \beta_1 X_{ij} + \epsilon \quad (1)$$

where the ith road segment is nested in the jth neighborhood, $\beta_0$ is the intercept (with $u_{0j}$ random intercept), and $\beta_1$ is the slope of road-segment specific independent variable X. The models were estimated using the R package *lme4* (version 1.1-23) in RStudio.

# 3. RESULTS

Over the period of 2010-2015, 2552 KSI accidents were recorded across the Greater London Area, (**Figure 1**). **Table 2** provides descriptive statistics of the proportion of road segments with KSI accidents for each of the socio-environmental exposures studied

**TABLE 1 |** Sample characteristics and cross-tabulations with KSI cycling accidents.

| Exposures | Number of features (% of total features) | Proportion of accidents | Mean (SD) with accidents | Mean (SD) without accidents |
|---|---|---|---|---|
| **Road types** | | | | |
| Dual carriageway | 10903 (35%) | 12% | – | – |
| Roundabout | 5116 (2%) | 2% | – | – |
| Single carriageway | 198213 (85%) | 74% | – | – |
| Slip road | 2030 (1%) | 2% | – | – |
| Traffic Island link | 4933 (2%) | 2% | – | – |
| Traffic Island link at junction | 11919 (5%) | 8% | – | – |
| | **Mean (SD)** | | | |
| **Vehicle type (count)** | | | | |
| 2-wheeled motor vehicles | 892.76 (2033.75) | – | 1833.77 (3353.013) | 883.09 (2013.45) |
| Car | 27439.16 (51949.38) | – | 24875.47 (39729.41) | 27465.51 (52059.47) |
| Bus | 784.97 (1232.2) | – | 1338.3 (2021.092) | 779.29 (1220.16) |
| Large goods vehicle | 5258.95 (10703.34) | – | 5801.64 (9270.168) | 5253.37 (10716.95) |
| **Commercial (count)** | | | | |
| Quartile 1 (0–104) | – | 9% | – | – |
| Quartile 2 (104–256) | – | 12% | – | – |
| Quartile 3 (256–607) | – | 20% | – | – |
| Quartile 4 (607–2237) | – | 59% | – | – |
| **Greenspace (%)** | | | | |
| Quartile 1 (0–2%) | – | 33% | – | – |
| Quartile 2 (2%–8%) | – | 21% | – | – |
| Quartile 3 (8%–32%) | – | 19% | – | – |
| Quartile 4 (32%–100%) | – | 27% | – | – |
| Length (meters) | 72.5 (81.18) | – | 92.3 (94.74) | 72.29 (81.001) |
| Distance to speed camera (meters) | 733.71 (541.21) | – | 545.18 (429.52) | 735.65 (541.9) |
| Population density | 76.18 (51.28) | – | 98.56 62.72) | 75.95 (51.1) |
| Number of alcohol locations | 13.12 (32.79) | – | 36.93 (58.98) | 12.89 (32.32) |
| Number of cyclists | 472.2 (1068.33) | – | 1396.92 (2273.35) | 462.5 (1044.56) |
| Number of commercial locations | 575.47 (1168.06) | – | 1393.32 (1975.67) | 567.06 (1153.84) |
| Greenspace proportion | 0.04 (0.09) | – | 0.02 (0.07) | 0.04 (0.09) |
| Proportion cyclists vs. all other traffic | 0.03 (0.1) | – | 0.06 (0.11) | 0.03 (0.1) |

in our paper. Based on unadjusted cross-tabulations, higher 2-wheeled motor vehicle and car traffic counts, higher density of alcohol outlets, and higher commercial and population densities appear to contribute to accident risk.

**Figure 2** is a forest plot that presents the results of our mixed-effect logistic regression results predicting the risk of 1+ KSI cycling accidents for road segments. Adjusted intraclass correlation of the model was 0.082, which means that approximately 8.2% of the variations of the outcome could be explained at the LSOA level. Compared to dual carriageways (reference group), roundabouts have 28% lower odds of KSI (OR 0.72, 95% CI 0.52–0.99), and single carriageways have 59% lower odds of KSI (OR 0.41, 95% CI 0.36–0.47). As expected, longer roads have greater odds of KSI compared to shorter roads, with each additional meter of road increasing the odds of KSI by 0.3% (95% CI 1.002–1.003). Each 10,000 additional two-wheeled motor vehicle traffic per year increases the odds of KSI by 65% (OR 1.65, 95% CI 1.22–2.24). Commercial density has a dose-effect relationship with KSI: compared to areas with the lowest commercial density (Q1), roads in Q2 have a 35% increased odds of KSI (95% CI 1.1–1.65), roads in Q3 have a 68% increased odds of KSI (95% CI 1.36–2.08), and roads in the highest commercial density areas (Q4) have a 124% higher odds of KSI (95% CI 1.78–2.82). The association between greenspace appears to be non-linear: compared to roads in areas with the lower greenspace density (Q1), roads in Q2 have a similar odds of KSI (95% CI

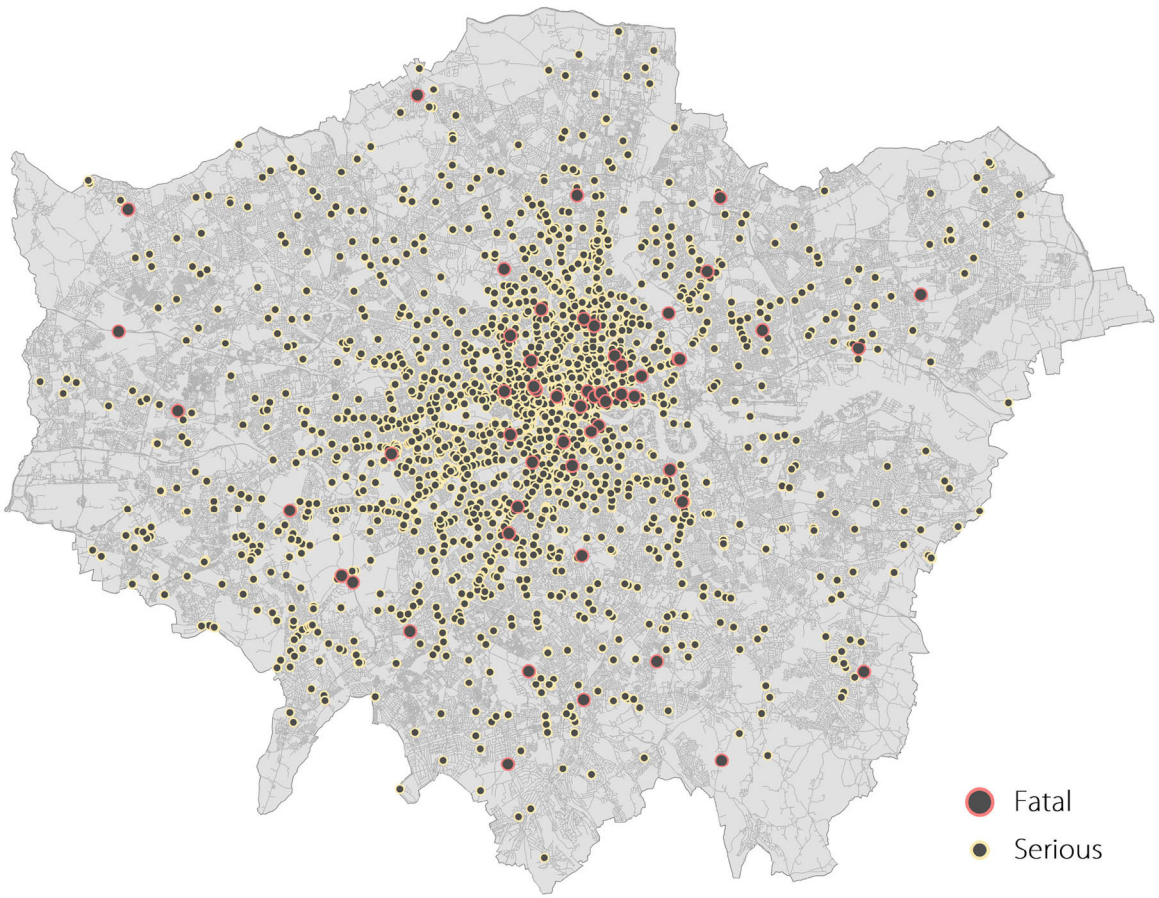


**FIGURE 1 |** Location of KSI Cycling Accidents, 2010–2015.

0.81–1.03), roads in Q3 have 13% decreased odds of KSI (95% CI 0.76–0.98), but roads in areas with the highest greenspace have 12% increased odds of KSI (95% CI 0.99–1.26). Population density has a positive association with KSI, where an addition of 1,000 people/km$^2$ increases the odds of KSI by 0.2% (95% CI 1.001–1.002). An increase of 1 standard deviation in the number of alcohol outlets (where 1 standard deviation is 32.79) increases odds of KSI by 7% (OR 1.07, 95% CI 1.03–1.12). Each 10,000 additional bus traffic per year increases the odds of KSI by 73% (OR 1.73, 95% CI 1.2–2.42). The proportion of cyclists to all traffic is not associated with KSIs.

## 4. DISCUSSION AND FUTURE WORK

Our study provides evidence that reinforce findings from previous studies, including risks associated with road characteristics, i.e., higher risk of KSI on dual carriageways and lower on roundabouts and single carriageways (Yau et al., 2006) and land use characteristics, i.e., higher in commercial and residential dense areas (Spoerri et al., 2011). Our study also confirms previous findings that higher car and bus traffic had a positive association with cycling accidents. Since the majority of bus lanes in London are also designated as official cycling lanes (Transport for London, 2020), specific mechanisms of how buses impact cycling accidents, including the role of shared bus and cycling lanes, should be investigated in future research. Furthermore, with the push by Transport for London and the mayor's office of London to increase cycling in the city, it is worth studying the impact on bus journey times and the potential increase in delays due to cyclists and buses sharing the same lanes (Aldred et al., 2019). We would like to further highlight that we use the term *accidents* since it is the official term from the UK national Police accidents records—but it does not imply that these are unavoidable.

Given the exploratory nature of this study, we note a number of interesting findings in our study regarding the influence of 2-wheeled traffic, alcohol outlets, and greenspace that will require further investigation. First, the independent association between 2-wheeled (motorcycle and moped) traffic and KSI accidents suggests the possibility that increased motorcyclist traffic may be linked to serious cycling accidents. The significance in the

**TABLE 2 |** Multilevel logistic regression model: factors associated with serious cycling accidents.

| | est | 2.5 % | 97.5 % | |
|---|---|---|---|---|
| (Intercept) | 0.005 | 0.003 | 0.006 | *** |
| **Nature of road** | | | | |
| Dual carriageway | ref | ref | ref | ref |
| Roundabout | 0.717 | 0.521 | 0.985 | * |
| Single carriageway | 0.407 | 0.355 | 0.466 | *** |
| Slip road | 0.804 | 0.565 | 1.145 | |
| Traffic Island link | 0.355 | 0.249 | 0.508 | *** |
| Traffic Island link at junction | 0.664 | 0.546 | 0.809 | *** |
| **Traffic flow** | | | | |
| 2 Wheeled-motor vehicles | 1.654 | 1.222 | 2.238 | ** |
| Cars | 0.937 | 0.899 | 0.977 | ** |
| Large/heavy goods vehicles | 1.068 | 0.861 | 1.325 | |
| Buses | 1.733 | 1.244 | 2.415 | ** |
| **Greenspace** | | | | |
| Quartile 1 (0–2%) | ref | ref | ref | ref |
| Quartile 2 (2%–8%) | 0.914 | 0.812 | 1.029 | |
| Quartile 3 (8%–32%) | 0.866 | 0.763 | 0.982 | * |
| Quartile 4 (32%–100%) | 1.118 | 0.994 | 1.256 | * |
| **Commercial establishments** | | | | |
| Quartile 1 (0–104) | ref | ref | ref | ref |
| Quartile 2 (104–256) | 1.345 | 1.095 | 1.652 | ** |
| Quartile 3 (256–607) | 1.682 | 1.363 | 2.076 | *** |
| Quartile 4 (607–2237) | 2.236 | 1.775 | 2.817 | *** |
| Length (m) | 1.003 | 1.002 | 1.003 | *** |
| Log number of cyclists | 1.005 | 0.997 | 1.0128 | |
| Proportion of cyclists in traffic flow | 1.001 | 0.709 | 1.412 | |
| Distance to speed camera | 0.9998 | 0.9998 | 0.9999 | |
| Population density | 1.002 | 1.001 | 1.002 | *** |
| Alcohol establishments z-score | 1.072 | 1.026 | 1.119 | ** |

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

relationship between two-wheeled motor vehicle traffic and KSI accidents has important implications for policy-makers. There are a large number of companies in London that specialize in delivery and courier services, especially in the food service industry. Given the high level of traffic on London roads, many courier services employ cyclists and motorcyclists as a way to avoid congestion (Greater London Authority, 2016), which contributes to the growing number of both groups on the road. Many of these companies employ free-lance motorcyclists with a provisional license, since a provisional license alone is sufficient to ride a motorcycle or moped in the UK. Further research should examine the on-road behaviors and interactions between motorcyclists and cyclists using longitudinal data or *in situ* observational studies to improve safety for both groups. Since Transport for London is currently in the process of standardizing the allowance of 2-wheeled motor vehicles on bus lanes across London as part of their Motorcycle Safety Action Plan (London Assembly Transport Committee, 2018), the risk associated with having bicycles, buses, and 2-wheeled motor vehicles on a shared lane needs to be further investigated.

Second, the finding that the presence of alcohol outlets was associated with KSI accidents provides preliminary evidence that warrants further investigations. Based on the findings of this study, it is unclear whether the elevated independent risk associated with alcohol outlet density is due to any number of factors including (1) outdoor drinking and smokers from pubs creating potential road hazards, (2) proximity to points of sales for alcohol leading to impaired cycling or driving, or (3) residual confounding due to imperfectly measured levels of commercial density and activity. While a growing number of studies have noted the elevated independent risk associated with alcohol outlet density and motor vehicle accidents at the neighborhood level, evidence from our study suggests that further investigation using a more rigorous method (e.g., longitudinal data or natural experiments to study the impact of new pub openings in KSI accidents) is required.

While most studies investigating the relationship between greenspace and cycling have focused on the role of the former to increase cycling as a form of active transport (Maas et al., 2008; Yang et al., 2019), there is a dearth of studies investigating the role of greenspace in cycling injury risk. Our study found evidence that the relationship between greenspace and cycling accident risk may be non-linear: as greenspace increased, we saw gradual decreases in the odds of accidents, but at the highest level of greenspace, we saw a 15% increased odds of KSI (95% CI 1.02–1.29) compared to the lowest level. The u-shaped relationship we found could be attributed to several reasons. The first is that risk is higher in areas with low levels of greenspace because those areas also tend to be densely populated with people and/or commercial areas and infrastructure. While we have controlled for cycling and motor vehicle traffic, population density, and commercial density in our models, there may still be a possibility for residual confounding. Risk can also be higher in areas with the highest levels of greenspace because cyclists may feel safer in areas such as parks and be less aware of dangers. Furthermore, commuter cyclists and recreational cyclists may have different risk profiles, and their travel patterns across parks vs. non-green areas are likely to have an uneven distribution. A study in London found that while the overall number of bicycles from the London bicycle sharing scheme made up only 16% of the bicycles they observed in their study around London, this proportion rose to 60% at one of the two recreational sites they chose: the large Hyde Park in the city center (Goodman et al., 2014). There is limited evidence that suggests that recreational greenspace may pose unique risks to cyclists. In a Los Angeles based study, Jerrett et al. (2016) found that areas adjacent to parks had the highest level of cyclist injuries. After controlling for potential confounders, being within a quarter mile of a park is associated with a 52% higher risk of serious cycling injuries compared to areas outside that buffer. The unique risk factors associated with recreational cycling that often occurs in parks and recreational areas should be investigated in future research.

Unlike previous studies (Richter et al., 2005; De Pauw et al., 2014), we did not find evidence that speed cameras are associated with KSI cycling accidents. Further research in the London context may draw on a field-based randomized controlled study design to investigate the introduction of speed cameras on roads (compared to similar control roads without cameras). A more nuanced design may also consider the potential differential effect

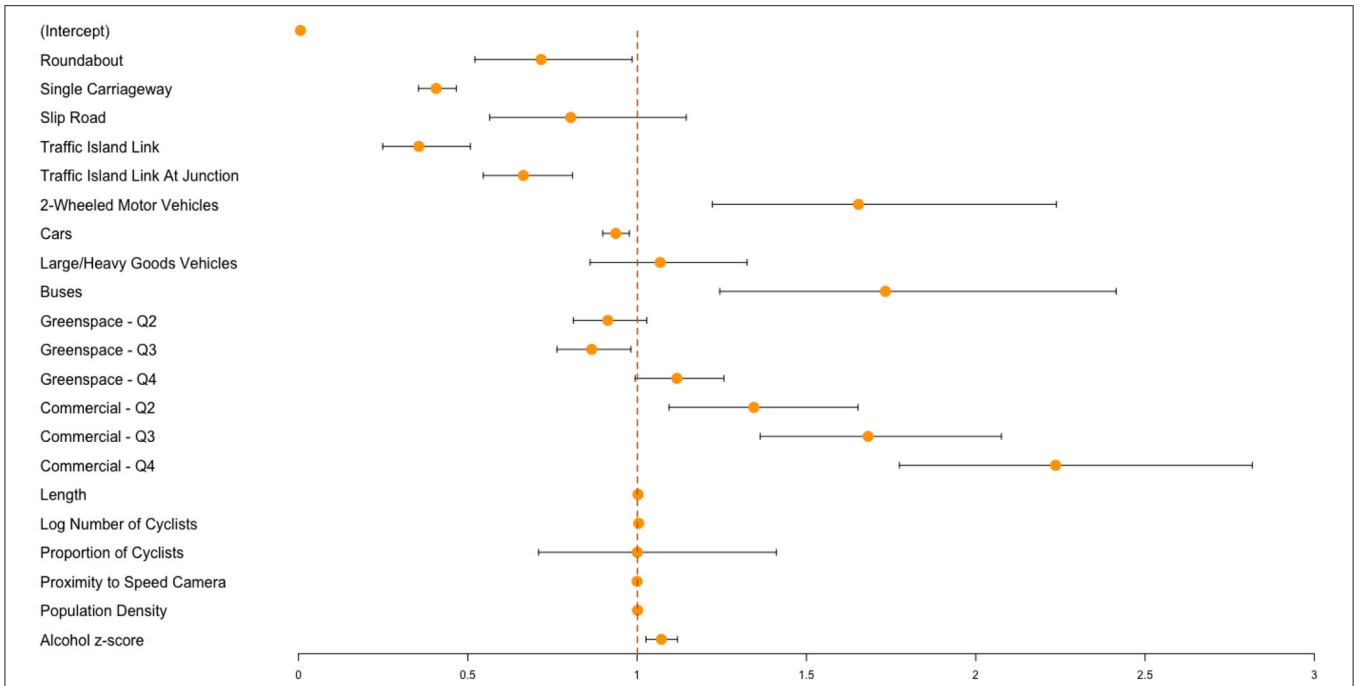


**FIGURE 2 |** Odd ratios of at least 1 KSI accident with 95% confidence interval (dotted line) for selected social and environmental factors.

between *the presence of speed cameras* vs. *being issued a traffic violation citation & being fined*. In this case, the introduction of two levels of intervention (sites with mockup non-functional cameras vs. real cameras that would record violations) along with control sites can be used to isolate and identify the effectiveness of speed cameras as an intervention.

While higher numbers of cyclist traffic has been cited as a significant protective factor against cycling accidents (Robinson, 2005; Fyhri et al., 2017), we did not find evidence that cyclist traffic (or proportion of cyclists to total traffic) to have a protective effect against KSI accidents after controlling for potential confounders, which was an unexpected finding. In a prior observational study based in Western Australia (Robinson, 2005), as the number of cyclists doubled over a 7 year period, cycling-related hospitalization decreased from 29 to 15 per 10,000 cyclist-years, and reported deaths and serious injuries fell from 5.6 to 3.8 per 10,000 cyclist-years. The authors suggested that the reasons for improvements in cycling safety were (1) motorists being more aware due to their regular encounters with cyclists on the road, and (2) larger groups of cyclists are more visible to motorists. The divergence of our results from previous literature may be due to the unique mega-urban context of Greater London or the number of confounders controlled in our study. Given the exploratory and cross-sectional nature of our study, it cannot preclude that an increase in cycling traffic on a given road over time would not lead to decreases in cycling accidents, which should be investigated in future longitudinal studies preferably with a fixed-effect (i.e., within-subject) approach that controls out the effects of time-invariant confounders. Further research should also investigate whether increased cyclist traffic may be protective against different levels of cycling accidents from minor to severe to fatal.

There are a number of limitations of note for this study. (1) The study is cross-sectional, where the KSI outcome and various exposures are simultaneously assessed, which precludes us from drawing causal inferences from the observed associations. (2) Data available to us from Transport for London on cycle paths in London do not differentiate between different types of cycling paths (e.g., dedicated and protected cycle paths vs. paths shared with other traffic such as buses). Since London has designated all bus lanes to be cycle paths (i.e., the majority of cycle paths in the city), cycle paths in the data may represent different cycling conditions with vastly different risk profiles. For this reason, we have not included this variable in our final model. (3) The KSI data did not include many details of the cyclist (e.g., gender and age) and whether the trip was for recreational or commute purposes, which precluded us from investigating whether the observed associations between the exposures and KSI may be different for recreational vs. commuting cyclists, or stratified by socio-demographic characteristics.

The major strengths of our study are (1) the inclusion of a broad range of social and environmental predictors of KSI accidents, (2) spatially referenced variables to account for neighborhood-level effects, and (3) the use of KSI accidents as an outcome that are well represented by official statistics (compared to minor accidents). A number of novel built-environmental correlates of KSI (such as with speed cameras, alcohol outlets, and greenspace) we

identified have important policy implications, and we suggest that further investigations into these built-environmental characteristics may yield information to design effective interventions to reduce KSIs. These interventions may include the use of speed cameras in areas with a high risk of KSIs (e.g., dual carriageway roads), and improving cycling safety infrastructure in areas with the highest density of greenspace and alcohol outlets.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

AL came up with the concept for the paper. AL and AC decided on the model and the independent variables and drafted the paper together. Both authors contributed to the article and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Effectiveness of a Drinking and Driving Campaign on Knowledge, Attitudes, and Behavior Among Drivers in Addis Ababa

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**Background:** In Addis Ababa, Ethiopia, road traffic crashes represent a major public health challenge. Driving under the influence of alcohol (drink driving) is a risk factor for road traffic crashes. Mass media campaigns can reduce the prevalence of drink driving. Few studies to date have evaluated the influence of anti-drink-driving campaigns on changes in knowledge, attitudes, and behaviors in low-income countries such as Ethiopia.

**Objective:** This study aims to examine the impact of an anti-drink-driving campaign on knowledge, attitudes, and behaviors around drinking and driving in Addis Ababa, Ethiopia.

**Methods:** The "Never Drink and Drive" campaign ran on media outlets in Addis Ababa and consisted of evidence-informed messages on the consequences of drink driving. Data for this study comes from two representative household surveys conducted among a sample of adult drivers aged 18–55 years in Addis Ababa pre-campaign ($n = 721$) and post-campaign ($n = 721$). Multivariate logistic regression is used to estimate the effects of the campaign on knowledge, attitudes, and behavior related to drink driving.

**Results:** After the campaign, participants were significantly more likely to have improved knowledge and attitudes about drink driving: post-campaign participants were significantly more likely to report feeling unsafe about drink driving ($OR = 1.51$, $p < 0.05$). Social norms showed a positive shift: post-campaign participants were over six and a half times more likely to report that someone talked to them about drink driving ($OR = 6.52$, $p < 0.05$). After the campaign, participants demonstrated improved knowledge and attitudes around drink driving laws and enforcement, including that they were significantly more likely to agree that they would be caught by police for drink driving ($OR = 12.66$, $p < 0.1$). Behavior also improved—post-campaign participants reported significantly lower rates of driving soon after drinking alcohol, compared with pre-campaign participants (31 vs. 42%).

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**Conclusion:** The anti-drink-driving campaign achieved gains in knowledge, improved attitudes, and reduced drinking and driving, which could help to curb road traffic crashes in Addis Ababa. This study offers some of the first evidence that an anti-drink-driving campaign, combined with enhanced enforcement of road safety laws, can be effective in changing knowledge, attitudes, and behaviors around drink driving in low-income countries.

**Keywords: mass media campaigns, evaluation, behavioral intentions, road safety, perceived risks, attitudes, enforcement, drink driving**

## INTRODUCTION

Road traffic crashes are the eighth leading cause of death globally and a major public health challenge that needs to be addressed. Every year, ∼1.35 million people die as a result of road traffic crashes and as many as 50 million others suffer from non-fatal injuries that may lead to disability (World Health Organization, 2018). In many countries around the world, road traffic crashes are not only a major cause of mortality, morbidity, and serious injuries but also impose financial burdens on families and society (Decker et al., 1988; Kenkel, 1993). In low-income countries, the risk of road traffic deaths is three times higher compared to high-income countries, with the greatest burden in the African region (World Health Organization, 2018). Road traffic crashes in Ethiopia have been rising along with rapid motorization, a lack of regulation of motor vehicles, and population growth. In Ethiopia, the road crash fatality rate for 2016 was estimated at 26.7 per 100,000 population, compared to 18.2 globally and 26.6 for the African region (World Health Organization, 2018).

Driving under the influence of alcohol (drink driving) is one of the major risk factors for road traffic crashes (Agent et al., 2002). The consumption of alcohol—even in relatively small amounts—affects drivers' judgement, vision, coordination, and reflexes and increases the risk of having a crash (Carvajal and Lerma-Cabrera, 2015; Pan American Health Organization World Health Organization, 2018). Even among professional drivers, there is a high prevalence of drink driving and poor self-reported road safety outcomes, road traffic fines, and crashes, regardless of the regularity or frequency of alcohol consumption (Useche et al., 2017). In addition, driving under the influence of alcohol leads to other high-risk road use behaviors, such as speeding, that can harm other road users who may be following traffic laws (Zhao et al., 2014; World Health Organization, 2018; Yadav et al., 2019). Finally, drivers with alcohol use disorders are more likely to be disqualified from driving as a result of road safety offenses, including crash involvement and traffic violations that lead to demerit points and/or loss of a driver's license (Martí-Belda et al., 2019).

While progress has been made in reducing alcohol-impaired driving crashes in many high-income countries, low-income countries face particular challenges in reducing drink driving, including social and cultural norms of alcohol use, lack of reliable traffic safety data, and lack of well-developed drink driving policies (Stewart et al., 2012). In Addis Ababa, road traffic crashes, and injuries represent a major public health challenge (Addis Ababa City Administration, 2017a). In 2013, Addis Ababa recorded 382 reported road fatalities, and from 2012 to 2014, the city recorded ∼12.5% of all reported road fatalities in Ethiopia (Addis Ababa City Administration, 2017a). Among adult deaths due to injury, road traffic crash was the most common cause with an increasing trend in Addis Ababa (Anteneh and Endris, 2020). Drink driving is an important factor contributing to the city's road safety crisis (Addis Ababa City Administration, 2017a). From September 2013 to August 2014, analysis of road traffic crash data in Addis Ababa suggest that over half of fatal road traffic crashes are due to "reckless driving behavior" (53.8%) and <1% are due to drink or drugged driving (0.6%) (Kebede et al., 2019). However, other studies have suggested that the prevalence of drink driving cases is as high as 9% and drink driving is significantly associated with road traffic crash injury and death in Addis Ababa (Mekonen, 2016; Bekele and Sima, 2019; John's Hopkins University, 2019).

