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Risk of fire in heavy vehicles in steep road-tunnels

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The present study examines the relationship between steep grades in road tunnels and the risk of heavy vehicle fires. The results show that fire risk in road tunnels increases with increasing maximum grade and with increasing length of steep grades. At grades above 7 percent, fire risk increases far more than at other grades, and 7 percent can be regarded as a “breakpoint” of increasing fire risk, especially among heavy vehicles. Subsea tunnels have far higher fire risk than other tunnels, mainly because they have both long and steep grades. The four most fire-prone subsea tunnels have grades over 7 percent that are more than 5 km long. These are the tunnels Oslofjord, Eiksund, Bømlafjord, and Byfjord. Most heavy vehicle fires in tunnels are caused by technical problems, mostly related to the engine. Overheating of the engine is often related to prolonged driving with a retarder downhill, followed by prolonged uphill driving. This pattern is typical in subsea tunnels. Overheating of engines is also often related to poor vehicle maintenance and insufficient vehicle inspections. To reduce heavy vehicle fire risk in tunnels, the most effective measure would be not to build tunnels with long steep grades (or to ban trucks from such tunnels). Other relevant measures to reduce vehicle fire risk include improved vehicle maintenance and inspections, as well as automatic fire extinguishing technology. Improved tunnel fire management, such as early detection and evacuation strategies, can contribute to avoid the most serious consequences. The introduction of new energy carries in the truck fleet, such as electric and hydrogen trucks, will affect both fire risk and fire management for heavy vehicles.

KEYWORDS

road tunnel, fire, heavy vehicle, gradient, subsea

1 Introduction

1.1 Background

Norway has more road tunnels than most other countries. There are over 1,250 road tunnels in Norway. Road tunnels are usually at least as safe as comparable open roads without intersections, exits, and pedestrian and bicycle traffic (Amundsen and Engebretsen, 2009). Nevertheless, road tunnels deserve special attention from a traffic safety perspective because vehicle fires may have disastrous consequences (Mashimo, 2002; Caliendo et al., 2013; PIARC World Road Association, 2008; Mashimo, 2002; Jenssen et al., 2006). This is shown by the three catastrophic fires in Central Europe, in the Mont Blanc and Tauern tunnels in 1999 and in the St. Gotthard tunnel in 2001. These fires claimed 62 lives.

Potentially catastrophic vehicle fires in road tunnels often start in heavy vehicles[1]. These have often fuel and cargo that can produce much heat and smoke. The most serious vehicle fires in tunnels in Norway in recent years started in heavy vehicles, often in long and/or steep tunnels. They were often caused by technical problems, for example, the fires in the Oslofjord tunnel in 2011, 2017 and 2021 the fires in the Gudvanga tunnel in 2013, 2015 and 2019, the Brattlitunnel in 2013 and the Skatestraumtunnel in 2015 (Nævestad and Blom, 2023). In the latter, a truck carrying 16,500 L of fuel burned. In several of these incidents, there have been dozens of road users inside the tunnels, who had to evacuate under very demanding conditions, partly because these are long single-tube tunnels. Fortunately, no lives have been lost.

Both Norwegian (Nævestad and Meyer, 2012; 2014; Nævestad and Blom, 2023) and international research (Haack, 2002; OECD, 2006) show that heavy vehicles are overrepresented in road tunnel fires. Heavy vehicles account for 14 percent of traffic in tunnels that are part of the Norwegian national road network, but they were involved in 38 percent of fires in these tunnels (Nævestad and Meyer, 2014).

Technical problems (overheated brakes and engines) are the most common cause of fires and accidents in heavy vehicles. This is particularly true in steep tunnels, which are significantly overrepresented among vehicle fires and accidents in Norwegian road tunnels. Norway has 41 subsea road tunnels, all of them with steep grades. In total, 5 percent of Norwegian road tunnels have grades above 5 percent. These tunnels account for 38 percent of fires and incidents in 2008–2021 (Nævestad and Blom, 2023).

Among the Norwegian subsea tunnels, some are more prone to fire than others. Nævestad and Blom (2023) found that only four subsea road tunnels accounted for half of all fires and incidents in tunnels with a steep grade (112 out of 226 fires) in 2008–2021. These are the Oslofjord Tunnel (39 fires and incidents), Bømlafjord Tunnel (32), Byfjord Tunnel (23), and Eiksund Tunnel (17).

Given the fire risk of heavy vehicles in steep road tunnels, it is important to develop effective measures to reduce the risk of vehicle fires. The Norwegian Tunnel Safety Regulations require compensatory measures in tunnels with more than a three percent grade, and they do not allow grades above 5 percent, unless this is the only geographically possible solution.

We found only one empirical study from a country other than Norway, that has investigated the relationship between fire risk and grades in tunnels. Casey (2020) has investigated the relationship between grades in tunnels and the number of fires in Australia. This study did not find any such relationship. However, the tunnels in this study have only short steep grades, and none of the tunnels has a grade above 8 percent.

The most detailed results are provided in a Norwegian study (Høye et al., 2019) and Nævestad et al. (2024). The study by Høye et al. (2019) is based on fires and near-fire incidents in Norwegian road tunnels in 2008–2015. Nævestad and Blom (2023) and Nævestad et al. (2024) updated this study and use data from 2008 to 2021 for both heavy and light vehicles. These studies find that fire risk is about doubled in tunnels with a maximum grade of 3-6 percent compared to flatter tunnels, and that fire risk increases even more in tunnels with grades of 7 percent or more. For heavy vehicles, fire risk increases already from a maximum gradient of 3-4 percent, and rises steeply at higher grades. Njå et al. 2022, who also studies Norwegian road tunnels, found that grade, tunnel length, heavy vehicle AADT and subsea tunnels contribute to vehicle fires in tunnels. The most important predictor for fires in heavy vehicles is whether or not a tunnel is subsea tunnel.

1.2 Objectives

The present study aims to answer the following questions:

1) Is there a causal relationship between tunnel grades and heavy vehicle fires?
2) Which measures may compensate for the high fire risk in steep tunnels?
3) Will there be changes during the next 10–20 years that will affect the risk of heavy vehicle fires in steep tunnels?

The concept of risk. From a preparedness perspective, risk is usually defined as the product of probability and severity of consequences. However, in the present study, risk refers to the number of fires per million vehicle kilometers. This is a road safety understanding of risk, which also is applied in statistical modeling of tunnel fires, similar to crash modeling (Elvik and Høye, 2022).

1.3 Previous research

1.3.1 Factors affecting fire risk in road tunnels in general

Høye et al. (2019) and Nævestad et al. (2024) developed statistical models for road tunnels in Norway to predict numbers of vehicle fires, accidents, and breakdown as a function of tunnel characteristics, including traffic volume, length, number of tubes, speed limit, and grades. The main results are described in the following.

Traffic volume: International research shows that traffic volume is a key factor affecting the risk of vehicle fires in road tunnels (OECD, 2006). In line with this, Høye et al. (2019) and Nævestad et al. (2024) found that increasing volume leads to more fires, accidents, and breakdowns, but the numbers increase far less than proportionally to traffic volume. On average, if volume increases by 10 percent, the number of fires and accidents increase by about five percent. Thus, as volume increases, risk decreases. However, volume is unlikely to be a protective factor in itself, but is it likely to be related to other factors that are related to fire risk, such as vehicle speed and type of tunnel.

Heavy vehicles: One of the main conclusions of Nævestad et al. (2016) is that heavy vehicles are overrepresented in road tunnel fires. On average, 14 percent of vehicles driving in Norwegian national roads in tunnels, are heavy vehicles. However, heavy vehicles are involved in 40 percent of fires in tunnels.

International research also shows that heavy vehicles are overrepresented in road tunnel fires. For example, in the St. Gotthard Tunnel, there were 42 vehicle fires in the years 1992–1998. Half of these involved heavy vehicles, although heavy vehicles only account for 15 percent of all traffic in the tunnel (Haack, 2002). Njå et al.

