Weather-Related Railway Infrastructure Failures in Sweden: An Exploratory Study

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The type of a submission
Type A: Research paper.

Abstract
The impacts of adverse weather conditions on railway infrastructure can result in delays and cancellations across the railway network and increased maintenance costs. The frequency and severity of extreme weather events are expected to rise due to climate change, making railways more vulnerable. This study aims to gain a better understanding of weather-related infrastructure failures (specifically track, catenary line, signal, and switch failures) between 2015-2020. We do so by using infrastructure failure data from the Swedish infrastructure manager, the Swedish Transport Administration. We use an exploratory data analysis approach to understand which infrastructure assets are most vulnerable to what weather-related phenomena and if infrastructure failures follow any seasonal trends. Results indicate that tracks and catenary lines are most vulnerable to fallen trees, likely linked to windy conditions, while switches are most vulnerable to snow and ice, and signals are most vulnerable to both snow or ice conditions and fallen trees. Additionally, most failures occur during the winter months. These results highlight the importance of increasing the resiliency of railways to extreme weather today and in the future.

Keywords
Extreme weather, Railway infrastructure failures, Vulnerability, Resilience, Adaptation

1 Introduction

In recent years, the call for adapting to climate change has gained increasing attention (Lindgren et al., 2009). Railways can play an important role in mitigating the negative effects of climate change by providing a mode of transportation which is low in carbon emissions (Baker et al., 2010). However, in order for railways to act as an attractive mode of transportation they must be reliable. Railway transportation is considered to be a type of critical infrastructure which is important in order to provide essential goods and services to society. A disruption to the system can lead to serious adverse economic and social impacts (Greenham et al., 2020; OECD, 2019). The increase of severity and frequency of extreme weather events and the uncertainty of climate change poses as a challenge for the operation and maintenance of railways (Garmabaki et al., 2022). Compared to road systems, railways are considered to be more vulnerable to disruptions due to capacity constraints and limited rerouting options (Mattsson & Jenelius, 2015). Furthermore, the impacts of disruptions are more prevalent in urban areas as the network is more congested, and therefore disruptions can propagate more easily across the network (Fisher, 2020).

In general, there are two ways in which weather can impact transportation networks and subsequently lead to disruptions (delays or cancellations): (1) those resulting from a behavioural shift of a train operator due to the stress of weather conditions such as limited visibility, and (2) those that occur due to an infrastructure failure caused by weather (Jaroszweski et al., 2014). Adverse weather conditions can lead to various infrastructure failures. For instance, extreme high temperatures can lead to failures due to track buckling or overheating of electrical equipment or catenary lines (Kostianaia et al., 2021; Palin et al., 2021). Sparks from the brake systems of rolling stock or maintenance equipment can result in fires during drought conditions (Fabella & Szymczak, 2021). Freezing temperatures may lead to track cracks, slippery rails, or freezing of other infrastructure assets such as catenary lines, switches, or signals (Kostianaia et al., 2021; Palin et al., 2021). Heavy precipitation (such as snowfall, rainfall, hail, or freezing rain) can lead to slippery rail conditions when occurring during freezing conditions (Kostianaia et al., 2021; Palin et al., 2021). In extreme cases heavy rainfall can lead to flooding which can lead to ballast or bridge washout (Kostianaia et al., 2021). Landslides, avalanches, or other earthflows can also occur due to extreme precipitation which result in debris blocking tracks, and bridge or ballast washout (Kostiania et al., 2021). Hail or freezing rain can result in ice build-up in tunnels, on switches, catenary lines, tracks or switches (Palin et al., 2021). A deficit of precipitation can lead to track misalignment due to a decrease in groundwater (Palin et al., 2021). During the fall season, improper trackside vegetation management, can result in leaves falling from trees leading to slippery rail conditions and this issue can be amplified due to wind (Fisher, 2020). Strong winds damage other infrastructure assets due to fallen trees. Wind may also lead to decreased wagon stability (Thaduri et al., 2021). In cases of electrified rails, there is a strong interdependency between transportation and the electricity sector (Johansson et al., 2011). During stormy conditions, electricity shortages can lead to signal failures and a complete halt to railway operations.

