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ORIGINAL ARTICLE

Assessing climate-induced risks to urban railway infrastructure

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Abstract Climate change and its severe impacts pose a number of challenges to transport infrastructure, particularly railway infrastructure, requiring immediate action. A railway system is a linear distributed asset passing different geographical locations and exposed to heterogeneous vulnerabilities under diverse environmental conditions. Furthermore, most of the railway infrastructure assets were designed and built without in-depth analysis of future climate impacts. This paper considers the effects of extreme temperatures on urban railway infrastructure assets, including rail, "switches and crossings". The data for this study were gathered by exploring various railway infrastructure and meteorological databases over 19 years. In addition, a comprehensive nationwide questionnaire survey of Swedish railway infrastructure, railway maintenance companies, and municipalities has been conducted to assess the risks posed by climate change. A risk and vulnerability assessment framework for railway infrastructure assets is developed. The study shows that track buckling and vegetation fires due to the effect of hot temperatures and rail defects and breakage due to the effect of cold temperatures pose a medium risk. On the other hand, supportability losses due to cold temperatures are classified as high risk. The impact analysis helps infrastructure managers systematically identify and prioritize climate risks and develop appropriate climate adaptation measures and actions to cope with future climate change impacts.

Keywords Railway infrastructure · Climate change adaptation · Climate risk · Vulnerability assessment · Risk analysis

1 Introduction

Climate change and its associated impacts are among the most critical global problems. A growing body of scientific literature suggests that, regardless of the success of global climate change mitigation initiatives that aim to reduce greenhouse gas emissions(GHG), climate change will continue for coming decades, and even centuries. (Lemmen et al. 2008). The IPCC6 (IPCC 2022) report highlights the established fact that human-induced GHGs have led to an

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increased frequency and/or intensity of some weather and climate extremes since 1850.

Railway transport infrastructure is an important mode of transport for passengers and freight, and it is expected to expand due to the green nature of the electrified railway system. Railway infrastructure assets are vulnerable to climate change impacts such as extreme temperature, precipitation, snow loads, windstorms, etc. (Norrbin 2016). Consequently, the increase in the frequency of the occurrence of extreme weather events and the interaction between multiple natural events and cascading effects of failures can create major challenges for the society and railway infrastructure (Kaspersen and Halsnæs, 2017; Norrbin 2016; Oslakovic et al. 2013; Palin et al. 2021; SMHI, 2022) (see Table 1 for more detailed information).

A variety of studies have focused on climate change's impact and its risks to critical infrastructures. For instance, the impact of temperature on thermal discomfort in underground railways has been studied by employing different climate change scenarios (Jenkins et al. 2014). Different models and approaches such as climate-integrated models for uncertainty and risk management to study pluvial flooding (Pregnolato et al. 2017), integrated climate models for underground flooding (Forero-Ortiz et al. 2020), and integrated approach for assessing climate change in urban settings (Andersson-Sköld et al. 2015) have also been developed. Jain and Singh (2021) studied the impact of climate change on metro rails and concluded that frequent delays might change the behaviour of passengers to move to other means of transportation. Ye et al. (2021) reviewed studies focusing on climate change-induced risks for urban systems and highlighted the need to develop holistic perspectives. Carter, 2015 (Carter et al. 2015) studied climate adaptation during the planning phase. However, only a few research studies have focused on the impact of climate change on the operation and maintenance of urban transport.

SMHI (SMHI 2022) projected climate change impact under different Representative Concentration Pathways (RCPs) and the following conclusions have been made for Sweden which are directly relevant to the railways and road infrastructure:

1. Hot temperatures (maximum daily temperatures greater than 25°C) will increase, especially in the south with largest temperature difference in the north
2. Zero-crossing will decrease in the south and increase in the north during winter. The northern regions will experience more rain and more snow at temperatures close to 0°C
3. The amount of snow will decrease, in general, but it will increase in the north
4. The amount of rain will increase throughout the country.