Mass media campaigns are an effective public health intervention for addressing social norms and changing health behaviors (Redman et al., 1990; Noar, 2006; Wakefield et al., 2010). For mass media campaigns to be effective, they must not only impart crucial health information, such as through the presentation of facts or figures, but also persuade through the use of emotional appeals, such as through evocative stories and images (Elliott, 1993; Ulleberg et al., 2009). In the context of road safety, evidence-based campaigns have been found to increase *knowledge* and change *attitudes*, leading to reductions in risky road *behaviors* (Redman et al., 1990; Tay, 2002). Campaigns to reduce alcohol-impaired driving that persuade individuals to not drink and drive and encourage them to prevent others from doing so; spreading messages about the physical dangers and legal consequences of drink driving also tends to be effective (Elder et al., 2004; Phillips et al., 2011; Young et al., 2018). Campaigns with concomitant activities for reducing alcohol-impaired driving, such as legislation and enforcement efforts against alcohol-impaired driving, are also beneficial for reducing road traffic crashes (Elvik et al., 2004; Phillips et al., 2011; Bachani et al., 2017).

Many countries around the world use the tripartite model of legislation-enforcement-advertising for effective campaigns against drink driving (Cheng et al., 2011). In high-income countries, campaigns, when coupled with legislation and enforcement of legislation, are an evidence-based public health tool that can reduce drink driving (Lastovicka et al., 1990; Redman et al., 1990; Murry et al., 1993; Mruk, 2007; Young

et al., 2018). However, there is a dearth of literature on this topic from low- and middle-income countries. More studies from low- and middle-income countries are needed, as this is where the majority of road traffic crash deaths occur. Also, it is important to examine the impact of anti-drink-driving campaigns on drinking and driving in these countries because results from studies in high-income countries may not be generalizable to low- and middle-income countries where traffic regulations and driving practices might be different. To our knowledge, no study has assessed the impact of anti-drink-driving campaigns in terms of knowledge, attitudes, and behaviors in low- and middle-income countries, such as Ethiopia. This study aims to address this gap by examining the impact of an anti-drink-driving campaign on knowledge, attitudes, and behaviors around drinking and driving in Addis Ababa.

The drinking and driving campaign in Addis Ababa was developed through a partnership between the Addis Ababa Transport Programs Management Office and Vital Strategies as part of the Bloomberg Philanthropies Initiative for Global Road Safety (BIGRS). This multi-partner program focused on reducing four risky road user behaviors: speeding, lack of seatbelt wearing, lack of helmet wearing, and drink driving. This campaign, coupled with police training on drink driving enforcement and the provision of breathalyzers and other critical equipment, was initiated based on results from an observational study in 2015 showing a high rate of drinking and driving in the city (as cited in Addis Ababa City Administration, 2017a).

**FIGURE 1 |** Image from PSA "Celebrate".

**FIGURE 2 |** Image from PSA "Testimonial".

## MATERIALS AND METHODS

### Study Design

This study uses a quasi-experimental design. In this intervention study, pre- and post- indices are assessed to evaluate the effect of a mass media campaign aimed at reducing the burden of drink driving, which contributes to road traffic crashes in Addis Ababa. To evaluate the campaign's impact, representative household surveys of adults based in Addis Ababa were conducted just prior to the launch of the campaign and immediately following its conclusion. Both surveys were conducted by the Sub Saharan Africa Research and Training Center (known as SART Consult), a research agency based in Addis Ababa, with the pre-campaign (or baseline) survey conducted from September 9 to September 18, 2016 and the post-campaign survey conducted from April 28 to May 5, 2017.

### Addis Ababa Government's Drink Driving Campaign

The Addis Ababa Transport Programs Management Office, in partnership with Vital Strategies, established the "Never Drink and Drive" campaign aimed to curb road traffic crash deaths and injuries that result from drink driving. Along with the mass media campaign, there were concomitant enforcement activities by traffic police on drinking and driving during the campaign period.

The campaign (see Appendix A in **Supplementary Material**) consisted of three message-tested public service announcements (PSAs) that use an emotional appeal, including storytelling, to communicate messages focused on the health, social, and legal consequences of drinking and driving. The first PSA, "Celebrate," depicts two friends at a bar; one tries to prevent the other from driving because he had been drinking alcohol, but the man laughs off his friend's concerns and drives home, and subsequently dies in a crash on his way home (see **Figure 1**). The first PSA communicates the message that, although a driver may believe they can drive safely after drinking, even a small amount of alcohol can make driving unsafe. The second PSA, "Testimonial," shows a grief-stricken mother whose daughter, a promising university student, died in a road traffic crash in which a driver had been drinking alcohol (see **Figure 2**). The second PSA communicates the impact of drinking and driving on families and the community. The third PSA, "Enforcement," shows real police officers using breathalyzers to check drivers' alcohol levels—deemed important as breathalyzers had not been used in Addis Ababa before—and includes an explanation of the legal limit for alcohol for drivers (see **Figure 3**). The third PSA communicates an enforcement message to increase driver perceptions of their risk of being caught and punished if they break the law.

**FIGURE 3 |** Image from PSA "Enforcement".

The campaign ran on multiple mass media outlets, including radio, television, billboards and posters, and on social media. The three advertisements were staggered in phases within the campaign, with "Celebrate" and "Testimonial" on air from October 18 to December 9, 2016 and again from April 6 to 21, 2017. "Enforcement" aired from March 29 to April 5, 2017 (Addis Ababa City Administration, 2017b). A total of 150 television exposures and 508 radio spots were purchased, including airings after the national television news on all weekdays. The spots were also aired 180 times total in two major cinemas and 1,800 times on an outdoor screen at a cinema complex. The campaign dates were synchronized with police enforcement activities around drink driving. Notably, this period marked the first time Addis Ababa police had used breathalyzers for systematic enforcement of drinking and driving.

## Sampling Method and Sample Size

A multistage stratified random sampling procedure was used to recruit participants for the surveys. The 2007 census was used as a sampling frame. Census enumeration areas for urban and peri-urban areas formed the primary sampling units. There were a total of 3,779 enumeration areas in Addis Ababa (Census of Ethiopia, 2007), distributed across all 10 sub-cities; 17 enumeration areas were selected across the 10 sub-cities, with one to three in each sub-city based on the population size. Census enumeration areas were selected at random, then households were selected from within these areas, and then participants selected from within these households. A Kish grid was used to select one participant from among multiple eligible participants in a household.

The study participants were current residents of Addis Ababa who were aged 18–55 years. The study selected participants who were current drivers of vehicles with four or more wheels (e.g., car, van, bus, or truck) and drove these vehicles frequently (four or more days a week). People were excluded from the study if, at the time of data collection, they worked in road safety (including traffic departments, non-governmental organizations that work in road safety, etc.); advertising; market research; or the alcohol, tobacco, or automobile industries. A total of 1,442 drivers were interviewed (721 each in the pre- and post-campaign surveys). These cross-sectional samples are used for this study. For details on the sampling procedure and sample size, see Appendixes B,C in the **Supplementary Material**.

## Measures

The data gathered in the study were quantitative and collected using close-ended questions. A few questions, such as those related to reactions to the campaign, attitudes, enforcement of drinking and driving laws, interpersonal communication, and support for the road safety campaign, were asked based on a five-point Likert scale. The following were key measures in the study (for details, see Appendix D in **Supplementary Material**).

### Campaign Awareness

Campaign awareness was assessed by showing participants images from each of the campaign PSAs (television, outdoors, and social media) and reading them a few sentences from the radio advertisement. Next, participants were asked what messages they recalled from the campaign. This was repeated for all three PSAs. All those who recognized any one of the campaign's three PSAs accurately (that is, they recognized any one of the campaign images or the radio script and they accurately recalled the campaign message) were categorized as "campaign aware." All other participants were categorized as "campaign unaware."

### Reactions to the Campaign

Reactions to the campaign were assessed by asking campaign-aware participants how strongly they agreed or disagreed with a series of statements about each PSA, for example, "the ad made me stop and think," "the ad made me feel more concerned about driving after drinking," and "the ad made me try to persuade others to not drink and drive" (see **Table 3** for a complete list of statements).

### Interpersonal Communication

Interpersonal communication about the campaign was measured through a series of yes-no questions; for example, campaign-aware participants were asked whether they "said something about the PSA or discussed the PSA with others" or if they "tried to persuade others to not drink and drive." They were also asked if someone had talked to them about drinking and driving in the previous 2 months.

### Knowledge

Knowledge on drink driving road safety laws was measured by asking, "Is there a law in your city related to drinking and driving?".

### Attitudes

Attitudes about drinking and driving were assessed by asking participants to what extent they agreed or disagreed with a series of statements on drink driving, for example, "I am capable of determining when I have had too much to drink and drive,"

"People should be free to judge how much they can safely drink and drive," and "The people important to me think that it is important to follow traffic rules" (see **Table 4A** for the complete list of statements). Attitudes toward road safety laws and their enforcement were also measured, e.g., "I am likely to be caught and fined by the police if I break a road rule," "It is easy to reduce or avoid road penalties by bribing the traffic police," and "Police enforcement of traffic laws only happens occasionally and on special occasions" (see **Table 4B** for the complete list of statements). Participants' risk perceptions were measured by assessing how safe or unsafe they felt when drinking and driving.

### Beliefs

Beliefs about enforcement were measured by asking participants how likely it was that drivers would be stopped by police for checks on drinking and driving and how likely it was that they would be caught by police for drinking and driving. Participants were also asked how often, if at all, they believed that drink driving laws were enforced and how strongly they agreed or disagreed that some people stopped at checkpoints are not breath tested for drinking and driving (see **Table 4B** for the complete list of statements).

### Behavior

Behavior around road safety and drink driving was assessed by asking participants how often in the past 2 months they had driven a vehicle soon after drinking any amount of alcohol.

## Data Analysis

Data were weighted by gender and sub-city level to adjust for representation at the city level and then analyzed using SPSS 25.0. Two-sided tests of equality for column proportion were done to understand the differences in proportions between the pre- and post-campaign periods. Logistic regression was applied to measure the impact of the campaign on various indicators of knowledge, attitudes, and behavior. Campaign period (pre-campaign and post-campaign) was regressed on dichotomized measures of knowledge, attitudes, behavior, perception of enforcement of road safety laws, and support for government action on road safety. Covariates included gender, age, marital status, education, occupation, family income, religion, being the chief wage earner, having children <12 years of age, and number of days on which alcoholic drinks were consumed in the previous week.

## Ethics Approval

Before initiating the interview, the study was explained to all the participants. Verbal consent was taken from each interviewee regarding their participation in the study. The questionnaire was administered only to those participants who agreed to participate. As an ESOMAR member, SART Consult complies with the professional and ethical standards of the ESOMAR International Code of Marketing and Social Research Practice.

**TABLE 1 |** Demographic characteristics of participants in pre- and post-campaign samples.

| Demographics | Pre-campaign ($n = 721$) | Post-campaign ($n = 721$) |
|---|---|---|
| | A | B |
| **Gender (%)** | | |
| Men | 87 | 85 |
| **Age (%)** | | |
| 18–25 years | 15 | 18 |
| 26–35 years | 49 | 53 |
| 36–45 years | 24 | 21 |
| Above 45 years | $12^{A}$ | $8^{B}$ |
| **Education (%)** | | |
| Illiterate or up to primary school | 8 | 8 |
| Secondary/high school | 50 | 52 |
| College and above | 28 | 26 |
| Technical and vocational | 14 | 14 |
| **Civil status (%)** | | |
| Single | 45 | 49 |
| Married/living in | 50 | 46 |
| Widow/separated/divorce | 4 | 5 |
| **Religion (%)** | | |
| Christian | 86 | 86 |
| Muslim | 14 | 14 |
| **Occupation (%)** | | |
| Manager/professional | $16^{A}$ | $30^{B}$ |
| Self-employed | $23^{A}$ | $15^{B}$ |
| Skilled worker | $58^{A}$ | $52^{B}$ |
| Others | 2 | 2 |
| Unemployed | 1 | 1 |
| **Children aged <12 years residing with family (%)** | $47^{A}$ | $37^{B}$ |
| **Monthly family income (in Ethiopian Birr) (%)** | | |
| <1,650 EB | 12 | 11 |
| From 1,651 EB −3,200 EB | 23 | 20 |
| From 3,201 EB −5,250 EB | 24 | 23 |
| From 5,251 EB −7,800 EB | $15^{A}$ | $23^{B}$ |
| More than 7,801 EB | 26 | 24 |
| **Consumed at least one alcoholic drink in last 30 days (%)** | | |
| None | 44 | 40 |
| Less than weekly | 22 | 25 |
| 1–3 days per week | 25 | 23 |
| 4–6 days per week or daily | $9^{A}$ | $12^{B}$ |
| **Type of 4-wheel or more vehicle driven (%)** | | |
| Four-wheeler personal | 59 | 59 |
| Four-wheeler commercial | 38 | 36 |
| 6 wheels and above | 3 | 5 |
| **Number of days driven (%)** | | |
| 4–6 days/week | $33^{A}$ | $40^{B}$ |
| Everyday | $67^{A}$ | $60^{B}$ |

*Values in the same row and sub-table not sharing the same superscript are significantly different at $p < 0.05$ in the two- sided test of equality for column proportions. Cells with no subscript are not included in the test. Tests assume equal variances.*

# RESULTS

## Sample Characteristics

Demographic characteristics of the participants in the pre- and post-campaign samples are presented in **Table 1**. In both rounds of study, a majority of the participants were male and around 86% of the respondents were Christian; the remaining 14% were Muslim. In terms of educational attainment, half of the respondents had attended secondary or high school and one-fourth had reached college level or above. Participants in the post-campaign survey were significantly younger, less likely to have children under the age of 12 residing with them, and more likely to drink alcohol 4–6 days per week or daily, compared with participants in the pre-campaign survey. They also varied by occupation—pre-campaign participants were significantly more likely to be self-employed and skilled workers (such as professional drivers, mechanics, carpenters, electricians, etc.), compared to post-campaign participants (23 vs. 15%; 58 vs. 52%, respectively). Family income results showed that 62 and 66% of the total respondents were in the monthly income range of 1,651–7,800 Ethiopian Birr in the pre- and post-campaign surveys, respectively. The type of vehicle that respondents drove varied very slightly between the two surveys: in both pre- and post-campaign surveys, 59% drove four-wheeled personal vehicles, 36 and 38% drove four-wheeled commercial vehicles, and 3 and 5% drove vehicles with six or more wheels in the pre- and post-campaign surveys, respectively. In terms of frequency of driving, a significant difference was observed whereby 33 and 40% of the participants in the pre- and post-campaign surveys, respectively, drove 4–6 days per week, while 67 and 60%, respectively, drove almost every day. There were no other significant differences between the pre- and post-campaign surveys.

## Campaign Awareness

Overall, recall of the campaign was high (see **Table 2**). Among the post-campaign survey participants, 92% recalled the PSA "Testimonial," 83% recalled "Celebrate," and 76% recalled "Enforcement." A total of 97% of participants recalled *any* one of the three PSAs and were designated as "campaign aware"; 66% recalled all the three PSAs (see **Table 2**). It was also observed that those who recalled all three PSAs reported significantly higher access to mass media platforms such as TV, radio, and the internet compared to those who recalled only one or two PSAs only. The drivers who recalled all three PSAs were significantly more likely to be members of younger age groups and the highest income groups, and to be alcohol consumers and drivers of personal four-wheeled vehicles. The main messages recalled by participants were "never drink and drive" (74%), "drinking and driving can kill you" (51%), and "drinking and driving is always risky" (50%).

## Reactions to the Campaign

Among post-campaign survey participants, those who were aware of the campaign rated it highly (see **Table 3**). The vast majority of participants who recalled the campaign agreed that the campaign PSAs were easy to understand (96%), believable (90%), made them stop and think (86%), and taught them something new (84%). In addition, among those aware of the campaign, more than 84% reported that the PSAs made them feel concerned about driving after drinking alcohol, and more than 82% said the PSAs made them more likely to try to not drive after drinking alcohol. More than 86% of those who recalled the campaign reported that they understood the consequences that drink driving can have on their own or others' lives. Campaign awareness also prompted interpersonal communication: 64% of campaign-aware participants discussed the PSAs with others, 52% tried to persuade others to not drink and drive, and 65% tried to stop driving after drinking. More than 82% of those aware of the campaign also reported that all three PSAs were effective anti-drink-driving PSAs (**Table 3**).

## Changes in Knowledge and Attitudes

There were significant differences in key measures of knowledge and attitudes about drink driving between pre- and post-campaign participants (see **Table 4**). After the campaign, there was a significant increase in the proportion of participants who agreed that *it is difficult to know how much alcohol you can drink and still drive safely*. A significantly greater proportion of post-campaign survey participants reported *feeling unsafe about driving after drinking alcohol*, compared with pre-campaign survey participants (68 vs. 59%). Likewise, after the campaign, participants showed significant improvement in several measures of knowledge around drinking and driving, compared with pre-campaign survey participants. Among post-campaign participants, 29% agreed that they were *capable of determining when they have had too much to drink and drive*, compared with 39% of pre-campaign participants. In addition, after the campaign, there was a significant reduction in the proportion of participants who agreed that *people should be free to judge how much they can safely drink and drive* (49 vs. 37%); and, a significant reduction in the proportion who agreed that *having one or two alcoholic drinks does not make them more likely to crash* (26 vs. 23%). Similar findings were observed in the studies done by Angle et al. (2009) and van Bueren et al. (2016).

After the campaign, social norms related to road safety also showed a positive shift. Post-campaign survey participants were more likely to agree that *people important to them think that it is important to follow traffic rules*, compared with pre-campaign survey participants. There was also an increase in interpersonal communication. More than four times as many post-campaign survey participants said *someone has spoken to them about drinking and driving in the previous 2 months*, compared with pre-campaign survey participants (26 vs. 6%). Finally, following the campaign, there was a statistically significant increase in the proportion of participants who said that *publicity and advertising about road safety should increase* (83 vs. 92%).

Post-campaign survey participants demonstrated significantly greater levels of knowledge about road safety laws, compared with pre-campaign survey participants. After the campaign, 93% of participants post-campaign reported that they have *knowledge about the drinking and driving laws in the city*, compared with 80% of pre-campaign participants. There was also a significant increase following the campaign in agreement with beliefs that laws would be enforced. Post-campaign survey participants who recalled the campaign were significantly more

**TABLE 2 |** Demographic characteristics of participants by number of PSAs recalled.

| Demographics | Aware of only one | Aware of only two | Aware of all three |
|---|---|---|---|
| | (*n* = 95) | (*n* = 145) | (*n* = 438) |
| | A | B | C |
| ***Recall*** | 12 | 17 | 66 |
| **Gender (%)** | | | |
| Male | 85 | 91 | 85 |
| **Age (%)** | | | |
| 18–25 years | 10 | 22 | 20 |
| 26–35 years | 55 | 52 | 52 |
| 36–45 years | 16 | 21 | 21 |
| Above 45 years | $18^{B,C}$ | 5 | 7 |
| **Education (%)** | | | |
| Illiterate or up to primary school | 10 | 12 | 7 |
| Secondary/high school | 58 | 57 | 50 |
| College and above | 19 | 19 | 28 |
| Technical and vocational | 13 | 13 | 15 |
| **Monthly family income (in Ethiopian Birr) (%)** | | | |
| <1,650 EB | 11 | $19^{C}$ | 8 |
| From 1,651 EB −3,200 EB | 27 | 23 | 19 |
| From 3,201 EB −5,250 EB | 19 | 20 | 23 |
| From 5,251 EB −7,800 EB | 21 | 23 | 24 |
| More than 7,801 EB | 23 | 15 | $26^{B}$ |
| **Access to mass media almost daily (%)** | | | |
| TV | 35 | 56 | $84^{B,C}$ |
| Radio | 34 | 35 | $55^{B,C}$ |
| Internet | 43 | 47 | $50^{B,C}$ |
| **Drink at least one alcoholic drink in last 30 days (%)** | | | |
| None | $55^{B,C}$ | 34 | 38 |
| Once in a week | 45 | 66 | 62 |
| **Type of 4 or more-wheel vehicle drive (%)** | | | |
| Four-wheeler personal | 50 | 51 | $63^{B}$ |
| Four-wheeler commercial | 42 | 42 | 33 |
| 6 and above wheeler | 8 | 7 | 4 |
| **Number of days you drive (%)** | | | |
| 4–6 days/week | 34 | 35 | 42 |
| Everyday | 66 | 65 | 58 |

*Values in the same row and sub-table not sharing the same superscript are significantly different at $p < 0.05$ in the two- sided test of equality for column proportions. Cells with no subscript are not included in the test. Tests assume equal variances.*

likely to agree that a *person is likely to be caught and fined by the police if they break a road rule* ($OR = 1.36$, $p < 0.05$); that *drivers would be stopped for drink driving, particularly at night* ($OR = 9.81$, $p < 0.1$); and that the *enforcement of laws and penalties for drink and driving in the city would occur* ($OR = 10.71$, $p < 0.1$). Similarly, after the campaign, fewer participants agreed that *it is easy to reduce or avoid road penalties by bribing the traffic police* ($OR = 0.80$, $p < 0.01$); that *some people stopped at checkpoints are not breath tested for drinking and driving* ($OR = 0.08$, $p < 0.1$); and that *police enforcement of traffic laws only happens occasionally and on special occasions* ($OR = 0.41$, $p < 0.1$), compared with pre-campaign participants.

Following the campaign, self-reported risk behavior showed improvement as well. Post-campaign participants reported lower rates of *driving soon after drinking any amount of alcohol*, compared with pre-campaign participants, although differences were not significant (31 vs. 42%). Linkenbach and Perkins (2005) and van Bueren et al. (2016) had similar findings in their studies.

## DISCUSSION

This study is one of the first that aims to capture knowledge, attitudes, and practices around drinking and driving and its enforcement in Addis Ababa. The results show that the campaign performed as intended and had a positive impact on social

**TABLE 3 |** Appraisal of campaign messages and actions taken as a result of campaign awareness in post-campaign period by PSA type.

| PSAs | Average % | Testimonial | Celebrate | Enforcement |
|---|---|---|---|---|
| | (*n* = 678) | (*n* = 654) | (*n* = 593) | (*n* = 525) |
| **Self-reported reaction to PSAs (% agree)** | | | | |
| Was easy to understand | 96 | 94 | 98 | 96 |
| Taught me something new | 84 | 78 | 84 | 90 |
| Made me stop and think | 86 | 86 | 89 | 83 |
| Was believable | 90 | 90 | 91 | 88 |
| Made me uncomfortable | 50 | 70 | 42 | 37 |
| Was relevant to me | 33 | 30 | 34 | 35 |
| Made me feel more concerned about driving after drinking alcohol | 85 | 85 | 86 | 84 |
| Made me more likely to try to not drive after drinking alcohol | 83 | 83 | 82 | 84 |
| Made me understand the consequences that drinking and driving can have on my life or others' lives | 89 | 90 | 91 | 86 |
| Was an effective anti-drinking and driving ad | 85 | 86 | 88 | 82 |
| **Interpersonal communication** | | | | |
| Tried to persuade others to not drink and drive | 52 | 51 | 49 | 56 |
| Said something about the PSA or discussed the PSA with others | 64 | 68 | 60 | 64 |
| Tried to stop drinking and driving | 65 | 64 | 65 | 66 |

**TABLE 4A |** Campaign impact on knowledge and attitudes and support for government action, by pre-campaign and post-campaign period.

| Campaign impact | Pre-campaign | Post-campaign | Adj. OR[2(†)] |
|---|---|---|---|
| | (*n* = 721) | (*n* = 721) | |
| | A | B | |
| **Knowledge about drink and driving law** | | | |
| Have knowledge about drink and driving law in the city (%) | 80 | 93[A] | 3.24* |
| **Attitude toward drink and drive** | | | |
| Agree that it is difficult to know how much alcohol you can drink and be safe (%) | 59 | 60[A] | 1.23*** |
| Feel unsafe when you drive after drinking alcohol (%) | 59 | 68[A] | 1.51** |
| Agree that I am capable of determining when I have had too much to drink and drive (%) | 39[B] | 29 | 0.63* |
| Agree that people should be free to judge how much they can safely drink and drive (%) | 49[B] | 37 | 0.63* |
| Agree that people important to me think that it is important to follow traffic rules (%) | 81 | 84 | 1.33*** |
| Agree that having one or two alcoholic drinks doesn't make me more likely to crash (%) | 26[B] | 23 | 0.85 |

*Values in the same row and sub-table not sharing the same superscript are significantly different at $p < 0.05$ in the two- sided test of equality for column proportions. Cells with no subscript are not included in the test. Tests assume equal variances.*

*$^{*}p \leq 0.1$; $^{**}p \leq 0.05$; $^{***}p \leq 0.001$.*

*[†] Covariates: gender, age, have child under <12 years, number of days have at least one alcoholic drink, education, marital status, occupation, religion, chief wage earner, family income.*

norms and on drivers' knowledge and attitudes toward drinking and driving in Addis Ababa. In addition, this study has great significance as a campaign evaluation, demonstrating the value of the intervention in Addis Ababa.

Recall of the campaign was impressively high, with 97% of study participants recalling any of the three PSAs and 66% recalling all three. Recall of all three PSAs was higher among participants who were younger, had higher incomes, and who reported drinking alcohol. Our findings of high rates of recall suggest that the media outlets—television, radio, and outdoor—were effective at reaching the target audience. Despite a constantly expanding social media user base in Addis Ababa, the PSA had the highest recall for those participants who viewed it *via* television. This is consistent with previous findings of

**TABLE 4B |** Campaign impact on risk perception, interpersonal communication, support for government action, and behavior, by pre-campaign and post-campaign period.

| Campaign impact | Pre-campaign ($n = 721$) | Post-campaign ($n = 721$) | Adj. OR[2(†)] |
|---|---|---|---|
| | A | B | |
| **Attitude toward drink and driving law enforcement** | | | |
| Agree that I am likely to be caught and fined by the police if I break a road rule (%) | 83 | 87[A] | 1.36** |
| Likely to be caught by police for drink and driving | 45 | 91[A] | 12.66* |
| *Perception that drivers will be stopped for drink and drive at (%)* Day | 23 | 51[A] | 3.38* |
| Night | 25 | 76[A] | 9.81* |
| Laws and penalties for drink and driving are always, often, or sometimes enforced in the city (%) | 46 | 89[A] | 10.71* |
| Agree that it is easy to reduce or avoid road penalties by bribing the traffic police (%) | 61 | 56 | 0.80*** |
| Agree that some people stopped at checkpoints are not breath tested for drinking and driving (%) | 79[B] | 23 | 0.08* |
| Agree that police enforcement of traffic laws only happens occasionally and on special occasions (%) | 60[B] | 39 | 0.41* |
| **Participants' support toward campaign** | | | |
| Believe that publicity and advertising about road safety should increase (%) | 83 | 92[A] | 2.39* |
| Support government running road safety campaign | 97 | 98 | 1.32 |
| **Interpersonal communication about road safety** | | | |
| Someone talked to the respondent about drink and driving in previous 2 months (%) | 6 | 26[A] | 6.52* |
| **Behavior toward drink and drive** | | | |
| Drove soon after drinking any amount of alcohol (%) | 42[B] | 31 | 0.94 |

*Values in the same row and sub-table not sharing the same superscript are significantly different at $p < 0.05$ in the two- sided test of equality for column proportions. Cells with no subscript are not included in the test. Tests assume equal variances.*

*$^{*}p \leq 0.1$; $^{**}p \leq 0.05$; $^{***}p \leq 0.001$.*

*[†]Covariates: gender, age, have child under <12 years, number of days have at least one alcoholic drink, education, marital status, occupation, religion, chief wage earner, family income.*

television being the most common source of information, and thus highest recall is reported through television (Angle et al., 2009; van Bueren et al., 2016).

This study showed positive changes in attitudes toward drink driving, and these were consistent with the campaign's intent. Post-campaign participants were over one and a half times more likely to report *feeling unsafe about drinking and driving* ($OR = 1.51$, $p < 0.05$) and nearly one-quarter times more likely to agree *it is difficult to know how much alcohol you can drink and drive safely*, compared with pre-campaign survey participants. These results indicate that the mass media campaign increased drivers' perceptions of the risks of drinking and driving. This campaign, as other effective campaigns, was successful in increasing risk perceptions, which encourages a shift in attitudes toward drink driving (Tay, 2002).