1.1 Previous Research

A clear understanding of how weather impacts railway infrastructure is important to navigate future uncertainties due to climate change and in developing appropriate adaptation strategies. Previous research has focused on quantifying the relationship between adverse weather conditions and infrastructure failures and operations, as well as identifying gaps in adaptation strategies. Stipanovic et al. (2013) investigated two tracks in the Netherlands and determined that during 2000-2010, 868 weather-related failures were recorded. Threshold values for failures were determined and it was concluded that failures are most probable to occur when temperatures exceed 35°C, when temperature drops below -12°C, or when snowfall exceeds 58 mm per day. When climate change projection data was added, it was found that failures related to cold temperatures and snow are expected to decrease while failures related to extreme hot temperatures may double. Ferranti et al. (2016) analysed heat-related infrastructures on England's Southeast railway network. It was found that majority of failures related to heat occur during the early and midsummer season due to a phenomenon known as *failure harvesting*. *Failure harvesting* is a term used to describe the increased resilience of the track throughout the summer due to the replacement of assets and maintenance occurring at the beginning of the season when failures first occur. This means that most failures occur during the early and midsummer season and therefore the early replacement of assets and maintenance increases the infrastructure resilience to failures in the later summer period. The study concluded that the assets in direct sunlight are most at risk to overheating and that failures related to heat not only lead to increased maintenance costs but also delays due to emergency speed restrictions. Additionally, a study by Forzieri et al. (2018) determined that damage from droughts, heatwaves, flooding, forest fires, and windstorms are expected to increase across Europe due to climate change, and that economic losses will be highest in the energy, industry, and transport sectors. Khah et al. (2021) found that snowfall, extreme heat, extreme cold, wind, and flooding are generally the most influential factors on railway infrastructure failures.

Taylor (2021) mentions that climate change is likely to increase infrastructure vulnerability to extreme weather, and therefore an understanding of current and future risks is important for infrastructure management. As railway infrastructure has a long lifespan, climate change can threaten the structural integrity of infrastructure and provide challenges for planning future maintenance and construction of new infrastructure. For instance, increased summer temperatures not only increase the risk of infrastructure failures due to heat, such as track buckling, but also restricts trackwork time due to the risk of heat on maintenance workers; and this may not be compensated during the expected milder winters as precipitation regimes shift towards more wet conditions.

Some studies aim to quantify the relationship between weather and infrastructure failures and/or the subsequent disruptions in terms of monetary value. Dobney et al. (2010) estimate the impact of heat-related delays and track buckles in the UK during a hot summer in 2003. Using a baseline weather scenario, heat-related delays cost the UK an average of £9.2 million, on the basis that the average cost of each delay minute is £73.47. Additionally, due to climate change it was estimated that the hot summer of 2003 will be normal in the 2050s under a high emissions scenario or the 2080s under a low emissions scenario. If the tracks are maintained to their current standard, it is expected that the total cost of delays related to heat will nearly double to £23 million. When analysing the impacts of flooding on railways across Europe, Bubeck et al. (2019) concluded that the current annual damage is about €581 million per year, and this is expected to increase by up to 310% due to climate change.

In a Swedish context, Thaduri et al. (2021) found that climate change will lead to an increase in disturbances and maintenance costs across Sweden's railway network due to the projected increase in severity and frequency of extreme weather events. However, the short and long-term effects depend on various factors such as infrastructure asset design, geographical location, and age, and therefore it is important to consider these factors in the planning of climate change adaptation. Similarly, Stenström et al. (2012) found that cold climate negatively impacts railway infrastructure in Sweden as it increases risks, maintenance, and quality of service. Additionally, switches were found to be the most vulnerable asset under winter conditions and work orders to fix switches were about two-three times greater in the winter compared to summer. Garmabaki et al. (2022) aimed to assess the effects of climate change on rail infrastructure in Sweden. It was concluded that the number of climate-related failures for switches and crossings displays an overall increasing trend over a 10-year moving average between 2001-2018.

Some studies include an aspect of how to adapt to the future uncertainties of climate change. Garmabaki et al. (2022) found that due to climate change, Sweden is expected to experience a wetter and warmer climate. They concluded that in order to plan for these uncertainties the level of adaptation awareness should increase; and that emergency planning and vulnerability and risk assessments are important prerequisites for climate change adaptation of railway systems. Similarly, Garmabaki et al. (2021) studied railway maintenance adaptation due to climate change in Sweden using qualitative methods, and interview results indicated that the level of climate change adaptation needs to be increased and better coordination between organisations regarding adaptation strategies is necessary. Additionally, the predominant risks identified were signal failures, track bucking, insufficient drainage, and bridge scour. Similar results were found by Dépoues (2017) in France, who addresses the challenges with implementation of adaptation strategies from a top-down approach down to the infrastructure managers. Instead, more emphasis should be put on bottom-approached involving all relevant stakeholders.

1.2 Research Aim

Past research indicates that railway infrastructure is vulnerable to adverse weather conditions and this vulnerability is expected to increase due to climate change (Taylor, 2021); meaning that today's extreme weather could become tomorrow's normal weather (Blackwood et al., 2022). To help avoid network disruptions and disturbances as a result of infrastructure failures related to extreme weather, railway operators and managers require knowledge on impacts of weather in order to prioritise and handle these issues (Taylor, 2021). Additionally, the effects of weather on infrastructure typically differ between geography and infrastructure age, use, and design (Stipanovic et al., 2013).