Fig. 1 shows the changes in winter temperature (December, January, and February) in Sweden (Eklund et al. 2015). As can be seen, the winter temperature is expected to rise above the annual average temperature, with the largest increase in northern Sweden. Hence this research focuses on the northern part of Sweden.

Zhao et al. (2020) reported that from 2000 to 2016, China railway disruptions caused by gales, rainfall, and snow were 13%, 72%, and 5% of the total reported disruptions, respectively. Furthermore, the effects of snow combined with freezing rain or strong winds can lead to the breakage of power lines and even transmission towers, resulting in long disruptions to the railway service, as happened in China in 2008, 2015, and 2018 (Gao 2016; Wang et al. 2020; Zhou et al. 2017).

Liljegren (2018) emphasized the need to better understand railway infrastructure operation and maintenance under several climate scenarios in Sweden. Recently, Nemry and Demirel (2012) provided a general EU-wide outlook about the future vulnerability of transport systems to climate change, focusing on road and rail transport and their infrastructures in the comprehensive European Commission. In addition, Boyle et al. (2013) addressed some climate change hazards and illustrated key potential impacts to transport infrastructure to be considered for policy making. For heat-induced failure modes due to climate change, such as rail buckling and derailment risks, the most common adaptation measures consist of speed limitation. Due to more intense and frequent hot days in summer, this could cause more frequent trip delays for rail transport with huge financial loss as some studies estimate the cost of speed restrictions as high as €31–39 million per year (Ciscar et al. 2014).

Flooding risk will rise with the likelihood of excess precipitation: surface water flooding as a result of direct accumulation, riverine/fluvial flooding as a result of excess runoff and river bank bursts, and groundwater flooding as a result of rises in groundwater levels, depending on diverse geology factors, land use, drainage condition and succession of weather events (Marteaux 2016). Some research has been conducted to assess the impacts of natural hazards on railway systems (see Forzieri et al. 2018; Garmabaki et al. 2022, 2021; Misnevs et al. 2015; Thaduri et al. 2021)).

These studies highlighted meteorological hazards in the transport system based on historical disaster statistics or quantitative risk assessments of specific transport lines, while there is a lack of detailed risk-level indicators. Therefore, to increase the resilience of the railway infrastructure and fulfill reliability, availability, maintainability, and supportability/safety (RAMS) requirements considering exposure time to an extreme weather event, there is an urgent need to conduct a comprehensive risk assessment considering various meteorological hazards (Calle-Cordón et al. 2018; Garambaki et al. 2016; Garmabaki et al. 2021).

Table 1 Effects of climate change on the railway network(Oslakovic et al. 2013)

Climate change effect category	Risk ranking	Vulnerable asset	Gaps in practice, knowledge, and information
Rainfall (including high amount falls, variations to mean rainfall, groundwater content, and soil moisture)	High	Track movement Line closure reduced operating speeds	Impact of rising in both average and extreme rainfall on groundwater content
Extreme high temperature (including air and ground temperature)	High	Track buckling Line closure reduced operating speeds	The interrelationship between temperature with other events such as solar storms, land-surface temperature, and sudden hot days. The position of high-risk track segments is related to forecasted incidences of high temperatures track stability at elevated temperatures than presently faced temperature levels
Railway enbarkmnet Flooding (including river and surface flooding)	High	Track washout Line closure reduced operating speeds	Current and future track segments with below-capacity drainage systems studying through 2040 and 2090 climate scenariosAssessment of Bridge scour
Inland erosion and instability	High	Disruptions from blockages decrease in track condition	Assessment of Geotechnical areas present in and around slip locations Effect of rising in both average and extreme rainfall on slips
Coastal flooding	High (‘true’ risk maybe medium)	Saltwater corrosion flooding causes line closures	The combined effect of both storm surge and sea-level rise on railway assets present lower levels
Windstorm	High (‘true’ risk maybe medium)	Rolling stock stability modest risk of railway equipment and destruction decreased operating speeds	Position and severity of gusts at higher wind location in connection with the national railway network
Snow and ice	High (‘true’ risk maybe medium)	Clogged areas form trees clearances of snow and further inspections	–
Fog and humidity	High (‘true’ risk maybe medium)	Arcing of conductive components in humid situations visibility is reduced below spotting of signal reduction of operating speeds	–
Coastal erosion	Medium	Coastal erosion threatens lines Erosion of coastal defenses	Scour rates in coastal areas
Fewer low-temperature episodes	Moderate	Frozen points	–