1 In this study, "heavy vehicles" refers to large trucks (over 7.5 ton)

(2022) found that an increase of the proportion of heavy vehicles by 10 percent is associated with a 14 percent increase of heavy vehicle fires in subsea tunnels, but only with a 5 percent increase in other tunnels.

Tunnel length: Høye et al. (2019) and Nævestad et al. (2024) found no monotonous relationship between tunnel length and fire risk. Norwegian tunnels with a length of 4–10 km have higher fire risk than other tunnels. However, most steep subsea tunnels are in this category, and length in itself is not related to fire risk.

Accidents as causes of fires: According to "The Handbook of Tunnel Fire Safety", more than 90 percent (55 out of 61 cases) of fires in road tunnels are caused by traffic accidents, especially rear-end collisions (Beard and Carvel, 2005). This contrasts with the survey by Nævestad et al. (2016), in which accidents were the cause of only 9 percent of fires and incidents. They also found that accidents more often caused fires in light vehicles than in heavy vehicles.

1.3.2 Factors affecting the risk of heavy vehicles fire in steep road tunnels

Heavy vehicle fires in steep road tunnels are associated with the same factors as described above for fires in road tunnels in general. However, there are several more specific factors that are relevant for heavy vehicles driving on roads with steep grades.

Grades. Fire risk increases with both the steepness and the length of steep grades in tunnels. For example, a tunnel with a 5% or greater gradient over 6 km has three times as many fires than a flat tunnel, while a 7% or greater gradient over the same distance results in ten times more fires on average.

Tunnel length: Tunnel length itself is not likely to be relevant for heavy vehicle fire risk, as described in the section above.

Traffic volume and the proportion of heavy vehicles: Road tunnels with high traffic volumes have more fires on average (OECD, 2006), and heavy vehicles have a higher risk of fire, especially in steep tunnels. However, Høye et al. (2019) and Nævestad et al. (2024) did not find a relationship between the proportion of heavy vehicles and the number of fires, when controlling for traffic volume and other factors. This is surprising, considering that heavy vehicles are overrepresented in fires in steep tunnels. Njå et al. (2022) found that a 10 percent increase in the proportion of heavy vehicles in subsea tunnels is associated with a 14 percent increase in the number of fires in heavy vehicles.

Heavy vehicle brakes and engines: Nævestad and Blom (2023) summarize the causes for 23 heavy vehicle fires and near-fires in steep tunnels as follows. The most common factors were engine problems and leakages from the engine. These accounted for 10 of the 23 incidents. Only two incidents were related to wheels or tires. In 11 cases, the cause was unspecified. Theoretically, both heating of the engine on uphill grades and heating of the retarder and brakes on downhill grades can contribute to fires. Both factors can explain why the length of grades for heavy vehicle fire risk is important.

Vehicle age and standard: In Norway, many foreign (especially Eastern European) trucks are old and have two axles, weaker engines (Safetec, 2011). A lower technical standard of trucks in the new EU countries is also highlighted by OECD (2006:12) as a contributing factor to vehicle fires. Old heavy vehicles often lack engine brakes, so-called retarders (Buvik et al., 2012). However, these studies are relatively old, and there is a need for updated knowledge.

Heavy loads and steep grades are especially challenging for trucks with a low technical standard. Safetec (2011) points out that Scandinavian trucks are better adapted to Scandinavian topography, which often is hilly and curvy. They have three axles, more powerful engines, and better retarders and brakes. This reduces the risk of overload and overheating on steep roads (Safetec, 2011). On the other hand, heavy vehicles from EU-countries have a lower permissible maximum load (40 ton) than Norwegian heavy vehicles (50 ton; Buvik, 2012). This should reduce the risk of overloading on steep grades.

Heavy vehicle drivers' competence and experience. Competent and experienced drivers are better prepared to drive under difficult conditions, such as on long and steep grades in tunnels. They are more likely to use retarder and brakes correctly, to choose an adequate speed, and to discover critical situations, such as overheating of the brakes (Nævestad and Blom, 2023).

2 Methods

2.1 Models to predict numbers of fires

2.1.1 Data

The current study is based on data from the years 2008–2021, with information on vehicle fires in Norwegian road tunnels, including both heavy and light vehicles (Nævestad and Blom, 2023; Nævestad et al., 2024)[2]. In the following, "fires" always includes both actual fires and near-fire incidents.

One of the main aims of the study was to investigate possible "breaking points" in the relationship between grade and fire risk (i.e., grades where the risk of fire increases significantly). Therefore, we investigated how the maximum gradient in the tunnels and the length of steep grades are related to vehicle fires. We performed different types of analyses:

- Fires per million vehicle kilometers: We calculated the number of fires per million vehicle kilometers and compared different groups of tunnels (e.g., tunnels with different maximum grades).
- Model calculations: We calculated statistical models that predict the number of fires per tunnel, based on tunnel characteristics, such as grade, speed limit, number of tubes, traffic volume, proportion of heavy vehicles and subsea tunnels. These are the same variables as used in Høye et al. (2019), except for subsea which was not included in 2019. We calculated separate models for different grade predictors.

All analyses were conducted for the total number of vehicle fires and the number of heavy vehicle fires.

Descriptive statistics providing general information about the tunnels (including traffic volume, traffic work and number of fires) the original Norwegian report that the study is based on. The original report can be found here: (Nævestad et al., 2024).

2 Tunnels opened after 2015 (84 tunnels) are not included in the analyses. For these tunnels, detailed information about the variables included in the model calculations is not available

2.1.2 Negative binomial regression and statistical significance

The statistical models for predicting numbers of fires are based on Negative Binomial (NB) regression (Lord and Mannering, 2010). The unit of analysis in all models is one tunnel in 1 year. In the following, we describe the model form and predictors variables, based on Høye et al. (2019).

The model form for negative binomial (NB) is:

$$E(n) = e^{\sum_i Predictor_i * Coeff_i}$$

E(n) is the predicted number of fires in a tunnel. Predictors are traffic volume and other tunnel characteristics; i is the subscript for the predictors.

Negative binomial models consider overdispersion in the data, i.e., the dispersion is greater than expected if the distribution of the number of accidents on individual road segments had followed a Poisson distribution. A negative binomial distribution is determined by two parameters, the mean and the overdispersion parameter. The overdispersion parameter is calculated as a variable (instead of a fixed) parameter. In the present study, its predictors are tunnel length and traffic volume. Thus, overdispersion is allowed to vary with tunnel length and volume. This avoids problems that often arise with a fixed overdispersion parameter (Geedipally et al., 2009; Hauer, 2001; Lord and Park, 2008; Miaou and Lord, 2003).

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Most predictors in the models are defined as dummy variables, i.e., they can only have one of two possible values. For variables with multiple categories, one dummy variable is defined for each category (e.g., "speed limit 70 km/t" vs "other" in one variable, "speed limit 80 km/t" vs "other" in another variable, *etc.*). The advantage of dummy variables is the ability to capture non-linear relationships between variables like speed limit and the number of fires, rather than defining a single numerical variable.

For dummy variables, the coefficients can be directly used to calculate the change in the dependent variable as a function of the predictor variable. The relative number of fires on roads with grade X compared to roads with a reference grade (flat, i.e., below 2%) is calculated as:

$$Rel.N\ of\ fires = e^{Coeff}.$$

Coeff. is the coefficient for grade X. For example, if the coefficient for "grade five percent or more" is 0.328, this means that tunnels with a grade of five percent or more have $e^{0.328}$ = 1.388 times as many fires as roads in which all grades are below five percent (all else being equal).

Traffic volume is available in terms of AADT (Annual Average Daily Traffic). The volume predictor in our models is the natural logarithm of AADT, i.e., Ln (AADT). The relative number of fires in a tunnel with volume X, compared to a tunnel with traffic volume Y, can be calculated as a function of volumes X and Y, and the coefficient for Ln (AADT):

$$Rel.N\ of\ fires = \frac{e^{Ln(X)*Coeff}}{e^{Ln(Y)*Coeff}}$$

The proportion of heavy vehicles is included as an additional predictor in all models.