Therefore, the aim of this study is an exploration of weather-related infrastructure failures in a Swedish context. Using infrastructure failure data from Sweden between 2015-2020 we aim to answer the following questions: 1) Are there any seasonal trends observed in weather-related infrastructure failures? 2) What infrastructure assets are most vulnerable to what type of weather-related phenomena? and 3) What are the implications of climate change on the management of infrastructure assets? The infrastructure assets considered in this study are: tracks, catenary lines, signals, and switches as they are the main components of the entire track infrastructure.

2 Method

2.1 Data Description

This study makes use of the infrastructure failure data from the Swedish Transport Administration from 2015-2020. Between these years 400,877 infrastructure failures were reported due to issues ranging from animals or unauthorised person on the track, to fire, or broken doors. The Swedish Transport Administration owns majority of the railway infrastructure in Sweden and is responsible for railway operation and maintenance.

The database for infrastructure failures is also maintained by the Swedish Transport Administration. The database includes information about the day a failure was reported, when it was fixed, who fixed it, and the location of the failure. The error report is comprised of two parts. The first part is the fault report itself, called the *symptom*, which is received and filled out by a technician at the Traffic Control Centre. These technicians are responsible for reporting until the fault is fixed with the aim of guiding the maintenance procedure and informing traffic operations. The second part is known as the *real error,* and this is reported by the technician on site who rectifies the failure. Finally, the technician on site also reports a *real cause*, what they assess as the cause of the error. The *real error* is thus the technician's assessment of the actual failure, while the *cause* is their assessment of the cause of the failure. Finally, they report *action*, which is a description on how the failure was fixed.

In this work we focus on weather-related failures, therefore in the data preparation stage, we filtered out all non-weather-related causes. The *symptom* was limited to slippery rails, fire, snow or ice, landslide, storm, and flood; while the *real error* was limited to buckling and fire; and the *cause* was limited to snow or ice, lightning, strong wind/storm, slippery rails, tree, and fire. One limitation of the database is that is does not explicitly define weather-related failures. It is up to the interpretation of the operating technicians and the contractors who fix the failure; therefore, the *symptom*, *real error*, and *cause* fields were chosen to capture potential weather-related infrastructure failures as best as possible. Finally, the selected data for this study includes 9,379 infrastructure failures potentially related to different weather phenomena.

2.2 Exploratory Data Analysis

In order to analyse the relationship between track, catenary line, signal, and switch failures and the different weather-related phenomena: flood, buckling, slippery rails, landslide, lightning, fire, snow and ice, storm, and tree falls, we make use of a more exploratory data analysis approach which allows for a more general understanding of data to complement later confirmatory studies (Tukey, 1980).

The data was aggregated to obtain the number of failures for each asset under each type of weather-related phenomena. The total number of failures was aggregated by month for each year in order to visually display data for interpretation (Wainer & Thissen, 1981; Keim et al., 2006). In this context, the use of an explorative technique can act as a first step towards understanding weather-related infrastructure vulnerabilities in a Swedish context. This can assist in decision-making to plan for addressing current vulnerabilities, by gaining insight into the past impact of weather on railway infrastructure. If railway infrastructure is not resilient to current adverse conditions, it will be challenging to adapt to the future effects of climate change.

3 Seasonality of infrastructure failures

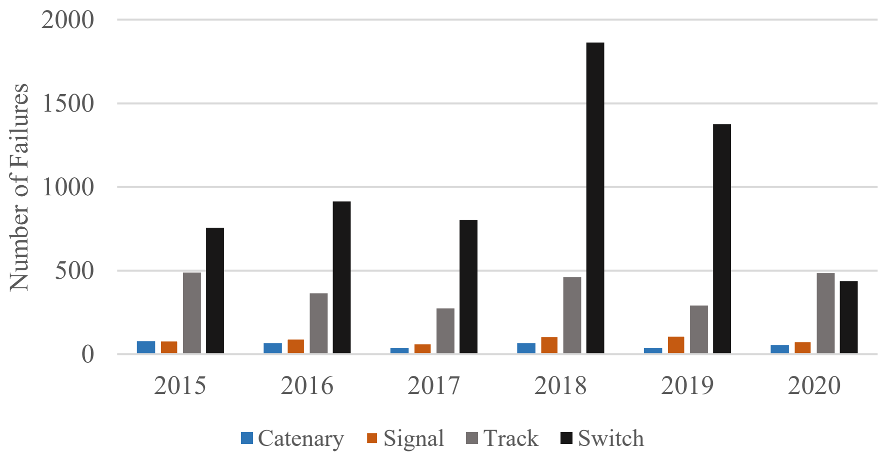

Figure 1: Distribution of failures over the years

Figure 1 highlights the distribution of total weather-related failures from 2015-2020 in Sweden for each of the assets of interest: catenary, signal, track, and switch. Overall switch failures are the most common with the exception of 2020 where the number of track failures was slightly higher. Track failures are the second most common type of failure. Signal and catenary lines have the least number of total failures during the six-year study period. 2018 experienced the highest number of total failures which is likely due to an extreme hot and dry summer experienced in Sweden which sparked wildfires. 2020 experienced the least amount of weather-related infrastructure failures.