Social norms have a powerful influence on how people approach risky road behaviors. The results of this study in Addis Ababa suggest a positive change in social norms related to drinking and driving. After the campaign, participants were one and a third times more likely to report *people important to them think it is important to follow traffic rules*, compared with pre-campaign participants ($OR = 1.33$, $p < 0.001$). Increased interpersonal communication about risky behaviors is an important proxy for changes in social norms, and it is essential that a PSA generates interpersonal communication that is effective and causes behavioral change (Southwell and Yzer, 2007). We found that interpersonal communication about drinking and driving significantly increased after the campaign. Following the campaign, the proportion of survey participants who said someone had spoken to them about drinking and driving had more than quadrupled, compared with pre-campaign survey participants. Among campaign-aware participants, interpersonal communication was even higher, with participants having discussed drinking and driving with others and having tried to persuade others to not drink and drive.

After the campaign, participants showed significantly greater levels of support for and confidence in enforcement activities, as well as an increased perception of the risk of getting caught for drinking and driving. Findings from this study build on previous literature examining the impact of anti-drink-driving mass media campaigns on enforcement. Along with communicating about health harms and changing people's risk perceptions, campaigns

and PSAs that showcase enforcement strategies as a means of message delivery have also been found to be effective in reducing crashes (Phillips et al., 2011; Alonso et al., 2015). This can also help increase support for enforcement and additional penalties for driving under the influence of alcohol (Agent et al., 2002). Linkenbach and Perkins (2005) found a campaign also affected attitudes toward impaired driving enforcement policy and generated support for policies to reduce impaired driving. Finally, this study, as have earlier studies, found that after the campaign the majority of post-campaign survey participants felt that they would be likely to be caught by the police if they were to drive after drinking (Angle et al., 2009).

In line with international best practice, this campaign was timed to coincide with widespread enforcement of drink driving laws by police in Addis Ababa. Prior to this initiative, police in Addis Ababa had not used breathalyzers or conducted routine drinking and driving screenings. Therefore, the visible police enforcement on the roads while the campaign was on the air is likely to have contributed to the changes in attitudes toward enforcement and toward the acceptability of drinking and driving. This is in line with previous studies (Stanojević et al., 2013; Esser et al., 2016) that found that strict enforcement made people fear being caught, resulting in desirable behavior change. Other studies concluded that a multi-pronged approach, such as the one used in Addis Ababa, was effective in changing behavior because it combined legal penalties for violations with communication campaigns (Anderson et al., 2009; World Health Organization, 2010; Cheng et al., 2011; Hoekstra and Wegman, 2011).

Participants in the post-campaign survey as compared to the pre-campaign were nearly two and a half times more likely to report increased support for publicity and advertising about road safety, suggesting that future campaigns on road safety risk factors may be equally well-received.

Finally, and perhaps most importantly, this study found that after the campaign there was improvement in self-reported risk behavior, which previous studies have also found (Tay, 2002). In the post-campaign survey, significantly fewer drivers reported that they drove soon after drinking any amount of alcohol (31% post-campaign vs. 42% pre-campaign). Given the measured change in attitudes and norms, and if both communication and enforcement efforts continue, it is reasonable to be optimistic that dangerous drinking and driving behavior will continue to decrease in Addis Ababa.

## STUDY LIMITATIONS

There are several limitations to the study. First, the study did not measure frequency of exposure to the campaign. To ensure that a media campaign has a strong impact, a sufficient level of media exposure is needed (Linkenbach and Perkins, 2005). Estimating the relationship between the frequency of exposure to the campaign and behavior change can inform the minimum level of exposure required for impact, which can be useful for developing cost-effective campaigns, especially in low-income countries with limited resources, and thus future studies can do so. Second, the study relied on many self-reported measures, including drinking, and driving practices; the reliability and validity of these measures is unknown. An assessment of blood alcohol concentration (BAC) in a randomly selected sample could potentially have yielded more reliable and valid results. That said, we used preexisting measures known to be reliable where possible. Pilot testing was done to ensure that the questions worked as intended. The questionnaire design, including consideration of order effects, sought to address any potential biases from self-reports. Third, there exist limitations in the study's design by which participants were not randomly assigned to campaign exposure; randomly assigning participants to campaign exposure and no exposure would allow for establishing causal effects of the campaign on knowledge, attitudes, and behavior, but this is generally impractical for a mass media campaign in a defined geographical area such as a city. Fourth, a limitation is that the results cannot be generalized to the whole of Ethiopia, since they are applied to a very specific area; however, this makes them especially useful for future interventions and communication campaigns in Addis Ababa. Finally, the study does not examine the campaign's impact on the prevalence of drink driving-related road traffic crashes or its long-term effects in Addis Ababa. To address this limitation, in future studies, it could be useful to compare self-reported results with data on road traffic crashes. In addition, follow-up surveys would be useful to measure whether the campaign's effects are maintained over time. Since governments are advised to conduct a series of campaigns, based on evidence that single campaigns have a limited long-term effect, a survey before the next campaign would provide information on long-term impacts, as well as serving as a baseline to measure the impact of later campaigns.

## CONCLUSION

Previous studies in high-income countries have found that mass media campaigns can play an important role in changing drink driving behaviors (Dejong and Charles, 1995; Linkenbach and Perkins, 2005; Geleta et al., 2020). Findings from this study reveal anti-drink-driving campaigns can be an effective public health tool to increase knowledge, change attitudes, and reduce risky road behaviors around drinking and driving in Addis Ababa. The objective of the campaign in Addis Ababa was to make drivers aware of the dire consequences of drinking and driving, and in turn change their related knowledge, attitudes, and behaviors. The campaign achieved gains in knowledge and improved attitudes toward drink driving, and, importantly, reduced drinking, and driving behavior, which could help to curb road traffic crashes and related deaths and injuries in Addis Ababa. Findings of this study are useful for local government and public health officials in understanding the efficacy of the campaign and messages for future mass media campaigns in Addis Ababa.

This study offers some of the first evidence that a campaign targeting drinking and driving, paired with enhanced enforcement of drinking and driving laws, can be effective, not

just in high-income countries, but in low- and middle-income countries as well. Almaz et al. (2014), Mekonen (2016), Bekele and Sima (2019), Kebede et al. (2019), and Geleta et al. (2020) suggested that multiple intervention programs that include public awareness, enforcement of drink driving laws, and other road safety laws have proven effective in controlling alcohol-impaired driving and alcohol-related crashes. Mass media campaigns on risky road behavior such as drink driving should be sustainably funded and scientifically developed to promote lasting behavior change.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, to other researchers on request, following publication. The researchers will sign a contract with Vital Strategies on data use.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

NSN: conception, study design and direction of data analysis, data interpretation, literature review, and writing. KS: help in writing and overall technical assistance for the campaign and evaluation. IM and SM: review and overall guidance of this evaluation. TA: conduct of the analysis. SK: strategic planning of mass media and implication of evaluation findings. AN: coordination with stakeholders. NK: review of analysis and help in writing. NM: conception, study design and direction of data analysis, data interpretation, and help in writing the paper. All authors: contributed to manuscript revision and read and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2020.563350/full#supplementary-material

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REVIEW
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# Are Connected and Automated Vehicles the Silver Bullet for Future Transportation Challenges? Benefits and Weaknesses on Safety, Consumption, and Traffic Congestion

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With the growing development of Cooperative, Connected, and Automated Mobility (CCAM), questions arise about the real impact of this innovative mobility on our daily life. CCAM originally promised to improve road safety. It is now a holistic solution for future mobility: the CCAM is there to optimize traffic, which can translate into strategies for reducing energy consumption or polluting emissions, without compromising road safety. The capability of CCAM is dependent on the reliability and robustness of its components, as it will be making life-impacting decisions. It is therefore necessary to be able to guarantee a high-level quality of sensors, communication, software, and hardware architecture. In this mobility ecosystem, the infrastructure and data that it will be able to produce is at the heart of current research issues. This paper addresses the following question: Are the Connected and automated Vehicles (CAVs) the silver bullet solution with which to answer the issues of the current mobility systems? This question is discussed by investigating the technologies used, the digital infrastructures, its robustness to cyber-attack, and their relationship with the claimed benefits on safety, energy and pollution management, traffic optimization, deployment strategy, and a link with the new generation of road infrastructures.

**Keywords: connected and automated vehicles (CAV), road safety, environment perception, traffic, communication technology, smart infrastructure, sensors technologies, impact of CAV**

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## 1. INTRODUCTION

Within the context of an increasingly marked international competition, economic growth is often based on technological innovation. That radical innovation leads to structural change and economic growth is a central hypothesis in many evolutionary perspectives on the relationship between technology and growth (Freeman and Soete, 1990; Verspagen, 2001). Transport and mobility are no exception to this observation, and the race for technological innovation in this field has, in the last 20 years, reached its climax with the digitalization of one of the most important players in mobility systems: the driver. This digitalization, commonly known as "driving

automation," does not occur in isolation but in a symbiotic way with progress in terms of communication systems whether based on infrastructure or vehicles. The latest advances made in communication systems are thus rapidly integrated into the development of automated transport systems and the requirements of these systems guide research on communicating systems.

To be useful to society, in addition to promising improvement of the economy, a technological innovation must also make it possible to improve safety (reduce the accident risks, Webb et al., 2020) and health and reduce the tensions that mankind has placed on the environment (rationalize the use of energy resources). Are automated transport systems offering these societal benefits on top of the economical ones?

As praise continues to accumulate on these promising technologies (Tesla, 2020; Waymo, 2020), concerns related to poor design or misuse have begun to emerge since 2015 (Schoettle and Sivak, 2015). Recent crash data analysis has highlighted misuse of driving assistance encompassing lateral and longitudinal control (Russell et al., 2018; Dunn et al., 2019). Despite the recommendations and warnings from car manufacturers, drivers continue to place too much trust in this technology. New ADAS are often sold with misleading names and capability description. On a recent Hype cycle carried out by the Gartner cabinet in 2019 (Gartner, 2019), the so-called level 4 Automated Vehicles (AV) has thus entered a phase of disillusionment, showing the generalization of fears on this subject. This topic of over-trust, according to Dixon (2020), is also influenced by marketing managers who overstate the AV capacities.

The impact of AV has already been assessed in different studies. In the works of Workshop) (2018), a list of potential issues was provided depending on the usage scenarios of AVs. However, the only figure provided deals with fuel economy in truck platooning, which is estimated about 10%. The works from Hörl et al. (2016) estimated the potential impact of AD on traffic, city planning, the car industry, work organization, user profiles, delivery, and price. A more user-oriented but speculative impact study has been carried out by Gruel and Stanford (2016), and it shows how the different usage can change with AVs. Another study for (Coelho and Guarnaccia, 2020) also proposed methodologies to evaluate the impact of Automated Driving (AD) on pollutants emissions, noise, and safety but relies on the estimation of driving pattern changes. A more recent work from Litman (2020) discussed the impact of ADs on transport planning, but it also provided an interesting timeline of AV requirement timeline that clearly shows what you should be proven before generalizing AV testing, usage, and eventually, finally, forbidding human from driving (in 2070).

The objective of this paper is to discuss potential impacts, benefits, but also the weaknesses of the new technologies on the mobility performances. The deployment of the connected and automated vehicles (CAV) enters in this domain. It is important to keep in mind that improving this domain will have a significant impact on the infrastructure, the mobility capacity and efficiency, the energy management, the pollution level, and the user's health. This study is therefore structured to highlight efficiency in terms of safety, energy use, and traffic congestion issues.

The remainder of the paper is organized as follows. In the first part, the concept of ADAS, its limitations, and future developments are addressed. The next section focuses on the communication technologies, management, and modeling dedicated to cooperative applications. Then, the following sections analyze the benefits, advantages, limitations, and weaknesses of the CAV in terms of safety, energy and pollution, and traffic. A last part addresses the societal aspects. Finally, the topics require further research, and improvements will be identified and discussed.

# 2. DRIVING ASSISTANCE, CONNECTED, AND AUTOMATED DRIVING

## 2.1. The Automated Transportation System

The core concept of automation is to delegate repetitive and elementary tasks to a machine rather than a human. The machine is expected to achieve these tasks faster in a reliable and repeatable manner within a well-defined environment. Automation has transformed several working environments and has deeply impacted the relationship between the humans and their workplaces. The application to the transportation field was envisioned several decades ago, but the first applications are more recent. Since the 80's, the development of automated transportation systems has spread worldwide, initially from the universities, the defense sector, and few car manufacturers or road operators. The race to develop this technology has strongly accelerated in the last 10 years with software and service companies.

### 2.1.1. Level of Automation

The Society of Automotive Engineers has provided a standard terminology of automation in transportation (SAE, 2016, 2018) from the initial works of BAsT (Gasser and Westhoff, 2012; Gasser, 2014, 2016). The level of Automation depends on the entity who oversees: the control of the actuators, the monitoring of the environment, the supervision of the system, the fallback solution, and the limitation of the operating domain. They range from 0 to 5, i.e., from no automation to full automation. The details, specific operating domains, and levels of human interactions of these different levels of automation are given in **Figure 1**.

### 2.1.2. Road Map for the AV in the Next 30 Years

The deployment Road Maps of AV technology are consistent worldwide. However, there is a distinction between the passenger car deployment path and the freight/urban mobility deployment path (**Figure 2**). Freight and passenger vehicles do not have similar constraints and objectives. Automated technologies related to passenger cars aim at improving mobility, road safety, and as passenger comfort. Given the broad variety of situations these vehicles will face, car manufacturers deployed their technology in a progressive manner, balancing advanced functionalities with the operating domain. The first, and simplest, application is to deploy Highly AD in a highway situation. The

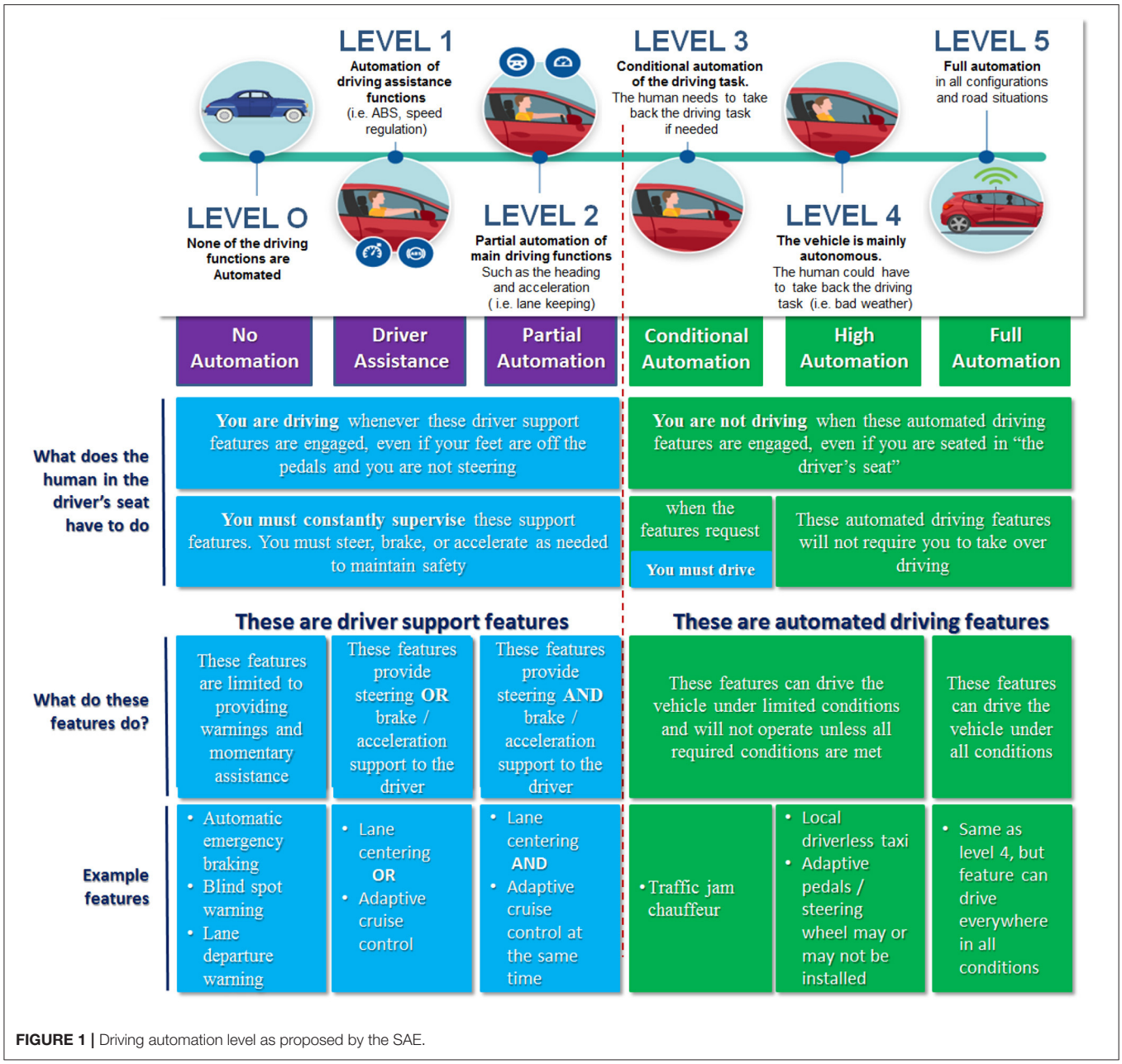



**FIGURE 1 |** Driving automation level as proposed by the SAE.

highway domain has many characteristics: limited interaction between users, such as only one-way traffic to monitor and limited lateral interaction. Highways also have well-maintained and high-quality infrastructure such as lane markings and traffic signs; vehicles are very unlikely to encounter pedestrian. Automation on highway provides comfort to the driver as it is often a long trip.

Automated technologies for freight and public transport have radically different design requirements. The ultimate objective is to remove the driver from the driving task, as the human salary is the largest operational cost in terms of fleet operation. Driver fatigue or drowsy driving is a safety risk for the road fleet transport industry. Legislation related to fatigue management introduces cost to fleet organizations. Heavy vehicle crashes receive tremendous media attention, which is another cost factor in addition to the societal cost of crashes.

Although long-distance freight transport share several automated features with passenger cars and follow the same progressive path, in a particular operational domain such as the highway, specific applications such as platooning are specifically design to reduce the truck's energy consumption. Short-distance transport, such as last mile delivery, public transport with shuttle, are drastically different, as they rely on a specific development of the AD system, noting that most new AVs are electric. These new forms of transports operate on a limited spatial domain with a predefined route and at low speed, and the technology

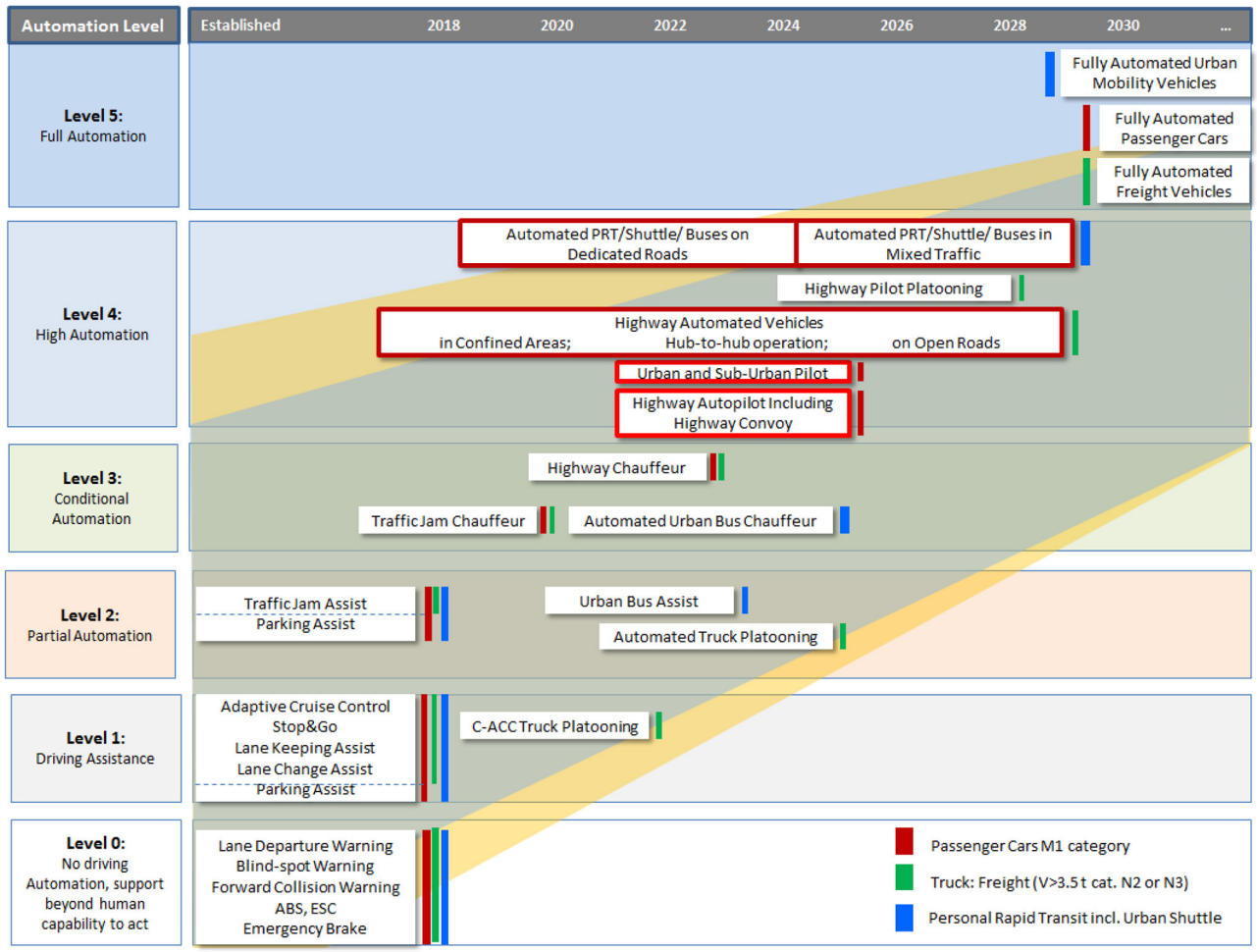



**FIGURE 2 |** Deployment path for Automated driving technology (Connected and Automated Driving Roadmap – ERTRAC – 3/2019), vehicle freight, and public transport.

deployment is not progressive. Shuttle manufacturers, for instance, aim at providing fully AV, without human intervention. In other words, they directly work on Level 5 SAE and ignore Level 3 and 4.

The availability of such technology is still discrete. Experiments of automated passenger vehicle or long-range transport (SAE level 4+) demonstrate that the technology is still not ready to manage all the situations, even in a specific domain, and is prone to failure (Dixit et al., 2016; Favarò et al., 2018). Automated shuttle's speed is very low and requires having an operator in the vehicle when it is moving on open road environment. A recent report from the Austroads (https://austroads.com.au/) forecasts the technology deployment and penetration in the automotive market in 2030. It concludes that despite a low adoption in the truck industry, the potential adoption and benefit may be promoted by the freight's operators; passenger cars may first benefit from Automated Emergency Braking and its derivatives and from connectivity, first with a cloud and then to provide C-ITS services. Highly AD functionalities will still be marginal in 2030.

## 2.2. Driving Assistance, Necessary but Not Sufficient

However, active applications up to the AV require very high reliability and robustness. A close and limited perception performance of the on-board sensors is no longer sufficient. Indeed, in SAE level 3 of automation, the human factor is still involved, and the driver can, at any time, be asked to resume the driving task. Unfortunately, to achieve this transition, it is necessary to guarantee a sufficient period of time for an inattentive driver to perceive the current environment as well as analyze and understand it in order to make the safest decision allowing to act on the vehicle actuators safely (pedals, steering wheel, and gearbox). Thus, to be informed of a disengagement from the AD system, it must have information distant enough spatially and temporally to allow it to analyze, interpret, and predict the future situation and estimate their level of risk. The mean take-over time (TOT) ranges from 0.69 to 19.79 s, most of the distribution being below 7 s (Zhang et al., 2019) with a strong time penalty in case of having a secondary task with a handheld device (Melcher et al., 2015; Zhang et al., 2019). With 7 s to take

over control, on a highway, the vehicle will have driven more than 200 m, far more than any available automotive sensor. The way to have this distant knowledge is to use the knowledge available to other road users through connectivity (connection of a vehicle to the road infrastructure and vehicles between them).

## 2.3. Connectivity, an Automation Enabler

By its capacity to exchange information between vehicles, and to increase (spatially, temporally, and semantically) the perception of the AV, connectivity is the key element with which to ensure a high level of security. The connectivity will allow the AV to face critical situations that it would not otherwise be able to face (construction site, toll zone, etc.). Its implementation is based on a single system: the Cooperative Intelligent Transport System (C-ITS). One also talks about V2X communication. The operating principle is as follows: vehicles have on-board sensors that they use to automatically generate messages on the situations they encounter (Site alert, slippery road, and obstacle on the road). These messages are broadcasted in their immediate environment and can be received by other vehicles (V2V: vehicle to vehicle) and by road managers (V2I: vehicle to infrastructure). The infrastructure manager can also transmit information related to the operation of its road network (traffic, network viability, road information, etc.) to vehicles fitted with on-board sensors (I2V: infrastructure to the vehicle). From a technical point of view, today there are three modes of communication for C-ITS, and these can be mixed to enhance connectivity:

- Very short-range "direct" communication using RFID antenna (Mohsen et al., 2018) and Zigbee (Von Arnim et al., 2008).
- Short-range "direct" communications using the either 2.4 or 5.9 GHz frequency band (ITS G5 based on the IEEE Wifi 802.11p standard). This communication mean is currently used for VANET (Vehicular *ad-hoc* Network).
- Long-range communications, which use the cellular networks of mobile operators (3/4 G cellular).

A delay, interference, or modification of the information contained in the data frame will have a significant impact on the extended perception of the environment and on the quality of the data (imprecision, uncertainty, reliability, and belief), making them potentially unusable under penalty of producing a wrong decision and by extension an accident. The same goes for the management of automated platoons. The only way to ensure the stability of a platoon of more than five vehicles and to avoid the "accordion" effects is to use communications so that the "leader" of the convoy transmits his maneuvering intentions to the other "follower" vehicles. In this case, all the vehicles in the convoy will be able to react at the same time and not have any accumulation of delay due to the limited scope of the perception and the inability to be instantly informed of the driver's maneuvers. In the European project SARTRE, Volvo Car Corporation and its partners have developed an automated platoon with a truck as leader following by four cars driving in full automated mode at a middle speed (90 km/h max) with, in some situations, a very small vehicle inter-distance (up to 4 m). Recent research about the cooperative and automated platooning applications has been developed, studied, implemented, and tested in Latrech et al. (2018) and Schwab and Lunze (2019). Another interesting work (Gong and Du, 2018) proposes to manage CAVs in a platooning configuration but with mixed traffic involving human drivers. In Smith et al. (2019), the authors propose an approach to balance safety and traffic throughput issues in a cooperative vehicle platooning context.

## 2.4. Performance of Communication Technology for AD

In order to be able to anticipate risky situations and develop a co-driver for delegated and automated driving, it is first necessary to study and to implement the communication means to be able to quantify the quality, performance and limits of the communication means. This communication means will be essential in the development of alert applications and Extended Dynamic Perception Maps building. Demmel et al. (2014) performed work on the impact of the communication use to reduce collisions first in simulation and then in real conditions. This very important work has made it possible to demonstrate that with a rate of 25% of communication equipment, a very significant reduction of collisions is obtained. Then, a study of WiFi communications (802.11p) in real conditions revealed certain limitations of this medium in terms of range and transmission delay as a function of the relative speed between a transmitter and a receiver and the size of the transmitted frame. The study made it possible to calculate a global risk, thus allowing for prediction of the presence of a risky situation more than 7 s in advance (Demmel, 2012). This result is also important because, in the development of automated mobility means and in the detection of problems at medium range, it will potentially give the driver enough time to safely resume the driving task.