Statistical significance: The coefficients that are estimated for all predictors in the statistical models, can have values both above and below zero. A value of zero means that predictor and number of fires are completely unrelated. If a coefficient that is greater or smaller than zero is statistically significant, this means that it would be very unlikely if its "true" value was zero.

Statistical significance depends on the size of the observed effect (how much the coefficient deviates from zero) and the size of the dataset. In a large data set, even coefficients that are close to zero may become statistically significant. Therefore, we regard both statistical significance and the actual values of coefficients when we interpret model results.

2.1.3 Data

All analyses are done at tunnel level, i.e., one tunnel for 1 year is one unit of analysis. The following table provides an overview of the variables included in the model calculations.

2.1.4 The tunnels

Information about all tunnel-characteristics, including exposure (Table 1); has been extracted from the Norwegian digital road map service "Vegkart"[3]. Missing information was found as far as possible with help of Google, Wikipedia or Google Maps. Information on grades has been supplemented by information from the Norwegian Public Roads Administration. The Norwegian Public Roads Administration also collected information on twin tunnels in urban vs rural areas.

The unit of analysis in the models is one tunnel in 1 year. Tunnels consist often of several elements in the original data:

- Twin tunnels (tunnels with two parallel tubes, see Table 1) are regarded as one tunnel, and twin (vs single) tunnel was included as a predictor in the models. Traffic volume in twin tunnels has been calculated as the sum of the volumes in both tubes. In the Opera Tunnel, all tubes were combined, except for one secondary tube at Bjørvika. The Fosskollentunnel consists of three tubes, but being the only three-tube tunnel, it is treated as a twin tunnel.
- Consecutive tubes are sometimes registered as separate tunnels in vegkart, but they are combined and treated as one tunnel.
- Tunnels connected by roundabouts are mostly combined and treated as one tunnel. Two tunnels, Butunnellen and Karmøytunnelen, have three tubes which are connected by a roundabout in the middle. Each of these are treated as one tunnel. In Tromsø, there are three tunnels which are connected by a roundabout which is part of the tunnels

3 https://www.vegvesen.no/vegkart/

TABLE 1 Overview of the variables included in the model calculations for tunnel fires.

	Type	Explanation
Dependent variable		
- Fires	Num	Fire and near-fire incidents (smoke without fire)
Exposure variables		
- Tunnel length	Num	Tunnel length in number of meters; calculated using road reference in Road Map (distance between first and last meter). Tunnel length is included in the models as "exposure variables", i.e., coefficient set to equal one in all models
Predictor variables		
- AADT	Num	Natural logarithm of the Average Annual Daily Traffic (Ln (AADT)); includes all motor vehicles)
- Heavy vehicle percentages	Num	Heavy vehicle volumes are not available; we used the share of long vehicles (length 5.6 m or more) in percent as a proxy variable
- Year		Year
- Type of tunnel	Dummy	Single tunnel (one tube, normally with traffic in both directions) vs twin tunnel (two tubes, with traffic in only one direction per tube)
- Gradient		*(only one gradient variable per model)*
o Length with at least 5/7 percent grade	Num	Two variables: Length of tunnel with at least 5%-grade and length of tunnel with at least 7%-grade
o Max. Grade	Num	Maximum grade (percent) in the tunnel
o Max. Grade more than 5/7 percent	Dummy	Two dummy variables: Max. grade at least 5 percent (vs not) and max. grade at least 7 percent (vs not)
o Max grade more than 2/3/4/5/6/7/8 percent	Dummy	Eight dummy variables: Max. grade at least 2 percent (vs not) and max. grade at least 3 percent (vs not), *etc.*,
- Height	Dummy	Signposted height of the tunnel ("free height"), above (vs below) 4.5 m
- Ramp in tunnel	Dummy	At least one ramp (vs no ramp) in the tunnel
- Subsea tunnel	Dummy	Subsea (vs other) tunnel

(Sentrumtangenten, Langnestunnelen and Breivik). These tunnels are treated as three separate tunnels because they have very different volumes.
- Ramps are not included in the analysis.

Information about the tunnels' opening year was found in road maps and, in case of missing information, by internet searches (mostly on Wikipedia).

Lengths of tunnels are calculated from road references (as the difference between "to meter" and "from meter").

All tunnels are included in all analyses either from the year after the opening year or from the year after major changes (e.g., if a tunnel was extended in length or if a second tube was built). If a tunnel was closed during the study period, it was included until the last year before closure.

2.1.5 Traffic volume

Traffic volume in tunnels is defined in two predictors:

- AADT: Total traffic volume (all motor vehicles; Ln (AADT) as model predictor)
- Heavy vehicle percentage: Defined as the share of vehicles with a length above 5.6 m; when AADT is measured, heavy vehicles are not recorded; instead, vehicles are divided into "short" and "long" vehicles. All heavy trucks will be recorded as "long vehicles"; some other vehicles that are not heavy trucks will also be included in this category, such as buses, but they will only be a minority.

Traffic volume in twin tunnels: In twin tunnels, traffic volume applies to both tubes combined. Since volume for twin tunnels is sometimes recorded per tube, and sometimes for both tubes combined, we checked all twin-tunnels manually to ensure that the correct volume is used.

AADT: Information on traffic volume (AADT) is available for most tunnels from 2017 to 2022. For some tunnels, information on AADT is available for only 1 year. For tunnels with missing information on AADT in 2017, information from a previous year within the analysis period, was used. For years without information on AADT, we estimated AADT with trend adjustment:

1) To replace missing AADT in years before the first available AADT, we assumed that volume has changed as much as on average on all Norwegian roads (Høye et al., 2019).
2) To replace missing AADT in years in between 2 years with available AADT, we used linear interpolation.
3) For tunnels with missing AADT after 2017, AADT is calculated with the same trend adjustment as described in point (1).

Missing values for heavy vehicle percentage are replaced by estimated values in the same way as for AADT.

2.1.6 Fires

Information on the number of fires per tunnel and year is based on data collected by Nævestad and Blom (2023) of fires in Norwegian road tunnels in 2008–2021. Fires include both actual fires and near-fire incidents. There were 613 such fires, and these were added to the data file based on the tunnel identification number.

2.2 Qualitative interviews

2.2.1 Informants

We interviewed 23 professionals in individual and group interviews with discussion in the fall of 2023. Most interviews were conducted digitally on Microsoft Teams. Two of the interviews were not individual interviews, but "group interviews", with maximum after two people The reason for conducting interviews with two people at the same time is that these were people from the same organizations.

The informants were asked to participate via email. Informed consent was obtained in advance of the interviews. A semi-structured interview guide was used, meaning that interviews were structured around some predefined themes. The guide is indicative, in the sense that it was possible to adapt questions and the order of the questions, and to follow up on new information or themes that came up during the interview.

The 23 informants interviewed are people from industry organizations, heavy truck drivers, insurance, national accident investigation, car manufacturer" accident investigation, fire inspectors from fire departments near fire-prone road tunnels, tunnel managers, truck manufacturers, truck mechanics, people involved in heavy truck training and people who are experts in analysis and measures in European tunnels that have had a strong focus on fire prevention (St. Gotthart, Tauern, San Bernadino, Mont Blanc). The latter are either tunnel managers or people involved in fire safety work in these tunnels.

2.2.2 Analysis

The purpose of the interviews was to gain insight into the following topics: 1) Causal relationships between tunnel grades and heavy vehicle fires, 2) Possible compensatory measures, and 3) Developments that may have changed fire risk in steep tunnels during 2008–2021, and expected developments over the next 10–20 years.

Qualitative in-depth interviews are particularly suitable when there is a need for in-depth knowledge on a topic (Kvale and Brinkmann, 2015). We conducted a thematic analysis of the interviews. This is a systematic method for identifying main themes in text material (Braun and Clarke, 2006). In the first step of the analysis, the interviews were read several times and coded. The codes were then systematized and arranged into rough categories. In the next step, the resulting categories were reviewed. Some categories described the same overarching concept and were merged, and others stood out as subcategories under a larger overarching factor.

