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Lateral Track Buckling in Sweden: Insights from Operators and Infrastructure Managers

Raheb Mirzanamadi [1,*], Erik Nyberg [1], Peter Torstensson [1,2] and Yvonne Andersson-Sköld [1,3]

[1] Swedish National Road and Transport Research Institute, VTI, SE-581 95 Linköping, Sweden; erik.nyberg@vti.se (E.N.); peter.torstensson@vti.se (P.T.); yvonne.andersson-skold@vti.se (Y.A.-S.)
[2] Department of Mechanics and Maritime Sciences/CHARMEC, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[3] Geology and Geotechnics, Department of Architecture and Civil Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
* Correspondence: raheb.mirzanamadi@vti.se

Abstract: Rail transport is expected to become a key component in the development of a long-term sustainable transport system. The planning, construction, operation, and maintenance of railway infrastructure are crucial in this effort. Hence, it is essential to ascertain that the railway infrastructure withstands and is adapted to extreme weather conditions and climate change. This study focuses on evaluating climate adaptation measures for lateral track buckling in Sweden. Through a literature review and interview with an expert at Swedish Transport Administration, it is highlighted that the maintenance status of railway infrastructure plays a significant role in the occurrence of lateral track buckling. According to the expert, inadequate track maintenance is the primary cause of lateral track buckling rather than weather variables like air temperature. The interview also clarifies that the chain of events related to the handling of track buckling is mainly initiated by the observation of a discrete lateral irregularity by a train driver, whereupon the train dispatcher at the traffic management center stops traffic until the location in the track has been inspected by a track entrepreneur. During the inspection, up to half of the observed cases of track buckling turn out to be false.

Keywords: lateral track buckling; climate change; climate adaptation; railway maintenance

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1. Introduction

Railway infrastructure plays a crucial role in modern society as a vital component of transportation. To establish a sustainable long-term transport system, it is imperative to carefully plan, construct, operate, and maintain railways [1]. One significant aspect to consider is to ascertain that railway infrastructure can withstand and adapt to extreme weather conditions and impacts of climate change. In Sweden, adverse weather conditions currently account for 5% to 10% of total railway infrastructure failures and contribute to 60% of delays in the railway transport system [2].

The effects of climate change on railway transport are influenced by various factors. These include the intensity, duration, and frequency of extreme weather events, as well as the structural characteristics of railway elements and their maintenance practices [3]. Additionally, the degree to which railway assets are adapted to handle extreme weather conditions also plays a crucial role [3].

Understanding the specific risks associated with each type of weather event is crucial for developing effective mitigation and preparedness strategies in rail operations. This comprehensive examination of the impacts of various weather hazards on rail infrastructure provides valuable insights into the challenges faced in maintaining an efficient and resilient transportation network.

Extreme weather events such as high and low temperatures, excessive precipitation, windstorms, and rising water levels have a profound impact on the transportation system

and can, in severe cases, cause infrastructure failures and damage to signal and electrical equipment. These disruptions can ultimately result in delays and even derailments [2,4–7]. For a comprehensive understanding, Table 1 provides a summary of the adverse effects of extreme weather conditions on railway infrastructure.

Table 1. Examples of the physical relationships between weather phenomena, associated hazards, and their possible adverse effects on railway infrastructure [2,4–7].

Event	Weather Hazard	Potential Impact on Transport System
Temperature	High temperatures, heatwaves, zero-temperature crossings	Thermal expansion in rail structures, lateral track buckling, line closure, lower operating speeds, inaccurate signaling and power wayside systems, reduction in outside working hours [2,5]
	Low temperatures, snow, ice, frost, freeze–thaw, permafrost degradation	Clogged areas form trees, snow maintenance, tunnel icing, cracking/breakage of rails, damage to overhead lines and signal equipment [2,5]
Precipitation	Intensive rainfall/flooding	Destruction of rail and bridge structures, bridge scour, flooding of underground rail transport systems, embankment collapse, landslips, erosion, slush flow avalanches, reduction in visibility and planned work, damage to drainage system, water damage to electronic equipment and supporting poles [6]
	Precipitation deficit	Drought, drying of soil, shrinkage cracking, landslide, instability of soil, infrastructure slope failure, fires over trackside due to destruction of electrical equipment, settlement of rail structures [5,6]
Wind	Windstorms/gales	Tree fall, reduction in visibility and planned work, structure instability, destruction of signal and electrical equipment, damage to pipelines [2,7]
Sea level	Changes in extreme coastal water levels, coastal flooding, wave overtopping, tidal river floods	Damage to rail structure, tunnel and track flooding, reduction in maintenance windows, improper structural inspections, bridge scour, corrosion [4,6]

Cold temperatures induce tensional forces in rails, while hot temperatures lead to contraction forces [4]. Contraction forces have the potential to cause rail breaks, while dilatation forces can result in track deformation [8]. These temperature-induced effects are particularly significant for continuous welded rail tracks, which have been widely adopted across Europe over the past 30 years [4,9,10]. According to Swedish Transport Administration (STA) [11], a localized lateral track deformation with a displacement of at least 25 mm per 10 m length, where heat is the triggering factor, is called lateral track buckling. Figure 1 displays images of lateral track buckling in continuously welded rail on concrete and timber sleepers in Sweden.

