BEST PRACTICES ON ADVANCED CONDITION MONITORING OF RAIL INFRASTRUCTURE SYSTEMS

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BEST PRACTICES ON ADVANCED CONDITION MONITORING OF RAIL INFRASTRUCTURE SYSTEMS

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EDITORIAL
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Editorial: Best Practices on Advanced Condition Monitoring of Rail Infrastructure Systems

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Keywords: rail, infrastructure, system, monitoring, resilience, vulnerability

Editorial on the Research Topic

Best Practices on Advanced Condition Monitoring of Rail Infrastructure Systems

COVID-19 has just proven that transportation systems are not immunized and are vulnerable. The coronavirus causes severe consequences including step changes in travel behaviors, risk perception and avoidance, transportation operations, network policies, and real capabilities to track, monitor, and contain the virus through social distancing, quarantine, and isolation within the transport networks. These too affect the standard and practice for managing infrastructure systems. We can no longer consider or treat resilience simply for better responses to environmental hazards as a business as usual. Societal, economic, and engineering resilience has become more underlyingly critical than ever. In fact, the virus underpins the necessity to manage temporal and spatial risks through advanced condition monitoring across transportation networks, modalities, and systems. Such needs have been the key theme in this special Research Topic that is emphasized on rail infrastructure systems designed to cope with multi hazards and extreme events.

This special topic is particularly interested in understanding the role of advanced condition monitoring for transportation assets and operations and the connections between multi hazards, infrastructure capacity, and real-time evaluation of measures to monitor the vulnerability, risks, uncertainties, resilience, and robustness of rail infrastructure systems and networks. These capabilities are fundamentally the technological enablers to enhance social and economic connections, and communities can quickly take up the opportunities offered by increased mobility (Kaewunruen et al., 2016). In other words, the technological enablers are the precursor to (i) promptly and effectively respond to any crisis; (ii) assure the quality of everyday life; and (iii) leave no one behind.

This Research Topic presents a set of novel findings stemming from the H2020 Marie Skłodowska-Curie Actions (MSCA)'s RISEN Project (Rail Infrastructure Systems Engineering Network). This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691135 (www.risen2rail.eu). The collaborative researches are aligned with United Nation's Sustainable Development Goals (SDGs) as well as European Directive's Plan S for Open Science. This Research Topic brings together the research and innovation associated with rail infrastructure systems issues related to advanced condition monitoring. Taken together, these following papers help to build knowledge for actions that will strengthen response and recovery from multi hazards and extreme events (including COVID-19) as well as other hazards and threats to transportation systems and the communities they support.

Despite the fact that rail system demands active interaction between inspection, operation, and maintenance, never been transparent nor fully open have the flows and sharing of critical data among stakeholders and the public. This Research Topic thus focuses on the advanced condition

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monitoring, which can play an important role in providing open and novel methodological approaches optimizing reliability, availability, and asset management.

Along this line, De Melo et al. reviewed systemically and comprehensively state-of-the-art methods to monitor and evaluate the deterioration of a railway track and its components in operational settings. More than 100 methods related to track deterioration monitoring and inspections have been highlighted and compared to enable new technological gaps and practical insights. The insights provide better understanding into the advantages and disadvantages of each method in practice, which will help engineers and managers manage rail infrastructure systems during disruptions and crises.

Sauni et al. developed a novel technique to diagnose the root causes of railway track geometry deterioration in the underlying track structures. Monitoring and predicting the degration are important as is investigating the root causes contributing to the deterioration. Without knowing the causes, assigned remediation and recovery actions might not result in a long-lasting correction. A new association rule data mining method, General Unary Hypotheses Automaton (GUHA), has been adopted. This method has been proven to be a suitable method for investigating the root causes of track geometry deterioration from comprehensive railway track structure data.

Reis and Almeida shared a new model for evaluation of increasingly significant freight transport. More specifically, the focus is placed on intermodal transport, which has arisen as a desirable alternative to long-haul road transport, as it creates opportunities for cost reduction and to decrease both polluting emissions and road congestion. As a case study, the capacity evaluation of the Freight Village of Turin has been demonstrated. This has been motivated by future changes in traffic demand, related with the neighboring Port of Savona-Vado. The model has highlighted inefficiencies of both rail and handling processes, as well as identified parameters influencing business resilience of intermodal freights.

Rosell et al. demonstrated the application, on a real scale, of an inertial system capable of determining track irregularities and their position through the recording of vertical accelerations. This application supports a maintenance work programme to comply with safety and comfort limits required by railway legislation. This application system has been implemented on a train on a regular service on the San Antonio-Los Lirios line (Chile) to validate correct operation. It has been proven that the track geometry parameters obtained from this novel application are in a very good agreement with the traditional measurement method.

Li et al. highlighted the effects of time-dependent phenomena on railway prestressed concrete sleepers. The authors investigate and compare the influences of creep and shrinkage on railway prestressed concrete sleepers. The comparison between prediction models underpinned by European Standard Eurocode 2, American Standard ACI, and Australian Standard AS3600-2009 enables the new practical insight into the time-dependent performance of railway concrete sleepers, which can be used in railway constructions in diverse continents. The outcome of this study will help rail track engineers to better design and maintain railway infrastructure, improving asset management efficacy.

These papers provide exciting new insights and state-of-the-art knowledge for actions toward smarter and more resilient railway systems. The topic editors are grateful to the review editors and associated editors. Finally, we encourage everyone to take part in the prestigious TRA VISIONS Competitions. The prestigious TRA Visions Competitions run every 2 years and the next one will be in 2022 (European Union, 2020). The awards recognise and celebrate the very best and brightest researchers who are or have recently been contributing to excellence in transport research and development in road, rail, waterborne, airborne, and cross modality.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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EDITORIAL
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Editorial: Best Practices on Advanced Condition Monitoring of Rail Infrastructure Systems, Volume II

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Editorial on the Research Topic

Best Practices on Advanced Condition Monitoring of Rail Infrastructure Systems, Volume II

None of us would have imagined that Covid-19 would last this long. However, recent insights demonstrate that we as a human will need to adapt and live with it for quite some time or even perhaps forever. Interestingly, due to COVID19, many news reports have shown a significant drop in public transport usages. In fact, the number of train passengers are at the lowest level in decades as demonstrated in **Figure 1**, revealing some daily facts of national rail usage in the United Kingdom over the period. The coronavirus causes severe long-lasting imprints on many sectors, and railway is not exempted. With the necessity to survive, railway sectors must adapt to enable and support the recovery of economic activities now.

Various standard and practice for managing infrastructure systems have been recently updated to tackle the challenges. However, with the risk of more and more staff getting contacts with the virus, contingency plan is necessary. Accordingly, there is an essential need to monitor and manage the integrity of the railway systems (including rolling stocks, infrastructures, signaling, and other aspects) through advanced condition monitoring across the networks. Such the essential need is the key theme in this special research topic that is emphasized on rail infrastructure systems designed to cope with multi hazards and extreme events. The second volume of this Research Topic will continue bringing together the research and innovation associated with rail infrastructure systems issues related to advanced condition monitoring, design and maintenance of infrastructure systems and components, and societal impacts. These aspects are the essential technological enablers to enhance social and economic connections where communities can quickly take up the opportunities offered by increased mobility (Kaewunruen et al., 2016). The technological enablers underpin 'The Sendai Framework for Disaster Risk Reduction' endorsed by United Nations Office for Disaster Risk Reduction. They will lead to: 1) promptly and effectively respond to any crisis; 2) assure the quality of everyday life; and 3) leave no one behind.

This research topic presents a set of new research findings stemming from the H2020 Marie Skłodowska-Curie Actions (MSCA)'s RISEN Project (Rail Infrastructure Systems Engineering Network). This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691135 (www.risen2rail.eu). The collaborative researches are aligned with United Nation's Sustainable Development Goals (SDGs) as well as European Directive's Plan S for Open Science.

Along this line, Edwards et al. presented a design process based on structural reliability analysis (SRA) concepts whereby target values for reliability indices (β) for new designs are obtained and compared with existing designs for further design optimization. The results showed the need for increased sleeper center bending capacity. Additionally, a reduction in rail seat bending capacity of approximately 40% is justified, reducing the size of the rail seat cross

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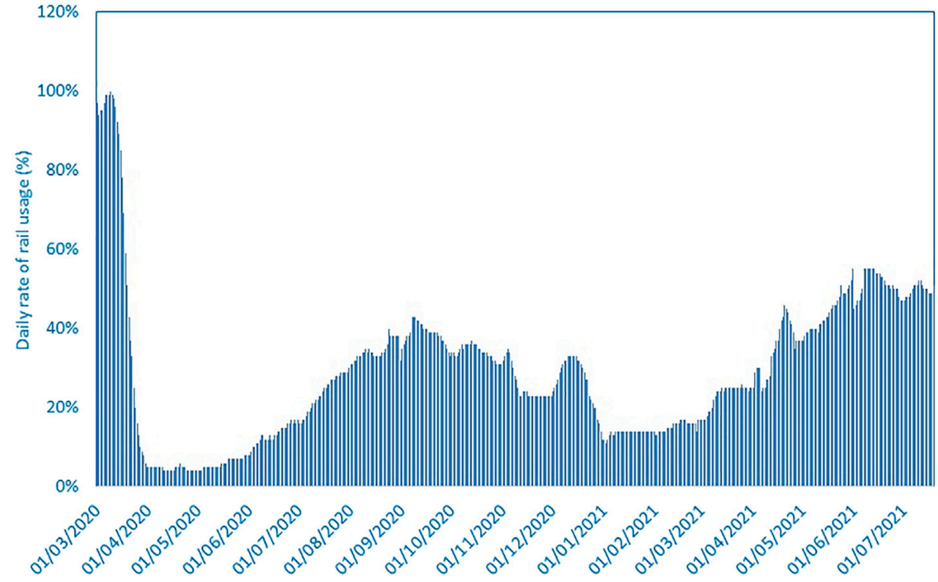

FIGURE 1 | Percentage of daily rate of national rail usage in the United Kingdom derived from the open data by United Kingdom Department for Transport (source: https://www.gov.uk/government/statistics/transport-use-during-the-coronavirus-covid-19-pandemic).

section by approximately the same magnitude. In most cases the proposed designs have fewer prestressing wires and a higher centroid of prestressing steel.

Kaewunruen et al. (2016) discussed about the design and testing procedures of composite materials, which have recently gained significant attention for applications in railway industry. In recent practice, composite sleepers and bearers have been used for bespoke replacements of aged timber components in critical areas such as switches and crossings, bridge transom sleepers, and special locations with either stiffness or clearance constraints. A new ISO standard has been drafted to accommodate the need to carry out standardized tests to benchmark the performance of polymeric composite sleepers and bearers. This study highlighted the test specifications in order to illustrate the profound insight into the test methods for polymeric composite sleepers in comparison with *in situ* conditions in real life situations. The study explored the effectiveness of the provision in the current design code for bending test methods under various support conditions. It vividly demonstrated that the test methods cannot fully represent *in situ* track conditions.

Pereira Silva et al. shared a new development of a ballast support condition back-calculator, a non-destructive instrumentation method and corresponding analysis tool that quantifies ballast pressure distributions under concrete sleepers without interrupting revenue service train operations. This study quantified the ballast pressure distributions beneath concrete sleepers under different types of rolling stock and evaluates how ballast support condition changes as a function of accumulated tonnage. It also demonstrated the potential of the back-calculator to provide a stand-alone non-invasive method to quantify ballast support conditions, sleeper health, and sleeper bearing stress. Back calculator data will aid the rail industry in optimizing tamping cycles, enhancing safety, and developing more representative concrete sleeper flexural designs based on actual support conditions.

Rungskunroch et al. highlighted the Paris Agreement, which has been launched as a global environmental policy. The agreement has been involved in the transportation industry, especially on railway and HSR networks. Implementing environmental concepts becomes a challenging issue for researchers and engineers in the railway industry. Despite the fact that railway sector is the lowest CO2 emitter, there have been several collaborations among railway industries, operators, policymakers, and other related sections to further respond to reduce global emission. The study provided three realistic key developments covering infrastructure, electric rail track, and vehicle's engine power. By following the proposed guidelines, the United Kingdom government's target to be net-zero carbon is more achievable.

Alawad and Kaewunruen discussed the emerging context of COVID-19 when the railway industry could employ new technology such as AI and related approaches (Internet of things (IoT), 5G, big data, and AI) for protecting and underpinning railway safety. Acknowledging already the solutions and potential measures that have been applied such as cleaning, disinfection, sanitization, redesign, physical and social distancing, relayout, ATP testing, or the air filtration and recycling air, the research highlighted the potential technology solutions in the industry for tackling COVID-19. The situation has led to rethinking how we consider and continue to benefit from technology in the current situation and for future crises, not only for the railway but for all businesses.

Liu et al. determined the casual effect and synergy of high-speed rail development on the modal transport changes in supply chain and logistics, which have not been considered well during the initial phase of any rail project design and development. This issue has impaired the systems integration and connectivity among the modes of transport in a region. This study provided the sensitivity analysis of supply chains via air-rail-road freight transportation and logistics stemming from the High Speed 2 case by the rigorous assessments into the capacity, performance and environmental changes that may follow the project's implementation. The research proposes a new method for estimation of consequences from a new transport project construction. The research findings demonstrate slight beneficial changes in freight transportation and logistics with a high potential for development; and reveal the project's weaknesses and opportunities for better systems integration and business synergy.

These papers provide exciting new insights and state-of-the-art knowledge for actions towards smarter and more resilient railway systems. The topic editors are grateful to the review editors and associated editors.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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ORIGINAL RESEARCH
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Capacity Evaluation of a Railway Terminal Using Microsimulation: Case Study of a Freight Village in Turin

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Increasingly significant freight transport had led to larger and more complex transport chains. More specifically, intermodal transport has arisen as a desirable alternative to long-haul road transport, as it creates opportunities for cost reduction and to decrease both polluting emissions and road congestion. Hence, achieving good levels of service in intermodal dedicated structures is of paramount importance for the success of this transport option.The global objective of this research is to determine the capacity of the Freight Village of Turin. This is motivated by future changes in traffic demand, related with the neighboring Port of Savona-Vado. The role of freight villages and other logistics centers is becoming progressively more substantial with saturating sea ports focusing on handling operations. Existing literature shows success in intermodal transport highly depends on terminal performance.To fulfill the already mentioned objective, a simulation model was developed, based on discrete-event methodology, which simulates rail and handling operation inside the freight village. The model is then used to test several scenarios with the purpose of investigating variation in operation techniques and resources and the respective impact it has on comprehensive capacity.Confronting the tested scenarios allowed to comprehend the inefficiencies of both rail and handling processes, hence concluding that locomotive operation presents the most limiting factor. Furthermore, by combining different operation conditions and resources, it was possible to conclude how these affect final capacity and overall performance.

Keywords: freight village, discrete-event modeling, simulation, capacity, intermodal transport

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INTRODUCTION

The introduction of transport unit drastically transformed the world of transport. By standardizing the way cargo is transported, handling and stocking activities were significantly optimized, thus reducing costs and overall dwell times.

Regarding sea ports, this change in size altered freight arrival dynamics. Ports now must deal with concentrated peaks of arrival which call for efficient handling processes and larger stocking dedicated areas. To address these issues, forwarding containers to the hinterland has been a common solution, thus shifting various functions from sea ports to the respective hinterland ports.

Therefore, hinterland ports now have a more significant role. These can often work as an extended gateway for sea ports. Customers can profit from having their cargo in closer proximity to their customers. Furthermore, hinterland ports can deviate road traffic from seaports, which are frequently highly congested, allowing for shorter dwell times and better planning of shuttle services (Rodrigue and Notteboom, 2009). Furthermore, this concept also includes the performance of added value activities (Iannone, 2012).

Regarding the case of North-Western Italy, a European project named VAMP UP has been approved in 2016, with the main objective of increasing traffic in the Port of Savona-Vado. Along with a renewed port authority for the western ports of the Liguria region, The VAMP UP project (Vado Multimodal Platform Intermodal Connection Optimization and Upgrading) aims to improve the port, regarding organization, infrastructure and technology. The first results are expected in the beginning of 2018. This initiative is also a result of the near saturation state of the ports of Genova and La Spezia, which form a bottleneck to the hinterland (Autorità Portuale di Savona-Vado, 2014).

Furthermore, it intends to promote an effective integration in the core TEN-T (Trans European Transport Network), namely the Mediterranean Corridor. Consequently, its objectives exceed the sea port itself and call for an overall incorporation of all agents regarding freight transport in the hinterland, as well as infrastructure improvements, namely in the rail sector.

One of these agents is the freight village of Turin, which has had an historical relationship with the port of Savona. Its position is favorable, given that it integrates the Mediterranean corridor. Additionally, it poses as an inland terminal between the Liguria region and the north-west of Europe, as well as a buffer point for the city of Turin and the Piedmont region.

This research aimed at identifying and testing alternative scenarios of resource allocation and process organization that would fulfill the service level requirements under different traffic demand conditions.

CASE STUDY

Port of Savona

The Liguria Region in Italy is the most important southern transport gateway to Europe. From the ports of Savona-Vado, Genova and La Spezia, over 3,2 million TEU containers pass every year (APM 2014). The port of Savona-Vado is composed by two sections (Savona and Vado). Located in a 6-km bay connecting the two cities. With a total surface of 100 ha, it currently presents 13 terminal operators, as well as 4 oil plants.

The VAMP UP project's main objectives include fortifying freight transport on the core network, namely the Rhine-Alpine and Mediterranean Corridor, along with last-mile connections, by achieving integration with other modes of transport, especially rail. Particularly, the technical documents state a road-to-rail shift with a final rail quota of 40%. The Port authority foresees an increase in container traffic up to 425000 TEU/year in the first year and 720000 TEU/year, when fully operational.

Turin distances 159 km by rail and 140 km by road from Savona. According to the foreseen data provided by the port administration, regarding container capacity, it is possible to reach an estimation regarding containers arriving in Turin's freight village, based on the current situation. According to the port authority, around 30% of the freight moved by rail will have Turin as a final or intermediate destination. Meaning, thus, an average of 51,000 TEU/year in the first years and 86,400 TEU/year, when fully operational, arriving in Turin. Given that the freight village of Turin is the only structure prepared to receive this traffic, estimative for upcoming traffic will be based on these values.

Freight Village of Turin

Turin's freight village is located in the city of Orbassano, south-west of the city of Turin. It has 350,000 m^2 dedicated to storage units and 750,000 m^2 for intermodal transport. More than 150 companies detain property inside the inland port. These warehouses act as buffers considering distribution for the city of Turin and the Piedmont region and represent an attraction factor toward the terminal as it allow lowering warehousing costs as well as increase adaptability from the forwarders (Rodrigue and Notteboom, 2009). Furthermore, there is also a dedicated area for customs, meaning for international movement of goods.

There are two areas dedicated to intermodal transport (**Figure 1**): SITO yard (managed by *Società Interporto di Torino*), the same entity which handles the freight village and Terminal Italia yard, also called RFI yard. The latter is managed by *Rete Ferroviaria Italiana* or RFI, which is the same entity which is responsible for rail operations within the terminal.

SITO is composed by four tracks (D, E, F, and G) in which is it possible to perform unloading and loading operations. As to complete intermodal operations, SITO yard has four reach stackers available. On the other hand, RFI yard has five tracks dedicated to intermodal operations, and it also owns four reach stackers.

The terminal detains two diesel locomotives to perform all the operations. Electrical installation goes up to the end of arrival yard. From then on, all movements need the diesel locomotive. Other than handling intermodal trains to both yards, locomotives are responsible for a sort of tasks related to control testing and the transport toward the FIAT factory, which benefits from a dedicated line departing from the freight village of Turin.

When it comes to RFI yard, operationally speaking there are some peculiarities. Due to the terminal underuse, trains are often split in half, even if there are no dimensional conflicts. This measure aims at optimizing the use of the reach stackers and it also happens because of the yard underuse. This option critically limits current terminal capacity, given that a train occupies two tracks instead of one.

LITERATURE REVIEW

The Concept of Freight Village

A Freight Village can be described as an area comprising all the activities related to transports, logistics and goods' distribution (Baydar and Çelik, 2017). According to the same authors, these are usually located outside cities and often allow stakeholders to develop added-value activities. However, if located near a large

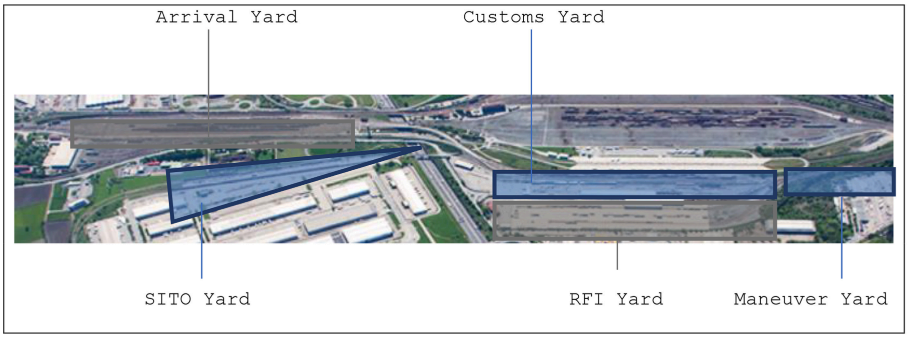

FIGURE 1 | The layout in the Freight Village of Turin.

city, freight villages also create opportunity for efficient local distribution in urban context (Ballis, 2006).

The concentration of activities promotes the creation of a synergy, fomenting thus coordination and collaboration between the different agents. Tsamboulas and Kapros (2003) underline the Freight Villages' role in stimulating intermodal transport. The same authors point out the importance of Freight Villages to the intermodal transport chain, pointing them as the "*principal component*," by allowing the transshipment of cargo between different modes of transport. More specifically regarding the present case study of Turin, the same authors highlight the importance of freight village as an integrator between maritime regions and densely populated inland areas.

On the other hand, Freight Villages can have a broader impact on the transport network, by acting has a hub for freight, along with allowing for modal change (Kapros et al., 2014). In fact, according to Ferguson (2013), freight villages can actually create opportunity for smaller companies to use intermodal transport.

Simulation

It is often impossible to perform experimentation in real life systems, due to cost or time associated reasons. For example, in this case, numerous trains would have to arrive at the freight village, to access capacity. And how would the stochastic factors, such as delays in arrivals or operations be tested? Simulation appears as a valuable technique of analysis, which allows to reduce reality into a model, in which several scenarios and hypothesis can be tested (Garrido, 2009).

Consequently, modeling requires abstraction, by including the details considered to be essential and disregarding the ones believed not to be important (Grigoryev, 2016). Furthermore, simulation modeling allows for an infinite variety of abstraction levels, each one consenting a certain degree of freedom. This could never be achieved in the real world and that is why simulation is considered to be a risk-free environment, where virtually all the possible scenarios can be experimented (Grigoryev, 2016). Additionally, with simulation, it is possible to track elements and trace variables (such as time or cost) which make possible to construct a statistical analysis.

Bearing this in mind, it is possible to distinguish two types of simulation, according to the level of abstraction and complexity, as well as the way system's elements interact with each other:

Discrete-Event

Developed in the 1960's, this category of simulation is one of the traditional methods regarding system modeling. Discrete-event simulation is a type of modeling in which a system changes at precise points in time and otherwise remains unaffected. It is also often referred as "Process-Centric" (Grigoryev, 2016) given its analysis of the system as a well-defined sequence of actions, completed by entities. Consequently, a process described by discrete-event simulation can be easily represented by a sequence of connected process blocks. Meaning that discrete-event is particularly appropriate for situations where variables change in well-defined moments and by well-defined actions (Özgün and Barlas, 2009).

Agent-Based

Developed during the 1990's, it is a more recent type of simulation which focus on the individual level, as opposed to the other types which concentrate more on the system itself. In agent-based simulation, the behavior or each agent is modeled. These are later put in a certain environment. The overall performance is, therefore, determined by all the different individual performances. Consequently, it is possible to build an agent-based simulation model having no knowledge of how the real system works, its dependencies and variables, as long as there is a clear notion of the entities (agents) and behavior (AnyLogic, 2017).

Several studies point out that discrete-event modeling is more appropriate for modeling as a strategic/tactical level, whereas continuous simulation is more suitable to perform strategic decisions (Tako and Robinson, 2012).

To sum up, opting for a type of simulation often depends on the kind of system to analyze and the sought objectives. As well as the desired level of complexity and abstraction.

More specifically in the case of intermodal transport, simulation is often pointed as the most adequate tool to analyze both rail terminal operations and port operations. Marinov and Viegas (2011) proposed a model to evaluate freight train operations in a rail network. Here, the importance of using simulation is justified by the possibility to test different scenarios as well as to explore system limitations. (Adamko et al., 2010) recommend simulation especially when a change in the system will take place and its consequences need to be anticipated. As an example, a change in the inbound flows. The same authors underline simulation as a valuable tool because it allows for experimentation, discovery of the system's properties and its response to different settings. Finally, Lin and Cheng (2011) emphasize the importance of simulation to recreate the complexity of rail operations and to test possible infrastructure improvements.

There are few studies on the assessment of inland intermodal terminals. Consequently, research was extended to maritime terminals, given that these are object to a superior number of investigation works. When analyzing former studies on terminals, it is possible to organize them according to their methodology and objectives. A summary is presented in **Table 1**.

Simulation is used to investigate various problems, from layout definition, to performance analysis. Also, it is possible to conclude that previous authors recurred mainly to discrete-event simulation to evaluate an intermodal terminal's performance. Continuous simulation was used in cases where the layout of the terminal needed to be defined or redesigned, always involving infrastructural and disposition alterations. In these cases, more variables can be simultaneously changed and therefore, they require a more complex analysis tool.

SIMULATION MODEL

AnyLogic was the chosen tool to build the simulation model, and it makes use of the 8.0.5 version. Firstly because of its comprehensive variety of complexity levels which allows to model any system with the desired level of detail.

As described in previous sections, the type of simulation is related with the pretended level of abstraction and complexity. Hence, going back to the objectives of this research, determining capacity and investigating problems and limitations, it is crucial to correctly define all the operation process sequence, along with resource allocation. Therefore, discrete-event simulation proves to be the indicated instrument to analyze the problem concerning the Freight Village of Turin.

Discrete-event presents as a suitable alternative, not only because all the processes performed can be described as discrete (loading/unloading of container, arrival of handling equipment) but also because the main purpose of this paper is to obtain service characteristics such as terminal capacity and dwell times. Furthermore, it is also important to have the possibility to test different scenarios, namely the present and future scenarios regarding the implementation of changes.

Model Definition

Firstly, the boundaries of the simulation were defined as the entrance of the rail terminal and the loading yards, where handling takes place. Consequently, the arrival and loading of trucks will not be consider in this study, nor the transport toward the different warehouses located within the terminal. Consequently, the physical model ends in the rail loading yards.

Given that the majority of the extend of the freight village is not electrified, all operations concerning the movement of trains require a diesel locomotive. Nevertheless, to reduce model's complexity, the locomotive is treated as a resource. Consequently, all the operations will be modeled as delays with a stochastic component. This allowed for simplifications in the terminal's physical appearance, by eliminating the locomotive dedicated tracks, as well as the locomotive depot and maintenance area.

Operation constraints were also considered when designing the simulation. The first one regards the locomotive schedule of operations, which determines how many locomotives (0, 1 or 2) are available in each moment. This schedule was provided by the operations department of the terminal. Moreover, there is an important contractual limitation when it comes to train operations, which limits trains waiting times to 2 h.

Model Architecture

In this section, the model is explained and detailed. Starting from the most abstract logic stages to the more objective options taken in terms of the software model. Conceptually, the model can be divided into three layers which interact with each other:

Modeling Environment—all the operations take place in a well-defined physical environment which is the rail terminal.

Process Logic—within the scope of discrete-event modeling, the process is developed using entities which flow through a sequence of operations.

Resources—certain operations need resources to be developed. These resources can be finite and its availability will limit the model progress and its results.

Model Structure

The following subchapters will explain the simulation model, taking advantage of its inseparability with physical space, by dividing the model into sections, each corresponding to a certain spatial section of the Freight Village (**Figure 2**). This is then followed by an animation subsection. To finish, the last subchapter will deal with the verification and validation of the model.

The model time unit is minutes and the simulation analysis comprises a week, starting on Monday 12/06/2017 at 5 am and finishing on the following Monday 19/06/2017 also at 5 am.

Train

The train is the main entity which flows through the chain of events. In order to accommodate different train typologies, different train populations were created. Each population has specific parameters which will alter their behavior in the chain of events and in the model. Furthermore, each trains population if connected to a *RailCar* population for color identification purposes.

The main reason behind the creation of agent populations was the possibility to depict the current traffic. Therefore, six different train typologies are part of the model. The train speed inside the freight village is obviously limited by the locomotive speed, which is 10 km/h. Each train agent is inserted in the system using a Train

TABLE 1 | A summary of simulation studies regarding sea ports and intermodal terminals.

Authors, Year	Case study	Objective	Methodology
Yun and Choi, 1999	Container terminal system analysis in Korea	Evaluate terminal's efficiency when dealing with growing incoming flows	Objected-oriented simulation
Rizzoli et al., 2000	Generic Rail/Road Intermodal Terminal	Develop simulation guidelines for a specific rail/road intermodal terminal	Discrete-event simulation
Legato and Mazza, 2001	Container terminal in Gioia Tauro	Layout planning and resources optimization	Discrete-event simulation
Lee et al., 2006	Designing a Rail Terminal in a Container Port in Korea	Propose a new design in order to deal with increasing rail transport quota. Determine the adequacy of resources.	Discrete-event simulation
Adamko and Klima, 2008	Generic Rail Terminal	Optimization of railway terminal design and operations	Continuous simulation
Marinov and Viegas, 2009	Freight rail network in Portugal	Provide a modeling methodology for analyzing freight train operations in a rail network	Discrete event simulation
Adamko et al., 2010	Generic Rail Terminal	Layout planning, terminal capacity determination and cost optimization	Continuous simulation
Gronalt and Rauch, 2015	Rail road terminal (transport of wood)	Performance analysis, evaluating systems capacity	Discrete event simulation

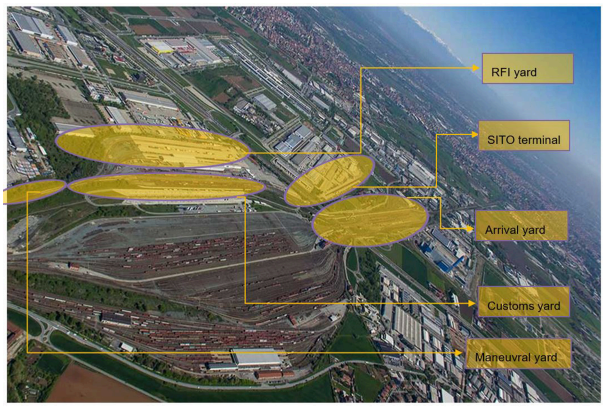

FIGURE 2 | Freight Village's layout.

Source block, which is related to an arrival schedule or defined by an interarrival time.

Arrival Yard

Figure 3 represents the process sequence taking place in the arrival yard, after train creation. "movArrivalLine" starts by inserting the train in the arrival yard, randomly choosing a free line. Then, the "{" icon represents the beginning of a restricted area. This means that if all loading lines are occupied, the incoming trains wait in the arrival yard until one of the trains exits the restricted area, after finishing the loading process. This ensures that no more than 9 trains move beyond the buffer zone. Then, "seizelocomotive" puts on a request for the locomotive.

Consequently, in case there are free lines for loading, the train then waits for the locomotive to arrive. To recall, the locomotive is represented by delays, consequently, "movtime1" represents the waiting time since the request to the arrival of the locomotive.

Customer and Maneuver Yards

The train then proceeds to the customs yard, again by randomly choosing between free lines. From the maneuver yard, the process diagram suffers ramifications according to destination yard and need to split. After this assortment, trains are moved toward the loading yard according to the initially defined parameters.

Loading Yards

After arriving to a loading track, the locomotive is let go and the loading process begins. The loading operation conveyed in this model is based on observations and it was subjected to validation by the operations staff at the Freight Village. Each yard has 4 reach stackers for the loading and unloading operations. when a train enters the loading area, the loading time is calculated using expression [1]:

$$\frac{2 * loading\ time\ per\ unit\ of\ transport * number\ of\ transport\ units}{\frac{total\ number\ of\ reachstackers\ present\ in\ the\ yard}{number\ of\ train\ being\ laoded\ in\ the\ moment\ the\ train\ entered\ the\ yards}} \quad (1)$$

The resulting time is then subjected to an exponential probabilistic function to create a stochastic delay. Moreover, this function has a static nature, meaning that it does not present a dynamic evaluation of the number of trains being loaded. Therefore, this function can either under or overestimate the loading time because it does not consider the trains that enter or exit while the process is performed. However, in the long run, these errors are compensated by each other. This is obviously a limitation associated with using discrete event simulation.

The loading process is followed by a sequence of "seize" and "release" of the locomotive and the bottleneck sections of the rail infrastructure, until it reaches the arrival yard, where the locomotive is again switched and the train can exit the terminal.

Model Animation

While not relevant to obtain results, a model animation was developed along with the logic process. This animation had two main purposes. The first one was related to the nature of this research. Being related to a real case study, the animation made it easier to convey the simulation role and its results to the Freight Village of Turin. This way, it is easier to understand even for those who are not familiar with simulation and, at the same time,

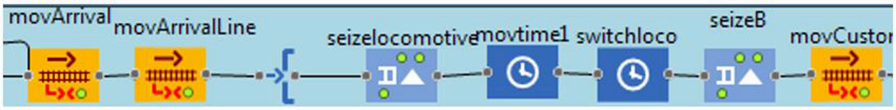

FIGURE 3 | Section of the block sequence.

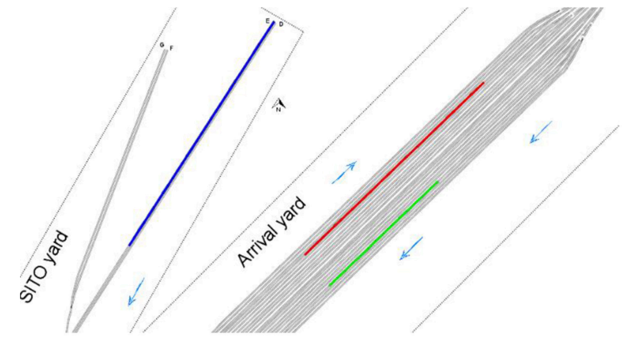

FIGURE 4 | Simulation window in AnyLogic.

TABLE 2 | Analyzed scenarios with respective changed variables.

	Current traffic	Current traffic + Savona traffic	Container traffic
Current resources and operations	Scenario A	Scenario B	–
Current resources with changes in operations	–	Scenario C	–
Varying resources (Locomotive and reach stackers)	–	Scenario D	Scenario E
Moving buffer area to customs yard (Changes in infrastructure and resources)			Scenario F

is visually attractive (**Figure 4**). The second reason regarded the debugging process inherent to any simulation model. Sometimes, the animation made it easier to understand the nature of the problem and allowed for verification that the compatibility between logic and spatial dimensions was achieved.

RESULTS

Before proceeding to the discussion of results, it is crucial to define the analyzed variables. While running the simulation is it possible to collect results regarding locomotive and yards utilization rates. These variables are important to convey to what extend are these elements being used, giving thusly, notions of underuse or overuse, as well as performance. Furthermore, other variables are collected in the end of each simulation run, using an Excel file. These variables are instants of time in which the agent train passes through the different stages of the process:

- Entering the arrival yard
- Leaving arrival yard
- Arriving to the loading track
- Time spent in loading process
- Leaving loading track
- Leaving the terminal

These variables are essential to understand the system's performance in terms of dwell times. Moreover, due to the limitations in terms of waiting times, it is important to check in every run if the contractual restrictions are being respected.

Scenarios

Different scenarios considered to analyze the present situation and future improvements (**Table 2**). The first scenario A regards the current circumstances in terms of traffic, resources and infrastructure. This scenario is used both to understand existing limitations and to serve as a tool for model validation.

The following scenario B overlaps scenario A with the upcoming traffic from Savona and it aims to check if there is compatibility between the two traffics. Scenario C is an improvement alternative of Scenario B, and it mainly focus on operation changes. Scenarios D, E and F allow for changes in resources (locomotive and reach stackers) and scenario F proposes a change in infrastructure. Scenario D is a consequence of scenario C and its main objective is to understand how resources affect the situation where the traffic of Savona is introduced in the present. Finally, scenarios E and F relate to the other objective of this thesis, which is the determination of capacity in terms of containers, considering thus alternative demand conditions.

The resources varied in scenarios D, E, and F could not be tested to exhaustion, therefore it was defined a limit of 2 locomotives and 8 reach stackers in each yard.

Consequently, scenarios can also be divided in three sections. Scenarios A represents the current scenario, scenarios, B, C, and D regard the advances in the VAMP UP project and the expected traffic coming from the Port of Savona. On the other hand, scenarios E and F aim to represent a hypothetical situation, in which all traffic resorts to transport units. Furthermore, scenarios E and F will investigate the terminal's capacity in terms of container units.

DISCUSSION

To perform an easier comparison between all scenarios, these are divided in three categories: scenarios which the current situation

A, scenarios regarding the additional traffic from Savona (B, C, and D) and scenarios which aim to determine the total terminal capacity in terms of container traffic (E and F).

Firstly, scenarios B, C, and D are compared with base scenario A. Because trains type 6 do not feature in scenario A, scenario B becomes the reference for this type of train.

By analyzing **Table 3**, it is possible to understand that inserting the traffic from Savona results in several increases in time, mainly for trains type 1 and 5, resulting, thus, in waiting times which do not respect contractual regulations (120-min waiting time).

Then, when analyzing scenario C, even though the improvements in terms of operations result in several reductions, both in loading times and service times, the accumulation of tasks regarding locomotive is the main reason why scenario C alone does not solve problems from scenario B. In fact, in some cases scenario C worsens the performance, while in other cases it improves it.

Scenario D shows as an additional solution, with the same requirements as B (brief and simple implementation) and it proposes to test the effect of varying the number of reach stackers, along with the operational changes made in C. The main conclusion is that one more reach stacker in RFI yard fixes the situation in terms of time requirements. Furthermore, it decreases overall dwell times. This result was expected given that these trains present considerable potential for improvement due to the fact of being constituted by transport units. Additionally, it also explains why increasing a reach stacker in RFI yard has a bigger impact than in SITO yard, because it targets both trains with transport units.

All in all, scenario D presents the most adequate and simple solution to solve the situation created by the introduction of trains from the Port of Savona. Growing the number of handling equipment by merely one unit in RFI yard, plus the operation alterations stated previously for scenario C allow to accommodate the foreseen changes in traffic.

Secondly, scenarios E and F deal with the issue of capacity, expressed in TEU/year. Scenario E proposes to study how the different resources impact on the freight villages final capacity,

TABLE 3 | Changes in scenario B, C and D regarding scenario A.

	Scenario B: introducing trains from Savona's Port					Scenario C: operation improvements						Scenario D: one more reach stacker in RFI yard					
Train type	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
Respects contractual limits?			No					No						Yes			
Arrival to loading (%)	6	-	-	4	-	8	13	23	43	3	2	12	4	12	39	29	2
Loading (%)	-	-	-	-	-	-	-	-	74	75	44	-	-	-	79	89	47
Loading to arrival (%)	14	-	-	-	8	5	36	23	123	8	3	3	26	14	25	5	3
Total Dwell time (%)	2	-	-	-	1	1	6	8	58	61	32	2	4	5	72	68	34

Figures in red represent increases in time while figures in green represent decreases.

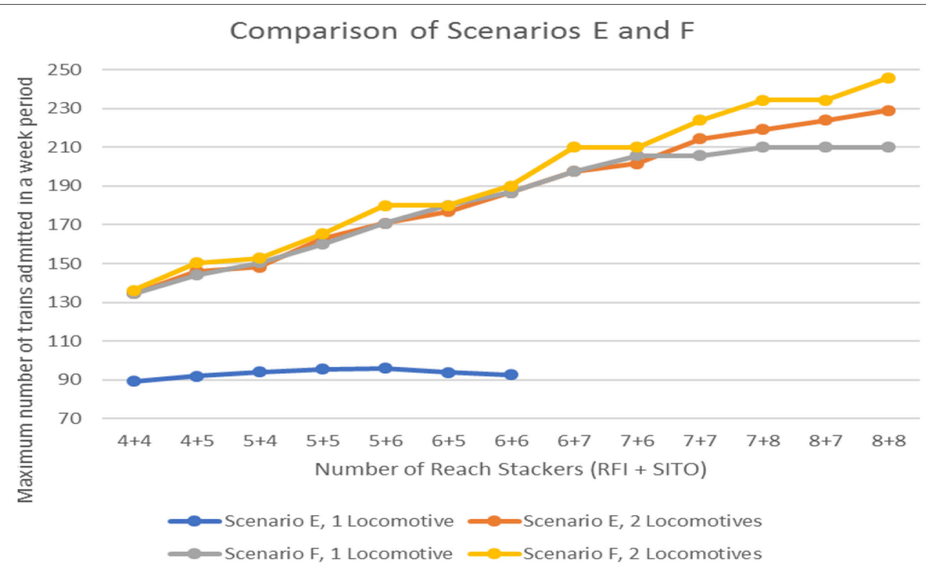

FIGURE 5 | Different throughputs in scenarios E and F.

whereas scenario F proposes a minor infrastructural change, which does not alter layout as it merely suggests an extension of electrified tracks with changes in operations regarding the buffer zone.

By analyzing **Figure 5**, scenario E with one dedicated locomotive presents the smallest capacity, with variation in the number of reach stackers having very low impact in the results. Furthermore, this scenario was tested only until the number of reach stackers in both yards reached 6. This is because, from 5+6 reach stackers, the capacity decreased. This was due to the significant train rotation which results in an overload of requests for the locomotive. The limitation of having only one locomotive is clear in the results, along with the inefficiencies of the current process, where the locomotive needs to go back and forth from the loading area to the arrival yard.

The remaining three scenarios present equivalent results in terms of capacity, with scenario F (2 dedicated locomotives) granting the highest capacity. Scenario E with 2 locomotives reinforces the conclusions drew previously, with one more locomotive allowing for much higher capacity. Having two locomotives in the conditions of scenario F brings little to none benefit, given that, in this case the capacity was limited by the loading process and not by the locomotive operation. This was evident on the low utilization percentages of this resource, denoting significant idle times.

For scenario E, the buffer zone is never capacity limiting, given that is allows for 18 trains to wait simultaneously. Consequently, time requirements are always surpassed before the buffer zone is fully occupied.

CONCLUSIONS

A methodology was outlined to evaluate the freight village's operational and handling processes, also by confronting diverse scenarios which aim to test the effect of varying mostly operation methods and resources. To meet this purpose, a simulation model was developed, having discrete-event modeling as a base. This model represents rail and handling operations performed inside the freight village, mainly focusing on the entity "train." Furthermore, the outcome in terms of analyzed variables was mainly related to time and resource's occupation rate, which allowed to evaluate and compare each scenario.

A total of six scenarios were analyzed, divided in two sections. The first section, composed by four scenarios, aimed at understanding the current situation and respective limitations, as well as determining the feasibility of introducing trains from the Savona-Vado port, along with testing the effects of operation and resources improvements. The second sections were developed with the objective of determining capacity in terms of containers, along with testing alternative scenarios in terms of resources and simple infrastructure changes.

In terms of total capacity, the effect of varying resources was successfully assessed, along with scenario F proposing an extend in the electrification grid present on the terminal, to make it possible to shift the buffer area toward the loading yards. In terms of performance, scenario F with one locomotive presents clear advantages because, not only allows to decrease locomotive use but is also presents the highest occupation rate of loading yards. On the other hand, scenario F with two locomotives does not allow for a significant improvement in capacity and it presents severely low utilization rates for the locomotive, making it a less attractive alternative

Concerning scenario E, having merely one locomotive strongly limits terminals' capacity, presenting the less appealing results. Increasing locomotive number for two allows to surpass this limitation, rising capacity values significantly. It is important to point out that inefficiencies found today in the freight village are mainly associated with the rail operation. This also relates to the inadequacy of the base infrastructure to perform intermodal activities. Therefore, the extensive path the locomotive goes through every time a train enter the terminal is surely something that needs to be addressed, as shown by the simulation results and it was the base from which scenario F was developed.

The results discussion focuses merely on capacity and performance. This is also conveyed by the analyzed variables. To investigate the validity of each scenario it would be interesting to perform a broad economic analysis to better understand if the extra costs related to resources and infrastructure improvements would be compensated by the increase in performance and, therefore, final capacity. This fragmented nature of the freight village, in terms of ownership and governance would be an obstacle to this end. Nonetheless, it would draw important conclusions in terms of feasibility.

The final considerations would have to do with a model which would test an overall improvement of infrastructure. Chiara et al. (2013) propose to adapt a former marshaling yard in Alexandria to a gateway terminal to better handle intermodal traffic. A study of the sort would be an interesting option for the freight village of Turin as it could convert the obsolete infrastructure into a terminal which is more adequate to present and future traffic conditions.

AUTHOR CONTRIBUTIONS

AA was responsible for developing the model, collecting the data and running the experiments. VR was responsible for model conceptualization and specification, and analysis of the results.

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frontiers in Built Environment

METHODS
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Investigating Root Causes of Railway Track Geometry Deterioration – A Data Mining Approach

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Railway track geometry deterioration indicates degradation in the underlying track structures. Monitoring and predicting this behavior are important as is investigating the root causes contributing to the deterioration. Without knowing the causes, assigned remediation might not result in a long-lasting correction. However, there is little research regarding the pragmatic aspects of investigating the root causes of track geometry deterioration utilizing real-world data sources. For this purpose, a new method was explored. After reviewing methodologies, the chosen approach was an association rule data mining method: General Unary Hypotheses Automaton (GUHA). The initial data used in data mining comprise data from asset management and multiple measurement systems, including a track geometry measurement vehicle, a track stiffness measurement device, ground penetrating radar, and lidar. The results of the GUHA data mining are hypotheses based on the initial data and can be used to indicate the most common and uncommon types of structures regarding their track geometry deterioration behavior and the attributes governing the behavior of a certain structure type. Therefore, the GUHA method was found to be a suitable method for investigating the root causes of track geometry deterioration from comprehensive railway track structure data.

Keywords: association rules, condition monitoring, data mining, railway track, track geometry deterioration

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INTRODUCTION

Railway track structures endure harsh conditions and countless damaging loading cycles in their life cycle. During this life cycle, which usually lasts many decades, the structures degrade and require intermediate maintenance. However, the need for maintenance is not generally homogeneous along the length of a track section: Some areas require much more frequent maintenance than others. If the heterogeneous nature of degradation is not accounted for, dangerous conditions regarding train safety can occur. Furthermore, if the uniform maintenance for the whole track section is assigned according to the needs of the weakest parts of the track, plenty of unnecessary maintenance will be conducted, and money will be wasted. Therefore, the condition of the whole track section needs to be monitored.

The condition monitoring of track structures is widely conducted using track geometry measurement vehicles that measure deviations of track geometry using onboard measurement systems (Esveld, 2001). The deviations indicated by the measurement systems indicate wear or movement in the track structures. These measurement systems continue to be developed, and new technologies are applied, for example, conducting measurements from in-service vehicles (Weston et al., 2015).