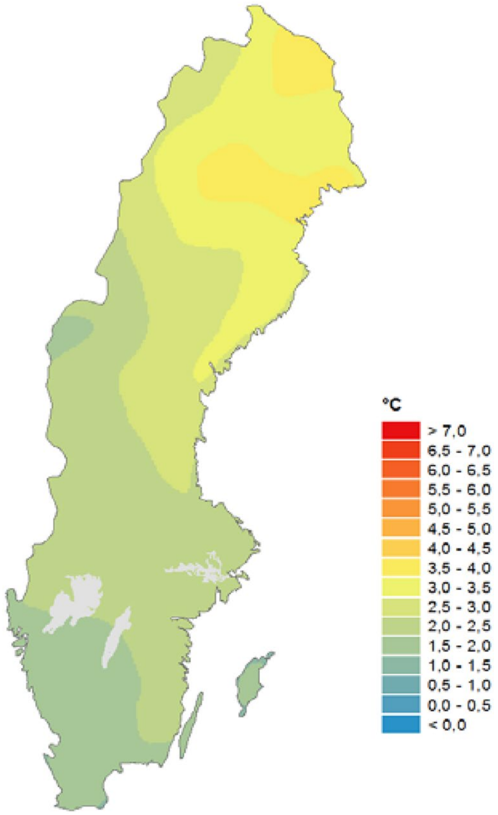


Fig. 1 Annual average temperature with the largest increase in northern Sweden, 2021–2050

In this paper, we have proposed a methodology to analyze the risk of temperature changes induced by climate change posed to railway assets, where we considered the asset's geographical location, asset features, and different failure modes. To this aim, various railway infrastructure databases, meteorological databases for the duration of 2000 till 2019 and questionnaire analyses have been explored to collect the required data. Integrating comprehensive data collection with expert knowledge enables us to perform risk assessments considering climate change indicators and exposure factors.

The rest of the paper is organized as follows: Sect. 2 highlights climate change and its impact on transport infrastructure. Section 3 presents the research methodology and purposes the framework for analyzing the risk. The framework is implemented and validated in Sect. 4. Sections 5 and 6 present the conclusions and future research.

2 Climate change and its impact on railway infrastructure in the northern regions

The impact of climate change is already evident through various observable phenomena, such as an increase in extreme weather events like heat waves, floods, and storms. It is important to note that climate change affects different regions unequally. There are a lot of models and databases that investigate climate change's effects all over the world. In this study, we focus on the northern regions of Sweden. The utilized data are from ERA5, the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of global climate patterns, covering the period from 1979 to 2021, with a spatial resolution of 30 km (Meteoblue, (2023)).

Figure 2 shows an approximation of the average annual temperature for Luleå, in northern Sweden. The dashed blue line represents the linear trend of climate change. The trend line slopes represent that the temperature in this area has been rising steadily over time, and that annual rainfall has also increased over the period studied. In the lower section of the graph, you can see the representation of warming stripes. Each colored stripe corresponds to the average temperature for a particular year, with blue colors denoting years colder than the average of 1979–2021 and red representing warmer years.