Figure 1. (**Left**) Lateral track buckling related to continuously welded rail on concrete sleepers in summer 2020, and (**right**) lateral track buckling related to continuously welded rail on timber sleepers in summer 2021 (photos provided by STA).

Lateral track buckling can have significant consequences, leading to delays and potentially catastrophic derailments. In the United States, statistical data from a five-year period between 1998 and 2002 revealed an average of 38 derailments per year, with damages reaching as high as USD 17 million in 2002 [8]. In the United Kingdom, future projections indicate that the cost of heat-related delays and lateral track buckling during extreme summers, under a high emissions scenario in the 2080s, could range between GBP £23 and £54 million [5]. These examples highlight the financial and operational impacts associated with buckling incidents in railway systems.

Although, plenty of work has been carried out by researchers [2–4,6,12,13] and the Swedish Transport Administration (STA) [10,14–21] to address the lateral track buckling, these studies primarily focused on specific subjects such as railway track maintenance or the impact of climate change on rail transport, or were merely a literature review. However, these studies and reports lack a holistic perspective and insights from traffic operators and infrastructure managers, which are crucial for a comprehensive understanding of the issue.

This study is aimed at understanding the measures currently implemented and those recommended for future use in managing the lateral buckling of rail tracks in Sweden as well as internationally. In this paper, we review the relevant literature concerning important mechanical properties and mitigation measures associated with lateral track buckling. Additionally, we present the knowledge acquired through the long-term efforts of the STA and other rail administrators in addressing lateral track buckling on the track networks. To gain insights from traffic operators and infrastructure managers, we conducted semi-structured interviews with an experienced expert at the STA and a former track driver.

This study is performed as part of the activities in a project with the objective of developing a method for the evaluation of climate adaptation measures of transport infrastructure based on socio-economic efficiency [22].

2. Method

This current study presents an analysis performed based on data provided by the STA as well as related works carried out in order to reduce lateral track buckling risks. This study focuses on the significance of the mechanical properties of the track structure in relation to lateral track buckling, and explores the measures implemented in Sweden to mitigate such events. Moreover, complementary interviews with an expert from the STA and a former train driver have been conducted.

This full project has gained access to data on rail traffic disruptions caused by weather-related events during the period 2010–2020 [23]. The data, which list train delays, are based on certain search words and terms on weather-related events, such as flooding and lateral track buckling. Delays are measured compared to the trains' timetables but do not, e.g., account for the cancellation of trains and sequential consequences. The data are used in an assessment to estimate the socio-economic cost due to lateral track buckling as well as other weather-related incidents such as fire and strong winds. For more details, the reader is referred to [22].

The interviews were based on a semi-structured interview method. In semi-structured interviews, the researcher prepares questions to focus on during the interview. However, the interview process remains open, allowing for changes in the order of questions and the emergence of new questions based on the answers provided by the interviewees [24]. The interview with the expert from the STA lasted approximately 120 min and was conducted through a face-to-face meeting. The interview was divided into six main categories: (i) measures used by STA to manage the risk of buckling in rail tracks, (ii) effectiveness of these measures, (iii) ranking of the measures, (iv) effects of climate changes on lateral track buckling, (v) cost of implementing the measures, and (vi) any additional comments. It is important to note that the answers to the questions were based on the interviewee's experiences and knowledge and available data and reports at STA, and therefore some categories may not have been covered comprehensively. Additionally, a 60 min online interview was conducted with a former train driver. The interview aimed at exploring the

initial stage of reporting when a potential lateral track buckling defect is identified during train operation. Both respondents have approved minutes from the interviews.

3. Results and Discussion

This section is divided into three subsections: (i) important mechanical properties and mitigation measures, (ii) lateral track buckling on the Swedish track network, and (iii) the interview.

3.1. Important Mechanical Properties and Mitigation Measures

The occurrence of buckling is influenced by various factors, including rail profile, fastening type, sleeper type, curve radius, and ballast profile [4,9]. The mechanisms and factors that influence the occurrence of lateral track buckling can be classified into two groups: resisting buckling and promoting buckling [9]. The resisting buckling category encompasses four components: (i) rail, (ii) sleeper, (iii) rail and sleeper fastening, and (iv) ballast. On the other hand, promoting buckling involves six components: (i) thermal forces, (ii) rail creep, (iii) designed rail neutral temperature, (iv) lateral discrete track irregularity, (v) rolling out of rail, and (vi) dynamic wheel–rail contact loads. A brief description of each component is given in Table 2.

Table 2. A brief description of each component related to resisting buckling and promoting buckling.