3 Results

3.1 Threshold values for grades

3.1.1 Maximum gradient: break points at 7 percent maximum gradient

Fires per million vehicle kilometers: Figure 1 shows relative numbers of fires per million vehicle kilometers for all vehicles and for heavy vehicles in 2008–2021 by maximum grade in the tunnels. Relative numbers of fires are calculated in relation to "flat tunnels" where the maximum gradient is below 2 percent. The relative number of fires in flat tunnels is therefore per definition equal to 1.0. The results show, for example, that tunnels with a maximum grade of 7 percent have 8.14 times as many heavy vehicle fires per million heavy vehicle kilometers as flat tunnels.

Maximum grades are simply the steepest grade in each tunnel, regardless of its length. They include both short and long grades. Tunnels with very short steep grades were checked manually, and steep grades were removed when they appeared unrealistic (e.g., 4 m with a 12-percent grade in an otherwise flat tunnel).

Tunnels with a maximum grade between 3 and 6 percent have more fires than flat tunnels, especially more heavy vehicle fires. However, there is no systematic relationship between the maximum gradient and the number of fires between 3 and 6 percent. This means that we do not see a gradual increase in risk of vehicle fires for each increase in maximum gradient, e.g., from three to four or from four to five percent.

Tunnels with a maximum gradient of 7 percent or more, have far more fires than tunnels with less steep grades, and heavy vehicle fires increase even more than the total number of fires. However, there is no systematic relationship between maximum grades above 7 percent and the number of fires. This is probably related to the data, i.e., the tunnels in Norway. Few tunnels have grades over 7 percent, and the relative numbers of fires for these tunnels will largely be influenced by chance. For example, there is no reason to assume that tunnels with a maximum gradient of 8 percent are safer than tunnels with maximum grades of 7 or 9 percent.

In summary, the results indicate that 7-percent grades are a relevant breakpoint in the relationship between maximum grade and fires. I.e., fire risk is far higher at grades above than below 7 percent.

The relationship between maximum grades below 7 percent and fires is discussed below.

Statistical models with dummy variables for maximum grade: Figure 2 shows the results from model calculations where maximum grade is among the predictor variables. We have calculated relative numbers of fires, with flat tunnels as reference. In contrast to the relative numbers of fires per mill. vehicle kilometers, the models control for several other tunnel characteristics. The estimated relative numbers of fires can therefore be interpreted as "if all else is equal". For example, if the results show that a group of tunnels

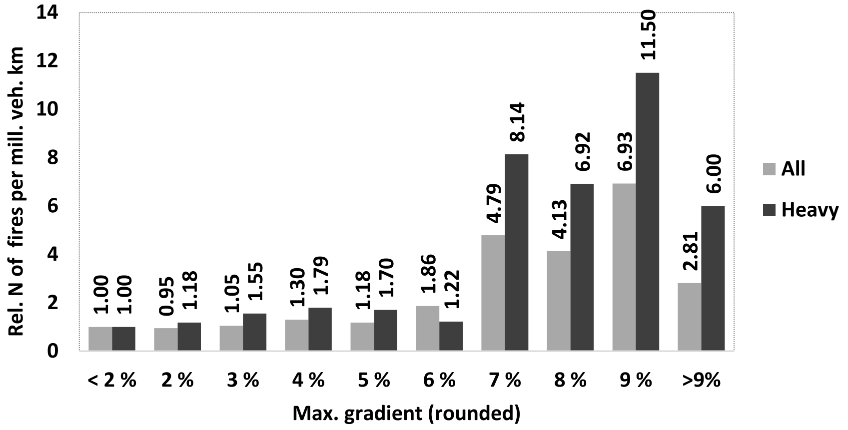

FIGURE 1
Relative numbers of fires per million vehicle kilometers by maximum grade (maximum grades are rounded; for example, "2%" includes all maximum grades from 2.00 to 2.99 percent).

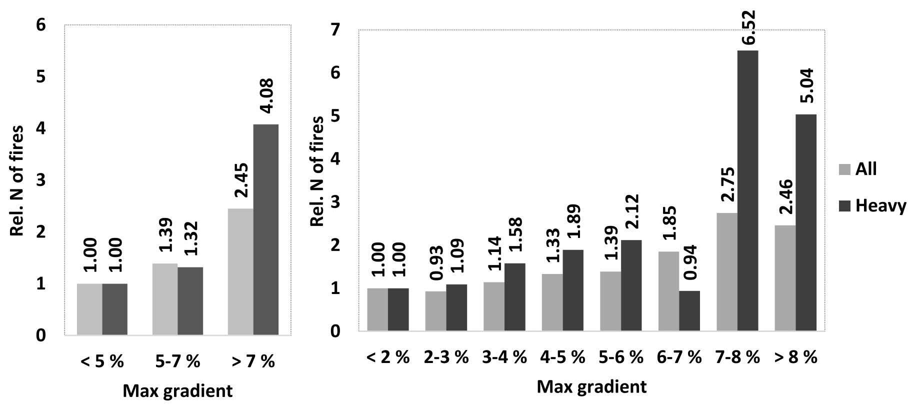

FIGURE 2
Relative number of fires in model calculations with dummy variables for maximum gradient, models for all vehicles and for heavy vehicles (explanations see text).

has "twice as many" fires than the reference, this refers to otherwise equal conditions, such as same volume, same type of tunnel, same speed limit, *etc*.

Figure 2 shows results from two types of models. In the first type of model (left in the figure), tunnels were divided into three categories by maximum grade. In the second (right in the figure), they were divided into 8 groups. Both types of models were developed for all vehicle fires and for heavy vehicle fires.

The models of the first type (three groups; left in Figure 2) show:

- Tunnels with a maximum grade of 7 percent or more have more fires, especially more heavy vehicle fires, than other tunnels (statistically significant for all and heavy vehicle fires).
- Tunnels with a maximum grade of 5-7 percent also have more fires than less steep tunnels, but fewer than the tunnels with maximum gradient of 7 percent or more and without difference between total and heavy vehicle fires. The difference to flat tunnels is statistically significant only for all vehicle fires, and not for heavy vehicle fires. The latter is due to few heavy vehicle fires in such tunnels.

The same models show that subsea tunnels have far more fires than other tunnels. They have 70 percent more fires in total, and 33 percent more heavy vehicle fires. Since the models include maximum grade as a predictor, these results indicate that steep grades are not the only factor that contributes to the high fire risk in subsea tunnels. One such factor is probably the length of the steep grades; subsea tunnels have mostly long steep grades, while steep grades in other tunnels often are shorter.

The models of the second type (8 tunnel categories, right in Figure 2) show the same pattern as the analyses for fires per million vehicle kilometers:

- Tunnels with maximum grades of 3-6 percent have more fires than flat tunnels, and the number of fires increases with increasing maximum grade. The small number of heavy vehicle fires at 6-7-percent maximum grades is most likely due to chance; there is no reason to assume that grades of 6-7 percent are safer than 5-percent grades.
- Tunnels with maximum grades of 7-8 percent or more have more vehicle fires in total and more heavy vehicle fires than flat tunnels.

Most results are not statistically significant. This, and the partly non-monotonous relationships between maximum grade and fires, is most likely due to the small numbers of fires in some groups of tunnels. Small numbers imply that differences must be large to be statistically significant, and that results are susceptible to chance variations. Therefore, the lack of statistical significance and the partly inconsistent findings do not weaken our main conclusion, that fire risk increases with increasing maximum gradient, especially over 7 percent and for heavy vehicles.

In summary, the results indicate that there is a breakpoint for increasing fire risk at a maximum grade of 7 percent, especially for heavy vehicle fires. Above 7 percent, our results do not indicate that maximum grade matters.

Below 7 percent, increasing maximum grade is also related to fires, but the relationship is much weaker than for maximum grades above vs below 7 percent, and there are only small differences between all and heavy vehicle fires.

3.1.2 Length of steep grades

Fires per million vehicle kilometers: Figure 3 shows the relationship between the length of steep grades and the relative number of total and heavy vehicle fires. The results are somewhat unsystematic, most likely because there are only few fires in many of the tunnel categories. Overall, the results indicate that increasing length of steep grades is related to an increasing number of fires, especially for heavy vehicle fires and for the steepest and longest grades.