2.1 Climate change projection scenarios for Northern Sweden

The effects of climate change can be seen in changes to local weather patterns and extreme weather events, such as heatwaves, droughts, floods, and storms. RCPs proposed by UN Climate Change Panel IPCC 6 can be used to project future climate changes (IPCC6 et al. 2022). Four RCP scenarios, RCP2.6, RCP4.5, RCP6, and RCP8.5, have been considered, which differ in their assumptions about future climate scenarios. Figure 3 illustrates the projected winter and summer temperatures for Luleå for various RCP scenarios. The results indicate a rise in temperatures across all scenarios, with the most notable surge almost reaching 5 °C under the RCP8.5 scenario.

3 Materials and methods

In this study, we aim to investigate the impact of extreme climate and assess its risks to the railway infrastructure. The research methodology emphasizes collecting and integrating various sources of data/information to map climate risks and better evaluate the climatic implications on the railway infrastructure. A questionnaire has been distributed to multiple

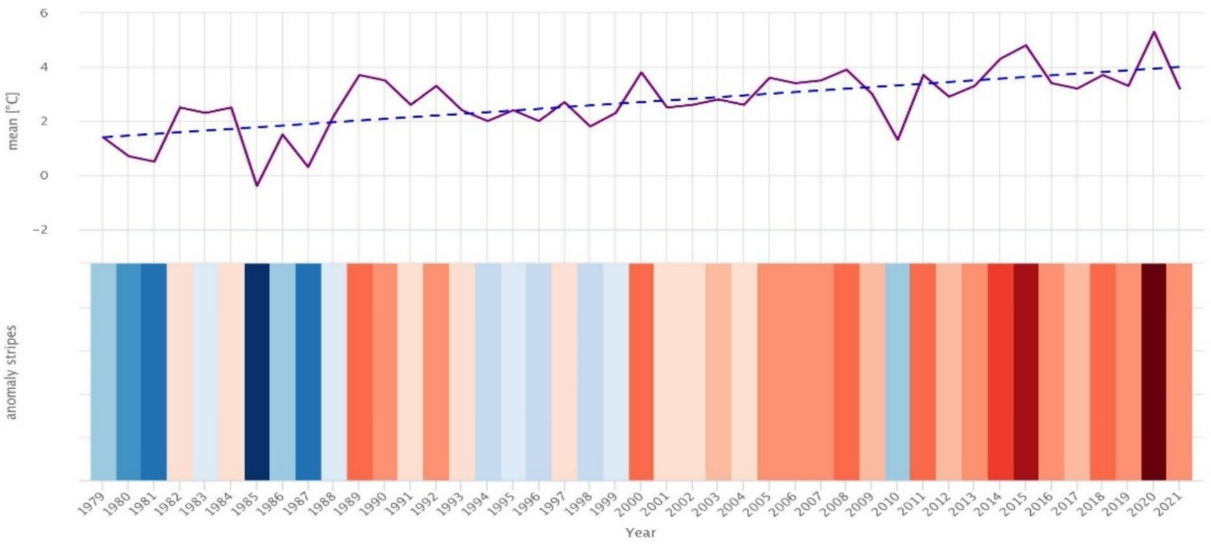
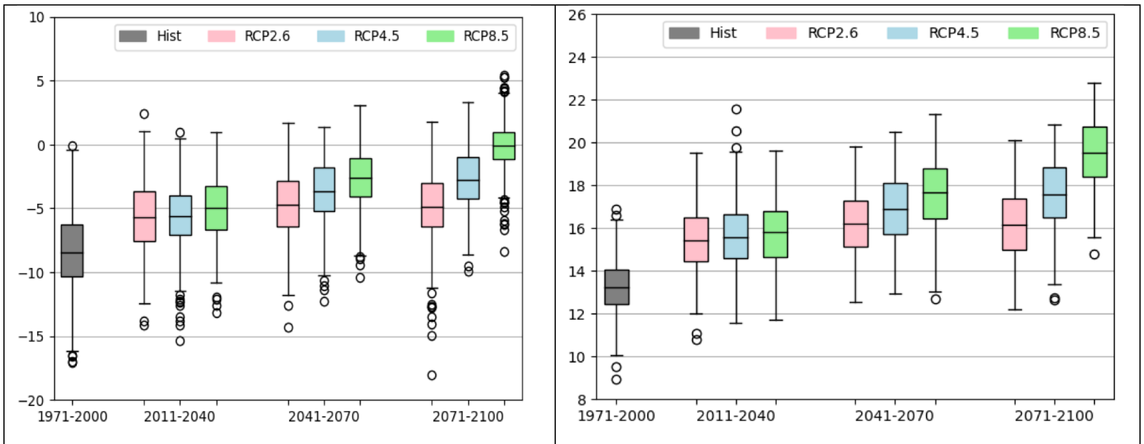