Group	Description
resisting buckling	Rail: The stiffness of steel rail provides lateral resistance [9]. For a constant length of a material, increasing the rail section size improves buckling resistance [25], but it does not impact thermal expansion. Thermal expansion depends on material properties [1]. Hence, larger rail sizes do not necessarily reduce buckling risk in continuous welded rail tracks [9]. Buckling occurrence is influenced by rail stiffness and applied load [25].
	Sleeper: The type, size, shape, weight, and spacing of sleepers impact the lateral resistance of ballasted tracks [26]. Different sleeper types, including concrete, steel, and timber, provide varying levels of lateral resistance. Concrete sleepers exhibit approximately 50% higher lateral resistance compared to steel sleepers, and they demonstrate roughly 80% higher lateral resistance than timber sleepers [27]. Additionally, steel sleepers present around 20% greater lateral resistance than timber sleepers [27]. Previous observations worldwide indicate that buckling commonly occurs in conventional ballasted tracks with timber sleepers [28]. On the other hand, using concrete sleepers can improve lateral resistance by an average of about 50%, although the specific value may vary depending on the type of concrete sleepers [26].
	Rail and sleeper fastening: Rail fastenings are crucial for providing torsional, lateral, and longitudinal strength to maintain track stability [8]. A stronger connection between the rail and sleepers enhances the rigidity of the rail track, resulting in increased resistance to buckling due to the formation of a ladder-like structure [9]. The torsional fastening resistance in concrete sleeper tracks has minimal impact on buckling resistance, whereas, in timber sleeper tracks, it has the potential to improve buckling resistance [28].
	Ballast: Comprising coarse-grained and angular materials provides resistance against compressive forces. The section of ballast packed at the end of sleepers is called shoulder or shoulder ballast, while the portion packed between sleepers is referred to as crib ballast [4]. Lateral resistance depends on shoulder and crib ballast, friction between sleeper and ballast, and sleeper characteristics [26,28]. Proper drainage and cleanliness of ballast, free from finer particles, are necessary to prevent water accumulation around sleepers, maintain ballast integrity, and prevent sleeper pumping, which in turn results in reduced lateral resistance [9]. Maintenance activities like tamping and sleeper replacement can impact ballast compaction, leading to reduced lateral resistance [26].
Promoting buckling	Thermal forces: Rail neutral temperature (RNT), also known as stress-free temperature (SFT), refers to the temperature at which rail tracks experience neither tension nor compression stresses [29]. When longitudinal movement is restricted at both ends, rail tracks are under compression stress when the rail temperature exceeds SFT and under tension stress when the rail temperature is below SFT [30]. Significant temperature changes above or below SFT can result in rail breaks or lateral track buckling, respectively.

Table 2. *Cont.*

Group	Description
Promoting buckling	Rail creep: Creep refers to the longitudinal movements of rail relative to sleepers or rail and sleepers relative to the ballast bed [9,29]. It occurs when thermal and dynamic forces, such as acceleration and braking, overcome the resistance to rail movement [29]. Creep induces compressive forces in some parts of the track and tension in others [9]. It not only disrupts the track structure but also alters the SFT (7). This disruption reduces resistance to lateral loads [9] and increases the risk of buckling and rail breaks [29]. QR National/Aurizon railway company in Australia [31] imposes a limit of 50 mm for total net rail creep over a 500 m section.
	Designed Rail Neutral Temperature (DNT): This refers to the stress-free temperature (SFT) during the design phase of rail tracks [9]. Initially, DNT and SFT are expected to be equal when the rail is laid and installed [9,29]. The DNT is influenced by factors such as maximum and minimum ambient temperature, local and seasonal conditions, geographical location, track shading, orientation, and the history of track buckling and rail breaks [1]. Factors like creep, track settlement, and maintenance practices can cause changes in the SFT [9]. A decrease in the SFT compared to the DNT increases the risk of track buckling, while an increase in the SFT compared to the DNT increases the risk of track breaks [9,29].
	Lateral discrete track irregularity: A perfectly straight track structure, without imperfections, is theoretically resistant to buckling even under extreme temperature changes [28]. However, initiating lateral irregularities requires the presence of initial imperfections. It is important to note that track buckling often begins at points with incorrect stress adjustment, track geometry issues, or low lateral resistance. These points typically include insulated joints, changes in track curvature, and areas with defective welds [9,28]. The extent of discrete irregularities directly correlates with an increased risk for buckling. Addressing lateral imperfections is best carried out during summer or early winter when rails tend to realign after the winter period [31]. QR National/Aurizon railway company in Australia sets a maximum limit of 50 mm for lateral displacement over a 100 m length [31].
	Rolling out of rail: Surface-initiated rolling contact fatigue cracks in rails are initiated by plastic deformation in the wheel–rail contact area [12]. Elongation and plastic deformation of the rail head can alter residual tensile stresses into compression stresses [25]. Rolling out of rail commonly happens in newly constructed or re-profiled tracks and can decrease the SFT by up to 9 °C [9,31].
	Dynamic wheel–rail contact loads: Loads developed in the wheel–rail contact cause the mechanical degradation of both rails and wheels [12]. Amplified dynamic wheel–rail contact forces, including emergency braking and heavy dynamic braking, can trigger lateral track buckling [4,8]. Fast-moving and heavily loaded trains create uplift waves that increase the risk of buckling [8]. Additionally, the lateral wheel–rail contact forces caused, for example, during curving generate bending stresses that increase the risk of lateral track buckling [31].

Lateral rack buckling mitigation measures can be classified into two categories: preventive measures and adaptation measures [4–6]. The preventive measures include three components: (i) identification of areas and structures with high risk to buckling, (ii) preventive actions to reduce compressive stresses in rails, and (iii) applying a speed limit. Furthermore, adaptation measures involve three components: (i) the prediction of exposure to lateral track buckling, (ii) reduction in vulnerability of assets, and (iii) effect of a failure. A brief description of each component is given in Table 3.

Table 3. A brief description of components for reduction in lateral track buckling risks.