The track geometry measurements require detailed analyses to ensure train safety, and they are traditionally done by comparing the measurement results to limit values set by the track owner. Many different techniques can be used in this type of results analysis as described by Berawi et al. (2010).

Analyzing the condition of track geometry using more sophisticated methods has been a popular branch of science as is evident from the number of different approaches for track deterioration modeling (Higgins and Liu, 2018). Especially, track geometry deterioration modeling has been popular. Track geometry deterioration is the process of uneven settling of track structures, which is observed by obtaining increasing deviations in track geometry, when new measurements are conducted and time progresses. If this process is modeled with great detail, either with a deterministic or a stochastic model, the required maintenance can be planned in advance, which leads to better use of the track availability and reduced maintenance costs.

Track geometry deterioration modeling is a worthwhile exercise as it has been proven to reduce costs in asset management (Andrews et al., 2014). However, deterioration modeling is solving only half the problem. Another important aspect to consider is investigating the root causes of track geometry deterioration. These root causes are here defined as the track structure features associated with increased track geometry deterioration rates, for example, insufficient drainage or subgrade deformation issues. Fixing these types of problems for the long term might require maintenance activities that are different from routine maintenance.

The most common maintenance activity for correcting track geometry deviations is tamping. Tamping is the process of lifting the rails and ties while compacting the ballast under the ties being lifted. Tamping can level the track geometry to provide a smooth running surface for trains. However, the effects of tamping are not permanent (Audley and Andrews, 2013). Furthermore, tamping does not increase the resilience of structures *per se*, but only provides temporary correction of geometry. Deteriorated or defective track structures continue to cause the track geometry to rapidly deteriorate to the state before tamping. Therefore, to attain a more lasting effect, the root causes for track geometry deterioration must be investigated to assign suitable remediation.

This aspect of investigating root causes for track geometry deterioration has been researched far less than track geometry deterioration modeling. Guler et al. (2011) used neural networks to predict track geometry deterioration based on certain track asset data. Sadeghi and Askarinejad (2009, 2012) have provided stochastic approaches to analyzing the effects of track structure conditions and track components to track geometry.

Although these studies have modeled the effects of different components and conditions, they do not strictly assess the root causes of track geometry deviations. For example, the severity of some features is assessed in these studies, but the commonness of a problem type is not. To advance the investigation of the root causes of track geometry deterioration, new methods have to be tested and applied. For this purpose, a method is explored: first, by searching a promising method by type, and second, by testing the chosen method using actual railway track structure data.

Choosing a method for investigating the root causes of track geometry deterioration can be taken in steps. First, it must be decided whether to create a deterministic model or use a stochastic approach. Using a deterministic model requires many experimental values and knowledge of the chain of events leading to deteriorated track geometry. Although many track settlement models are available (Dahlberg, 2001), their use for this purpose may not be suited as these models rely greatly on detailed descriptions of different loading and support conditions. This information is practically impossible to provide for all the different types of structures on a track section.

Stochastic models, on the other hand, can utilize already available data, and inarguably, there is a great volume of data recorded from track structures that can be utilized. This data, in the case of Finland, includes the track geometry measurement history; ground penetrating radar (GPR) measurements that can provide a continuous thickness and moisture index for different structure layers; laser scanning (lidar) results to indicate embankment shape, from which drainage depth can be assessed; track asset data, such as bridges, turnouts, and culverts; and continuous track deflection measurements conducted as demonstrated by Luomala et al. (2017).

Therefore, the next step should be to select one stochastic approach, from which there are many to choose. Considering the complexity of the multivariate heterogeneous initial data, the search should be pointed to data mining methods that can digest this type of data.

Data mining can be understood in many ways and terms. Terms, such as machine learning and deep learning, are associated with the subject and are sometimes used interchangeably. Even though there is no single conclusive definition of data mining, one well-established way to define it is to use the terminology provided by Fayyad et al. (1996). In this terminology, data mining is a step in a larger process that is knowledge discovery from data (KDD). KDD begins with raw data, and after many steps in preprocessing the data and applying data mining methods and expert judgment, knowledge can be retrieved as the result. In this process, data mining is the step in which data analysis and discovery algorithms are applied to produce patterns or models from the data (Fayyad et al., 1996).

Data mining is in itself a whole branch of science, from which there are many methods to choose. As previously mentioned, the terminology in the field is not irrefutable, but some generalizations can be made. Data mining can be divided into two categories with different primary goals: predictive or descriptive methods (Fayyad et al., 1996). The predictive or supervised methods, in other terminology (Tsui et al., 2006), focus on learning past behavior and predicting future observations based on a given input. Descriptive or unsupervised methods, in other terminology (Tsui et al., 2006), find patterns or relationships within the provided data, thus giving new insight about the data that could not be observed with human effort. Most methods do not belong to one category absolutely but generally exhibit stronger ties to one than the other (Fayyad et al., 1996).

Of these two methodologies, descriptive data mining is the more fitting choice because finding root causes of track geometry deterioration is closely related to finding novel patterns and relationships from data and presenting them to the end user. Descriptive data mining methods can be classified to include clustering, summarization, association rules, and sequence discovery (Dunham, 2003) of which clustering and association rules provide the best descriptions of the relationships between different data sources, whereas summarization and sequence discovery are more useful in cases such as text mining or customer purchase tracking, respectively.

Clustering is organizing the data into groups that represent data points that are more similar to data inside the cluster than outside it (Jain et al., 1999). Association rules provide insight on which data sources are most associated with other data sources with a specified confidence, often using Boolean logic (Agrawal et al., 1993). Of these two tasks, association rules better fit the purpose of this research.

To enhance current practices regarding track geometry deterioration analysis, the ability to investigate the root causes of track geometry deterioration using the association rule data mining algorithm General Unary Hypotheses Automaton (GUHA) was tested. The choice of the method was based on the reviewed methodologies and tasks. GUHA provides a way to assess the relationship of different input data attributes. In practical terms, using GUHA, associations between available railway track structure data sources and developments in track geometry can be investigated.

MATERIALS AND METHODS

Initial Data

The initial data used in the data mining presented in section "Results from Applying GUHA to Railway Track Structure Data" concern the Luumäki–Imatra track section located in Eastern Finland. The track section was initially built in the 1960s and was renewed at the beginning of the 21st century. The track section is a 65-km-long electrified single-track line, which has both passenger and cargo traffic. A major renewal is being planned on the track section in question because faster and heavier trains are required to increase the line's efficiency. The condition of the track section varies: Some sections of the track exhibit problematic structures, whereas others have required little maintenance during their life cycle.

The initial data available from the structures of this track section were conformed into a single matrix (CSV spreadsheet), in which a row of data depicts a 1-m-long section of track that is described by the columns representing the features of the track structure. The initial data matrix contained 65,142 rows and 25 columns. Of the 25 columns, 24 contained attributes used in data mining, and one column contained location information in the form of track meters. This was used only for locating interesting occurrences, not for data mining. **Figure 1** presents a snapshot of the initial data, and **Table 1** elaborates the attributes of the data.

The initial data were essentially either ratio or nominal data depending on the data origin. Ratio data, in this context, refers to data having a true zero, order, and quantifiable differences between data points. Nominal data, in this context, refers to categorical or binary data in which no ordering, direction, or distances for the data points are present.

The attribute for track geometry deterioration rate is further elaborated in section "Track Geometry Deterioration Rate". Track deflection was measured using a continuous track deflection measurement device presented by Luomala et al. (2017). Two attributes were created from the track deflection measurements: deflection level (mean) and variations (variance) in deflection. Furthermore, track deflection measurements provided geometry cant data, which were used to identify track geometry elements such as curves and straights.

GPR measurements provided the structural layer moisture indices and layer boundaries, using which layer thicknesses were calculated. The structural layer thicknesses were calculated for ballast, subballast, and embankment. Furthermore, an attribute for the whole structure thickness, a combination of the aforementioned, was provided. GPR measurements also revealed bedrock depths in places where the bedrock level was shallow.

As a peculiarity, Finnish track structures are relatively thick compared with structures in warmer regions. The lowest allowable new track structure thickness using frost-resistant materials varies between 2.0 and 2.6 m, depending on the region. If the required track structure thickness is not met or if frost heave problems are observed on old track sections, frost insulation boards can be installed in the track substructure to reduce frost penetration. These frost insulation boards are extruded polystyrene boards that can withstand high pressure. Before the 2000s, some expanded polystyrene (EPS) boards were installed in track structures, but these did not endure well, and the use of EPS boards in track structures has since been banned.

As presented in **Table 1**, ditch depth was calculated from the laser scanning point clouds. Soil maps and historical data were used to assess the frost susceptibility of the subgrade. Asset data included binary and categorical attributes for frost insulation boards, stations, level crossings, bridges, culverts, turnouts, cuttings, and wayside signaling equipment. Some of the asset data were retrieved from the railway asset management data warehouse, and some of the data were created using the video feed of the track section combined with the GPR interpretations and laser point clouds. Accordingly, track assets could be accurately located.

The used initial data exhibited missing values. However, due to the GUHA method's ability to handle them and their small quantity, the missing values were left in the data. Some missing data were intentionally left blank and was handled in the software as an attribute category. For example, an empty value for a bridge implies the non-existence of a bridge. The actual missing values included ballast thickness on bridges without a ballast layer and ballast moisture in some turnouts where GPR measurements were distorted by the frog.

Track Geometry Deterioration Rate

The process for calculating the track geometry deterioration rate is not unambiguously defined throughout literature. Therefore,

km+m	KPSD20	MoistBallast	MoistSubBal	MoistEmbank	MoistAll	Sation/Line	Turnout	Bridge	Cut/Embk	FrostSusc	Signalling	DitchL	DitchR	...
258+131	0,37	63,8	52,6	39,2	55,5	Rasinsuo	10	0	0	3		-1,3	-1,2	...
258+132	0,29	63,8	53,4	39,9	55,9	Rasinsuo	10	0	0	3		-1,3	-1,2	...
258+133	0,29	63,8	54,3	40,6	56,3	Rasinsuo	10	0	0	3		-1,4	-1,2	...
258+134	0,27	62,1	53,2	40,3	55	Rasinsuo	10	0	0	3		-1,4	-1,2	...
258+135	0,2	58,6	50,1	39,1	52,1	Rasinsuo	10	0	0	3		-1,4	-1,2	...
258+136	0,18	55,1	47	38	49,2	Rasinsuo	10	0	0	3		-1,4	-1,2	...
258+137	0,18	51,6	43,9	36,8	46,3	Rasinsuo	10	0	0	3		-1,4	-1,2	...
258+138	0,18	48,1	40,8	35,6	43,4	Rasinsuo	10	0	0	3		-1,4	-1,1	...
258+139	0,2	46,6	39,3	35,4	42,2	Rasinsuo	10	0	0	3		-1,4	-1,1	...
258+140	0,21	47,3	39,6	36,3	42,8	Rasinsuo	10	0	0	3		-1,4	-1,1	...
258+141	0,23	48	39,9	37,2	43,4	Rasinsuo	10	0	0	3		-1,4	-1,1	...
258+142	0,22	48,7	40,1	38	43,9	Rasinsuo	10	0	0	3		-1,4	-1	...
258+143	0,25	49,4	40,4	38,9	44,5	Rasinsuo	10	0	0	3		-1,4	-1	...
258+144	0,23	49,6	41	39,2	44,9	Rasinsuo	10	0	0	3		-1,4	-0,8	...
258+145	0,16	49,5	41,9	39,1	45,1	Rasinsuo	10	0	0	3		-1,4	-0,7	...
258+146	0,15	49,4	42,9	39	45,4	Rasinsuo	10	0	0	3		-1,4	-0,7	...
258+147	0,12	49,3	43,8	38,9	45,6	Rasinsuo	10	0	0	3		-1,4	-0,6	...
258+148	0,1	49,2	44,7	38,8	45,8	Rasinsuo	10	0	0	3		-1,4	-0,5	...
258+149	0,1	49,5	45,5	38,9	46,2	Rasinsuo	10	0	0	3		-1,4	-0,4	...
258+150	0,08	50,3	46	39,3	46,8	Rasinsuo	10	0	0	3		-1,4	-0,3	...
258+151	0,09	51,1	46,5	39,7	47,5	Rasinsuo	10	0	0	3		-1,4	-0,3	...
258+152	0,1	51,9	47	40	48,1	Rasinsuo	10	0	0	3		-1,4	-0,3	...
258+153	0,1	52,7	47,5	40,4	48,7	Rasinsuo	10	0	0	3		-1,4	-0,2	...
258+154	0,11	52,6	46,7	41,9	48,7	Rasinsuo	10	0	0	3		-1,4	-0,2	...
258+155	0,11	51,6	44,4	44,4	48	Rasinsuo	10	0	0	3		-1,4	-0,2	...
258+156	0,11	50,6	42,2	47	47,3	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+157	0,11	49,5	40	49,5	46,6	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+158	0,1	48,5	37,7	52	45,9	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+159	0,1	47,9	36,8	52,1	45,4	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+160	0,09	47,8	37,3	49,8	45	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+161	0,08	47,7	37,7	47,5	44,7	Rasinsuo	10	0	0	3		-1,5	-0,2	...
258+162	0,08	47,6	38,1	45,2	44,3	Rasinsuo	10	0	0	3	OP	-1,5	-0,2	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	

FIGURE 1 | Snapshot of the initial data.

TABLE 1 | Attributes used in data mining.

Data origin	Data attribute	Data type	Data preprocessing
Track geometry car	Track geometry deterioration rate	Ratio	Annual 20 m SD growth
Continuous track deflection measurement	Track deflection mean	Ratio	20-m mean
Continuous track deflection measurement	Track deflection variance	Ratio	20-m variance
Continuous track deflection measurement	Geometry elements straight and curve	Binary	Calculation of cant indicating a curve
GPR	Structural layer moisture indices	Ratio	Signal attenuation calculations
GPR	Structural layer thicknesses	Ratio	Signal rebound calculations
Continuous laser scanning point cloud	Ditch depth	Ratio	Minimum value from 4 to 8 m perpendicular to the track centerline in a 20-m distance
Soil maps	Subgrade frost susceptibility assessment	Categorical	Subjective classification
Photos and visual assessment of data	Foundation type	Categorical	Subjective classification
Asset data and visual assessment of data	Asset data	Categorical and binary	Subjective classification
Tamping records	Tamping history	Categorical	Subjective classification

it is pertinent to fully elaborate how the calculations have been conducted, especially as the track geometry deterioration rate is used as the predominant measure of durability.

The track geometry measurement data were produced using a track recording vehicle, Plasser and Theurer EM 120 (Ttr1 51), which uses relative measurements from three bogies to determine track geometry deviations. The measurement data contained biannual measurements from 2008 to 2018. Longitudinal geometry deviations were used in calculating the deterioration rate because the longitudinal geometry is mostly affected by the movements in the structures below the track rather than only by the rails or sleepers themselves.

Different chord lengths and parameters were tested calculating the track geometry deterioration rate. A 20-m running standard deviation (SD) calculated from longitudinal deviations (LD) was chosen as it best described the original longitudinal geometry deviation signal. The SD values obtained from the consecutive measurements were used to calculate the annual increase or decrease in track geometry deterioration. The mean of the increased annual values was used to describe the track geometry deterioration rate. If the SD values significantly decreased from 1 year to another, the reduction was ignored in the track geometry deterioration rate because a large reduction in the deviation implied tamping or other maintenance and repair actions. The track geometry deterioration rate was calculated for each point in the track section in 1-m intervals to be in conformity with the other initial data.

The average deterioration rate for the Luumäki–Imatra track section was 0.103 mm/a. Track geometry deterioration rate was lower than average on 70% of the track section, meaning that problematic areas were not as common as non-problematic areas but exhibited much higher deterioration rates than the non-problematic areas. This result was expected because problematic areas are not generally long sections of the track.

Figure 2 presents an example of the track geometry deterioration rate of two cross-sections in which the y-axis represents 20 m SD values of LD. The deterioration behavior of the two cross-sections is very different. The cross-section at track kilometer 260 + 390 is at the edge of a section having frost insulation boards. The cross-section at track kilometer 260 + 360 is approximately 20 m away from the section having frost insulation boards.

The track geometry deterioration rate for cross-section 260 + 390 was 0.35 mm/a, whereas the corresponding value for cross-section 260 + 360 was 0.05 mm/a. Tamping can be observed to have taken place before the 2012 and 2016 winter measurements. Surprisingly, the 2012 tamping has increased deviations at cross-section 260 + 360, which might be due to uneven ballast settlement after tamping. However, the effect is nearly negligible because the deviations at cross-section 260 + 360 do not tend to grow, and the 2016 tamping has restored the deviations to their original level. In the spring of 2011, the track geometry was measured both in April and May. These measurements produced different results at cross-section 260 + 390. Winter of 2010–2011 was especially cold in Finland, and the measurements indicate the time before frost thaw and after frost thaw as deviations have significantly increased between the two measurements.

The calculated track geometry deterioration rate was visualized and compared with other available data. The deterioration indicates the condition of a track structure. Known problem areas, such as bridge transitions (Li and Davis, 2005) and stiffness variations (Dahlberg, 2010), could be detected based on the deterioration rate. In addition, tamping and frost heave problems could be observed from the track geometry history as large reductions or fluctuation in the deviations. The track geometry deterioration rate was generally used as the succedent attribute in GUHA data mining.

GUHA Method

The GUHA method was initially developed in the 1960s and 1970s, and its background was elaborated by Hájek and Havránek (1978). An up-to-date and comprehensive presentation of the method can be found in Jan Rauch's Observational Calculi and Association Rules (2013). The GUHA method is considered a descriptive data mining method. Hence, it is not used to make deductions or predictions, but to describe and present input data in new ways to users by producing hypotheses.

The GUHA method is based on logic formalism: the statements about data are either true (data support a statement) or false (data do not support the statement). The user provides general questions about the data. Typical data can produce millions of statements, among which only a few are true and interesting to the user. True statements, referred to as hypotheses, are considered to be answers to the user's questions.

Data mining was conducted using the LISp-Miner program, an application of the GUHA method (Rauch, 2013). The practical aspects of using LISp-Miner have been elaborated by Berka (2016). The GUHA method and its application, LISp-Miner, have considerably evolved since their discovery and are still being further developed (Novák et al., 2008; Hájek et al., 2010; Piché et al., 2014).

Figure 3 presents the generic process for using the GUHA method and the LISp-Miner program. This process begins with collecting and formatting data into an initial data matrix that is suitable for data mining. In the initial data, rows contain observations, and columns contain attributes (also called predicates), meaning the properties the observations have. In GUHA data mining, the key is to set relevant questions, called analytical questions, related to the data. These questions can be translated into the GUHA language. Then, GUHA data mining produces various hypotheses based on the input data. The hypotheses are automatically generated according to boundary conditions that are selected by the user. The hypotheses can vary from trivial to interesting in a single data mining task. The user can choose the meaningful ones and further explore them by assessing their contingency tables and associated predicates. After analyzing the results, the user can subjectively translate the numeric results into comprehensible human language.

The boundary conditions of the predicates assigned by the user include antecedents, succedents, conditions, and quantifiers, which adjust the preconditions and consequences of data mining. Adjusting these boundary conditions influences the types and number of results produced. The user should intend to achieve a limited number of results to reveal the strongest correlations within the data.

Antecedents, succedents, and conditions are attributes from the initial data. Any attribute can be set as an antecedent, succedent, or a condition, and any number or combination of attributes can be chosen. Furthermore, the assessment of attribute categories can be adjusted by choosing the coefficient

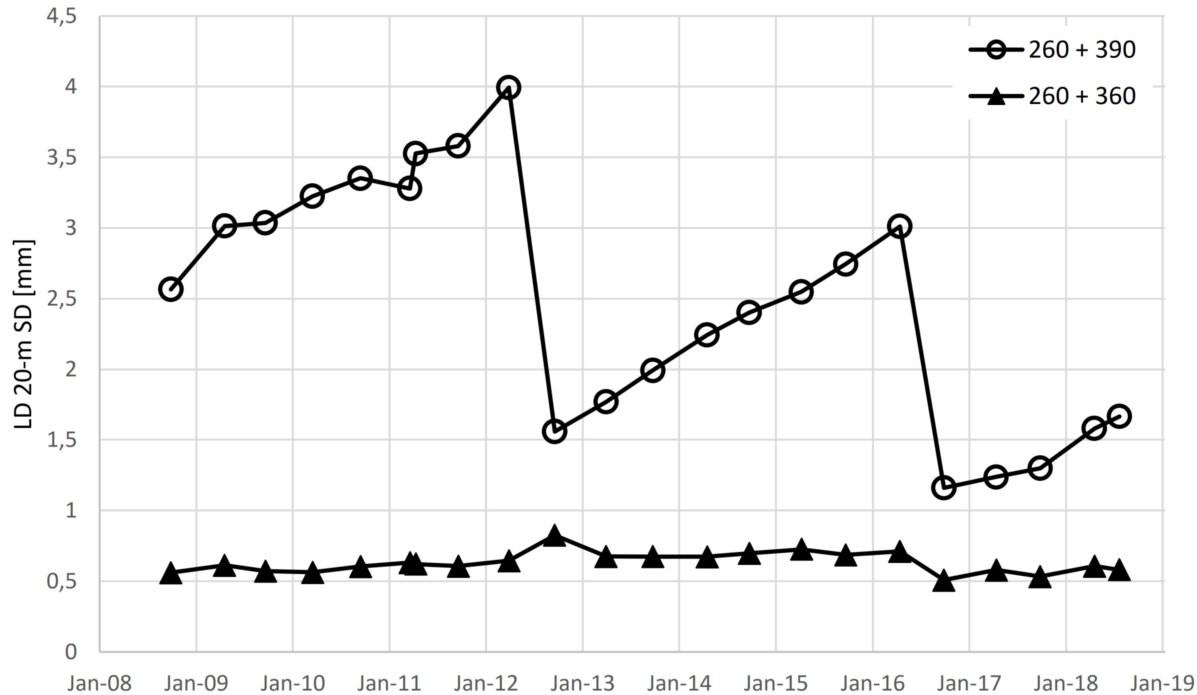

FIGURE 2 | LD 20-m SD of two cross-sections.

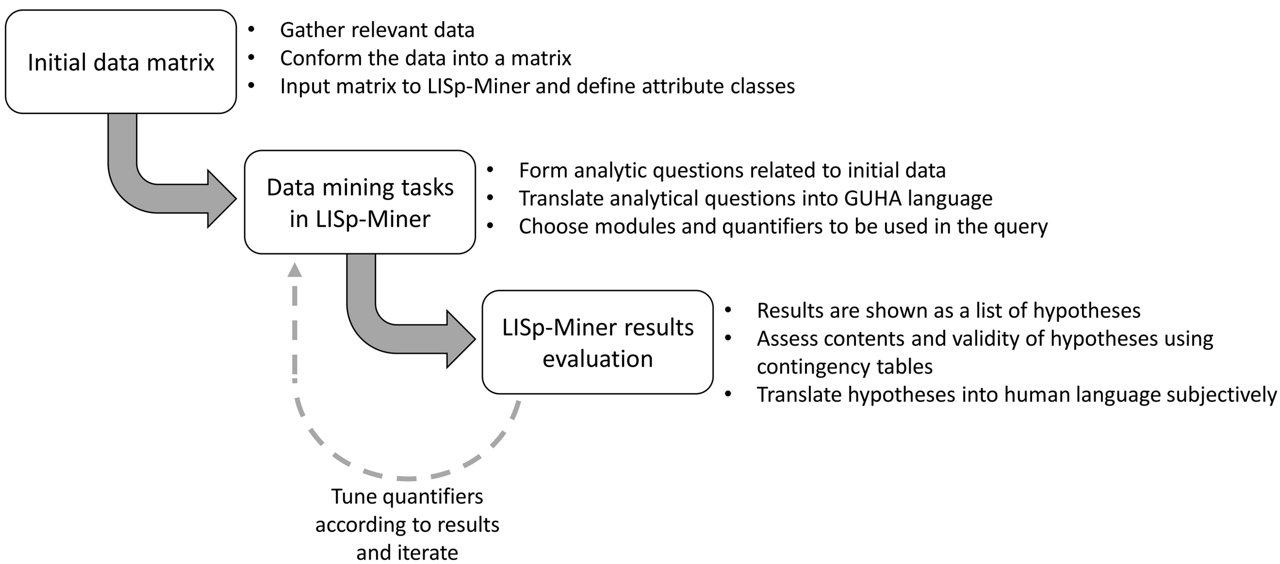

FIGURE 3 | Principle of the data mining process using LISp-Miner.

type and length. This process adjusts how many attribute categories are regarded in one category and how the combined categories are comprised.

The results (hypotheses) in the LISp-Miner program are presented to the user as contingency tables (**Table 2**). Based on the contents of the contingency tables and hypotheses, the user can assess the meaning and importance of the hypotheses and also subjectively examine the initial data and determine the rows from the data that support a hypothesis and those that oppose a hypothesis.

In **Table 2**, n is the number of initial data matrix rows regarded in a contingency table ($n = a + b + c + d$), when a is the number of objects satisfying both φ and ψ; b is the number of objects satisfying φ, but not ψ; c is the number of objects not satisfying φ, but satisfying ψ; and d is the number of objects not satisfying φ nor ψ (Turunen, 2018).

Ten data mining modules have been implemented into the LISp-Miner software, two of which were applied in the investigation of root causes for track geometry deterioration. In the 4ft-Miner module, several quantifiers can be used to evaluate the contingency table antecedent's (φ) relationship to its succedents (ψ) when condition (γ) is satisfied. In the AC4ft-Miner (action miner) module, two contingency tables are assessed and compared when some attributes remain stable and others change (called flexible attributes) between the tables (Berka, 2016). Pairs of rules specific for each quantifier are available to test the contingency tables' data.

GUHA quantifiers have an intuitive meaning, for example, "often implies," "almost equivalent," and "above average." Association rules based on quantifiers founded implication (also called p-implication or PIM) and above-average dependence were applied in both modules used. Founded implication assesses the commonness of the relationship p between contingency table parameters a and b. This can be expressed by,

$$\frac{a}{a+b} \geq p \text{ and } a \geq Base \text{ (Rauch, 2013)}. \quad (1)$$

By adjusting p, the user can choose to inquire hypotheses for which the antecedents and succedents are fulfilled in $0 < p \leq 1$ of cases (Rauch, 2013). For example, the query may involve asking in which cases the antecedent φ and succedent ψ are simultaneously fulfilled in more than 90% of cases. In other words, the association between φ and ψ is supported by the data if at least 90% of the cases in which φ is satisfied also ψ is satisfied.

The association rule based on the above-average quantifier tests how much more common succedent ψ is among the antecedents φ in relation to all the instances of ψ in the whole data set. This is defined more explicitly by

$$\frac{a}{a+b} \geq (1+p)\frac{a+c}{a+b+c+d} \text{ and } a \geq Base \text{ (Rauch, 2013)}. (2)$$

when $p > 0$. Now, by adjusting p, the user can choose how many more times above-average dependence must appear for the hypothesis to be accepted. For example, by choosing $p = 1$, the software will search the cases in which ψ appears two times more often in relation to φ than ψ appears in the whole data.

Frequencies related to quantifiers are also implemented into the modules. These regulate the *Base* value: the number of occurrences in different contingency table slots. For example, a quantifier for the contingency table parameter $a \geq Base = 1000$ can be given. Then, LISp-Miner will not present any hypotheses for which fewer than 1000 cases have fulfilled the antecedents, succedents, and conditions regardless of other chosen quantifiers.

Examples of how analytical questions are formed to GUHA questions and how hypotheses found by LISp-Miner procedures are interpreted into comprehensible language can be found in the next section.

TABLE 2 | Contingency table satisfying condition γ (Berka, 2016; Turunen, 2018).

γ	ψ	¬ψ	Σ
φ	a	b	$a + b = r$
¬φ	c	d	$c + d = s$
Σ	$a + c = k$	$b + d = l$	n

RESULTS FROM APPLYING GUHA TO RAILWAY TRACK STRUCTURE DATA

In this section, the application of the GUHA method to railway data is demonstrated by conducting three different exemplary GUHA data mining tasks. The demonstrations show how the software is used and the types of results that can be obtained. This section only presents the data mining queries and their results. The results' domain knowledge interpretations and the possible broader implications to railway domain applications are presented in the discussion.

In the demonstrations, analytical questions about the development of the track structure condition are formed and translated to GUHA language in LISp-Miner, and answers (hypotheses) to the questions are presented. The analytical questions were inquired using the data concerning the Luumäki–Imatra track section. The technical information concerning the queries and their results is composed into **Table 3**.

Analytical Question 1: What kind of track structure attributes are associated with a certain type of track geometry deterioration rate with more than four times above-average dependence?

The first query was conducted using 4ft-Miner module. *Base* parameter for contingency table parameter $a \geq 2000$ and quantifier over four times above-average dependence were applied. All attributes except for the track geometry deterioration rate could be chosen for antecedents, but the program was limited to choose 2–5 attributes. The only succedent was the track geometry deterioration rate, for which 1–4 sequential classes could be chosen by the program. No conditions were applied.

The query concerning analytical question 1 resulted in 112,059,584 verifications (contingency tables), of which 163 were in accordance with the preconditions (antecedents, succedents, conditions, and quantifiers). These hypotheses were displayed

TABLE 3 | Technical information of queries.

Query	Module	Quantifier	*Base* quantifier	Verifications	Number of hypotheses
1	4ft	AAD ≥ 4	$a \geq 2000$	112,059,584	163
2	4ft	PIM ≥ 0.9	$a \geq 5000$	111,967	50
3	AC4ft	State before PIM ≥ 0.7 State after PIM ≤ 0.4	State before $a \geq 1000$ State after $a \geq 300$	2070	40

TABLE 4 | Contingency table for analytical question 1 and 2 hypotheses.

	Hypothesis 1		Hypothesis 2	
	Succedent	**¬Succedent**	**Succedent**	**¬Succedent**
Antecedent	2106	1338	5350	415
¬Antecedent	5247	56,451	28,948	9,441

TABLE 5 | Attributes for analytical question 1 hypothesis.

Antecedent	**Class**
Liner or station	Line
Culvert	No
Bridge	No
Substructure moisture index	>50 (%)
Frost insulation board	Yes
Succedent	**Class**
Track geometry deterioration rate	>0.20 mm/a

to the user. One of the 163 hypotheses is presented below. Its contingency table is presented in **Table 4**, and attributes are presented in **Table 5**.

Hypothesis that is one answer to analytical question 1 (statement supported by the data): When the track section is located on a line section that contains no bridges or culverts, its substructure exhibits a high moisture index, and a frost insulation board is installed in the track structure, the highest class of track geometry deterioration rate is observed 4.4 times more often than on average.

No conditions were set for the analytical question 1 query, so the whole track section, composed of 65,142 (=2106 + 1338 + 5247 + 56,451) rows of data, is presented in the hypothesis and contingency table.

Analytical Question 2: What kind of track structure attributes have the highest correlation to some types of track geometry deterioration rate on a line section without track structure discontinuity or frost insulation boards?

Analytical question 2 query was also conducted using the 4ft-Miner module. *Base* parameter $a \geq 5000$ and founded quantifier PIM must be over 90% ($p \geq 0.9$) were used. Antecedents included all track structure attributes aside from the track geometry deterioration rate, discontinuity attributes, stations, and frost insulation boards. The succedent included the track geometry deterioration rate, from which the program could choose 1–4 sequential classes. Sections with signaling equipment, stations, culverts, bridges, level crossings, turnouts, and frost insulation boards were excluded using conditions.

Analytical question 2 query resulted in 111,967 verifications, of which 50 were in accordance with the preconditions. One of the 50 hypotheses is presented below. Its contingency table is presented in **Table 4**, and attributes are presented in **Table 6**.

Analytical question 2 hypothesis (statement supported by the data): A lower than average track geometry deterioration rate is observed on 93% of the track structures that are founded on an embankment, exhibit 300- to 500-mm-thick ballast layers, exhibit a low structure moisture index, are located on straights, and have low track deflection variance.

Because conditions were used to exclude certain types of track, only 44,154 (=5350 + 415 + 28,948 + 9441) rows are now presented in the contingency table, meaning that 20,988 rows contained discontinuities, stations, or frost insulation boards and were not included in the data mining task.

Analytical Question 3: If some track structure attributes are stable, how does a change in the attribute for frost insulation boards affect a certain type of track geometry deterioration rate on a line section without track structure discontinuities?

The third analytical question was conducted using the 4ft-Action Miner (AC4ft). *Base* parameter a $\geq$ 1000 for the before state and $a \geq 300$ for the after state were used. Founded implication $p \geq 0.7$ for the before state and $p \leq 0.4$ for the after state were applied. Antecedents' stable part included all track structure attributes except for frost insulation boards, track geometry deterioration rate, stations, and discontinuities. Antecedent attribute part included frost insulation boards. The succedent stable part was the track geometry deterioration rate from which the program could choose 2–4 sequential classes. In the conditions, signaling equipment, stations, culverts, bridges, level crossings, and turnouts were excluded.

Analytical question 3 query resulted in 2070 verifications, which led to 40 results. One of the 40 results is presented below. Its two adjacent contingency tables are presented in **Table 7**, and attributes are presented in **Table 8**. There were 47,881 rows of data that met the conditions and were examined in the hypothesis.

Analytical question 3 hypothesis (statement supported by the data): When the track moisture index is very high and the number of tamping times is low, a high track geometry deterioration rate is observed on 79% of the structures where a frost insulation

TABLE 6 | Attributes for analytical question 2 hypothesis.

Antecedent	**Class**
Foundation type	Embankment
Ballast thickness	300–500 mm
Structure moisture index	10–40 (%)
Straight or curve	Straight
Track deflection variance	<0.01 mm
Succedent	**Class**
Track geometry deterioration rate	<0.10 mm/a
Condition	**Class**
Signaling equipment	No
Straight or curve	Straight
Foundation type	Embankment
Culvert	No
Bridge	No
Level crossing	No
Turnout	No
Frost insulation board	No

TABLE 7 | Contingency tables for analytical question 3 hypothesis.

	Frost insulation board		No frost insulation board	
	Succedent	**¬Succedent**	**Succedent**	**¬ Succedent**
Antecedent	2014	533	371	2216
¬Antecedent	4996	40,338	6639	38,655

TABLE 8 | Attributes for analytical question 3 hypothesis.

Antecedent	**Class**
Structure moisture index	>50 (%)
Number of tampings	1–2
Frost insulation board	Flexible attribute
Succedent	**Class**
Track geometry deterioration rate	>0.14 mm/a
Condition	**Class**
Signaling equipment	No
Straight or curve	Straight
Foundation type	Embankment
Culvert	No
Bridge	No
Level crossing	No
Turnout	No

board has been installed and on 14% of track sections where no frost insulation board has been installed.

DISCUSSION

Case Track Section Data Mining

The hypothesis for analytical question 1 presented the combination of parameters that were more commonly associated with high track geometry deterioration rates, meaning that the track section is abnormal as regards track geometry deterioration, and the hypothesis attributes should be investigated further.

The attributes of the hypothesis include common attributes, such as line sections instead of stations and the exclusion of bridges and culverts. These do not create a distinct attribute combination as the vast majority of the track section shares these attribute types. The other two antecedents are far more infrequent in the data: high substructure moisture index and frost insulation boards. However, these two attribute values are connected due to the GPR measurement technique. Frost insulation boards increase the GPR moisture index of the substructure layer because they cause the GPR signal to deflect and give high readings that would normally indicate the appearance of moisture. Therefore, it is reasonable to deduct that the frost insulation boards are playing a major role in this hypothesis. Based on this information, the areas located on line sections in which frost insulation has been installed should be further investigated. Such investigations have been reported in Sauni et al. (2020).

The analytical question 1 hypothesis has good confidence as more than 2 km of track support the statement, and about 1.3 km of track oppose it. If the same hypothesis were to be created for the rest of the track section, only around 5.2 km of track would support it, and more than 56 km oppose it. Considering these lengths, the behavior of the track section in accordance with the hypothesis antecedents is unusual to say the least.

The hypothesis for analytical question 2 demonstrated the highest correlation to a particular type of track geometry deterioration rate. The result implied that almost all cases (93%) of track sections in accordance with the antecedents exhibit only low track geometry deterioration rates. This correlation does not deviate from the average correlation (75%) of the rest of the track section as much as the correlations in hypothesis for analytical question 1. Nevertheless, this hypothesis showed that the correlation is particularly strong as more than 5 km of track satisfying the antecedents behaves almost uniformly.

The antecedents of the hypothesis for analytical question 2 exhibit properties traditionally associated with good structures such as low moisture and low deflection variance. The results are intuitive and demonstrate that the presumptions regarding the properties presented in the antecedents are justified. Furthermore, when all the hypotheses for analytical question 2 were examined, it was apparent that all hypotheses' succedents were related to low track geometry deterioration rates. This may be the result of opting out track discontinuities and frost insulation boards from the antecedents.

A difference could be observed between the types of hypotheses obtained from analytical questions 1 and 2. Analytical question 1 produced results concerning abnormal behavior of track structures, whereas analytical question 2 produced results concerning typical behavior.

The third analytical question provided a comparison of two populations that differed by one antecedent class: frost insulation boards. According to one produced hypothesis, the existence of a frost insulation board divides track sections consisting of track built on embankment without discontinuities. On these structures with frost insulation boards, high track geometry deterioration rates are observed on 79% of structures. When only the attribute for frost insulation boards is changed to *no frost insulation board*, the commonness of high track geometry is practically converse at 14%. This result highlights the major effect of frost insulation boards on the track geometry deterioration rate.

Prospective of GUHA in Railway Track Structure Condition Monitoring

In this section, the use of the tested LISp-Miner GUHA data mining modules and quantifiers is discussed in a broader context regarding railway track structure condition monitoring.

Stochastic analysis of railway track structures inherently leads to handling heterogeneous data that originate from multiple sources. The requirement for an analysis method and software to handle this type of data is met using LISp-Miner, as text, numerals, binary, and categorical data can all be used as they are. Furthermore, missing data and outliers can be handled within the LISp-Miner software when creating attribute categories. Thus, the GUHA method and LISp-Miner software provide an adequate basis for track structure data analysis.

From the heterogeneous track structure data, the GUHA method could be used to ask questions related to correlations between variables and their combinations. Three different types of questions were asked, for which different module-quantifier combinations were used.

The **4ft-Miner module with the PIM quantifier** can be used to inquire about the most common types of attribute combinations. For the investigation of the causes of track geometry deterioration, these questions help in understanding the most common types of track structure behavior. This helps in identifying structures, i.e., the combination of attributes that generally exhibit only a certain type of behavior.

The **4ft-Miner module with the above-average quantifier** can be used practically for the contrary of purpose as 4ft-Miner with PIM. The above-average quantifier provides extraordinary correlations between variable combinations when compared with other variables' correlations. In the context of investigating the causes of track geometry deterioration, this approach can be used to detect abnormal behavior of some structure types. This information is of value in detecting the peculiar structure types that exhibit problematic behavior.

The **AC4ft-Miner module with the PIM quantifier** approach investigates the effects of changing one or some of the attribute classes in a hypothesis. In practice, this method can reveal which attributes have the dominant effect on a certain type of structure's behavior. This feature can be used to individually detect the attributes contributing to geometry deterioration rate.

The encountered limitations of the GUHA method were the dependence on initial data and the amount of effort required for result analysis. The dependence on initial data stems from the descriptive nature of the method. If the input data do not entail the features affecting the behavior of the structure, the method cannot produce results that exhibit such features. The initial data available for the case track section were vast. However, such data sets are not readily available for all track sections. To ensure reliable and interesting results, the method should be used only if extensive data are available.

The other encountered limitation was the difficulty to communicate the results to people not familiar with GUHA. The contingency tables and attributes can be subjectively translated into comprehensible language, which aids communication. However, some of the translated hypotheses can be difficult to fully comprehend as they might contain many variables and details. To counter the difficulties, visualizing the results should be further researched.

CONCLUSION

Successful condition monitoring of track geometry requires not only measurements and maintenance responses to deviations but also investigations into the root causes for its deterioration. For the investigations, an approach with flexible data handling and good generalization ability is required. Thus, stochastic models were examined instead of deterministic models as the latter requires much too specific input information, which is not usually available in asset management.

From the stochastic models, an association rule data mining method, GUHA, was selected to be tested. The method is a descriptive data mining method, meaning that it describes the input data and presents it to the user in an informative way. The GUHA method is applied in software, LISp-Miner, which can handle multivariate heterogeneous data and produces hypotheses that are statements generated from the input data.

The use of the GUHA method was tested on actual track structure data from the Finnish state rail network. Three GUHA module-and-quantifier combinations were examined. The results from the data mining were used to generalize the types of domain information that can be investigated using the GUHA method. Three following applications for approaches were identified:

- 4ft-Miner and PIM quantifier identifies the structure types (attribute combinations) that correlate strongly to a certain track geometry deterioration rate.
- 4ft-Miner and above-average quantifier identifies the structure types that exhibit behavior, which differs from the typical behavior of structures.
- AC4ft-Miner module and PIM quantifier identify the structure attributes affecting the behavior of structures when changed.

Using the information obtained from these approaches, the causes of track geometry deterioration can be investigated from asset data. The method points out the structure types correlating to certain behavior and identifies the attributes governing the behavior. The main limitation of the method is the dependence to the input data. If a feature is not depicted in the initial data, it cannot be present in the results either. The GUHA method and LISp-Miner contain many more approaches in addition to the three tested ones. Exploring the applicability of these in the future would be valuable.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

MS was responsible for gathering and processing the initial data and conducting the data mining. HL and PK were responsible for organizing the research and participated in the analysis of the data mining results. ET supervised the data mining process. All authors contributed to the article and approved the submitted version.

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Parametric Studies Into Creep and Shrinkage Characteristics in Railway Prestressed Concrete Sleepers

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It is well known that prestressed concrete is highly suitable for railway sleepers because of its many advantages in performance, maintenance, sustainability, and construction. Prestressed concrete design can improve structural performance since the prestress enables fully compressed cross sections. Higher tensile resistance of prestressed concrete can then take place. However, longer-term performance and durability of concrete sleepers largely depends on creep and shrinkage behaviors. On this ground, the effects of time-dependent phenomena on prestressed concrete sleeper are investigated in this study. In the past decades, a number of material models have been established to estimate creep and shrinkage behavior, but those were mostly based on a generic reinforced concrete design concept. The common uses of prestressed concrete have led to practical concerns by practitioners whether those existing predictive models could be realistically applied to prestressed concrete applications. Due to a relatively higher initial elastic shortening in prestressed concrete, the creep and shrinkage effects should be critically reevaluated among flexural members. This study embarks on comparative studies into the effects of creep and shrinkage on prestressed concrete railway sleepers. A thorough comparison between prediction models underpinned by European Standard Eurocode 2, American Standard ACI, and Australian Standard AS3600-2009 enables new insights into the time-dependent performance of railway concrete sleepers installed in various locations or in different continents. This implies that the durability of railway concrete sleepers can be undermined differently when exposed to different conditions even in the same rail network. The insights stemmed from this study will help track engineers to better design and maintain railway infrastructure, improving asset management efficacy.

Keywords: railway sleepers, creep, shrinkage, prediction model, comparative study

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INTRODUCTION

Railway sleepers (or called "railroad ties"), which are generally manufactured using timber, concrete, steel, or other engineered materials, are one of the main safety-critical components of railway track structures (Esveld, 2001). Concrete sleepers have been initially used on rail tracks since 1884 and have recently been used almost everywhere in the world. The major roles of sleepers are (i) to transfer wheel loads from the superstructure to the substructure and (ii) to secure the gauge between rails for safe passages of trains. In reality, wheel/rail interactions over common defects in either a wheel or a rail can cause severe impact loading conditions (Remennikov and Kaewunruen, 2005; Kaewunruen, 2014; Remennikov and Kaewunruen, 2015; Kaewunruen and Remennikov, 2008a,b,c; Remenikov and Kaewunruen, 2008; Remennikov et al., 2011; Fujino and Siringoringo, 2016; Kaewunruen et al., 2016a; Yahiaoui et al., 2017). The impact loads can significantly undermine structural integrity and durability of railway sleepers over the time. Such actions can exacerbate the structural behaviors of the concrete sleepers affected by extreme or hostile environmental conditions. For example, shrinkage cracks can be further open from the dynamic actions, resulting in water and chloride penetrations, as well as carbonation and corrosion. On this ground, it is vital to understand the time-dependent behaviors of concrete sleepers in order to pre-design and risk-manage the concrete sleepers over their entire service life.

Reinforced concrete was initially used for railway sleepers over a century ago. However, poor structural performance and extensive damage have proved that traditional reinforced concrete design was not an effective solution for railway sleepers. Therefore, a prestressed concrete design concept has been developed and adopted for railway sleepers instead of traditional reinforced concrete structures. The prestressed concrete concept can result in lower maintenance costs and longer life cycles in terms of economic and technical aspects. Nowadays, the most commonly used type of sleepers around the world is the prestressed concrete type, which can provide higher serviceability, stability, and safety, especially in suburban and heavy haul rail networks (Kaewunruen and Remennikov, 2010; Parande, 2013; Taherinezhad et al., 2013; Kaewunruen, 2014; Tang et al., 2015; Padhi and Panda, 2017). Prestressed concrete sleepers must successfully perform to satisfy two key responsibilities: first, transfer the wheel loads from the rails to the ground, and later, restrain the rail gauge to ensure the dynamic and safe travels of trains. However, in some cases, creep, shrinkage, and elastic shortening stemmed from improper, unexpected material responses can foul the rail gauge by excessive time-dependent behaviors (for example, too tight rail gauge, splitting cracks at fasteners, vertical cracks along dowels, holes or web openings). Note that, in reality, concrete sleepers are often modified at construction sites to fit in other systems, such as cables, signaling devices, and drainage pipes. These modifications can further result in structural damages in concrete sleepers when excessive time-dependent behaviors are present.

Creep and shrinkage responses can largely influence the durability and long-term behaviors of prestressed concrete railway sleepers (Wakui and Okuda, 1999; Gustavson, 2002). A number of material models have been developed to predict creep and shrinkage, but those are mostly based on a generic type of concrete and on certain applications of traditional reinforced concrete structures (Wang, 1996; Warner et al., 1998; Bentz, 2000). Worldwide adoptions of prestressed concrete in long-span bridges, stadiums, silos, and confined nuclear power plants have led to various concerns by practitioners whether those predictive models could be realistically applied to prestressed concrete components (Ercolino et al., 2015; Li et al., 2015). Due to high initial prestress and elastic shortening in prestressed concrete, the creep and shrinkage effects need to be critically reevaluated. This study investigates and compares methods to evaluate creep and shrinkage effects in prestressed concrete railway sleepers. Comparison among design codes of EUROCODE2, ACI, and AS2009-3600 will provide practical insights into the long-term behavior and durability of railway concrete sleepers. The outcome of this study will help track engineers to better design, manufacture, inspect, and maintain railway infrastructures, improving asset management efficacy.