Fig. 2 Yearly Temperature Change in Luleå (Meteoblue, (2023))



a. Projected winter at Luleå

b. Projected summer at Luleå

Fig. 3 Projected winter and summer temperature (°C) in Luleå city in Sweden in the historical period 1971–2000 grey boxes, and the periods 2011–2040, 2041–2070, and 2071–2100 according to RCPs. The boxes represent the interquartile range (IQR) of the data, the line within represents the median, and the whiskers extend from the box by 1.5xIQR. Data points outside the whiskers are marked by circles. a Projected winter at Luleå. b Projected summer at Luleå

experts to collect their opinions on climate change hazards to railway transport. A framework is proposed to identify vulnerable assets considering different climatic parameters, as illustrated in Fig. 4. The expected outcomes of the framework are:

1. Enhancing the level of awareness by stimulating different scenarios.
2. Assessment of extreme temperature risks and its consequences considering exposure factors.
3. Identification of appropriate climate adaptation measures.

The framework consists of four different steps as described in the following:

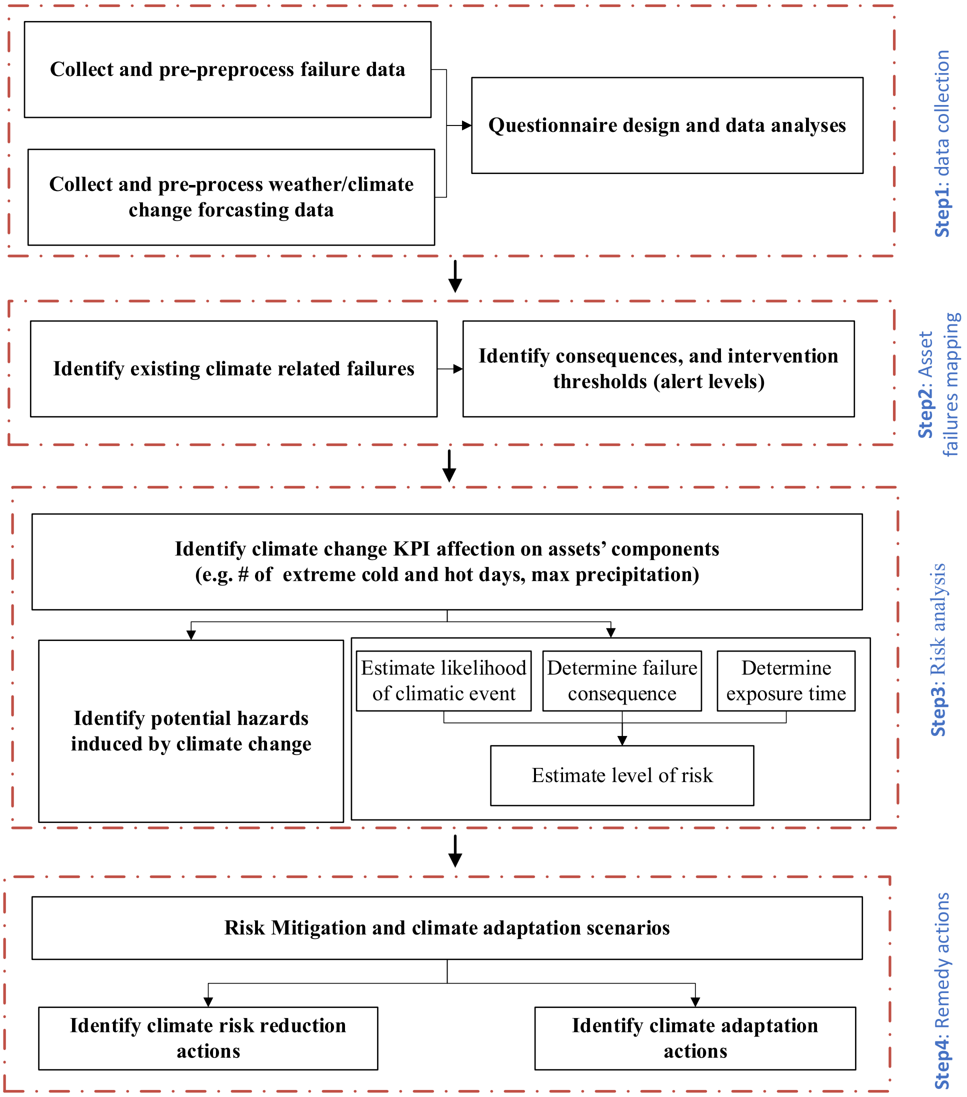


Fig. 4 Research methodology framework (A.H.S Garmabaki, 2023)

3.1 Step 1–Collecting railway infrastructure asset data and meteorological parameters.

Different types of data, including failure data, asset registry data, geographical and meteorological data for the period 2001 till 2022 have been collected. The Swedish transport infrastructure (TRV) collects all operation and maintenance data of switches and crossings. Meteorological observation datasets were created from SMHI open-access database and VViS database. Swedish Transport Administration has its own weather stations, "VViS database" which are mainly distributed across the road infrastructure.

For the present study, a questionnaire with 38 questions was designed (see supplementary materials Garmabaki