Model calculations: We calculated models with the length of steep grades among the predictor variables. These models contained two continuous variables for length of steep grade: Length of grade between 5.0 and 7.9 percent, and length of grades above 7 percent (8.0 percent or steeper).

All models show a clear relationship between the length of steep grades and the number of fires (Figure 4). In Figure 4, the relative number of fires is set equal to one for tunnels without grades above 5 percent.

The results show that increasing length of steep grade is associated with increasing numbers of fires, especially for heavy vehicles and for grades above 7 percent.

Since length of steep grade is a set of two numerical variables, the curves in Figure 4 cannot be used to identify a breakpoint in terms of a critical minimum length of steep grade.

The subsea tunnel predictor is non-significant in both models. This suggests that the high fire risk in subsea tunnels is mainly influenced by grades that are both long and steep.

3.2 What causes heavy vehicle fires?

3.2.1 Causal imputation

Causes of tunnel fires were classified primarily based on the official incident log, supplemented with information from other sources, including tunnel safety officers, fire services, and news archives. About half of the heavy vehicle fires and near-fire incidents in Norway in 2008–2021 have an unclear cause (Nævestad and Blom, 2023). Knowing the causes is important to implement effective measures to prevent heavy vehicle fires in tunnels. Based on the dataset from Nævestad and Blom (2023); vehicle fires in tunnels in 2008–2021), we used imputation to map unknown causes. Imputation is a statistical method used to calculate missing values based on existing values in a dataset. Registered and imputed causes are shown in Table 2.

Almost nine out of ten fires and near-fire incidents are caused by technical problems in vehicles, while just over one in ten (13%) occurred in traffic accidents. Accidents with subsequent vehicle fires were mostly collisions, and only very few single vehicle accidents. In subsea tunnels, all fires occurred after technical problems and none of the fires occurred after an accident.

Although the imputed percentages are uncertain because of the high percentage of original "Unclear/no data", these results indicate that better vehicle maintenance and vehicle standards are more important for preventing vehicle fires than preventing accidents.

3.2.2 Interviews

Information about assumed causal mechanisms for heavy vehicle fires in steep road tunnels was provided in interviews with three experts on heavy vehicle mechanics and maintenance, as well as in some of the other interviews. According to the informants, most fires in heavy vehicles have technical causes, especially related to the engine and the brakes. During uphill, driving with maximum load on the engine, an "exploding" overheated turbo is a typical cause, while overheated brakes were a main cause for fires on downhill slopes.

In general, there are three main groups of vehicle-related factors that can cause heavy vehicle fires: (1) Retarder use in subsea tunnels; (2) electrical faults; and (3) "extreme heavy transport".

Retarder use in subsea tunnels: Norwegian informants with heavy vehicle expertise emphasized that truck drivers generally use retarders during downhill driving, and not foot brakes. One of them mentioned that a "good driver" only brakes 1% of the distance driven.

The retarder is operated with a lever by the steering wheel, and has five stages, providing increasing resistance. The retarder breaks the engine either with a hydraulic or an electric system which slows the driveline. The retarder allows continuous breaking over time, without overheating the brakes. Retarder technology was introduced on the market in 1998, and it has become a lot more powerful over time. Many trucks also have an engine brake, i.e., a damper on the exhaust after the turbo, often in addition to the retarder. While engine brakes are very effective for short-term breaking, retarders are more suitable for long-term breaking.

Retarders (and engine brakes) allow somewhat higher speeds on long downhill grades. One informant said that while in the old days people would often stay behind trucks on downhill grades because they were careful about using brakes (rolling slowly), hydraulic

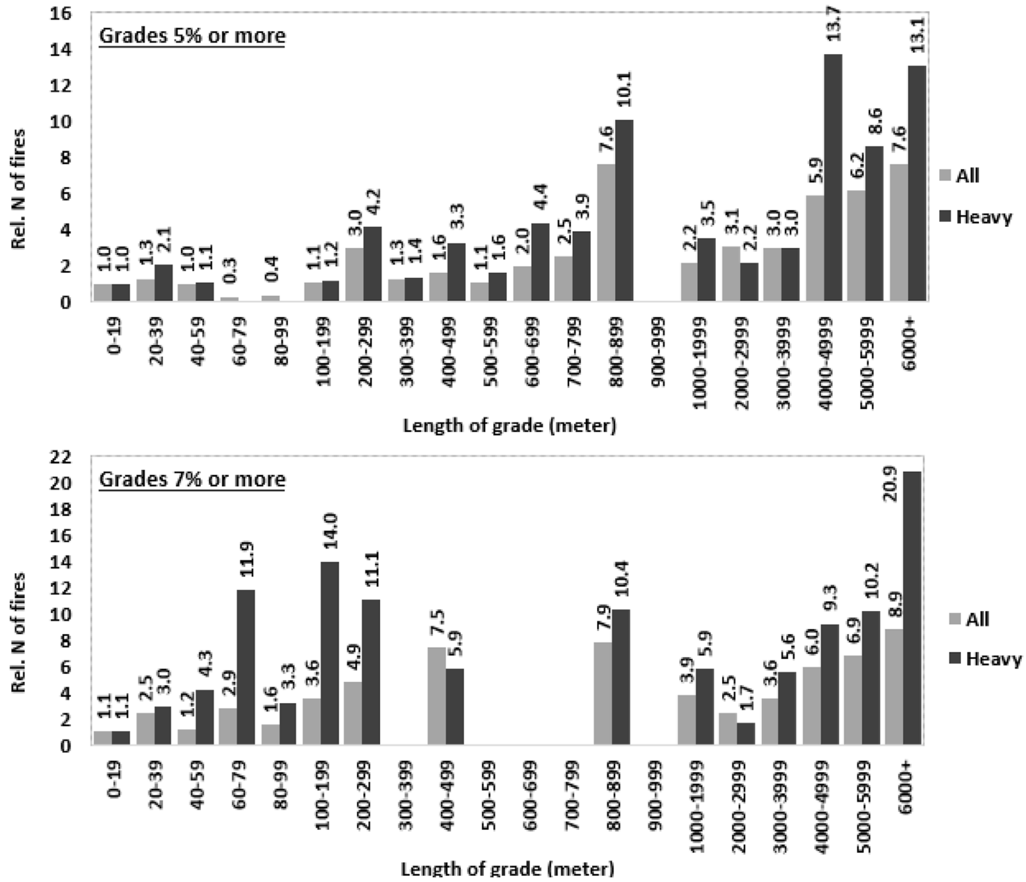

FIGURE 3
Relative numbers of fires per million vehicle kilometers in tunnels by number of meters with grades of 5 percent or more (top) or 7 percent or more (bottom); relative number of fires in tunnels without grades of 5/7 percent or more is set equal to one in both figures.

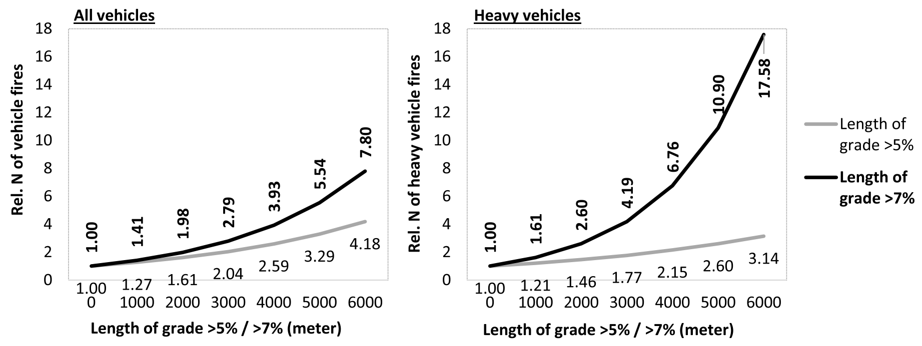

FIGURE 4
Relative number of fires (all vehicle fires: left; heavy vehicle fires: right); as a function of the length with maximum gradient above 5%/above 7%, calculated with the coefficients in fire model 1; relative number of fires equal to one in tunnels with maximum gradient below 5%.

retarders on newer trucks provide so much resistance that trucks can maintain the same speed as the rest of the traffic through the tunnel.