However, this work raises other questions. Indeed, the use of the number of collisions to assess the contribution of an inter-vehicle communication system for the safety of a line of vehicles was always more pessimistic than the use of a severity criterion using the Equivalent Energetic Speed (EES). The EES is the speed equivalent to the energy being dissipated in a collision. The study also shows that, while the number of collisions decreases significantly, the severity of the remaining accidents does not necessarily decrease. Additional studies based on a more optimistic criterion (i.e., the number of collisions) would be relevant in order to identify the exact causes of this behavior and show its repeatability in different use cases. This raises questions about the reaction and the decisions to be made by embedded applications. Is it better to allow collisions to minimize the rate of serious injuries, or is it imperative to minimize the number of collisions at the risk of fatalities?

Additional theoretical studies have been carried out (Giang et al., 2015) concerning the capacity and energy of message transmission for *ad-hoc* vehicle networks (VANET). Theoretical models have been developed in order to be able to approach spatial reuse in a precise manner, and to analytically calculate the optimal distance between the transmitters for good communication. Beyond this problem of theoretical network capacity, this study allows us to evaluate the limit capacity of a network to ensure a certain level of quality of communication

for V2X applications by taking into account interference, the SINR (Signal / interference and noise ratio), and the error rate in the frames. All these models can be used as a first tool for sizing the communication means for safety applications (Giang et al., 2015). In fact, the more information is transmitted "practically" simultaneously in the same spatial area, the more message "collisions" will lead to loss of communication. It is therefore important to be able to propose dynamic VANET organization strategies to optimize the capacity and effectiveness of communications. The works of Zhang and Cassandras (2019) also showed how the use of communication systems in a traffic system could reduce energy consumption.

## 3. IMPACT OF CAV AND AD ON SAFETY

How could the mobility ecosystem be defined? From a high-level overview, this complex system can be summarized with the following definition: the road ecosystem is made up of humans/users who use/interact/cooperate with technologies and mobility means on dedicated and adapted infrastructures to move efficiently and optimally according to four main criteria (Safety, Energy and pollution, Mobility and traffic, Comfort and health) for personal or economic goals. For each level, domain, and key components (KC), research is currently ongoing to improve the efficiency of mobility means with new technologies.

**Figure 3** gives an overview of this road ecosystem with a set of existing researches dedicated to the use, improvement, management, study, and modeling of the four key domains: the users (vulnerable and non-vulnerable), technologies (vehicles, sensors, hardware, and software architectures), infrastructure (new generation of road with new functionalities, communication means, smart road signs, etc.), and mobility's rules, regulations, and strategies. Of course, these four domains are inter-dependent and are an active part of cities, clusters of cities and their suburbs (agglomerations), and territories. The research works on each domain have for main task to optimize the mobility means with respect to three key issues (safety, energy, and mobility/traffic) and an additional one about comfort and health. Acting on one of these issues generates a positive or negative feedback on the other ones. OREED represents the 5 KCs (Obstacle, Road, Ego-vehicle, Environment,

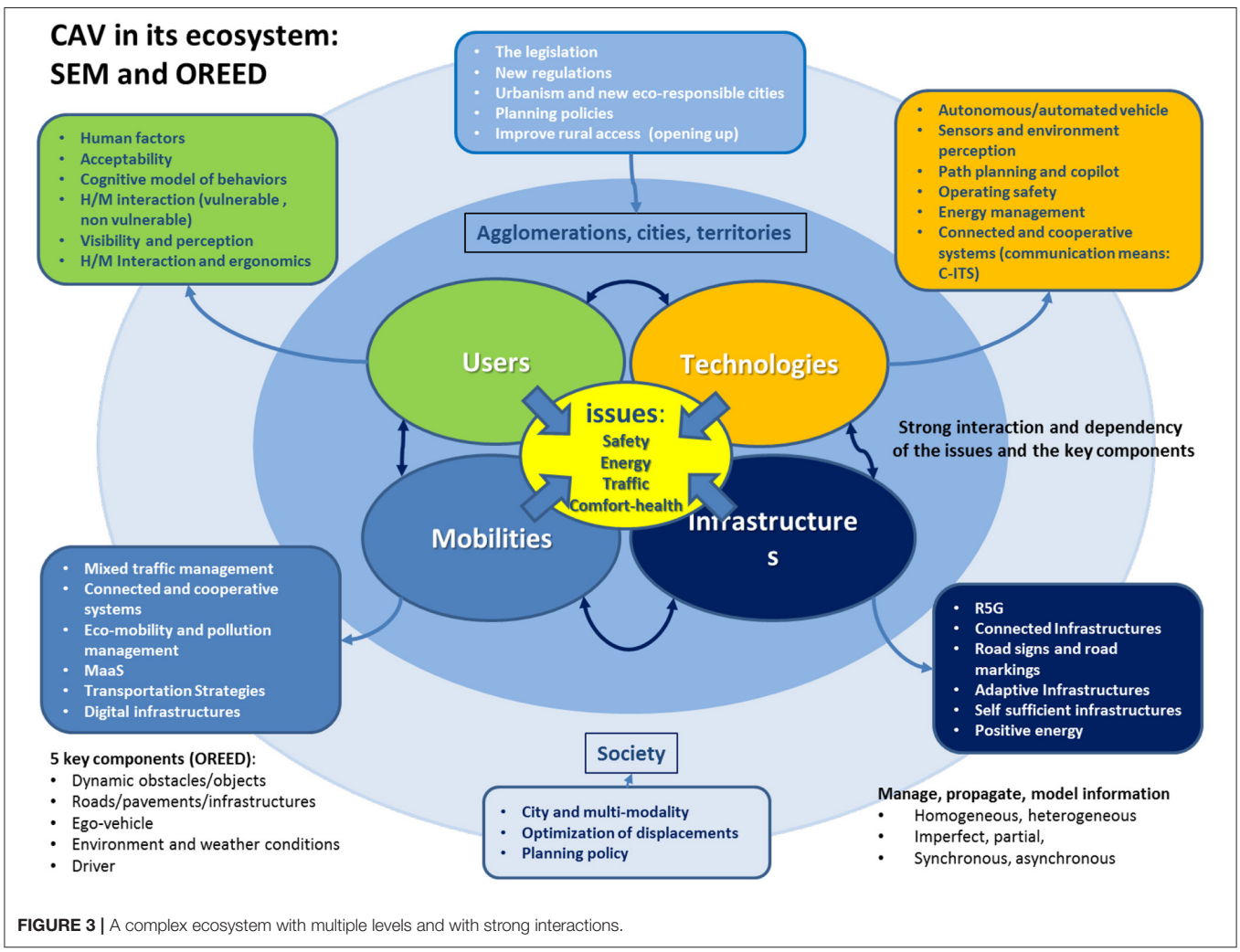



**FIGURE 3 |** A complex ecosystem with multiple levels and with strong interactions.

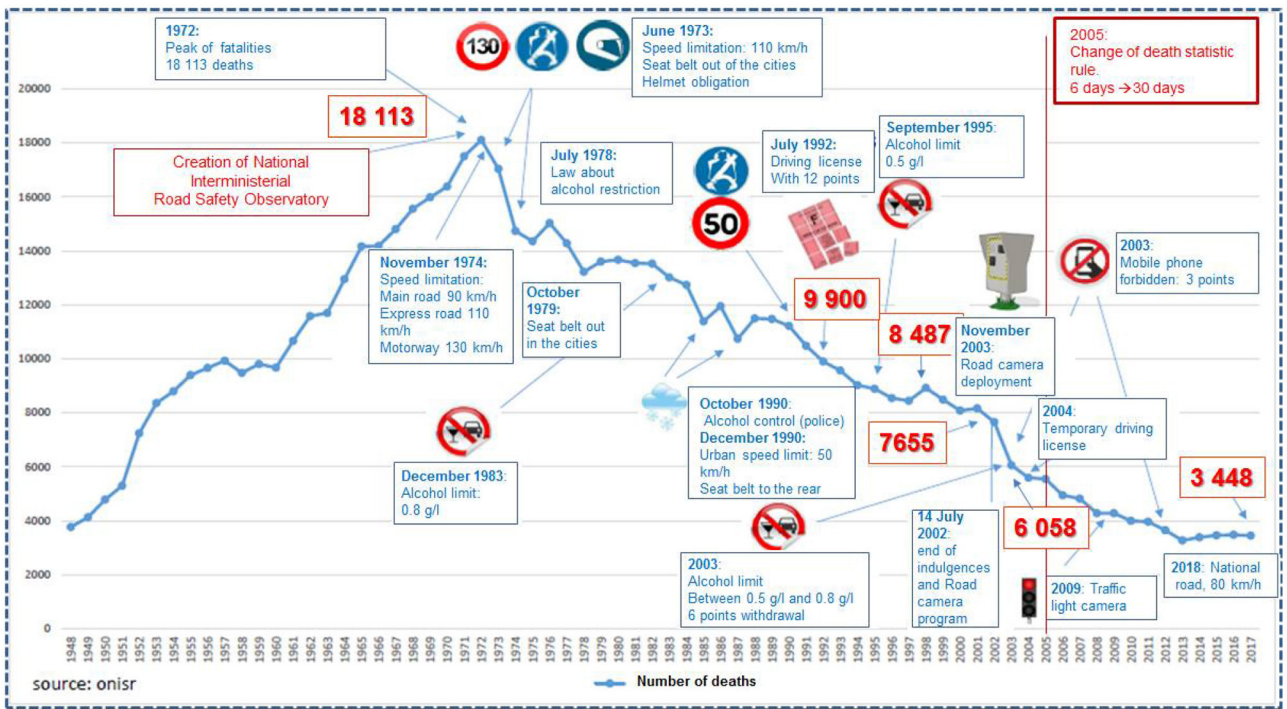
and Driver) needed to build the perception maps. It is important to keep in mind that the new generation of ADAS needs to find a relevant, efficient, and adequate balance between these issues. By reducing perception/decision/actions errors, CAVs could potentially reduce trauma and deaths from road crashes (Fagnant and Kockelman, 2015).

## 3.1. The Driver as the Main Contributing Factor to Crashes?

Recent statistics from the European Commission about road crashes (European Commission, 2019) show an important issue with 1 million road crashes per year, 1.4 million injuries per year, and 25,600 fatalities per year. Worldwide, road crashes cause 1.35 million fatalities and 20–50 million seriously injured or disabled each year [World Health Organization, Road Traffic Injuries, 2019 (https://www.who.int/health-topics/road-safety)]. From French statistics (**Figure 4**), it can be concluded that with the application of specific interventions, a plateau of fatalities has been reached for a couple of years with an average of 3,400 fatalities per year. But if injured people are taken into account, the figure is higher with 70,000 fatalities and injuries. It is a huge cost for the society.

What is the real responsibility of the human in these accidents? Based on the numerous statistical studies carried out over the past decade on the crash causation in North America, Europe, and Australia, it appears that the main contributing factor to road crashes is the driver. Human error is a contributing factor in 93% of crashes (NHTSA, 2008, 2015). Errors could occur at perception, interpretation, evaluation, decision, or action levels.

More precisely, the driver may lack visibility or may, due to the complexity of road situations, have a raw and/or hasty entry of information, leading to a misunderstanding and a wrong scene interpretation. This is of course adds to the problems of deliberate traffic violation, alcohol or narcotics consumption, driver inexperience, and problems of fatigue, hypo-vigilance, monotony, or even distraction. From NHTSA (2015) (US stats), crash reasons attributed to driver behavior mainly focus on Recognition errors (41%), Decision errors (33%), Performance errors (11%), Non-performance error like sleep, hypo-vigilance, monotony (7%), and other causes (8%).




| | Pedestrians | e-Scooters | Cyclists | Mopeds | Motorcyclists | Car users | LCVs | HGVs | Public Transport | Other users | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010 | 485 | | 147 | 248 | 704 | 2117 | 146 | 65 | 4 | 76 | 3 992 |
| | *12%* | | *4%* | *6%* | *18%* | *53%* | *4%* | *2%* | *0%* | *2%* | *100%* |
| 2018 | 471 | | 175 | 133 | 627 | 1637 | 92 | 44 | 3 | 66 | 3 248 |
| | *15%* | | *5%* | *4%* | *19%* | *50%* | *3%* | *1%* | *0%* | *2%* | *100%* |
| 2019 | 483 | 10 | 187 | 134 | 615 | 1622 | 98 | 36 | 4 | 55 | 3 244 |
| | *15%* | *0%* | *6%* | *4%* | *19%* | *50%* | *3%* | *1%* | *0%* | *2%* | *100%* |

**FIGURE 4 |** Road crashes fatalities and injuries trends in France (National Inter Ministerial Road Safety Observatory: ONISR).

The human-related errors demonstrate a huge potential in car fatalities and injury reduction. The initial idea was to propose embedded system in order to limit the impact of the human failure and to mitigate or avoid the collisions and/or ego-vehicle crashes. This is the topic of the L1 and L2 marketed functions. But it is also clear it is not enough. The second idea is to develop PADAS (Partially Automated Driving Assistance Systems) and automated systems to replace the driver in controlled road environments. But now, the question is about the real capability of the "copilot" to improve the road safety. In the European H2020 project MANTRA (Penttinen et al., 2019), the authors tackle this research question. In fact, the efficiency of automated systems will depend on how safely AD functions could carry out the driving task they are designed for. But in specific and critical situation, the automated system should have the ability to self-disengage to give back the driving task to the driver. Moreover, in L4 and L5, the system should guarantee it could both safely reduce human errors but also be tolerant and robust to system failures (sensors, hardware and software systems)(OECD/ITF, 2018).

Is it relevant to replace human driver by automated functions that copy human tasks and behavior? Under what conditions and configurations is it useful? According to Wickens et al. (2003) and ITF/OECD (2018), a first set of responses are given and are coherent with previous paragraphs:

- In dangerous situations or configurations that prevent the human driver from carrying out a driving task (alcohol or narcotics consumption, fatigue, hypo-vigilance, monotony, or even distraction).
- In specific situations where it is impossible for human driver to carry out the driving task [night-time sensing, strong adverse weather conditions (rain, snow, and fog)].
- In a specific situation where it is difficult for the human driver to carry out a driving task (scene misunderstanding and interpretations, very fast reaction times needed).
- Just for the pleasure to travel in an automated vehicle.

According to ITF/OECD (2018), the current deployment of AD functions seems to be mainly motivated by all these different measures improving road safety. The comparison of human and Hardware/Software performances in various aspects is summarized in the **Figure 5**. Safety considerations in automation levels L2 to L4 are the main issues in the safe handover from automated systems to the human driver when the system could not perceive/interpret/understand its environment with a high level of accuracy, confidence, robustness, and reliability. Another issue is how to efficiently manage the handover of the driving task when the vehicle is simply approaching the end of its Operational Design Domain (ODD). The following issues need to be addressed when assessing the potential safety effects of the use of AD systems (ITF/OECD, 2018; Noy et al., 2018).

| Aspect | Human | Hardware/software system |
|---|---|---|
| **Speed** | Relatively **slow** (Reaction time: approximately 500ms) | **Fast** (lower than 100ms) |
| **Power output** | Relatively **weak** (20 watts for the driving task), variable control | **High power** (>200 w), smooth and accurate control |
| **consistency** | **Variable, fatigue** plays a role, especially for highly repetitive and routine tasks (vigilance decrease, monotony appearance) | **Highly consistent** and repeatable, especially for tasks requiring **constant vigilance** |
| **Information processing** | Generally **single channel**. Difficult to have several conscious tasks in same time (issue of resources allocation) | **Multi-channel, simultaneous processing** |
| **Memory** | Best for **recalling/understanding principles and strategies** (low accuracy), with flexibility and creativity when needed, high long-term memory capacity (but with a degradation of information accuracy) | Best for **accurate, formal information recall**, and for information requiring restricted access, high short-term memory capacity, ability to erase information after use |
| **Reasoning** | **Inductive and handles ambiguity well**, relatively easy to teach, slow but accurate enough results, with good error correction ability. | **Deductive** and **does not handle ambiguity well**, potentially difficult or slow to program, fast and accurate results, with poor error correction ability (difficult to assess the level of reliability and robustness). Machine learning and deep learning as a solution (weakness with intentional interference and disturbances) |
| **Sensing** | **Large** (120°) but accurate in the center and blur on each side (movement perception), **dynamic ranges** for each sense (assessment of the range and speed), **multifunction**, able to apply judgement especially to **complex or ambiguous patterns** (but capability obtains with a long-term training) | **Superior at measuring or quantifying signals, poor pattern recognition ability** (especially for complex and/or ambiguous patterns), able to detect stimuli beyond human sensing abilities (e.g. Infrared, electromagnetic, ...) |
| **Perception** | **Better** at handling **high variability** or **alternative interpretations**, vulnerable to effects of signal noise or clutter | **Worse** at handling **high variability** or alternative interpretations, also vulnerable to effects of signal noise , clutter, bias, .... |

**FIGURE 5 |** Fitts list of strengths and weaknesses of both Human and embedded system (sensors/computer/processing) across various criteria according to ITF/OECD (2018), Schoettle (2017), Cummings (2014), and de Winter and Dodou (2014).

- Task allocation: Which tasks are left to the humans, and which are handled by automation?
- De-skilling: Lack of practice or imperfect situational awareness leads to reduced skills and may hence cause delays for humans to carry out the driving tasks when required.
- Cognition: Lack of cognitive engagement in the driving task leads to lower levels of situational awareness, and hence longer reaction times if the AD function disengages.
- Control: Driving is a learned skill; less time spent driving can lead to worsening skills in handling the vehicle.

However, these results are often questioned, in particular with regard to the methodology used, based on an analysis of the direct reports of accidents by police units which often judge drivers for insurance reasons. It would be entirely possible, by carrying out a detailed analysis, to find, in certain errors of perception or decision by drivers, an origin linked to infrastructure. However, there is still a fairly broad consensus that the driver is primarily responsible for accidents. Also, this is consistent with other areas of transport, such as aviation, where 85% of accidents are due to the pilot as shown by Li's work (Li et al., 2001) in 2001 on the basis of more than 27,000 accidents. Moreover, there is also the field related to the creation of new typologies of crashes because of the interaction between CAV and human. Less driver experiences reduce the control capacities of human drivers.

## 3.2. Driving Assistance as a Solution to Mitigate Accidents Risks

### 3.2.1. Advantages of CAV Deployment

It is therefore this observation that gave the idea that it is essential to reduce the number of accidents and to minimize the risk of a road situation. To reach this goal, it would be necessary to provide the driver with both informative (alerts, instructions, and expertise) and active (automation, delegation, and sharing of conduct) assistance. These assistances must then make it possible to remedy, at best, the limits of perception, action, and driver failures. These driving assistances necessarily involve a dynamic and adaptive perception of the environment and the construction of cooperative local and global dynamic perception maps integrating an assessment of the KC attributes. Having information on the state of all these KCs, then ensures a sufficiently comprehensive perception to be usable by a large number of on-board "short-term" security applications.

In Benson et al. (2018), the authors present results about potential reductions in crashes, injuries, and deaths from large-scale deployment of ADAS and by extension AV. In this paper, the technologies examined [forward collision warning (FCW), automatic emergency braking (AEB), lane departure warning (LDW), lane keeping assistance (LKA), and blind spot monitoring (BSM) systems] are estimated to have the potential to prevent a combined total of approximately 40% of all passenger-vehicle crashes, 37% of injuries that occur in crashes involving passenger vehicles, and 29% of all deaths in crashes that involve passenger vehicles. FCW/AEB and LDW/LKA systems were each estimated to have the potential to help prevent approximately 14% of all motor vehicle crash fatalities. However, FCW/AEB systems were estimated to be relevant to more than four times as many crashes and injuries as LDW/LKA.

The European project eIMPACT (eIMPACT project, 2008) (**Figure 6**) has shown the great safety potential of ADAS deployment. This project has studied and assessed the expected reduction in fatalities in Europe in the high penetration rate scenario in 2020, as well as the potential reduction if all vehicles and roads would be equipped. Results show that few systems

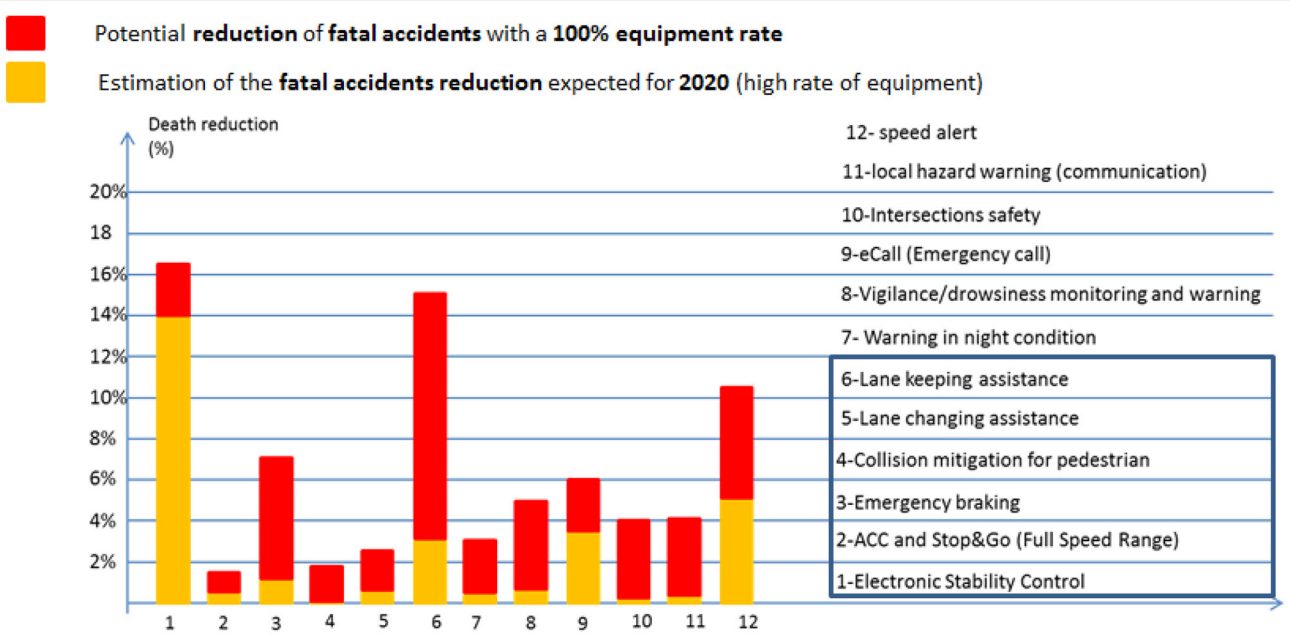



**FIGURE 6 |** Benefit (in percentage reduction in fatalities) of 12 ADAS. Assessment made in eIMPACT project (eIMPACT project, 2008) for 2020 extrapolation scenario.

have a real and strong impact on safety improvement. But some of them have a small impact. As a benchmark, each percentage reduction in fatalities represents approximately 230 fatalities. In the case of ESC in the 2020 high rate of equipment scenario (14%), 3,253 fatalities would be avoided at the penetration rate of about 75%.

For the cooperative systems using infrastructure, eIMPACT also shown that the potential of eCall (implying 100% penetration for a fair distribution of infrastructure equipment costs) represented a significant reduction of fatalities and severe injuries. The difference in penetration rate explains the large differences between the 2020 high scenario and the potential scenario for some systems, such as the Lane Keeping System. But it is necessary to stay prudent with these data because this project made a 10-year projection.

From the existing applications 1 to 6 presented in **Figure 6** and good monitoring/decision/path planning strategies, it is theoretically possible to design an efficient copilot function. For instance, in this study, which is based on simulation stages and in specific critical situations, a huge benefit can be remarked on in term of safety and fatality reduction if all the vehicles are equipped with the identified set of ADAS.

Fildes et al. (2015) provides some more recent results about the real impact of Low Speed AEB technology of the crash reduction. He highlights that this technology led to a 38% reduction in real-world rear-end crashes. Moreover, they affirm there was no significant difference between urban and rural crash benefits. Moreover, Low Speed AEB technology needs widespread fitment for maximum benefits.

Although these driver assistance systems are considered, the ideal solution for reducing the number of accidents, the first developments of AVs, representing the pinnacle of driver assistance systems, has faced many cases of accidents, some of them fatal. The works of Morando et al. (2018) using traffic simulation (Vissim software) showed that the number of potential safety conflicts will be reduced whatever the test scenario is. However, despite millions of kilometers traveled in automated mode, Waymo, Tesla, Delphi, Audi, and others have already faced serious accidents such as the fatal accident of Uber in 2017 which put its AV program on hold or even the Tesla accident in 2016. Noy et al. (2018) also claims that safety benefits of AD and human driver errors are often exaggerated and it should be more relevant to better analyze how the road infrastructure or the technology-induced human driver errors.

### 3.2.2. Is CAV Really Reducing Collisions and Improve Safety?

In 2015, according (Schoettle and Sivak, 2015), AVs had statistically five times more accidents than vehicles driven by human beings. It is worth mentioning that this study focused on prototype vehicles. Automated features are still under development, and the crash rate may therefore be higher. Also, according to Hsu (2017), an AV should drive more than 250 million miles without incident to be considered as safe as a standard vehicle. At the time of its fatal accident in 2016, the Tesla had only traveled 130 million miles. CAVs are still under development, therefor the access to real crash database involving SAE level 3 or more CAVs are limited. Trials, worldwide, depict the current state of the art in terms of automated driving systems. In **Figure 7**, Favarò et al. (2017) found that CAVs were over-represented in the front position during rear-end collisions. The detailed database from the California Department of Motor Vehicles (CaDMV) shows the collision often results from human driver misunderstanding of the CAV behavior. Events such as "emergency braking when nothing happens in the environment" or "stopping at an intersection when the roads are clear" are mentioned in the collision report. Such collisions occur mostly at low speed with no injuries reported.

At the time of this study, the CaDMV (Californian Department of Motor Vehicles) published 26 reports. Moreover, several methods and approaches exist to estimate the impacts of AD and their limitations. In fact, three types of methods are used: the first approach employs historical crash data to investigate the potential impact of CAVs, the second uses integrated multi-level custom-built simulation framework to simulate CAVs, which generally incorporates traffic simulator, and the last one uses traffic micro-simulation software and its extensions. It is also mandatory for all experimenters to report disengagements in less concise reports. Dixit et al. (2016) and Favarò et al. (2018) (**Figure 7**) evaluate from a component of the dataset ($n$ = 2,616, on nearly 6,000 now) events resulting in a disengagement. System failure (52%) and Human factors (30%) refer mostly to the understanding of the situation and the interaction between users. They are the most predominant reasons (reckless driver, cyclist, pedestrian, or take over from the expert driver because of safety and discomfort). The disengagement mostly occurs in an urban environment (street 49%) in good weather conditions (noted as clear 82%).

Of course, this result does not formally demonstrate that the Tesla vehicle is more dangerous in automated mode than in normal mode, but it demonstrates that one should not have blind faith in these systems.

Also, theoretical studies on the AV show the risks associated with changing the driving mode, which is very complex to implement in specific cases. It is indeed difficult to ask the driver to take over by hand at any time, even when the vehicle performs all of the driving tasks for him. This therefore poses a technical problem of interactions between humans and machines but also a legal problem of knowing whether one can really ask a passenger to become a driver during a journey while the vehicle is moving. Also, this transfer task requires at least 8 s to be completed (Lu et al., 2017), until the user is physically ready to regain control of his vehicle.

In Dixit et al. (2016), a study made to identify the type of accidents involving an AV (**Figure 8**) clearly showed that the main causes of the crashes involving an AV are due to system failure or driver inexperience.

Finally, from this point of view, V2X systems can provide a solution making it possible to partially or entirely overcome these problems as has been demonstrated in the work of Demmel (2012) and Gruyer et al. (2013).

To understand why the AV can, in some cases, be more dangerous than a conventional vehicle, it is necessary to give details on its constituents that can lead to a danger.