Three approaches have been adopted in order to meet the research aim. Initially, the design codes have been rigorously reviewed in order to understand how these design codes can be used to properly predict creep and shrinkage. In this stage, a calculation sheet for each code has been developed. All calculations have been carried out analytically. The, the analytical data are analyzed. The sensitivity analysis has been carried out to study the effect of creep and shrinkage. The different codes of practice are performed in order to conduct a comparative study. In practice, the concrete sleepers are manufactured within a day by accelerating the concrete strength to meet the transfer requirements. As such, more realistic losses of prestress and the resultant sleeper shortenings can be established.

This research aims at providing a principal understanding of creep and shrinkage effects for railway prestressed concrete sleepers' design and manufacture. After introducing the design codes, the parametric analyses are presented. In this investigation, four key parameters (strength, relative humidity, age at first loading, and curing time) are considered to highlight creep and shrinkage effects. The loss of prestress as a result of deformations due to creep and shrinkage are discussed. This research will also provide a state-of-the-art review of common design criteria of prestressed concrete based on Eurocode 2, the American Concrete Institution code, and Australian Standard 2009–3600. It will then determine creep and shrinkage effects in prestressed concrete railway sleepers (Gjorv, 2013; Kaewunruen and Remennikov, 2013). The creep and shrinkage characteristics in prestressed concrete sleepers have been thoroughly investigated in the past. This study provides new findings to better understand the sensitivity of key vulnerable parameters that can significantly affect railway concrete sleepers exposed to various environmental conditions even in the same railway line in a rail network. In addition, the insights into the application of the design methods will be illustrated in order to provide a new guideline for applying those existing codes of practice.

CREEP

Neville (1995) stated that the strain increases with time even when the concrete is loaded constantly, due to creep effect. Therefore, creep can be defined by the increase of strain in concrete under a sustained stress. With time increments, the increased strain can be several times larger than initial strain. Generally, creep is a considerable factor in concrete structures. Bhatt (2011) stated that creep can be defined as the increase of strain with time when the stress is held constant. The displacement of concrete can gradually increase with time when the load is left in place. Such displacement can reach a value as large as three to four times of the initial or immediate elastic deformation. The inelastic deformation due to the constant load is known as creep deformation. **Figure 1** shows the behavior of the creep strain over time.

Creep develops in cement paste, which is made of colloidal sheets formed by calcium silicate hydrates and evaporable water. Creep can be influenced by several factors such as concrete mix and environmental and loading conditions. Creep is commonly inversely proportional to concrete strength (e.g., higher strength concrete tends to have lesser creep). In addition, aggregate content and size as well as water/cement ratio can also affect creep strain. Environmental factors like relative humidity, temperature, and exposure conditions also play a significant role on creep. Duration and magnitude of stress and the first loading age are external loading parameters in the creep predictions (Vittorio, 2011). When creep is taken into account, its influences on the design life of concrete sleepers are always evaluated under quasi-permanent combination of actions irrespective of the design situation considered, i.e., persistent, transient, or accidental. Based on such complex situation, various codes of practice simplify each critical parameter to suit its local conditions. On this ground, it is crucial to revisit each code of practice.

Eurocode 2

The total creep strain $\varepsilon_{cc}(t, t_0)$ of concrete due to the constant compressive stress of σ_c applied at the concrete age of t_0 is given by

$$\varepsilon_{cc}(t, t_0) = \varphi(t, t_0) \times \frac{\sigma_c}{E_c}$$

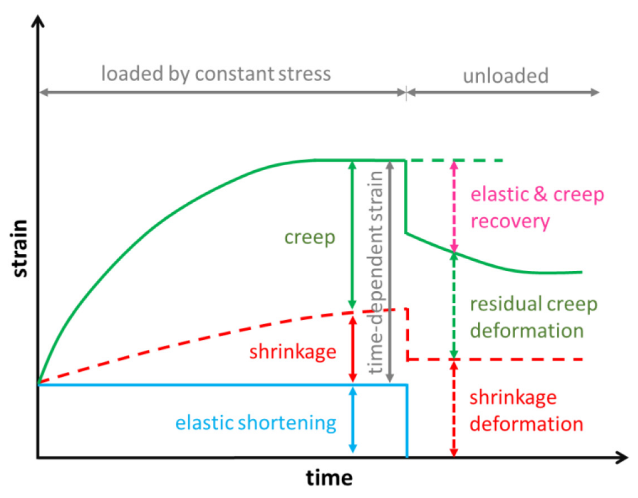

FIGURE 1 | Creep strain over time.

where $\varphi(t, t_0)$ is the final creep coefficient; E_c is the tangent modulus.

$$\varphi(t, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})}$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, \; f_{cm} \leq 35MPa$$

$$\varphi_{RH} = \left(1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}} \alpha_1\right) \alpha_2, \; f_{cm} > 35MPa$$

$$\alpha_1 = \left(\frac{35}{f_{cm}}\right)^{0.7}, \; \alpha_2 = \left(\frac{35}{f_{cm}}\right)^{0.2} \; f_{cm} = f_{ck} + 8 \text{ MPa}$$

$$t_0 = t_{0,T}\left(\frac{9}{2 + t_{0,T}^{1.2}}\right)^{\alpha} \geq 0.5, \; \alpha = \{-1\,(S), \; 0\,(N), \; 1(R)\}$$

where RH is the relative humidity in percentage; h_0 is the ratio of cross-sectional area and perimeter of the member in contact with the atmosphere, $h_0 = 2A_c/u$; S, R, and N refer to different classes of cement.

ACI Code

According to ACI 209-92, the only predicted parameter is creep coefficient $\varphi(t, t_0)$, and its empirical equation is given by

$$\varphi(t, t_0) = \frac{(t - t_0)^{\psi}}{d + (t - t_0)^{\psi}} \varphi_u$$

where $\varphi(t, t_0)$ is the creep coefficient at any time t when a load is applied at age t_0; d (in days) and ψ are considered constants for a given member shape and size that define the time-ratio part. ACI-209R-92 recommends an average value of 10 and 0.60 for d and ψ, respectively; φ_u is the ultimate creep coefficient. For the ultimate coefficient φ_u, the average value is suggested using 2.35. However, the creep coefficient still needs to be modified by correction factors:

$$\varphi_u = 2.35\gamma_c$$

$$\gamma_c = \gamma_{c,t0}\gamma_{c,RH}\gamma_{c,vs}\gamma_{c,s}\gamma_{c,\psi}\gamma_{sh,\alpha}$$

where $\gamma_{c,t0}$ is the loading age factor; $\gamma_{c,RH}$ is the ambient relative humidity; $\gamma_{c,vs}$ is the volume-to-surface ratio of the concrete section; $\gamma_{c,s}$ is the slump; $\gamma_{c,\psi}$ is the amount of fine aggregate; $\gamma_{sh,\alpha}$ is the air content.

Australian Standard AS3600-2009

In accordance with AS3600, the creep coefficient at any time φ_{cc} can be determined by

$$\varphi_{cc} = k_2 k_3 k_4 k_5 \varphi_{cc.b}$$

where k_2 is the development of creep with time; k_3 is the factor which depends on the age at first loading τ (in days); k_4 is the factor which accounts for the environment; k_5 is the factor which accounts for the reduced influence of both relative and humidity and specimen size; and φ_{cc} is the basic creep coefficient.

The development of creep with time k_2 can be calculated by

$$k_2 = \frac{\alpha_2(t-\tau)^{0.8}}{(t-\tau)^{0.8}+0.15t_h}$$

$$\alpha_2 = 1.0 + 1.12e^{-0.008t_h}$$

$$t_h = 2A_g/u_e$$

where t is any time in days; t_h is the hypothetical thickness; A_g is the cross-sectional area of the member; and u_e is the portion of the section perimeter exposed to the atmosphere plus half the total perimeter of any voids contained within the section.

Factor k_3 which depends on the age at first loading τ can be shown as

$$k_3 = \frac{2.7}{1+\log(\tau)} \quad (\text{for } \tau > 1 \ \text{ day})$$

Factor k_4 accounts for the environment:

$$k_4 = 0.7 \text{ for an arid environment}$$

$$k_4 = 0.65 \text{ for an interior enviroment}$$

$$k_4 = 0.60 \text{ for a temperate enviroment}$$

$$k_4 = 0.5 \text{ for a tropical or near} - \text{coastal enviroment}$$

Factor k_5 is given by

$$k_5 = 1.0, \ \ f_c^{'} \leq 50 \text{ MPa}$$

$$k_5 = (2.0-\alpha_3) - 0.02\,(1.0-\alpha_3) f_c^{'}, \ \ 50 \leq f_c^{'} \leq 100 \text{ MPa}$$

where $\alpha_3 = 0.7/(k_4\alpha_2)$.

The basic creep coefficient φ_{cc} can be determined by interpolation or extrapolation from **Table 1**.

SHRINKAGE

Concrete shrinkage is the time-dependent strain in an unloaded and unrestrained specimen at a constant temperature. Shrinkage is not an entirely reversible process in comparison with creep. Both creep and shrinkage are influenced by similar factors such as relative humidity, concrete strength, and cement. Shrinkage can be divided into plastic shrinkage, chemical shrinkage, thermal shrinkage, and drying shrinkage. The shrinkage strain is usually considered to be categorized into drying shrinkage and endogenous shrinkage. Drying shrinkage is the volumetric reduction due to the loss of water during the drying process. Endogenous shrinkage is sometimes used to refer to the other part of shrinkage of the hardened concrete that is not associated with drying (i.e., this is the sum of autogenous and thermal shrinkage) (Bhatt, 2011; Gilbert et al., 2016).

Eurocode 2

The total shrinkage strain ε_{cs} can be given by

$$\varepsilon_{cs} = \varepsilon_{ds} + \varepsilon_{as}$$

where ε_{ds} is the drying shrinkage strain; ε_{as} is the autogenous shrinkage strain.

The drying shrinkage strain ε_{ds} can be estimated by

$$\varepsilon_{ds} = \beta_{ds}(t, t_0) \times \varepsilon_{cd0} \times k_h$$

$$\varepsilon_{cd0} = 0.85\left[(220 + 110\alpha_{ds1}) \times \exp\left(-\alpha_{sd2} \times 0.1 f_{cm}\right)\right] \times 1.55\left[1-(0.01RH)^3\right]10^6$$

$$\beta_{ds}\,(t, t_0) = \frac{(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}$$

where k_h is a coefficient which depends on the national size h_0; RH is the relative humidity in percentage; h_0 = 2Ac/u in mm, Ac is the cross-sectional area, and u is the perimeter of the member in contact with the atmosphere. The values of parameter α_{ds1} and α_{ds2} as a function of the type of cement are shown in **Table 2**.

The autogenous shrinkage strain ε_{as} can be calculated from

$$\varepsilon_{as} = \beta_{as}(t) \times \varepsilon_{ca}(\infty)$$

$$\varepsilon_{ca}\,(\infty) = 2.5 \times (f_{ck} - 10) \times 10^{-6}$$

$$\beta_{as}\,(t) = 1 - \exp(-0.2t^{0.5})$$

ACI Code

The shrinkage strain $\varepsilon_{sh}\,(t)$ at age of concrete t (days), predicted from the start of drying at t_c, can be calculated by

$$\varepsilon_{sh}\,(t) = \frac{(t-t_c)^{\alpha}}{f+(t-t_c)^{\alpha}}\varepsilon_{shu}$$

$$\varepsilon_{shu} = 780 \times 10^{-6} \text{ mm/mm (in/in)}$$

where f (in days) and α are considered to be constant values for a given member shape and size that define the time–ratio factor, respectively. The average value for f is recommended to be 35 days of moist curing, and α is suggested to use 1.0. ε_{shu} is the ultimate shrinkage strain, and $(t - t_c)$ is the time between end of curing and any time after curing.

For the ultimate shrinkage strain ε_{shu} , the average value is suggested to be $780 \times 10^{-6}\ mm/mm$. However, the shrinkage strain still needs to be modified by correction factors:

$$\varepsilon_{shu} = 780\gamma_{sh} \times 10^{-6} \text{ mm/mm (in/in)}$$

$$\gamma_{sh} = \gamma_{sh,tc}\gamma_{sh,RH}\gamma_{sh,vs}\gamma_{sh,s}\gamma_{sh,\psi}\gamma_{sh,c}\gamma_{sh,\alpha}$$

TABLE 1 | Basic creep coefficient in accordance with AS3600.

$f_c^{'}$ (MPa)	20	25	32	40	50	65	80	100
$\varphi_{cc.b}$	5.2	4.2	3.4	2.8	2.4	2.0	1.7	1.5

TABLE 2 | Cement type and coefficient.

Cement type	α_{ds1}	α_{ds2}
S	3	0.13
N	4	0.12
R	6	0.11

where $\gamma_{sh,tc}$ is the initial moist curing coefficient; $\gamma_{sh,RH}$ is the ambient relative humidity coefficient; $\gamma_{sh,vs}$ is the volume-to-surface ratio of the concrete section coefficient; $\gamma_{sh,s}$ is the slump coefficient; $\gamma_{sh,\psi}$ is the fine aggregate coefficient; and $\gamma_{sh,c}$ is the cement content factor coefficient; $\gamma_{sh,\alpha}$ is the air content coefficient.

Australian Standard AS3600-2009

The total shrinkage strain ε_{cs} is shown below:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$$

where ε_{cse} is the autogenous shrinkage strain; ε_{csd} is the drying shrinkage.

The autogenous shrinkage can be calculated by

$$\varepsilon_{cse} = \varepsilon'_{cse}\left(1.0 - \exp\{-0.1t\}\right)$$

$$\varepsilon'_{cse} = \left(0.6f'_c - 1.0\right) \times 50 \times 10^{-6}\ (f'_c \text{ in MPa})$$

$$\varepsilon_{csd.b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd.b}$$

where $\varepsilon'_{csd.b}$ depends on the quality of the local aggregates and may be taken as 800×10^{-6} for concrete supplied in Sydney and Brisbane, 900×10^{-6} in Melbourne, and 1000×10^{-6} elsewhere.

The drying shrinkage strain ε_{csd} after the beginning of drying $(t - \tau_d)$ can be estimated as

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b}$$

where k_1 is the factor, which describes the development of drying shrinkage with time; k_4 is the factor, which accounts for the environment.

The factor k_1 can be given by

$$k_1 = \frac{\alpha_1 (t - \tau_d)^{0.8}}{(t - \tau_d)^{0.8} + 0.15t_h}$$

$$\alpha_1 = 0.8 + 1.2\exp\{-0.005t_h\}$$

The factor k_4 accounts for the environment:

$$k_4 = 0.7 \text{ for an arid environment}$$

$$k_4 = 0.65 \text{ for an interior enviroment}$$

$$k_4 = 0.60 \text{ for a temperate enviroment}$$

$$k_4 = 0.5 \text{ for a tropical or near} - \text{coastal enviroment}$$

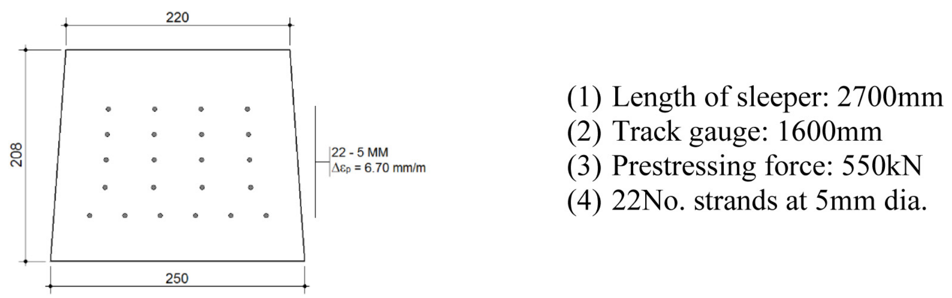

FIGURE 2 | Cross section of railway sleepers (Remennikov et al., 2011).

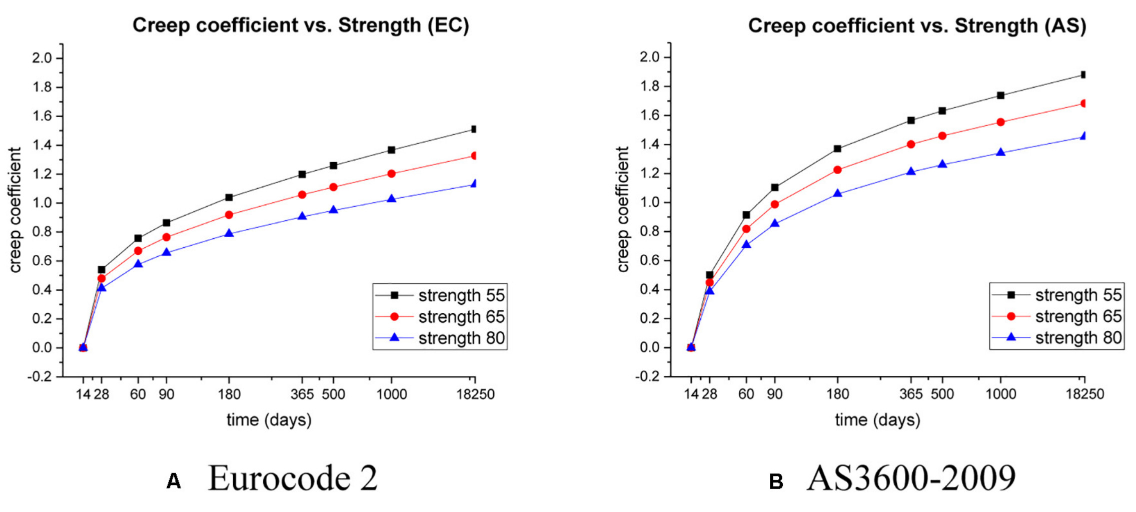

FIGURE 3 | Strength–creep relationship. **(A)** Euro Code 2 and **(B)** AS3600-2009.

RESULTS AND DISCUSSION

The effects of various key parameters that have significant influences on creep, shrinkage strain, and loss of prestress are evaluated, in order to establish new practical insights for design, manufacture, and maintenance of railway concrete sleepers under uncertain settings (Kaewunruen et al., 2015, 2016b; Setsobhonkul et al., 2017; Li and Kaewunruen, 2019). The fundamental engineering properties of prestressed concrete sleepers used for calculation are based on previous investigations by Remennikov et al. (2011). The parametric results are generated for comparisons between Eurocode 2 (EC2), the American Concrete Institution's code (ACI), and Australian Standard AS3600-2009 (AS). **Figure 2** shows the cross section at rail seat of the prestressed concrete sleepers.

Creep Parametric Study

Strength of Concrete

Parametric studies into the effect of concrete strength have been conducted using different characteristic strength of concrete (55, 65, and 80 MPa) in order to determine the relationships between the strength of concrete and creep curves, which are

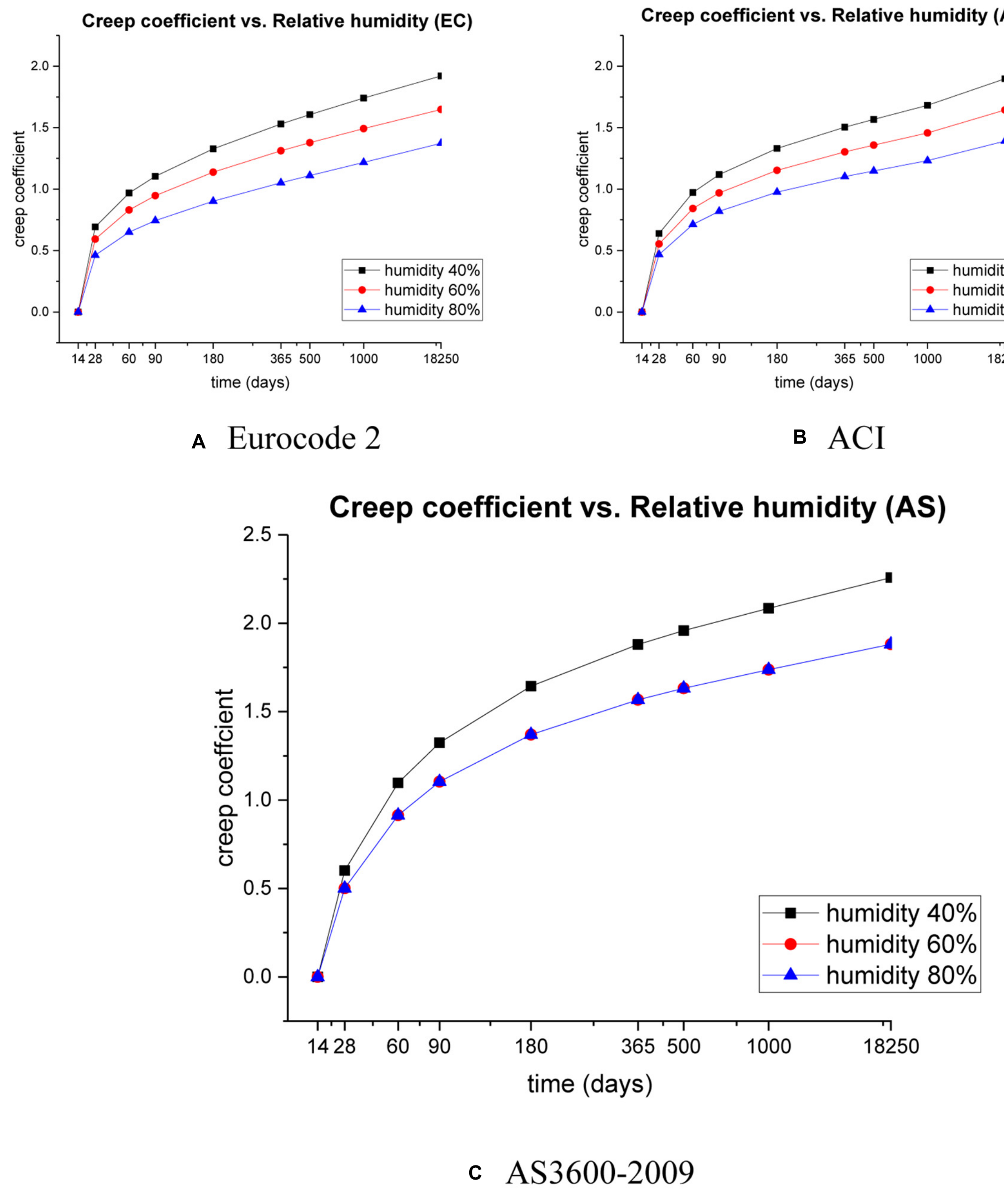

FIGURE 4 | Relative humidity–creep relationship. **(A)** Euro Code 2, **(B)** ACI and **(C)** AS3600-2009.

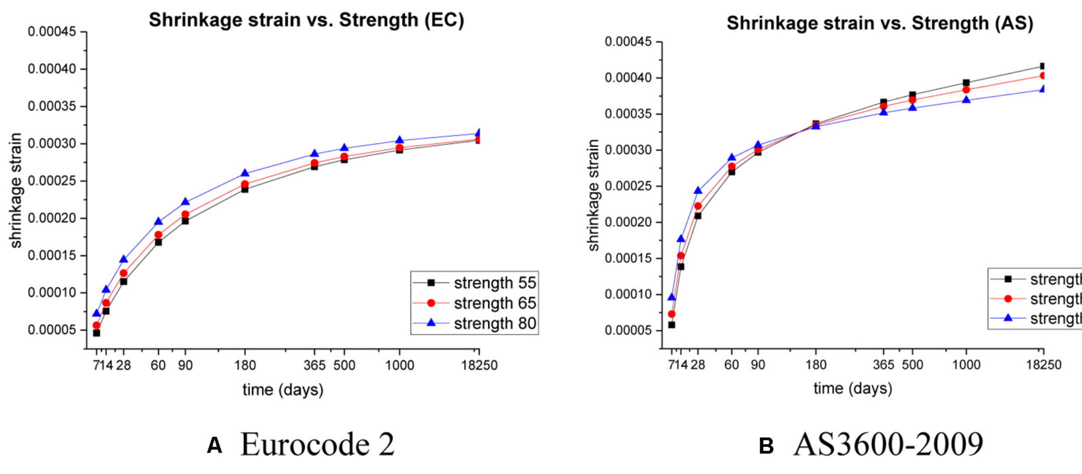

FIGURE 5 | Strength–shrinkage relationship. **(A)** Euro Code 2 and **(B)** AS3600-2009.

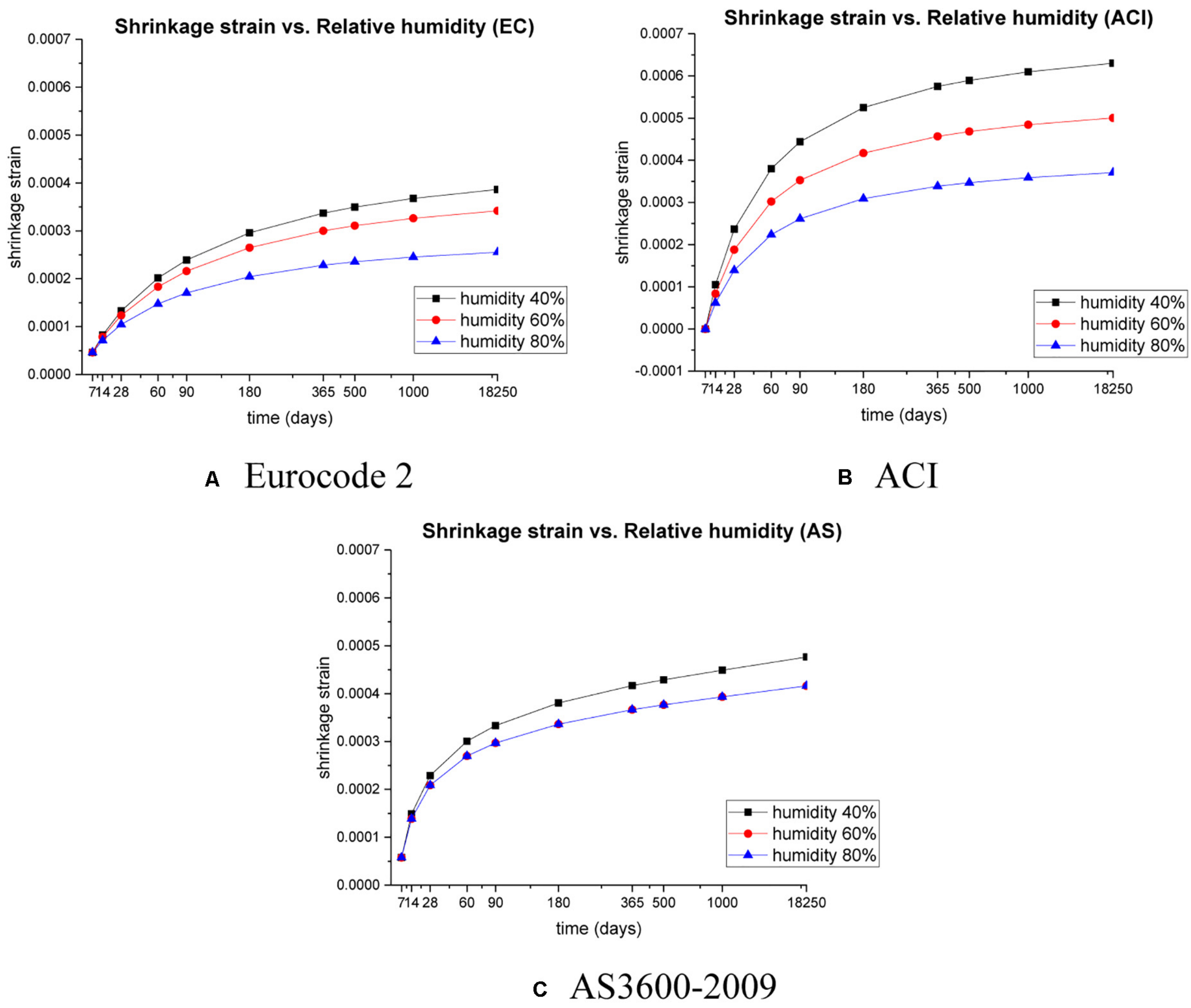

FIGURE 6 | Relative humidity–shrinkage relationship. **(A)** Euro Code 2, **(B)** ACI and **(C)** AS3600-2009.

illustrated in **Figure 3**. It is important to note that, according to the empirical formula in ACI209R-92, the creep coefficient calculation is not directly related to concrete strength. As a result, the creep strain and creep coefficient behaviors are determined by only EC2 and AS3600, respectively. All cases are estimated from 14 days up to 18,250 days (50 years, which is a design service life of concrete sleepers) in the same conditions (e.g., uniform dimension of sleepers, 70% relative humidity, and first loading at 14 days).

Relative Humidity

To investigate relationships between the relative humidity and creep, three cases with different relative humidity (40, 60, and 80%) are displayed from the obtained data as shown in **Figure 4**. The creep strain and creep coefficient are determined by using EC2, ACI, and AS3600-2009 codes, respectively. All cases are estimated from 14 days up to 18,250 days (50 years) in the same conditions (uniform dimension of sleepers, 55 MPa strength of concrete).

Shrinkage Parametric Study

Strength

Figure 5 demonstrates the influences of different strengths on shrinkage behaviors. Note that according to the formula in ACI209R-92, the shrinkage behavior is also not directly related to concrete strength, analogously to creep. On this ground, this study focuses only on EC2 and AS3600 approaches.

Relative Humidity

Figure 6 highlights the influences of different relative humidity (RH) on the shrinkage characteristics.

Curing Time

Figure 7 shows the shrinkage behaviors affected by different curing times.

Discussion

Based on the sensitivity analyses, the creep and shrinkage behaviors that occurred within prestressed concrete sleepers can

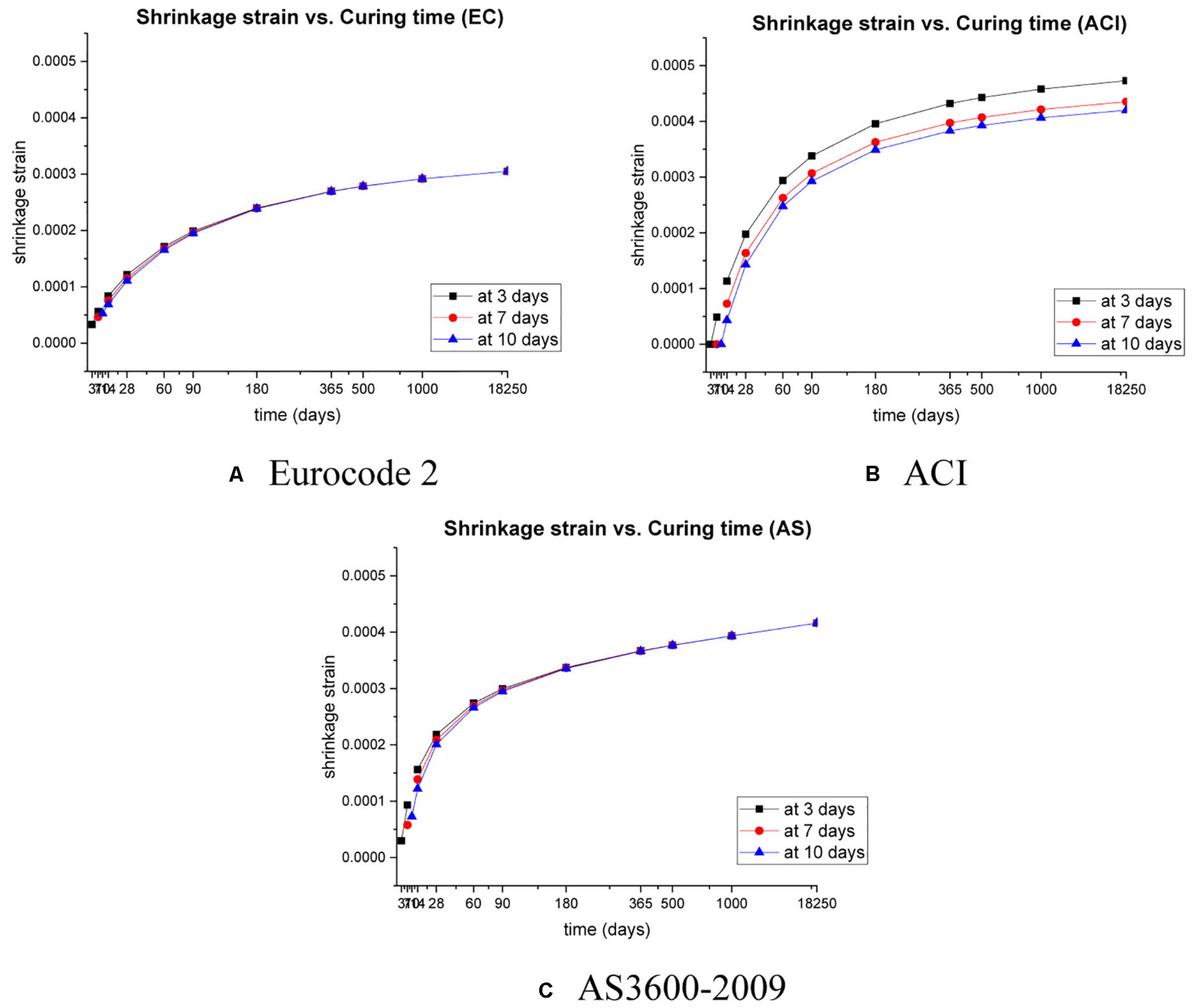

FIGURE 7 | Curing time–shrinkage relationship. **(A)** Euro Code 2, **(B)** ACI and **(C)** AS3600-2009.

be dependant to a variety of factors. According to the analysis results, the loss of prestress depends largely on axial strain. This implies that a large strain will result in more prestress loss in prestressed concrete sleepers.

Considering a variety of concrete strengths (i.e., 55, 65, and 80 MPa), the parametric characteristics of creep coefficient and shrinkage strain are given in **Figures 3**, **5**. It can be observed that a higher strength of concrete exhibits lesser creep. However, the characteristics of shrinkage strain are different from creep. It is apparent that a higher-strength concrete sleeper has higher shrinkage strain at the initial stage. However, over a longer term, the total shrinkage strain of higher strength concrete becomes lesser than that of lower strength concrete. The total shrinkage strain consists of autogenous shrinkage and drying shrinkage, which is an allowance for early thermal shrinkage and is assumed to develop relatively rapidly and to increase with concrete strength.

With respect to the relative humidity, the characteristics of creep coefficient and shrinkage strain are demonstrated in **Figures 4**, **6**. It is clear that, with the increase in the relative humidity, both creep and shrinkage in prestressed concrete sleepers decrease.

Our studies illustrate that autogenous shrinkage causes more losses of prestress for higher-strength concrete in comparison with relatively lower-strength concrete at the initial period (Australian Building Codes Board, 1994; Fryba, 1996; Stevens and Dux, 2004). In fact, our prediction results confirm the experimental investigation campaigns done in Australia (Remennikov and Kaewunruen, 2014, 2015).

By comparisons among EC2, ACI, and Australian Standard, it can be observed that the prediction results obtained from each method are not similar even exactly under the same conditions. The main reason leading to different results can be attributed to the fact that different design codes concentrate on different parameters and have been established differently. For example, the predicted strain values are largely dependent on the relative humidity and concrete strength. Higher relative humidity causes lesser creep and shrinkage, which induce lower losses of prestress. Note that the environmental factors according to Australian geographic climate are utilized in Australian Standard instead of the relative humidity. In the ACI code, the concrete strength is not directly used for time-dependent behavior predictions, but the main parameters, which are related to the concrete strength such as cement content, air content, and fine aggregate content, are heavily used in the predictions.

CONCLUSION

The service life of railway prestressed concrete sleepers depends largely on a variety of factors such as concrete and material characteristics, environmental conditions, dynamic loading amplitude, and external abrasions. However, time-dependent behaviors of the concrete sleepers can also influence their durability and long-term performance in the field. In real life, creep and shrinkage strains can potentially have more significant influence on the deformation of track components. In harsh environments, the railway infrastructure generally experiences highly aggressive loading conditions from increased traffics and load demands. At certain scenarios, a train derailment could happen because of track gauge change (i.e., tight gauge at such critical locations as crossing, slips, etc.). The track gauge change can be stemmed from the shortening and inelastic deflections incurred by creep and shrinkage in prestressed concrete sleepers. There are a number of existing codes of practice, enabling the predictions of creep and shrinkage. Three main design codes are examined critically in this paper. Key parameters that influence creep and shrinkage from a theoretical viewpoint for prestressed concrete sleepers are emphasized. A state-of-the-art review of research on time-dependent creep and shrinkage has been carried out in order to establish comprehensive methods for comparative analyses. This research embarks on the comparative parametric investigations into a variety of methods to determine creep and shrinkage effects in prestressed concrete railway sleepers. Comparisons among the design codes, including European Standard EUROCODE2, the American Concrete Institute ACI Code, and Australian Standard AS3600-2009, provide new practical insights into the time-dependent performance of concrete sleepers. The parametric effects of creep and shrinkage strains have been determined. Limitations of existing codes have been identified together with the recommendations and guidelines for code applications. The outcome of this study will help track engineers to better design, manufacture, inspect, and maintain railway infrastructures in order to enhance asset management efficacy and effectiveness.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

DL analyzed the data. SK contributed the materials and analysis tools. PR and AR provided technical review and advice. All authors wrote the manuscript.

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frontiers in Built Environment

REVIEW
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Methods to Monitor and Evaluate the Deterioration of Track and Its Components in a Railway In-Service: A Systemic Review

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When planning a new track or improving a track that is currently in-service, it is important to predict the probable rate of track deterioration as a function of the variables related to the train and its periodicity. This literature review reveals that there are currently no track deterioration methods available analyze the condition of a railway track. A prediction of deterioration requires accurate quantification of each track component and track geometry behavior and a better knowledge of interactions between components and geometry. This extended survey found more than 100 methods (or studies) related to track deterioration, including other literature reviews, but very few of these methods work when several track deterioration issues occur. This paper aims to build upon these, adopting a methodology for a systematic critical literature review that identifies, evaluates, and classifies these primary studies to predict the track deterioration according to criteria of assessment. Finally, it establishes the gaps and the challenges that will need to be overcome in future research.

Keywords: railway track, permanent way, track components, track geometry, track deterioration, track degradation, track monitoring, systematic literature review

INTRODUCTION

The effects of adverse traits on the railway track, which is known also as the permanent way, are cumulative. Railway materials such as the rail, sleepers, fastenings, and ballasts require routine attention and renewal at frequent intervals (Hay, 1982). If the permanent way is not impeccably aligned and leveled, roughness contributes to vibration (Yan et al., 2019) and oscillations of the train, which can cause discomfort to the passenger, damage to the freight (Tzanakakis, 2013), and in worst case scenarios, catastrophic accidents. The condition of the permanent way has an important function in the behavior of a railway system (i.e., maintenance, operational safety, and passenger comfort) and it is important to consider any irregularities and ascertain the phenomena that cause track deterioration, and to forecast irregularities (Gong et al., 2016).

Track conditions must be assessed by measurable degradation parameters (El-Sibaie and Zhang, 2004). These include the condition of railway components and geometry, which have a close relationship within the process of track degradation. According to Guler et al. (2011), if a component is in poor condition this will contribute to the deterioration of the component, and it will not be able to fit the desired track geometry. Each parameter must be weighed for its magnitude in impacting the permanent way activity (El-Sibaie and Zhang, 2004).

This literature investigation has shown that there are no ready methods of evaluating the deterioration and condition of the railway track. A prediction of track condition requires accurate quantification of each track component and each track geometry and a better knowledge of interactions between components and geometry. During this extended survey, more than 100 methods and studies related to track deterioration were found. Very few of these methods of inquiry covered more than one track deterioration issue.

This systematic critical review aims to identify, evaluate, and classify primary studies of track prediction into groups according to the complexity of both the method and the validation, whilst also taking into account the quality of the study. The application of tactics in evaluating the track deterioration and its elements (track components and track geometry parameters) are also evaluated. Consequently, it compares these track deterioration studies with a hypothetical study (the best one) and identifies gaps in research.

This paper is structured into five sections. Section "Background" presents a background of the permanent way and its environment. Following this, Section "Methodology" presents the methodology used to develop this systematic literature review. Section "Results and Discussions" then discussing the main findings, sharing these methods and assessing their complexities and qualities in order to group them. Lastly, Section "Conclusion" concludes the paper and outlines gaps in this research.

BACKGROUND

The function of a railway track is to support the load of the railway vehicles (Hay, 1982) and to guide their movements (Iwnicki, 2006), enabling the railway vehicles to move without risk of derailment (Lichtberger, 2005). To investigate the specific load effect on the track, it is necessary to create a map of the different parts of the system.

A modern conventional track can be subdivided into seven components (rails, rail pads, sleepers, ballast, sub-ballast, geosynthetics, and subgrade), each having a specific function in trainload support (Le Pen, 2008). In turn, this same permanent way has a position in the space, called track geometry, which is the spatial position of the rail track. According to Faiz and Singh (2009), the "X-axis" of the track represents the distance along the direction of travel, "Y" is the axis parallel to the running top rail (surface), and "Z" defines the axis perpendicular to the running permanent way. Each rail has 2 degrees of freedom, and these 4 degrees of freedom are normally replaced by an equivalent system consisting of cant, level, alignment, gauge, and twist (Esveld, 2001), which represent track geometry. Descriptions and the function of these track components, including thresholds and geometry, are explained in detail by Hay (1982), Selig and Waters (1994), Esveld (2001), Lichtberger (2005), Profillidis (2006), Tzanakakis (2013), and Li et al. (2016).

A railway wheel causes vertical and horizontal forces on the permanent way. Additionally, the long-welded permanent way is subject to the influence of longitudinal forces arising because of changes in temperature (Lichtberger, 2005). The permanent way is stressed by quasi-static (low-frequency) and dynamic force components of higher frequency (Lichtberger, 2005). According to Iwnicki (2006), the principal difference between a railway vehicle and other types of wheeled vehicle is the guidance provided by the permanent way. The combination of vehicle and track should be regarded as one, because they are an integrated system. The separation between these subsystems is also the place where this interaction manifests: the wheel-rail contact, which enables vehicle bearing and guidance (Li et al., 2016).

Both the railway vehicle and the permanent way have irregularities, which produce different magnitudes of force due to the resonances they create within the permanent way components (Tzanakakis, 2013). To understand the relationship between permanent way failure behavior and track geometry, it is important to identify the forces on the rail created by a train traveling on it, and the responses made to those forces. It is also important to recognize the causes of these forces to be able to eradicate them and increase the longevity of the rail (Tzanakakis, 2013).

According to Li et al. (2016), wheel loads and train speeds have increased and lines have been optimized during the last decade, which has placed increased demands on the track structure. A combination of delayed permanent way maintenance together with more production (i.e., traffic, axle load, and speed) has caused the rate of permanent way degradation to increase (Martland, 2013). The most significant factor in degradation (wear, fatigue, and settlement) is therefore the dynamic load (De Man, 2002; Kaewunruen and Remennikov, 2008), which is related to the axle load and track geometry (Tzanakakis, 2013). Many factors can influence the permanent way and adequate methods must be applied in maintaining it (Jovanovic et al., 2014).

Track condition is divided into two groups of measurable parameters. The first contains the component deterioration parameters, which is the usual term used to describe the deterioration of each component in a permanent way (El-Sibaie and Zhang, 2004). In other words, it is which, how, when, and how much a component with a specific composition, form, dimension, and mechanical property loses its function as part of the permanent way. According to Guler et al. (2011), it is hard to apply a unique descriptor that records the status of all deterioration.

On the other hand, according to Vale and Ribeiro (2014) the second group of measurable parameters, namely geometry degradation is random by nature. The geometry of the permanent way is the position of the railway track in three-dimensional space (Faiz and Singh, 2009). According to Vale and Ribeiro (2014), track degradation is the decrease in quality of geometrical parameters (i.e., longitudinal and transversal level, gauge, twist, and cant) over a period of time. In another definition, track geometry degradation is which, how, when, and how much one or more than one geometric dimension in a finite space of the track fails to maintain their known standard characteristics. Component deterioration and geometry degradation are both affected by the environment, traffic, vehicle speed, construction methods, and maintenance history.

Bing and Gross (1983) discuss a common basic method of degradation analysis, which involves using an empirical model (i.e., correlation, variance, and regression) to assess a huge sample of observations about track parameters. However, alterations in data recording and explanation may undermine the outcomes. Simulating track degradation in this way makes it possible to allow for uncertainty in predictions of track degradation, as they are expected to increase with time, due to the imperfect methods of determination of the input parameters used in the model (Bing and Gross, 1983).

Additionally, in empirical modeling, a modern approach called Artificial Intelligence – AI (i.e., Artificial Neural Networks – ANNs and Neuro-Fuzzy Logic – NFL, a combination between ANN and fuzzy logic) is increasingly used among scientists, as discussed by Elkhoury et al. (2018). These methods are recognized to have high predictive accuracy. In multi-layered neural networks, the neurons are arranged in a layered fashion. The input and output layers are separated by a group of hidden layers in which the layer-wise architecture of the neural network is referred to as a feed-forward network (Aggarwal, 2018). Guler (2014) modeled railway track geometry degradation with ANN, considering the variables involved in track geometry degradation, which produced important findings on the relationships between the rate (deterioration) and independent variables.

An alternative to empirical models is mechanistic models, which involve establishing the mechanical properties of track components (Zhang et al., 2000). They are based on physical information, establishing the mechanical properties of all the elements of the track and railway vehicles (Sadeghi and Askarinejad, 2011). Track structure analysis methods based on mechanical models are used to calculate individual track components including forces, stresses, and defects. They are successful in calculating forces, tensions, and the probability of the development of failures in the individual components of the permanent way (Zhang et al., 2000).

According to Soleimanmeigouni et al. (2016) several researchers, including Sadeghi and Askarinejad (2010) and Rhayma et al. (2013), have also attempted to combine physical and empirical models to explore the best application of both methods. By complementing the mechanistic model with an empirical one, it is possible not only to study the structural behavior of the track components, but also to analyze the functional performance of the track geometry. Thus, this leads to the development of an empirical-mechanistic method, which allows a more dynamic and current interaction.

Shafahi and Hakhamaneshi (2009) have compared four models including one mechanistic model suggested by the Office for Research and Experiment of the International Union of Railways (ORE) and three empirical models: the Markov chain model, the ANN, and the Neuro-Fuzzy models. In this study, the Markov model proved to be robust in predicting the random behavior of the track deterioration process, and seems to be superior to conventional regression models, such as the ORE model.

The full railway track complex is preserved to deliver satisfactory track geometry. This is why there are track components. Repair decisions are frequently controlled by the geometry, and they are necessary not only when many track rail failure corrections ruin the geometry, but also in instances when track ballasts can no longer preserve the design geometry, or sleepers and fastenings cannot conserve the permanent way gauge. However, according to Esveld (2001), the process of determining whether, when, where, and how best to intervene is far more complex, as it involves evaluation of track condition and how much it is influenced by both track structure and track geometry, and consideration of the relationship between them. Systematically identifying the tactics (model and approach) that are used around the world to evaluate track deterioration is the first step in establishing the gaps in literature on this topic and proposing new techniques to fill them.

METHODOLOGY

Based on the systematic literature review method proposed by Kitchenham (2004) and Torres-Carrion et al. (2018), this research is divided into planning, conducting, and reporting the review. **Figure 1** provides an overview of the macro-procedure of this methodology.

