WEATHER AND TRAIN DISRUPTIONS IN SWEDEN, 2011–2019

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ABSTRACT

The impacts of adverse weather conditions on railway systems can lead to large delays and cancellations across the entire network. In this paper, we aim to understand the relationship between weather and train disruptions (i.e. cancellations and large delays) across the entire Swedish railway network for the years 2011–2019. Using railway operations data and snow depth, temperature, precipitation, and wind data aggregated on a weekly level, we use visual graphical analysis to understand this relationship. The results indicate that the disruption shares increase with higher amounts of snow and rainfall, and wind speeds. Results show that disruptions increase dramatically both at cold temperatures, with high snow depths, and at high wind speeds. High temperatures and precipitation levels also correlate with increased disruptions, but less dramatically. With projected increases in temperatures and precipitation due to climate change, and an increased frequency of storms, some of these relationships are expected to become more significant, while winter-related problems are likely to decrease. The results highlight the importance of increasing the resilience of railways to adverse weather conditions and the need for appropriate adaptation strategies.

Keywords: extreme weather, temperature, precipitation, snow, wind, railway, disruptions.

1 INTRODUCTION

Reliable railway systems are essential to an operating and developing society [1], [2], and weather is one factor that can lead to disruptions in a railway system, decreasing its reliability. When compared with road infrastructure, railways are more vulnerable to disturbances and disruptions due to capacity constraints and limited rerouting alternatives [3]. Adverse weather conditions demonstrate railways' vulnerability to the current climate, and due to climate change this vulnerability is likely to increase [4].

Heavy rain or snowfall can lead to visibility issues, flooding of track and tunnels, blockages on tracks, and also impacts soil stability near slopes and retaining walls which can lead to landslides, mudflows, and other earth flows [4], [5]. Freezing rain can cause ice build-up on infrastructure such as tracks or overhead contact wires, and precipitation deficit may lead to track misalignment due to decreased amounts of groundwater [5]. Low temperatures can lead to problems such as cracking of railway tracks, slippery track conditions, or freezing of overhead lines and signalling equipment; and in contrast, high temperatures can cause problems such as track buckling, or overheating of signalling equipment [4], [5]. Strong winds can also lead to disruptions due to fallen trees blocking tracks, damage to electrical equipment, and decreased train wagon stability [6], [7].

To mitigate the negative effects of climate change on railway systems in the future, increase network resiliency, and to develop subsequent adaptation measures, it is important to understand the past and current effects of adverse weather conditions on railway systems [4]. Hence, the aim of this study is to analyse the past effects of weather on railway disruptions in Sweden (i.e. cancellations or large delays) and consider how these may change along with changing climate conditions.

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2 PREVIOUS RESEARCH

2.1 Past weather and train delays or disruptions

A number of researchers have investigated the connection between various types of weather and train delays or disruptions. Ling et al. [8] found that rail delays in China are strongly correlated with extreme weather conditions related to rain and snowfall. Brazil et al. [9] studied the effects of weather conditions on train delays in Dublin, Ireland and concluded that rainfall is the main variable leading to delays, especially when it occurs together with high winds. Diab and Shalaby [10] studied the impact of weather on outdoor track segments of the metro system in Toronto, Canada and concluded that snow on the ground and rainfall led to more service interruptions.

In the Netherlands, Xia et al. [7] concluded that bad weather accounts for 4–8% of all train disturbances, and that wind gusts of more than 19 m/s have significant effects on disruptions. A study by Ludvigsen and Klæboe [11] analysed the impact of the 2010 winter on freight rail operations in Switzerland, Poland, Sweden, Norway, and Finland. The results indicate that the harsh winter weather conditions of long periods of heavy snowfall, long periods of cold temperatures, and long periods of strong wind played a serious role in the punctuality of freight trains. In Norway, Zakeri and Olsson [12] studied the effects of extreme weather conditions on delays and punctuality between 2007 and 2016 and concluded that harsher winters resulted in more delays compared to more mild winters, and that snow depth was found to be the main weather variable that best explains both daily and weekly punctuality variations. In Sweden, Palmqvist et al. [13] found that punctuality dropped by almost 2% points when a quarter of all trains analysed accumulated at least 30 mm of precipitation, drops by 2% when wind speeds exceed 10 m/s and by 9% when they exceed 23 m/s, and that punctuality decreases exponentially when temperatures fall below 0°C and or reach high temperatures. Wang et al. [14] studied the impacts of winter climate on high-speed passenger trains in Sweden, between Umeå and Stockholm, and found that that low temperatures and high humidity in the winter months decrease train punctuality.