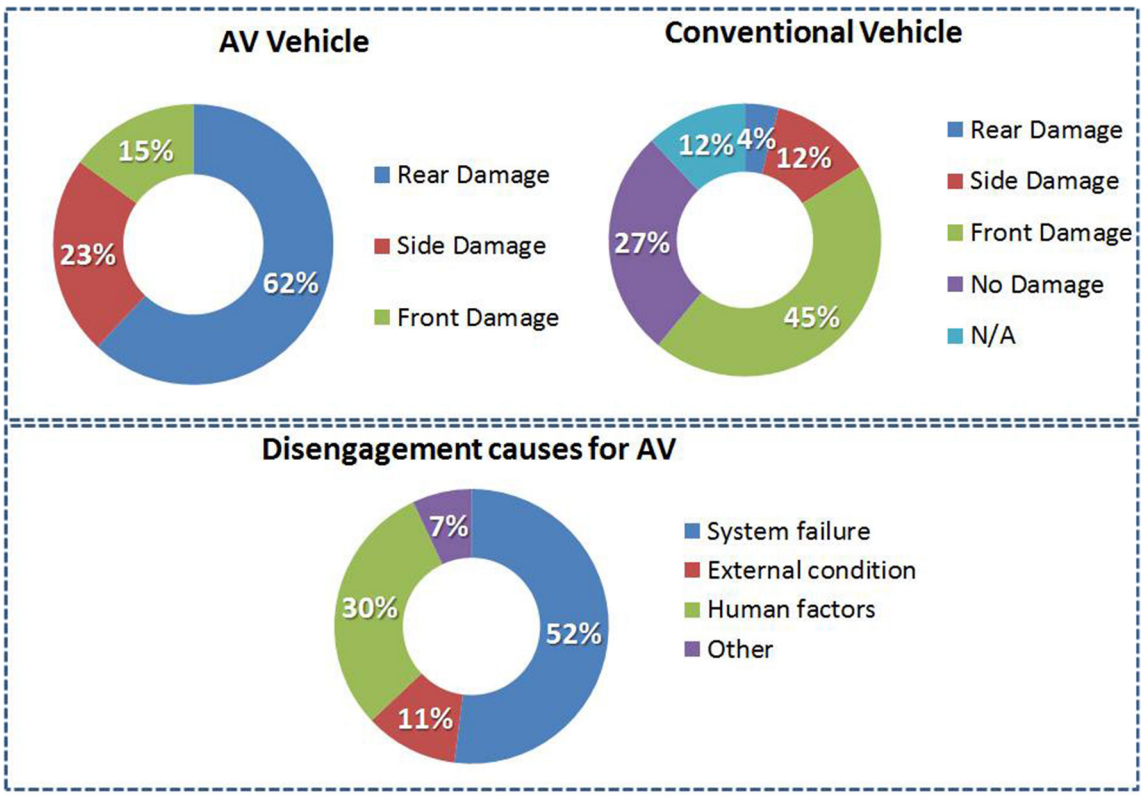



**FIGURE 7 | (Top)** Automated vehicle crashes and damage locations (Favarò et al., 2017), and **(Bottom)** disengagement of embedded automated systems in reports from Dixit et al. (2016) and Favarò et al. (2018).

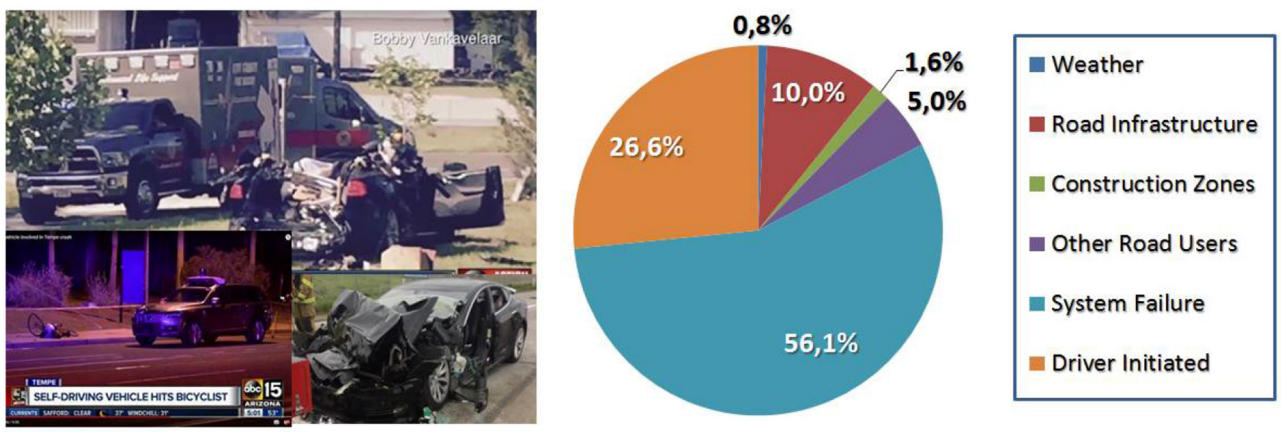



**FIGURE 8 |** AVs crashes and identification of the causes.

- Embedded Sensor technologies: Enough reliable new technologies are yet to be developed (laser depth camera, Event camera, multi-modal Radar, etc.), and there are issues about sensors operating in adverse weather conditions (heavy rain interferes with roof-mounted laser sensors, snow can interfere with cameras, etc.).
- Operating safety: Monitoring of embedded systems (computers / sensors / actuators / algorithms) is necessary to detect and to identify malfunctions and failures. Even just a minor glitch could cause worse crashes than anything that human error might bring about.
- Sensitivity to hacking: Getting into the vehicle's software and controlling or affecting its operation would be a major security issue.

In AD applications, the more critical part is the sensor part. Without an adequate perception level, it will be impossible to

achieve an efficient, reliable, and safe automated driving task. But what about this sensor layer and about the capabilities of the existing technologies? Are they reliable enough in all conditions and road situations? The next section tries to give an answer.

### 3.2.3. Is Embedded Sensor Technologies Enough to Guarantee Data Quality?

From **Figure 9**, it is possible to have a clear overview of the different frequency/wavelength intervals used by the different information sources technologies with their potential overlapping. But now, what are the issues encounter by each technology in each frequencies bands? The **Figure 10** gives a first overview of the advantages, disadvantages, limits, and weaknesses of the different technologies of embedded sensors. It is clear that only one type of sensor could not guarantee a level of quality enough high for the AV deployment. The development of new technologies, new data processing and filtering, and new multi-sensors data fusion architecture will be essential.

In Gruyer et al. (2017), a study is proposed about the embedded sensors technologies used in perception,

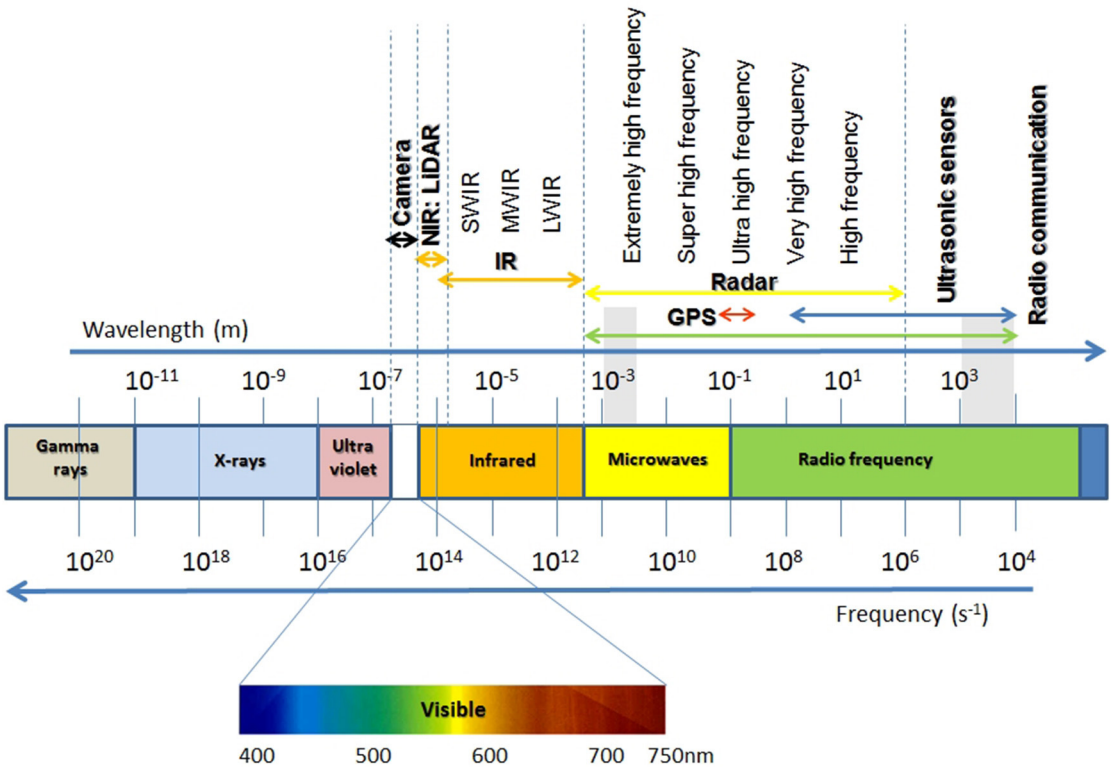



**FIGURE 9 |** Electromagnetic spectrum: a better understanding of the operating range of each type of information sources used in CAV development.

| | | | Detection objective | | | | Identification objective | | | | Main interest | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| type of information | Frequency | Wavelength | Benefit in sunlight | Benefit in darkness | Through atmosphere | Through fog and rain | Vegetation vs. Object | Human vs. Object | Human vs. Vegetation | Metal vs. Other | | |
| Sensor technology | | | | | | | | | | | | |
| Camera (visible) | VIS | 380 - 740nm | ☑ | ☹ | ☑ | ☹ | ☑ | ☹ | 😐 | ☹ | Sunlight | Sensing windows |
| LiDAR | NIR | 865nm - 1550nm | ☑ | ☹ | ☑ | ☹ | ☑ | ☹ | 😐 | ☹ | Vegetation | for the robotic |
| Infra Red Camera | SWIR | 1.4 - 3 µm | 😐 | 😐 | ☑ | 😐 | 😐 | ☹ | ☹ | ☹ | Eye safe | vehicle |
| Infra Red Camera | MWIR | 3 - 5 µm | 😐 | 😐 | ☑ | 😐 | 😐 | ☑ | ☑ | ☹ | Human | Possible extension |
| Infra Red Camera | LWIR | 8 - 14 µm | ☹ | ☑ | ☑ | 😐 | ☹ | ☑ | ☑ | ☹ | Human | Possible extension |
| Infra Red Camera | 3 Thz | 100 µm | ☹ | 😐 | ☹ | ☹ | 😐 | 😐 | ☑ | ☑ | | Possible extension |
| Millimeter sensor | 0.3 Thz | 1 mm | ☹ | ☹ | ☑ | ☑ | 😐 | 😐 | 😐 | ☑ | Fog and rain | Possible extension |
| RADAR | 79 - 24 Ghz | 3.8 - 12.5mm | ☹ | ☹ | ☑ | ☑ | ☹ | 😐 | 😐 | ☑ | Cars | Robotic vehicle |

**FIGURE 10 |** Trends of perception technologies for CAVs. Green color means *Yes*, Red color means *No*, and Orange represents *Maybe* (Tschudi and Girardin, 2018).

information processing and modeling stages. In this paper it is clearly demonstrated that sensors and perception methods/approaches/modules are critical stages in the AD application development. In this study, the weakness and limitations of sensors and perception architecture are highlighted. In Brummelen et al. (2018), a complementary survey of current and future works and technologies of perception applied to the CAV is also proposed. These two review papers give a clear overview of the main issues and challenges to be addressed to guarantee a good enough perception quality for CAV.

Recently, new methods and applications have been proposed for two complementary objectives. The first objective is about accurate and certain objects and situation detection and identification. The methods which are now developed are mainly based on the use of IA and Deep Learning methods to be more efficient in the environment segmentation and semantic area recognition. Unfortunately, even if, in the majority of cases, the results are good enough, some specific configurations (intentional or unintentional disturbances) provide failures. Moreover, these methods are based on a training stage. This implies that applications learn only the features included in the training dataset, and it needs to use a very large and representative database. The second objective addresses the fault, drawbacks, and failures detection and identification.

#### 3.2.4. Is Complexity of Data Processing Too High?

In this context, is there any hope that the AV will become sufficiently safe? If a comparison of this objective is made with what is achievable in a benchmark sector (aviation), it is clear and obvious that the AV already contains much more on-board technology than an airplane. A current premium vehicle can thus contain up to 100 computing units, which is more than an Airbus A380; a Boeing 787 Dream liner will contain 6.5 million lines of code, and an AV can reach 300 million showing that the complexity is well superior (McCandless, 2015). This difference in the number of lines of code, resulting from the differences in terms of the environment, interactions with other users and the types of objects to be detected, does not mean that as long as security is treated at the same level. For the moment, it is likely that the developers of AVs will focus on the feasibility of autonomy and that safety will come later. Many researchers are thus satisfied with 95 to 98% efficiency of their algorithms when the reliability should reach 99.9999% to be identical to that of a human being. From the estimate of ARM (2019), there are probably 1 billion lines of code that will have to be embedded to obtain a fully automated car.

## 4. ENERGY, POLLUTION, AND TRAFFIC: COMPLEMENTARY AND ADDITIONAL CHALLENGES TO SAFETY

Safety is not the only important issue, and for the last 20 years, a great effort has been set on the energy management and the traffic regulation. On one side, we are facing global climate change induced by human activities, especially due to greenhouse gas emissions and on the other hand, air pollution became a serious threat to health. Every year, according to the WHO (World Health Organization), 4.2 million of fatalities are related to outdoor air pollution and a share of this pollution is due to the transportation sector.

Concerning $CO_2$ emissions, for instance, more than 60% of the $CO_2$ emissions are due to the SEDAN (in France more than 50%) (**Figure 11**). So an international decision has been taken to reduce the $CO_2$ emissions up to 130 grams per kilometers and this limit is going down year by year. To reach this goal, road KCs must be addressed. These KCs involved the ego-vehicle, the road, the obstacles, the environment, and the driver. The vehicle consumption is considering the three firsts. ADAS must consider conflicting parameters in the cost function to optimize as road safety, energy consumption, and time spent in the traffic. Moreover, in non-AD systems, the driver behavior could have a significant impact on the energy consumption, and the environment KC could provide an estimation of visibility distance and infrastructure singularities.

More and more the road network suffers from a strong growth of the vehicle density and of course of the traffic jams. So now in the development of the new ADAS, it is necessary to solve a multiple criteria and constraint equation involving the safety, the energy consumption, and the traffic. Unfortunately, these three constraints are very dependent.

Moreover, in the development of these new services and solutions, we need to estimate and to use the five KCs of the mobility system.

Then, to summarize, a very interdependent and complex system has to be handled with not only one safety objective but three interdependent objectives. So, in the development of the new ADAS, it is necessary to find the best balance between these three constraints to minimize the energy consumption and maximize the traffic efficiency without compromising (and even improving) the road safety.

### 4.1. Eco-Driving for Fuel Consumption Optimization

Recent research and studies over the past decade have shown than eco-driving applications could have has a major impact on fuel consumption for automated vehicles. In these recent studies, the use of real-time "eco-coaching" for human driver has shown a significant reduction of consumption between 10 and 20%. In the virtual copilot system, it could be relevant to apply a layer in the decision process in order to follow eco-driving best practices. Nevertheless, in an automated vehicle, some automated driving functionalities could affect the fuel economy even with the using of eco-driving modules. These functions that impact the eco-driving capability include adaptive cruise control, V2I communication, and V2V communication (for instance for platooning, risk assessment, extended perception, and warning). Studies have proven that a direct result of these functions is a reduction of the braking. For thermal motor, braking is a direct waste of energy, so any reduction in braking increases energy efficiency. With electrical engines, it is a bit different because of

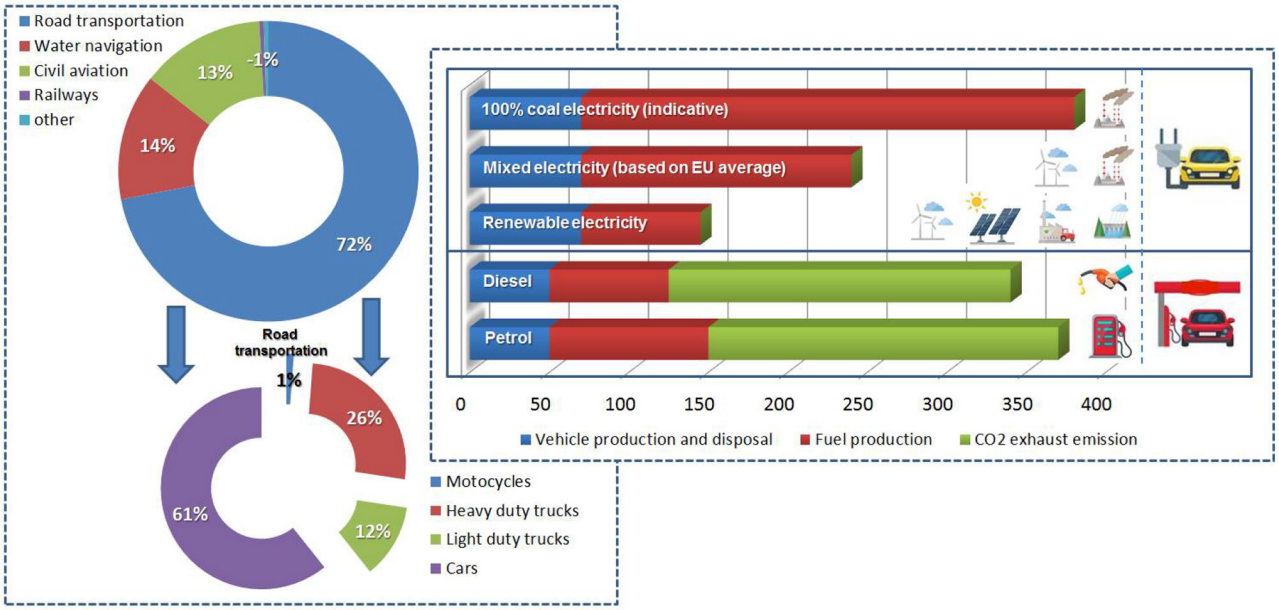



**FIGURE 11 |** $CO_2$ emission in the different mean of transport https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics. **(Left)** Emissions breakdown by transport mode (2016); **(Right)** Range of life-cycle $CO_2$ emissions for different vehicle and fuel types.

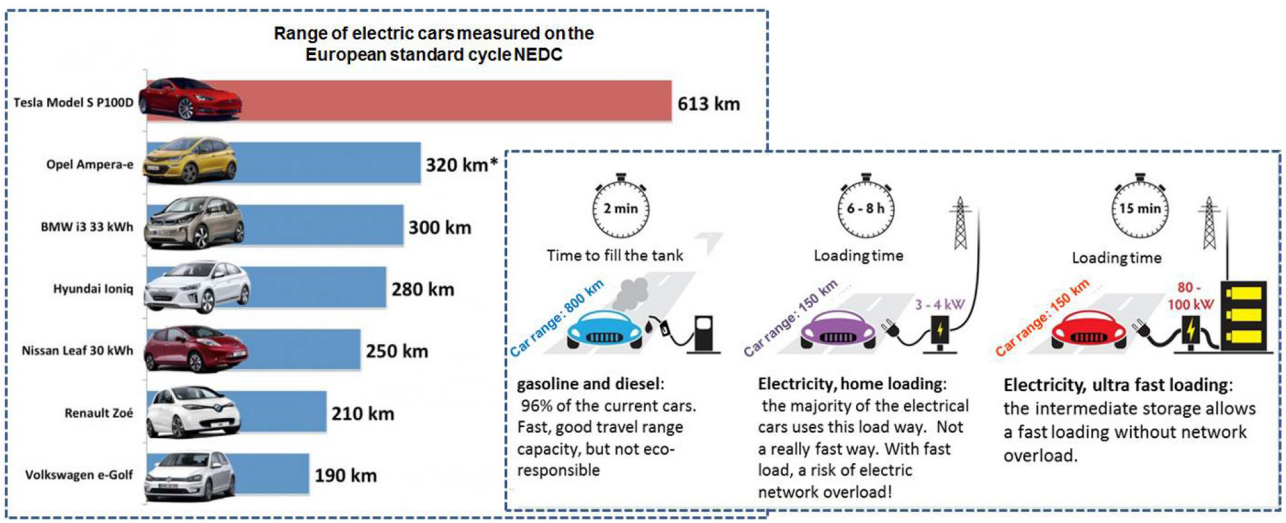



**FIGURE 12 |** Is electric mobility good enough in term of autonomy and energy loading time? **(Left)** Current electrical car autonomy. **(Right)** Different ways to load car battery with associated waiting time.

the regenerative functionality which collects the braking energy in order to reload the batteries.

Nevertheless, fuel consumption reductions could plateau due to congestion caused by the slower driving speeds and smoother accelerations inherent to eco-driving practices (Zia et al., 2016). In her researche, Freitas (2016) obtained a solution that allowed her to save up to 20% of energy.

In Mersky and Samaras (2016) some results show that AV following algorithms designed without considering energy efficiency can degrade fuel economy by up to 3%, while the use of specific and well-tuned strategies focused on energy efficiency could provide equal or slightly better results (up to 10%) than the existing EPA (Environmental Protection Agency) fuel economy test results. This remark suggests the need to

propose new approaches in fuel economy tests to better take into account the deployment of connected and automated vehicles. In addition, this tells us very clearly that the development of automated vehicles must not only be done from the safety point of view but must also take into account, very seriously, the energy management aspects.

## 4.2. Transportation Emissions on the Rise

Significantly reducing $CO_2$ emissions from transport will not be easy, as the rate of emission reductions has slowed. Other sectors have cut emissions since 1990, but as more people become more mobile, $CO_2$ emissions from transport are increasing. Efforts to improve the fuel efficiency of new cars are also slowing. After a steady decline, newly registered cars emitted on average 0.4 g of $CO_2$ per kilometer more in 2017 than the year before.

To curb the trend, the EU is introducing new $CO_2$ emission targets, which aim to cut harmful emissions from new cars and vans. MEPs adopted the new rules during the plenary session on 27 March. On 18 April, MEPs also approved a proposal to cut $CO_2$ emissions from new trucks by 30% by 2030 compared to 2019 emission levels.

Makridis et al. (2020) has made a recent micro-simulation about the impact of AV and CAV on traffic flow and $CO_2$ emission. The results show that with traditional car-following models AVs seem not facilitate Traffic Flow, and generate the highest $CO_2$ emission values per kilometer. CAVs increase the capacity of the network and therefore during peak hours, they generate more emissions in absolute values. Moreover, the differences in emissions per kilometer driven between CVs (Conventional Vehicle), AVs, CAVs do not exceed 6%. Unfortunately, this work is questionable because it uses Gipps model (collision free) and the AIMSUN's micro-simulation, which is not really reliable for this type of study. Moreover, the communication is too simple (also perfect communication). About acceleration parameters, the authors use different values for the three types of vehicles.

## 4.3. Passenger Cars as the Main Polluters

$CO_2$ emissions from passenger transport vary significantly depending on the transport mode. Passenger cars are a major polluter, accounting for 60.7% of total CO2 emissions from road transport in Europe (**Figure 11**). However, modern cars could be among the cleanest modes of transport if shared (as opposed to driving along), but with an average of 1.7 people per car in Europe, other modes of transport, such as buses, are currently a cleaner alternative.

In this context, the main levers for action by driver assistance systems to reduce the impact on the environment are: The number of kilometers traveled, the efficiency of the vehicle-driver couple and external factors (traffic, road geometry, weather, etc.). Several studies have shown, in this sense, that driving assistance can reduce energy consumption by 5–15% under real conditions of use (Freitas, 2016; Fontaras et al., 2017). Also, optimizing the speed profile of an automated vehicle to ensure that it practices eco-driving is also an important step in reducing its energy use. Then, down-sizing reduction works on vehicles make it possible to reduce the vehicle mass and thus the size of the engine without compromising the passive safety of the vehicle. Finally, innovative mobility services such as car sharing or ride splitting make it possible to quickly reduce the number of kilometers traveled while limiting congestion. While these services improve the impact of vehicles on energy consumption, there is no evidence to suggest that automating them would further improve the situation. Several studies have thus been initiated to understand the impact.

Among the interesting solutions at this point, platooning can be cited. But Platooning applications must be based on communication systems to be effective. This strategy, which consists of placing several vehicles in a line with low inter distances, minimizes aerodynamic efforts. Consumption of follower vehicles can thus be reduced by up to 16 and by 8% for the leading vehicle (Lammert et al., 2014; Muratori et al., 2017). In Tsugawa et al. (2016), the relationship between the fuel saving improvement and the gaps within the platoon is given and confirm the previous results. These gains can be further increased by introducing automated vehicle control with low latency communications.

The works of Zia et al. (2016) and the US energy administration shows that many factors implemented in AVs could indeed reduce the total consumption of vehicles, but certain factors can also affect this consumption, such as vehicles maintained higher on the highway, new features present in vehicles (large screens, connectivity, etc.), the increase in journeys due to the reduction in costs and therefore the increase in demand and the new uses calling for new customers in the form of a mode transfer transport. The works from (Vahidi and Sciarretta, 2018) also assessed how AD could influence energy efficiency on a theoretical and mechanical point of view.

## 4.4. Is Electric Mobility the Solution?

More and more, the solutions to reduce the carbon impact of transportation means seems to be the hybrid, hydrogen, or electrical technologies. In terms of electrical technology, recent research has provided relevant and future solutions, such as the additional batteries rental concept. This solution is proposed by the start-up EpTender (https://eptender.com/). Moreover, new battery technologies have appeared, such as batteries with a solid electrolyte (Pr. Goodenough). This solution seems to have several advantages: an energy density three times higher than the lithium-ion batteries, no problem of battery burning, more robustness, compatibility with fast load systems, and the ability to operate up to –20 degrees Celsius. This new generation of battery with solid electrolyte is made from glass with an alkali metal anode that can be composed of lithium, sodium, or potassium. It is clear that the capacity and efficiency of the new generations of battery and their ultra fast loading will be strongly improved in near future (**Figure 12**). Nevertheless, it is relevant to consider the method of energy generation; for instance, in Australia (Queensland), a small electric car (Renault Zoe) could pollute more than a four-wheel Drive diesel car (**Figure 11**). Also, it is interesting to remark that a human driver has an energy consumption of approximately 2 watts while the embedded functionalities necessary for CAV will be upper than 200 Watts. In Baxter et al. (2018), an estimation made with only

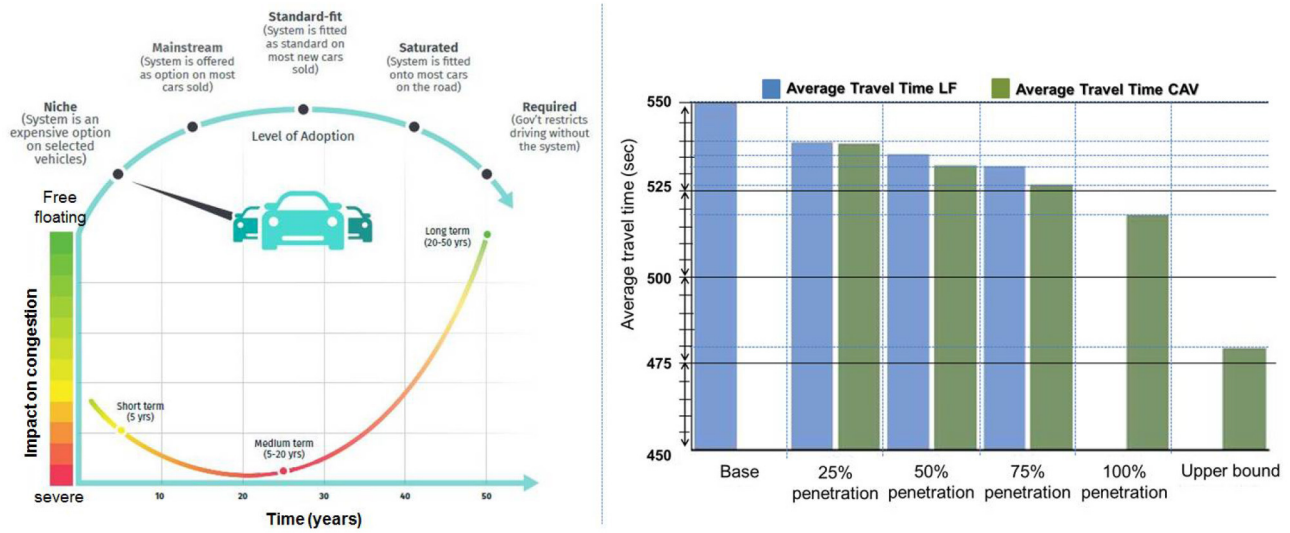



**FIGURE 13 |** Is CAV deployment an interesting solution in order to optimize traffic? **(Left)** Impact of CAVs deployment on traffic congestion; **(Right)** Impact of CAV on travel time saving (ATKINS, 2016).

one configuration taking into account embedded sensors and computer energy consumption is provided. This consumption is 200 watts for 3 LiDAR, 2 RADAR, 1 camera, 1 IMU with a GNSS, and 1 computer. For instance, the OUSTER's LiDAR 3D has a consumption between 14 and 20 watts. If we apply the sensor configuration (28 sensors) expected for L5 vehicle presented in Tschudi and Girardin (2018), the same energy consumption of at least 200 watts is obtained. So, from the energy point of view, the AV will be less efficient than human.