After long-term use of the retarder on the downhill section in a subsea tunnel, the engine is often very hot at the bottom, and the engine gets even warmer when you drive uphill,

TABLE 2 Distribution of causes for tunnel fires. Numbers in parentheses show 95% confidence interval.

Cause	Before imputation	After imputation
Technical problems	32%	87.2% (82.6%–91.8%)
Single accident	3%	6.2% (3.0%–9.4%)
Collision	4%	6.6% (2.9%–10.4%)
Unclear/no data	61%	-

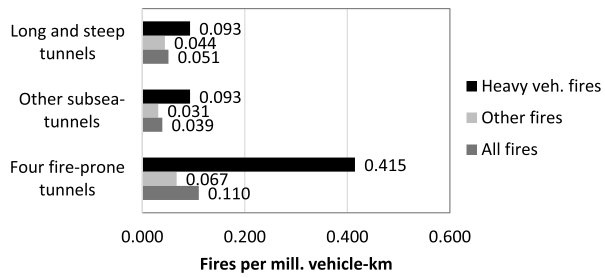

FIGURE 5
Fires per million vehicle kilometers in subsea tunnels; the four fire-prone subsea tunnels, five long and steep subsea tunnels (grades over 7 percent and tunnel length over 5 km), and other subsea tunnels (n = 29).

according to one of the informants with a technical background in the study by Nævestad et al. (2024):

> "…the operating temperature of the engine and such is at its absolute maximum (…) if you're going down a hill with a retarder for a kilometer or two. (…) Then you engage the drive again to use the torque (…) The system is built to handle it, but then it reaches 110°. [When you] then apply full torque to drive uphill, it gets very hot (…) degrees. The slightest oil leak at that point, and it's already above the self-ignition temperature of the oil, and then it catches fire. (…) There are a lot of hot components (…) It doesn't take much oil spillage or wood chips, for example, if it's wood chip trucks or other types of vehicles."

Overheated brakes seem less important as a cause of vehicle fires in road tunnels. Four of the informants also emphasized that heavy vehicle fires that are related to brakes, are easier to handle; they do not escalate in the same way as fires that start in the engine.

On this background, the largest problem in subsea tunnels seems to be the long and steep uphill grade that follows immediately after an equally long and steep downhill grade. Each of these grades is often as long as 4–5 km.

The informants emphasized that engines are designed to withstand high heat. When an engine starts to burn, it has mostly some underlying problems, and these start often long before the truck enters the tunnel. Such problems include undetected technical problems and leakages of oil or other things that can catch fire when the engine or engine parts (manifold) become very hot. All of this can be prevented with regular and good maintenance.

Electrical faults: Another important cause of heavy vehicle fires is electrical faults and wires melting near the exhaust pipes. One informant suggested that fires in heavy vehicles can start due to a current leak, for example, when a cable has slight ground contact, possibly caused by a misplaced bolt. In such cases, the fuse does not blow, and that will lead to heat development. This can eventually cause an electrical fire in a cable bundle. Such current leaks occur often ("weekly") in heavy vehicles. In many cases, it results from a mechanic's mistake, while other times, it is caused by the driver's actions. A common scenario is when a driver needs power for something inside the cab and improperly taps into the electrical system.

Extreme heavy transport: A third cause of heavy vehicle fires mentioned is related to "extreme heavy transport", which often involves modified trucks, such as those used to pull excavators. These converted vehicles can pose challenges because their modifications may deviate from standard designs. Fires in such trucks are often linked to engine problems, such as engine failure, making frequent and thorough maintenance essential. These trucks, sometimes called machine trailers, typically consist of a cabin and frame, with a large stainless-steel cabinet often installed behind the cabin. When a fire starts in a heavy vehicle, heat can become trapped in this enclosed space, increasing the risk of ignition. Another fire risk comes from custom exhaust placement, as customers may choose whether the exhaust outlet is positioned under the vehicle or on either side. If placed incorrectly, especially in high-temperature operating conditions, it can create heat sources in unsafe locations, increasing fire risk.

Insurance perspective: Furthermore, a person who had an insurance perspective, stated that fires in tunnels are not a big issue. Most fires happen when heavy vehicles are parked, and "violence" (intentional human actions) is a main cause. However, this does not mean that heavy vehicle fires in tunnels are unimportant.

3.3 Why are some Norwegian subsea tunnels far more fire-prone than others?

Road tunnels with steep grades account for approximately 5 percent of all Norwegian road tunnels, but they had 38 percent of all fires in tunnels in 2008–2021 (Nævestad and Blom, 2023). Half of all fires in steep tunnels occurred in four subsea tunnels: Oslofjord Tunnel (39 fires), the Bømlafjord Tunnel (32), the Byfjord Tunnel (23) and the Eiksund Tunnel (17).

Based on Norwegian road tunnels analyzed in section 3.1.1, we compared the four most fire-prone tunnels, five other long and steep subsea tunnels (grades 7–9 percent and tunnel length above 5 km), and other subsea tunnels.

Risk in the most fire-prone and other tunnels: Figure 5 shows the numbers of fires per million vehicle kilometers in the three groups of tunnels. The fire numbers refer to all vehicle fires, heavy vehicle fires, and other fires (fires in light vehicles).

The number of heavy vehicle fires per million vehicle kilometers is over four times as high in the most fire-prone tunnels than in other subsea tunnels. The difference in heavy vehicle fires is much bigger between the four most fire-prone tunnels and all other subsea tunnels, regardless of grade and length. The differences between the long and steep subsea tunnels and the “other” subsea tunnels are small.

Characteristics of the most fire-prone and other tunnels: Table 3 illustrates summarized information on the number of tunnels, length, traffic volume, heavy vehicle traffic volume, gradient length and fires for the selected tunnels. This information is available from the analyses in section 3.1.1. The differences between the most fire-prone and other subsea tunnels are as follows:

- Length: The most fire-prone tunnels are on average about twice as long as the other subsea tunnels. However, the five long and steep subsea tunnels are about as long as the most fire-prone tunnels. Length is therefore unlikely to explain the high fire risk in the most fire-prone tunnels.
- Traffic volume: Traffic volume (AADT) is 65 percent higher in the four most fire-prone tunnels than in other subsea tunnels. The five long and steep subsea tunnels have even lower volumes. Thus, volume is a potential contributing factor to the high fire risk in the four most fire-prone tunnels. However, it is unclear how volume may contribute to fire risk.
- Heavy vehicle volume: The proportion of heavy vehicles in the most fire-prone tunnels is about the same as in other subsea tunnels, and even lower than in the five other long and steep subsea tunnels. The number of heavy vehicles (heavy vehicle volume) is higher, but it is unclear how this might contribute to the high *risk* of heavy vehicle fires.
- Single vs twin tunnels: The four tunnels most at risk of fire are single tunnels. The same applies to most other subsea tunnels, with two exceptions (the Opera and Tromsøysund tunnels are twin tunnels).
- Length of steep gradient (above 7 percent): The most fire-prone tunnels have far longer steep grades than other subsea tunnels. Their steep grades are also far longer than in the five other long and steed subsea tunnels. Thus, the length of the steep grade seems to be the most important contributing factor for the high fire risk in the most fire-prone tunnels.

3.4 Compensating measures

The second objective of the present study was to find measures that may compensate for the fire risk associated with steep grades in tunnels, and to investigate possible effects of such measures. Measures may focus on reducing either the risk or the consequences of heavy vehicle fires. In a literature search, we found no studies about possible effects of risk-reducing measures. Our considerations of compensatory measures are therefore primarily based on interview results.

The most effective measure to prevent heavy vehicle fires in Norwegian road tunnels would be to avoid building tunnels with long and steep grades. Our study shows clearly that tunnels with long and steep grades have significantly higher fire risk than other tunnels. Most such tunnels are subsea tunnels. These tunnels are also particularly challenging in terms of evacuation. They have no alternative exits, all evacuation must use the tunnel in which it is burning, mostly in the uphill direction, and there are limited options for controlling smoke through fire ventilation.