Planning

This systematic review aims to summarize existing information on track deterioration. Prior to conducting this review and following Torres-Carrion et al. (2018), it was ensured that the review itself was necessary, live reviews of the phenomenon of interest were identified. The current state of track degradation studies is the starting point of this review, before the development of research questions, and a contextualization of the scenario of research.

The following research questions are proposed in this paper:

- Research Question 1 (RQ-1): Which methods have been developed in predicting an integrated track deterioration in an in-service railway?
- Research Question 2 (RQ-2): How have these methods been designed?
- Research Question 3 (RQ-3): What predicting technologies have been applied to monitor the track deterioration processes?

One of the fundamental devices used to provide a good understanding of the issue was the “mentefacto conceptual,” a tool for addressing a complex situation, represented by an ideogram (Torres-Carrion et al., 2018). In this paper, the track deterioration is the issue, and the permanent way or track is the study. This is different from some kinds of regular interaction, for instance, track design, and track schedule. This process permits monitoring before a track component fails (Yan et al., 2019); it also provides information on downgrading the track quality. **Figure 2** shows the “mentefacto conceptual” of this review.

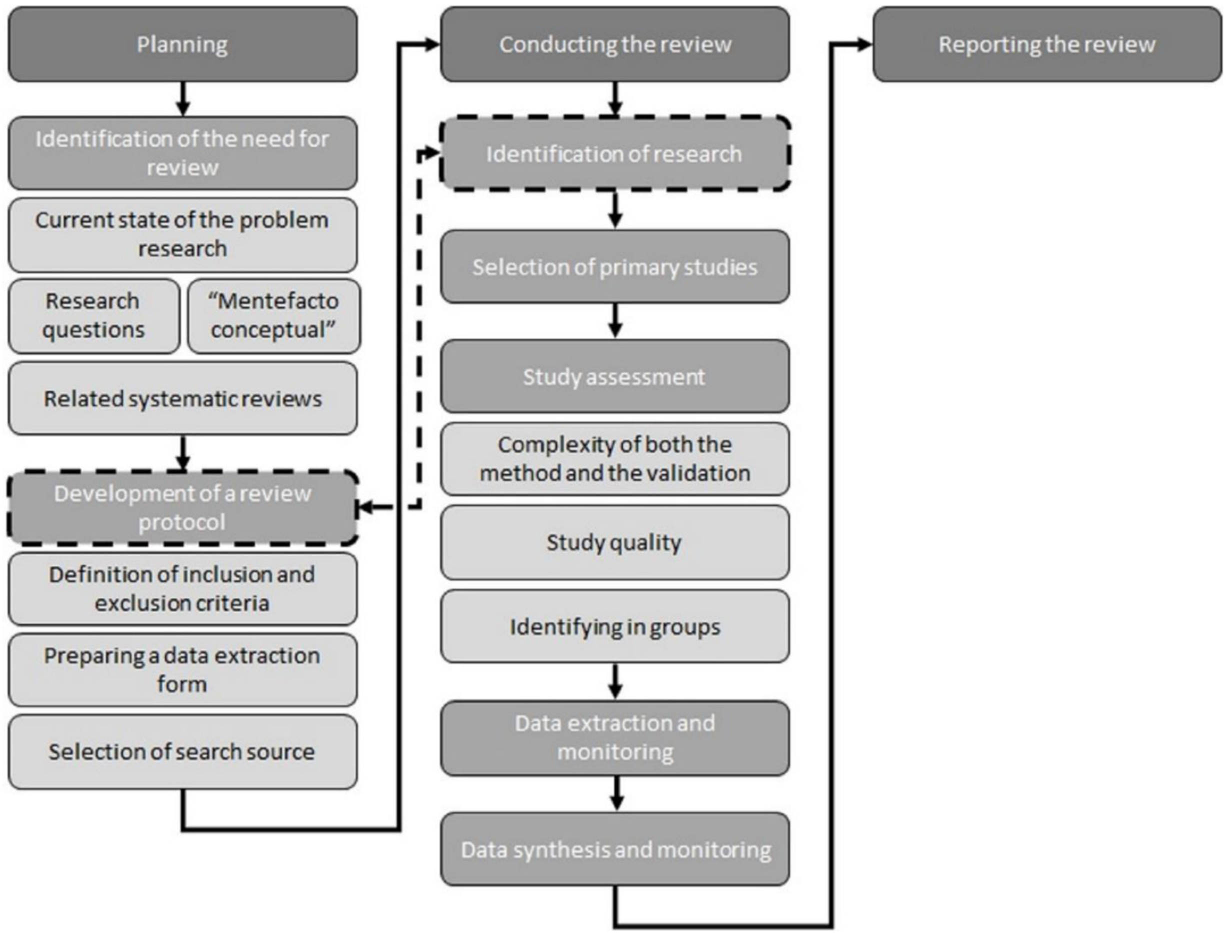

FIGURE 1 | Flowchart of the Methodology.

The platform used for the first filtering is "Primo de Ex Libris," under library license. This is a systematic search using a semantic sentence in the English language and identifying literature through specific words.

Conducting

In Kitchenham (2004), when the protocol has been accepted, the review can be developed. The steps are iterative/incremental, which means the research will run until the research questions are answered. The main idea of this type of review is to find as many primary sources related to the research question as possible avoiding, for example, a language bias. The "identification of research" is complementary to the protocol. Torres-Carrion et al. (2018) also suggest conducting a literature search in the Web of Science, Scopus, and Google Scholar. Once the relevant potential primary studies have been identified, they need to be assessed for their relevance (Kitchenham, 2004).

The sub-stage study assessment is supported by the criteria of inclusion and exclusion, the complexities of both the method and the validation, and the study quality, represented in criteria such as approach, systematics, extension, context, and peer review, among others. In this paper, it is proposed that the primary studies will be assessed according to three indicators: the complexity of the method, complexity of the validation, and study quality. A primary issue is that there is no agreed concept of study quality.

In this research the complexity of the method is used as an indicator of how much the method considers the requirements necessary for it to be complete. It has a rank of −5 to +5, which represents how much the study applies its potential to develop the research about track conditions. In order to assess the complexities of the methods of the primary studies previously listed, seven criteria are proposed: approach, type (or model), systematics, element, segment, scale, and extension. The maximum total value (35 points) and the minimum total value (seven points) are marked on a scale of −5 to +5, proportionality. The criteria used are described in **Table 1**.

A second indicator – the complexity of the validation – is also ranked from −5 to +5, according to whether the studies validate their respective research on track condition. In order to assess the complexities of the validations of the studies previously listed, six criteria are proposed: time period, reach, the error of measurement, context, correlation, and test-oriented. The maximum total value (30 points) and the minimum total value

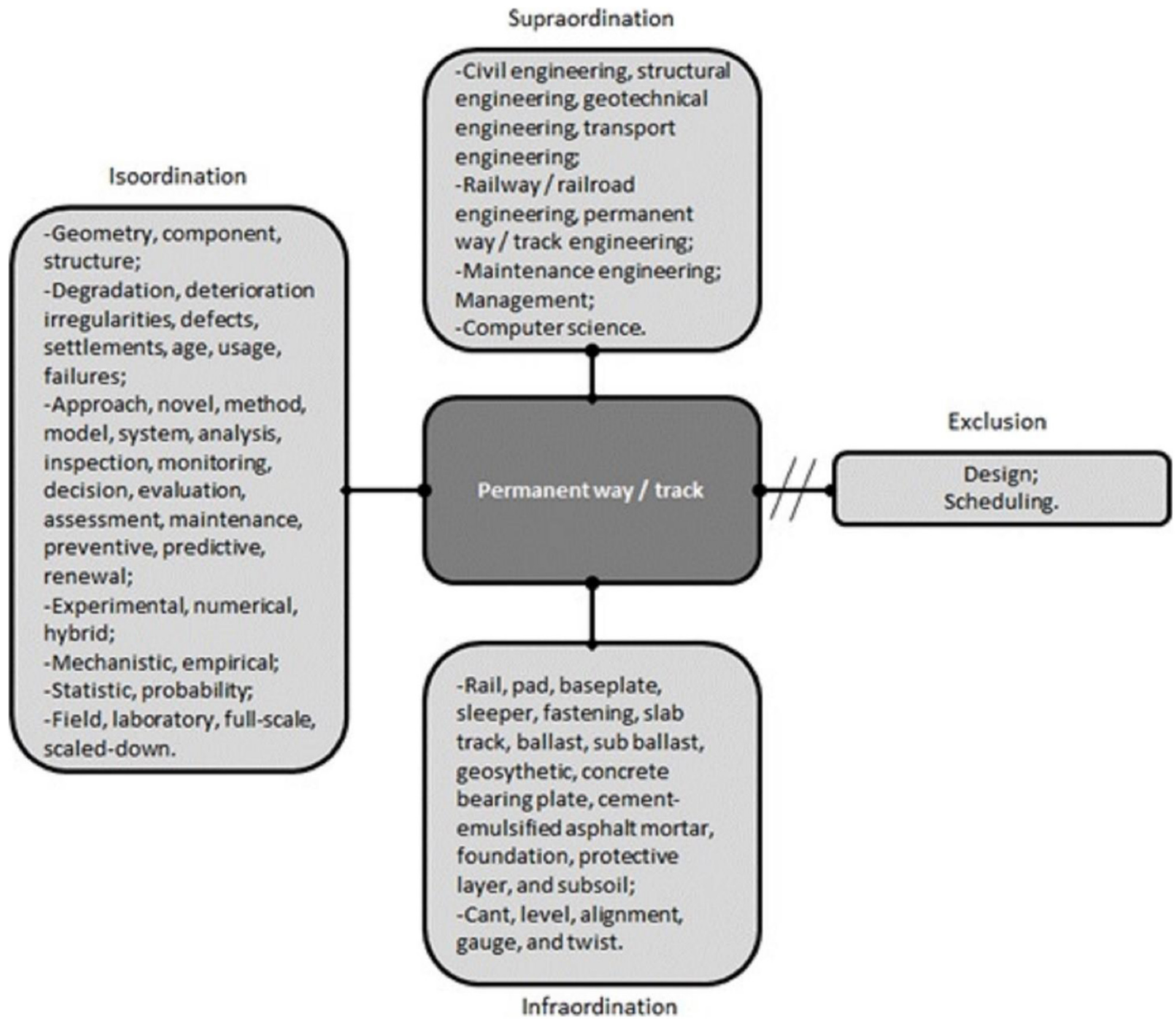

FIGURE 2 | "Mentefacto conceptual."

(6 points) also fit to a scale of −5 to +5. The criteria used are described in **Table 2**.

In this paper, study quality is the third proposed indicator, which is ranked from 1 to 5, representing how much the study applies the full potential to develop the research about track conditions. To assess the quality of the primary studies examined, eight criteria were used: peer review, thick description, analysis of the variables, omitted variable bias, credibility, transferability, reliability, and confirmability. The maximum total value (40 points) and the minimum total value (8 points) are fitted to a scale of 1–5. The criteria are presented in **Table 3**.

With the objective of identifying the groups in which the listed studies might be classified, it is that the values be plotted in a scatter bubble chart, showing on the X-axis, the complexity of the validation; on the Y-axis, the complexity of the method; and, on the diametric independent axis, the study quality. At this stage, the quality of the systematic review is defined (Torres-Carrion et al., 2018). This synthesis is descriptive, involving a quantitative summary that shows the principal findings and gaps.

Reporting the Review

According to Torres-Carrion et al. (2018), outcomes are published to the scientific community to gain opinion from other experts in the field. Systematic improvements to a review are always needed and this is a continuous process that has seen early benefits as a result of its implementation.

RESULTS AND DISCUSSION

In this paper, the results and discussions are organized as follows: the related literature reviews of the issue, then the primary studies about track deterioration, and then a summary of these primary studies.

TABLE 1 | Criteria of assessment to the complexity of the method.

Criteria	Description	Factor	Value
Approach	The input of the method	Numerical	1
		Experimental	3
		Hybrid	5
Type	The output of the method	Mechanistic	3
		Empirical	1
		Empiric al-Me chanistic	5
Systematics	The process of the method	Full	5
	(data collecting, analysis, validation)	Partial	3
		Unique	1
Element	The part of the permanent way	Full	5
	(superstructure substructure Geometry)	Partial*	3
		Unique	1
Segment	The layout of the permanent	Full	5
	way (straight, curve, tunnel bridge, switch ramp up/down)	Partial*	3
		Unique	1
Scale	The real scale of the study	Full	3
	(full reduced, mixed)	Down	1
		Mixed	3
Extension	The extension of the studies	Full	5
	(field, laboratory, office)	Partial	3
		Unique	1

**Two or more.*

TABLE 2 | Criteria of assessment to the complexity of the validation.

Criteria	Description	Factor	Value
Time period	Time period in which is	<2 years	1
	developed the validation	2 years $< p < 4$ years	3
		>4 years	5
Readier	Length of the	<100 km	1
	permanent way in which is developed the validation	100 km $< p <$ 200 km	3
		>200 km	5
Error of measurement	Whether there is	Yes	5
	standard error of measurement	No	1
Context	Whether characteristics	Yes	5
	and test characteristics aren't separated	No	1
Correlation	Whether there is a	Yes	5
	correlation between test scores on parallel forms	No	1
Teste oriented	Whether the test is a	Yes	5
	teste oriented, rather than item oriented	No	1

TABLE 3 | Criteria of assessment to the study quality.

Criteria	Description	Factor	Value
Peer review	Whether there is a pear review	Yes	5
		No	1
Thick description	Detailed description of the	Full	5
	phenomenon	Partial	3
		None	1
Analysis of the variables	Analysis of the main effect variables	Full	5
	in the model	Partial	3
		None	1
Omitted variables bias	Whether there is omitted variables	Yes	1
	bias	No	5
Credibility	Internal validation (feedback on	Full	5
	results from the participants)	Partial	3
		None	1
Transferabilitv	External validation (the degree that	Full	5
	findings can be transferred or generalized to other settings)	Partial	3
		None	1
Reliability	Describing the changing contexts	Yes	5
	and circumstances that are fundamental to qualitative research (observing the same finding under similar circumstances)	No	1
Confirmability	Refers to the extent that the	Yes	5
	research findings can be confirmed or corroborated by others (searching for negative cases that run contrary to most findings)	No	1

Related Literature Reviews

As described in the methodology section, the related literature reviews of track deterioration answer the research questions proposed in this paper. The answer to each of the six studies is no, at least partially. **Table 4** presents these studies, charting whether they have answered the research questions.

The unanswered research questions are specified and labeled in **Table 4**. Although the literature reviews in these studies do not fully answer the research questions, they support this paper by complementing the survey.

Primary Studies

Using the methodology outlined above, 106 primary studies were initially selected. Most of these are concentrated in five countries, China, the UK, the US, Sweden, and Iran, however, other countries such as Germany, India, Japan, Spain, Austria, and Switzerland are also represented. The US is a highlight due to the research carried out by the Association of American Railroads – AAR through the Transportation Technology Center, Inc. (TTCi), and supported by the Federal Railroad Administration (FRA), a regulatory authority. Most of these studies examine high speed or cargo/passenger railway systems, and the papers were published in peer-reviewed journals during the between 2010 and 2019. Most studies have an observable approach (measured data from a recording vehicle, for instance), a supporting empirical formulation (statistical analysis such as

TABLE 4 | Related literature review.

Author	Title	Related research's question (RQ)*	Has the author answered the RQ?	Why the author hasn't answered (fully) the RQ
Soleimanmeigouni et al. (2016)	A Survey on track geometry degradation modeling	RQ-1 andRQ-2	RQ-I-No;RQ-2: Yes (partially)	RQ-1: focus on track geometry
Elkhoury et al. (2018)	Degradation prediction of rail tracks: a review of the existing literature	RQ-1 andRQ-2	RQ-I:No-RQ-2: Yes (partially)	RQ-1: focus on track geometry or track components
Higgins and Liu (2018)	Modeling of track geometry degradation and decisions on safety and maintenance: A literature review and possible future research directions	RQ-1	Yes (partially)	RQ-1: focus on track geometry
Dahlberg (2001)	Some railroad settlement models – a critical review	RQ-1	Yes (partially)	RQ-1: focus on track components
Soleimanmeigouni et al. (2018)	Track geometry degradation and maintenance modeling: a review	RQ-1 andRQ-2	RQ-I:No;RQ-2 Yes (partially)	RQ-1: focus on track geometry
Ferreira and Murray (1997)	Modeling rail track deterioration and maintenance current practices and future needs	RQ-1 andRQ-2	RQ-I-No;RQ-2: Yes (partially)	RQ-1: focus on track geometry or track components
Ngamkhanong et al. (2018)	State-of-the-art review of railway track resilience monitoring	RQ-3	Yes (partially)	RQ-3: focus on track components

See Section 3.1 "Planning."

regression and/or probability), and focus on track geometry. **Figure 3** illustrates this data.

An empirical model was built from a set of input and output variables. In modeling deterioration this can be used to deal with many descriptive factors that influence track conditions (Yousefikia et al., 2014). One of the advantages of this method is that, since actual data is used to build the deterioration process, an adequate estimate of the track condition can be obtained (Yousefikia et al., 2014). On the other hand, a major drawback is the lack of a physical basis for permanent way components and their interactions, which may result in some directionless outcomes (Sadeghi and Askarinejad, 2010).

The mechanistic model involves establishing the mechanical properties of track components. One of the advantages of this is that it can integrate the reaction of the track to production parameters. For instance, a unique defect on the fastening system may not cause any significant consequences, but several defects will cause the deterioration of other components and the full track. This indicates that these models cannot handle a range of operating, environmental, and maintenance conditions and do not allow for different degradation behaviors (Lovett et al., 2013).

Dahlberg (2001) and Guler et al. (2011) present other studies on the mechanistic formulation, discussing advantages and drawbacks. Guler et al. (2011) analyzed several mechanistic methods looking at the degradation of permanent way geometry, including the track damage model proposed by Sato (1995), the track degradation developed by British Rail Research, and the settlement model presented by the Technical University of Munich. Dahlberg (2001), comparing several important track prediction models, including those from Japan, the United States, the European Union, Africa, and Australia.

Sadeghi and Askarinejad (2010) have elaborated on a deterioration model combining mechanistic novel and statistics that took into account data on both track geometry and track components. The basic advantage derived from the use of an empirical-mechanistic model is that it allows the parameterization of geometry and basic properties. Therefore, these parameters can be altered and adapted to the different range requirements (Melo et al., 2019a), allowing for spatial variations, temporal effects, and fatigue of the elements.

Additionally, for the success of an empirical-mechanistic model, it is necessary to carry out laboratory and field experiments (examining track components) in building experimental models, using measurement data (track geometry) in the calibration process. Examples gathered in the field must take into account the sort of segment (straight, curve, switch, bridge, tunnel, ramp up/down, etc.) and build all the elements of the permanent way in the laboratory. Additionally, avoiding bias, and allowing for measurement errors and validation tests is essential (Melo et al., 2019b). This model is partially observed in studies by Guerin (1996) and Frohling (1997), and in models by Sadeghi and Askarinejad (2007) and Rhayma et al. (2013). These four studies approximate the hypothetical target when researching the track deterioration process (Melo et al., 2019b), because they apply specifically – but not only – the empiric-mechanistic model and the hybrid (numerical and experimental) approach to the study of track deterioration.

After analyzing and selecting these primary studies, they are classified in four different groups: Level III (L-III; low complexity of both the method and the validation), Level II-a (L-II-a; high complexity of the method and low complexity of the validation), Level II-b (L-II-b; low complexity of the method and high complexity of the validation), and Level I (L-I; high complexity of both the method and the validation). Additionally, the selected studies are assessed by their quality, as described in the methodology (Section "Methodology" above).

To offer one a more facetted assessment of these primary studies, an indicator of study quality was applied. The studies were classified into a range of 1–5, independently of the group previously described. This indicates whether the study has been

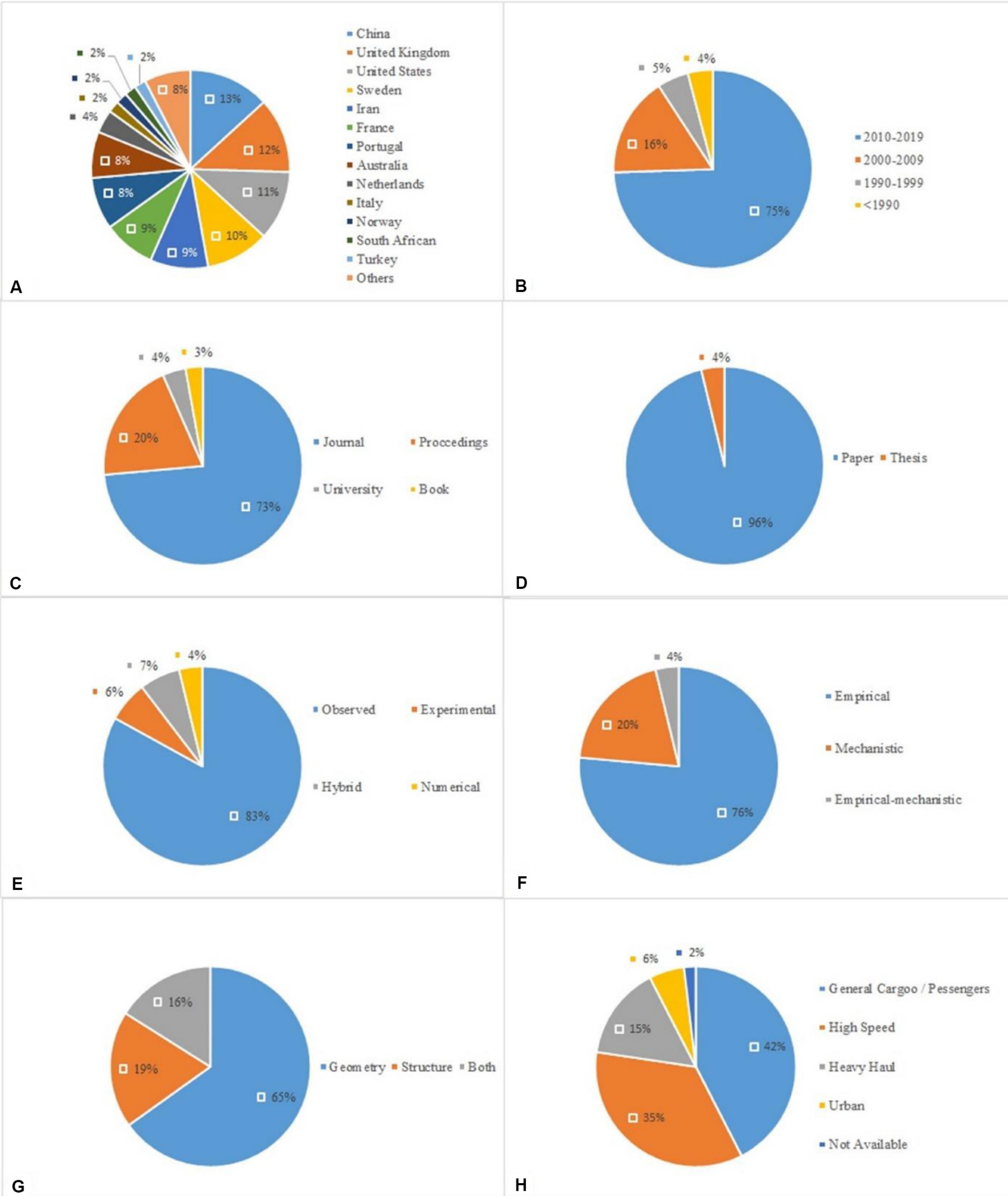

FIGURE 3 | Primary studies: **(A)** applied country, **(B)** published in, **(C)** sort of publication, **(D)** document type, **(E)** approach, **(F)** model, **(G)** element studied, and **(H)** railway system.

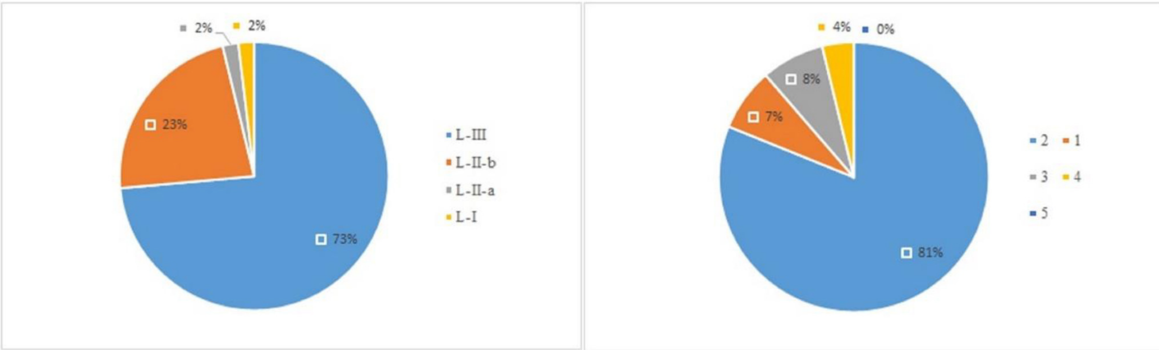

FIGURE 4 | The primary study distribution in groups (left), and in study quality (right).

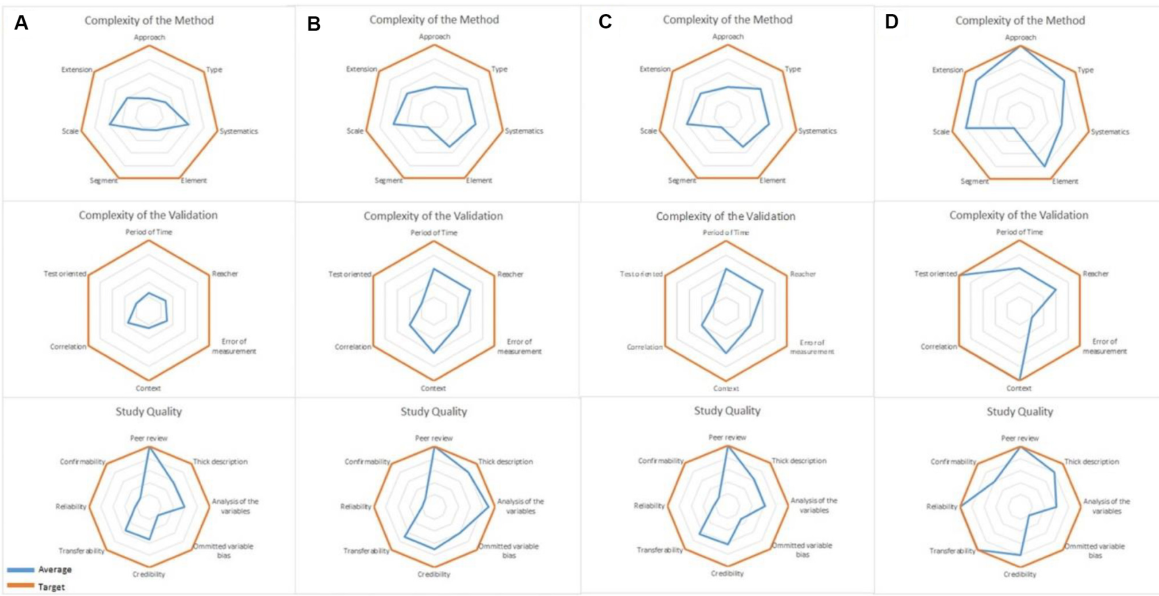

FIGURE 5 | The average of complexity of both the method and the validation, and the study quality of the primary studies classified in groups: **(A)** L-I, **(B)** L-II-b, **(C)** L-II-a, and **(D)** L-III.

subject to checks and controls, including a peer review. Most of the studies selected were evaluated as being 2 on the scale from 1 to 5. **Figure 4** illustrates this data, and **Figure 5** summarizes the study assessment.

Level III (L-III) Group

L-III is the group where most of the studies are plotted (73%). Based on the criteria of the complexity of the method and the complexity of the validation, the L-III group includes studies that have low complexity in both the method and the validation. This means that the studies have not only applied a more observable (not experimental) approach and empirical analysis but also carried out a short validation process.

Level II-b (L-b-II) Group

The L-II-b is the second group where most of the studies are plotted (23%). This group includes studies that have low complexity in their method and high complexity in validation. This means that the studies have focused more on validating the method than on the method itself. In this case, there is more attention paid to the measurement of errors. In turn, these studies have applied a more empirical formulation.

Level II-a (L-a-II) Group

The L-II-a group represents studies that have high complexity in their method and low complexity in validation. This means that these studies have used more numerical and/or experimental approaches, and empirical mechanistic models. On the other hand, less attention has been given to the validation process.

Level I (L-I) Group

Lastly, there is a group named L-I, which has few studies classified into it (only two studies in total). The L-I group represents studies that have high complexity in both their

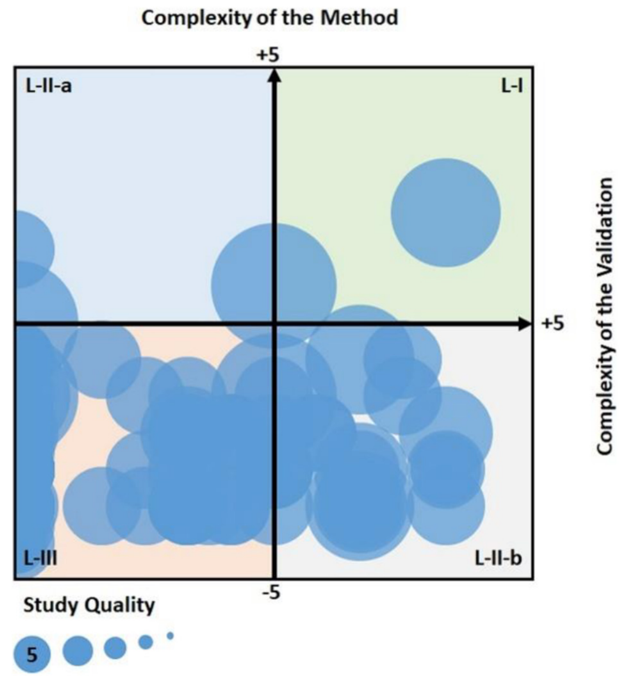

FIGURE 6 | The study groups in according to the complexity of the validation, the complexity of the method, and the study quality.

method and validation. This means that the studies have not only applied more numerical and/or experimental approaches, empirical mechanistic models, and systematic research (field, laboratory, and office) but also, that they have developed an extended validation process. It is at this level that the best methods for studying track deterioration are located.

TABLE 5 | Selected primary studies and their respective groups.

Group	Authors
L-III	Hamid and Gross, 1981; Bing and Gross, 1983; Shenton, 1985; Kearsley and As, 1995; Zhang et al., 1997; Simson et al., 1999; Tolppanen et al., 2002; El-Sibaie and Zhang, 2004; Jovanovic, 2004; Kawaguchi et al., 2005; Hokstad and Langseth, 2005; Meier-Hirmer et al., 2006, 2009; Lobo-Guerrero and Vallejo, 2006; Sadeghi and Askarinejad, 2009, 2010, 2011; Antoni and Meier-Hirmer, 2008; Kumar et al., 2008; Dell'Orco et al., 2008; Shafahi et al., 2008; Shafahi and Hakhamaneshi, 2009; Oberg and Andersson, 2009; Zwanenburg, 2009; Faiz and Singh, 2009; Faiz, 2010; Sadeghi, 2010; Quiroga and Schnieder, 2010; Chang et al., 2010a; Guo et al., 2010; Luber et al., 2010; Guler et al., 2011; Vale and Calçada, 2011; Xu et al., 2011; Gong et al., 2016; Mercier et al., 2012; Andrade and Teixeira, 2012, 2013b; Andrews, 2012; Corriere and Vincenzo, 2012; Chaolong et al., 2012; Prescott and Andrews, 2013, 2015a,b; Lovett et al., 2013; Audley and Andrews, 2013; Andrews et al., 2014; Khouy et al., 2014, 2016; Li and Xiao, 2014; Yousefikia et al., 2014; Vale and Ribeiro, 2014; Khouzani et al., 2014; Wei and Liu, 2014; Zhu et al., 2015; Bai et al., 2015, 2016; Jovanovic et al., 2015; He et al., 2015; Ahac and Lakusic, 2015; Shafiee et al., 2016; Ivanov et al., 2016; Qian et al., 2016; Mahmoud et al., 2016; Cardenas-Gallo et al., 2017; Chen et al., 2017; Do et al., 2017; Wei et al., 2017; Minbashi et al., 2017; Das and Bajpai, 2018; Sadri and Steenbergen, 2018; Peralta et al., 2018; Sadri et al., 2018; Nielsen and Li, 2018; Osman and Kaewuruen, 2018; Chiachio et al., 2019; Al-Jubooria et al., 2019
L-II-b	Li et al., 2006; Zhang et al., 2000; Lyngby, 2009; Chang et al., 2010b; Berawi et al., 2010; Andrade and Teixeira, 2011; Guler et al., 2011; Quiroga and Schnieder, 2011a,b; Sadeghi and Askarinejad, 2012; Westgeest et al., 2012; Andrade and Teixeira, 2013a,b; Xu et al., 2013; Guler, 2014; Nguyen et al., 2016; Nimbalkar et al., 2016; Karttunen et al., 2016; Xin et al., 2016; Zarembski et al., 2016; Karimpour et al., 2017; Falamarzi et al., 2018; An et al., 2018
LII-a	Sadeghi and Askarinejad, 2007; Rhayma et al., 2013; Vale and Lurdes, 2013; Andrade and Teixeira, 2015
L-I	Guerin, 1996; Frohling, 1997

Summary of the Primary Studies

The primary studies included in this review are summarized in **Figure 6** and **Table 5**, which illustrates an overview of all 106 selected studies. The figures show the concentration of these studies in the groups L-III and L-II-b, with low complexity of the method, varied complexity of the validation, with most of them ranked as a 2 for study quality. This means that most of the studies related to the track deterioration process do not have the necessary complexity and quality to deal with evaluating the track condition and how much it is influenced by both track structure and track geometry, as well as the relations between them. In other words, they do not have the accuracy to predict track deterioration. This may explain why, to some extent, this review largely found that studies were underpinned by empirical models (statistical, for example), which are more easily developed than, for instance, mechanistic or even empirical mechanistic ones.

Supported by these studies and findings, it is possible to identify which tactics – including model and approach – have been established by more than one peer review process. **Table 6** shows that the most of valid tactics (established tactics) are related to both empirical (statistical) models and observable approaches (recording vehicles, for example) when these are applied to the elements of track components (except "all" elements together). This replicates an empiric model when it is associated with the elements of track geometry, being the most usual and less complex procedure. This may also clarify why most of the studies under investigation are related to the empirical formulation (both track components and track geometry), and also observable approaches (applied predominantly to the track geometry). In different circumstances, there are more complex techniques, termed empirical mechanistic models and hybrid (numerical and experimental) approaches. These are recognized as potential tactics and are applied in various studies, indicating potential opportunities in the development of more advanced investigations of track deterioration.

This critical review has two main outcomes. In general, the studies included in this literature review do not deal with the interrelation between track components and track geometry when analyzing track deterioration. The most used and least complex techniques (empirical models and observable approach, not experimental) are "established tactics" while the less ordinary and more complex ones (empirical mechanistic models and the hybrid approach) are recognized generally as potential tactics. In other words, few studies have developed advanced investigation techniques for analyzing track deterioration with numerical and

TABLE 6 | The established and potential tactics in evaluating track deterioration and its elements.

Application of tactics (model and approach) in evaluating the track deterioration and its "elements" (components and geometry)			Tactics: Model			Tactics: Approach			
			Empiric (statistical)	Mechanistic	Empiric-mechanistic	Observed	Experimental	Numerical	Hybrid (numerical and experimental)
Track element	Track component	Rail	Established	Established	Potential	Established	Established	Established	Potential
		Fastening system	Established	Potential	Potential	Established	Established	Potential	Potential
		Sleeper	Established	Established	Potential	Established	Established	Established	Potential
		Ballast	Established	Established	Established	Established	Established	Established	
		Sub ballast	Established	Potential	Potential	Established	Established	Established	Potential
		Reinforcement	Established	Established	Potential	Established	Established	Established	Potential
		Subgrade	Established	Potential	Potential	Established	Established	Potential	Potential
		All	Potential	Potential	Potential	Potential	Potential	Potential	Potential
	Track geometry	Gauge	Established	Established	Potential	Established	Established	Potential	Potential
		Super elevation	Established	Potential	Potential	Established	Potential	Potential	Potential
		Vertical Leveling	Established	Established	Established	Established	Established	Established	
		Alignment	Established	Potential	Potential	Established	Potential	Potential	Potential
		Twist	Established	Potential	Potential	Established	Potential	Potential	Potential
		All	Established	Potential	Potential	Established	Potential	Potential	Potential

Established tactic, Potential tactic.

experimental modeling supported by statistic, probabilistic, and mechanistic models together.

Although it is recognized that this review does not include all existing studies, this critical systematic literature review does establish a reasonable understanding of how track deterioration is discussed. These studies provide insights that will aid in the development of this research over time, indicating that approaches to track deterioration must be updated. That is also why this kind of critical literature review is qualified as "systematic." In response, it is recommended that future reviews revise this methodology and increase its accuracy to include other languages in the search, such as Spanish, French, German and Portuguese, and improving the "mentefacto conceptual" by including for example, the keywords "fouling" and "wear" as related to, respectively, the ballast and the rail.

CONCLUSION

This study has proposed a procedure for undertaking a systematic literature review identifying, evaluating, and classifying primary studies that predict the process of track deterioration (structure) and degradation (geometry) in an in-service railway. More than 100 studies that deal with this process were selected, most of which concentrated on five countries, namely China, the UK, the US, Sweden, and Iran, though it did identify some studies focused on other countries, including Germany, India, Japan, Spain, Austria, and Switzerland. Most of these discuss high speed or general cargo/passenger railway systems and were published in peer-reviewed journals during the last 10 years.

Although there are a wide variety of methodologies for evaluating track condition, generally they have focused on an observable approach (recording vehicle) of the track geometry, supported by empirical analysis (statistical), with a low degree of validation, as shown in **Figure 6** (Level III group) and **Table 6** (established tactic). It is recognized that this critical review has its limitations and it could be improved once other languages and countries are included in the search and reviewed using the "mentefacto conceptual."

The figures reveal that despite the advances in statistic analytical methods there remains scope to improve existing track condition methodologies. One of these improvements is related to applying the best theoretical target in fully predicting track deterioration (Level I group), which includes associating the empirical mechanistic model (the best of statistic and mechanistic formulation) and the hybrid (numerical and experimental) approach. This is the main finding of this investigation.

In practice, unlike other techniques, a hybrid numerical and experimental approach and an empirical mechanistic model together may take into account the interactions between track elements (track components and track geometry) and the environmental effects through real measured data (experimental), and a complex mathematical calculation (numerical analysis and mechanistic model). Additionally, these tactics assume uncertainties (statistic and probabilistic model) in preventing even the best method being a perfect in model over time, due either to input parameters, for example axle loads, temperature variation, and material strengths, and outcomes such as displacements, forces, stresses, and strains. This systemic review has attempted to demonstrate that by using technological advances in computational methods and by incorporating these techniques, it is possible to fill the current gap in modeling, and create models that allow for the multiple processes that lead to track degradation.

AUTHOR CONTRIBUTIONS

AM wrote the manuscript with support from other authors and developed the systematic research. SK, MP, LB, and RM gave very useful comments on this manuscript and contributed to the proposal methodology. All authors contributed to the article and approved the submitted version.

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Use of Field Flexural Demand Data for Reliability-Based Analysis and Design of Concrete Railroad Sleepers

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Concrete sleepers are commonly used to constructed ballasted track infrastructure in demanding locations on heavy axle load (HAL) freight railroads with steep grades, sharp curves, and high annual gross tonnage. Center flexural cracking is one of the most common factors limiting the service life of concrete sleepers in North America, and rail seat cracking has also been documented as a performance concern. As such, development and implementation of a structural design method that enables optimization of sleeper design for varied applications and loading environments will reduce initial capital cost and recurring maintenance expense. Field instrumentation has been developed to reliably capture revenue service field flexural demands, facilitating a probabilistic design method for the flexural capacity of concrete sleepers with bending data as the primary input. This paper presents a design process based on structural reliability analysis (SRA) concepts whereby target values for reliability indices (β) for new designs are obtained and compared with existing designs for further design optimization. New (proposed) designs are quite different from current ones. The need for increased sleeper center bending capacity is indicated. Additionally, a reduction in rail seat bending capacity of approximately 40% is justified, reducing the size of the rail seat cross section by approximately the same magnitude. In most cases the proposed designs have fewer prestressing wires and a higher centroid of prestressing steel. In all cases the flexural capacities at the sleeper center and rail seat are better balanced from a structural reliability standpoint. The method proposed is applicable to ballasted track infrastructure constructed with monoblock concrete sleepers.

Keywords: railroad, concrete sleeper, rail seat bending moment, reliability, flexural demand, center negative bending moments

BACKGROUND

The flexural design of concrete sleepers is widely considered as the most critical design element, given its direct relationships to the structural integrity and long-term performance of the sleeper. To date, flexural design is based largely on a static analysis of loads, with the application of empirically derived impact factors that vary widely in the international railway engineering community. The primary input into the flexural design of sleepers is the rail seat load, which is considered in conjunction with assumed sleeper support conditions. Quantification of these values has been challenging from an experimental standpoint, thus assumptions are made related to increase in wheel load over static (i.e., dynamic and impact loading), percentage of wheel load transferred to the rail seat under the point of load application, and expected support condition for both center and rail seat regions.

Prevailing international concrete sleeper design practices are deterministic in nature. They rely on load factors to ensure conservatism in design that covers the probabilistic nature of both the loading (demand) and the capacity of sleepers. Additionally, there are no known design practices that require incorporation of empirical field bending moment data, largely due to the scarcity of these data and the challenges associated with interpolation and extrapolation of field results to the variety of applications in which concrete sleepers are used.

In the United States, exceptions to the normal method of design include the application of structural reliability analysis (SRA) to light rail transit sleepers as presented by Canga Ruiz et al. (2020) and research aimed at using field data, and other best practices, to design the next generation of concrete sleepers for Amtrak's Northeast Corridor (NEC) (Quirós-Orozco et al., 2018). Additionally, reliability analysis methods were developed at the University of Wollongong in Australia (Remennikov et al., 2012). The methodologies presented in this paper extend this preliminary work to a broader set of data from a critical rail transport mode and develops a framework for both the analysis of existing sleeper designs and design of future sleepers using a probabilistic approach based on SRA methods. The research methodology presented in this paper is applicable to the design and performance concrete monoblock sleepers used for initial construction and ongoing maintenance of ballasted track.

INTRODUCTION

Documentation of the need for concrete sleeper structural design optimization in the United States can be found as early as 1970 (RMSA, 1970), coinciding with their initial installation. Since then, the optimization of concrete sleeper design has been pursued through a variety of approaches. Using 2D numerical simulations and some laboratory experimentation, Namura et al. (2005) investigated optimum dimensions of concrete sleepers to minimize ballast stress and sleeper deflection for a Japanese system. Sadeghi and Babaee (2006) performed numerical simulations to optimize an Iranian sleeper by comparing 40 alternative geometrical configurations and choosing the one that minimized flexural demands and ballast pressures. Instead of modifying sleeper geometry, Harris et al. (2011) focused on maximizing the capacity of an existing sleeper's geometry and concluded that the capacity of an existing sleeper can be increased most efficiently by increasing both the diameter of the prestressing strands and concrete strength (Lutch, 2009).

To efficiently design concrete sleepers, it is necessary to understand the relevant structural design parameters that govern their performance to ensure selection of the correct design philosophy. Worldwide research and the guidance provided by standards and manuals provide useful insight into such parameters. By deploying sleepers instrumented with load cells at the rail seats and the sleeper bottom in various field service conditions, Sadeghi (2008) concluded that dynamic load factors and rail seat loads are accurately estimated by AREMA, but sleeper support conditions are best estimated using UIC (2004) methods. Realizing this deficit, Wolf et al. (2015) built on the earlier findings of McHenry (2013) in an effort to revise AREMA to better account for non-uniform sleeper support conditions when designing for rail seat positive bending, which resulted in updated recommendations in 2017 version of the American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017. You et al. (2017) presented a side-by-side comparison of various standards and recommendations with respect to the most common design variables, including the often-controversial design assumptions for sleeper support conditions. When it comes to design practices, Kaewunruen et al. (2019) documented how many of the most prevalent concrete sleeper design standards can lead to over conservative design solutions, thus generating material waste that could be avoided if dynamic forces and reactions were considered instead of only static (or quasi-static) ones. In most cases, however, standards and manuals lack widespread examples of field collection of sleeper bending moments for the purpose of determining design moment, including the recommendations within AREMA (American), EN 13230 and UIC 713 (European), and Australian Standard AS 1085.14 (Standards Australia, 2003). One such exception is a reference in the European Norm (EN) 13230 (European Committee for Standardization, 2009) that allows for field collection, although this is rarely used in favor of theoretical support assumptions as described in UIC 713R (2004).

As concrete sleeper design practices shift from the traditional allowable stress design to the load resistance factor design, there is a need to establish clear limit states. Kaewunruen et al. (2012a,b) suggested that "the key detrimental factor for prestressed concrete sleepers relies on the ultimate limit state," as concrete common designs of sleepers tend to easily satisfy serviceability limit states. Murray (2015) considered strength, operations, serviceability, and fatigue as being the limit states necessary for a "rational cost-saving method" of sleeper design. Cyclic loading failure is one aspect that has been considered in this area, including fatigue of steel tendons (Wakui and Okuda, 1997; You et al., 2017), rail seat failure from impact loads (Kaewunruen and Remennikov, 2009), and flexural failure due the interaction of cracks with moisture (Bastos, 2020). Given that controlled center cracking can be accepted in the European context based on language in the prEN 13230-6 (European Committee for Standardization, 2014), fatigue and durability need to be well understood as identified by Zanuy and Albajar (2018), who tested sleepers to investigate their fatigue performance.

Recently, probabilistic design approaches have emerged with a greater focus on structural reliability. Kaewunruen and Remennikov (2009) implemented modern reliability tools to assess the structural safety of prestressed concrete sleepers using the Australian standard AS1085.19 (Standards Australia, 2003) and previous work converting this standard to limit states design format (Remennikov et al., 2007). They used wheel impact load distributions quantified by Leong (2007) to represent the demand model. The capacity model were distributions of rail seat and center flexural stresses, which were generated by combining the effects of 12 random variables. They also considered the reliability at transfer of prestressing forces (initial stage) and the reliability indexes for steel wires. Soltanian et al. (2018) developed a probabilistic model for time dependent reliability analysis for prestressed concrete sleepers subjected to corrosion in aggressive chloride environments.