## 4.5. And What's About the Impact of CAVs on Traffic?

The approach to optimally manage traffic using communication technologies is also presented to overcome a number of difficulties that can be caused by AVs in terms of congestion and traffic.

A position aspect of CAVs on traffic congestion has been evaluated by Condliffe (2017) and Stern et al. (2018). In their experiment, they use 20 vehicles moving in a loop with only one automated vehicle. The goal was to try to minimize the traffic congestion effect. The authors of this experiment have shown that with a simple control law and a well-chosen strategy, the traffic congestion fully disappeared. Moreover, some other studies have proven that, in specific situations, the CAVs could improve the capacity of a road network and reduce the congestion and the wave effect of congestion (cooperative and connected platooning). In terms of cooperative platooning, however, some questions still have to be solved. Which strategies have to be applied in order to manage platoon entrance/exit? Which strategy must be developed and applied in order to change the platoon leader? How do we efficiently manage the interaction and cooperation within and outside of the platoons? (Konstantinopoulou et al., 2019). Which strategy do we use to negotiate and manage compromises in singular and complex situations like intersections and roundabouts?

Nevertheless, traffic could be coordinated more easily in urban areas to prevent long tailbacks at busy times. Commute times could be reduced drastically.

Speed limits could be increased to reflect the safer driving, shortening journey times.

The theoretical study of Friedrich (2016) is dedicated to the impact of AV on traffic and more specifically traffic capacity and stability. Macro traffic models have been used to show that traffic capacity would be increased up to 36% if all vehicles were automated. A different study from Lu et al. (2019) has found similar figures (23% increase of capacity) but using traffic micro simulation.

On the one hand, we are facing new situations where vehicles can have no occupants. If people who commute by car then send their car home because parking is too expensive near their place of work, then the traffic demand could therefore almost double. Some jurists (Muoio, 2017) have consequently already proposed the introduction of a tax on the kilometers traveled by AVs (0.025$ / mile).

Also, it is well-known that drivers do not respect safety distances in large cities. However, the AVs will initially be required to comply with them, which again risks increasing the length of congestion queues. Second, AVs will have more difficulty interacting with vulnerable users, thereby slowing traffic in areas with high pedestrian density.

In terms of the human factor point of view, automation of the mobility will reduce the driving skills of human drivers who therefore risk bringing additional problems in the event of mixed traffic whether it be in terms of safety, energy consumption, or fluidity of the traffic. For instance, recent studies (**Figure 13**) shows a worse view of the expected traffic conditions for the next decades with partial CAVs deployment rate. With mixed traffic,

the traffic congestion will be worse until a high level of CAV deployment. The same remark can be done for the average travel time which will not give a significant gain.

Finally, the deployment of automated vehicles will also allow many people with reduced mobility, and who could not drive and move easily, to have easier access to mobility. This will also be the case for teenagers and elders. Consequently, the risk of the large-scale deployment of the CCAM could be to strongly increase the number of vehicles on the roads network and to aggravate the traffic problems.

# 5. DISCUSSIONS

## 5.1. Trusting the Virtual Copilot and Its Capabilities

Watching the impact of the AVs on various objectives such as the environment, safety, or even traffic conditions independently provides initial information to understand the role of this technology. However, these same objectives are strongly correlated. A change in traffic conditions will immediately have an impact on energy consumption and road safety.

For example, when the technology for driving autonomously improves, the safety requirements to use them will decrease accordingly, generating new safety-related risks, such as very low inter-vehicular distance. This will clearly increase the road traffic capacity and reduce the energy use but will generate accidents risks. An interesting anthropological approach has been undertaken by Pink et al. (2020) to propose new frameworks for trust in AD. About these CAV capabilities and impact on traffic rules, the question is how to tune the copilot system and how to trust in this system? (ATKINS, 2016). For instance, if a high assertive behavior is applied then it means that a great confidence is given to the copilot, in this condition, the safety distance can be strongly reduced. What happens in case of a car failure? On the other hand, if an extremely cautious behavior is applied, then the capacity of road traffic should collapse and serious congestion situation could occur. Another time, it will be necessary to find the good balance between safety, energy, and traffic criteria.

## 5.2. Development of a New Generation of Road Infrastructure

In the deployment of the future automated mobility means and HQoS communication for transport applications and services, it is important to address the digital and physical infrastructures and what their future configurations and features could be.

The importance of the physical infrastructure and its link with the digital infrastructure has been emphasized by Ehrlich et al. (2016). Indeed, to move safely, AVs need to access accurate knowledge in terms of which road they are traveling on. AVs are expecting from infrastructure that it fulfills some requirement in order to maximize safety. In fact, the infrastructure needed to be "readable" by the vehicle. Ehrlich et al. (2016) investigates the concept of High Quality of Service Highway (HQoSH), and the main infrastructure features (and their metrics) were identified. Among them, lane marking, traffic light status, and road sign readability can be quoted. Moreover, road attributes (curvature, cant, slope, and skid resistance), geometric and weather visibility, and singularities detection (ruts, potholes, ruptures, and cracks) also are relevant. All these features are useful for vehicle stability and guidance.

At first glance, the technical challenge is to develop the relevant indicators that link the state of these infrastructure elements with the sensing capacities of the automated vehicles, and to develop maintenance strategies to maintain these indicators at a suitable level. In addition, because of the dynamics of change of certain infrastructure components, in particular due to weather conditions, HQoS of communication is again the solution to obtain a dynamic map of these indicators. This digital map is thus an additional layer of the physical infrastructure, initially designed for the human driver. One might speak about a hybridization of the physical infrastructure.

This is where the problem becomes complex. Due to the constant evolution in sensor development (or the absence of technical standards of AVs technologies), it is therefore difficult to develop standards for the infrastructure that follow the same development as the strategic goals of road owners, namely, reducing the direct costs and the environmental footprint of existing road infrastructures and road transport. There is thus a permanent conflict between two policy objectives: road asset management and road innovation. This conflict can be solved by changing the regulation or by finding innovative solutions, which combine cost reduction and problem resolutions (Hautière et al., 2017).

This is the aim of the 5th Road Generation (R5G) research program (Hautière and Bourquin, 2017) (**Figure 14**) developed by University Gustave Eiffel (r5g.ifsttar.fr), linked with the Forever Open Road program (www.foreveropenroad.eu). These programs aims at designing and building demonstrators following a system approach of a new road generation that takes into account all challenges related to road infrastructures and gathers the best ideas all over the world (Lamb et al., 2012; Hautière, 2019). While aiming at easing the deployment of electric vehicles and automated vehicles, the goal of the program is to reduce the total cost of ownership of road infrastructures of 30% by 2030 while meeting the multiple goals of the different societal transitions.

The strategy is to put into synergy three elements in a gradual manner: The Automated Road, the Adaptable Road, and the Resilient Road. The timing is as follows: Individual components testing from 2010 to 2015, subsystem experimentation from 2015 to 2020, and system integration after 2020.

### 5.2.1. The Automated Road

The challenge of the automated road is to make the most of technologies to manage road traffic, and to support the development of new forms of mobility like CAVs.

The first step is to put in place new traffic management strategies. These are based on the growing connectivity and automation of vehicles (Ehrlich et al., 2016; Ehrlich, 2017a,b) in order to improve the performance of the road system, increase its profitability, and make journeys safer and more reliable. They make it possible to optimize the use of infrastructures by taking

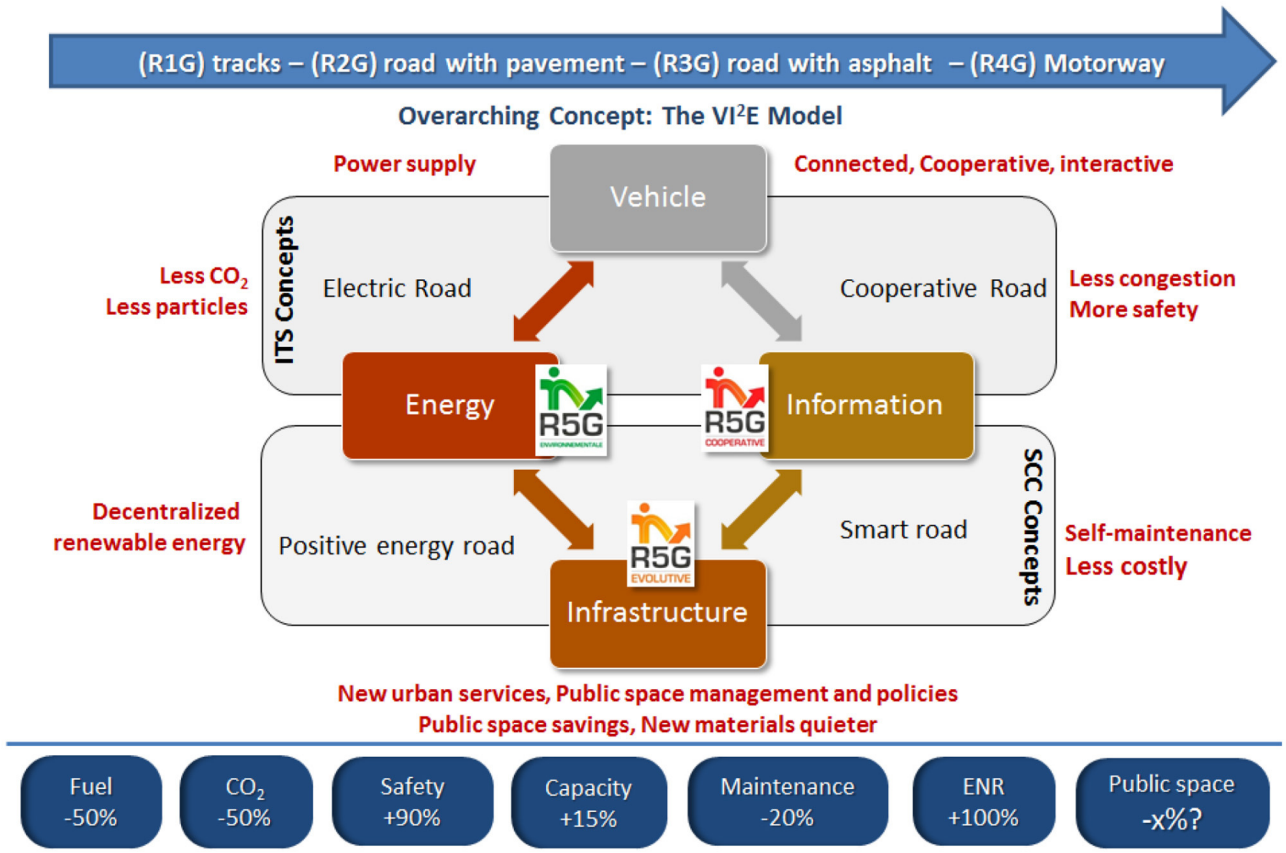



**FIGURE 14 |** R5G, the 5th Road Generation for a smart, sustainable, and resilient infrastructure useful for CAVs deployment.

advantage of cooperative ITS, vehicle convoys, tariff variations or even personalized traffic information. Among the current challenges, three can be quoted: The first one is the construction of collective optima combining collective measures of traffic management and individual nomadic services, the second one is about the construction of reliable data chains, and the last one address the coexistence of automated and conventional vehicles.

The next step is to deploy roadside systems merging data from sensors integrated in infrastructure and on-board vehicles. The goal is to be able to use existing sensor systems while integrating new generations to build more accurate and less expensive traffic data acquisition (Besnier et al., 2014). This requires open and standardized interfaces to put suppliers in competition and cooperate between actors independent of the supplier. The challenge is to avoid rapid obsolescence of investments.

Behind these objectives lie legal obstacles that must be removed by building a regulatory framework adapted to the deployment of cooperative ITS and traffic automation. Finally, it is a matter of supporting the players in their transformations through a harmonized deployment framework, involving managers and training the players in new skills.

In Carreras et al. (2018), the authors propose a simple classification scheme of the features, functionalities, and services coming from infrastructure and improving the quality of the CAV services. This proposal of classification is one of the topics developed in the H2020 European project INFRAMIX (https://www.inframix.eu/). This modeling starts from two observations: Firstly, the perception coming from embedded sensors and perception modules is limited by the capability of the sensors. Secondly, the road infrastructures have growing capacities. Effectively, road infrastructure operators have implemented a lot of sensors on the infrastructure in order to monitor both weather and traffic conditions. It is clear that this information could be useful in order to improve the perception of automated vehicles.

This classification proposes, like for SAE levels, to harmonize the capabilities of a road infrastructure in the CAV context. These levels are shared into two main categories. The first one provides the road infrastructure capabilities in their current state (conventional infrastructure) and the second one supplies the future digital capabilities. This classification, and its levels, is called ISAD for Infrastructure Support for Automated Driving (**Figure 15**). These levels have main objectives with which to provide the "readiness" state of the road network for the deployment of automated mobility (mainly in highway areas). With level A and in mixed traffic, the AVs can been seen as variables for traffic optimization.

### 5.2.2. The Adaptable Road

As not all new mobility offers are likely to be deployed, the challenge of the adaptable road is to provide a flexible and

| | Level | Name | Description | Digital information provided to Avs: digital map with static road signs | VMS, warnings, incidents, weather | Microscopic traffic situation | Guidance: speed, gap, lane advice |
|---|---|---|---|---|---|---|---|
| Conventional infrastructure | E | Conventional infrastructure/ no AV support | Conventional infracstructure without digital information. Avs need to recognise road geometry, road signs, and road markings. | | | | |
| | D | Static digital information/ Map support | Digital map data is available with static road information (signs and markings). Map data could be complemented by physical reference points (landsmarks). Traffic lights, short term road works and VMS need to be recognized by Avs. | ☑ | | | |
| Digital infrastructure | C | Dynamic digital information | All dynamic and static infrastructure information is available in digital form and can be provides to Avs | ☑ | ☑ | | |
| | B | Cooperative perception | Infrastructure is able to perceive microscopic traffic situations and to provide this data to Avs in real time. | ☑ | ☑ | ☑ | |
| | A | Cooperative driving | Based on the real-time information on vehicle movements, the infrastructure is able to guide Avs (groups of vehicles or single vehicle) in order to optimize the overall traffic flow. | ☑ | ☑ | ☑ | ☑ |

**FIGURE 15 |** ISAD, the levels of readiness of road infrastructure for AVs deployment.

profitable road system, capable of adapting to future travel demands. The key solutions to make the road more scalable are of different kinds.

The first step is to develop new methods of road construction. These will be prefabricated in the factory with modular solutions (de Larrard et al., 2013). These techniques indeed offer rapid replacement solutions in the event of damaged sections while natively integrating quality control procedures. These processes will be based on low-carbon, recycled materials requiring little energy for their implementation and self-repairing to allow increased longevity of the heritage (Blanc et al., 2019).

The next step is to develop wearing courses offering a good compromise between rolling noise, water uplift, rolling resistance, and grip, which 3D printing technologies will allow. Robotics or automated methods will allow increased requirements in terms of maintenance and upkeep, including under traffic. Solutions include the inclusion in pavement structures of sensor mats to monitor road conditions (Barriera et al., 2020).

Finally, the road must be able to integrate, if necessary, supply systems and renewable energy capture to recharge electric vehicles (Laporte et al., 2019; Vizzari et al., 2020) and power equipment, such as roadside units, signage, or public lighting (Shahar et al., 2018).

### 5.2.3. The Resilient Road

The road must also be more resilient to the effects of climate change. Among the actions to be taken, the following actions might be highlighted:

- Identifying the needs of managers in terms of climate.
- The harmonization of climate data at European level.
- Assessment of the economic and social impacts in the event of disruption.
- The identification of possible network vulnerabilities.
- Establishing future service levels for road networks.
- Identification of key technologies contributing to mitigation objectives.
- Investigation of cost-effective adaptation processes.

In this busy agenda, a number of off-the-shelf solutions can already be listed, such as drainage systems capable of adapting to an increase in the frequency and severity of precipitation, thermo-regulated pavements for reduce surface freezing and the effects of extreme heat (Touz and Dumoulin, 2015; Asfour et al., 2016), including in the city of depolluting materials (Le Pivert et al., 2019).

## 5.3. Cyber-Security, Failure, and Fault Detection and Identification

Additionally, cyber-security issues are more prominent, such as those relating to interference generation and malicious deception. These attacks, which can have several objectives (data theft, intentional failure, takeover, etc.) are becoming more and more common and require the implementation of increasingly complex security strategies and protocols. Gupta et al. (2020), Alnassera et al. (2019), Will et al. (2017), Kaur and Kad (2015), and Mokhtar and Azab (2015) give an overview of the concept of security and the underlying issues for CAV using VANETs. The security constraints of V2X can be divided into five categories: availability, data integrity, confidentiality, authenticity, and non-repudiation. However, in V2X, the most

dangerous attacks are those that target information availability. This is because they prevent authorized users from accessing information. It is obvious that this type of problem will be a challenge is term of CAVs security and will have a significant impact on the efficiency of the CAVs as well as on the safety and traffic aspects.

## 5.4. Societal Impact of CAD

CAD will not only impact technology-oriented aspects but also the everyday lives of users and people living with them. A first list of already identified and potential advantages of AD cars has been developed:

- Impact in terms of security, safety, accessibility, employment, emissions reduction, and management required time should be considered.
- Without the need for a driver, cars could become mini-leisure rooms. There would be more space and no need for everyone to face forwards. Entertainment technology, such as video screens, could be used without driver distraction.
- People who historically have difficulties with driving, such as disabled people, older citizens, as well as the very young, would be able to experience the freedom of car travel. A study from (Spence et al., 2020) generalized this question of mobility for all people. The AVs will change the way people are moving and their conclusion is that AVs might be the most used travel means for local travel in 2050s,
- AVs could bring about a massive reduction in insurance premiums for car owners.
- Possible reduction of the social health insurance cost (less fatalities and injuries).
- Self-aware vehicles would lead to a reduction in car theft, but it will be necessary and essential to take into account hacking issues, possible misuse of this technology for terrorism, and illegal activities. For instance, the works of Boloor et al. (2019) showed how it was possible to easily hack vision-based end-to-end AD technology.

At the same time, all those advantages could have their drawback counterparts:

- AD vehicles would likely be inaccessible to most people when introduced, likely costing over $100,000. A study from Kolarova et al. (2019) showed that the perceived value of travel-time savings using AVs is lower than conventional vehicles apart from shared AVs.
- Truck drivers and taxi drivers may lose their jobs, as AVs would take over even if new services and new work will be created: communications specialists, IT technicians, electrical engineers, mechatronics, analysts, AD engineers, modeling and simulation specialists, researchers, software programmers, mechanics and maintenance, cyber protection. Those issues are discussed in Pettigrew et al. (2018). Their conclusions are that there is a need for planning in advance required changes within the society and all companies should be prepared for the AV revolution (Alonso et al., 2020),
- If the vehicle crashes without a driver who would then be the responsible party: the software designer, the car maker, the OEM, the infrastructure (local authorities), or the owner of the vehicle?
- The cars would rely on the collection of location and user information, creating major privacy concerns. The principles of data avoidance and data economy need to be balanced between the requirements of data protection, cyber-security, road safety, and the competitiveness in global value-added chains. The implementation of different modes of CAD therefore requires reasonable solutions in the areas of processing and exploitation of data. The interoperability among C-ITS deployments around the world will also need to be ensured. In this context, the goals of data protection and promotion of innovations do not necessarily contradict each other but may jointly create an added value.
- Ethical problems could arise that a machine might struggle to deal with. Faced with a choice between plowing into a group of schoolchildren or going off a bridge and killing all its passengers, what does the vehicle do? Should the vehicle always serve to avoid animals on the road or always prioritize the safety and comfort of passengers? Here, a study using the moral machine of the MIT (Awad et al., 2018, https://www.moralmachine.net/) gave us some insight into what people think about this issue. However, this automated decision system issue is still debated.
- Human behavior such as hand signals are difficult for a computer to understand. What will then be the future interactions between humans, especially vulnerable road users, and AVs?
- How would the police interact with AD vehicles, especially in the case of accidents or crimes? Here, another dimension of the liability issues is highlighted and needs to be addressed.

All these remarks and questions have been taken into account in the first international proposal for CAV deployment rules (committee, 2020). This regulatory text has been adopted in June 2020. Nevertheless, these first rules from the United Nations are very cautious. The UN clearly wants to control with a high level of safety the deployment of these new mobility means. The UN confirms these first rules, and this first regulation document are just an introduction. In the future, this regulatory text will be adapted in order to respond properly to new needs. The main adopted rules are the following:

- A level 3 of AD can be activated as soon as a human driver takes place in the driver's seat with seat belt fastened.
- The UN prohibits the use of embedded automated systems on roads where pedestrians and cyclists are around AV. At this moment, the mixing of traffic with vulnerable users is forbidden.
- It is also forbidden to use AD system on a road that does not contain a physical separation between the two traffic lane directions. This rule will imply specific infrastructure adaptation.
- A restricted speed is adopted. The CAV maximum speed will be fixed to 60 km/h. It is too low for Highway use (in France, given a normal traffic density, the minimum speed is 80 km/h). This rule will imply adapted infrastructure for CAV use.

- The on-board multimedia screens must be disconnected when the driver regains vehicle control.
- It is necessary to install additional sensors in the AD system to monitor the driver's behavior and check his ability to get back the driving task (acting on actuators). This rule is critical and appropriate Human/Machine Interactions should be developed.
- It is necessary to equip the vehicle with a "black box," called "data storage system for AD," which is started automatically when AD is activated.
- AD systems must keep up to date on cyber-security aspects to avoid hacking. Same question about the drawback, failures, and fault detection, identification, and potential correction/mitigation.

## 6. CONCLUSION

The development and deployment of automated mobility are complex issues that cannot be done without using communication. However, there are still many questions and constraints to address in order to obtain an optimized, reliable, and robust medium for its use in active and automated mobility interacting with its environment. Various questions arise, such as the transmission range, the loss rate, the induced delays, the interference, and security issues. There are also questions about strategies to be implemented to manage and transmit information while guaranteeing a High Quality of Service. With the deployment of 5G (Brahmi et al., 2019), even if it will increase the level of security and speed, there is the problem of the effective transmission range.

In Lee et al. (2016), the authors define the following concept: Internet of Vehicles. The authors start from the notion of Intelligent Grid and apply this concept to the AV. In this case they define the Vehicular "Fogs" concept. By fogs, they mean an extension of cloud concept. The authors address the Internet of vehicles, the vehicular cloud, the fog computing, and the vehicular network for CAVs. This research and concepts proposal address the issue of the efficient management and Quality of Service of these distributed, cooperative, and connected moving and highly dynamic network of CAVs.

The development of the new active and connected mobility needs the management of a great quantity of information with various properties and constraints. Effectively, this information will be imperfect (uncertain, inaccurate, unreliable, and unconfident), incomplete, asynchronous, multi-scale, and multi-modal. Moreover, the processing stages will be distributed and cooperative. The information sources will be also different and will address different frequency domains. It will be relevant to detect and manage conflict and ambiguities. To avoid crashes, these systems of systems will have to guarantee the quality, the robustness and the reliability of information and sub systems. An additional level of processing will thus be necessary in order to monitor the reliability and the current operating state of embedded and distributed systems.

To understand the current and future complex and interactive environments, it will be essential and critical to build local and extended dynamic perception maps. These dynamic perception maps will have to assess the main KCs representing the road environment. It is obvious that, to guarantee a high level of information, perception, and service quality, the infrastructures will have to be reworked and redesigned to be smarter and more adapted to the CAVs.

In summary, the next generation of CCAM means will have to meet the challenge to handle, manage, filter, analyze, and interpret a huge quantity of data in order to understand and to anticipate both the KCs behaviors and the causes of singular events (collision, near accident, etc.).

Until the human stays in the driving loop, a Driver Monitoring System is necessary. The L3 and L4 systems can be seen as adaptive ADAS. These active ADAS must manage interdependent issues: safety, energy consumption and pollution, traffic management, comfort, and health.

The environment is the interaction and the cooperation of several independent worlds inside and outside the vehicle but with constraints. In this framework, the next generation of road networks will be essential for an efficient deployment of automated and connected mobility. It is now critical to take into account not only the user but also the surrounding with a real redesign of the road infrastructures and services. Increasing amounts of studies and concepts are proposed on these topics: the "readiness" (ISAD levels), "resilient," "smart," "automated," and "hybrid" road infrastructures. An interesting overview of this topic is given by Intel in an e-book (Sehra and Staff, 2020), which addresses the question of "how city and transportation leaders can develop Smart City strategies for improving road infrastructure." In this context, infrastructures will have to be adapted in order to be ready, readable, and cooperative in all context and weather conditions. The communication will play a crucial role.

But in all the possible solutions, information and data stay the main issue and the core of the new generation of transportation means. It is essential to address them and to know how to analyze, model, merge, use, and manage them. These different levels of processing will allow answers to be provided with more efficiency to tackle the challenges of tomorrow: an interactive, cooperative, active, optimal, reliable, and robust mobility for and between cities and for and with users, for a smart, responsible, and resilient world.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SYSTEMATIC REVIEW
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# The Impact of Route Choice on Active Commuters' Exposure to Air Pollution: A Systematic Review

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As air pollution varies significantly in both space and time, commuter exposure may differ considerably depending on the route taken between home to work. This is especially the case for active mode commuters who often have a wider range of route choices available to them compared with those traveling by private motor vehicle or by public transport. The aim of this study was to investigate the effect of route choice on air pollution exposure among active commuters, and to estimate, based on modeling, the health benefits able to be achieved from air pollution exposure reductions, modeled across a population, through route optimization. We searched for studies that used portable personal air pollution monitoring equipment during active mode commuting, and reported measurements of air quality on at least two routes, either as a journey to work or to school. The World Health Organization (WHO) model AirQ+ was then exploited to estimate the premature deaths attributable to air pollution according to route choice. Ten publications were identified that met the inclusion criteria. Ultrafine particle counts (UFP), black carbon (BC), and carbon monoxide (CO) were the most commonly measured pollutants in the studies identified. The exposures associated with "high exposure" and "low exposure" routes (categorized based on differences in traffic counts on the roads along the commute route or walking on opposite sides of the road with different levels of traffic traveling in each direction) were found to vary on average by 30 ± 8%, 42 ± 35%, and 55 ± 17% for BC, CO and UFP, respectively. On the basis of modeling, and on the estimated exposures to BC, up to 36 out of 10,000 deaths could be prevented by choosing a low exposure route compared with a high exposure route during active commuting. The results of this study may be useful for both individuals in their commute planning, and also for urban transport planners as impetus for investing in infrastructure to support healthy active mode commuting.