2.2 Future climate change impacts on railway systems

Other studies have been concerned with understanding the future impacts of climate change on railway systems. Palin et al. [15] used future temperature projections to study the impacts of climate change on railways in the UK, and project that an increase in temperatures will not only cause stress on infrastructure such as track buckling or overheating of overhead power lines, but also on operations as heat can cause stress on workers. Similarly, Dobney et al. [16] quantified the effects of high summer temperatures related to climate change on rail buckling and consequently delays in the UK. They concluded that the number of buckles and therefore rail delays per year will increase if tracks are maintained to their current standard. The effect of climate change on the frequency of critical meteorological conditions in Austria was simulated by Kellermann et al. [17], who concluded that extreme cold temperatures and snowfall will become less common but heatwaves and intense rainfall will become more frequent, calling for a shift in adaptation measures.

Chinowsky et al. [18] conducted a study on the impacts of climate change on railway operations in the United States in order to understand the future vulnerabilities. They estimate that the railway network may encounter an increase in delay-minute costs of between $35 and $60 billion over historic costs through to 2100. Forzieri et al. [19] found that damage from heat waves, droughts, flooding, windstorms, and forest fires is expected to increase across Europe as climate change progresses which will result in higher costs of adaptation. Ilalokhoin et al. [20] developed a multi-track model for estimating railway journey impacts from extreme weather events in Great Britain, which highlighted the importance of increasing resilience to flood and storm events that are predicted to become more frequent in the future. Bubeck et al. [21] focused on the impacts of climate change on flood risk around Europe and concluded that currently the annual damage of flooding on railways in Europe is currently €581 million per year, however, this is expected to increase by up to 310% in light of climate change.

3 METHODS

In this study we make use of two datasets, railway operations data and weather data from 2011–2019 across the entire Swedish railway network.

The railway operations data comes from the Swedish Transport Administration and includes about 100 million registered arrivals at stations where the trains stop, not merely pass by. The data covers both passenger and freight trains. In this study, we define disruptions as arrivals that were cancelled or delayed by more than 60 minutes. Overall, about 10 of the 100 million arrivals were cancelled, and slightly less than 1 million delayed by more than 60 minutes. This leads to a baseline rate of disruptions of about 11%. A large part of the cancellations can be explained by freight trains, where operators often apply for more train paths than will be used, because they do not know far in advance exactly which of the paths will be required. Unfortunately, we do not have data on how far in advance trains are cancelled, so all cancellations are included in our data, though we would ideally like to focus on late-stage cancellations. An option would be to focus exclusively on passenger trains, but because freight trains are also important and affected by severe weather, we instead opt to include both types of trains and a higher baseline rate of cancellations.

We made use of the open access weather data provided by the Swedish Meteorological and Hydrological Institute (SMHI). These cover historical meteorological observations of average snow depth, average precipitation, average temperature, and maximum wind speed across the entirety of Sweden. Table 1 provides an overview of the weather variables used in this study. Snow depth, temperature, and precipitation are recorded once a day at each weather station while wind speed was recorded hourly.

Table 1: Overview of studied weather variables.

Weather variable and unit	Number of observations	Observation frequency	Number of weather stations
Snow depth (m)	505,317	Daily	217
Temperature (°C)	692,773	Daily	241
Precipitation (mm)	778,131	Daily	312
Wind speed (m/s)	10,938,298	Hourly	153

Since weather stations are not located at train stations an algorithm was created to match the coordinates of the weather station to the nearest train station on a day-by-day basis. Then the railway operations and weather data were aggregated on a weekly basis to determine the shares of disruptions that occur for each studied weather variable, which was then plotted in order to visually analyse trends.

4 RESULTS

Fig. 1(a) shows the shares disrupted plotted against the average weekly snow depth. The frequency of disruptions begins to increase at about 0.2 m and rises steadily until about 0.7 m, at which point the disruptions level off. At this point, about one in three trains is cancelled or severely delayed, up by about 300% from the baseline rate. Most observations, by far, fall in the range of 0–1 m of snow, and we should not read too much into the fluctuations above 1 m of snow depth.