Remennikov et al. (2012) presents an approach that infers rail seat loads, and resulting flexural demands, from Wheel Impact Load Detector (WILD) data. This process, when combined with the preceding research mentioned above that informed it, is the most robust concrete sleeper design method proposed to date, considering both field loading and design capacity in a probabilistic manner. The inference of rail seat loads from WILD data (Van Dyk et al., 2014), however, leaves room for error. Results from field experimentation have shown substantial variability in the percentage of wheel load that is transferred to the rail seat beneath the point of load application (Edwards et al., 2017a,b). This research also found that even small gaps (less than 1/4 in.) between the sleeper and ballast can result in wide variability in applied rail seat loads and bending moments. Controlled laboratory experimentation, varying support conditions, and quantifying their impact on bending has also been undertaken to demonstrate how bending moment demand is sensitive to support conditions (Bastos, 2016; Bastos et al., 2017). Research has also shown that variability in temperature can affect field bending moments (Wolf et al., 2016b; Canga Ruiz, 2018; Edwards et al., 2018; Canga Ruiz et al., 2019), which is another factor that is not considered in a method that relies solely on input loading at the wheel rail interface to calculate flexural demand.

Bending moment variability is due to a variety of factors that relate to the stiffness of the track structure, the uniformity of ballast beneath the sleeper, and the external (train-induced) loading level on the sleepers. The effect of these predictor variables was investigated in previous research by Edwards (2019). Additionally, the relationship between wheel loads and rail seat loads, and thus bending moments, is non-linear, as shown by Prause and Kish (1978) and more recently by Gao et al. (2017) and Quirós-Orozco (2018). This finding further demonstrates the importance of using bending moment data as the primary input into a design process for concrete sleepers and not being reliant on functional relationships between wheel loads and bending moments. These findings indicate that the topic of bending moment variability warrants additional research to holistically quantify moments under a variety of operating and loading conditions.

PROBABILISTIC DESIGN

The concept of probabilistic design was proposed within the United States rail industry by Kalay and Samuels (2002) in the context of reducing the "stress state of the railroad" and there are international examples of the emergence of probabilistic design dating back to the 1970s (Heath et al., 1972). Stress state reduction in general, and the specific application of sleeper design lends itself to a probabilistic analysis. Their proposed approach viewed changes to track infrastructure design, rolling stock gross rail load, and wheel condition in terms of its impact on either the stress (i.e., demand) or strength (i.e., capacity) of the system. SRA is a well-developed and documented method (Ang and Tang, 2006), which has been frequently applied to structural design (Soares, 1997; Elishakoff, 2017). The field of SRA continues to evolve (Frangopol et al., 1997; Der Kiureghian, 2008; Steenbergen et al., 2013) and provides a viable method for assessing the design of many types of structural elements, including sleepers, further substantiating the need for, and feasibility of, a probabilistic design approach.

Concrete sleepers must be designed to fulfill a variety of performance requirements; ensuring their flexural capacity, base pressure, lateral resistance, and rail seat abrasion resistance are adequate for the loading demands placed on them. To date, there has been no comprehensive application of SRA methods to concrete sleeper flexural design using field-collected bending moments as the input for generating a demand model, although an initial analysis by Canga Ruiz et al. (2020) was undertaken to demonstrate the viability of such an approach for light rail transit. Beyond the aforementioned research related to concrete sleepers, there has been limited probabilistic consideration of the analysis of the track substructure and its behavior (Lee, 2013) and a track superstructure application related to the performance of rail steel, albeit in terms of risk assessment and not rail strength or sectional design (Jamshidi et al., 2017).

The best input into an SRA, or probabilistic design methodology, for the flexural capacity of concrete sleepers are field data representative of the actual flexural demands. Such a methodology has been developed (Edwards et al., 2017b) and deployed by researchers at UIUC to answer a variety of engineering questions related to sleepers and the field moment demands placed on them (Wolf et al., 2016b; Canga Ruiz, 2018; Edwards et al., 2018; Quirós-Orozco et al., 2018; Canga Ruiz et al., 2020).

The application of SRA and probabilistic design for the analysis and design of concrete sleepers is interesting from an academic standpoint for several reasons. First, large variation in loading conditions are generated by a variety of different types of railroad rolling stock and a wide range of wheel conditions and resulting impact loads (Van Dyk, 2014; Van Dyk et al., 2014). Second, the occurrence of both positive and negative bending at the rail seat (Prause and Kish, 1978; Edwards et al., 2018) and center (Wolf et al., 2016a; Edwards et al., 2018) cross sections due to differing sleeper support conditions is of interest and is largely absent from other prestressed concrete applications. Finally, the availability of large quantities of reliable demand data collected using field instrumentation is unique. The benefits of reducing sleeper cross-sectional area are primarily due to manufacturing (first) costs, but there are also benefits accrued from reducing the level of pre-tensioning (i.e., being able to design to lower bending moments), thus reducing the stress state of the sleeper and mitigating failure modes such as end splitting.

PART I – ANALYSIS

As an initial step toward concrete sleeper probabilistic design, and to quantify the potential value in pursuing such a method, we undertake a quantitative evaluation of the center flexural capacity of existing sleeper designs using SRA methods similar to what was demonstrated by Canga Ruiz et al. (2020) for another rail transit mode. It is important to note that there is a difference between the design specification value and actual flexural capacity of a sleeper. This difference represents an internal safety factor that concrete sleeper manufacturers apply to ensure that even their "weakest" sleepers exceed the design value specified by the end user to minimize rejection of product due to inadequate flexural capacity.

Additionally, a portion of this differential may be due to the discrete nature of key inputs in the sleeper design and manufacturing process (e.g., an integer number of wires can be used, finite grades of prestressing steel, etc.). Beyond this safety factor, results from previous field experimentation have indicated that there is significant excess design capacity (actual capacity exceeding service demand), highlighting the need for optimization of sleepers and the selection of a probabilistic design method (Wolf et al., 2016a; Edwards et al., 2017b, 2018; Quirós-Orozco et al., 2018). This is especially true for rail transit sleepers (Edwards et al., 2018).

Prevailing international concrete sleeper design standards are static in nature and rely on the use of deterministic parameters for estimating both the demand and capacity of concrete sleepers. The demand is augmented with dynamic and impact factors to increase the static bending moment. The capacity is augmented by applying safety factors to account for variability in this deterministic application. The specific values used to incorporate variability and estimate capacity and demand are often derived through trial and error, occasionally supported by experimental results.

For the probabilistic design method described in this paper, bending moment is the metric used, measured in kip-inches (kN-m in SI). This is due to the fact that bending moments are the most widely used metric to quantify the "strength" of concrete sleepers. Sleepers behave as beams (transverse loads are applied causing them to bend), thus are considered as flexural members. Additionally, probability density functions (PDFs) are used as the primary means of visualizing bending moment data.

Development of Demand Model

The first element in the SRA process employed in this research is the assessment of concrete sleepers to obtain reliable field data that represent the flexural demands placed on concrete sleepers. These data need to be collected at both the center and rail seat sections given that both regions are critical sections that warrant independent design analysis using a sectional method (Bastos, 2016).

Instrumentation Technology – Concrete Surface Strain Gauges

To quantify sleeper bending moments, concrete surface strain gauges were deployed in the field during revenue service train operation. This method was previously developed, deployed, and validated under heavy axle load (HAL) freight operations (Edwards et al., 2017b). The calibration process uses the relationship described in Equation 1 to relate a known bending moment to the concrete sleeper's sectional properties and response to load:

$$M_s = \frac{\varepsilon_s E_c I_s}{d_s} \quad (1)$$

Where:

M_s is the sleeper bending moment at section "s," kip-in (kNm),

ε_s is the strain measurement from the surface strain gauge at section "s," in/in (mm/mm),

E_c is the elastic modulus of the concrete, psi (kPa),

I_s is the moment of inertia at section "s," in^4 (mm^4),

d_s is the distance from the surface strain gauge to the neutral axis of bending of the sleeper at section "s," in. (mm).

Section "s" refers to the cross-section of the sleeper where the strain gauge is located, which must be consistent between the calibration sleeper and the test sleeper in the field. The terms E_c, I_s, and d_s are unique to the sleeper and are determined in an aggregate fashion through laboratory calibration. For the sleepers described in this manuscript the laboratory calibration factors were found to be 790,928 kip-in/ε (89,363 kNm/ε), 591,921 kip-in/ε (66,878 kNm/ε), 684,533 kip-in/ε (77,342 kNm/ε), for Gauges A, C, and E, respectively.

Instrumentation Deployment on Sleeper

In order to quantify the flexural behavior of the sleeper under load, bending strains were measured at critical locations along the length of the sleeper (Edwards et al., 2017b). Concrete surface strain gauges were applied oriented longitudinally along the chamfer near the top surface of the sleeper. For some of the sleepers at each field-testing location, five strain gauges (labeled A–E) were applied, with one at each of the two rail seats, one at the center, and another located approximately halfway between each rail seat and the sleeper center (**Figure 1**). The research discussed in this paper, related to flexural design of sleepers, will only draw upon data from Gauges A, C, and E (i.e., center and rail seats).

The dimensions shown in **Figure 1** account for a specific instrumented sleeper with a total length of 102 in. (258 cm), a common sleeper type used in North America on HAL freight railroads. Images of instrumented sleepers in the field with fully protected gauges can be seen in **Figure 2**.

Further information on the deployment of instrumentation is described in Edwards et al. (2017b). **Table 1** also includes the owner-provided "specification" value that must be met or exceeded to avoid sleeper cracking. Design values represent the first crack capacities associated with the unique sleeper designs that are supplied by the sleeper manufacturers. To relate the field-measured strains to center and rail seat bending moments, calibration factors were generated through

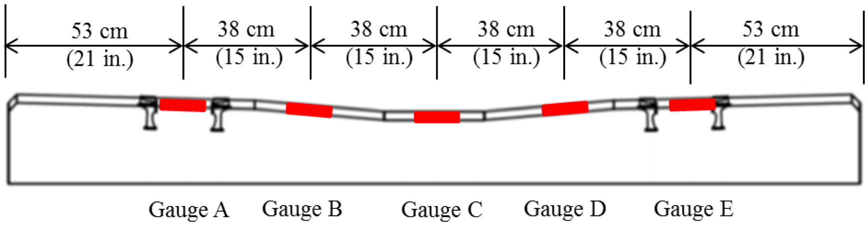

FIGURE 1 | Profile view of sleeper showing locations of strain gauges (Wolf, 2015).

FIGURE 2 | Images of sleepers instrumented with concrete surface strain gauges at a HAL freight railroad field experimentation location.

laboratory experimentation at UIUC's RAIL per the methods described by Edwards et al. (2017b).

Field Instrumentation Deployment

The field instrumentation and data collection discussed in this paper were conducted on ballasted track locations on a high-density mainline HAL freight railroad location in the western United States (hereafter referred to as "HAL freight"). Because of the observed variability of support conditions observed in past field experimentation (Wolf et al., 2015; Gao et al., 2016; Edwards et al., 2017a,b), and knowledge of load dispersion (Hay, 1982; Kerr, 2003; Van Dyk, 2014), data were collected and processed from multiple consecutive sleepers. Thus, instrumentation was placed in two locations, or "zones," of tangent track, spaced approximately 60 ft. (18.3 m) apart on center (**Figure 3**).

Findings

A dataset containing a random sample of approximately 5,000 center and rail seat bending moment observations were extracted using simple random sampling without replacement to generate unbiased datasets for the center and rail seat demand models. These data were extracted from a larger set containing approximately 142,600 and 138,000 center and rail seat bending moment observations (**Figure 4**). Research by Edwards (2019) provided confidence that the data set is representative of the population.

To develop bending moment demand distributions and establish fitted curves for further analysis, data were analyzed in MATLAB and the commercially available software EasyFit (by MathWave Technologies). EasyFit considers 65 of the most common distributions (e.g., log-logistic, Gamma, normal, Weibull, etc.) and facilitates the estimation of parameters for fitted PDFs and cumulative distribution functions (CDFs). To evaluate the adequacy of the fit of the selected distributions both the Kolmogorov–Smirnov (K–S) and Anderson–Darling tests were employed.

As compared to the K–S test, the Anderson–Darling test has advantages that are applicable to the engineering

TABLE 1 | Characteristics of HAL freight railroad loading conditions and sleeper structural geometric properties for the locations considered in this study.

Sleeper/System characteristic			System of units	
			SI	**US Cust.**
Static wheel loads	Loaded 286 k Car		159 kN	35.8 kips
	Empty 286 k Car (Approx.)		36.7 kN	8.25 kips
Sleeper geometry	Length		2.59 m	8′ 6″
	Tie spacing		0.61 m	24″
Sleeper prestressing	Number of wires			20
	Jacking force		31.1 kN	7 kips
	Precompression (Center)		15. kN/m2	2.24 ksi
Sleeper cracking moment	Center negative	Specification	26.0 kN-m	230 kip-in
		Design	26.0 kN-m	230 kip-in
	Center positive	Specification	N/A	N/A
		Design	21.0 kN-m	186 kip-in
	Rail seat positive	Specification	33.9 kN-m	300 kip-in
		Design	43.1 kN-m	381 kip-in
	Rail seat negative	Specification	N/A	N/A
		Design	24.7 kN-m	219 kip-in

questions being considered here. The Anderson–Darling method is especially useful for this application because it increases the power of the K–S statistic to investigate the tails of the distribution and produces a weighted statistic (Darling, 1957; Press et al., 2002; Engmann and Cousineau, 2011). Additionally, there is evidence that the Anderson–Darling test can detect very small differences in the goodness of fit for distributions, even for large sample sizes such as what are used for this research (Engmann and Cousineau, 2011).

Focusing on the tail is important given our application for the design of future railway track infrastructure components. Current structural engineering design methodologies consider Ultimate Limit State (ULS) to bound the failure conditions of a structure using an extreme event that is defined depending on the function of the structure. In a similar fashion, this paper aims to better address the design for failure of concrete sleepers, thus being of paramount importance the understanding of the most demanding, yet most infrequent, loading scenarios. The best-fit (optimal) distribution was then selected using the Anderson–Darling criteria, with priority given to distributions that are more commonly recognized, and of a lower order (e.g., avoidance of three or four parameter models).

Table 2 summarizes the best fit for each of the data sets collected, as indicated by the Anderson–Darling test criteria. The majority of the best-fit models contained two and three parameters. Additionally, **Table 2** contains the distribution types, PDF functions, and parameter estimates for each model.

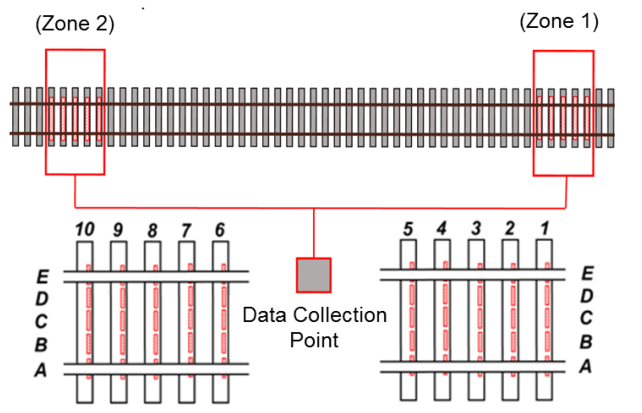

FIGURE 3 | Field site layout with ten sleepers in two test zones (Wolf, 2015).

While the "best" fit distribution is most useful for modeling the flexural demand of a specific HAL freight railroad system, a more general distribution for representing the data is useful for widespread application of the demand curves and the broader probabilistic methodology described in this paper. This is due in part to the fact that distributions with more than two parameters are likely overfitting (Kutner et al., 2005) the existing field demand data to reflect the specific attributes of a given rail transit system.

As such, and as shown in the bottom two rows of **Table 2**, the selection of a Weibull distribution for center moments and a normal distribution for rail seat moments is deemed most practical. These two distributions were selected due to widespread knowledge of their use. Additionally, the normal distribution is reflective of the uniform nature of rail seat bending moments given that they are not as sensitive to variable support conditions. Weibull distributions were generated in the context of engineering and fatigue analysis and excel at representing extreme events (Weibull, 1951), an attribute of the center bending moment data that must be considered. In **Figure 5**, the selected distributions are overlaid on the histograms of raw data.

The authors understand the influence of accurate curve fitting on SRA model results and have thus compared curves obtained from the field data reported in this manuscript to other field data to ensure consistency in the type and fit of distribution. To further improve the demand model, data collected at discrete field sites could be extrapolated to consider a variety of other support conditions that could be present over the entire railway network. Such an extrapolation was documented by Quirós-Orozco et al. (2018) in conjunction with the redesign of Amtrak's concrete sleeper for the Northeast Corridor (NEC). The study of support condition variability is non-trivial, and the cost of obtaining a holistic understanding of an entire rail corridor would be substantial. For purposes of this research, the demand curves listed above will be used.

There is also a time dependency in the demand curve. Factors influencing this are initial construction loads (e.g., ballast trains on track with no ballast layer that may be placed on a crowned sub-ballast) and the time and tonnage dependent

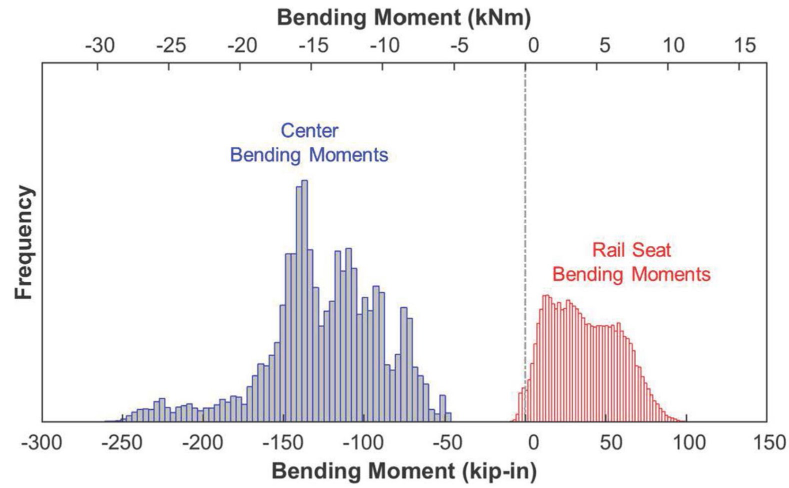

FIGURE 4 | Histogram of raw data of sleeper rail seat and center bending moments used to generate demand models for HAL freight.

TABLE 2 | Descriptions for best fit and final demand models, with equations and parameters.

System	Location	Distribution	Function	Parameters
Initial (Best Fit) Model	Center	Burr	$f(x) = \frac{\alpha k\left(\frac{x-y}{\beta}\right)^{\alpha-1}}{\beta\left(1+\left(\frac{x-y}{\beta}\right)^{\alpha}\right)^{k+1}}$	k = 1.7615 a = 4.9579 b = 142.25
	Rail seat	Pert	$f(x) = \frac{1}{B(\alpha_1,\alpha_2)}\frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}}$	m = 31.413 a = − 10.311 b = 104.91
Final (Generalized) Model	Center	Weibull	$f(x) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{\left(-\frac{x}{\lambda}\right)^{k}}$ *when* $x \geq 0$	$k = 3.494 \lambda = 138.94$
	Rail seat	Normal	$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$	$\sigma = 36.74 \mu = 21.71$

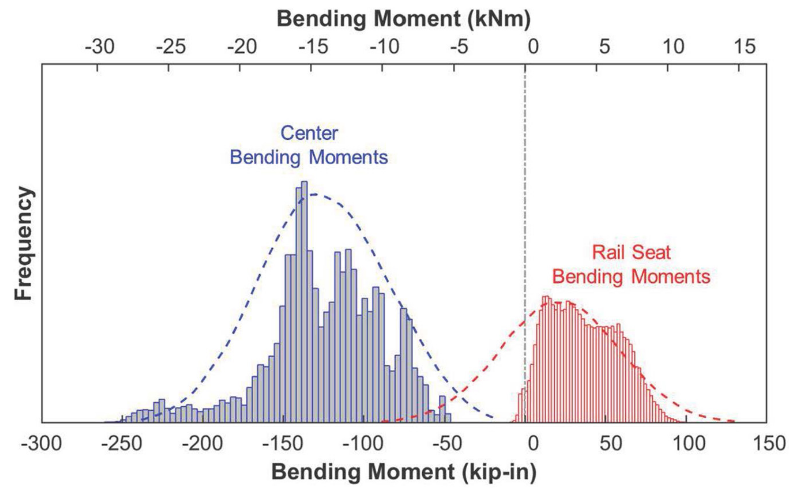

FIGURE 5 | Fitted PDFs overlaid on raw data of sleeper rail seat and center bending moments used for demand models for HAL freight.

deterioration of track support conditions. Other than hand calculations to confirm the former, and pilot projects to quantify the latter (Wolf, 2015), these factors are largely unquantified and require separate study.

Generation of Capacity Model

Method

Most prestressed concrete sleepers in the United States are designed as Class U (uncracked) members using the American

Concrete Institute (ACI) Building Code Requirements for Structural Concrete and Commentary, ACI 318-14 (American Concrete Institute [ACI], 2014). Their flexural capacity is defined based on first crack, typically occurring at the extreme tensile fiber (e.g., top center of sleeper in center bending). This is similar to what AREMA MRE, Chapter 30 (2017) states except that AREMA requires a crack to penetrate to the first level of prestressing from the tensile surface of the sleeper.

As such, the total stresses at the extreme tensile fiber cannot exceed the modulus of rupture (f_r) of the concrete (Equation 2), an empirically derived limit that provides an indirect measure of concrete's tensile capacity. The three terms in Equation 2 represent precompression, the internal moment caused by the eccentricity of prestressing, and the external moment due to passing wheel/axle loads.

$$-\frac{F_{se}}{A_c} - \frac{F_{se}(e)c}{I_c} + \frac{M_c c}{I_c} \leq f_r \quad (2)$$

Where:

f_r = modulus of rupture of concrete (ksi) [0.627 ksi for $f_c^{'}$ of 8 ksi],

M_c = center negative bending moment (kip-in),

F_{se} = effective prestressing force (after losses) (kips),

A_c = cross-sectional area (in^2),

I_c = section moment of inertia (in^4),

e = eccentricity of prestress centroid (in.),

c = distance from neutral axis to extreme fiber (in.).

For concrete with a compressive strength ($f_c^{'}$) of 7 ksi (typical for concrete sleepers) the value for f_r is 0.627 ksi according to Table 24.5.4.1 in ACI 318-14 (American Concrete Institute [ACI], 2014). The modulus of rupture is likely higher for high strength concrete, but absent sufficient experimental data to refine this limit, we have chosen to follow the ACI formulation as a lower bound. The strength of a prestressed concrete member is typically governed by cracking at the tensile surface, not crushing in the compression region due to the manner in which it is loaded (e.g., uniform load or two distributed rail seat loads). McNeely and Lash (1963) suggests use of distributions for f_r with a standard deviation of 8.5% based on experimental results from split tensile tests on cylindrical specimens.

Compared to the tensile strength, the crushing limit for concrete is much higher, on the order of 4.2 ksi for concrete with a compressive strength ($f_c^{'}$) of 7 ksi according to ACI 318-14 (American Concrete Institute [ACI], 2014). Literature also indicates that the fatigue life of concrete should be considered, but the inclusion of concrete fatigue criteria into this largely static design process and evaluation is challenging (American Concrete Institute [ACI], 1997). In general, fatigue limits are more conservative than the $0.6f_c^{'}$ limit, and are recommended in the range of $0.2f_c^{'}$ to 0.4 (American Concrete Institute [ACI], 1997). This does not seem reasonable with respect to the present application, thus no additional reduction of concrete's compressive strength will be considered for fatigue. As noted in ACI 318-14 (American Concrete Institute [ACI], 2014) section R24.5.4.1, fatigue tests on prestressed concrete beams have shown that the compressive failure of concrete is not the controlling criterion.

The limit state values for both tensile and compressive strength of concrete specified by ACI 318-14 (American Concrete Institute [ACI], 2014) are conservative. This is especially true for compressive strength, which is reduced by 40%. Future research should include a sensitivity analysis in which the strength reduction factors are varied within reasonable ranges based on data from prior experimentation.

To align with conventional mechanics terminology, compressive stresses are characterized as negative, and tensile stresses are positive. Additionally, the negative second term in Equation 2 ($\frac{F_{se}(e)c}{I_c}$) indicates that the eccentricity induced by the prestress produces compression in the top of the sleeper that is used to counteract a positive bending moment. The stresses listed in Equation 2 can also be represented graphically for the case of center negative bending.

The critical stress-related value that must be quantified in order to identify when the structural member will fail, is the bending moment, as indicated earlier. Equation 3 is generated by solving Equation 2 for the cracking moment that would indicate that the total stresses in the tensile surface equal the modulus of rupture (f_r), which defines the maximum moment capacity at first crack at a given section.

$$M_{cr} = \frac{I_c}{c_{tens}} \left(f_r + \frac{F_{se}}{A_c} + \frac{F_{se}\,(e)\,c_{tens}}{I_c} \right) \quad (3)$$

Where:

M_{cr} = cracking moment (kip-in);

c_{tens} = distance from neutral axis to extreme tensile fiber (in).

For brevity, only the sleeper center region was considered when providing a background to prestressed sleeper design, and the tensile (top) surface will be the location of greatest attention. The rail seat flexural considerations are similar, although limited by tension on the bottom surface of the sleeper as a result of positive bending moments. The "minor" bending moments, rail seat negative and center positive, are also considered using this same method but with minor modifications listed below.

The proposed process will generally follow a procedure in which limit state functions define the boundary between failure and functionality of a component. This represents the location in which the capacity and demand model cancel each other as shown in Equation 4.

$$g\,(x) = C\,(x_1) - D(x_2) \quad (4)$$

Where:

x_1 denotes the vector of random variables which define capacity;

x_2 denotes de vector of random variables that define the demand;

x denotes the vector of random variables combination of x_1 and x_2;

g(x) denotes the limit state function;

$C(x_1)$ denotes the capacity model;

$D(x_2)$ denotes the demand model.

Thus, when the limit state function has a negative result, failure occurs, as the induced demand exceeds the provided capacity of the concrete sleeper. The probability of failure is based on the likelihood of the demand [D(x)] being greater than the capacity [C(x)], as indicated by the overlap of the two curves. This methodology facilitates evaluation of current designs, and can also be applied to development and optimization of future designs. For reference, earlier probabilistic design literature has referred to the curves using the terms of resistance (R) and load effect (Q) (Szerszen and Nowak, 2003).

As a part of this application of the SRA methodology, limit state equations for each of the critical design cross sections were derived, that map to the stress level at top and bottom fibers of the sleeper based on AREMA (American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017) and ACI 318 (American Concrete Institute [ACI], 2014). These equations define the transition of the component from functional to failed and were previously documented by Canga Ruiz et al. (2020). Failure is defined as "cracked." Equations 5 and 6 represent limit state equations at the top and bottom of the center cross section, respectively.

$$g_1(x) = 7.5\sqrt{f_c'} + \frac{F_{si}}{A_{center}}(1-\text{loss}) + \frac{F_{si}\ e\ y_{t_{center}}}{I_{center}}(1-\text{loss}) - \frac{M_{field}\ y_{t_{center}}}{I_{center}} \quad (5)$$

$$g_2(x) = 0.6f_c' - \frac{F_{si}}{A_{center}}(1-\text{loss}) + \frac{F_{si}e\ y_{b_{center}}}{I_{center}}(1-\text{loss}) - \frac{M_{field}\ y_{b_{center}}}{I_{center}} \quad (6)$$

Similarly, Equations 7 and 8 represent the rail seat limit state equations at top and bottom, respectively. In Equations 5–8, the capacity of the material is represented in the first time on the right of the equality and the demand is calculated using the remaining terms.

$$g_3(x) = 0.6f_c' - \frac{F_{si}}{A_{rail\ seat}}(1-\text{loss}) + \frac{F_{si}\ e\ y_{t_{rail\ seat}}}{I_{rail\ seat}}(1-\text{loss}) - \frac{M_{field}\ y_{t_{rail\ seat}}}{I_{rail\ seat}} \quad (7)$$

$$g_4(x) = 7.5\sqrt{f_c'} + \frac{F_{si}}{A_{rail\ seat}}(1-\text{loss}) + \frac{F_{si}\ e\ y_{b_{rail\ seat}}}{I_{rail\ seat}}(1-\text{loss}) - \frac{M_{field}\ y_{b_{rail\ seat}}}{I_{rail\ seat}} \quad (8)$$

Additionally, there are four more equations for $g_5(x)$ through $g_8(x)$ (Equations 9–12) that represent the lesser bending moments that can be induced at the center (positive) and rail seat (negative) that are not shown in this paper for the sake of brevity.

Results

Equations 5–12 are then used as limit state functions for a first order reliability method (FORM) analysis to generate reliability indices (Zhao and Ono, 1999). To solve the problem using FORM, a MATLAB (2012) toolbox created by the University of California Berkeley for SRA topics to conduct the simulation was used (Der Kiureghian et al., 2006).

TABLE 3 | Random variables used in concrete sleeper flexural capacity models.

Variable	Symbol	Distribution	Units	Mean	Standard deviation
Concrete compressive strength	f_c'	Lognormal	ksi	7	1.05
Jacking force (initial, before losses)	F_{si}	Normal	kips	7	0.42
Prestressing losses	loss	Lognormal	%	15	3.00

The factors considered in the analysis are listed in **Table 3**, along with the type of distribution and its simple statistics. Concrete compressive strength was obtained from prevailing concrete sleeper specifications. Compressive strength distribution characteristics were obtained by a review of relevant literature (Bartlett and MacGregor, 1999; ACI Committee 214, 2002; Mertol et al., 2008; Remennikov et al., 2012; Nowak and Collins, 2013; Rakoczy and Nowak, 2013, 2014). The jacking force value of 7 kips (75% of prestressing steel ultimate capacity) and resulting losses were estimated based on the ACI 318-14 (American Concrete Institute [ACI], 2014) assumption of 15% total losses and a reasonable standard deviation associated with the process of stressing wires and its inherent complexity.

To provide a graphical output of an aggregate capacity curve that can be compared to the field demand curve, Monte Carlo Simulation (MCS) was used. Using MCS, the distribution of possible flexural capacities was generated by using approximately 10,000 iterations that can be considered representative of the population. The method by which data were selected within the MCS was direct sampling. This method is appropriate given the fact that the input variables are all independent and there is no correlation among them. Beyond this graphical representation generated using MCS, FORM, and second order reliability methods (SORM) are considered to be more accurate methods to execute an SRA (Frangopol et al., 1997; Zhao and Ono, 1999). Due to the linear nature of this work, SORM does not improve the results (Canga Ruiz, 2018), thus FORM was deemed appropriate and reliable.

Figures 6, **7** present graphical results from the MCS of the sleeper design under consideration, showing both rail seat and center sectional results for both positive and negative bending moment applications. To represent the field data, Weibull and normal distributions were chosen (**Table 2**).

In the field of SRA, the probability of failure is quantified using a "reliability index," defined as "β." This term is functionally related to the probability of failure (P_f), as shown in Equation 13 (Ditlevsen and Madsen, 2007; Nowak and Collins, 2013).

$$\beta = -\Phi^{-1}(P_f) \quad (9)$$

Where:

Φ^{-1} represents the inverse of the standard normal cumulative distribution function.

P_f represents the probability of failure.

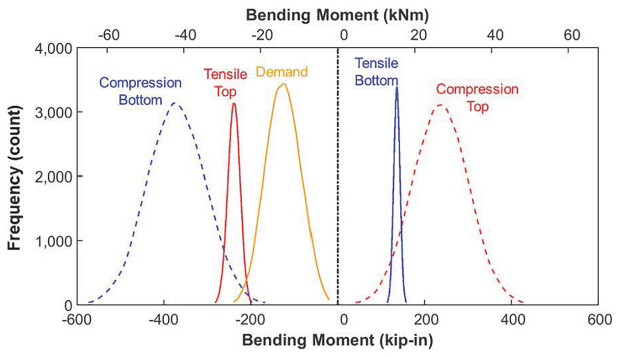

FIGURE 6 | Results from MCS of sleeper center bending moments for HAL freight.

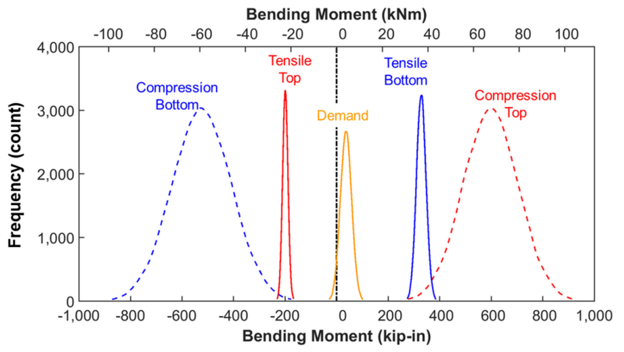

FIGURE 7 | Results from MCS of sleeper rail seat bending moments for HAL freight.

Table 4 includes individual values for the reliability indices (β) that represent failures in either positive or negative bending at the center and rail seat sections. The results indicate the design imbalance in terms of probability of failure between the center and rail seat sections, with a far greater design robustness for the rail seat section. Greater uniformity of probabilities of failure at both the center and rail seat is desirable, and will be the focus of the parametric study described in Part 5.

The aforementioned analysis is based on the flexural strength at initial concrete cracking, and not the component's ultimate capacity or some location within the transition zone that is also specified by ACI 318-14 (American Concrete Institute [ACI], 2014). As discussed previously, this definition differs from the American Railway Engineering and Maintenance-of-Way Association [AREMA] (2017) definition, which does not define a sleeper as failed until the crack has penetrated from the tensile surface to the first level of prestressing steel. In the future, the residual capacity could be defined in reference to ultimate capacity, which is approximately double the cracking moment capacity as demonstrated experimentally by Bastos et al. (2017, 2018).

TABLE 4 | Reliability index and probability of failure for the studied limit state functions obtained using FORM.

Extreme fiber in bending	β	P_f
Center top	2.6614	0.0038908
Center bottom	2.6637	0.0038643
Rail seat bottom	9.6322	2.9232e-22
Rail seat top	6.4435	5.8375e-11

PART II – DESIGN

Demand Model

For design, the same demand model that was used in the analysis of existing designs will be employed, given that the data are representative of conditions likely to be encountered in the field. The demand model could be further refined to consider a variety of possible support conditions. This requires additional assumptions and is a topic that warrants further research.

Capacity Model

The capacity models are generated using FORM, while incrementally changing sleeper geometry (height and width), number of prestressing wires, and prestress centroid within the bounds that are described in **Table 5**. The initial models were run at coarser increments for sleeper geometry, and subsequently re-run at a finer increment [0.25 in (6.35 mm)]. Final model increments were also selected to be compatible with reasonable prestressed concrete manufacturing tolerances.

Additional constraints placed on the model are infeasible cases in which (1) the sleeper top width exceeds the bottom width at either the rail seat or center, (2) the centroid of steel is less than the height of centroid of concrete at the center, and (3) the location of the centroid of steel is greater than the height of centroid of the concrete at the rail seat. For each set of discrete design variables selected, the random variables in **Table 5** were simulated using FORM. The result of each simulation of the various design permutations were reliability indices (β) at the sleeper center and rail seat regions.

For selection of the optimized design, the authors assumed values for β that are representative of the current state of practice in the United States. Szerszen and Nowak (2003) concluded that the ULS of prestressed beams designed using ACI 318 (American Concrete Institute [ACI], 2014) have an equivalent β ranging from 4.2 to 4.4. These values were calculated by varying material, geometry and load values, and resulted in a target reliability index (β_T) of 3.5. This research utilizes a previous approach that treated load and resistance parameters from ACI as random variables to statistically determine reliability indices (Szerszen and Nowak, 2003) which is described by Nowak and Collins (2013). This equivalent β defines what is an acceptable design following the concrete structures design code in the United States (Nowak and Collins, 2013; Canga Ruiz, 2018). The argument could be made for a lower value of β_T given the less-severe consequences of a single sleeper failure, compared to a bridge girder or other typical applications for prestressed concrete.

TABLE 5 | Bounds for sleeper design deterministic input parameters.

Dimension/Value	Units	Range	Increment	Current design
Bottom width at center (g_1)	in. (mm)	10–13 (254–330)	0.25 (6.35)	11.00 (279)
Top width at center (g_1)	in. (mm)	5–10 (127–254)	0.25 (6.35)	9.00 (229)
Height at center	in. (mm)	5–10 (127–254)	0.25 (6.35)	6.75 (171)
Bottom width at rail seat (g_1)	in. (mm)	10–13 (254–330)	0.25 (6.35)	11.00 (279)
Top width at rail seat (g_1)	in. (mm)	7–11 (178–279)	0.25 (6.35)	9.00 (229)
Height at rail seat	in. (mm)	6–12 (152–305)	0.25 (6.35)	8.73 (222)
Number of wires (g_4)	num	8–26	2	20
Height of steel centroid (y)	in. (mm)	2–4 (51–102)	0.25 (6.35)	3.75 (95.3)

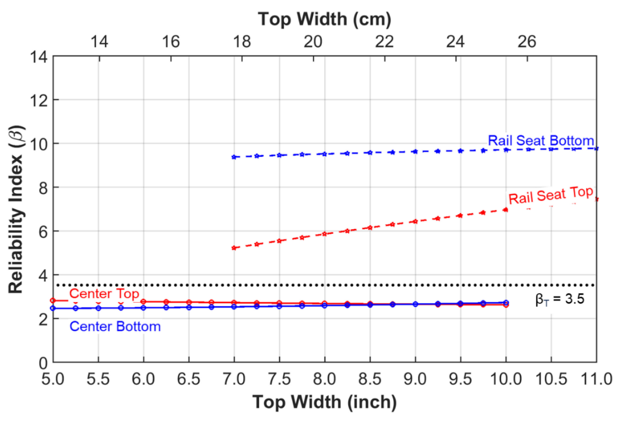

FIGURE 8 | HAL freight center bending moment structural reliability indices (β) as a function of top width, while holding other parameters constant.

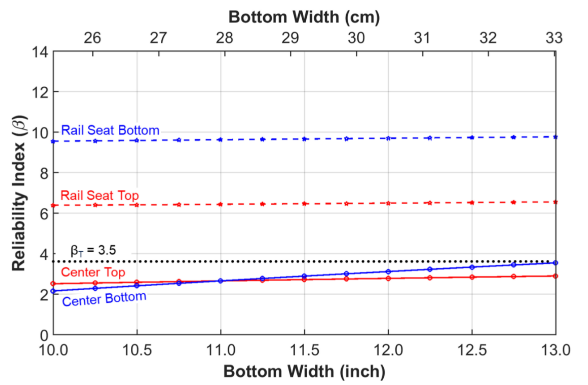

FIGURE 9 | HAL freight center bending moment structural reliability indices (β) as a function of bottom width, while holding other parameters constant.

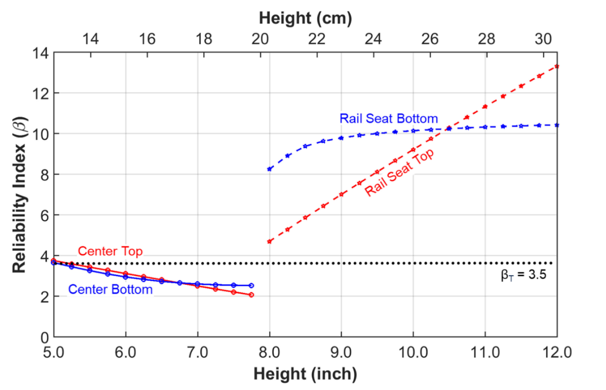

FIGURE 10 | HAL freight center bending moment structural reliability indices (β) as a function of height, while holding other parameters constant.

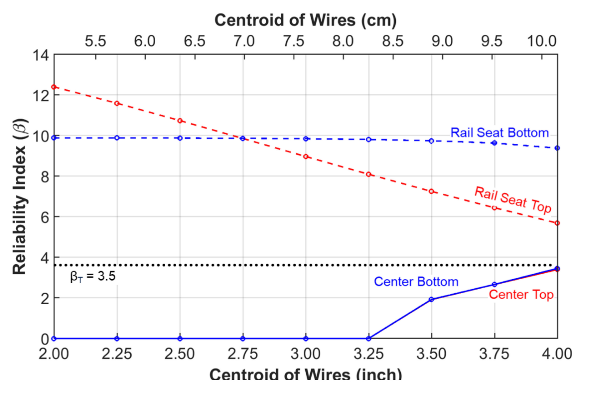

FIGURE 11 | HAL freight center bending moment structural reliability indices (β) as a function of prestressing centroid, while holding other parameters constant.

This discussion is akin to that of Szerszen and Nowak (2003) with respect to primary and secondary members, and the fact that secondary members can have a lower threshold for β_T. The proposed approach focuses on the reliability of a single element (a sleeper) as opposed to a system (the track, which has inherent redundancy due to load sharing among adjacent components).

Given that end users may desire different levels of risk for the center and rail seat, it is possible that the two values for β_T should be considered independently. The reasoning behind different values for β_T at the center and rail seat relates to the consequences of failure at each location and the ease with which failures can be inspected at each location. After preliminary discussions with railroads and concrete sleeper manufacturers, acceptable values of β_T for the rail seat should be higher. This is because rail seat cracks are more difficult to detect, and the consequence of failure at this location can have an immediate effect on the sleeper's ability to fulfill its purpose

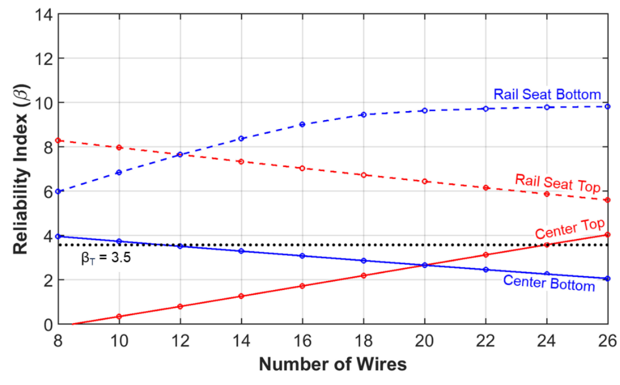

FIGURE 12 | HAL freight center bending moment structural reliability indices (β) as a function of number of wires, while holding other parameters constant.

of holding gauge and supporting the rail. Center cracking has been shown to be less critical by recent research by Bastos et al. (2017), but is a location that is often found to be out of compliance with the FRA Track Safety Standards (CFR 213) (Federal Railroad Administration [FRA], 2014) that require no visible prestressing strands or wires. For purposes of this analysis, which aims to create a balanced sleeper (e.g., equal risk assumed at rail seat and center), we will use values $\beta_T = 3.5$ at both rail seat and center.

Parametric Study Results

The model was next used to conduct a parametric study for evaluation of various sleeper design changes. Values for β at the top and bottom of both center and rail seat sections were plotted as a function of changes in each deterministic input parameter (**Figures 8–12**). For all figures, the deterministic parameters that are not being addressed within the specific figure are held constant at the current design values shown in **Table 5**.

The above results provide insight into the sensitivity of design changes as a function of changes in deterministic input parameters. Most of the positive slopes are intuitive, given that increases in deterministic input variables increase the reliability index. For example, as the height of the sleeper changes (**Figure 10**) at both the center (left lines) and rail

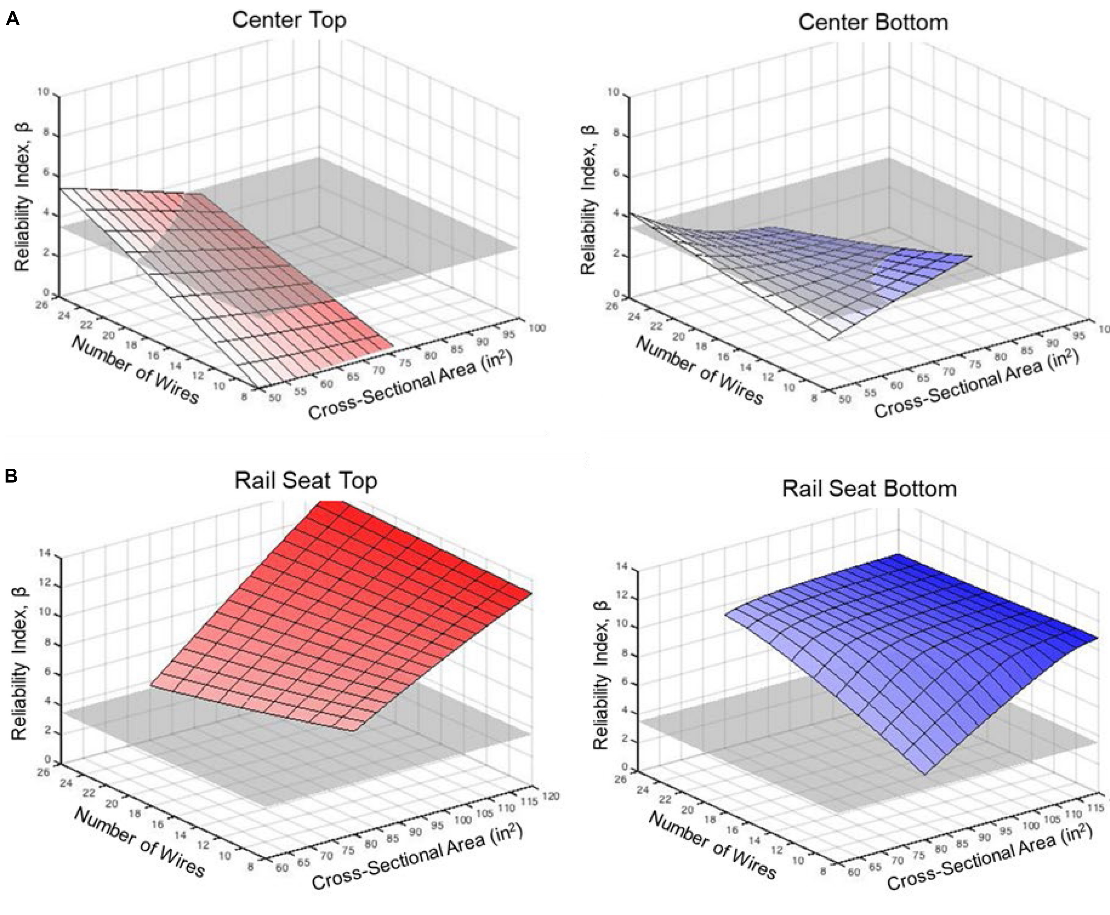

FIGURE 13 | HAL freight center **(A)** and rail seat **(B)** bending moment structural reliability indices (β) as a function of cross-sectional area of sleeper center **(A)** and rail seat **(B)** and number of wires.

seat (right lines) distinct changes in reliability indices (β) are noted. For the sleeper center, as the height is increased, there is less conservatism in the designs due to a reversal of the eccentricity that works against the primary bending. Conversely, at the rail seats, any increase in depth of the section increases design conservatism given that the additional concrete material always improves the sleeper's resistance to positive bending given the section centroid is always above the prestressing steel centroid.

Changes in wire centroid (**Figure 11**) are of particular interest, given their relation to the eccentricity of the sleeper, a primary benefit of prestressing. As the centroid increases (moves upward in the cross section) values for β decrease for the rail seat and increase for the center. The center β values are especially sensitive to centroid location, as its role in resisting negative bending at the center is the most recognizable benefit of using prestressed concrete for sleeper applications. Negative slopes are also present for rail seat negative and center positive bending as a function of increased wires (**Figure 12**). This is due to the eccentricity of prestress that is designed to compensate for the primary bending modes; center positive and rail seat negative. By definition, the eccentricity will only add additional tensile capacity for either positive or negative bending, thus the less prevalent bending modes are the ones that are penalized.