**Keywords: air pollution, route choice, health outcome, active commuters, systematic review**

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## INTRODUCTION

Over the past half a century, urbanization and the reliance on passive transport (especially private cars) have led to low levels of physical activity across the world (World Health Organization, 2020c), which is a major risk factor for mortality (World Health Organization, 2010). More than 1.4 billion people of the world's population are deemed to not be sufficiently active to be healthy (Thornton, 2018), with insufficient physical activity contributing to a higher risk of cardiovascular disease, Type 2 diabetes, dementia, and some cancers (Guthold et al., 2018).

The promotion of active transportation (AT) is one of the strategies that has been used by governments to help address the issue of inactivity (Goodin, 2015). While AT has traditionally been considered to be walking, running and cycling, this category includes any type of transport powered by human energy (Litman, 2018). AT can, to a large extent, provide sufficient physical activity to remain healthy (Shoham et al., 2015) and, if rolled out at scale, worldwide, it could potentially prevent 3.2 million deaths due to inactivity (Guthold et al., 2018). AT is also associated with environmental improvements, and has been shown to also have social and cultural benefits (Hong, 2018). For instance, parents who choose active transportation influence their children to also be active, and employees using active transport have been shown to help in encouraging co-workers to change their choice of mode of transport to ones that are more active (Hong, 2018).

Active commuting is also a more environmentally sustainable mode of transport than the use of private vehicles as it requires little in the way of fossil fuels or cost (Banister, 2009; Page and Nilsson, 2017; Hong, 2018). Private cars also contribute more to soil and water pollution through the production of vehicle spray, and the dry deposition of particles from vehicles and roads dispersed into roads' verges and surface water (Schipper et al., 2007; Maibach et al., 2008; Hong, 2018).

Despite the important advantages of AT, there are some associated risks, with the fear of traffic injury being a common reason given by many for their preference for motorized transport over walking or cycling (Sonkin et al., 2006). While this perception is not unfounded [the risk of hospital admission due to traffic related crashes is higher for walkers and cyclists than for drivers (Mindell et al., 2012)], the risk is none-the-less low in comparison with many activities such as do-it-yourself repairs (DIY) at home, as well as common recreational activities (Chieng et al., 2017).

The risk that is often not taken into account in active transportation is the health impact caused by exposure to air pollution (Bigazzi and Figliozzi, 2014; Dirks et al., 2018). Active travelers tend to spend more time than passive commuters traveling the same distance, and experience higher minute ventilation, potentially increasing the net dose of air pollution received by the body and consequently, for the same origin/destination pair and the same route, active commuters may experience a higher dose of pollution compared with passive commuters (Bigazzi and Figliozzi, 2014; Cepeda et al., 2017; de Nazelle et al., 2017; Targino et al., 2018).

One approach that has been used to reduce active commuters' exposure and promote active commuting is through changes in the urban design of cities, such as increasing the separation between commuters and motorized road traffic. For example, in one study, it was found that a separation of 100 meters decreased ultrafine particle counts (or UFPs which are particles smaller than 100 nanometers in diameter), black carbon (BC) and carbon monoxide (CO) concentrations relative to the roadside by 60 to 80 percent (Zhu et al., 2002). Providing such a separated path has also been found to result in the public perception of active transport as safe from the point of view of road traffic injury (Hull and O'Holleran, 2014). Thus, creating the appropriate transport infrastructure for active commuters can encourage people to shift from private cars to active commuting (Caulfield et al., 2012). Another strategy can be to limit road traffic, particularly HCVs (heavy commercial vehicles including buses and trucks) in specific areas, and to redesignate these as active commuter areas, as shown by Mueller et al. (2020).

In the absence of any information regarding air pollution exposure and route choice, active commuters tend to choose routes that involve the least number of directional changes or the shortest distance (Shatu et al., 2019). Given that the shortest route is not always the one associated with the lowest air pollution dose (Armeni and Chorianopoulos, 2013), the provision of information regarding air pollution and traffic could help commuters shift toward lower exposure routes (Bunds et al., 2019). The information could be provided using either traditional environmental monitoring equipment or low-cost sensors with community involvement provided at a grass-roots level (Mahajan et al., 2020). As such, governments may exploit citizen science (a process in which people with potentially minimal relevant experience become involved in data collection) to provide fine-grained information using mobile apps and low-cost sensors (Mahajan et al., 2020). In such a case, academic scientists are often responsible for implementing and interpreting the results (Eitzel et al., 2017). In this case, this would be in relation to identifying the least polluted routes, and estimates of health gains, for example, that could be achieved by using such routes.

Exposure assessment at the individual level is a key tool for assessing health impacts and developing suitable exposure-reduction policies. Traditionally, estimates have been made based on fixed-site monitoring, supplemented by exposure modeling, albeit with a high degree of uncertainty due to the high spatial and temporal variability of air pollution levels (Dias and Tchepel, 2018). A more reliable and accurate way of estimating personal exposure is through the use of personal portable air pollution monitoring devices in combination with a Global Position System (GPS) to track location (Dias and Tchepel, 2018). Consequently, a large and growing body of literature has explored individual's exposure using such devices (Strak et al., 2010; Jarjour et al., 2013; Dirks et al., 2016, 2018; Good et al., 2016; Pattinson et al., 2017; Hofman et al., 2018; Jereb et al., 2018; Brand et al., 2019; Luengo-Oroz and Reis, 2019). While such studies provide, at the individual level, reliable exposure information, they do not generally link directly to health outcomes. In particular, there is a lack of research into the health benefits that could be achieved though route optimization.

In recent years, there has been a growing interest in the use of health impact assessments (HIA) to estimate the potential benefits to health associated with various interventions (Mueller et al., 2015). Many models have been developed for such a purpose, including those published by the European Study of Cohorts for Air Pollution Effects (ESCAPE) project and the American Cancer Society (ACS) (Malmqvist et al., 2018). The World Health Organization (WHO) model AirQ+ (World Health Organization, 2020b) is designed to allow estimation of both the long- and short-term health impacts of exposure to different pollutants based on a concentration-response function extracted from epidemiological studies. In light of the many

health effects attributed to combustion-related BC, including all-cause and cardiopulmonary mortality (Janssen et al., 2012; Kirrane et al., 2019), this study links evidence from the literature about the reduction in exposure to BC able to be achieved through route optimization, and uses an HIA approach to estimate the associated predicted human health benefits.

This paper begins with a systematic review of measurement studies that have used portable air quality monitoring equipment to investigate differences in air pollution exposure experienced by active mode commuters' exposure, taking different routes for the same origin-destination pair. The extent of health benefit that may be able to be achieved through route optimization is then estimated using AirQ+ software.

# MATERIALS AND METHODS

## Systematic Review

The systematic review was performed based on the PRISMA guidelines for the reporting of systematic reviews (Moher et al., 2009). The search was conducted in October 2019 using the following databases: MEDLINE, Web of Science, and Scopus. The following keywords were used in the search:

("route choice" or (route AND optimi*) OR "short* path") AND ("air pollut*" OR "air quality" OR emission* OR "traffic pollut*" OR (pollut* AND exposure)) AND (walk* OR bicycl* OR cyclist OR cycling OR bik* OR pedestrian OR "active commut*" OR "active transport*")

The search was restricted to publications written in the English language and that included an abstract. The eligible papers also had to meet all of the following criteria:

1. Air pollution data were measured directly (not modeled) using portable air pollution monitors.
2. Air pollution exposure was measured for at least two routes for the same origin and destination pair.
3. Quantitative results of dose/exposure were reported for the time when the routes were traversed.
4. The percentage reduction achieved by taking the lowest exposure route compared to the highest exposure route was reported or able to be calculated based on the figures provided.

The study data collected included air pollution exposure, sample size, location, time and date of sampling, and target group (children or adults). The literature search, study selection, data extraction, and synthesis were performed between February and March 2020. The primary outcome measure was the percentage difference in exposure between the highest and lowest exposure route. The mean exposures for the high and low exposure routes were extracted. If the study involved more than two routes, the route with the highest exposure was selected and compared with the route with the lowest exposure.

## Estimate of Health Effects

Based on the results of the systematic review, the long-term health benefits, able to be achieved by taking the low exposure route rather than the high exposure route, were estimated. This was based on the predicted health effects of exposure to BC for a commuter who travels the same route every working day for a year. All-cause mortality was chosen as it is an important public health benchmark, providing more robust results than cause-specific mortality and morbidity (Rojas-Rueda et al., 2016). The proportion of deaths attributable to BC was also able to be provided by AirQ+ on the basis of limited data input requirements.

To estimate the annual mean exposure to air pollution, a series of assumptions were made. Firstly, it was assumed that a person spends 1 h per day [which is the average time of daily travel to work for many countries (Silveira Neto et al., 2014; Perry, 2016)] over 236 days of a year in the transport microenvironment (assuming 25 days of holidays and 104 weekend days), and that a person is exposed to background levels of BC at other times. The mean exposures for the person commuting the high exposure route and the low exposure route were calculated for each of the reviewed studies. By dividing the difference by 24, the daily difference (for a weekday) of exposure was calculated. This number was then multiplied by the fraction of working days over a year to get the yearly reduction in the long-term exposure to BC for a commuter who consistently follows the low-exposure route compared with the high exposure route. The background concentration was calculate by assuming (arbitrarily) the ratio of the background to the average concentration along the low exposure route to be 1, 0.5, 0.33, 0.25, and 0.20. On this basis, the annual exposures for both the high and low exposure routes were calculated for each of the studies identified in the systematic review. The final output is the annual mean predicted BC exposure for a given route.

To estimate the long-term health effects of exposure to BC, AirQ+ was used (World Health Organization, 2020b). This model employs concentration-response functions derived from a systematic review of epidemiological studies until 2013 (World Health Organization, 2020b). In contrast with other models, such as ACS and ESCAPE, each of which was developed for a specific region and for a limited number of pollutants, AirQ+ includes BC (which is not included in the other models) and is considered to be applicable across a range of countries, including those in Western Europe and in North America (World Health Organization, 2020b).

To quantify the attributable proportion of all-cause mortality using AirQ+, the model requires a cut-off value of concentration (we considered this to be zero) and air quality data, including long-term exposure to BC (above the cut-off). The attributable proportion is given by Ansari and Ehrampoush (2019) as

$$AP = [(RR(c) - 1)^{*}p(c)]/[RR(c)^{*}p(c)]$$

where RR(c) is the relative risk for the health endpoint in a specific category of exposure (c), and p(c) is the proportion of the population in the category of exposure (c). For calculating the RR, the default values provided by AirQ+ were used, and a linear-log method was exploited to estimate the relative risks associated with different exposures. In this study, the differences in the estimated attributable proportion of deaths for high and low exposure routes have been considered to be the contribution

to mortality reduction of the least polluted commuting route compared with the most polluted route.

## RESULTS

This section is divided in three subsections. The first part explains the results of the search. Then, a description of the extent of reduction in exposure to pollutants found in the searched studies is provided. Finally, a health impact assessment approach, used to estimate the health benefit able to be achieved through route optimization for air pollution exposure, is presented.

### Search Result

In total, 333 studies were identified with 25, 72, and 233 from Medline, Scopus, and the Web of Science, respectively, and another three studies identified from other sources. Of the 333 studies, 24 were duplicates and were thus removed. Additionally, MR screened the titles manually and deleted 31 more studies because of duplication. After screening the title and abstract, 18 papers were considered to meet our inclusion criteria. The full

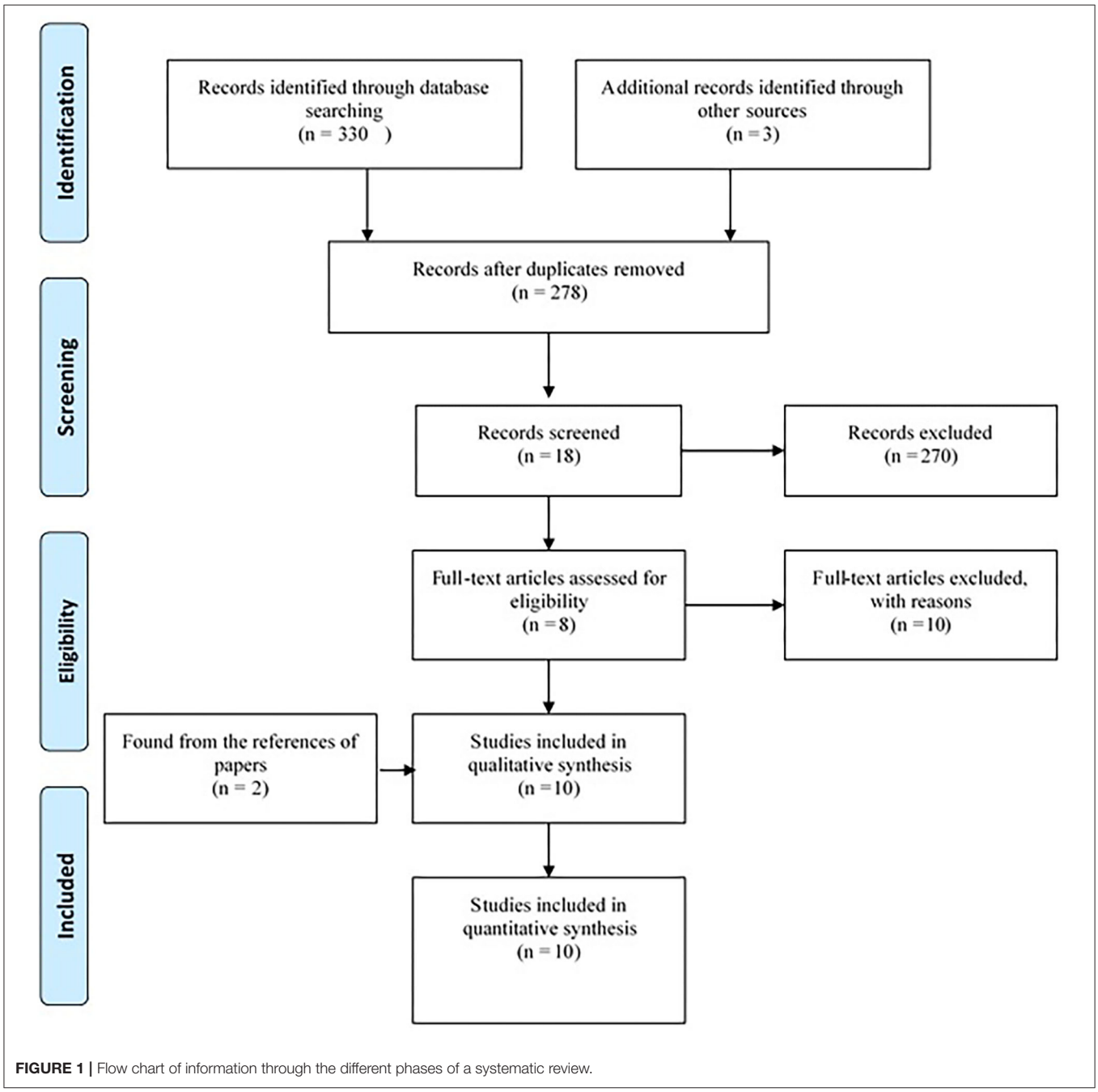


**FIGURE 1 |** Flow chart of information through the different phases of a systematic review.

texts were then analyzed to assess for eligibility. Eight papers were considered to be eligible according to our criteria. Two more studies were included through cross-references, leaving a total of 10 studies for the systematic review (**Figure 1**).

**Table 1** shows the main characteristics of the included studies, such as the pollutant of interest, the mode of travel, the country and the city in which data collection took place, the population density of the city, the study group, the mean and standard deviation of the exposure for each route, the number and time of day of the trips, and the mean percentage difference associated with the low exposure route compared with the high exposure route.

## Exposure Reduction

The most commonly measured pollutants were UFP (seven studies), BC (five studies), and CO (four studies). However, other pollutants, including PM2.5 and PM1, (particulate matter of <2.5 and 1 micrometers in diameter) were also measured. The mean ratios of high-to-low exposure were found to be 1.30 ± 0.08, 1.55 ± 0.16 and 1.42 ± 0.035 for BC, UFP and CO, respectively. In each of the studies, two routes were compared with respect to the active commuters' exposure to air pollution. One of the routes was through high traffic roads (or on the high traffic side of the road), and the other route was either away from traffic or on the low traffic side of the road. The percentage reduction in exposure between routes varied depending on the type of pollutant, the time of day, data collection location and the device used.

**Figure 2** shows concentration differences in UFP ranging from 7,990 to 44,090 pt/cc, depending on the device used and the study setting. By reviewing the dates of the data collection for the different studies measuring UFP exposure, it was found that older studies tended to result in higher mean exposures compared with the more recent studies. For example, the highest mean UFP exposure was observed in the study by Strak et al. (2010) in which data collection took place in April 2007, while the second highest exposure to UFP was measured in Christchurch by Pattinson et al. (2017) based on data collected in 2009. However, in the other studies, the UFP concentration in the high exposure route was found to be close to 20,000 pt/cc or less.

BC was measured in four of the studies. The study by Brand et al. (2019) measured BC at three different cities (**Figure 3**). In this study, the mean reduction in exposure between routes was found to be 1.21 (SD = 0.97) $\mu g/m^3$. The highest values of BC were observed by Brand et al. in Sao Paulo and the lowest in Rotterdam (Brand et al., 2019). Furthermore, the highest reduction in exposure to BC achieved by choosing the low exposure route compared to the highest route was found in the study conducted in Sao Paulo (Brand et al., 2019).

Four studies measured CO. One of these reported only the percentage difference in the mean exposure (−10%, CI=-20 ± 1), which was found to be not significant. The other three studies provided the numerical means for each route (**Figure 4**). The mean reduction was found to be 0.23 (SD = 0.31) ppm. The highest ratio of reduction was found in a study by Pattinson et al. (2017) based on measurements made in 2009. This suggests that higher levels of concentration tend to be recorded in older studies carried at a time when the vehicle fleet technology was less advanced.

In some studies, other pollutants were measured, including soot, PM2.5, PM10, and PM1. In two studies, PM2.5 was considered (Jarjour et al., 2013; Good et al., 2016). In both studies, the reduction in mean exposure between routes was found to be not significant. Strak et al. reported 8.10 $\mu g/m^3$ and 1.68 $\times 10^{-5}$/m reductions in cyclist's exposure to PM10 and soot, respectively. One study considered PM1 (Pattinson et al., 2017) and observed a decrease of 1 $\mu g/m^3$.

In these studies, various instruments (with different settings) were used for the measurement of pollutants. For example, three different devices [the CPC TSI 3007 (Strak et al., 2010; Jarjour et al., 2013; Pattinson et al., 2017), P-Trak (Dirks et al., 2016, 2018; Hofman et al., 2018), DiscMini (Luengo-Oroz and Reis, 2019), and MiniDiSC (Good et al., 2016) were used to measure UFP numbers for particle sizes in the range of 0.01 to 1 μm, 0.02 to 1 μm (Matson et al., 2004), 0.01 to 0.3 μm (Testo SE and Co, 2019), 0.01 to 0.3 μm (NANEOS, 2020)]. All of the studies presented in this review used an AE51 for measuring black carbon (Jarjour et al., 2013; Hofman et al., 2018; Brand et al., 2019), except for one (Jereb et al., 2018) which used an AE33. The aethalometer AE51 measures only BC at a wavelength of 880 nm, and is used to detect black carbon. An AE33 can be operated using various different wavelengths. However, in the study by Jereb et al. (2018), a pair of wavelengths, 470 and 950 nm, was used to measure traffic-related BC. In some studies, soot and BC were considered to be the same, although there are fundamental differences between them (Long et al., 2013). Optical methods were used to measure BC but for the quantification of EC, Strak et al. (2010) post-processed PM10 filters using a Smoke Stain Reflectometer (model M43D; Diffusion Systems, London, UK) and transformed the results into absorbance. For evaluating CO, two instruments were used: a Langan (Good et al., 2016; Dirks et al., 2018) and a Qtrak (Jarjour et al., 2013).

Of the ten studies included in the review, five compared either morning and afternoon or evening exposures (Dirks et al., 2016, 2018; Hofman et al., 2018; Jereb et al., 2018; Brand et al., 2019). Of the five studies, three considered UFP, one considered CO and three considered BC. For the studies that considered UFP, the ratios of the morning-to-afternoon concentrations were found to be 2.80, 1.30, and 1.65 for Auckland, New Zealand (Dirks et al., 2018), Bradford, UK (Dirks et al., 2016) and Antwerp, Belgium (Hofman et al., 2018), respectively. The one study (Auckland) that measured CO (as well as UFP), reported a ratio of morning to afternoon mean concentration of 1.04 (Dirks et al., 2018). Mixed results were found for BC. It was shown that in Sao Paulo, Brazil, Rotterdam, The Netherlands, and Antwerp, Belgium, the mean morning exposures to BC were 49, 13, and 33% higher than in the evening, respectively. The morning-to-afternoon black carbon levels measured in Celje, Slovenia were found to be 0.94 and 1.12 on the main and alternative routes, respectively. Brand et al. (2019) also observed lower concentrations in the morning relative to the evening, with a ratio of 0.93. Therefore, although the differences in exposure between morning and afternoon or evening varied, most studies found average exposures to be

**TABLE 1 |** Main characteristics of the studies included in the systematic review (Int = interval, Pop den = Population density, cutoff: the threshold for the size of particles).

| References | Modes | Pollutant | Location | Equipment | Group | Difference in exposure (%) | Mean (SD) | Trips |
|---|---|---|---|---|---|---|---|---|
| Dirks et al. (2018) | Walking | CO<br>UFP | Auckland, NZ | UFP:<br>P-Trak (8525 TSI incorporation, US, cutoff: 20 nm)<br>CO: Langan (Langans Products, Inc,UK) | Children | a.m.:<br>UFP: 57<br>CO: 0<br>p.m.:<br>UFP: −0.02<br>CO:0.08 | a.m.:<br>UFP (pt/cc)<br>R1: 20,100 (1,300)<br>R2: 12,800 (900)<br>CO (ppm)<br>R1=R2: 0.73 (0.07)<br>p.m.:<br>UFP (pt/cc)<br>R1: 5,800 (1,000)<br>R2: 5,900 (900)<br>CO (ppm)<br>R1: 0.42 (0.11)<br>R2: 0.39(0.32) | 18 (9 north + 9 south) a.m.<br>6 (3 north + 3 south) p.m.<br>10/2015(Spring) |
| Dirks et al. (2016) | Walking | UFP | Bradford, UK | UFP:<br>P-Trak (8,525 TSI incorporation, US, cutoff:20 nm) | Children | a.m. UFP: 14<br>p.m. UFP:2 | a.m.:<br>R1: 17,680 (21,060) (pt/cc)<br>R2: 20,100 (22,000) (pt/cc)<br>p.m.:<br>R1: 14,716 (19,683) (pt/cc)<br>R2: 14,383 (17,016)(pt/cc) | 5 trips a.m.<br>5 trips p.m.<br>11/2015(Winter) |
| Luengo-Oroz and Reis (2019) | Cycling | UFP | Edinburgh, Scotland | UFP: DiSCmini (Testo SE & Co. KGaA, Germany, cutoff: 10 nm) | Adults | UFP: 97 | R1: 9,824 pt/cc<br>R2: 7,990 pt/cc<br>R3: 19,310pt/cc | 3 routes * 9 days * 2 (onward and return)<br>a.m.<br>06/2018 to 07/2018(Spring) |
| Jarjour et al. (2013) | Cyclist | UFP<br>CO<br>$PM_{2.5}$<br>BC | Berkeley California, US | UFP: CPC (model 3,007; TSI Inc., US, cutoff: 10 nm)<br>CO: Q-Trak (7,565, TSI Inc., US)<br>$PM_{2.5}$: DustTrak (8,520, TSI Inc., US)<br>BC: microAeth® (AE51, TSI Inc., US, 880 nmwavelength) | Adults | UFP: 30<br>CO: 14<br>$PM_{2.5}$: 0.05<br>BC:0.15 | UFP (pt/cc)<br>R1: 14,311 ± 15,381<br>R2: 18,545 ± 42,482<br>CO (ppm)<br>R1: 0.79 ± 0.39<br>R2: 0.90 ± 0.64<br>$PM_{2.5}$ ($\mu g/m^3$):<br>R1: 4.88 ± 1.41<br>R2: 5.12 ± 1.86<br>BC<br>R1: 1.76 ± 2.58<br>R1: 2.06 ±3.23 | 9 (sampling days) *2 (routes)* 15 (people)<br>a.m.<br>04/ 2011 to 06 / 2011<br>(Spring: dry season inBerkeley) |
| Strak et al. (2010) | Cycling | $PM_{10}$<br>soot<br>UFP | Utrecht Netherlands | $PM_{10}$<br>Indoor pumps (model SP-280E; Air Diagnostics and Engineering, Harrison, ME, US)<br>Soot<br>Smoke Stain Reflectometer (model M43D; Diffusion Systems, London, UK)<br>UFP:<br>CPC (model 3007; TSI Inc., US, cutoff:10 nm) | Adults | $PM_{10}$:0.04<br>UFP: 59<br>Soot:0.39 | $PM_{10}$ ($\mu g/m^3$):<br>R1: 45.67 (28.35)<br>R2: 44.01 (29.39)<br>UFP (pt/cc)<br>R1: 27,813 (5,919)<br>R2: 44,090 (10,036)<br>Soot ($10^{-5}/m$):<br>R1: 4.35 (3.19)<br>R2: 6.03(3.53) | 12 days for UFP<br>a.m.<br>04/2007 to 05/2007(Spring) |