Group	Description
Preventive	Identification of risky area: Analyzing previous data, information, and statistics from past buckling events can provide valuable insights for identifying susceptible areas and rail structures prone to buckling [6]. These data may include rail temperatures, STF, rail profile, curve radius, initial misalignments, ballast profile, and fastening/sleeper types and conditions, as well as data related to lateral, torsional, and longitudinal resistances [9,32].
	Preventive actions: The regular monitoring of rail temperature and track alignment is essential for minimizing compressive stresses in rails [8]. Factors such as ambient temperature, humidity, wind intensity, and solar radiation influence rail temperature [4]. Implementing measures like shade trees or rail painting, such as using white paint, can significantly reduce rail temperature [29]. Monitoring and adjusting rails to the appropriate DNT are important due to potential deviations from the SFT caused by factors like settlement, creep, and maintenance activities [9,29]. Rails are more stable under tension stresses below the SFT [9]. Choosing a higher DNT suited to the rail's environmental conditions can effectively reduce compressive stresses [4,13,31].

Table 3. *Cont.*

Group	Description
Preventive	Speed limit: By imposing a speed limit, a specific threshold for rail temperature is established to mitigate compressive stresses on the rails [33]. A commonly used approximation suggests that rail temperature is approximately 1.5 times the ambient air temperature. In the UK and Australia, speed restrictions are imposed when the air temperature exceeds 36 °C, regardless of rail temperature [4,34]. For lower air temperatures, speed limits depend on the condition of the ballast. The allowable speed limit is narrower for tracks with good ballast compared to those with inadequate ballast. Although speed restrictions are effective in mitigating the risk of derailment, they can have several drawbacks, including delays, longer transit times, a reduced capacity for goods and passenger transfers, and increased operational costs [4,6].
Adaptation	Prediction of lateral track buckling: Prediction methods are often more cost-effective than continuous monitoring practices [6]. As climate change leads to elevated temperatures, it can disrupt rail networks extensively [1]. However, measuring rail temperature can be expensive, limiting the feasibility of monitoring. Therefore, it is crucial to develop reliable technologies and methods for weather forecasting and rail temperature prediction. For instance, Sanchis. V. I. et al. [1] utilized Monte Carlo simulations to predict future buckling events for the Spanish rail network. Their findings highlighted a significant increase in the number of buckling events if current standards and maintenance procedures remain unchanged.
	Reduction in vulnerability: Factors such as ballast condition, track condition, and lateral movements play a significant role in the buckling process, rather than just higher rail temperatures [1,4]. To mitigate risks associated with extreme weather events and climate change, it is important to adapt railway infrastructures through changes in design, operating practices, and staff training [5]. Strategies such as incorporating wider ballast shoulders, fuller crib levels, alternative fastening methods, and different sleeper types can enhance buckling safety [26,27,32]. Additionally, selecting a higher DNT appropriate for the environmental and practical conditions can reduce compressive stresses and buckling events [13]. Maintenance practices also play a crucial role in preserving the SFT during repairs and ballast resurfacing [4,31]. Improved maintenance routines and timetables, considering location and climate changes, are necessary [4].
	Effect of a failure: Upon occurrence of buckling and disruption of the infrastructure, providing an alternative service route can be helpful to reduce the pressure on the rail transport network [5].

3.2. Lateral Track Buckling on Swedish Track Network

Based on data from the STA, Sweden's rail network experienced more than 998 instances of lateral track buckling between 2008 and 2022 [11]. These occurrences are found to be highly dependent on temperature fluctuations [11]. Figure 2 displays the total train delays attributed to lateral track buckling incidents between 2010 and 2020, alongside the corresponding maximum air temperatures in Sweden during the same period. Train delay data were extracted from the Swedish Transport Administration's database, Ofelia [23], and air temperature data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) [35]. A clear relationship between train delays caused by lateral track buckling and maximum air temperatures is observed. In Figure 3, train delays versus maximum air temperatures is shown for five different regions (north, south, middle, west, and east) individually. Notably, in all regions, an increase in maximum air temperature corresponds to an increase in the risk of lateral track buckling.

Historically, the primary causes of lateral track buckling incidents in Sweden have been identified as (i) inadequate ballast, (ii) material shortage or other deviations such as incorrect or unknown stress-free temperatures, incorrect insulated rail joints, absence or damage to track components (rail, fastenings and sleepers), and significant lateral track irregularity, and (iii) maintenance work that can impact rail track stability or alter stress-free temperatures [19]. Figure 4 shows the causes of lateral track buckling in Sweden between 2017 and 2022 [11,15–19]. As can be seen, inadequate ballast was consistently identified as the primary cause of track buckling incidents in 2018, 2020, and 2021. In 2017, maintenance work was the primary cause and, in 2019, material shortages took precedence. Interestingly, in 2022, none of these causes emerged as the predominant reason, highlighting the need for future research to gain a deeper understanding of lateral track buckling issues in Sweden.