Fig. 1(b) plots the frequency of disruptions against the level of precipitation. The line is mostly flat, indicating a weak relationship. Towards the far right of the figure, at levels greater than 15 mm/day for a week, we can see a slight increase in disruptions, up to about 17%. This is a modest increase, compared to the extremes of other weather variables, but still up by about 50% from the baseline rate of 11%.

Fig. 1(c) shows the relationship between temperature and disruptions. To the left, we see a steep increase in disruptions as temperatures fall below 0°C. At its most extreme, about 66% of trains suffer from disruptions in connection with cold temperatures, up by about 600% from the baseline rate. To the right in the figure, we see a much more modest but still pronounced increase in disruptions as temperatures rise. At the most extreme, about 18% of trains suffer from disruptions in connection with high temperatures, up by about 60% from the baseline rate. We can see roughly linear increases in both directions.

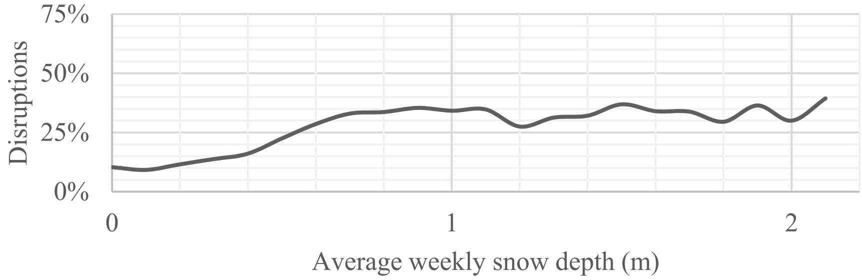
Finally, Fig. 1(d) illustrates the relationship between the maximum wind speed and the frequency of disruptions. Somewhat surprisingly, we see an elevated rate of disruptions when wind speeds are very low, although periods without any wind for an entire week are rare. More interestingly and reasonably, we see that the frequency of disruptions begins to increase as wind speeds exceed about 20 m/s. The increase is modest at first, but then picks up, and at the most extreme, about two out of every three trains suffer from disruptions, up by about 600% from the baseline rate.

5 DISCUSSION

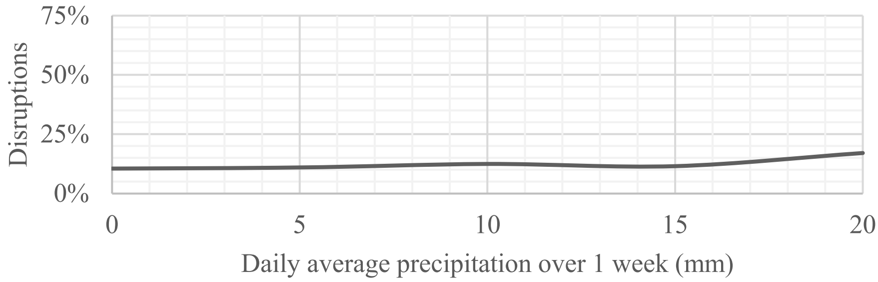
The results from our graphical visual analysis highlight that the shares disrupted on the Swedish railway network between 2011–2019 increase with temperature, precipitation, snow depth, and wind speed. In regard to temperature, the relationship is stronger when temperatures are below freezing compared to above. Moreover, the relationship between precipitation and disruptions is the weakest when compared to the other weather variables.

Due to climate change, it is expected that Sweden will see a greater increase in precipitation in the winter months compared to summer months [22]. In some regions, this will lead to greater snowfall and depths. In other regions, the increasing temperatures will mean that even in the winter, more of the precipitation will fall as rain rather than snow, and thus lead to lower levels of snow depth and shorter periods of snow cover [6]. On balance, this is likely to lead to less railway disruptions due to snow, but there will be regional variations. The overall increase in precipitation levels may lead to slightly more disruptions, and attention will have to be made to the more extreme cases, which may lead to flooding events and major disruptions.