Using three dimensional (3D) plots it is possible to observe the effects of multiple parameters on β (**Figure 13**), holding all other parameters constant at the values previously discussed. **Figure 13** show the effect of changes in the sleeper's cross-sectional area and number of wires on its structural reliability index, β. Gray planes within **Figure 13** represent a target β of 3.5. Results are presented for the four critical limit state functions that were previously presented; top and bottom of both center and rail seat (**Figure 13**).

At the rail seat, the value of β increases as a function of both cross-sectional area and number of wires. Conversely, at the center section of the sleeper, β increases as a function of both cross-sectional area and number of wires. **Figure 13** also indicates that there is significant residual capacity at the rail seat under the range of typical cross-sectional geometries and number of wires. The design of the center and rail seat, while commonly handled independently through sectional analysis, are linked due to geometry requirements driven by the number of strands and the location of the centroid. As such, a globally optimal sleeper design will still have one of the two critical cross-sections that has a significantly higher value for β, likely in excess of the target value of 3.5.

CONCLUSION

A probabilistic approach for the analysis and design of concrete sleepers was undertaken. The approach incorporated the use of SRA principles that were implemented using both FORM and MCS.

1. For the HAL freight sleeper, the center section was under-designed. As such, sleepers designed for HAL infrastructure could benefit from having a similar or slightly higher bending moment at the sleeper center.
2. For the HAL freight sleeper, the rail seat section could be reduced by as much as 40%.
3. Additionally, proposed designs would have fewer prestressing wires and a higher centroid of prestressing steel.
4. Application of the above recommendations would result in better balancing of the flexural capacities at the sleeper center and rail seat from a structural reliability standpoint.

The process proposed and demonstrated in this paper can be applied to ballasted track monoblock concrete sleeper designs from other locations. The analysis and design process should also consider demands that may not be representative of the exact location in which field data are collected (e.g., track transition zones, joints, etc.). This requires extrapolation of track stiffness and support conditions, a challenging undertaking that involves multiple assumptions (Quirós-Orozco, 2018).

DATA AVAILABILITY STATEMENT

Portions of the raw data will be made available by the authors, upon request, without undue reservation.

AUTHOR CONTRIBUTIONS

JE, JB, YL, AR, and MD: study conception and design, analysis and interpretation of results, and draft manuscript preparation. JE and MD: data collection. All authors reviewed the results and approved the final version of the manuscript.

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On Hogging Bending Test Specifications of Railway Composite Sleepers and Bearers

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INTRODUCTION

Railway sleepers (also called "railroad ties" in North America) are safety-critical components of ballasted railway tracks and the embedded type of ballastless tracks (Australian Standard: AS1085.14, 2003; Griffin et al., 2014). In addition, other types of sleepers that are used in other special locations are often termed differently to acknowledge the special conditions. For example, railway bearers are used to define the crossties used in railway turnouts (or switches and crossings). Railway transom or bridge beams are terms often used to refer to the flexural members used over the railway bridges (without a ballast top). Despite the fact that the support and boundary conditions are different, the critical duties of railway sleepers, bearers and transoms are identical: (i) to redistribute dynamic loads from the rail foot to the underlying ballast bed; and (ii) to maintain the rail gauge for safe passages of trains (Neilsen, 1991; Cai, 1992; Grassie, 1995; Kaewunruen and Remennikov, 2006). These functions demonstrate the criticality for safety of rail operations. If they are sufficiently damaged, trains can derail.

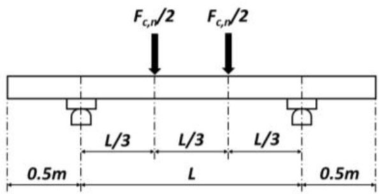
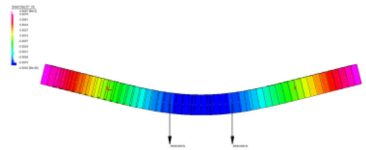
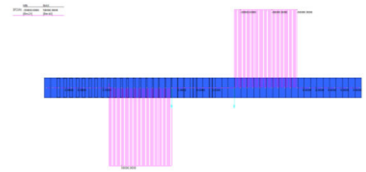
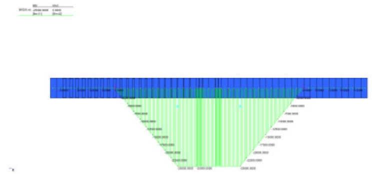
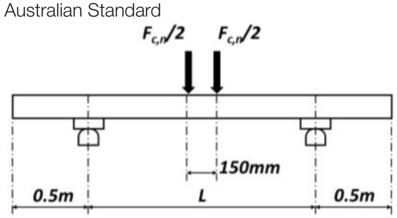
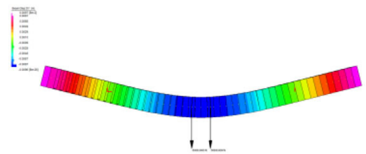
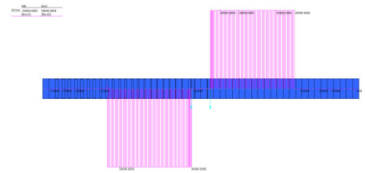
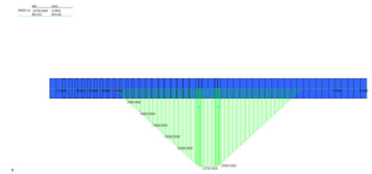
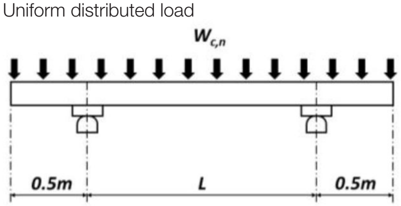
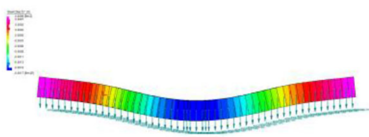
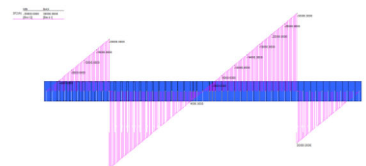
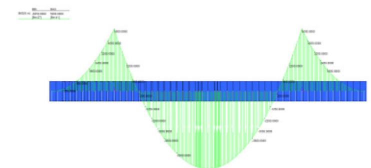
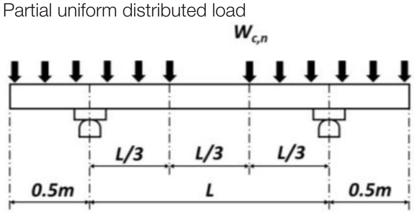
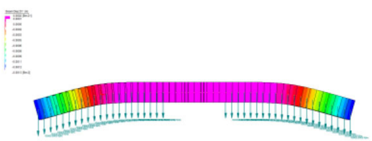
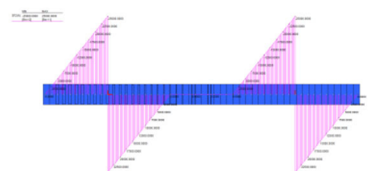
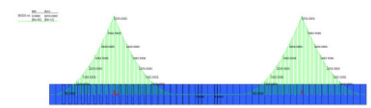
In recent years, composite materials have gained momentum in the railway industry. However, there is not much of a track record on their performance. This is probably because there are so many types of composite materials: some perform well but many do not (Kaewunruen, 2014; Kaewunruen et al., 2017; Silva et al., 2017). For example, "fiber-reinforced foamed urethane (FFU)" composites have been used as turnout bearers and embedded sleepers in Australia, Japan, UK, Germany and other places around the world for just over 40 years (Sengsri et al., 2020a). In contrast, "CarbonLoc composite" (with steel reinforcement) has been used as bridge transoms in Australia for a few years. With these in mind, there has been an effort to develop a brand-new ISO standard (ISO 12856) for standard test specifications of polymeric composite sleepers (with the scope to cover sleepers, bearers, and transoms). The draft standard has now been made available for a technical review.

The aim of this paper is to highlight the test criteria with respect to the design and actual *in situ* behaviors of composite sleepers in track systems. As a case study, full-scale experiments to investigate the test load behaviors of full-scale "fiber-reinforced foamed urethane (FFU)" sleepers have been adopted from very recent investigations. Influences of the standardized support conditions are highlighted in this paper. Comparative studies with *in situ* behaviors of composite sleepers in a ballasted railway are illustrated in order to improve the insight into the benchmarking of the ISO standard's test specification criteria.

FINITE ELEMENT ANALYSES

It is commonly known that the two-dimensional Timoshenko beam model is the most suitable option for 2D modeling of concrete sleepers (Neilsen, 1991; Cai, 1992; Grassie, 1995; Griffin et al., 2014). Using a general-purpose finite element package STRAND7 (G+D Computing, 2001), the

TABLE 1 | Comparisons of test methods and resultant responses (deflection, shear force, and bending moment).

Cases	Deflected shapes	Maximum mid-span deflections (m)	SFDs (N)	BMDs (Nm)
ISO 		0.0083	 Max = 50000 Min = -50000	 Max = 0 Min = -25000
Australian Standard 		0.0096	 Max = -50000 Min = 50000	 Max = 0 Min = -33750
Uniform distributed load 		0.0017	 Max = -30000 Min = 30000	 Max = 5000 Min = -6250
Partial uniform distributed load 		0.0000	 Max = -25000 Min = 25000	 Max = 6250 Min = 0

(i) Finite element modeling of composite beams has been verified by full-scale experiments under both static and dynamic loads.
(ii) $F_{c,n}$ = 100 kN, L = 1.5 m, $W_{c,n}$ = 40 kN/m for uniform distributed load, $W_{c,n}$ = 50 kN/m for partial uniform distributed load.

numerical model includes the beam elements, taking into account shear and flexural deformations, for modeling the composite sleeper. An industry-standard rectangular cross-section of 0.16×0.26 m is assigned to the composite sleeper elements. In this investigation, the finite element model of a composite sleeper has been previously developed and calibrated against both experimental static and dynamic results. The previous experimental results of full-scale composite sleepers (Sato et al., 2007; Sengsri et al., 2020a,b) show that the composite sleeper is likely to have a brittle failure mode with large deformation before failure. Under dynamic loading conditions, the first bending mode in a vertical plane of a composite sleeper clearly dominates the first resonant mode of vibration under a free-free condition (Sengsri et al., 2020b). Also, the dynamic modal parameters of the composite sleeper are reduced when damages occur. As a result, they reduce with damage severity (Sengsri et al., 2020b). The linear static solver is thus used in this study. The elastic modulus of the composite is set as 8.1 GPa with the density of 740 kg/m^3. In this model, the full length of the sleeper is 2.5 m. The length between two rigid supports (L_c) is 1.5 m.

Since the ISO standard (ISO 12856) has been drafted without sufficient clarification for test methods for center-section under negative load test, this study compares the ISO test arrangement with an existing test method complied with the Australian Standard: AS1085.14 (2003). It is noted that the Australian Standard: AS1085.14 (2003) has prescribed the test method for evaluating the bending moments for both railway sleepers and bearers. Although the most critical loading conditions on the track systems are related to wheel impacts, the current design procedure takes the dynamic effects into account by using a dynamic load factor and treats the wheel burden as a quasi-static load (Remennikov and Kaewunruen, 2007). In practice, the wheel load generally imparts the positive bending moment at the railseat whilst providing the negative bending moment at mid span of the railway sleepers. To obtain comparable insights into a test method for the center section under a negative load test, this study considers four different load arrangements in accordance with (i) draft ISO standard provision, (ii) Australian standard provision, (iii) simulated ballast support as a uniform distributed load, and (iv) freshly tamped ballast condition simulated by a partial distributed load (illustrated in **Table 1**). It should be noted that the negative reference test load ($F_{C,N}$) at the center section of the sleeper is chosen to be 100 kN for benchmarking purposes. This could imply that a rail seat force is 50 kN.

Firstly, according to the ISO standard provision, two-point loads (50 kN each) are applied with the distance of $L_c/3$ (500 mm in this case) in between the two-point loads. Secondly, the distance between two-point loads are reduced to 150 mm to comply with the Australian Standard. Thirdly, the uniform distributed load of 40 kN/m (equivalent to a total of 100 kN point load) is applied to reflect the full redistribution condition of ballast support (this condition represents poor track maintenance). However, in the railway industry, a proper ballast tamping and packing enable the partial support condition in practice. These activities can affect the flexural response of railway sleepers subjected to a spectrum of ballast stiffnesses including the asymmetrical ballast condition (Kaewunruen and Remennikov, 2007a,b, 2009; Shokrieh and Rahmat, 2007; Kaewunruen et al., 2016) and thus the uniform distributed load at mid-span is removed by the length of $L_c/3$ in the last case to reflect this condition (as recommended by AS1085.14). The comparative results presented in **Table 1** include deflected shape, maximum deflection at mid span, Shear Force Diagram (SFD) and Bending Moment Diagram (BMD).

DISCUSSION

The finite element analyses exhibit critical static effects stemmed from a variety of boundary conditions (representing test methods and ballast conditions). The effects of support conditions together with ballast conditions on the static flexural behaviors of composite sleepers are highlighted for comparison. Under the conditions specified by standards (ISO 12856 and AS1085.14), the results clearly show that the bending moment resultants are affected by the spacing between load arms ($F_{c,n}/2$). The ISO standard test method tends to yield a lesser bending moment by 35%, implying that component testing by AS1085.14 method is more efficient. In addition, there was a myth that the standard test methods could offer a situation close to *in situ* ballasted conditions. When considering the deflected shapes, it is evident that none of standardized test methods can completely mimic *in situ* behaviors. This new finding is aligned well with other studies (Reiff et al., 2007; McHenry et al., 2008; Davis et al., 2009; Tangtragulwong et al., 2011; Kaewunruen et al., 2018; McHenry and Gao, 2018; Qian et al., 2019). When considering the purpose of performance benchmarking, it is apparent that the Australian test setup condition (AS1085.14) can better represent the hogging deformations at the mid span than the test provision of ISO standard (ISO 12856). The insight into the bending moment resultants is very critical for track engineers and test engineers, who should be aware that the results obtained from standard test methods should be interpreted with cautions.

Composite materials have recently gained significant attention for applications in railway industry. In recent practice, composite sleepers and bearers have been used for bespoke replacements of aged timber components in critical areas such as switches and crossings, bridge transom sleepers, and special locations with either stiffness or clearance constraints. A new ISO standard has been drafted to accommodate the need to carry out standardized tests to benchmark the performance of polymeric composite sleepers and bearers. This study highlights the test specifications in order to illustrate the profound insight into the test methods for polymeric composite sleepers in comparison with *in situ* conditions in real life situations. This study explores the effectiveness of the provision in the current design code for bending test methods under various support conditions. The results clearly demonstrate that the test methods cannot fully represent *in situ* track conditions.

AUTHOR CONTRIBUTIONS

SK, CN, and PS developed the concept and validated the work. MI advised on ISO standard matter. All authors contributed to the article and approved the submitted version.

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Quantification of the Effect of Train Type on Concrete Sleeper Ballast Pressure Using a Support Condition Back-Calculator

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Monitoring ballast support condition and improving current sub-structure and ballast maintenance strategies is critical to ensuring safe and efficient railroad operations. Researchers at the University of Illinois at Urbana-Champaign (Illinois) have developed a ballast support condition back-calculator, a non-destructive instrumentation method and corresponding analysis tool that quantifies ballast pressure distributions under concrete sleepers without interrupting revenue service train operations. This laboratory-validated non-intrusive method uses concrete sleeper bending moment profile and rail seat loads as inputs to back-calculate the reaction distribution using a Simulated Annealing optimization algorithm that incorporates Pareto Distribution as the random variable generator. In order to further understand in-service ballast support conditions, concrete surface strain gauges were installed on concrete sleepers at a revenue service field site to measure strains that could subsequently be converted into bending moments. This site is on a shared use rail corridor with traffic ranging from high speed passenger to heavy axle load (HAL) freight trains. Rail-mounted strain gauges were used to measure strains that were used to calculate the vertical wheel-rail loads to approximate rail seat loads. This paper quantifies the ballast pressure distributions beneath concrete sleepers under different types of rolling stock and evaluates how ballast support condition changes as a function of accumulated tonnage. A wide range of loads were observed at the field site, ranging from 4 to 35 kips (18–156 kN). Corresponding ballast pressures ranged from 14 to 175 psi (97–1,207 kPa), with sleeper-ballast contact area corresponding to 60% of the bottom of the sleeper area. The accumulation of 12.24 million gross tons (MGT) (12.44 million tons) did not generate a quantifiable change in ballast pressure values nor did it generate a change in the ballast support condition. The research results presented in this paper demonstrate the potential of the back-calculator to provide a stand-alone non-invasive method to quantify ballast support conditions, sleeper health, and sleeper bearing stress. Back calculator data will aid the rail industry in optimizing tamping cycles, enhancing safety, and developing more representative concrete sleeper flexural designs based on actual support conditions.

Keywords: substructure, condition monitoring, non-destructive, support condition, field instrumentation, smart sleeper, ballast pressure

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INTRODUCTION

The fourth industrial revolution, defined as the current trend of automation and data exchange in manufacturing technologies (Qian et al., 2019), has brought significant change to many sectors of today's economy. As such, the railroad industry has recently experienced many changes and improvements, especially through the adoption of technology to increase track capacity, improve safety, and optimize maintenance processes. Change is achieved through improved designs, condition inspection, and monitoring and/or maintenance optimization.

Distributed motive power, Positive Train Control (PTC) (Resor et al., 2005), Automatic Train Control (ATC) (Kim et al., 2015), and self-driving cars (Bruner, 2018) are examples of implementing technology to improve safety and efficiency of transportation operations. And while wheel impact load detectors (WILDs) (Van Dyk, 2014) and hot bearing detectors (Tarawneh et al., 2020) have been around for decades, there is increased interest in analyzing data from these systems to develop predictive maintenance strategies for the rolling stock. Autonomous track geometry measurement systems (ATGMS) (Van Dyk, 2014; Saadat et al., 2018), unmanned aerial vehicles (UAVs) (Baniæ et al., 2019), and machine vision and laser-based inspection systems (Ye et al., 2019; Fox-Ivey et al., 2020) are being developed and deployed to provide actionable information about the overall state of the track's health (Stuart et al., 2012; Saadat et al., 2014). Despite these encouraging advancements, more research is needed to develop and implement condition-based track maintenance strategies for individual components that make up the track structure. Improving both component-level and overall track health can improve vehicle ride quality, reduce track damage through the reduction of dynamic loads, extend maintenance intervals, and make rail transport more economical and competitive (Selig, 1994).

When considering the inspection and monitoring systems, it should be observed that many of these are not continuously acquiring data as a function of time. Further, though there are technologies that have been deployed to quantify track support [e.g., ground penetrating radar (GPR) (Artagan et al., 2020) and matrix based tactile surface sensors (MBTSS) (McHenry et al., 2015), and pressure cells (Xiao et al., 2020)], these technologies typically disturb either train traffic or the *in situ* track conditions during installation. For example, GPR inspections are performed at fixed intervals and MBTSS require jacking the rail and sleepers during installation of the sensors (McHenry et al., 2015), generating changes that can alter the final results by way of the observer effect (Tanathong et al., 2017; Rose et al., 2018). Without an automated and systematic monitoring system, railroad track infrastructure owners lack wholistic and cost-efficient options for optimization of maintenance operations (Qian et al., 2019). Therefore, there remains an opportunity to continually monitor the track condition without needing to disrupt the track.

Given ballasted track is the most prevalent type of railroad track throughout the world (Hay, 1982; Köllõ et al., 2015), the research discussed in this paper is focused on development and deployment of a method to continuously assess its condition. Ballast is a critical track component that is located between, below, and around the sleeper (Hay, 1982; Kerr, 2003). Ballast support conditions are known to substantially influence concrete crosstie flexural response (Kaewunruen and Remennikov, 2009; Kaewunruen et al., 2016; Bastos et al., 2017; Canga Ruiz, 2018). Along with bearing and distributing the load from the sleepers to the substructure, ballast also facilitates the drainage of water, keeps vegetation from interfering with the track structure, and provides lateral stability to hold the track in place during the passage of trains and mitigating movement during a reasonable range of longitudinal rail stress changes (Solomon, 2001).

Researchers at the University of Illinois at Urbana-Champaign (Illinois) developed a novel, non-intrusive technique to accurately and continuously measure the ballast support condition immediately below the sleepers. The ballast support condition back-calculator (hereafter referred to as the "back-calculator") analyzes concrete sleeper flexural data recorded under revenue service traffic to indirectly quantify both the ballast support condition beneath concrete sleepers and the pressure at the ballast-sleeper interface (Qian et al., 2019). This paper leverages initial progress on the development of a back calculator to expand its functionality as a "smart sleeper" that can quantify sleeper flexural demands, ballast pressures, and support. The data, when properly transformed into actionable information, will lead to improved railroad maintenance planning and railroad track design. The specific focus of this paper will be the quantification of ballast pressures of concrete sleepers installed on a shared corridor with mixed intercity passenger trains and heavy axle load (HAL) freight traffic.

BACKGROUND

The back-calculator is an indirect technique to estimate a sleeper's ballast support condition using rail seat loads and bending moments captured at discrete locations along the sleeper. Based on force equilibrium and the basic principles of statics, for a two-dimensional subject, only one combination of reaction forces (i.e., one support condition) can generate a given moment profile under a set of applied loads. Considering this principle, the concrete sleeper is simplified as a two-dimensional beam, and its ballast support condition can be back-calculated from the bending moments along the concrete sleeper and the corresponding rail seat loads, both of which can be quantified during experimentation (Qian et al., 2019).

Concrete surface strain gauges applied using a method described by Edwards et al. (2017) have successfully quantified the bending strains experienced by concrete sleepers in both laboratory and revenue service field experiments (Quirós-Orozco et al., 2018; Edwards et al., 2019; Canga Ruiz et al., 2020). Bending strains can then be converted into bending moments when laboratory-derived calibration factors are applied using the method described by Edwards et al. (2017). Rail seat loads are computed directly via locally installed strain gauges or indirectly from nearby Wheel Impact Load Detector (WILD) sites using a modified version of the recommended equation

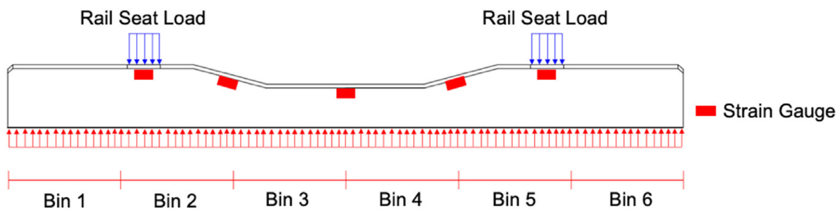

FIGURE 1 | Simplified two-dimensional sleeper model (Qian et al., 2019).

given in the American Railway Engineering and Maintenance-of-Way Association [AREMA] (2017) Manual for Railway Engineering (MRE).

The simplified two-dimensional sleeper model used in this research is shown in **Figure 1**. The model describes a typical North American 102 in (260 cm) long concrete sleepers and is divided into six discrete bins that are 17 in. (43 cm) in length. Each bin contains a percentage of the total ballast reaction force, and the reaction force within each bin was assumed to be uniformly distributed within the bin. The ballast reaction forces are converted into ballast pressures by dividing the forces by the area of the bin [i.e., bin length multiplied by sleeper width of 10.3 in. (26 cm)]. A total of five concrete surface strain gauges were installed longitudinally along the top chamfer of the sleepers. No formal optimization of gauge locations was undertaken. The two rail seat and one center gauge locations were selected to answer broader questions about the magnitude of sleeper rail seat and center bending moments. The intermediate gauges were centered between these to capture additional bending moment profile data. Since the sleeper is not restrained at the two ends under any feasible ballast support condition, the bending moments at the two ends are zero. Consequently, when combining these end values with five measured moments obtained from strain gauges, the instrumented sleeper can output a total of seven known bending moments. The rail seat loads were assumed to be uniformly distributed over the width of each of the 6 in. (15 cm) rail seats (Qian et al., 2019).

A total of nine back-calculator inputs, comprised of seven known bending moments and two approximated rail seat loads are used in the model. Two boundary conditions are also included. First, based on force equilibrium, the total ballast reaction force should equal the total rail seat loads. This dictates that the forces in all six bins should sum to approximately 100%. Second, the value of each bin should not be less than zero, as it is unrealistic to have a negative reaction force for ballast (e.g., ballast provides no tensile capacity).

Once rail seat load magnitudes are input into the back-calculator, an optimization process generates combinations of reaction forces that satisfy the two boundary conditions. For each reaction force combination, the back-calculator generates the bending moment profile of the sleeper based on the rail seat loads and compares it to the actual input bending moment profile. The optimization process terminates when the difference between the calculated and actual bending moment profiles reached its minimum, and the reaction force combination that generated the calculated bending moment profile became the resultant support condition. The optimization process is summarized in **Figure 2**.

In the optimization process, Simulated Annealing and Bi-polar Pareto Distribution were used as the optimization algorithm and the random variable generator. By simultaneously implementing the two methods, an improved solution could be generated in less time (Englander and Englander, 2014), and convergence on local optima was avoided (Kirkpatrick et al., 1983). For a given set of inputs, the maximum computational time was approximately 1 min, which was deemed reasonable for the application.

FIELD EXPERIMENTATION

To quantify field ballast support conditions under revenue service traffic using the back-calculator, field experimentation was conducted on a double track portion of Amtrak's Northeast Corridor (NEC) in Edgewood, Maryland, United States. The field site was located on tangent track constructed of concrete sleepers spaced 24 in. (61 cm) on center, at a location that sees the passage of approximately 55 regional, intercity, and high-speed passenger trains, commuter rail trains, and a variety of HAL freight trains each weekday (on the track instrumented). In total, the route accumulated 42.6 million gross tons (MGT) in the year of 2017 (with 18.5 MGT on the track instrumented). The location and diversity of traffic provided the opportunity to quantify the effect of both tonnage and traffic type on sleeper support conditions and ballast pressure magnitude beneath concrete sleepers. The mixed traffic at this location was primarily comprised of four types of trains: ACELA passenger trains, Intercity Amtrak trains operating with Amfleet passenger coaches, Maryland Area Regional Commuter (MARC) commuter trains pulled by diesel-electric locomotives, and Class I HAL Freight Trains with cars having a variety of maximum Gross Rail Loads (GRLs).

In addition to the strain gauge instrumentation, three thermocouples were installed to capture ambient temperature as well as the temperature at the top and bottom of the sleeper. Rail mounted strain gauges were used to quantify the wheel loads, and these data were obtained from a nearby WILD site. The nominal wheel load for each axle (obtained from WILD data) was used to approximate the rail seat load by using a modified version of the recommended equation given in the American Railway Engineering and Maintenance-of-Way Association [AREMA] (2017). A value of zero (0) for the Impact Factor (IF) was selected given the input wheel loads used were actual loads that

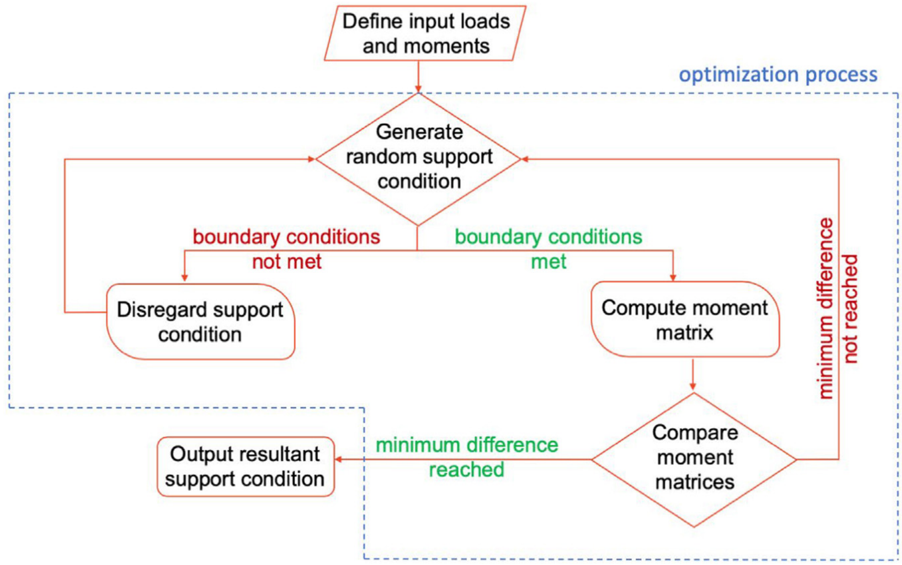

FIGURE 2 | Flowchart for ballast support condition assessment system (Qian et al., 2019).

incorporated any dynamic influence. The Distribution Factor (DF) of 0.505 was obtained from AREMA MRE **Figure 30-4-1** based on a concrete sleeper spacing of 24 in (61 cm) on center. These approximated rail seat loads were used as the input for the support condition back-calculator.

Data were collected from more than 2,550 train passes between January and August 2017. While more than 23,000 axles were analyzed by the back-calculator, or approximately 5,750 axles per train type, the results were filtered based on two parameters (1) the maximum Mean Squared Error (MSE) resulting from the optimization process and (2) temperature differential between the top and the bottom of the sleeper. Filtering resulted in a final count of 400 trains that met the aforementioned specifications that were established to isolate the specific variables of interest. The trains varied in length between 28 and 500 axles. The number of axle passes after filtering provides a 95% confidence level that the results are an accurate representation of the broader set of data.

The maximum MSE value used for final analysis was 10 kip-in (1.13 kN-m). This represents an allowance of 5 kip-in (0.56 kN-m), positive or negative, for every strain gauge measurement. This corresponded to approximately 10% of the average strain gauge reading. Further, given temperature induced strain has been shown to exert significant influence on concrete sleepers bending results (Wolf et al., 2016) it was also selected as a control parameter. More specifically, prior research found that a linear relation between temperature gradient and flexural behavior of concrete sleepers, where each variation of 1-degree Fahrenheit (0.56-degree Celsius) between sleeper top and bottom can lead to a bending moment variation of approximately 1 kip-in (0.11 kN-m) (Canga Ruiz et al., 2019). Therefore, data selected for final inclusion in the analysis had temperature gradients less than ±1-degree Fahrenheit (0.56-degree Celsius). Filtering was undertaken given the focus of this research was evaluation of the support conditions and pressures under the operation of different types of rolling stock, and the effects of thermal gradient and subsequent sleeper bending were thus isolated. It should be noted that the range of actual pressures and support condition configurations would be expected to exceed that of what is demonstrated in this paper, due to the effect of thermal gradient (Canga Ruiz et al., 2019).

Existing Ballast Pressure Limit States

The AREMA MRE recommends a maximum allowable ballast pressure of 85 psi (586 kPa) under concrete sleepers for track constructed with high quality, abrasion resistant ballast (American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017). This value is inclusive of a safety factor to prevent bearing capacity failure or undue creep under the loaded area (American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017). Therefore, this value is used for a pressure limit state to correlate the back-calculator results and aid the evaluation of the pressures obtained through the field experimentation.

RESULTS

The following sections provide the results from field experimentation conducted on Amtrak. The rail seat loads, ballast pressures, and support conditions are quantified and compared both quantitatively and qualitatively. After filtering, the data were separated into 2 temporal categories—Quarter 1 (Qtr. 1) and Quarter 3 (Qtr. 3)—to analyze how the increase in MGT with the passing of time affected the ballast pressures. Qtr. 1 data was acquired in January and February 2017, while Qtr. 3 data were obtained in August 2017 after 12.2 MGT (12.44 million tons) of accumulated tonnage.

Rail Seat Loads

To characterize the demands on the sleeper, rail seat loads from each train type were calculated. **Table 1** summarizes the median and 95th percentile rail seat loads for each train type. **Table 1** is divided between the four types of trains and each of these categories is subdivided into locomotives and rail cars. Further, freight trains are sub-divided as loaded and empty to better quantify the effect of specific traffic, especially under the homogeneity of unit train operations.

Data in **Table 1** demonstrate the wide range [5–23 kips (22–102 kN)] of loads observed at the field site. The lowest rail seat load values were generated by Empty Freight Cars and the highest values were generated by Freight Locomotives and Loaded Freight Cars.

Qualitative Assessment of Sleeper Support Condition

Figure 3 provides qualitative outputs from the back-calculator for an ACELA Power Car, an ACELA Passenger Coach, and an Empty Freight Car. **Figure 4** shows both the magnitude and location of the rail seat loads as well as the ballast reaction forces on the sleeper.

Processed results from the back calculator indicate a lack of center support (Qian et al., 2019). This type of support is often associated with newly tamped track (Bastos, 2018) and could lead to accelerated deterioration of the ballast directly below the rail seat If loads exceed the strength of the ballast (Branson et al., 2019). Good support under the rail seat is often viewed as a "starting" support condition that is likely to transition to center bound support as a function of time and tonnage. Further, this support condition leads to increased rail seat positive bending moments and the corresponding possibility of rail seat positive cracks. This support condition differs from what is assumed by American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017, in that it is assumed there is uniform support from the end of the sleeper through the gauge side of the rail seat, whereas at Euro Norm (EN) (European Committee for Standardization, 2009) and the Australian Standard (AS) (Standards Australia, 2003) this support condition is considered as a newly tamped support condition, as summarized by You et al. (2017).

TABLE 1 | Median and 95th percentile rail seat loads for each type of train.

Type of train/rail car	Rail seat load (kip)			
	Median		95th percentile	
	Qtr. 1	Qtr. 3	Qtr. 1	Qtr. 3
ACELA power car	16	16	17	17
ACELA passenger coach	12	12	13	13
Amtrak intercity locomotive	17	19	19	19
Amfleet passenger coach	10	10	12	12
MARC locomotive	16	18	19	21
MARC passenger coach	10	10	11	11
Freight locomotive	20	20	23	23
Loaded freight car	20	20	23	22
Empty freight car	5.1	4.8	8.4	7.4

Quantitative Assessment of Ballast-Sleeper Interface Pressure

The relationship between rail seat load and ballast-sleeper pressure has been the subject of prior investigation. Median collected rail seat loads varied from 5.1 kips (22.7 kN) to 20.9 kips (93 kN) providing the opportunity to investigate the effect of load on pressure and compare to it to different approaches. First, we will compare it to Talbot's approach, which indicates a direct positive linear relationship (Talbot, 1980). The second comparison is going to be related to the Eisenmann's approach of how to calculate pressures at the tie-ballast interface (Eisenmann, 2004a,b; Giannakos, 2014). Therefore, the maximum ballast pressures directly below the sleeper were plotted against these rail seat loads and are presented in **Figure 4** along with the expected sleeper-ballast pressure predicted by Talbot (1980).

The data indicates that the pressure is linear as a function of rail seat load (R^2 = 0.998) which is in good agreement with both Talbot (1980) and Eisenmann (2004a,b). However, the measured magnitude is uniformly larger than Talbot. This uniform differential is due to Talbot's assumption of 67% of the bottom of the sleeper being engaged in load transfer, whereas the sleeper that is subject of this paper engages only 60% of the bearing area. Regarding Eisenmann's approach, when assuming that 89% of the bottom of the sleeper is being engaged in load transfer, it closely approximates to the field results obtained in this research. The 85 psi (586 kPa) AREMA recommended limit is exceeded when rail seat loads are greater than approximately 17 kips (76 kN). As a reference, when this same rail seat load is applied to a sleeper with a uniform support condition, the average ballast pressure is equal to approximately 30 psi (207 kPa), well below the value in American Railway Engineering and Maintenance-of-Way Association [AREMA] (2017). This indicates that a change in support conditions can lead to an 183% increase in the ballast pressure.

When reviewing international concrete sleeper flexural design recommendations, we find some noticeable differences. The current AREMA method for concrete sleeper flexural analysis considers a factored approach dependent on sleeper length, sleeper spacing, annual tonnage, and train speed, assuming a uniform ballast reaction along the sleeper (American Railway Engineering and Maintenance-of-Way Association [AREMA], 2017). The current AS method for sleeper flexural analysis is dependent on sleeper length, sleeper spacing, and axle load (Standards Australia, 2003). EN 13230-1 defers the analysis of design bending moments to UIC 713R (European Committee for Standardization, 2009). The UIC 713R method is dependent on sleeper length, sleeper spacing, axle load, rail pad attenuation, and train speed, providing a pair of safety factors, one to account for "variation in sleeper reaction due to support faults" and another to account for "irregularity in the support along the sleeper" (International Union of Railways, 2004). AS 1085.14 and AREMA both differ from UIC 713R by excluding reductions for rail pad attenuation or safety factors to account

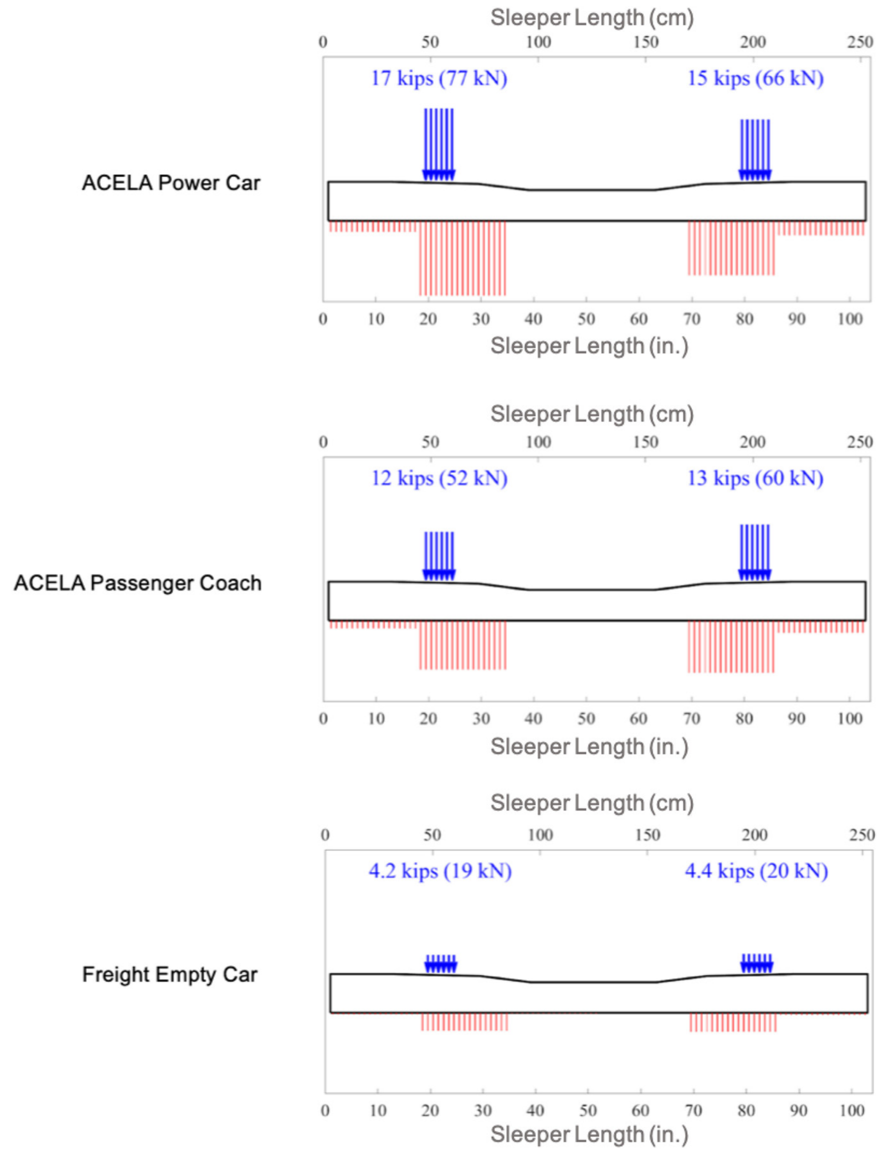

FIGURE 3 | Ballast support condition with the passing of an ACELA Power Car, an ACELA Passenger Coach and a Freight Empty Car.

for support irregularities or voids (Wolf et al., 2015). Given how a change in ballast support condition can further increase concrete stresses within a sleeper, quantifying the actual support can improve the accuracy of the design recommended by both AREMA and AS.

To quantify the overall demand on the ballast and sub-structure, ballast pressure data were plotted in a cumulative distribution function (CDF) (**Figure 5**). The AREMA maximum allowable surface stress of 85 psi (586 kPa) is shown using a vertical dashed red line. Data from all of the bins analyzed during this study are shown, as well as the individual data from the rail seats, center, and end of the sleeper that were included to further investigate the distribution of support and its influence on ballast pressure along the sleeper bottom (**Figure 5**).

When considering data from all bins, approximately 4% of recorded values exceed the AREMA allowable ballast pressure. However, when analyzing only data from bins immediately beneath the rail seats, this value increases to 10%. This supports the hypothesis that this support condition would lead to increased demands at the rail seat, thus creating the potential for accelerated ballast deterioration at this location. When analyzing the pressure at both the ends and at the center of the sleeper, it is possible to determine that these bins are under comparatively little stress—well below the AREMA limit.

Effect of Traffic Type on Ballast Pressure

Given the variety of traffic operating on Amtrak's NEC, pressures were quantified under a variety of rail seat loads (**Figure 4**), traceable by type of rolling stock. **Figure 6** shows the median

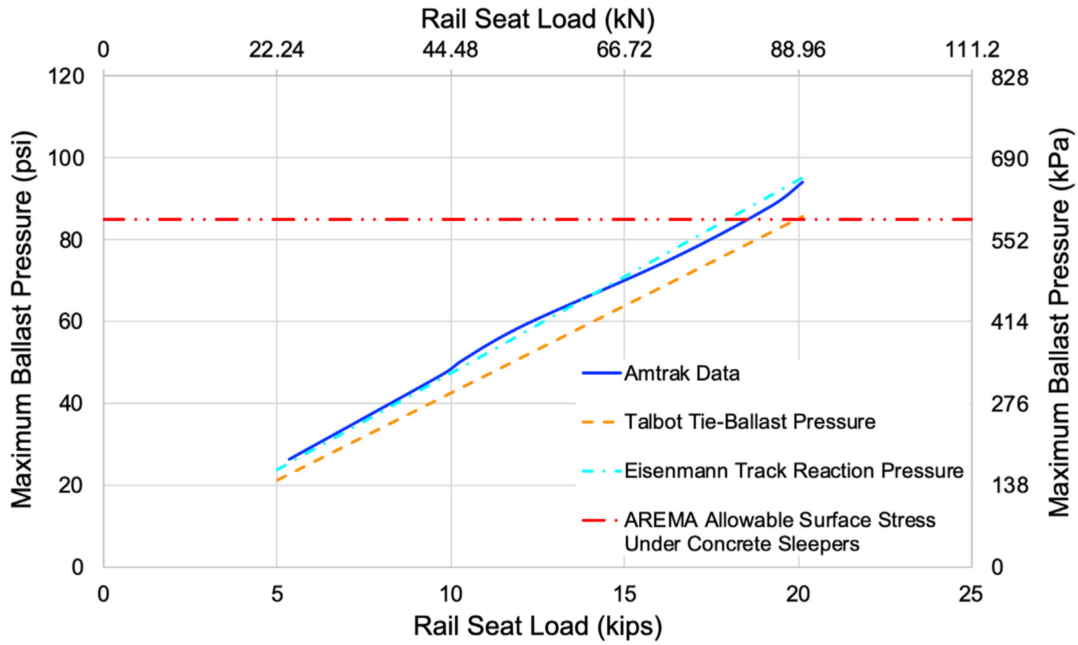

FIGURE 4 | Relationship between rail seat load and maximum ballast pressure.

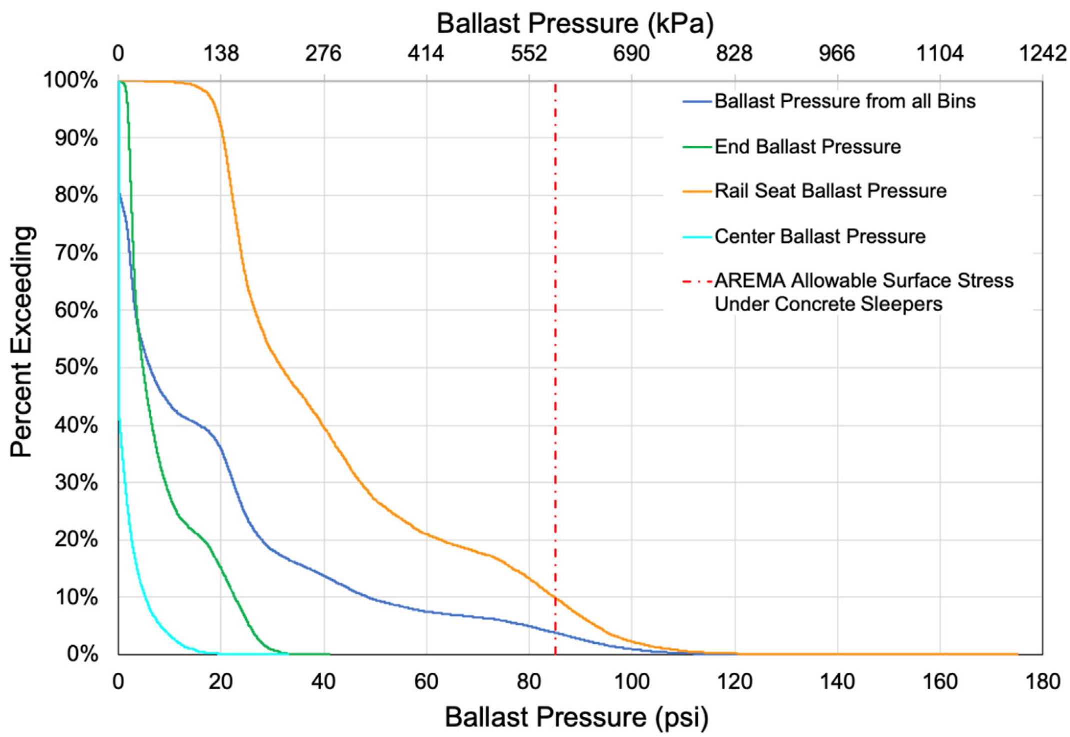

FIGURE 5 | Cumulative distributions of ballast pressures for various bins combinations.

and 95th percentile ballast pressures at each bin for all rolling stock classifications, separating the data into the previously stated classification of Qtr. 1 and Qtr. 3 (shown diagonally within each bin).