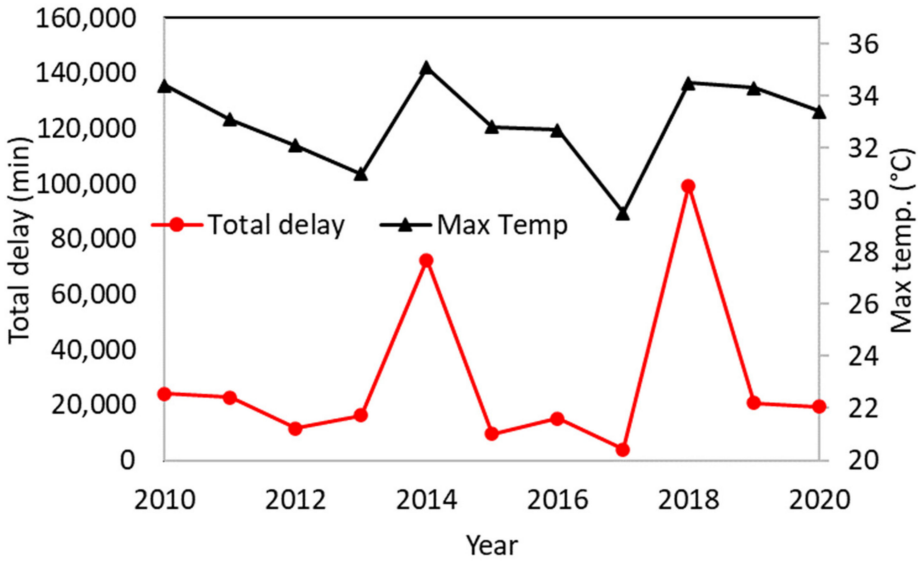

Figure 2. The total delay of Swedish rail traffic due to the occurrence of lateral track buckling and the corresponding maximum air temperatures during the period of 2010–2020.

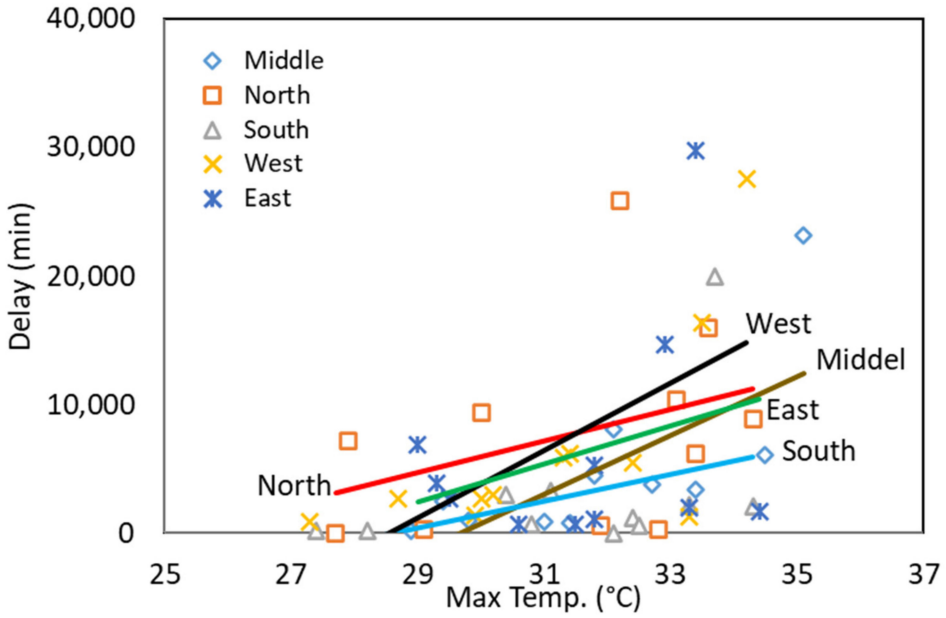

Figure 3. The relationship between delays in Swedish rail traffic across various regions caused by lateral track buckling and the corresponding maximum air temperatures.

Regardless of the cause of lateral track buckling, the data [11,15–19] indicate that railway tracks with timber sleepers, especially with continuously welded rails, are more exposed to lateral track buckling; see Figure 5. It is noteworthy that this finding aligns with results in the literature, which also highlighted a greater risk of lateral track buckling for railway tracks constructed with timber sleepers compared to those with concrete sleepers [4].

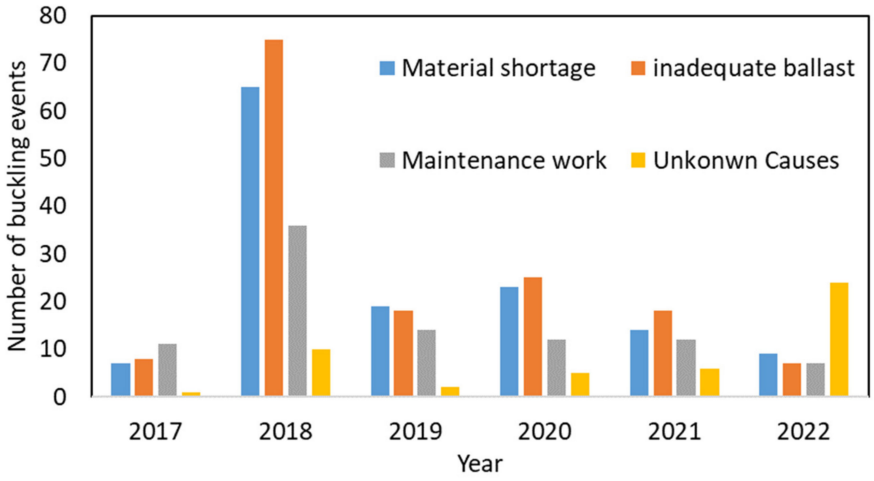

Figure 4. Causes of lateral track buckling in Sweden between 2017 and 2022 [11,15–19].