Table 2 Description of the questionnaire and its structure

Questions	Description
Q1–Q5	General description of the experts and their domain of expertise
Q6–Q11	Risk of high temperature to railway network (temperature greater than 27 degree)
Q12–Q15	Risk of low temperature to railway network
Q16–Q25	Risk of snowstorms, snow & ice to railway network
Q26–Q31	Risk of flooding, landslide and groundwater level to railway network
Q32–Q38	Risk of high wind to railway network

et al. 2020, 2021). The target groups for the questionnaire were TRV experts, municipalities, maintenance contractors, academics, and other related stakeholders. The general description of the questionnaire and its structure is summarized in Table 2. It should be noted that this research is focused on the extreme temperature risks expressed using Q6–Q11 and Q12–Q15. However, the developed framework is designed to cover all the threats posed by climate change. The detailed description and analysis of these responses are presented in subsequent sections.

In this study, we are exploring only extreme temperature impacts on railway infrastructure asset, switches-crossing, located in northern Sweden.

3.1.1 *Questionnaire data*

The selection of the use cases is based on TRV interest and the availability of the data for the selected assets. For the study, the selected assets are rail track and switches-crossing. Five extreme climate parameters were identified for the Swedish railway network based on interviews with experts and a literature review. The selected climate parameters include High Temperature, 2) Low Temperature, 3) Snow and Ice, 4) Flooding/Landslide and 5) High Wind. The questionnaire was designed to evaluate the likelihood of failure and its consequences on the selected assets while considering exposure time for the above-mentioned climatic hazards. Therefore, various exposure times have been defined based on the literature review and according to expert opinions.