The data provides clear visual representation of the increased magnitude of ballast pressures directly below the rail seats for all vehicle types and the lack of support at the center and ends of the sleeper. While rail seat pressures are higher, AREMA

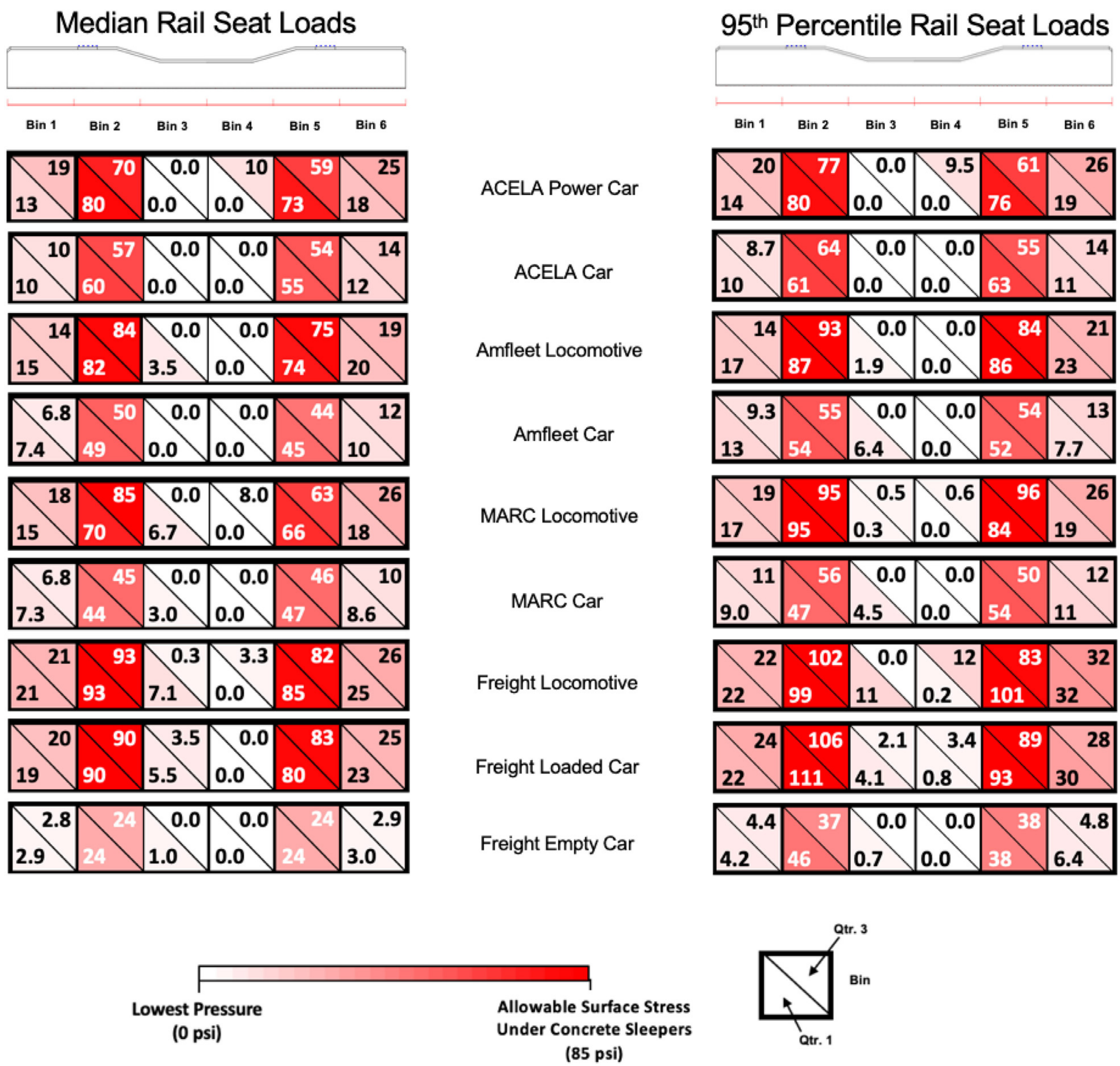

FIGURE 6 | Ballast pressure distribution.

allowable surface pressure is only exceeded under the Amtrak Intercity Locomotive, MARC Locomotive, Freight Locomotive, and Loaded Freight Car. This is reasonable given their nominal wheel load would produce rail seat loads that exceed 17.5 kips (78 kN). Therefore, if predicting ballast deterioration at this discrete location, one would expect deterioration to primarily occur under these vehicles and not the passenger coaches or empty freight cars. Given the disparity in pressure demand at the sleeper-ballast interface, it may be possible to quantify the amount of deterioration the increased pressures produce. From this, mechanistic-empirical (M-E) analysis and design could be pursued to ultimately develop a concept for rail engineering that is analogous to the equivalent single axle load (ESAL) highway loading concept developed by American Association of State Highway Official (AASHTO), therefore establishing the relationship between demand and damage (American Association of State Highway and Transportation Officials [AASHTO], 1993).

The data also indicate that pressure is non-linear as a function of increased rail seat loads, confirming earlier work by Quirós-Orozco et al. (2018). At lower rail seat loads (Empty Freight Car), Bins 1 and 5 exhibit pressures that are approximately 10% of the rail seat pressures as measured by Bins 2 and 4. However, as rail seat loads increase (Loaded Freight car), pressures in Bins 1 and 5 increases at a greater rate than the rail seats; in excess of 20%. Therefore, while **Figure 6** indicates a positive linear relationship

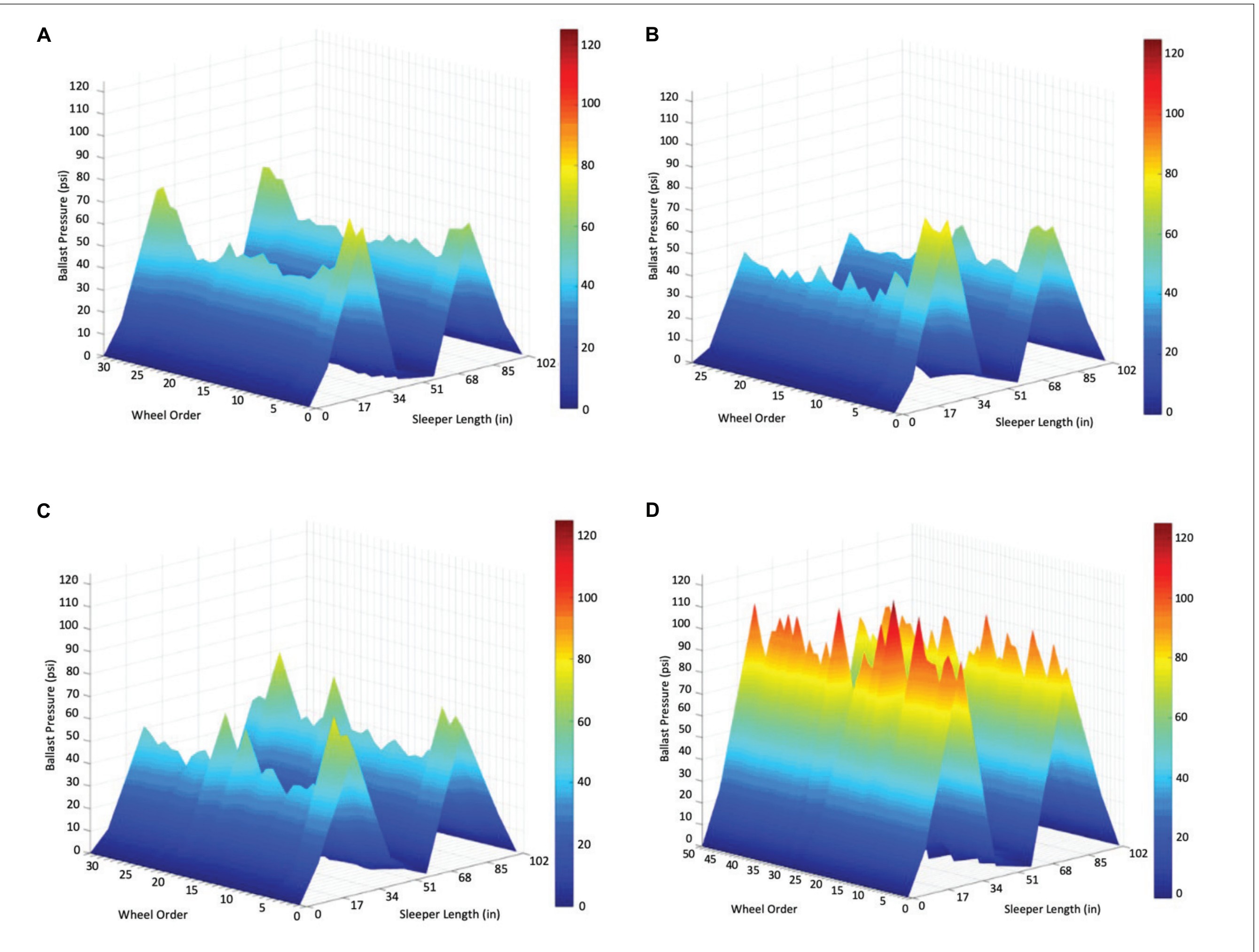

FIGURE 7 | Ballast pressure distribution for representative train passes from various types of rolling stock: **(A)** ACELA, **(B)** Amfleet, **(C)** MARC, and **(D)** Freight Locomotives.

between rail seat load and maximum pressure, there is non-linearity in how the pressures are distributed along the bottom of the sleeper. It is also possible to identify differences between the values obtained within Bins 2 and 4, with both bins being located directly beneath the rail seats (**Figure 6**). This can be explained by the influence of uneven rail seat loads observed in the field (Edwards et al., 2018).

Additionally, **Figure 6** indicates support conditions remained largely constant after the accumulation of 12.24 MGT over the course of this investigation. An analysis of variance (ANOVA) was conducted to compare the data, establishing H_0: Quarter 3 ballast pressures are equal to the Quarter 1 ballast pressures and H_1: At least six Quarter 3 ballast pressures are different than Quarter 1 ballast pressures ($\alpha = 0.05$). The p-value obtained was 0.209, meaning that there is insufficient evidence to reject the null hypothesis that the population means are all equal. Thus, the support condition remains the same, and there isn't a significant change in ballast pressure values with the accumulated tonnage. This highlights one of the possible uses of the back-calculator as a potential monitoring tool to predict ballast degradation and better optimize maintenance scheduling.

Ballast Pressure Variation Within a Train Pass

To further quantify the distribution of pressures along the sleeper, and throughout the passage of a train, the pressures under each axle were plotted for different train types (**Figure 7**). As alluded to previously, quantifying the frequency and location of pressures will lead to improved ballast deterioration models and improved track designs—feeding into burgeoning M-E analysis and design practices (Quirós-Orozco, 2018).

The locomotives and power cars are clearly visible within the axle distribution and are more defined than passenger coaches in figures (a), (b), and (c). More specifically, in **Figure 7A** it is possible to observe the ACELA Power Cars at both ends of the train are applying approximately 30 psi (207 kPa) greater pressures to the ballast than the passenger cars. Unlike the passenger equipment, **Figure 7D** indicates that the pressures generated by HAL freight trains are similar throughout the length of the train, and in this instance, are significantly greater in magnitude than any of the passenger pressures. More specifically, when comparing **Figures 7B–D** the maximum pressure of the passenger car of 40 psi (276 kPa) is only 35% of the maximum freight car pressure of approximately 110 psi (758 kPa).

CONCLUSION

The use of surface-mounted strain gauges on concrete sleepers has been shown to provide reliable and accurate results to quantify stresses, moments, and pressures, in a non-intrusive and non-destructive manner. The back-calculator was applied to shared corridor field data, and demonstrated efficacy as a reliable monitoring tool to quantify the ballast support condition at the sleeper-ballast interface at the analyzed shared corridor. Some of the specific conclusions that can be drawn from its use are:

- There is a wide range of loads experienced on Amtrak's NEC, ranging from approximately 4 to 35 kips (18–156 kN) with corresponding ballast pressures ranging from 14 to 175 psi (97–1,207 kPa), being the lowest rail seat load values generated by Freight Empty Cars and the highest vales generated by the Freight Locomotive and the Freight Loaded Cars, with a difference of more than a factor of 8.
- Data indicate that the relationship between pressure and rail seat load is linear (R^2 = 0.998), where the sleeper-ballast contact area for the subject sleeper in this paper corresponding to 60%.
- The 85 psi (586 kPa) AREMA recommended maximum ballast pressure limit is exceeded when rail seat loads are greater than approximately 17 kips (76 kN) given a lack of center support condition.
- When considering data from all bins, approximately 4% of recorded values exceed the AREMA MRE. However, when analyzing only the data from the bins immediate beneath the rail seats, this value increases to 10%. When analyzing the pressure at both the ends and at the center of the sleeper, it is possible to determine that these bins are under comparatively little stress, and well below the AREMA allowable ballast pressure limit. This supports the hypothesis that this support condition would lead to increased demands at the rail seat, thus creating the potential for accelerated ballast deterioration at this location.

The accumulation of 12.24 MGT did not lead to a significant (α = 0.05) change in ballast pressure values nor did it change the ballast support condition. This highlights one of the possible uses of the back-calculator as a potential monitoring tool to predict ballast degradation and better optimize maintenance scheduling.

This study showed the effect of different types of trains on the pressure beneath a single concrete sleeper with an initial support state that was representative of rail seat support. In the future, the authors encourage widespread use of the back-calculator on a larger sample size of sleepers (including adjacent sleepers) to obtain different initial support states in conjunction with the use of use of smart sleepers. The resulting data will helps quantify the frequency and location of excessive pressures on sleepers, facilitating mapping of said pressures to deterioration rates. This in turn will lead to improved ballast deterioration models and improved track designs—feeding into broader M-E analysis and design practices.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

MD and JE: study conception and design. MD and CS: data collection. MD, CS, and JE: 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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OPINION
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5G Intelligence Underpinning Railway Safety in the COVID-19 Era

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INTRODUCTION

The COVID-19 pandemic has impacted all global transportation systems and the rail industry has been no exception. Indeed, the rail industry has been severely affected (Metropolitan Transportation Authority, 2020), as passengers tend to stay away from the trains. Moreover, because of the COVID-19 lockdown, there have been changes in passenger behavior. According to a United Kingdom-wide survey commissioned by the Department for Transport and undertaken in May–June 2020, there has been a significant drop in traveling and a loss of confidence in traveling by train (Marshall et al., 2020).

Even with the rail business facing this low demand, they are still required to offer services regulated by enhanced health and safety standards to protect the public, passengers, and the workforce from possible infection. However, due to the pandemic, train operators have faced unique difficulties in meeting these regulatory requirements (Stephanie, 2020). As a response to the challenges faced, artificial intelligence (AI) technology has been suggested as one possible tool to help address the current and future situations such as a pandemic. Of course, AI has already been used in many areas of the rail industry, for example, in real-time, predictive, decision support, and here, it has proved to be a powerful tool. Now, in the case of COVID-19, innovative digital explications may contribute to dealing with social distancing and managing stations, crowds, and train occupancy, including customer apps, smart CCTV, and the big data for safety health services (International Union Railway-UIC, 2020). Moreover, big data can be beneficial in terms of risk assessment, supporting the decision-makers in real time, reducing human errors, predicting hazards, and raising safety and security efficiency while also reducing the cost. This method can be fully integrated into passenger data and business models (Alawad et al., 2019).

AI is a powerful tool, and it seems to have some useful features that could be employed in the fight against the COVID-19 pandemic. The AI applications have been seen in airports in thermal and vision imaging, and this control measure provides valuable data input for public health in identifying the possible afflicted people in crowds and detecting passengers who are not wearing masks. Also, AI-based computer vision has been used for social distancing measures and to detect suspicious individuals. Technologies such as AI applications and sensors with biometrics have a significant role in detecting fever and a temperature and diagnosing and tracking geographical induction spread and public health and safety monitoring.

This could also be applied in other public areas such as railway stations, including their platforms and entrance areas. Some ideas have been raised where AI can fight COVID-19 using early warnings and alerts, tracking, recognition, prediction, and social control (Naudé, 2020).

Furthermore, AI applications have been used in the field to detect and implement social distancing and wearing of facial coverings and to detect whether workers are wearing their personal protective equipment (PPE), such as helmets or gloves (Wykle and Van Hecke, 2020). In addition, it may even be possible to forecast the next epidemic from the COVID-19 history mobile network data.

In this article, it is discussed whether, in the context of COVID-19, the railway industry could employ new technology such as AI and related approaches (Internet of things (IoT), 5G, big data, and AI) for protecting and underpinning railway safety. Acknowledging already the solutions and potential measures that have been applied such as cleaning, disinfection, sanitization, redesign, physical and social distancing, relayout, ATP testing, or the air filtration and recycling air, we are attempting here to highlight the potential technology solutions in the industry for tackling COVID-19.

CCTV AND COVID-19

Detecting the possibly affected people is key to tackling the spread of COVID-19. In railway stations, this could be achieved with the help of CCTV cameras and other tools such as biometric screening using infrared systems. To achieve this, AI requires massive data to learn and predict, which are available as raw data in the field but need effort and structural strategies for gathering suitable data. The information can be captured through indicators or indices, which create the rules depending on the inputs. The necessary inputs can be collected from devices, such as sensor-based programming or CCTV, and the estimate can be calculated with AI methods and generated from servers.

In railway stations, CCTV is already playing a role in monitoring for security, safety, and health in the COVID-19 context. It has also been used for restrictive measures such as wearing masks and social distancing and can provide accurate accounts of the number of people in specific places. The image or video input is important raw data that can be analyzed via AI technology to predict the risks. This approach is increasingly driven by GPU computing developments with methods of machine and deep learning (ML–DL) applications (Alawad et al., 2020b).

In the United Kingdom, for safety and protecting human resources in the railway, some of these methods have already been implemented. Thermal cameras have been installed in critical locations of Network Rail. The body temperatures can be detected on entry to the site and the cameras can measure up to 30 people simultaneously (Thales Mobility Team, 2020). However, the temperature symptoms may not be sufficient in detecting COVID-19 and there is a shortage of customized cameras for the railway system. Nevertheless, these intelligent thermal imaging cameras provide reliable, accurate (±0.3°C) measures of COVID-19. The thermography smart cameras can detect the individual body temperature level without contact and give an alarm for a specific threshold. These systems can be integrated into a related control system such as a smart helmet (Mohammed et al., 2020) or glasses and algorithms of video analysis. They can be used in UAVs that can cover and investigate large crowds of people seen at the stations and the platforms (UIC Covid Task Force, 2020).

AI AND RAILWAY STATIONS

AI also has operational intelligence for managing, for example, overcrowding in the stations, which can control the spread and assist in reducing COVID-19 transmission. It is more imperative to control and prevent overcrowding risks quickly and in real time in places such as railway stations and platforms. In this context, the importance of prediction has been referred to and is now more pertinent than any time in the past as crowding has led to the spread of COVID-19 and thus affected the safety, security, and health concepts and strategies (Alawad et al., 2020a). Managing the crowd reflects the space between the passengers and provides a safe flow in the station's different points, such as platforms or the narrow sides, which is required to protect the passengers and staff from COVID-19 and other health and safety issues.

INTELLIGENT INTERNET OF THINGS AND 5G

The sensors can be wearable (on-body sensors), connected to a machine or device or asset and then connected to a network that provides information. After that, from this information, you can do advanced management and analytics, which is the concept of IoT that connects people and things. This requires high-speed data transmission, lower latency, high resolution, a more reliable connection, and real-time services and operation. 5G is beginning to expand across the world and there is a great deal of research being conducted regarding its viability and challenges in terms of regulation, battery drain on devices, coverage, the licensed band (Lu et al., 2019), security and privacy (Khan et al., 2020), and the cost of infrastructure and upgrading devices to be compatible with 5G. Still, 5G seems to be offering numerous opportunities and supports others, such as its coexistence with Wi-Fi 6 (Oughton et al., 2020), IoT, applications based on virtual reality, augmented reality with lower latency, higher capacity, high speed, and reliability (Ding and Janssen, 2018), and enhancing users' perceived quality of service/experience (Agiwal et al., 2016). Moreover, it provides higher data rates and enables technologies such as IoT and AI applications, improves railway environments by making them smart, uses advanced wireless access and connectivity, including operational, control, commercial, and both passenger and high-speed railway (HSR) communication requirements. Furthermore, 5G can support more devices with seamless mobility, offer higher bandwidths, use licensed and license-exempt spectrum, and provide widespread indoor and outdoor coverage and lower latency for end-users (Soldani, 2020). Additionally, these railway service improvements could encourage the public to choose the railway to travel, especially as it is a low-carbon transport and enables passengers to reduce their total carbon footprint.

It is expected that 5G and other advanced networks in the future will provide faster and faster connectivity and more capability with the growth of applications of IoT, AI, cloud, and edge computing.

Such applications lead to smart things, cities, retail, intelligent stations, and other smart applications. This intelligent monitoring connects hundreds of thousands of sensors, devices, people, and operations for gathering big data for

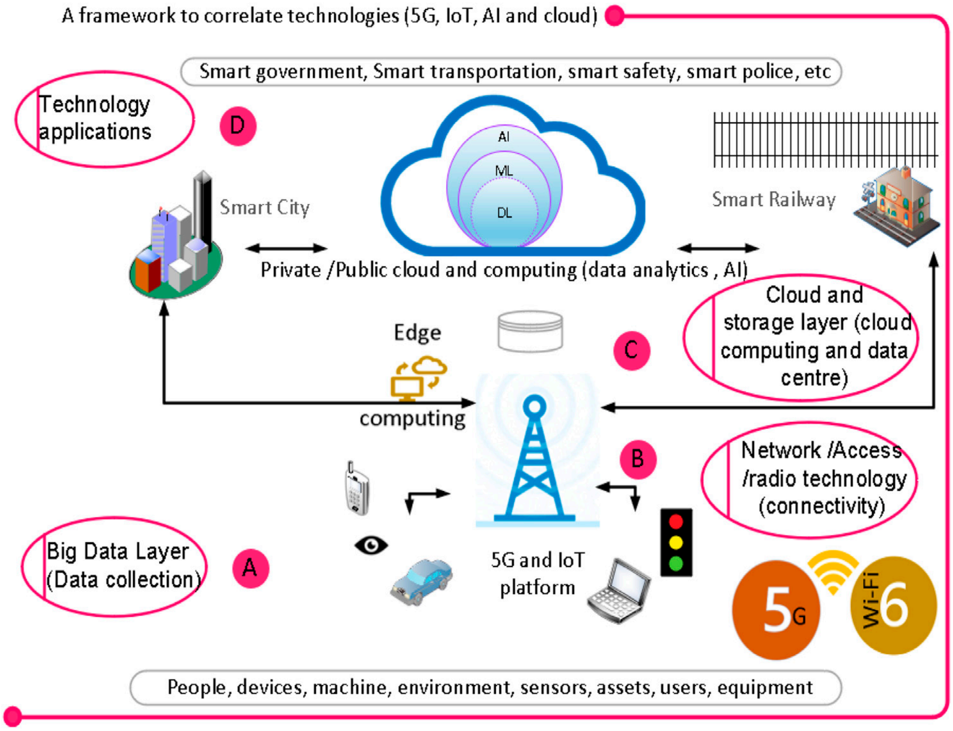

FIGURE 1 | Illustration of how the smart systems integrate the cloud, 5G, and IoT into the outlined health, safety, and security framework of the railway system.

predictive, analytical, control, health, safety, security, and autonomous applications via synchronization systems on 5G and the cloud (see **Figure 1**). This approach is an integration model and can be a contributor to the transportation business models of the future, such as the concepts of the door-to-door and Mobility-as-a-Service platform.

Globally, 5G or beyond (B5G or 6G) has been noted as a connectivity network approach aiding in effectively managing infectious diseases such as COVID-19, which has a faster bitrate, greater capacity and volume, reduced latency, and a large amount of IoT handling. In addition, it fulfills the connectivity criteria of machinery, remote control, driving operations, accessibility, real-time UHD image transmission via 5G-networked UAVs, quality inspection, device detection, and automatic identification via Unmanned 5G AGVs (Automatic Guided Vehicles).

5G applications have been deployed to cover COVID-19, for instance, to track passenger conditions in traffic centers, and 5G IT-based infrared temperature monitoring has already been used in a variety of cities (Shamim Hossain et al., 2020).

The integration of IoT with the cloud and AI in the public transportation locations such as railway stations and airports will generate a robust, broad range railway control environment for enhancing health, safety, and security. For instance, it can help track individuals who are diagnosed with COVID-19 who may be out and around the city, including the railway, and who may later become sick.

Network Rail in the United Kingdom supports the next generation of digital technology for smart infrastructure in coping with the expected growing demand, and a 5G and full-fiber broadband Trials Program has been conducted. This rail industry improvement of communication will reflect on many aspects, such as increased capability, flexibility, automation, and autonomy.

Moreover, it is expected that 5G will increase environment and asset sensing to improve the availability of actionable intelligence insight and increased predictability and reliability with high levels of safety and security (Rail Network, 2019).

DISCUSSION/CONCLUSIONS

Data availability, privacy, and security remain a challenge for applying AI in the railway industry. In addition, future investment in the infrastructure of rail will bring new technological transportation competitors such as autonomous vehicles or hyperloop trains and other technological inventions. This will force the redesign of strategic plans and may create some fear because of the future new technologies in the field, such as hydrogen passenger trains. Nonetheless, it is expected that after COVID-19, there will be an acceleration in the shift from air to rail in Europe and China because of climate awareness and because rail is healthier and less risky in relation to disease, all of which will improve the rail market (UBS, 2020).

The applications that have been used so far in AI are now playing a vital role in the fight against COVID-19, and the shortage of data has been acknowledged. Notably, the railway needs to be ready for this revolution of technology in terms of infrastructure such as the cloud, regulations and standards, communication systems, corporations, and skills. The AI applications and IoT need integration with the communication systems to comply with the high data rate for the railway system, thus improving the system to handle the tremendous rate of data such as HD video, which requires 5G as essential for upgrading to the 6G or combining 5G with Wi-Fi 6. Innovative technologies such as wireless sensors, IoT devices, and passenger apps are beneficial not only for cases of COVID-19 but also for making more effective decisions and enhancing security, safety, and health in organizations. The big data from IoT via 5G is exemplary for AI exploitation. The advantage of minimum users or less human intervention is the core for protection from COVID-19, which can be delivered from IoT. For smart railway stations, it has been suggested that it is possible that the same concept of the smart cities can also be applied to railway stations. The railway station innovation, data businesses, and services will add extra value to both, for instance, sharing and tracking information related to the pandemic between the NHS and the railway. Generally, the leading smart criteria in the stations include smart mobility, infrastructure, and management, so that all technologies such as AI, cloud, 5G, and IoT together can play a vital role in the health and safety of the railway industry future. No doubt, in the future, the AI and revolution of data technology will be a part of the rail industry providing essential contributions (Alawad and Kaewunruen, 2018). Moreover, the demand and usage of face technologies such as computer vision, CCTV, face recognition, and Iris of the eye linked with AI algorithms are expected to increase. This has already proven to be an accurate and safe method of timely monitoring with less human intervention, which can help provide a safe social distance in the case of COVID19. To sum up, we ask again whether the industry will be more competent in the face of future pandemics. If the lessons are learned, the answer will be yes. Finally, COVID-19 has led to rethinking how we consider and continue to benefit from technology in the current situation and for future crises, not only for the railway but for all businesses.

AUTHOR CONTRIBUTIONS

Both authors wrote and contributed their experience and industry outcomes to the manuscript.

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Getting It Right on the Policy Prioritization for Rail Decarbonization: Evidence From Whole-Life CO_{2e} Emissions of Railway Systems

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INTRODUCTION

In the past several years, global warming has caused essential issues that all sectors must respond immediately. The Paris Agreement has turned into a critical framework provoking public and private sectors worldwide (Dimitrov, 2016; Pye et al., 2017). One approach to solving this problem involves the use of green energies and reducing CO_2 emitted from all sectors.

Regarding the transportation sectors, it emitted CO_2 above one-fourth of the global emission. A well-known problem with over emission is that some countries have inadequate public transportation and non-environmental policies. The low-fare service and high accessibility on public transit are major strategies to reduce emission from a private car (Krishnan et al., 2015; De Andrade and D'Agosto, 2016). These schemes eventually promote a long-term shift from self-vehicle to public transportation services. The United Kingdom government has been concerned with the global warming issue and provided new strategies to reduce CO_2 emission in all sectors, such as launching new public transportation (Kaewunruen et al., 2018; Logan et al., 2020). Additionally, the United Kingdom's railway network is considered the lowest CO_2 emission per passenger over other public services. Regarding the global climate policies, the United Kingdom government has still intended to cut off the railway's emission by replacing it with alternative fuels and changing the current diesel engine system toward the decarbonization concept, mainly reducing the emission from the operational process.

Even though the CO_2 emission from the railway's life cycle predominantly comes from the railway infrastructure, the United Kingdom government and rail sectors exceptionally focus on reducing those emissions from the operational stage. In this research, the authors believe that only promoting strategies to reduce CO_2 in the operational process cannot bring the United Kingdom government to reach its targets by 2050. In contrast, the government should also consider other effective and practical strategies.

In order to understand the amount of CO_2 emission from the railway network, the research deeply examines the entire life cycle analysis (LCA) through the high-speed rail (HSR)'s infrastructure. This research aims to provide future strategies and policies to cut the CO_2 off the railway network. Furthermore, the decarbonization concepts and practical approaches to the railway system have been stated in this study.

THE DECARBONIZATION CONCEPT IN THE RAILWAY SYSTEM

The Paris Agreement has been launched as a global environmental policy. It targets to keep global temperature below 1.5°C compared with the pre-industrial era (Dimitrov, 2016; Streck et al., 2016). The agreement has been involved in the transportation industry, especially on railway and HSR networks. Implementing environmental concepts becomes a challenging issue for researchers and engineers in the railway industry. The International Union of Railways (UIC)'s report states that transportation shared 24.7% of CO_2 emission or 8 billion tCO_2. The railway sector, well-known as the lowest CO_2 emitter, has produced 26.64 million tCO_2 across the European countries (Korea Ministry of Land, 2008; Kaewunruen et al., 2016; UIC, 2017). Also, many attempts to reduce global emission have been applied to the railway industry. There were several collaborations among railway industries, operators, policymakers, and other related sections to respond to governmental policies.

Based on the United Kingdom's targets to achieve net-zero by 2050 and reduce 80% of greenhouse gases (GHGs) emissions relative to 1990 levels (GOVUK, 2019; ORR, 2019). The principal of the net-zero refers to the balance between the emitted GHGs and their amount in the atmosphere. The discharged and taken out GHGs can be equivalent by using high technologies such as carbon capture and carbon storage (Bonsu, 2020). In fact, the GHGs are mainly composed of CO_2; hence, the amount of emission is commonly measured in the CO_2 unit. Moreover, the government launches the net-zero plan to produce low carbon industries across the United Kingdom. Nevertheless, the strategies are unable to bring the United Kingdom to reach its targets due to a lack of reducing CO_2 emissions in other sections such as infrastructural emission.

Department for Transport (DfT)'s report (2020) reveals that the decarbonization plan decreases 43% of emissions while increasing the country's economy by 75%. It illustrates significantly advanced progress over other sectors. The Rail Safety and Standards Board (RSSB) states that the United Kingdom's rail system has a high potential to provide net-zero carbon by 2050 (ORR, 2019; LSE, 2020). The statement confirms the United Kingdom's rail network in response to European's policy toward a decarbonizing framework. Following the global guidelines, the United Kingdom's government has proposed a vision to remove all diesel trains from the network by 2040. According to the United Kingdom railway network, it has been widely linked across the country in a total of 16,209 km of distance (Stittle, 2004; Network Rail, 2020). The railway takes 2% market share of public transportation and 10% of passenger mile traveled in Great Britain. The transport sector's emission shows at 28%, which the rail sector shared 3% of total transport's emission (Power et al., 2016; ORR, 2019; RSSB, 2019). The rail network is expected to use electrical and other renewable sources as alternative energy. Moreover, an effective plan to reduce CO_2 from the network is adopted in all related rail activities, that is, using zero-carbon self-powered vehicles, increasing energy efficiency, and reducing pollution emissions.

The decarbonization concept refers to the termination of CO_2 emission from fossil fuel (RSSB, 2019). The government plans to operate an entire network without CO_2 emission by 2050. All diesel trains will not be allowed in the United Kingdom's rail network, and the existing engines need to be replaced with an electric system. Moreover, the government is encountering unsupported infrastructural issue because only 42% of the United Kingdom's network is an electrical track (RSSB, 2019). Alternative energies have been applied to the railway network, such as hydrogen (H_2) fuel cell, battery, solar energy, and biomass. Some research compares an engine performance between the existing diesel trains and electric trains. The outcomes state that the fuel cell and the electrification systems do not significantly improve the train's performance. In contrast, the H_2 train has higher efficiency than other low-carbon vehicles, but it is the most expensive option (Anandarajah et al., 2013). The electric hybrid vehicle is highly recommended as it is able to reduce the fuel consumption by more than 20%. As a result, the GHG emission can be reduced up to 15–30% (Cheli et al., 2006).

In this day, the United Kingdom's HSR network, namely, "HS2," has been continually constructed. The HS2 project strictly follows the government's net-zero targets and decarbonization concept since the beginning of the construction phase (HS2, 2021). The HSR service has limited the lower speed at 250 km/h, while the conventional rail's speed at 200 km/h. The HS2 project is expected to be the most sustainable railway network in the world, reducing CO_2 emission than cars and planes. Regarding the future developments toward the rail network, the decarbonization vision should be turned into practice. The government must consider the cost of electrical track and power engines replacement.

THE LIFE CYCLE ANALYSIS OF HIGH-SPEED RAIL'S INFRASTRUCTURE

The LCA, a tool to identify environmental impacts along the life cycle, is applied to this research. This assessment clearly shows the CO_2 emission in each life cycle stage that leads to sustainable development. To overcome this problem, some approaches have also been made with the decarbonization of the railway. The outcomes have precisely estimated the CO_2 emission from each LCA stage; moreover, the insight provides practical recommendations to reduce the railway system's emission.

The LCA of HSR's infrastructure consists of manufacturing, operation, maintenance, and demolition (Kaewunruen et al., 2019). The manufacturing stage comprises rail track construction that the CO_2 is emitted during its construction and logistic processes. The three characteristics of the rail infrastructure include ballasted track, bridge, and tunnel. The material requirements on each characteristic are dissimilar, caused by the unequal amount of their emissions, as shown in **Table 1**.

The research compares ballasted track, tunnel, and bridge in terms of embodied energy requirement and CO_2 emission. The results clearly show that the ballasted track, which consumes 1,712,694 kJ and emits 4,727 kg CO_2, is the lowest emitter. The

TABLE 1 | The summary of material used (*μ*: *kg*), embodied energy (*ω*: *kJ/kg*), and emission (***p***;*kgCO2/km*) in 1°km of ballasted track, tunnel, and bridge (adopted from the Department for Business, Energy and Industry Strategies, 2020; Global source, 2020).

Material(s)	Ω	*p*	Ballasted track			Tunnel			Bridge		
			μ	ω	*p*	μ	ω	*p*	μ	Ω	*p*
Gravel/Sand	1,000	4.32	530	530,000	2,290	696	696,000	3,007	0	0	0
Concrete	9,500	0.13	34.3	325,850	4	465	4,417,500	60	673	6,393,500	87
Steel	235,200	1350	1.3	305,760	1,755	14.7	3,457,440	19,845	36.8	8,655,360	49,680
Steel low-allowed	244,000	1.77	0.74	180,560	1	1.58	385,520	3	0	0	0
Zinc	490,000	3.41	0	0	0	0.006	2,940	<1	0	0	0
Copper wire	882,200	1612	0.42	370,524	677	0.055	48,521	89	0	0	0
Ceramics	33,330	2.537	0	0	0	1.6	53,328	4	0	0	0
Aluminum alloy	211,850	9110	0	0	0	0.05	10,593	456	0	0	0
PVC	158,000	0.48	0	0	0	0.0653	10,317	<1	0	0	0
Excavation soil	800	0.0048	0	0	0	4,850	3,880,000	23	0	0	0
Summary			–	1,712,694	4,727	–	12,962,159	23,487	–	15,048,860	49,767

CO_2 emission from the ballasted track is lower than that in rail's tunnel and bridge five and ten times, respectively.

The maintenance and operational stages are necessary to maintain the safety conditions of rail infrastructure. The operational and maintenance stages are typically the longest phase in the lifecycle. Moreover, these stages include the standard operation plan, emergency operation, and related activities (Kaewunruen et al., 2019; Li and Zhang, 2020). This research examines LCA with an assumption of significant operation and maintenance that are allocated every 5 years. And, the material requirements are estimated at 15% on the amount of initial construction. The timeframe of infrastructure's LCA is placed at 70 years. As a result, the total emission of these stages is 9,927.56 $kgCO_2$/km.

Last, the demolition stage is assigned at the final step and aimed at recycling non-using parts. All of the nonrecyclable materials with the toxic chemical are cleaned up. Then, they are transferred to the shredding process and landfill. On the other hand, recyclable parts such as steel, concrete are sent to cleaning, crushing and shredding processes. The small pieces of materials are shifted to the melting process for reforming to the new products. The rail infrastructure composed the recyclable and nonrecyclable parts. In this study, the ballasted track, which is the majority, is analyzed toward the demolition stage (Network Rail, 2020; Rungskunroch et al., 2021). As a result, the calculation shows that the final stage emits 0.248 $kgCO_2$/km.

In conclusion, the LCA's result reveals 14,655.22 $kgCO_2$/km. The fractions of emission in manufacturing, operation and maintenance, and demolition are shared at 32.25, 6, and 0.001%, respectively. It can conclude that a significant amount of CO_2 emission comes from operation and maintenance.

DISCUSSIONS AND RECOMMENDATIONS

Following the national energy consumption statistics, the total GHG emission is 351.1 million tonnes (Mt), containing 280.88 $MtCO_2$ (Department for Business, Energy and Industrial Strategy, 2020). The transportation sector denotes 28% of total emission across the United Kingdom, whereas the railway network shares only 2% of CO_2 emission of that sector (RSSB, 2019). It can be estimated that CO_2 emission from the United Kingdom rail network is 15.72 $MtCO_2$ or 970.40 tCO_2/km per annual. The Office of Rail and Road (ORR) reports that the United Kingdom's CO_2 emission for passenger train shows at 36.6 gCO_2 per passenger kilometer (pkm), whereas 25.3 gCO_2 per tonne-kilometer (tkm) from freight train emission (ORR, 2019).

Since eliminating diesel train is not enough response to the government's targets, the implications of these findings are discussed as the solutions to tackle the CO_2 emission from the United Kingdom railway network as follows:

Railway Infrastructure Construction and Maintenance

Various policies have been announced without concerns for the improvement of railway structure. The LCA's infrastructure results show that 14,655.22 $kgCO_2$/km is emitted in the 70 years of timeframe. It can also be increased to 72,811.52 and 154,284.07 $kgCO_2$/km on constructing a rail's tunnel and bridge, respectively. Most of the CO_2 emission occurs at the operational and maintenance stages. Moreover, the volume of emissions can be increased when the track requires remarkable maintenance, that is, severe accident, natural disaster, and vandalism. Hence, the emissions by infrastructural activities should not be neglected. Future research should consider the negative effects of CO_2 during infrastructural construction and maintenance carefully (Kaewunruen et al., 2014; Kaewunruen et al., 2015, Kaewunruen et al., 2016).

Replacement of Diesel Engine

RSSB reports that 80% of the traveling distance uses electric trains, and the rest diesel trains. The United Kingdom government has faced political issues of buying the new freight train because none of the current models meets the United Kingdom's net zero-emission targets (Stittle, 2004; Kaewunruen and Lee, 2017). Therefore, the existing freight trains, which are high-level of CO_2 emission, must be continually serviced. This research highly recommends replacing diesel engines with an H_2 fuel cell or biofuel. These alternative sources offer lower CO_2 emission and reduce energy consumption than the diesel model.

Installation of Electric Track Along With the United Kingdom Rail Network

42% of the entire network is an electric track. It means that only those numbers of tracks can push the government's targets forward. Some researchers offer critical development on the environmental perspectives by installing electric tracks (Marin et al., 2010; Kirkwood et al., 2016; Krezo et al., 2018; Chovančíková and Dvořák, 2019). This study also recommends replacing the standard track with the electric track for long-term sustainability goals. Future research on electric track might provide cost details and efficiency about direct current (DC) and alternate current (AC) networks. As found, the DC network shows tangible benefits in terms of power control and noise nuisance (Alnuman, Gladwin and Foster, 2018), while the AC network offers low heat loss.

CONCLUSION

Regarding the Paris Agreement, the United Kingdom government responds to that by planning to make zero-emission across the United Kingdom by 2050. Leading strategies push forward governmental regulation by removing diesel trains out of the network by 2040. Nevertheless, the emission of CO_2 in the railway network occurs from various sections. Therefore, the LCA is applied to rail infrastructure to precisely describe the CO_2 emission on each lifecycle stage. As shown, the CO_2 predominantly emits from operation and maintenance stages. In this study, both LCA stages have emitted approximately 60% of the total emission in a whole life cycle. It brings the total emission of infrastructure at least 14,655.22 kg CO_2/km.

Conversely, the CO_2 emission in the railway operational stage is 36.6°g CO_2/pkm annually, which exceedingly depends on the volume of a passenger. The research's broad implication is that the railway system's reduction of CO_2 emission should be widely considered along with the rail network, especially on the railway infrastructure. Our study provides three realistic key developments covering infrastructure, electric rail track, and vehicle's engine power. By following these guidelines, the United Kingdom government's target to be net-zero carbon is more achievable.

AUTHOR CONTRIBUTIONS

PR carried out data analytics and visualization. PR and SK developed the concept and methodology for the investigation. All authors contributed in the writing of the opinion paper.

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Sensitivity of a High-Speed Rail Development on Supply Chain and Logistics *via* Air-Rail-Road Freight Transportation

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The casual effect and synergy of high-speed rail development on the modal transport changes in supply chain and logistics have not been considered well during the initial phase of any rail project design and development. This has impaired the systems integration and connectivity among the modes of transport in a region. In the United Kingdom, High Speed 2, a large-scale railway project with a planned completion date in 2033, affects many transport stakeholders. The project influences the existing transport systems, but the transport systems integration design has not been well depicted, resulting in a pressing concern on systems connectivity and social value. This is evident by many public protests along the planned route of the project. Therefore, it is important to evaluate different aspects for any possible changes in supply chains caused by the development of high-speed rail networks. This paper is the world's first to provide the sensitivity analysis of supply chains *via* air-rail-road freight transportation and logistics stemming from the High Speed 2 case by the rigorous assessments into the capacity, performance and environmental changes that may follow the project's implementation. The research proposes a new method for estimation of consequences from a new transport project construction. The research findings demonstrate slight beneficial changes in freight transportation and logistics with a high potential for development; and reveal the project's weaknesses and opportunities for better systems integration and business synergy.

Keywords: supply chain analysis, sensitivity, freight transportation, high speed rail, business resilience, logistics

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INTRODUCTION

With infrastructural development in the railway field and scientific and technological progress, there has been a dramatic evolution of railway systems. The evolution is not only for railway speed acceleration but also for transport capacity improvement. Hector et al. (2012) find that United Kingdom does not have any plans to build its High-Speed Rail (HSR) until 2004. Consequently, United Kingdom finally enters the era of HSR after the completion of the first high-speed line (HS1) from the Channel Tunnel to London. In addition, High Speed 2 (HS2), which connects London, Birmingham, Manchester, the East Midlands and Leeds, is the largest European transport project so far with an estimated cost of 55.7 billion pounds sterling (GBP). According to a report published by Transport Statistics Great Britain (2019), 808 billion passengers' kilometres travelled in the United Kingdom in which 83% of the passengers travelled with cars, taxis and vans. On the other hand, about 8.3 billion journeys in 2018/2019 over public transport vehicles. In contrast to this, the remaining journeys were similar to what they were in the previous year. This depicts that transport is essential for people in Britain, which makes it necessary for the government to emphasise infrastructure development. Although the construction project might significantly affect the existing transport system of the United Kingdom (Department for Transport, 2017), it could bring huge transport, economic and environmental benefits. However, the project might affect many stakeholders in the long-term run due to its large expense (High Speed 2, 2019).

Since the main purpose of constructing HS2 is to shift freight haulage from road to rail, it is essential to analyse the probable impact on air-rail-road freight transportation systems to understand the causal effect and synergy of high-speed rail development. In line with Gunasekaran et al. (2001) and Chan (2003), the research method for supply chain analysis will be focused on performance measurement to study the number of metrics related to different parties' interactions. As Beamon (1999) states, it is necessary to consider several metrics to derive a detailed understanding of supply chain characteristics and identify their importance.

Evaluating the high-speed train project is that the entire project involves a huge cost, increasing the risk of this project. In this manner, the lack of evaluation can result in project failure and loss of investment. Therefore, the evaluation of the high-speed rail project has been carried out in this study. In the study of Yeo and Ren (2009), it has also been argued that it is vital to assess the risks involved in huge projects as the chances of failure are more associated with high-cost projects. Concerning the public hearing, people support the entire project, making their communication much more efficient. It is because high-speed rail will reduce the travelling time between towns, which will provide quick service to passengers and save them a lot of time. However, it was also revealed from public hearing that some of the residents are against the entire high-speed railway project in the United Kingdom as the infrastructure invade their space (BBC.com, 2020). Concerning the project of HS2, the major source of delay for the entire project is that the project has been split into two sections. The construction for London to Birmingham route began in 2017 and is expected to be completed by 2026. However, Birmingham to Manchester or Leeds route started in the mid-2020s and is expected to be completed by 2032.

This research intends to evaluate the possible impact of the HS2 project on supply chains by analysing air-rail-road freight transportation and logistics and numerically considering different aspects of changes. In this case, the HS2 project's advantages and disadvantages would be fully demonstrated and discussed. In this paper, four different stages of rail freight will be discussed: Business, as usual, Carbon Reduction, Carbon Survival and Manufacturing that indicate different aspects in environment and capacity improvements. According to High Speed 2. (2021), H2S is considered the new high-speed railway linking up Scotland, the North, Midlands and London while serving more than 25 stations. In addition to this, it also includes its operations in the eight largest cities of Britain while ensuring the connection of 30 million people. This construction of a new railway has been divided into three phases. The first phase link West Midlands and London, and the second phase are also divided into sub-phases in which phase 2a link the North and West Midlands through Crewe. In contrast to this, phase 2b completes the railway to Leeds and Manchester. With the construction of a new railway line, the project takes the fast trains off the present railway and place them over their dedicated tracks. It helps o better connect the major cities and towns in the country. In addition to this, it also allows local and slower trains to bunch up over the existing lines while providing ample space across the country for various freight trains and commuter services (Kaewunruen et al., 2016; Office of Rail and Road, 2019).

Sensitivity analysis is the method used to predict the outcome of a decision in case of a different situation compared to key predictions. It has also been argued in the study of Shariat et al. (2018) that sensitivity analysis helps predict the outcome of decisions in case of different situations compared to key prediction. In this manner, the riskiness of the strategy is determined with the help of sensitivity analysis. Moreover, it also determines how the dependent has been the output over a particular input value. This study has been carried out to conduct a sensitivity analysis of a high-speed rail development on supply chain and logistics *via* air-rail-road freight transportation. In this manner, the results of this study are beneficial for the risk assessment of the H2S railway project. Furthermore, the study over the sensitivity analysis of high-speed rail development on supply chain and logistics *via* air-rail-road freight transportation has not been carried out before, making the results of this study unique while providing a significant contribution towards existing literature.