In Figure 2 the seasonality of infrastructure failures is shown. Majority of the failures occur during the winter months, specifically in the beginning of the year between January and February. Between February and April there is a sharp decrease in total number of failures. Then, between May and July there appears to be a slight increase again, but the number of failures in summer are far less than the winter overall. By November the number failure starts to increase again. This indicates that Sweden experiences more infrastructure failures in winter months associated with snow, ice, and temperatures below freezing. Due to Sweden's geographical location, the climate is more continental, with some of the country within the Arctic Circle (Peel, 2007). This means that winters are typically colder and the summers more mild.

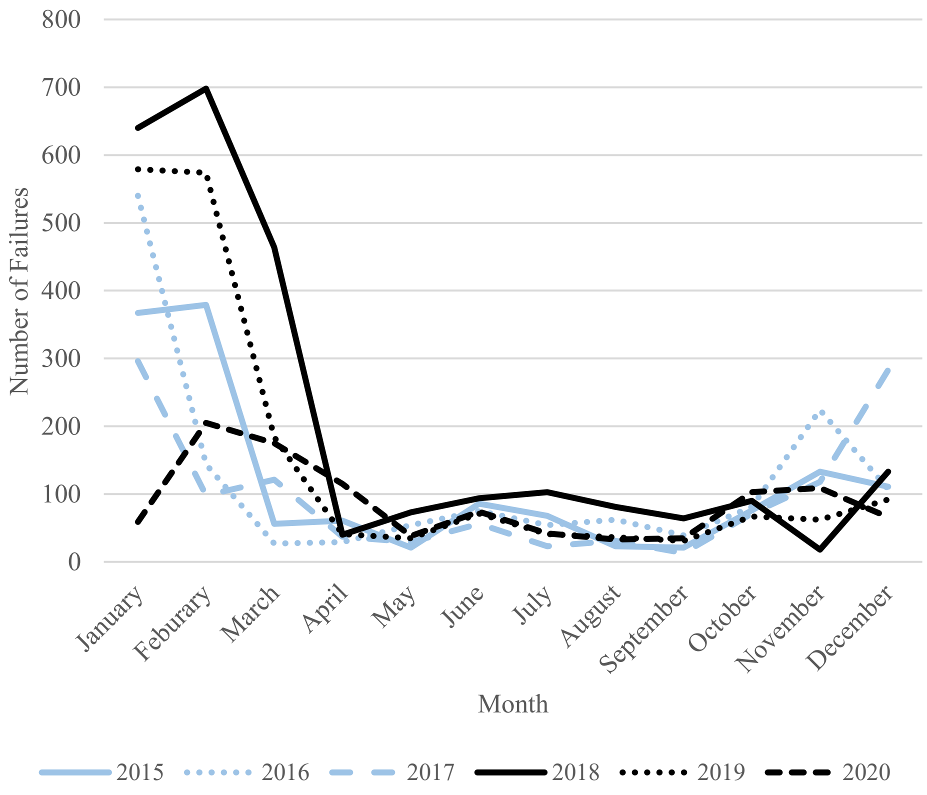

Figure 2: Seasonality of infrastructure failures

4 Failures due to different weather-related phenomena

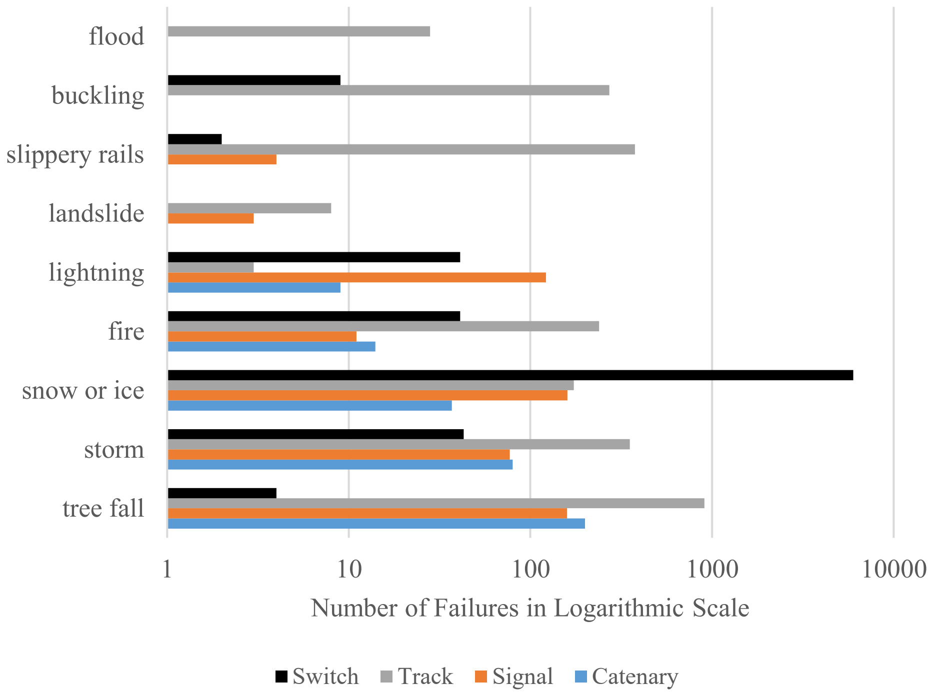

Figure 3: Number of infrastructure failures due to different weather-related phenomena, in logarithmic scale

Figure 3 indicates the number of switch, track, signal, and catenary failures under various weather-related phenomena in order to capture insights into infrastructure vulnerabilities. Due to the large amount of switch failures, Figure 3 is depicted in Logarithmic Scale for easier visualisation.

Switches are moving components along the tracks that guide trains from one track to another. Based on Figure 3 switches are most vulnerable to snow and ice conditions. Ice and compact snow formation is a major problem that can block the switch tongue and prohibit the movement of the switch, which then does not allow a train to move from one track to another. Many switches are equipped with a special heating device to try to mitigate this problem, however, not all switches in Sweden are equipped with one and they consume a lot of energy, approximately €10-15 million Euros annually (Kapoor, 2022). Switches are also connected to the signalling system which is dependent on electricity. Storm, lightning, and tree falls are likely related to problems with high wind speeds where trees can fall onto switches, or storm and lightning conditions can cause power failure impeding the mechanics of switch movement. Slippery rails may be related to adhesion due to leaves or ice on the switches which leads to trains having to operate at slower speeds and can also result in the degradation of wheels on the rolling stock. Fire and buckling may be linked to extreme heat, which also can prohibit the movement of a switch.

Figure 3 indicates that tracks are most vulnerable to failures related to fallen trees. This is likely related to windy conditions when trees or branches fall and can block the tracks.