3.1.2 *.Selection of experts*

We define the expert as "a person who has a background in the subject matter at the desired level of detail and who is recognized by his/her peers or those conducting the study as being qualified to solve the questions" (Naseri & Barabady 2016a, 2016b); Otway and Winterfeldt (1992). To select the study experts, we considered various features e.g., having work experience in the operation and maintenance of transport infrastructure or having knowledge on climate change impacts on transport infrastructure. In the study, the total number of experts in Swedish transport infrastructure with related backgrounds and expertise is not exceeding 500 (population size) and our targeted sample size based on ± 10% margin of error where 82 experts. The response rate of questionnaire is around 27%. In the survey, several experts were asked to assess the likelihood of the occurrence of certain failures and their associated consequences.

The pie chart in Fig. 5 shows the distribution of different professions of the experts. We received responses from 25 experts, of which three were later removed from the study due to quality issues and missing information in the responses. There were three female and 19 male experts in the study.

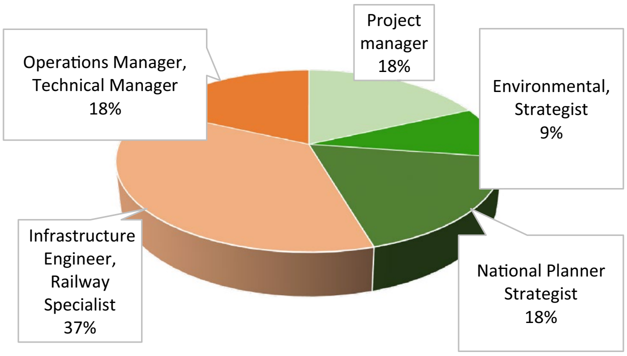


Fig. 5 Participant expertise and their ratios in the questionnaire study

Table 3 Failure mode frequency and causes due to climate change for the period 2001 till 2022

Climate ID	Traffic is interrupted	Traffic is not interrupted	Total
Abnormal temperature	461	3902	4363
Accessibility in track due to weather	0	2	2
Buckling	11	4	15
Drainage	0	3	3
Fire	23	205	228
Flood	1	1	2
Heavy wind / Storm	11	77	88
Natural events	212	48	260
Platform weather	14	7	21
Slippery track	0	10	10
Snow and ice	3879	19,631	23,510
Storm	0	116	116
Switch failure snow storm	59	753	812
Thunderstorm	89	259	348
Total	4760	25,018	29,778