The most common causes of heavy vehicle fires are technical problems, mainly in the engine or electric system. Heavy vehicle fires in subsea tunnels start often when the retarder gets warm on the downhill part of the tunnel and then gets overheated on the uphill grade. Insufficient maintenance increases the risk of technical problems. It is therefore particularly relevant to implement measures to improve vehicle maintenance and inspections. The latter is especially important for converted and modified heavy vehicles.

Technology for automatic fire extinguishing in engine compartments is also a very relevant measure in addition to improved vehicle maintenance and inspection. Such technology is already available in buses, construction machinery, and mine driving machines, and it would be likely to be effective in heavy vehicles as well. Automatic fire extinguishing in engine compartements would be most relevant in tunnels where evacuation is challenging.

To increase the uptake of automatic fire extinguishing, it may be introduced either as a national or an EU requirement. Approving such EU requirements may be time-consuming, but it would also target foreign trucks in Norway. About 10 percent of truck kilometers in Norway are driven by foreign trucks, most of them from EU countries. Norway has probably a stronger interest in such technology, and it may therefore be reasonable to start by implementing a national requirement.

To reduce heavy vehicle fires in tunnels, some countries (e.g., Sveits) have installed “portals” at the entrances to long mountain tunnels where heavy vehicles are automatically scanned and investigated manually if high temperatures are discovered in critical places. Compared to the Norwegian subsea tunnels, these tunnels are equally long or longer, but they are not steep, and they have high traffic volumes. Another difference is that trucks often arrive, potentially overheated, after long uphill climbs at the Swiss tunnels, while overheating in the Norwegian subsea tunnels typically occurs in the tunnel. Therefore, portals would be likely to be less effective at Norwegian subsea tunnels than in Switzerland, and they would also be far less cost-effective because of the low traffic volumes. However, portals may be a relevant measure at other long tunnels, especially those that have long and steep uphill grades before the tunnel. We know that about half of all heavy vehicle fires in Norwegian road tunnels that were caused by technical problems (55 out of 101 in 2008–2021) occurred in tunnels *without* steep grades. It would be interesting to investigate the vertical profile of the roads outside these tunnels, which has not been possible in the current study.

Another measure that may become important in the future, is cooperative ITS (Cooperative Intelligent Transport Systems, C-ITS). C-ITS utilizes wireless technology to enable real-time communication from vehicle to vehicle and from vehicle to infrastructure. Modern trucks are equipped with many sensors that can alert the driver of technical faults or other critical situations. With C-ITS, it would be possible to exchange sensor information or warnings, for example, about overheated engines, between vehicles in the same area. Vehicles could also receive information directly from the tunnel if a vehicle starts to catch fire. A challenge with C-ITS is that there are many different types of technology that are not always able to communicate with each other, and that would

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TABLE 3 Number of tunnels, length, traffic volume, gradient and fires for different groups of subsea tunnels.

	N of tunnels	Length (m)	AADT	Heavy vehicles y (%)	Heavy veh. AADT	Length of grade above 7% (m)	N of fires	Heavy veh. fires	Per mill. veh. km	
									Fires	Heavy veh. fires
Four fire-prone tunnels										
-- Byfjordtunnelen	1	5 875	9 470	12.0	1,136	**5 443**	22	10	0.077	0.286
-- Bømlafjordtunnelen	1	7 913	6 620	11.0	728	**4 757**	31	13	0.116	0.426
-- Eiksundtunnelen	1	7 849	2 928	7.0	205	**6 765**	17	7	0.145	0.815
-- Oslofjordtunnelen	1	7 261	9 089	15.0	1,363	**5 022**	41	22	0.122	0.430
All fire prone	4	7 225	7 027	11.3	794	**5 497**	111	52	0.110	0.415
Other subsea	29	3 653	4 260	11.9	507	**2 095**	96	31	0.039	0.093
Long and steep subsea tunnels[a]	5	6 086	2 356	16.3	384	**2 871**	15	4	0.051	0.093

[a]Tunnels with a gradient of 7–9 percent and a tunnel length of more than 5 km; all of these are subsea, and they are therefore included in the group "Other subsea".

require harmonization. Although pilot projects are carried out, there are divided opinions about optimal solutions in the future.

3.5 Future developments

The third goal of the study was to describe likely changes over the next 10–20 years that can be expected to affect the risk of heavy vehicle fires in steep tunnels. In the interviews, our informants focused primarily on changes with regard to powertrains, especially on the likely increase in the use of electric and hydrogen trucks. This may have a large impact on both fire risk and consequences of heavy vehicle fires in tunnels.

The Norwegian National Transport Plan (NTP), EU-regulations and climate targets set political guidelines for the introduction of zero-emission vehicles. The NTP describes that "by 2030, …50 percent of new trucks should be zero-emission vehicles". For heavy vehicles, an EU CO2 emission regulation came into force in August 2019. According to this regulation, emissions must be reduced by 15 percent from 2025, and by 30 percent from 2030, compared to the reference period. Initially, the requirements apply to large trucks (over 16 tons). The EU's CO2 requirements for trucks imply that car manufacturers must develop battery-electric or hydrogen trucks for sale in Europe by 2025 and 2030. It is assumed that at least half of the reduction must be achieved by selling zero- or low-emission trucks.

According to the informants who are experts on energy and drivelines, a transition from diesel to electric batteries is likely to decrease the risk of heavy vehicle fires. However, a fire in the batteries of an electric truck in a tunnel is far more difficult to extinguish and likely to have far more serious consequences than a fire in a diesel truck. Extinguishing battery fires requires enormous amounts of water. Ideally, the whole vehicle should be immersed in water, which is obviously unrealistic to achieve in a tunnel. Fires in electric batteries also produce more dangerous gases than diesel, and therefore cause greater harm to people evacuating the tunnel.

Moreover, even if electric trucks become more common, gas-powered trucks are assumed to remain relevant for many years to come. Fires in gas vehicles in tunnels produce high fire loads, and even small leakages of gas may lead to an explosion (Reitan et al., 2016). Another problem is that the operating temperature often is higher in gas-than in diesel-powered vehicles. Moreover, once gas catches fire, it must "burn out". There is a lack of knowledge about how aging and wear affects safety mechanisms and leakage from gas tanks, and there are accidents where safety mechanisms that should have prevented fires after gas leakages, have failed (Reitan et al., 2016). For example, there was a major fire in a gas-powered truck in the Merraskot Tunnel in 2021. The truck had just driven through the Oslofjord Tunnel.

In hydrogen-powered trucks, fuel cells convert hydrogen into electricity. The electricity is used to drive an electric motor, which sends power to the drive wheels, and it can also be stored in a battery. Tungt. no writes on 28 April 2023, that no hydrogen trucks were registered in Norway since 2021, according to figures from OFV. Only four hydrogen trucks were registered in Norway in 2019 and 2020.[4] At the same time, Tungt. no launched the news in the spring of 2023 that a German company is building a "Norwegian version" of a hydrogen truck, which can be ordered from April 2023. This has the same payload as diesel trucks - and a model with up to 1,400 km of range that is specially adapted to Nordic conditions. Hydrogen is very flammable and explosive, and thus challenging in terms of fire safety. It has a low ignition point, low ignition energy

4 https://www.tungt.no/article/view/1027013/quantron_bygger_norgesversjon_av_hydrogenlastebil_kan_bestilles_na

and wide explosion limits. Leaking hydrogen will immediately ignite and form a jet flame.

4 Summary and discussion

4.1 Fire risk increases with maximum grade, especially if the grades are long and over 7 percent

Our analyses show that fire risk in tunnels increases strongly in tunnels with long and steep grades. On average, the total number of vehicle fires in a tunnel with a 5-percent grade over a length of 6 km is 7.6 times as high as in a flat tunnel, if all else is equal.

Tunnels with grades of 7 percent or more have even higher fire risk, especially for heavy vehicle fires. Compared to a flat tunnel, tunnels with a 7-percent grade over 6 km have 8.9 times as many vehicle fires per million vehicle kilometers in total, and 21 times as many heavy vehicle fires per heavy vehicle kilometers.