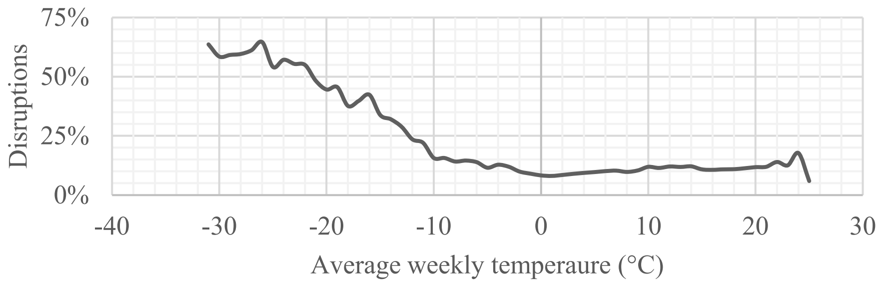
The mean annual temperature in Sweden will rise, with the highest rises expected to occur during the winter months [6]. We would thus expect the severe disruptions associated with cold temperatures to decrease. The increase in temperatures in the summer months will, on the other hand, likely lead to more disruptions. More trains are also likely to be affected by very high summer temperatures than by the more extreme cold periods, which often happen



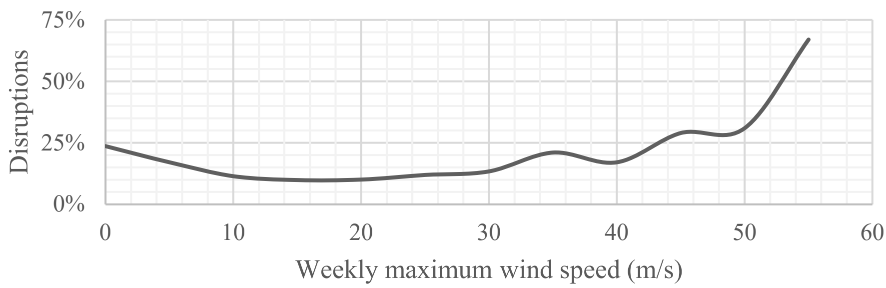
(a)



(b)



(c)



(d)

Figure 1: The frequency of disruptions plotted against average (a) Snow depth, (b) Precipitation, (c) Temperature, and (d) Maximum wind speed across a week.

in less densely populated areas of the country. Care must thus be taken so that performance does not suffer too much during the summers.

Future wind climate is challenging to estimate. Thaduri et al. [6] points towards an increase in storms and storm intensity due to increased sea surface temperatures with more water vapour. However, ocean warming may also lead to less low-pressure systems originating in the northern hemisphere. If Sweden sees an increase in frequency and severity of windstorms in the future, we might expect more disruptions caused by high wind speeds, and adaptation measures should be considered to avoid the most severe disruptions.

6 CONCLUSION

In this paper we have studied some 100 million scheduled train arrivals across the entire Swedish railway network during the period 2011–2019. Roughly 10 million of these arrivals were cancelled, and almost 1 million delayed by more than 60 minutes. Considering these two together as disruptions, we see a baseline rate of disruptions at about 11%.

We have seen how this frequency of disruptions is affected by severe weather conditions. Cold temperatures and high winds are both associated with the most severe disruptions, being associated with up to sixfold increases in disruptions. Snow depth also has a strong influence and can lead to threefold increases in disruptions. High temperatures can also be problematic, and we have observed a 60% increase in the rate of disruptions during warm summer weeks. Finally, high levels of precipitation can cause problems, and we have observed up to a 50% increase in the rate of disruptions. Importantly, however, these weather extremes are rather rare, and the effects are usually more modest.

With a changing climate, we would expect some of these conditions to occur more often, and to be even more extreme, than in the past. For instance, temperature, precipitation levels and wind speeds are expected to increase. For snow depths the picture is more complex, where some regions may experience less snow cover, and others experience greater depths but for shorter periods. If the frequency of disruptions is going to be reduced, then adaptation measures will have to be taken to reduce the risks of extreme events. In the context of resiliency, understanding the past patterns is one crucial piece to understanding the vulnerability to extreme weather.

Some future research directions may be to apply machine learning methods to predict disruptions from weather forecasts, to identify particular geographical hotspots, and to explore and develop appropriate adaptation strategies to increase the resiliency of railways.

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