The layout of this paper is as follows: it begins with the review of previous literature in *Literature Review* section, including definitions and roles of parties, an overview of papers related to supply chain analysis, industry trends and a summary of forecasts and reports. *Methodology* Section outlines the data selected principles and data analysis methods, including performance measurement and environmental effect analysis. Further, *Results and Discussion* section discusses the findings that are derived and evaluated for each relevant result. The conclusions of the research are presented in Conclusion section.

LITERATURE REVIEW

Roles and Definitions

The figure above shows the detailed map of the company's supply chain process in a detailed manner. The above figure shows that the direct supply chain involves three stages in which the flow of goods and services initiates from suppliers and ends at customers. However, the ultimate supply chain initiates with the ultimate supplier and ends at the ultimate customer. On the other hand, the extended supply chain initiates with the supplier's supplier and ends at the customer's customer.

There are various definitions for logistics and supply chains. Mentzer et al., 2001 finds that 'supply chain management (SCM)

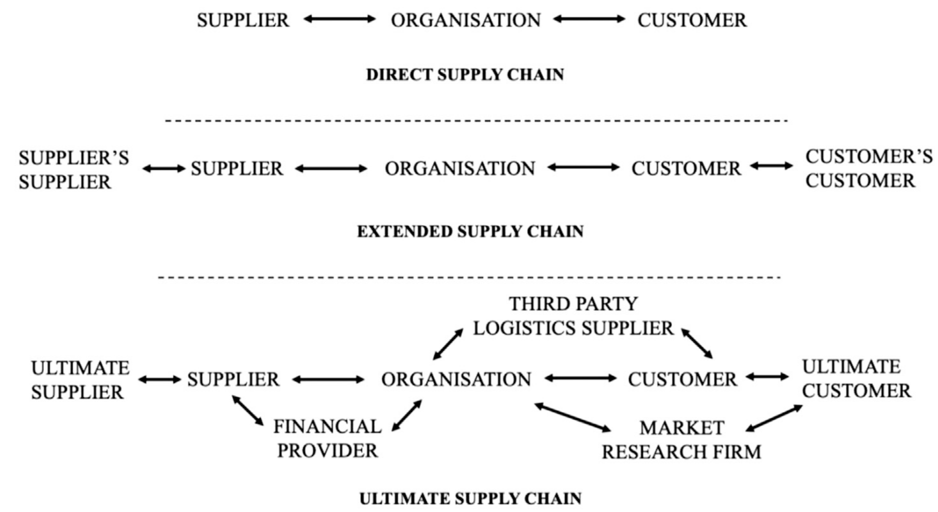

FIGURE 1 | Types of supply chain complexity [9].

is rarely used in its full term. Instead, followed by Christopher (2005), the short term 'supply chain' is often used to describe 'the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole. Although SCM and logistics overlap, Mentzer et al., 2001 claims that SCM deals with manufacturing and marketing to improve corporate competitive advantages, whereas logistics deals with transportation and warehousing. Supply chain management is considered the management of the flow of services and goods, including all the processes that transform the raw materials into finished goods. In addition to this, it includes the active streamlining of different supply-side activities of the business to maximise customer value while gaining a competitive advantage in the industry. A supply chain comprises three units represented by upstream distribution, downstream distribution, and the final customer. Different types of supply chain complexity are illustrated in **Figure 1**. Moreover, there is significant connectivity between supply chain management and logistics management practices, as it is based on the implementation and control of the effectiveness and efficiency of the flow and storage of goods, services and information between the points of origin and point of consumption to meet the requirements of the consumers (Yang and Zhang, 2018). Therefore, logistics management is all about fulfilling the requirements of the consumers and higher their satisfaction level.

Several research studies have considered the role of transportation in logistics systems. It has been shown that they are related in many fields. Tseng et al. (2005) note the following: 1) profound interdependencies between transportation and logistics systems. On the one hand, transportation is an integral process of logistics. On the other hand, a logistics system could positively affect traffic and reduce environmental impact; 2) transportation has the highest contribution to logistics system costs; therefore, how to increase its monetary and nonmonetary performance should be considered. The dependence of successful logistics strategies on transportation proposes the consideration of related business models. The function of transportation provides essential service in linking the companies to its customers and suppliers with the help of moving goods from locations in which they are sources to the locations in which they are demanded. In this manner, transportation is considered an essential activity in the logistics function while supporting the economic utilities of time and place. As per the study conducted by Mantoro (2021), transportation mode refers to several ways people or goods are transported from one place to another through sea, land or air. In addition to this, the transportation modes are also through space, cable and pipelines. Concerning the transportation of people, there are several modes which include by air, sea, land. Specifically, land includes different transportation means in which cars, trains, motorcycles, and other motor vehicles are included.

Supply Chain Analysis

Although performance measurement has been considered for supply chain analysis (Mishra et al., 2017: Hosseini, Ivanov and Dolgui, 2019), limited attention has been given to measuring supply chain for designing or evaluating the whole system. Adapted from Beamon (1998), the performance measures will be the basis for this research. In addition, the importance of different aspects of performance measurements needs to be considered, categorised and enabled to set the targets for further detailed studies. As the first framework for evaluating supply chain performance, Supply Chain Operations Reference Model (SCOR) model is proposed by Stewart (1995) to demonstrate supply chain development. By examining the revenues and costs of the supply chain system, high performers among supply chains could be identified. Similarly, Wilting and van Oorschot (2017) indicated that the allocation of functional areas led to the emergence of the concepts of supply logistics (procurement logistics), production logistics, distribution logistics and books with corresponding titles in the domestic literature. In foreign logistics management, the term "input logistics" refers to logistics functions in procurement. The term "output logistics", focused on integrating logistics functions and operations in distribution, is often encountered. But it should be emphasised that there is no single approach to identifying the functional areas of logistics among scientists and specialists. Some domestic researchers narrow these areas to individual functions, and therefore, on the shelves of bookstores, one can often find books with the titles: "Customs Logistics", "Insurance Logistics", "Transport Logistics", "Warehouse Logistics", "Information Logistics" etc., (Raoufi et al., 2017) The point, of course, is not the title, but they sometimes lack a constructive idea, and the very word "logistics" is added to the title of books, often for opportunistic reasons. Consider the key logistics function - "transportation".

Regarding the importance of quantitative and qualitative evaluation, three elements of the performance measurement system are identified for this paper: resource, output, and flexibility. In addition, as presented by Neely et al. (1995), cost, time, quality, and flexibility might also contribute to supply chain evaluations. Previous research has also tended to apply performance measurement to gauge the degree to which organisations successfully collaborate with their business partners in a supply chain (Lambert and Pohlen, 2001). The importance of discovering the elements of the performance measurement system is to match the priorities highlighted by different parties and achieve different levels of operational performance.

The supply chain relationship is critical with completing the entire project and the risks involved in the project. Supply chain management is directly associated with the capacity, performance, and environmental changes that might follow the implementation of this project. Therefore, this paper provides the sensitivity analysis of supply chains *via* air-rail-road freight transportation and logistics stemming from the High Speed 2 case by the rigorous assessments into the capacity, performance and environmental changes that may follow the project's implementation. It has also been discussed in the study of Larsson and Larsson (2020) that supply chain management significantly contributed towards the completion of the entire project.

Gunasekaran et al. (2001) implemented empirical analysis to assess strategic planning, order planning, supplier, production, and delivery. On top of that, performance metrics will be defined according to the level of their importance. Specifically, Gunasekaran et al. (2001) obtains quantitative data from received questionnaires in 21 companies out of the 150. Moreover, transport enterprises operate in a market economy: a market for transport services has been formed, competition between enterprises and various modes of transport has intensified, and the requirements for tariffs and quality of transport services on consumers have become stricter (Dolgui et al., 2018). The modern transportation mission in the logistics service system can be briefly formulated as: "to deliver the right product of the required quality and quantity at a given time with optimal costs." In the structure of logistics costs, transportation costs account for a significant share of 20–40% or more (Suryanto et al., 2018). Therefore, optimisation of solutions in transportation will allow logistics management to obtain significant cost savings but will also require special attention. Transport plays a special role in the formation and development of logistics. Domestic transport and forwarding companies involved in the international transportation of goods were the first to see the need to introduce modern logistics technologies for transportation and cargo handling (Tarne et al., 2018). Large United States state and private transport and forwarding companies actively created their terminal networks, freight distribution and logistics centres, information and computer support systems for logistics services.

As various performance metrics exist, and all of them have different importance, a systematic approach has been implemented for supply chain evaluation. Gunasekaran et al. (2001) developed the performance measurement framework, representing the financial and non-financial metrics allocated in strategic, tactical and operational levels, which encourages appropriate decision-making in supply chain analysis. Although Gunasekaran et al. (2001) study provides the foundations for supply chain analysis for the HS2 case, not all the metrics are related to freight transportation that requires further research.

Freight Transportation Industry Trends

HS2 is a long-term project that will be constructed over more than a decade. Therefore, it is essential to consider trends in freight transportation and global development. As transport systems are used for passenger and freight movements, it is important to understand their interdependencies. Speranza (2018) has identified and considered systematic, collaborative, and dynamic directions from the following main trends in supply chain management:

- Systemic focus: optimisation of the entire supply chain network, customer value co-creation.
- Information synthesis: information is holistically shared.
- Collaborative relationships: joint accountability and rewards, total system value creation.
- Demand shaping: proactively influencing demand, total system value creation.
- Transformational agility: constantly changing conditions.
- Flexible network integration: dynamic selection of partners upstream and downstream.
- Global optimisation.

It is identified that costs and environmental conditions are driven by sustainable, political, and emerging business opportunities that could cause rapid alterations in logistics and transportation.

Freight transport moving through cities is continuously growing and should be controlled. Crainic et al. (2004) design goals for logistics, which could improve the quality of life in cities, including reductions in pollution, noise, congestion, and growth of mobility without hurting business. The research discusses the significance of intermodal freight transportation, logistics' facilities allocation and distinguishes the possible efficiency of satellite platforms. In addition, Tseng et al. (2005) discusses the provisional future of logistics with logistics centres' development and assume the growth of single trip loads and collaboration in delivery between small and medium-sized companies.

In each country, shipping goods is considered a significant part of the economy. As per the report presented by Statista, the contribution of truck transportation has contributed about $150 billion to the GDP of the United State in the year 2016 (Stfalcon.com, 2021). Exclusively, FedEx, which is the leading freight transportation company, has generated over $60 million of the revenue in 2016. On the other hand, the intelligent transport system emphasises achieving traffic efficiency by reducing traffic problems. In addition to this, it also emphasises reducing commuters' time while enhancing their comfort and safety. This relates to the HS2 project as the project focuses on providing high-speed transportation service to the public while reducing the time and traffic load. Furthermore, modern ideas about the transportation of goods began to change significantly with the development of market relations, from transport as an industry, equated to industrial sectors, to the service sector—transport service. Therefore, consumers of transport services choose such types of transport and transportation methods that provide the best quality of logistics services (Ahmed et al., 2018). Sadatsafavi et al. (2017) stated that transport service in modern conditions includes the transportation of goods from the supplier to the consumer and many forwarding, information operations, cargo handling services, insurance, security, etc., Therefore, transportation can be defined as a key logistics function associated with the movement of products by a vehicle (or means) using certain technology in the supply chain and consisting of logistics operations and functions, including forwarding, cargo handling, packaging, transfer of ownership of goods, insurance of risks, customs procedures, etc.

Based on various studies, information technology (IT) has been discussed as a significant influencer of logistics and freight transportation. Effective information exchange is important for performance metrics related to customer service and scheduling (Bhagwat and Sharma, 2007). IT solutions are widely used in city logistics and help transport costs and emission reduction (Tseng et al., 2005). The growth of demands and related problems have promoted the development of intelligent transportation systems (ITS). Specifically, the term ITS is 'generally used in many industries, infrastructure, and services, as well as the planning, operation, and control methods to transport persons and freight' (Grainic et al., 2009). In the research of Crainic et al. (2004), possible freight ITS' accomplishments are discussed, and three directions for development related to vehicles and infrastructure, hardware and software, models and algorithms are examined. Moreover, Torre-Bastida et al. (2018) indicated that the incorporation of Information technology in freight logistics is also improving the flow of information and help in developing a smooth communication channel between the suppliers and companies. Therefore, it has become easier for companies to improve their overall infrastructure with strong communication channels, leading to better economic development. Most developed where there is a dense network of airlines. The most significant fleet of ships is in the United States, Canada, France, Germany, Australia. The cargo turnover scheme unites over 1,000 airports around the world. Singh et al. (2021) research also indicated that the share of air transportation accounts for a very small part of the cargo worldwide, no more than 1–2%. This is due to the high cost of shipping and a large number of restrictions. Air transport is used mainly for the transportation of perishable and unique goods. After all, its indisputable advantage is speed. Aircraft is the only way to move cargo quickly over long distances.

TABLE 1 | Hierarchy of the drivers affecting the implementation of green SCM (Diabat and Govindan, 2011).

Drivers	Level
Certification of suppliers' environmental management system (1)	3
Environmental collaboration with suppliers (2)	2
Collaboration between product designers and suppliers to reduce and Eliminate product environmental impacts (3)	4
Government regulation and legislation (4)	5
Green design (5)	1
ISO 14001 certification (6)	2
Integrating quality environmental management into the planning and Operation process (7)	1
Reducing energy consumption (8)	1
Reusing and recycling materials and packaging (9)	1
Environmental collaboration with customers (10)	2
Reverse logistics (11)	5

Sustainability has become one of the most important issues for citizens and governments. Several research studies consider drivers for sustainable supply chain management and outline how the situation could change in the future. Cucchiella et al. (2012) define key enablers for the United Kingdom's private sector as: 'customer requirements, reputational risk, organisational factors including strategic, people and functional issues, and stakeholder involvement; whereas possible obstacles cost reduction, other corporate preferences, lack of long-term planning and customers' impact. In addition, Diabat and Govindan (2011) discover drivers for green supply management and establish a hierarchy running from 1 (the top) to 5 (the bottom), as shown in **Table 1**.

The data obtained by Cucchiella is related to several large companies, therefore, small and medium-sized organisations were not analysed. Diabat and Govindan's study was based on an investigation of Indian manufacturing companies, thus, allocation levels could differ for other countries or industries. These research studies have helped understand the importance of sustainable supply chain management in current and future environments.

METHODOLOGY

Research Design

Supply chain analysis, which comprises capacity evaluation, performance measurement and estimation of carbon emissions, is implemented to evaluate the possible impact of HS2 construction on existing air-rail-road freight transportation and logistics. Data for previous years is obtained from the government's statistical reports, whereas projected data is derived from forecasts published on departmental government websites. Evaluation of the freight transportation system is conducted to identify the existing capacity of the previously mentioned modes of transport. Then the balance between passenger and freight usage of railways is identified, and the potential traffic for the case when the railway is used only for freight transportation is calculated. The data from the forecasts are used to predict demand and shares of domestic cargo transport by mode in 2033, when HS2 will be completed.

The criteria for selecting data have been the websites and reports that present transport data of the United Kingdom since the project has been initiated in the United Kingdom and will be operational in the cities. Therefore, the data considered in this study would be relevant for the analysis of risks assessment of H2S projects in the United Kingdom A business as usual is considered as the scenario for future patterns of activity which undertakes that there will not be a significant change in the priorities and attitudes of people or no massive change in the policies, economics and technology, and for this purpose, the normal circumstances can be anticipated to remain unchanged. On the other hand, the carbon reduction strategy describes particular steps that businesses can take to implement practical, sound and climate-related corporate policies. With the help of these strategies, the companies can ensure the carbon survival and manufacturing of goods based on sustainable practices.

A framework for measuring the performance of a supply chain, providing financial and non-financial performance metrics, is applied to the project (Gunasekaran et al., 2001). Performance metrics are analysed by basis and level of importance (Beamon, 1998). As this approach could be utilised for the whole supply chain, including delivery and storage aspects and production and planning, some metrics are not relevant to the project. The environmental effect of possible alterations in freight transport mode usage is evaluated by comparing carbon emissions before and after HS2 will be delivered. The environmental effect of possible alterations in freight transport mode usage is evaluated by comparing carbon emissions before and after HS2 will be delivered. The method used in this research could be applied to evaluate the impact of a new transport project construction.

Forecasts and Reports

As the final phase of HS2 is expected to be constructed in 2033, available reports estimating possible air-rail-road freight transport sector development have been considered. 'Foresight' is the program driven by the Government Office for Science, which provides strong data for policymakers to support and define strategies for the future (Government Office For science, 2013). Two reports developed under this program have been used for this research: 'Understanding the United Kingdom Freight Transport System' developed by MDS Transmodal and 'The Future of Mobility (Government Office For science, 2019a). One more MDS Transmodal report about future freight demand has been used in the study (National Infrastructure Commission, 2019). 'Implications for the Air Freight Sector of Different Airport Capacity Options', a report created for the Freight Transport Association and Transport for London, was also examined (York Aviation, 2015). The previously mentioned forecasts and reports for the Department for Transport (DfT) have been utilised; however, it has been considered that the data obtained may comprise some level of inaccuracy.

Capacity Evaluation

The latest data for rail market shares available for 2017 presented by the Office of Rail and Road allowed information to be obtained about how much freight was lifted and moved by rail and road in heavy goods vehicles (HGV) (Office of Rail and Road, 2018). In this study, airfreight transportation statistics are derived from several report tables. The 'goods lifted' (million tonnes) figure is taken as the total amount, including domestic and international movements (Department for Transport, 2018a). 'Cargo tonne-kilometres flew' (freight and mail) for domestic movements is used for carbon emissions' calculations because this figure is more related to the case than the total number for domestic and international flights (Department for Transport, 2018b).

The possible capacity for railway freight transportation usage is obtained by multiplying the data of freight lifted and moved and the coefficient of growth. Here the potential capacity of the existing railway is derived as a sum of passengers (130 million) and freight (34 million) rail vehicle kilometres statistics' data available for each purpose (Department of Transport, 2018c) Then the coefficient of growth is identified by a division the sum, that was obtained previously by the current rail freight capacity. There are various limitations related to potential capacity evaluation due to the complexity of logistical systems, market tendencies and unclear interdependencies between modes of freight transportation; hence, this approach is not exhaustive, and other statistical data could be utilised for the analysis.

Several strategies for forecasting rail and road freight demand are 'Business as Usual, 'Carbon Reduction', 'Carbon Survival' and 'Manufacturing Renaissance' for 2050. The two strategies with the highest demand in the road and rail freight transport are Business as Usual and Manufacturing Renaissance. Carbon Reduction and Carbon Survival scenarios focus on emissions' mitigation, but the main difference is that the second one excludes HGV electrification. Forecasted data also are calculated for the HS2 case, where part of road freight movement capacity has shifted to the railway to reach its maximum load, as determined previously. The estimated freight lifted by air transport in 2033 is 3.4 million tonnes, calculated from current (2.64 million tonnes) data and forecasted (4.2 million tonnes) data for 2050. Freight moved by air transport (billion net tonne-kilometres) is determined by proportion to the growth of the freight lifted.

Performance Measurement

Performance measurement is implemented based on several works presented below. The framework developed by Gunasekaran proposed a list of financial and non-financial performance metrics divided into three levels: strategic, tactical and operational. On each metric, the basis of the evaluation is allocated: cost, flexibility, customer responsiveness, cost and customer responsiveness, cost and activity time (Beamon,

TABLE 2 | Freight transport stakeholders and expectations (Government Office for Science, 2019b).

Stakeholders	Expectations
Freight transport operators	Congestion-free infrastructure Efficient goods and delivery collection
Shippers	On-time deliveries to customers Cost-effective transportation service
National government	Efficient use of strategic infrastructure Efficient goods delivery and collection Minimising externalities (CO2, air quality, congestion)
Infrastructure providers	Congestion-free infrastructure Maximising revenue
Citizens	Availability of a variety of goods High quality of life
Receivers	On-time deliveries Short lead time
Local government	Well-being residents Efficient use of local infrastructure Efficient goods delivery and collection

1998). In addition, the levels of importance are defined for the performance metrics according to the ratings presented by Gunasekaran. Not all of the metrics provided by Gunasekaran fully matched the performance measures in supply chain modelling provided by them in the later study; therefore, the importance of those metrics is allocated by a degree of propriety (Gunasekaran et al., 2004). The probable consequences of HS2's construction are estimated in terms of key stakeholders and their expectations, presented in **Table 2**. Risks for each group of stakeholders are determined in the case of possible failure of their expectations.

Cost-based performance metrics are evaluated by comparing the current and forecasted data for 2033, calculated for different strategies proportionally from the 2050 forecast (National Infrastructure Commission, 2019). There is no statistically proven and projected data for domestic air cargo costs in the United Kingdom. In addition, a comparison of the value of goods moved by transport mode is implemented.

As there is no scheduling for road freight delivery and air cargo movements can be scheduled, and non-scheduled, estimation of time-based metrics are implemented by analysing available statistic data for the reliability of deliveries for road and rail transport modes. Flexibility and customer experience assessments are implemented by estimating possible changes in technologies, information exchange, and the development of new transport hubs, which accompany the HS2 construction (Department for Transport, 2017).

Environmental Effect

The report' Carbon dioxide emissions by transport mode' presented by the DFT provides figures 'by source', 'by end user' and 'by industry'. The most suitable data associated with freight haulages are in the 'by source' section, representing direct emissions from transport. In addition, rail freight transport is mostly moved by diesel engines and the share moved by electric insignificant. Therefore emissions are taken 'by source'. The data from road freight transport is calculated as a sum of the emissions from HGVs and light goods vehicles (LGV). Values for 2016 are used because changes in transport emissions for 2016–2017 were about 0%, and there are no available statistical reports for 2017 (BEIS Annual Report and Accounts 2016 to 2017, 2017). To calculate emissions values for strategies considered in the capacity evaluation paragraph, current figures for each mode (million tonnes of carbon dioxide) are divided by current freight figures moved (billion net tonne-kilometres) and multiplied by forecasted values for freight moved. The values for the emissions per 1,000 net tonne-kilometres are calculated by the division of the emissions of a million tonnes of carbon dioxide by the freight moved (billion net tonne-kilometres), and then the result is multiplied by 1,000.

RESULTS AND DISCUSSION

Capacity Evaluation

The comparison of freight and passenger rail usage in rail vehicle kilometres shows that the existing system could be used for 4.85 times greater levels of freight haulage than it currently is. Analysis of capacity shows that after the HS2 construction, from 14 to 16% of freight could be moved by rail, whereas it may remain at 5% of the overall amount without this project. This has also been supported in the study of Gharehbaghi et al. (2020) that the construction of high-speed rails allows efficient freight forwarding. The biggest part of freight is moved by road transport, while airfreight is accountable for the smallest market share, less than 1%. **Table 3** shows freight lifted and moved by transport mode for current and forecasted situations. Shares of the market for rail and road modes of freight transport for different strategies are displayed in **Figure 2** and for different strategies for the HS2 case in **Figure 3**.

Capacity evaluation enabled the identification of the 'Business as Usual' strategy as having the biggest load for freight transportation with the smallest share of rail freight; while 'Manufacturing Renaissance' conversely holds the lowest level of load with the biggest share of rail haulage capacity, which could be caused by a focus on global trade and advanced technological

TABLE 3 | Freight lifted and moved by transport mode.

Domestic freight transport By mode	Freight lifted (million tonnes)	Freight moved (billion net Tonne-kilometres)
Current situation 2017		
Road (HGV)	1,397	147
Rail	76	17
Air	2.64	0.021
The possible freight capacity of the existing railway system		
Rail	369	82
Forecast 2033 (strategy: Business as usual)		
Road (HGV)	2,507	206
Rail	103	19
Air	3.4	0.027
Forecast 2033 (strategy: Manufacturing renaissance)		
Road (HGV)	2,225	167
Rail	118	24
Air	3.4	0.027
Forecast 2033 (strategy: Carbon reduction)		
Road (HGV)	2,325	176
Rail	99	18
Air	3.4	0.027
Forecast 2033 (strategy: Carbon survival)		
Road (HGV)	2,330	175
Rail	110	21
Air	3.4	0.027
Forecast 2033 (strategy: Business as usual) HS2 case		
Road (HGV)	2,241	143
Rail	369	82
Air	3.4	0.027
Forecast 2033 (strategy: Manufacturing renaissance) HS2 case		
Road (HGV)	1974	109
Rail	369	82
Air	3.4	0.027
Forecast 2033 (strategy: Carbon reduction) HS2 case		
Road (HGV)	2055	112
Rail	369	82
Air	3.4	0.027
Forecast 2033 (strategy: Carbon survival) HS2 case		
Road (HGV)	2071	114
Rail	369	82
Air	3.4	0.027

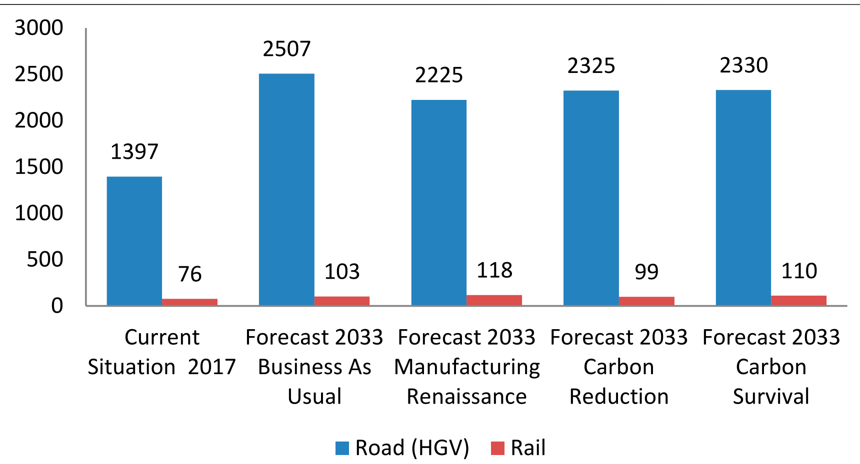

FIGURE 2 | Freight lifted by transport mode.

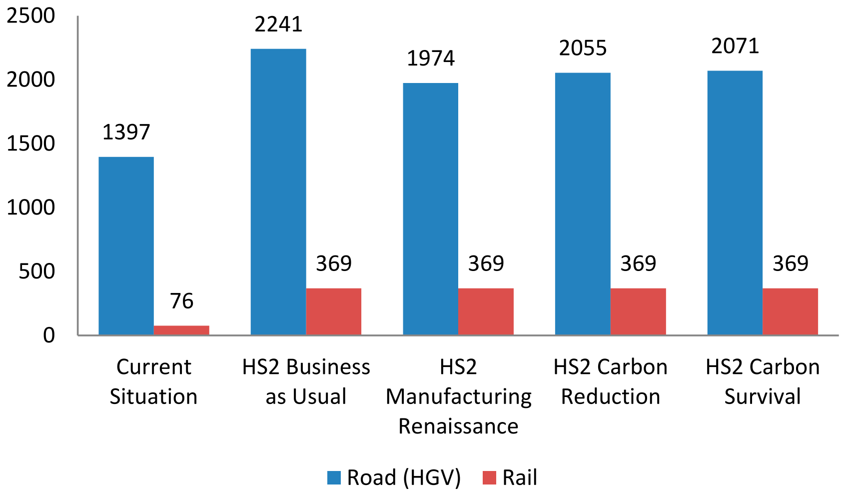

FIGURE 3 | Freight lifted by transport mode HS2 case.

production output. The total difference between these strategies is around 10%, while for the two other carbon strategies, it is about 7% compared to 'Business as Usual.

The HS2 case is considered based on the calculated value for the existing rail system's possible utilisation. Statistics for freight lifted and moved in the case of the maximum railway load reveals the situation with the current demand for 2017. There are some features, such as a percentage of freight carload and empty running, which could change over time; therefore, the level of maximum rail freight capacity would be higher if trains were loaded fully. This has also been supported in the study of Li and Zhang (2020) that the capacity of rail freight could be maximised if the trains are fully loaded.

Statistics and forecasts available for freight transportation mostly show rail and road transport are the most competitive; while airfreight is usually analysed separately, and seems insignificant, and was considered as supportive to the others, which may be caused by different features, strengths and weaknesses of air and land logistics. In the study of Tamannaei et al. (2021), it has also been argued that rail and road transportation are both considered most competitive for freight transportation. Capacity evaluation could be implemented by other reports or forecast analysis. Various statistics' data comparisons could derive the balance between passenger and freight rail usage for the existing system. LGV as a part of road transport could be analysed and freight transportation executed by different means, such as waterborne or pipelines.

Performance Measurement

Shifting freight from road to rail may positively affect the haulage industry and reduce congestion on the roads. This argument is also supported in the study of Pittman et al. (2020) that freight through rails can reduce the congestions on the roads. The share of railway freight is noticeably smaller than that of road transport; therefore, there is a probability that changes could be insignificant. The performance of rail freight transportation has a large potential to solve related to overall effectiveness, empty running and loads of railway carriages which could be improved by applying IT, new technologies and modern management techniques. Also, the study of Blagojević et al. (2020) argued that rail freight transportation could enhance the overall effectiveness of the transport industry. A framework for measuring the performance of a supply chain is presented in Supplementary Appendix S1.

Cost analysis for rail and road freight transportation, as displayed in **Figure 4**, shows that the maximum price for road transport is for the 'Business as Usual' and 'Carbon Survival' strategies, which the overall consumption of goods could cause, there is no ban on diesel and tax increases. The minimum cost for rail freight haulage is under the 'Carbon Survival' strategy, probably because of a shift to electric engines, technological development and tendencies in the market (Ehrenberger et al., 2021). The minimum cost for rail freight haulage is under the 'Carbon Survival' strategy, probably because of a shift to electric engines, technological development and tendencies in the market. There is no price information for air freight for the same strategies, but usually, this mode of transport costs are larger by four to five times (The World Bank, 2009). Airfreight logistics have speed, flexibility, convenience, regularity as advantages and high costs as a disadvantage (Tseng et al., 2005), while land logistics are much cheaper and have significantly different features.

Approximately 94% of freight trains arrived on time, whereas around 13–14% of road deliveries failed, revealing that rail freight transport is more reliable and has no dependence on road congestion. Therefore, all the time-related metrics evaluated for the HS2 case are favourable.

The HS2 construction will accompany transport hubs and stimulate new logistics centres that could directly affect companies' planning (Department for Transport, 2017). Reliable transport and warehouse accessibility allow increasing inventory turnover revealed by Tseng, which contributes to profitability, and hence flexibility, so responsiveness metrics are seen to be enhanced (Kamalahmadi et al., 2021).

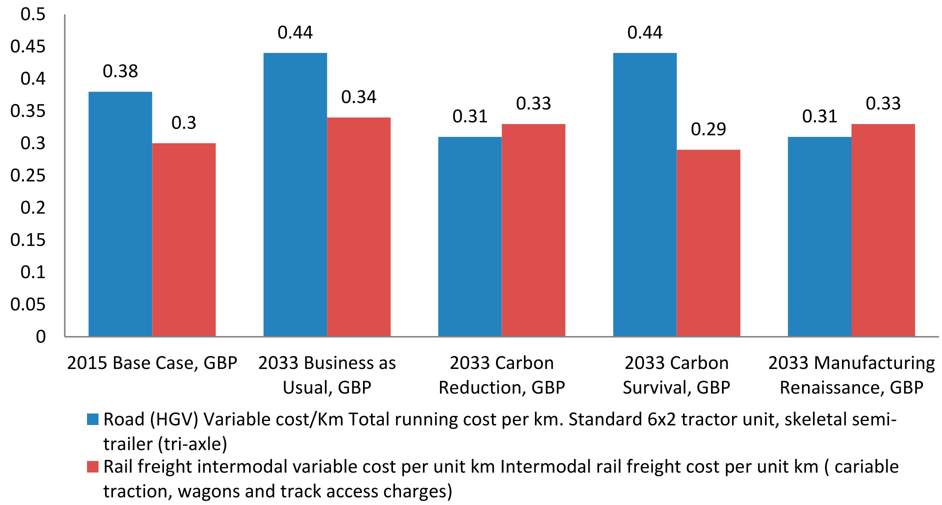

FIGURE 4 | Cost assumptions to the GB Freight Model.

TABLE 4 | Risk identification.

Stakeholders	Expectations	Risks
Freight transport	1) Congestion-free infrastructure	1) Freight share insignificance
Operators	2) Efficient goods delivery and collection	2) Lack of efficient growth in comparison with the current situation
—	3) Low-cost of transportation	—
Shipper	4) On-time deliveries to customers	3) Insensible effect on customer experience
—	5) Cost-effective transport service	4) Possible charges for the service at logistics centres
—	—	5) Late delivery due to congestion
National	6) Efficient use of strategic infrastructure	6) Insensible growth of efficiency
Government	7) Efficient goods delivery and collection	7) Little effect on road congestions due to rail freight share insignificance
—	8) Minimising externalities (CO2, congestion)	—
Infrastructure	9) Congestion-free infrastructure	8) Little effect on road congestions due to insignificance of rail freight share
Providers	10) Maximising revenue	9) Growth of expenditures/taxes
Citizens	11) Availability of a variety of goods	10) Insensible effect on customer experience
—	12) High quality of life	11) Overcrowded trains, noise from business/logistics' centres around
Customers	13) On-time deliveries	12) Insensible effect on customer experience, increased delivery cost
—	14) Short lead time	13) Insensible growth of lead time
Local	15) Well-being of residents	14) Noise and congestions around business/logistics' centres or railway path
Government	16) Efficient use of local infrastructure	15) Negative impact on uninterested stakeholders, business shift
—	17) Efficient goods delivery and collection	16) Lack of efficient growth in comparison with the current situation

It is possible that changes associated with customers would not be significant and may depend on information exchange about their deliveries. Modern technologies enable this to be carried out relatively high but could be improved with overall industry development. The risk identification presented in **Table 4** is based on stakeholders' expectations of failure. The proposed level of demand and load shows that the share of rail freight would be noticeably smaller; consequently, freight haulage as an industry could receive less significant benefits than passenger transportation.

Performance framework analysis provides an evaluation of HS2 construction in terms of metrics and basis. However, this approach could be improved by a deeper investigation of each element, and the possible impact could be expressed numerically (Elshaikh et al., 2018). In addition, the performance measurement of large United Kingdom companies working in the air/rail/road freight transportation industry, which is based on this technique, could be implemented to identify the possible impact of HS2.

Environmental Effect

Environmental effect analysis implemented in terms of carbon emissions shows that values for the HS2 case would be smaller than if there was no shift of freight from road to rail in all the strategies considered (as shown in **Table 5**). However, once actual results are received in the future, the impacts could be even less, as calculations in the research are executed based on current vehicle emissions, and the technological effects of new engines working on alternative energy sources were not considered. Total carbon emissions for air-rail-road freight transport are shown in **Figure 5**.

Total carbon emissions for the 'Business as Usual' strategy are the largest, whereas the lowest is for 'Manufacturing Renaissance',

TABLE 5 | Different emissions for stages.

	Business as usual	Manufacturing renaissance	Carbon reduction	Carbon survival
Forecast	58.7	48.9	50.6	50.7
HS2 case	48.9	40.4	41.2	41.7

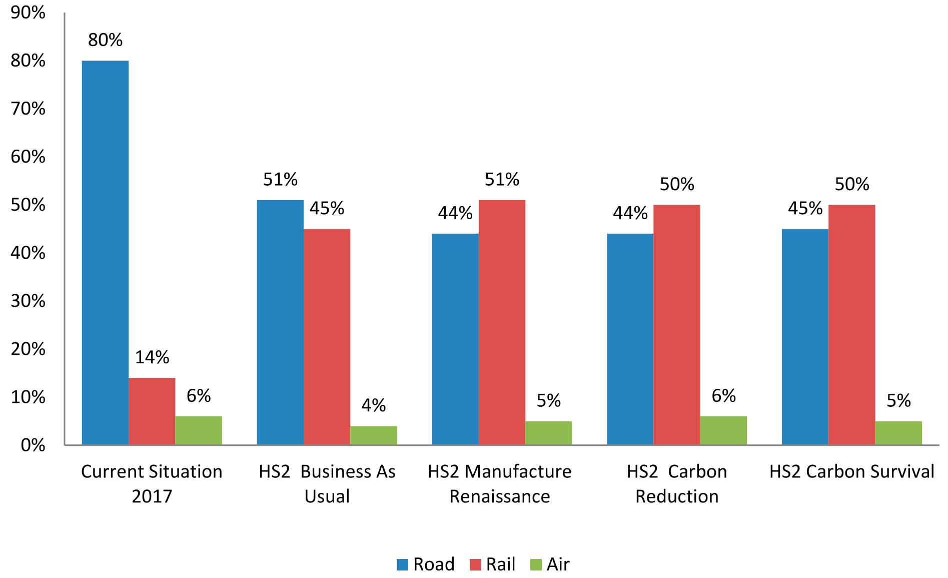

FIGURE 5 | Possible total reduction of carbon dioxide emissions.

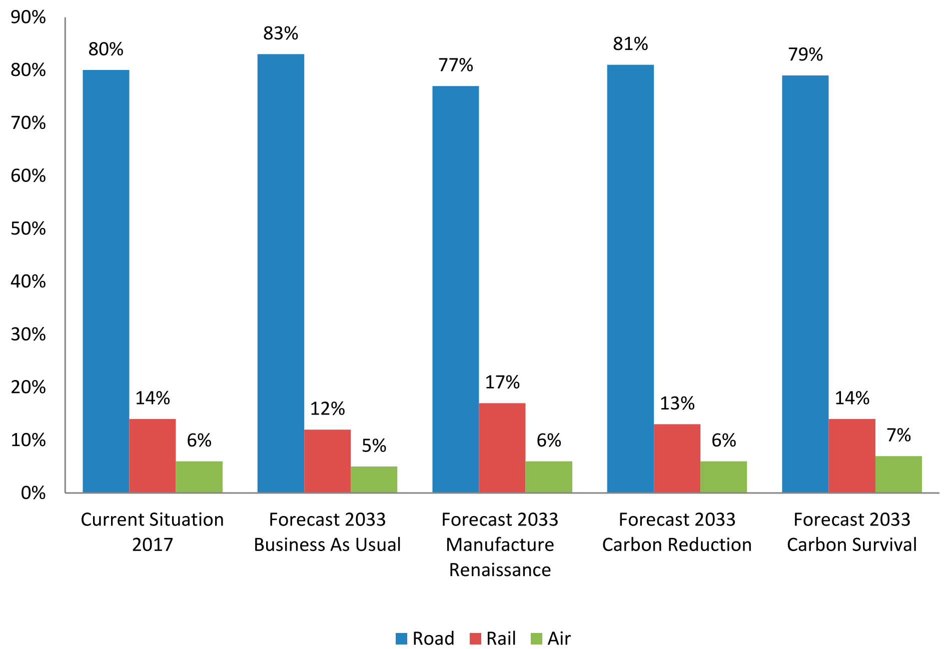

FIGURE 6 | Emissions of carbon dioxide.

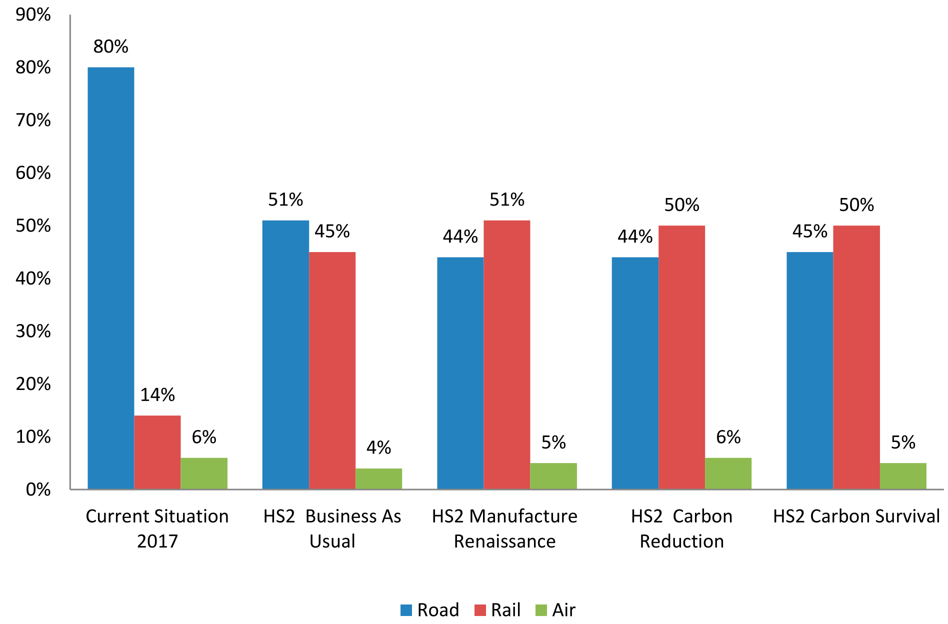

FIGURE 7 | Emissions of carbon dioxide HS2 for different situations.

which has insignificant distinctions with two carbon strategies. Forecasted data for the different strategies are shown in **Figure 6**, and for the HS2 case are shown in **Figure 7**. This distribution of shares may be due to economic and social trends, which are included in the characteristics of the strategies under consideration. Calculations of emissions show that road freight transportation produces 265 tonnes of carbon dioxide per 1,000 net tonne-kilometres, which is 2.3 times greater than rail transport. In addition, it is known that each tonne of freight moved by rail reduces carbon emissions by 76% in comparison with road transport, and a freight train may shift 43–76 HGVs from the roads (Department for Transport, 2016). Calculated emissions for airfreight transport are 71,429 tonnes per 1,000 net tonne-kilometres. Such a distinction could be caused by the small size of the freight and the high emissions from aircraft engines. This data once again confirms that air transport is significantly different from land transport, and with large 'emissions per unit of goods moved', it contributes the largest share of carbon emissions.

It is carbon dioxide and other types of emissions discharged by transport; therefore, future research could be improved by other available data analysis. Also, the potential effect of alternative energy sources, electric engines, and new technologies could be considered and the environmental impact for those cases analysed.

The data used in Supplementary Appendix S1 can be helpful in terms of determining the performance metrics concerning the level, i.e. strategic, tactical and operational. The financial and non-financial metrics provided against the performance metrics will help the project determine the importance and type. In this manner, the determination of risk mitigation strategies would be more effective as the company would already know the intensity of each performance metric.

CONCLUSION

This study is the world's first to investigate air-rail-road freight transportation and logistics to determine the possible effect of the HS2 project supply chains. The overall results indicate favourable but slight changes with a high potential for improvement. In particular, the capacity evaluation points out the growth of rail freight transportation from 5% to 14–16%, which could contribute to a decrease in road congestion, whereas the environmental effect, evaluated in carbon emissions, reveals a 17–19% reduction. Apart from the capacity evaluation and the environmental effect, economic factors should not be ignored. Airfreight represents the most expensive loop for freight transportation. Information is derived by comparison of the data from government reports and industry forecasts. To identify methods for supply chain analysis, relevant studies are considered, and a framework for performance measurement is chosen as the appropriate investigation approach. Alterations in performance do not seem directly linked to the HS2 railway construction and are associated with infrastructure and technological development. The research demonstrates that air cargo transportation does not appear to be noticeably affected by land freight haulages. HS2 has been presented to society as a project that could bring many benefits, but the research outcomes indicate that some of the advantages are questionable and may not justify those high expenditures. In terms of environmental impacts analysis, it has been analysed that HS2 shows smaller in case of no shift of freight from road to rail in all strategies. Moreover, there are also various types of emissions discharged by transportation. Therefore, there is a significant gap in identifying other variables that impact this emission. The impacts of alternative energy sources, such as electric engines, implementation of new technologies, and changes in the requirements should also be considered in conducting an in-depth analysis. There is a limitation to the research presented herein that only three modes of freight transport are considered. Therefore, it is suggested for future researchers to consider other transportation sources that would help them provide more significant findings concerning freight transportation.

Despite all the results presented, a possible effect of the HS2 construction could be evaluated by the utilisation of various approaches and additional data analysis. There are various modes of transport, such as LGV and waterborne, which occupy a share of freight haulage and could be considered. A survey of players from key industries in the United Kingdom could be executed to identify their vision of issues and uncertainties related to HS2. It is important to consider the possible effects of new technologies and the development of alternative energy sources. The method used in this research could be applied to evaluate the impact of a new transport project construction. Results and data from this study could also be utilised in future research on HS2. In addition to this, the construction of HS2 will also accompany the development of a transport hub and stimulate new logistics centres that can directly or indirectly impact the planning phase of the companies. However, the development of a reliable and effective transportation system and warehouse units can allow the increase in inventory turnover, which can positively contribute to the profitability and flexibility of the organisation. However, in terms of performance measurement, the research has examined that freight shifting from road to rail may positively impact the haulage industry and reduce congestion on the roads. There is a significant gap that has been investigated between the share of railway freight and road transportation. Therefore, the performance of rail freight transportation has a significant potential to solve overall effectiveness, empty running and load on railway carriages, however, to resolve such complexities and challenges, there is a need for significant information technology development and implement modern management techniques.

In terms of analysing the reasons for the construction of HS2 is to shift freight haulage from road transportation to rail transportation. In this way, the research study of Gunasekaran et al. (2001) has provided in-depth information related to supply chain analysis and relate it with performance management. In a similar manner, the research study of Chan (2003) also indicated that the analysis of supply chain has a significant connection with performance management and it improves the interaction of various parties because of significant supply chain analysis. While on the other hand, Yeo and Ren (2009) indicated that in terms of supply chain analysis, it is necessary to investigate the risks. However, in terms of performance measurement, Gunasekaran provided a list of non-financial and financial metrics. While Beamon (1998) also demonstrated that the metric for performance measurement evaluates the performance based on cost, flexibility, customers' responsiveness and cost and activity time. Furthermore, Elshaikh, Jiao & Yang (2018) indicated that performance framework analysis provides an evaluation of HS2 construction in terms of metrics and basis. However, this approach could be improved by a deeper investigation of each element, and the possible impact could be expressed numerically. It also has been analysed that the sensitivity analysis provides useful insight in terms of predicting outcomes of the decision. However, in terms of talking about sustainability, it has become a critical issue for companies and even for the government. The research study of Cucchiella et al. (2012) highlighted key drivers for private sectors in the United Kingdom, such as customers' requirements, reputational risks, organisational factors, functional issues and involvement of the stakeholders. In similar manners, Diabat and Govindan (2011) also indicated the significance of green supply chain management in terms of ensuring the implementation of effective strategies for sustainability. However, both the research studies have focused on different contexts. Therefore, these research studies have lack empirical evidence to investigate the actual importance of sustainability management. However, it also has been analysed that environmental carbon emission assessment demonstrates that values for the case HS2 would be less than if all the solutions studied do not include transfers of freight from road to train. But if real results are obtained in future, the impact might be even lower because study calculations are carried out based on current emissions from vehicles and no account was taken of the technological impact of new engines that function on alternative energy sources. The Capacity Evaluation enabled the "business as usual" strategy to be identified as carrying the biggest freight transport load with the smallest rail freight share; while the 'renaissance manufacturing' holds the lower freight level, with the largest rail freight capacity, due to the focus on international trading and advanced production technology.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, upon a reasonable request.

AUTHOR CONTRIBUTIONS

RL, AS, and SK developed the concept; RL, AS conducts data collection, curation and data analysis; All authors contributed to the manuscript; SK reviewed the paper. All authors wrote the paper. All authors have read and agree to the published version of the manuscript.

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