Regarding slippery rails this could be a result of fallen leaves on the track due to seasonal change and/or wind, or ice formation during temperatures below freezing or because of heavy precipitation. This means the train operator must drive slower and it may take longer to accelerate and brake. Storm and lightning conditions are likely linked to wind and/or extreme precipitation conditions which may lead to debris blocking the tracks or causing other damage to the ballast or track geometry. Buckling and fire are most likely related to extreme hot temperatures when trains cannot operate or must operate slowly due to track buckles or trackside fire. Snow and ice may infer to snowy days with temperatures below freezing when snow blocks tracks or ice forms on the tracks. Additionally, tracks can crack under stress from freezing temperatures. Floods and landslides are typically less common in Sweden due to the geography. However, extreme cases may lead to debris blocking the track, ballast washout, or other deformation to the track geometry.

In Sweden most of the railway lines are electrified and therefore the catenary transmits electrical power to the trains via a pantograph. Figure 3 indicates that catenary lines are most vulnerable to fallen trees followed by storms. Fallen trees are likely connected to wind during stormy conditions when trees or other vegetation can fall on the catenary line. Storms can also bring lightning which can result in electricity outages. Since most railway lines in Sweden are electrified, there is a strong dependency to the electricity sector (Johansson et al., 2011). Therefore, any electricity failure can lead to a catenary failure and subsequently a halt in railway operations. With snow and ice, formation of ice or heavy snow fall leads to sagging or freezing of the lines which results in contact issues between the catenary and the pantographs of trains. The sagging of catenary lines can also occur due to extreme heat transmitted by trackside fires.

The signalling system is important for controlling traffic throughout the railway network and is an important asset for ensuring the safety of railway operations. Signals are used to separate the railway network into sections known as *blocks* where only one train can occupy one block at a time. The signal relies on electrical circuits and in the event of a failure the signal light remains red, which halts operations within the network. Figure 3 indicates that the signalling system is most vulnerable to snow or ice conditions and tree falls. During the winter snow or ice can lead to short circuits, leading to signal failure. Trees falls, lightning, and storm are likely connected to strong winds and/or heavy precipitation. A tree fall or lightning strike may also result in a short circuit. Fire or slippery rails also can impact signals due various factors such as freezing or overheating. Lastly, landslides may lead to debris flows destructing the signal.

5 Current and future implications

Based on our findings, railway infrastructure in Sweden is most vulnerable to winter and stormy conditions. Railway tracks and catenary lines are most vulnerable to fallen trees while switches are most vulnerable to snow and ice conditions, and signals are most vulnerable to snow and ice conditions and fallen trees. Infrastructure managers today often focus on increasing resilience to today's weather conditions (Dépoues, 2017) but it is also important to consider how climate change will impact railway infrastructure in the future, especially since railway infrastructure has a relatively long lifespan.