When we compare otherwise similar tunnels with different maximum grades, those with a maximum grade of 7 percent or more have far higher fire risk, especially higher heavy vehicle fire risk, than tunnels with less steep grades. Compared to tunnels with a maximum grade below 5 percent, tunnels with a maximum grade between 5.0 and 7.9 percent have about 40 percent higher fire risk, and tunnels with a maximum grade above 7 percent have about 2.45 times as high fire risk in total and 4.1 times as high risk of heavy vehicle fires.

These results show that grades of 7 percent can be regarded as a breakpoint for increasing fire risk. It is probably related to tunnel type: Most subsea tunnels have grades of 7 percent or steeper, and these grades are not only steep, but also long. In tunnels with less steep grades, the grades are mostly shorter than in the subsea tunnels. Since the combination of long *and* steep grades is most critical for fire risk, we assume that our 7-percent breakpoint is mainly due to the fact that most long and steep grades are above 7 percent (and not, for example, 6 or 8 percent).

At grades below 7 percent, there is also a relationship between maximum grade and fire risk and between length of grade and fire risk. These relationships are weaker than the relationship between grades above vs below 7 percent and fires, and partly inconsistent. However, the inconsistencies in the results can be explained with small numbers of fires and random variation.

On this background, we cannot conclude that there is a "safe" grade. Fire risk increases with increasing grade, from about 3 percent, and risk increases more on longer and steeper grades.

Methodologically, a weakness of our study is that the combined effect of grade and length of grade could not be investigated statistically. Such an approach would have allowed to identify more specific breakpoints, such as "risk increases most if grade exceeds X percent and length of grade exceeds Y meters". However, such an approach would require far more data.

4.2 Most heavy vehicle fires in tunnels are caused by technical problems, mostly related to the engine

Our study show that about nine out of ten vehicle fires in tunnels are caused by technical problems. Most technical problems are related to the engine. Overheating of the engine is often related to prolonged driving with a retarder downhill, followed by prolonged uphill driving. This pattern is typical in subsea tunnels: First, they have to drive down a long and steep slope which puts a lot of strain on the retarder and can produce significant heat in the engine (depending on the type of retarder). Then, they have to drive up an equally long and steep slope, which puts even more load on the already hot engine. This may lead to overheating of the engine and increase fire risk.

Overheating of engines is also often related to poor vehicle maintenance and inspections.

The remaining one out of ten fires start in traffic accidents. This is based on updated analyses by Nævestad and Blom (2023), who used statistical imputation techniques to find likely causes for fires with missing information about the cause in the original data.

These results indicate that the prevention of vehicle fires is more about vehicle maintenance and inspection than about accident prevention. The importance of traffic accidents as a cause of fires has decreased over time, probably because accident risk has decreased strongly. Nævestad et al. (2022) find that the risk of injury accidents with heavy goods vehicles has decreased by 73 percent from 2007 to 2020. The corresponding reduction in the risk of fatal accidents is 61 percent.

4.3 Long and steep slopes are the key to fire risk in the most fire-prone subsea tunnels

Subsea tunnels have higher fire risk than other tunnels because they have both long and steep grades. Among Norwegian tunnels with steep grades, four tunnels account for half of all heavy vehicle fires, and these tunnels have about four times as high fire risk as other tunnels with steep grades. The main contributing factor to fires in these tunnels is the combination of long *and* steep grades.

We compared several tunnel characteristics between these four fire-prone subsea tunnels and other subsea tunnels. The results show clearly that the four fire-prone tunnels are unique with regard to the length of steep grades. The presence of steep grades (above 7 percent) or long grade alone, increase fire risk compared to flat tunnels, but are not sufficient to explain the extremely high numbers of fires in the fire-prone tunnels. However, the grades in the most fire-prone subsea tunnels are both steep (over 7 percent) and long (over 5 km), and this is the most important difference to less fire-prone tunnels.

The fire-proneness of tunnels with long and steep grads is also consistent with our findings about the contribution of engine overheating to vehicle fires in subsea tunnels (see section above).

4.4 Which measures are most promising to prevent fires in Norwegian road tunnels?

We found no research about the effects of measures to reduce heavy vehicle fire risk in steep road tunnels. Based on expert interviews, these are the most promising measures:

1) Avoid building long and steep road tunnels, or ban heavy trucks from such tunnels.
2) Improved vehicle maintenance and inspections, as well as automatic fire extinguishing technology for heavy vehicle engines.
3) Improved tunnel fire management, including early detection and evacuation strategies, and portals with automatic thermal scanning of heavy vehicles
4) Cooperative ITS for heavy vehicles.

4.5 What do we need more knowledge about?

How can heavy truck drivers' competence be increased? Competence and experience of heavy truck drivers contribute to the fire risk in steep tunnels. Future research may map the experience, competence and attitudes among Norwegian and foreign heavy truck drivers, amongst other things as a basis for training and information campaigns. Such campaigns may also focus on the importance of vehicle maintenance to prevent vehicle fires, and on the importance of not driving into long tunnels in the presence of error messages such as overheating.

What influences maintenance routines in transport companies? Poor vehicle maintenance is often related to the economic conditions of transport companies. A weak economy may also be related to older vehicles with a higher risk of technical failures which may lead to fires. Connections between framework conditions, economy, maintenance, and fires should be investigated in future research.

How can the adoption of automatic engine fire extinguishing systems for trucks be increased? Some examples show that Norway has introduced stricter requirements than EU rules and has been a driving force for stricter EU requirements. For example, Norway has introduced a national requirement for collision protection in buses (Nævestad and Blom, 2023). Perhaps, one may learn from this process in a possible work to achieve a requirement for an automatic motor fire extinguishing system in the engine compartment of trucks. Norway has a strong interest in such technology because of its many fire-prone steep subsea tunnels.

Fire risk of new energy carriers and how to manage it: Electric and gas-powered vehicles have different fire and explosion characteristics compared to conventional fossil-fuel vehicles. This raises new fire safety challenges in road tunnels. There is a growing need for knowledge about fire risks, potential consequences, and appropriate response strategies for heavy vehicles using alternative fuels. Fires in electric and gas-powered trucks may require different preventive measures, extinguishing methods, and risk assessments than those in traditional vehicles. Currently, significant uncertainty remains regarding fire risks and effective mitigation strategies for these new energy carriers, highlighting the need for further research.

Why did accident risk decrease in recent years, but not vehicle fire risk? Among heavy vehicles, accident risk has decreased considerably in recent years, by 73 percent for injury accidents and by 61 percent for fatal accidents from 2008 to 2021. The most important contributing factors to these decreases are new vehicle technology (e.g., electronic stability control), changes in driving behavior (lower speed) and more inspections by the Norwegian Public Roads Administration and the police. Accident risk has decreased among both Norwegian and foreign trucks in Norway.

Despite the large decreases in accident risk, fire risk has remained relatively unchanged over time. In our interview, several informants from Alpine countries believed that reducing the risk of heavy vehicle fires in tunnels is challenging, and that it is more promising to focus on the consequences. This implies that more focus should be put on early detection, extinguishing systems, and evacuation (e.g., emergency exits and evacuation lights). However, there are some important differences between mountain tunnels in alpine countries and Norwegian subsea tunnels. The long mountain tunnels have often high traffic volumes, two tubes, and emergency exits, while Norwegian subsea tunnels are mostly single tunnels, often with low volumes, and it would be far more difficult to install emergency exits.

On this background, future research about tunnel fire safety might focus on how one could learn from road safety work to reduce fire risk, especially among heavy trucks, in addition to investigating options for improving fire management strategies (detection, evacuation, *etc.*).

Data availability statement

The datasets presented in this article are not readily available because anonymized data might be shared. Requests to access the datasets should be directed to ton@toi.no.

Ethics statement

The studies involving humans were approved by Norwegian Agency for Shared Services in Education and Research. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

T-ON: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review and editing. AH: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing. JB: Conceptualization, Data curation, Formal Analysis, Methodology, Writing – original draft. LE: Formal Analysis, Investigation, Methodology, Writing – original draft.

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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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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