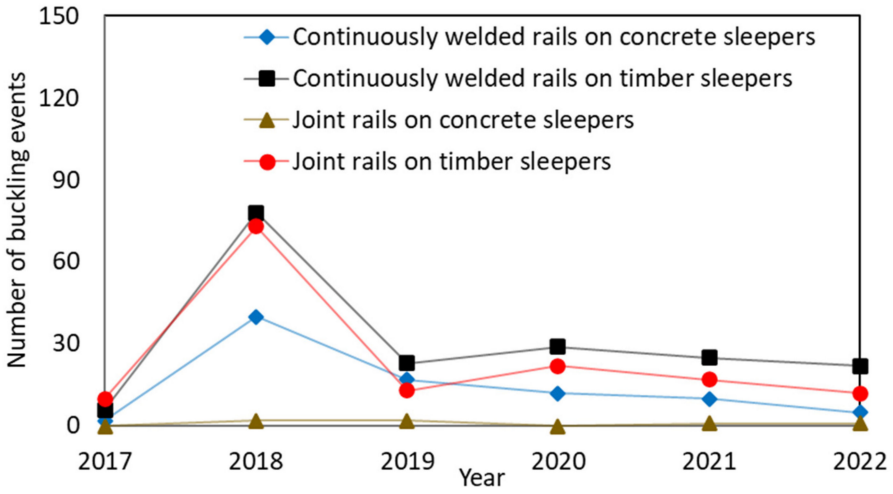

Figure 5. Number of lateral track buckling occurrences from 2017 to 2022, considering track constructed with continuously and joint rails mounted on timber and concrete sleepers, respectively.

Following the significant number of observed buckling problems in the Swedish rail network during the hot summer of 2018, the STA formulated an action plan to enhance maintenance practices, improve reporting procedures, identify high-risk areas susceptible to lateral track buckling, and propose specific measures aimed at reducing future buckling problems [36]. Since then, the STA has placed increased emphasis on the construction and maintenance of track with joint rails [18]. Furthermore, in 2019, the STA initiated work on developing a risk model to evaluate the impact of lateral track buckling with the objective to establish guidelines for traffic operation, determining when and where traffic disrupting measures such as speed limitations should be implemented [16]. Additionally, starting from 2021, the control of stress-free temperature has been integrated into maintenance contracts to develop an effective strategy that involves the maintenance entrepreneurs in the work to reduce the risk of lateral track buckling occurrences. For further details, readers are referred to [16,18,19].

Measures to address lateral track buckling on the railway network managed by the STA are introduced in TRVINFRA-00012 [20,37]. The document provides information about rail neutral temperature and stress-free temperatures in different parts of Sweden. It also specifies permissible rail temperatures during the construction and inspection of rails when temperatures are expected to exceed 30 °C. Measures to be taken if lateral track buckling occurs for both track with continuous welded rails and joint rails are considered. The supplementary document TRVINFRA-00014 [38] outlines measures aimed at reducing the

risk of lateral track buckling for newly constructed or recently maintained tracks. Prescribed measures herein should be implemented until the track has been stabilized (subjected to an accumulated traffic load of 100,000 gross tons). Prior to achieving full stabilization, it is required to impose speed restrictions or limitations on the allowed axle load [38]. For further details on the permitted vehicle speeds on track subjected to different levels of accumulated traffic loads, the reader is referenced to Section 10 of TRVINFRA-00014 [38].

In 2018, the STA received reports of a total of 416 suspected incidents of lateral track buckling out of which 200 cases were confirmed as cases of lateral track buckling [18]. In 2019, there were 91 reported cases, and out of those, 55 were confirmed as actual cases of lateral track buckling [16]. In 2020 [17] and 2021 [19], there were 63 and 53 confirmed cases of lateral track buckling out of a total of 120 and 116 received reports, respectively. The data reveal that, on average, approximately 50% of reported observations are finally identified as actual cases of lateral track buckling. Thus, enhancing the system to identify/report incidents of lateral track buckling has the potential to reduce costs associated with train delays [16–19]. TDOK 2014:0667 [21] outlines a flow chart for reporting and registering incidents of lateral track buckling. The flow chart comprises six main steps, including reporting suspected buckling problems, registering in the database of traffic disruptions Ofelia [23], evaluating and reporting the problem to the maintenance contractor, reviewing the accuracy of the registration and reporting in Ofelia, providing information to the national statistics and analysis center, and ultimately collecting all reports related to lateral track buckling at the national level. Suspected incidents of lateral track buckling can be reported by various actors such as train drivers, maintenance inspectors, and the general public [21,23].

3.3. Interview

The expert from the STA highlighted that measures aimed at preventing or reducing the risk of lateral track buckling are integral to the comprehensive maintenance plan for the entire rail network. The STA's approach is primarily focused on mitigation measures, given the limited information available regarding the stress-free temperature of rails. This approach includes accurate maintenance to reduce the risk of lateral track buckling. Notable progress has been made using laser scanners to assess ballast conditions, a task previously reliant on visual inspections. This technological enhancement improves the precision and effectiveness of maintenance activities. Furthermore, the STA has initiated the collection of data related to the stress-free temperature of rails within the Baninformationssystemet (BIS), addressing the knowledge gap in this crucial area.