In Sweden, it is expected that both the annual precipitation amount and average annual temperature is expected to increase overall but specifically during the winter and spring months (Thaduri et al., 2021). This could result in more infrastructure failures occurring in the future due to heavy precipitation. As Sweden is a large country with varying geography, the impacts of climate change may differ from region to region. Some regions may encounter more infrastructure failures related to snowfall and heavy rain in the future. Combined with the projected increase in temperature, a heavy snow cover may melt quickly in the spring leading to flooding (Thaduri et al., 2021). In other regions, an increase in precipitation combined with an increase in temperature may lead to shift from infrastructure failures related to snow to those related to heavy rainfall. The increase in temperature in general could mean switches and signals may decrease their vulnerability to cold temperatures however, there may be a shift towards more extreme heat related issues not fully experienced yet. Regarding future wind climate, this is more challenging to estimate as directions point towards an increase in storm frequency and intensity but also a potential decrease in low-pressure systems originating in the northern hemisphere due to increased sea surface temperatures (Thaduri et al., 2021). If Sweden sees an increase in wind related weather events and storms the vulnerability of catenary lines and track assets may increase.

Maintenance planning may be affected in similar ways. The increase in temperatures in summer months may restrict the opportunities for undertaking trackwork due to unsafe worker conditions, however due to the projected more mild but wetter winters it may be challenging to move trackwork from summer to winter months (Taylor, 2021). Additionally, corrective maintenance may occur more frequently due to the increase of infrastructure asset vulnerability due to climate change. This can lead to cascading effects due to speed restrictions, or if the track must be closed for a period of time this may result in train delays or cancellations as well as increased maintenance resources and costs.

6 Discussion

In the future, an increase in preventative and predictive maintenance may be one way to increase resilience to extreme weather, however this can also be costly and requires sufficient resources. Adapting railway infrastructure to the effects of climate change is one way to increase the resilience of infrastructure. A combination of more traditional engineered or 'hard' solutions and 'soft' solutions may be beneficial to adapting. Soft measures such as policies and strategies should not only focus on a top-down approach but a more bottom-up approach which includes relevant stakeholders such as infrastructure managers and maintenance works who work with the problems first hand. Understanding the current weather-related risks on railway infrastructure is one step towards assisting decision-making in the future. As infrastructure has a long-life span it is important to understand these risks in order to plan for maintenance of current railways as well as proper planning for future construction.

More engineering 'hard' solutions can complement strategies and increase resilience of current and newly planned infrastructure. Examples include change in the rail installation procedure in order to increase the threshold of track thermal expansion, use of fans for cooling, heating tracks and switches with more energy efficient ways such as heat pumps (Kapoor, 2022), installation of lightening conductors, and the expansion of drainage capacity (Blackwood et al., 2022). Furthermore, Sweden is planning on moving to a ETCS Level 2 Signalling system. This would allow for a more flexible system, entail fewer components in the signalling system and fewer optical signals which may reduce the vulnerability of signal failures due to short circuits. Nature-based solutions are graining more traction as a complement to other adaptation measures. Trackside vegetation can provide slope stability to reduce the risk of landslides, can provide shading to avoid asset overheating, and can retain precipitation to reduce the risk of flooding (Blackwood et al., 2022). However, proper vegetation management is essential in order to reduce the risk of debris blocking tracks or catenary lines and to avoid leaf adhesion during the fall (Taylor, 2021).

A limitation of the study is the constraints of the infrastructure failure database used for this study. Before 2015, there was a vast underreporting of infrastructure failures in the database, a reason for limiting the study presented here from 2015-2020. Additionally, weather-related infrastructure failures are not always clearly identified in the database. There could be some an error by the reporter, or the failure may be coded as something else when it was in fact related to weather. By adjusting the reporting guidelines to better capture weather-related incidences could also allow for the Swedish Transport Administration to gain a better understanding of the current weather-related risks they are facing and what priorities they can set. Another limitation of this study is the failure counts under various weather-related phenomena are not normalised under how often these weather events occur. However, the results are nonetheless useful for understanding current vulnerabilities of infrastructure assets, which in turn is of importance for planning of maintenance of current infrastructure and design of new railway lines. Future work includes analysing the relationship between failure frequencies and weather variables such as wind speed, temperature, precipitation, and snow depth. Doing so can allow for the identification of thresholds to better understand at what point is infrastructure vulnerable to failure under what weather conditions. Additionally, since Sweden is a large country with varying geographies, future research may focus on the differences between regions to future understand the vulnerabilities within Sweden.