*(Continued)*

**TABLE 1 |** Continued

| References | Modes | Pollutant | Location | Equipment | Group | Difference in exposure (%) | Mean (SD) | Trips |
|---|---|---|---|---|---|---|---|---|
| Jereb et al. (2018) | Cycling | BC | Celje/Slovenia | Magee Scientific Aethalometer (AE33, Aerosol d.o.o., Ljubljana, Slovenia, a pair of 470 and 950 nm wavelengths were used) | Adults | a.m. BC: 13<br>p.m. BC:42 | Morning<br>R1: 6.0 ± 5.1 $\mu g/m^3$<br>R2: 5.3 ± 4.8 $\mu g/m^3$<br>Afternoon<br>R1: 6.4 ± 4.9 $\mu g/m^3$<br>R2: 4.5 ± 6.0$\mu g/m^3$ | One day:<br>Twice in the morning<br>Twice in afternoon<br>05/2017(Spring) |
| Hofman et al. (2018) | Cycling | BC<br>UFP | Antwerp/Belgium | BC: microAeth® (AE51, TSI Inc., US, 880 nm wavelength)<br>UFP: P-Trak (8,525 TSI incorporation, US, cutoff:20 nm) | Adults | BC:156<br>UFP:14 | BC ($\mu g/m^3$)<br>R1: 3.38<br>R2: 1.32<br>UFP (pt/cc)<br>R1: 14553<br>R2:12818 | 10 days twice morning and twice afternoon then all measured data were averaged along each route.<br>01/2017 to 03/2017(Winter) |
| Brand et al. (2019) | Cycling | BC | London/UK<br>Rotterdam/Netherland<br>SaoPaulo/Brazil | AE51 microAeth® (AE51, TSI Inc., US, 880 nm wavelength) | Adults | London: 48<br>Rotterdam: 6<br>Sao Paulo:52 | London<br>R1: 5.53 $\mu g/m^3$<br>R2: 3.73 $\mu g/m^3$<br>Rotterdam:<br>R1: 1.63 $\mu g/m^3$<br>R2: 1.73 $\mu g/m^3$<br>Sao Paulo:<br>R1: 7.23 $\mu g/m^3$<br>R2: 4.76$\mu g/m^3$ | Morning<br>Afternoon<br>Evening<br>8-12 trips<br>Rotterdam<br>(10/2017) Autumn<br>London (12/2017)<br>Winter<br>Sao Paulo<br>(02/2018)Summer |
| Pattinson et al. (2017) | Cycling | UFP<br>CO<br>PM1 | Christchurch/NZ | UFP: CPC (model 3007; TSI Inc., US, cutoff: 10 nm)<br>CO: Langan (Langans Products, Inc, UK)<br>$PM_1$: Dust monitor (Model 1.107, GRIMM Aerosol Technik,Germany) | Adults | R3 to R1<br>UFP: 70<br>CO: 111<br>PM1:24 | UFP (pt/cc)<br>R1: 42,480 ± 27,176<br>R2: 28,765 ± 18,638<br>R3: 24,977 ± 19,650<br>CO (ppm)<br>R1: 1.12 ± 0.59<br>R2: 0.89 ± 069<br>R3: 0.53±0.39<br>$PM_1$ ($\mu g/m^3$)<br>R1: 5.1 ± 2.9<br>R2: 5 ± 2.6<br>R3: 4.1 ±2.1 | 5 days sampling<br>afternoon<br>various distances to road<br>(03/2009 to 04/2009)Autumn |
| Good et al. (2016) | Cycling | BC<br>CO<br>$PM_{2.5}$<br>UFP | Collins, US | $PM_{2.5}$ :PEM, SKC<br>BC: microAeth® (AE51, TSI Inc., US, 880 nm wavelength)<br>UFP: DiSC Mini (Matter Aerosol AG, Testo Inc, Switzerland, Cutoff: 1,000 nm)<br>CO: Langan (Langans Products, Inc,UK) | Adults | BC (mean) −23 (−32, − 13)<br>BC (cumulative) −35 (−51, − 12)<br>CO (mean) −10 (−20, +1)<br>CO (cumulative) −30 (−46, − 9)<br>(mean) −7 (−20, +9)<br>$PM_{2.5}$ (cumulative) +3 (−18, +28)<br>UFP (mean) +1 (−35, +59)<br>UFP (cumulative) +17 (−29,+93) | – | 381 days of data were collected, including 678 valid commutes (350 morning and 328 evening),<br>8 commute days for each participant<br>11/ 2012 to 02/ 2014<br>Winter |

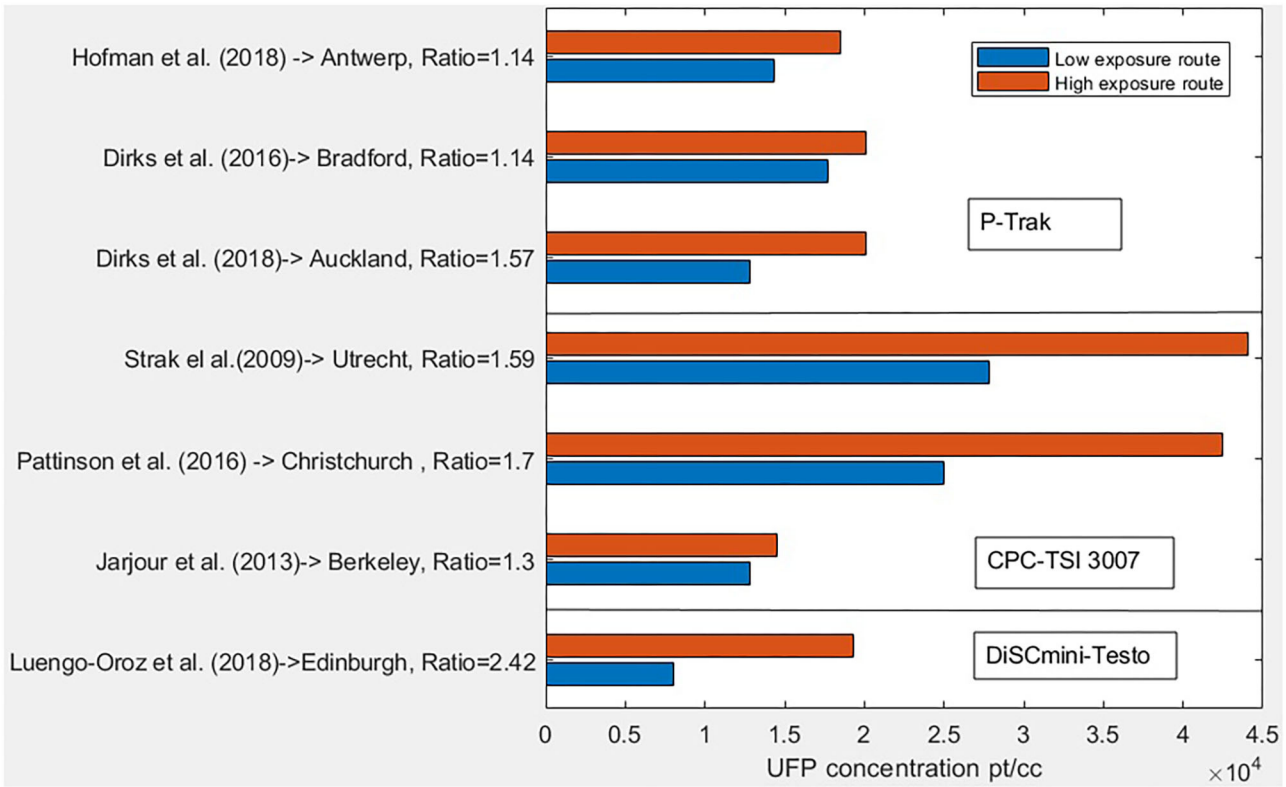


**FIGURE 2 |** Comparison of the concentration of UFP in the studies. High exposure is in orange color and the low exposure in blue. The ratio is the mean of high exposure divided to the low exposure route.

higher during the morning rush hour than at other times of the day.

## Long-Term Health Outcomes

Using AirQ+, the Estimated Attributable Proportion of the all-cause mortality– fraction of mortality attributed to exposure to black carbon for both the high and low exposure routes were calculated based on the average commuting exposures, along with the differences between the two routes. Four studies provided cyclists' exposure to BC in six different cities. Based on the data presented in the studies reviewed, the mean exposures and background concentrations were calculated based on the measurements made for the different cities, and for when the ratios of the background concentration to the low exposure route are 1, 2, 3, 4, and 5, as presented in **Table 2**. Given that the background concentrations are not the same around the world [some cities (including Auckland) tend to have cleaner air, while many cities have much worse conditions], the five different background concentrations for each city were calculated by dividing the low exposure route to 1, 2, 3, 4, and 5 to account for the variability in background concentration. The annual exposure was computed by choosing low and high exposure routes and considering various background exposures (**Table 3**). The results of the model output from AirQ+ are presented in **Table 4**. Note that the differences in the attributable proportion of mortality is affected significantly by route choice, though the levels of background concentration also have an influence, with the relative difference being smaller in conditions of high levels of background. On average across cities, the difference in attributed proportions was found to be 0.17%, indicating that, on average, 17 of 10,000 deaths (of the people biking 1 h per day to and from their work) could be prevented by taking a lower exposure commuting route. In Sao Paulo, where the highest difference in exposure between routes was recorded, on the basis of this methodology, up to 36 in 10,000 deaths may be able to be prevented (Brand et al., 2019).

# DISCUSSION

This systematic review compiled papers investigating the extent to which reductions in air pollution exposure could be achieved by the selection of lower exposure alternative routes by active mode commuters. The review showed that, generally, using alternative routes significantly decreases active commuters' exposure to air pollution, with average reductions of 55, 42, and 30 percent for UFP, BC, and CO, respectively. The extent of the reductions varied depending on the nature of the alternative routes considered, with more significant reductions observed for those commuting through green spaces, for example, where the route involved significant separation from the road.

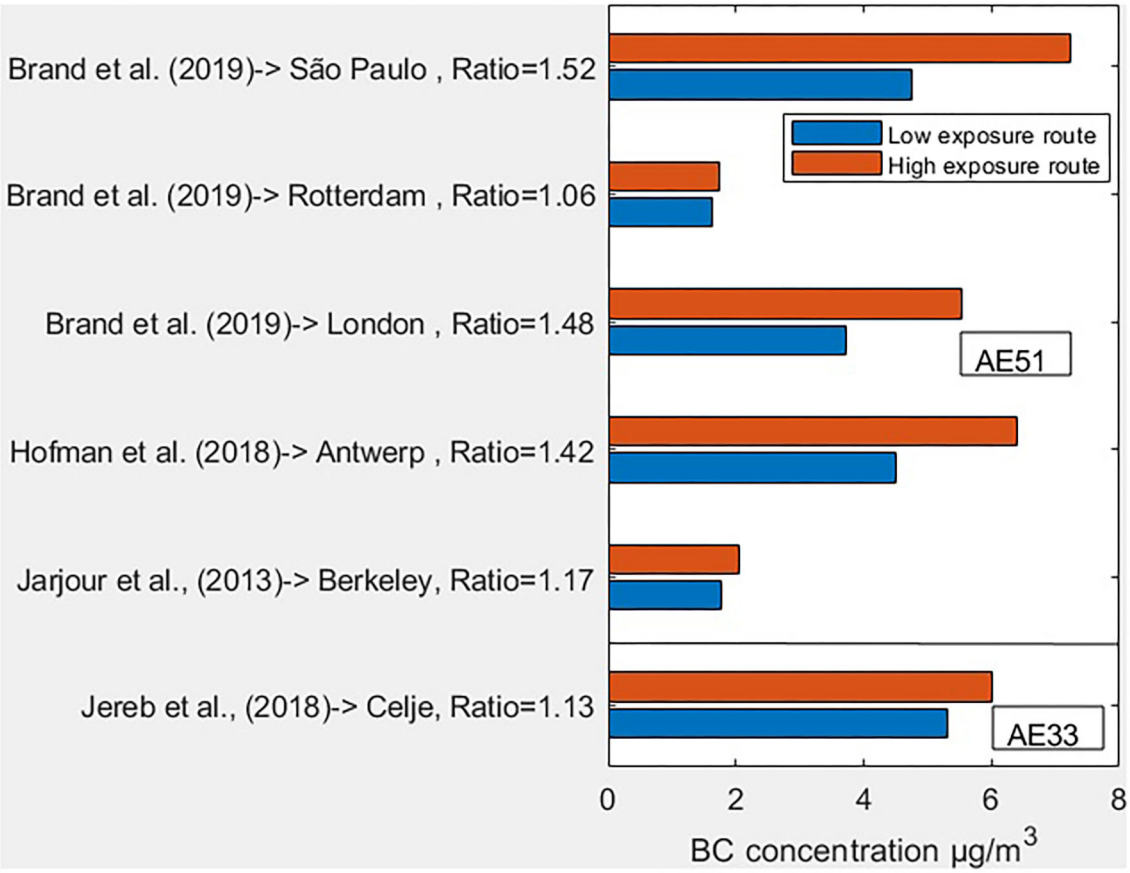


**FIGURE 3 |** Comparison of low and high exposure routes in different cities. The blue bar shows the mean of the low exposure route. The high exposure route is illustrated in orange color. Brand et al. (2019) measured BC exposure for the cyclist in three routes in three different cities. We used the mean of three low exposure and three high exposure routes for each city.

The measured exposure depends on many factors which can vary from one pollutant to another. These include the instruments used for capturing pollutant concentrations, the time of day, the season and the year of data collection, the fleet composition, and the population density. Furthermore, factors such as passing construction sites, intersections and heavy duty vehicles were shown to lead to spikes in exposure to UFP whilst active traveling (Dirks et al., 2018; Luengo-Oroz and Reis, 2019). Significant reductions in exposure can thus be achieved by avoiding these sources by, perhaps temporary, changes in routes.

While CO is mostly associated with emission exhaust from petrol cars (Kingham et al., 2013), diesel vehicles such as trucks and buses are responsible for high rates of emissions of UFP (Luengo-Oroz and Reis, 2019) and BC (Longley et al., 2019); Heavy-duty vehicles, generally powered using diesel fuel, emit higher amounts of BC (Kumar et al., 2018) and UFP (Knibbs et al., 2011) per vehicle than petrol cars. Note that the ratio of the emission factors between heavy-duty vehicles and light-duty vehicles has been estimated to be about four for BC (de Miranda et al., 2019) and up to 40 for UFP (Xiang et al., 2019). High traffic roads tend to have larger numbers of heavy-duty vehicles than roads with relatively light traffic (i.e., low numbers of vehicles of all kinds) (Jarjour et al., 2013).

The estimation of the long-term effect of exposure to black carbon in relation to route choice showed that, based on the average exposure of all studies, 17 of 10,000 deaths would be able to be prevented if active mode commuters took the associated low exposure route rather than the high exposure route for their journey to work. Based on the highest difference between the low and high exposure routes, which was recorded in Sao Paulo, it is estimated that up to 36 in 10,000 deaths are able to be prevented on the basis of the route. By comparing the impact of various levels of background concentration, it was found that when the background concentration was higher, the effect of route choice was smaller. However, if other pollutants and also short-term peaks in exposure are considered (which are commonly observed in active traveling), the number of preventable deaths could be significantly more.

It should be taken into account that active commuters are at high risk of air pollution exposure; they may inhale higher amounts of air pollution compared with other commuters, due to their close proximity to the source of air pollution, their

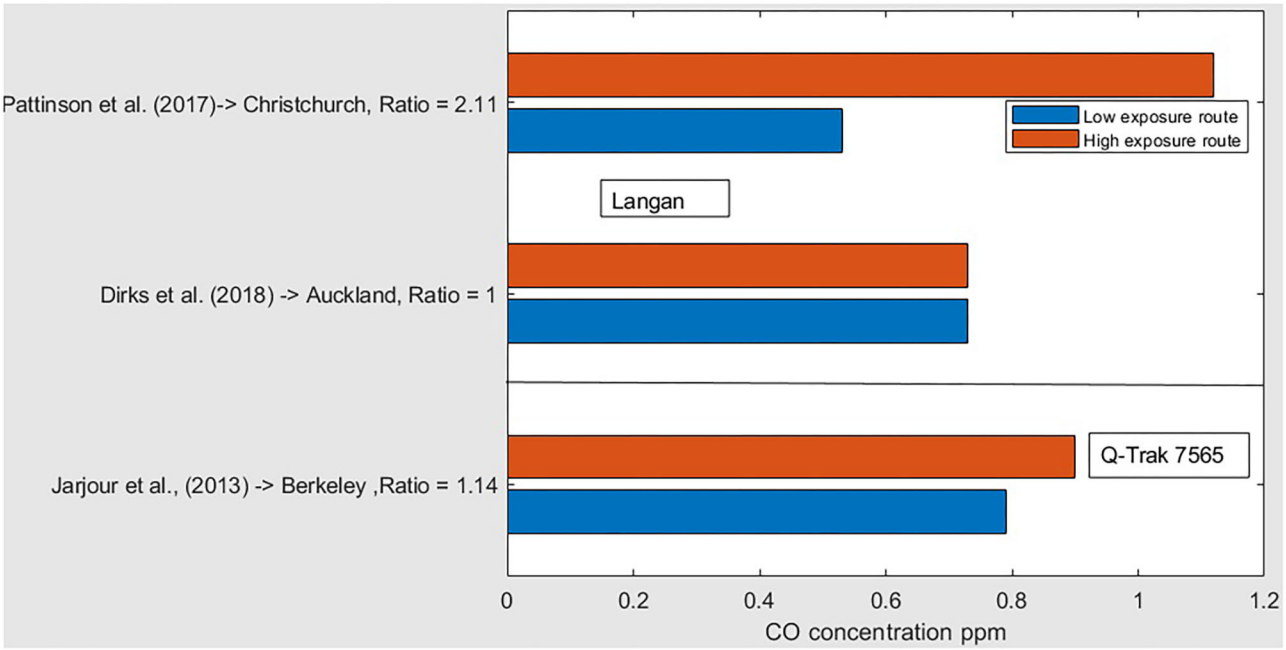


**FIGURE 4 |** Comparison of concentration of CO in low and high exposure route in the studies. High exposure is in orange color and the low exposure in blue. The ratio is the mean of high exposure divided to the low exposure route.

**TABLE 2 |** The reduction in exposure to pollutants by taking an alternative route in cycling (R = ratio of mean low exposure route to background, the unit for all numbers is $\mu g/m^3$).

| | Mean high exposure | Mean low exposure | Difference | Background ($R = 1$) | Background ($R = 2$) | Background ($R = 3$) | Background ($R = 4$) | Background ($R = 5$) |
|---|---|---|---|---|---|---|---|---|
| Celje | 6.20 | 4.90 | 1.30 | 4.90 | 2.45 | 1.63 | 1.23 | 0.98 |
| Rotterdam | 1.73 | 1.63 | 0.10 | 1.63 | 0.82 | 0.54 | 0.41 | 0.33 |
| London | 5.53 | 3.73 | 1.80 | 3.73 | 1.87 | 1.24 | 0.93 | 0.75 |
| Sao Paulo | 7.23 | 4.76 | 2.47 | 4.76 | 2.38 | 1.59 | 1.19 | 0.95 |
| Antwerp | 3.38 | 1.32 | 2.06 | 1.32 | 0.66 | 0.44 | 0.33 | 0.26 |
| Berkeley | 2.06 | 1.76 | 0. 3 | 1.76 | 0.88 | 0.59 | 0.44 | 0.35 |
| Mean | 4.83 | 3.61 | 1.21 | 3.61 | 1.81 | 1.20 | 0.90 | 0.72 |

**TABLE 3 |** Mean annual BC exposure by taking each route (L = low exposure, H = high exposure route, the unit for all numbers is $\mu g/h.m^3$, R = ratio of mean low exposure route to background).

| | Route | Celje | Rotterdam | London | Sao Paulo | Antwerp | Berkeley | Mean |
|---|---|---|---|---|---|---|---|---|
| $R = 1$ | L | 4.900 | 1.630 | 3.730 | 4.760 | 1.320 | 1.760 | 3.613 |
| | H | 4.935 | 1.633 | 3.778 | 4.827 | 1.375 | 1.768 | 3.646 |
| $R = 2$ | L | 2.516 | 0.837 | 1.915 | 2.444 | 0.678 | 0.904 | 1.855 |
| | H | 2.551 | 0.840 | 1.964 | 2.511 | 0.733 | 0.912 | 1.888 |
| $R = 3$ | L | 1.721 | 0.573 | 1.310 | 1.672 | 0.464 | 0.618 | 1.269 |
| | H | 1.756 | 0.575 | 1.359 | 1.739 | 0.519 | 0.626 | 1.302 |
| $R = 4$ | L | 1.324 | 0.440 | 1.008 | 1.286 | 0.357 | 0.476 | 0.976 |
| | H | 1.359 | 0.443 | 1.056 | 1.353 | 0.412 | 0.484 | 1.009 |
| $R = 5$ | L | 1.086 | 0.361 | 0.826 | 1.055 | 0.292 | 0.390 | 0.800 |
| | H | 1.121 | 0.364 | 0.875 | 1.121 | 0.348 | 0.398 | 0.833 |

**TABLE 4 |** Estimated attributable proportion by taking the routes based on the measured black carbon (Diff = difference in attributable proportion, L = low exposure, H = high exposure route).

| | Route | Celje | Diff (%) | Rotterdam | Diff (%) | London | Diff (%) | Sao Paulo | Diff (%) | Antwerp | Diff (%) | Berkeley | Diff (%) | Mean | Diff (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $R = 1$ | L | 24.84 | 0.15 | 9.06 | 0.01 | 19.53 | 0.23 | 24.22 | 0.29 | 7.40 | 0.29 | 9.75 | 0.04 | 18.98 | 0.15 |
| | H | 24.99 | | 9.08 | | 19.76 | | 24.52 | | 7.70 | | 9.79 | | 19.14 | |
| $R = 2$ | L | 13.64 | 0.18 | 4.76 | 0.01 | 10.56 | 0.25 | 13.27 | 0.34 | 3.87 | 0.31 | 5.13 | 0.04 | 10.25 | 0.17 |
| | H | 13.81 | | 4.77 | | 10.81 | | 13.61 | | 4.18 | | 5.17 | | 10.42 | |
| $R = 3$ | L | 9.54 | 0.18 | 3.28 | 0.02 | 7.35 | 0.26 | 9.28 | 0.35 | 2.67 | 0.31 | 3.54 | 0.05 | 7.13 | 0.18 |
| | H | 9.73 | | 3.30 | | 7.61 | | 9.63 | | 2.98 | | 3.58 | | 7.31 | |
| $R = 4$ | L | 7.42 | 0.19 | 2.53 | 0.02 | 5.70 | 0.27 | 7.22 | 0.36 | 2.06 | 0.32 | 2.73 | 0.05 | 5.53 | 0.18 |
| | H | 7.61 | | 2.55 | | 5.97 | | 7.58 | | 2.37 | | 2.78 | | 5.71 | |
| $R = 5$ | L | 6.13 | 0.19 | 2.08 | 0.02 | 4.70 | 0.27 | 5.96 | 0.36 | 1.69 | 0.32 | 2.25 | 0.05 | 4.56 | 0.18 |
| | H | 6.32 | | 2.10 | | 4.97 | | 6.32 | | 2.01 | | 2.29 | | 4.74 | |

often longer travel times and their increased minute ventilation (Bigazzi and Figliozzi, 2014; Cepeda et al., 2017; Targino et al., 2018). Additionally, exposure to spikes in pollution (a high concentration of air pollution for a short period of time) during walking or cycling may also result in adverse health effects (Michaels and Kleinman, 2000; Dons et al., 2019). However, it has been reported that as long as the average air pollution exposure throughout the commute remains below 1.1 and 2 times the background level for a cyclist and walker, respectively, on average, the benefits of active travel can be considered to outweigh the health risk of air pollution exposure (Johan de Hartog et al., 2010). However, exposure to traffic-related pollution may negate the benefits of active travel when commuting along high-trafficked routes, particularly for people with pre-existing conditions such as COPD and ischemic heart disease (Sinharay et al., 2018).

There are some limitations associated with this review that need to be recognized. Although the search terms used were comprehensive, the review was limited to articles written in English; non-English studies were excluded. The lack of Asian and African studies is acknowledged. A small number of cities in this study were analyzed. All of the cities except one (Sao Paulo) were from developed countries, indicating a lack of studies in least developed and developing countries. However, had a larger number of studies from cities from developing, least developed as well as developed countries been included in the study, a larger range of differences in exposure between low and high exposure routes may have been found. In this study, for each of the publications included in the review, only two routes were investigated: a high exposure route and a low exposure route. However, many active commuting routes include a mix of low and high exposure sections along the route, sometimes with choice available, and sometimes not. Thus, is may not always be possible to choose a low exposure route for the whole of the journey. In the present study, only the air pollution exposure along the routes was considered, with other factors influencing an active commuter's route choice, including the presence of trees and the route topography, ignored.

The Health Impact Assessment aspect of this study included a number of assumptions. For example, we assumed that the commuter spends 1 h per weekday traveling. Additionally, the estimates of health impacts are based only on what is known about the health effects associated with one pollutant (BC). Had other pollutants been considered, the results might have been different. However, BC is considered to be one of the pollutants most strongly associated with adverse health outcomes (Magalhaes et al., 2018). Additionally, only the long-term health impacts were considered; the short-term effects induced by exposure to spikes in air pollution, should also be taken into account in evaluating the risks associated with high exposure routes compared with low exposure routes.

It is also noted that there are limitations associated with the use of AirQ+ for estimating the health risks. For example, the estimate of relative risks rely on studies taken place in situations of high pollution (World Health Organization, 2020a). Also, the model equations are based on studies carried in Western Europe and North America (World Health Organization, 2020a), with little input provided from other continents with cities also affected by traffic-related air pollution. Therefore, model predictions may not be reliable for these regions. The model also assumes that ambient concentrations are reliable indicators of population exposure (World Health Organization, 2020a). Thus, invariably, there is a risk of, introducing bias in the estimation as a result (Evangelopoulos et al., 2020). Furthermore, the equations used for estimating the health risks are based on concentration-response functions in which many assumptions have been made. This includes issue of transferability, the generalizability of health impacts from one population to another, and the use of individual pollutants derived from single-pollutant statistical models rather than from a mixture of pollutants (World Health Organization, 2020a), which may or may not be realistic, depending on the specific situation.

This research has identified many questions that are also worthy of further investigation. In particular, future research is needed to examine more closely the links between the nature of vehicle fleets and traffic congestion, and their impact on air pollution exposure. Additionally, there is limited information on the health effects associated with exposure to short-term spikes in air pollution. Thus, there is abundant room for further progress to be made in terms of understanding the health consequences

of exposure to the intermittent spikes in concentration typical of traffic pollution concentration traces.

Furthermore, there remains a lack of research regarding children and elderly people, especially given these groups are more vulnerable to the adverse effects of air pollution (Friedrich, 2018). Children's organs are not fully developed, hence their respiratory and immune systems are less efficient than those of adults (Zielinska and Hamulka, 2019). Moreover, epidemiological studies suggest that excess mortality due to air pollution is greater among older age groups (especially 75+) (Simoni et al., 2015).

The review also suggests that there is a lack of studies focused specifically on walking. Walkers are more susceptible to traffic-related air pollution due to the long travel time as walking generally takes longer to travel the same distance compared to other modes of transport, and because of walkers' close proximity to traffic. Walkers are also at risk of exposure to short-term spikes since there are no physical barriers between the source of traffic pollution and pedestrians (Dirks et al., 2016). Therefore, more research is required to determine the benefits of choosing alternative routes with respect to exposure amongst children and the walking mode of transport.

It is also acknowledged that in many cities, particularly in developing or least developed countries, the selection of low exposure routes and the associated avoidance of exposure to air pollution might simply not be feasible. In the short term, an economic alternative could be to encourage active travelers to wear effective masks, such as N95, that can result in significant reductions in exposure to airborne particles (Kyung et al., 2020). This could be particularly effective for susceptible groups of the population and people using various open vehicles (e.g., motor scooters, open delivery vehicles, etc.) who are exposed to large amounts of traffic pollution due to their mode choice and the amount of time spent in the transport microenvironment. It is noted that wearing a mask should be considered to be a short-term solution to limit exposure to air pollution exposure in anticipation of more effective solutions, including the widespread introduction of clean vehicle technology.

## CONCLUSIONS

The main goal of the current study was to review studies investigating the role of route choice on the air pollution exposure of active mode commuters. The results clearly indicate that significant reductions can be obtained by choosing low traffic routes away from traffic congestion. Moreover, identifying the cleanest path from the point of view of air pollution is important in active commuters' route planning, as even a modest reduction in daily air pollution exposure can lead to a significant reduction in exposure to a population as a whole, or for an individual when considering their cumulative exposure over a period of years. People, especially those who walk/cycle the same route every day, would benefit from information about air pollution for the purpose of route planning.

Governments play a crucial role in helping to reduce active commuters' exposure to air pollution by the provision of transport infrastructure that is conducive to improved localized air quality. Although the most important factor in active commuters' route choice is often the distance involved or the number of directional changes required, route choice is a complex function of other parameters, considered in varying amounts, including safety aspects and route aesthetics. Planners should consider identifying and targeting paths of low exposure, in addition to active commuters' influencing factors regarding preferred routes when considering further infrastructure development, thus encouraging more journeys along such routes. Furthermore, active commuters themselves may also have an important role to play, with opportunities for community participation via the use of mobile apps to help in finding the least polluted routes and in raising awareness regarding air pollution (Mahajan et al., 2020). This would help to increase the levels of participation in active transport and makes the city more liveable (Koh and Wong, 2013) while promoting active commuters' health.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

Data extraction was conducted by MR. It was subsequently sent to KD for cross-checking and consultation. MR screened all of the papers and carried out the health impact assessment. The extracted data were crosschecked by KD who monitored all levels of the screening. AW suggested adding a health impact assessment. KD supervised the project. All authors discussed the results and contributed to the final manuscript by providing critical feedback.

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