The STA leverages documents such as TRVINFRA-00012 [20,37], providing valuable guidance and recommendations for managing lateral track buckling issues. These documents offer specific actions and expert advice to inform decision making and actions. In addition, the STA utilizes documents like TRVINFRA-00014 [38], which outline requirements and provide guidance for the stability of track constructions, ensuring the integrity of the rail infrastructure. Recognizing the importance of knowledge enhancement, the STA invests in training programs for personnel involved in measures that impact track stability. This ongoing training supports their expertise and effectiveness in addressing lateral track buckling concerns. In addition, the STA has collected a vast volume of data, the analysis of which poses a considerable challenge. This data analysis has the potential to improve problem identification along the rail track, paving the way for more advanced and data-driven methods to handle lateral rail buckling issues.

One of the challenges in improving the effectiveness of lateral track buckling measures is the accuracy of temperature forecasts provided by the SMHI, primarily consisting of average temperature values, which may not be highly effective for managing local buckling problems. Furthermore, the effectiveness of the measures undertaken greatly depends on the quality and extent of work performed by contractors. The level of work that they deliver plays a pivotal role in the success of these measures, especially in urgent cases. In cases where multiple buckling incidents occur concurrently, the STA takes immediate action with

urgent measures. However, these measures are often viewed as short-term solutions and may not offer a sustainable, long-term resolution to the issue. The timing of these measures is critical to their effectiveness. For example, an urgent need to replace sleepers outside of the planned schedule can inadvertently increase the risk of future buckling incidents.

The reporting system for maintenance work that may impact track stability needs an update. Currently, there is no special reporting of this type of measure. Addressing this gap in the reporting system is essential for providing a more comprehensive overview of ongoing maintenance with potential impact on risk for lateral track buckling. In preparation for the future, climate forecasts are expected to evolve by incorporating extreme values, including extreme temperatures. This adaptation will provide a more comprehensive and accurate outlook, enabling better preparation for buckling issues arising from temperature extremes. The STA acknowledges the need for a systematic plan to effectively manage buckling problems. Such a plan will promote a proactive approach to implementing appropriate measures, ensuring a more efficient and well-coordinated response to lateral rail buckling concerns.

Ranking measures for addressing buckling incidents poses a significant challenge, primarily attributed to the sporadic geographic occurrence of these incidents. Unlike many other issues that exhibit consistent patterns, buckling events can occur unexpectedly in various locations, making it challenging to establish a uniform ranking system. Looking ahead, there is a growing recognition that a more comprehensive and systematic plan is necessary to effectively prioritize measures related to track infrastructure. By establishing such a plan, it becomes possible to methodically address and prioritize measures for lateral track buckling. One approach within this plan may involve setting specific criteria and considerations for prioritizing actions, such as the replacement of timber sleepers under continuous welded rails. While past practices have leaned toward budget-driven prioritization, the future vision acknowledges the need for a more informed and strategic approach to measure ranking. This approach aims to optimize resources and enhance the overall resilience of the rail track, ensuring a more proactive and structured response to potential buckling challenges.

STA has put primary emphasis on gathering comprehensive information related to lateral track buckling incidents. This data-centric approach facilitates a more informed and tailored response to buckling issues. Furthermore, it is important to recognize that buckling problems extend beyond being solely weather-related. While temperature fluctuations can certainly trigger these incidents, they are inherently linked with maintenance-related considerations. A holistic perspective acknowledges the multifaceted nature of lateral track buckling and the need to address both weather and maintenance aspects. The timing of maintenance and, in particular, actions that impact track stability, is vital in the effective management of buckling incidents, especially in the context of climate change and the rising occurrence of warmer days.

The economic implications of buckling problems within railway systems can exhibit a broad spectrum of costs, varying from relatively modest expenses to considerably significant investments required for improvement. For instance, in the event of a derailment, substantial damage may occur. The establishment of a temporary clearance route to the accident site incurs a substantial cost. This cost is separate from the expenses associated with the derailed train, its cargo, and the infrastructure, as well as the delays and traffic disruptions. However, it is crucial to note that despite the evident financial impact, the STA currently lacks extensive information concerning the broader social and economic dimensions of buckling in railways.

Historically, the STA struggled with limited knowledge regarding the stress-free temperatures in many rail sections, which posed a challenge in effectively managing the risk of buckling incidents. The absence of comprehensive data on stress-free temperatures hindered the STA's ability to proactively address temperature-related issues in rail systems. Furthermore, the STA held the belief that specific hotspots were more prone to buckling incidents, for example, curves with radii smaller than 700 m or sections near fixed points

such as track switches, bridges, level crossings, and platforms. However, it has become evident that the occurrence of buckling varies from year to year, and the factors contributing to these events are multifaceted. Geography and the structural characteristics of rail tracks have a pivotal influence on the occurrence of buckling, challenging the idea that buckling only happens in specific areas.

According to the interviewee, during warm summers, approximately 90% of reported suspected buckling problems are confirmed as real buckling issues. In contrast, during typical summers, this confirmation rate is approximately 50%. One of the reasons for incorrect reports of lateral buckling is the complexity of identifying these problems while operating a train. Safety takes precedence over effectiveness. If train drivers perceive any unsafe situations during their journeys, they prioritize reporting them. However, this emphasis on safety can sometimes result in an increase in the number of incorrect reports that turn out to be false or unrelated to actual buckling issues.