7 Conclusion

The study we present here focusses on the relationship between weather-related phenomena and infrastructure in Sweden between 2015 and 2020. The infrastructure assets of interest were switch, track, signal, and catenary. The study shows, using 9,379 weather-related infrastructure failures, that tracks and catenary lines are most vulnerable to fallen trees, while switches are most vulnerable to snow and ice, and signals are most vulnerable to both snow or ice conditions and fallen trees. This indicates that Sweden's railway infrastructure is particularly vulnerable to windy conditions and during the winter when temperatures fall below freezing and precipitation falls as snow. In the future, extra care should be given to increase resiliency to wind and winter conditions to ensure failure does not result in severe delays or cancellations across the railway network.

The seasonal trends indicate that more failures occur during the winter compared to summer months. Due to climate change, we expect warmer temperatures, an increase in precipitation, and potential change in wind patterns. Therefore, there may be a shift in seasonal trends with less failures related to winter conditions but more in the summer related to extreme heat. If the number of weather-related infrastructure failures is going to be reduced, adaption to the effects of climate change is important. A combination of 'soft' policies and strategies that consider engagement with infrastructure managers and operators along with more 'hard' engineering adaption measures are ways to adapt and increase resiliency. Understanding the past and current risks of extreme weather on railway infrastructure is one important step in understanding the future impacts of climate change on railway systems, thus assisting in the decision-making process of maintenance planning and the design process of new infrastructure construction.

8 Acknowledgements

This research has been funded by the Swedish Transport Administration through grant numbers TRV2021/99838, TRV2020/119576, and the Bandat project. The authors would like the thank Ruben Kuipers, Kah Yong Tiong, Emil Jansson, Grace Mukunzi, and Alexandra Rojas Mullor for comments on earlier drafts of this work, and Johan Berger from the Swedish Transport Administration for the description of the Ofelia database.

References

Baker, C.J., Chapman, L., Quinn, A., Dobney, K. 2010. "Climate change and the railway industry: A review", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 224, iss. 3, pp. 519-528. https://doi.org/10.1243/09544062JMES1558

Bubeck, P., Dillenardt, L., Alfieri, L., Feyen, L., Thieken, A. H., Kellermann, P. 2019. "Global warming to increase flood risk on European railways", *Climatic Change*, vol. 155. iss. 1, pp. 19-36. https://doi.org/10.1007/s10584-019-02434-5

Dépoues, V. 2017. "Organisational uptake of scientific information about climate change by infrastructure managers: the case of adaptation of the French railway company", *Climatic Change*, vol. 143, iss. 3–4, pp. 473–486. https://doi.org/10.1007/s10584-017-2016-y

Dobney, K., Baker, C. J., Chapman, L., & Quinn, A. D. 2010. The future cost to the United Kingdom's railway network of heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *224*(1). https://doi.org/10.1243/09544097JRRT292

Fabella, V. M., Szymczak, S. 2021. "Resilience of railway transport to four types of natural hazards: An analysis of daily train volumes", *Infrastructures*, vol 6, iss. 12, pp. 174. https://doi.org/10.3390/infrastructures6120174

Ferranti, E., Chapman, L., Lowe, C., McCulloch, S., Jaroszweski, D., Quinn, A. 2016. "Heat-related failures on southeast England's railway network: Insights and implications for heat risk management", *Weather, Climate, and Society*, vol. 8, iss. 2, pp. 177–191. https://doi.org/10.1175/WCAS-D-15-0068.1

Fisher, R. S. 2020. *"Quantifying the Vulnerability of GB Rail to Temperature and Precipitation in Order to Improve Resilience"*, [Doctoral Thesis, The University of Birmingham] http://etheses.bham.ac.uk/id/eprint/11229

Forzieri, G., Bianchi, A., Silva, F. B., Marin Herrera, M. A., Leblois, A., Lavalle, C., Aerts, J. C. J. H., Feyen, L. 2018. "Escalating impacts of climate extremes on critical infrastructures in Europe", *Global Environmental Change*, vol. 48, pp. 97–107. https://doi.org/10.1016/j.gloenvcha.2017.11.007

Garmabaki, A. H. S., Odelius, J., Thaduri, A., Mayowa, S., Kumar, U., Strandberg, G., Barabady, J. 2022. "Climate change impact assessment on railway maintenance", In: *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)*, Dublin, Ireland, pp. 2913–2920. https://doi.org/10.3850/978-981-18-5183-4_S25-01-126-cd

Garmabaki, A. H. S., Thaduri, A., Famurewa, S., Kumar, U. 2021. "Adapting Railway Maintenance to Climate Change", *Sustainability*, vol. 13, iss. 24, pp. 13856.

https://doi.org/10.3390/su132413856

Greenham, S., Ferranti, E., Quinn, A., Drayson, K. 2020. "The impact of high temperatures and extreme heat to delays on the London Underground rail network: An empirical study", *Meteorological Applications*, vol. 27, iss. 3. https://doi.org/10.1002/met.1910

Kapoor, S. 2022. "*Energy Usage in Railway Wayside Object Heating: Modeling of melting of Ice, Estimation of Heating Power Requirement in Switch and Renewable Energy Feasibility for a Railway System",* [Master's Thesis, KTH Royal Institute of Technology] https://kth.diva-portal.org/smash/get/diva2:1695230/FULLTEXT01.pdf

Keim, D.A., Mansmann, F., Schneidewind, J., Ziegler, H. 2006. "Challenges in Visual Data Analysis", *10th International Conference on Information Visualisation (IV'06)*, pp. 9-16. Doi: 10.1109/IV.2006.31

Khah, S. M., Tinoco, J., Campos e Matos, J. 2021. "Effect of climate change on railway maintenance: A systematic review", In: *Proceedings of the 31rst European Safety and Reliability Conference (ESREL 2021)*, Angers, France, pp. 1085-1092. doi: 10.3850/978-981-18-2016-8_371-cd

Kostianaia, E. A., Kostianoy, A. G., Scheglov, M. A., Karelov, A. I., Vasileisky, A. S. 2021. "Impact of Regional Climate Change on the Infrastructure and Operability of Railway Transport", *Transport and Telecommunication Journal*, vol. 22, iss. 2. pp. 183-195. https://doi.org/10.2478/ttj-2021-0014

Jaroszweski, D., Hooper, E., Chapman, L. 2014. "The impact of climate change on urban transport resilience in a changing world", *Progress in Physical Geography*, vol. 38, iss. 4, pp. 448–463. https://doi.org/10.1177/0309133314538741

Johansson, J., Hassel, H., Cedergren, A. 2011. "Vulnerability analysis of interdependent critical infrastructures: case study of the Swedish railway system", *International Journal Critical Infrastructures*, vol. 7, iss. 4, pp. 289-316. https://doi.org/10.1504/IJCIS.2011.045065

Lindgren, J., Jonsson, D. K., Carlsson-Kanyama, A. 2009. "Climate Adaptation of Railways: Lessons from Sweden", *European Journal of Transport and Infrastructure Research*, vol. 9, iss. 2, pp. 164–181. https://doi.org/10.18757/ejtir.2009.9.2.3295

Mattsson, L.-G., Jenelius, E. 2015. "Vulnerability and resilience of transport systems – A discussion of recent research", *Transportation Research Part A: Policy and Practice*, vol. 81. pp. 16-34. https://doi.org/10.1016/j.tra.2015.06.002

OECD 2019. *Good Governance for Critical Infrastructure Resilience,* OECD Reviews of Risk Management Polices, OECD Publishing, Paris. https://doi.org/10.1787/02f0e5a0-en

Palin, E. J., Stipanovic Oslakovic, I., Gavin, K., Quinn, A. 2021. "Implications of climate change for railway infrastructure", *Wiley Interdisciplinary Reviews: Climate Change*, vol. 12, iss. 5. https://doi.org/10.1002/wcc.728

Peel, M.C., Finlayson, B.L., McMahon, T.A. 2007. "Updated world map of the Köppen-Geiger climate classification", *Hydrology and Earth Systems Science,* vol. 11, pp. 1633-1644. Doi: 10.5194/hess-11-1633-2007

Stenström, C., Famurewa, S. M., Parida, A., Galar, D. 2012. "Impact of cold climate on failures in railway infrastructure Effect of Cold Climate on Failures in Railway Infrastructure", In: *The 2nd International Congress on Maintenance Performance Measurement & Management Conference Proceedings (MPMM 2012).*

Stipanovic, I. O., ter Maat, H., Hartmann, A., Dewulf, G.P.M.R. 2013. "Risk Assessment Of Climate Change Impacts On Railway Infrastructure", In: *Working Paper Proceedings of the Engineering Projects Organization Conference (EPOC 2013)*, Devil's Thumbs Ranch, Colorado. https://research.utwente.nl/en/publications/risk-assessment-of-

climate-change-impacts-on-railway-infrastructu
Taylor, M.A.P. 2021. *Climate Change Adaptation for Transportation Systems*. Elsevier. https://doi.org/10.1016/C2018-0-00205-4
Thaduri, A., Garmabaki, A., Kumar, U. 2021. "Impact of climate change on railway operation and maintenance in Sweden: A State-of-the-art review", *Maintenance, Reliability and Condition Monitoring*, vol. 1, iss. 2, pp. 52–70. https://doi.org/10.21595/mrcm.2021.22136
Tukey, J.W. 1980. "We Need Both Exploratory and Confirmatory", *The American Statistician, vol.* 34, iss. 1, pp. 23-25. https://doi.org/10.2307/2682991
Wainer, H., Thissen, D. 1982. "Graphical Data Analysis", *Annual Review of Psychology,* vol. 31, iss. 1, pp. 191-241. Doi: 10.1146/annurev.ps.32.020181.001203