Train drivers report the incidents of lateral track buckling through two main methods: visual observation and sensory perception. The high operating speed of passenger trains makes visual detection of buckling problems extremely difficult. However, for vehicles operating at lower speeds such as freight trains, visual identification is relatively easier. Alternatively, the discrete lateral track irregularity/buckling is perceived as a transient lateral acceleration in the drivers compartment as the train passes over the current spot. The ability to identify possible cases of lateral track buckling largely relies on the experience of the train driver. Train drivers often find it easier to assess the condition of the opposite track compared to the track that their train is running on. This is primarily due to the positioning and visibility from the driver's perspective. When operating a train, the view of the opposite track is generally more accessible and provides better visibility, allowing drivers to observe any potential issues or abnormalities more easily.

The reported location of an identified case of lateral track buckling is typically approximate, as there is currently no system on the train to record its exact location. One way to compensate for this deficiency is to increase the frequency of track-side inspections. While manual inspections may not offer real-time detection, they serve as a compensatory approach to ensure that incidents of lateral track buckling are identified and addressed in a timely manner. The new European signal safety system RTMS (Railway Traffic Management System) under implementation on the Swedish rail network will assist train drivers in accurately reporting the exact location of incidents. The respondent mentions that the accuracy of reported cases of lateral track buckling can be increased through improved education of train drivers. However, the potential is commented to be moderate due to the fact that the teaching of train drivers primarily emphasizes theoretical knowledge rather than practical experience. One approach to enhance the effectiveness of education is using simulators. However, the implementation of simulators can be costly and, currently, there is a lack of specialized simulators with dynamic and movable features available in Sweden for training train drivers.

The STA holds the responsibility of determining whether a report of lateral track buckling is correct or not, which can assess the severity of the situation. When evaluating the urgency of a reported incidence, the STA considers various factors, including the frequency of reports from a particular location and the level of traffic in that area. If a location with high traffic consistently reports problems within a short time period, the STA is likely to take faster action. This approach allows the STA to prioritize their response and allocate resources to address lateral track buckling effectively.

4. Conclusions

Incidents of lateral track buckling can lead to significant delays and, in some cases, complete halts in rail traffic. For instance, in Sweden, between 2010 and 2020, there were 759 instances of lateral track buckling, resulting in an average annual delay of 28,820 min in rail traffic. Various factors such as geography, the structural characteristics of rail tracks, and climate conditions can influence the occurrence of lateral track buckling from year to

year, making it challenging to predict the specific locations where buckling may happen. Despite the various causes of lateral track buckling, it is noteworthy that railway tracks with timber sleepers, especially those with continuously welded rails, are particularly susceptible to lateral track buckling.

To better understand the causes of lateral track buckling, additional and less aggregated data need to be collected, and the relationships between track buckling and weather conditions, as well as technical aspects, need to be analyzed in depth. Furthermore, it is important to develop effective reporting systems, improve training, and integrate new technologies. For example, in this study, approximately 50% of the reported suspected lateral track buckling incidents are found to be incorrect. Despite the need for updating the buckling incident reporting system, it is important to develop a special reporting system for maintenance work performed by contractors, as maintenance work can impact track stability and lateral track buckling. An enhanced reporting system would benefit from being combined with more automatic monitoring, such as laser scanners for ballast monitoring. Additionally, the current inspection and reporting system could be improved through more frequent and standardized reporting.

To prepare for and minimize the consequences of long-lasting and extreme weather events, especially those affecting lateral track buckling, proactive measures are essential. To implement these measures, a deeper collaboration with meteorological institutes is needed to obtain climate prognoses. For lateral track buckling, such data should include the value and duration of expected maximum temperatures, as well as long- and short-wave radiation at track locations. Furthermore, a more detailed understanding of the relationship between rail temperature and ambient air temperature is required.

Ranking measures used to address lateral track buckling incidents is challenging, primarily due to their sporadic nature of occurrences and unpredictable emergence in various locations. Historical data alone may not be sufficient for ranking measures, with urgent situations often taking precedence. Moreover, factors such as budget constraints and the timing of maintenance and stabilization efforts, especially in the face of climate change, influence the effectiveness of the measures implemented. Hence, it is necessary to develop a systematic plan to effectively rank the measures. The plan should aim at optimizing resources, time, budget, and the resilience of the rail track. The information acquired through enhanced reporting systems and data analysis could be utilized to develop a strategic plan and scheme for urgent, short-term, and long-term actions. For instance, the plan can include creating a well-defined timetable for the replacement of rail components such as timber sleepers, implementing speed limits, and monitoring the stress-free temperature of rail tracks. This strategic plan can minimize unexpected maintenance issues and rail traffic halts caused by actual or potential buckling during hot weather conditions. The need for a holistic and strategic plan is increasingly important in a changing climate with longer and more extreme warm periods, particularly when not only rail traffic but also other transport sectors are simultaneously affected by adverse weather conditions. Moreover, to achieve an optimized plan, it is necessary to conduct cost–benefit and social cost analyses concerning the incidents of lateral track buckling and the frequency of rail traffic closures.

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Nomenclature

Symbols:

BIS	Track information system
DNT	Designed Rail Neutral Temperature
Ofelia	Fault reporting system for railway infrastructure in Sweden
RNT	Rail Neutral Temperature
RTMS	Railway Traffic Management System
SFT	Stress-Free Temperature
SMHI	Swedish Meteorological and Hydrological Institute
STA	Swedish Transport Administration
TRVINFRA	Swedish Transport Administration's infrastructure regulations

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