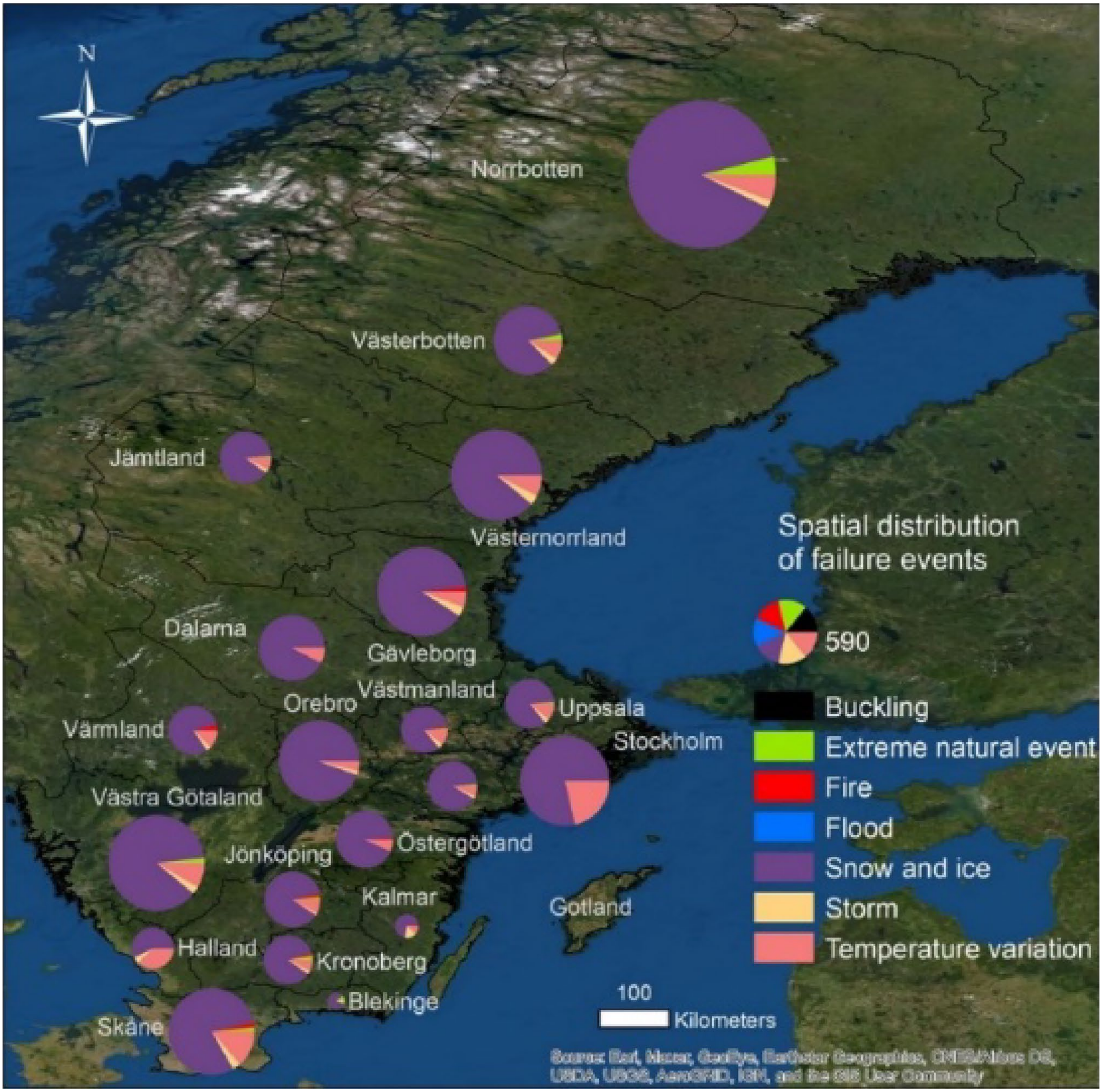
3.1.3 *Expert opinion elicitation*

The risk analysis results depend on expert opinions as a key source of data. Expert opinion elicitation is "the process of obtaining the subjective opinions of experts through specifically designed methods of communication, such as surveys, interviews, group meetings, and questionnaires" (Meyer & Booker 1991). In this research, a qualitative approach was utilized for expert opinion elicitation, and experts expressed their opinions about a parameter in the form of a five-scale rating, in addition to the option, "I do not know" to reduce guess impact) (Cooke & Shrader-Frechette 1991). In addition, to check the reliability of the questions, Cronbach's alpha was calculated as 0.75 and 0.91, which indicates an acceptable to good consistency range.

3.2 Step 2: Asset climate-induced failure mapping

In the next step, Climate ID for asset failure data is designed to identify climate-related failures utilizing error codes and cross-checking with various databases. For this study, **29,778** climate-related failures were identified. The failure modes, causes, and their associated consequences are tabulated in Table 3. Snow and ice, thunderstorms, and abnormal temperature are the dominant factors. At the time of each failure, the last 24 h of whether conditions were collected from the nearest weather stations belonging to Trafikverket (VViS) and/or SMHI.

Figure 6 represents the distribution of climate-related failure over the country. Each Climate ID is represented by color, and the circle's magnitude represents the occurrence's frequency.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 6 County-wise spatial distribution of the reported failure events

3.3 Step 3: Risk assessment modelling framework

Mapping the climate risks to transport infrastructure networks, overlain by the spatial distribution of climate change projections in Geographic Information Systems (GIS) helps us better assess the climatic implications on the railway infrastructure.

3.3.1 Identify climate change KPI affecting assets

About 60 different climate KPIs have been utilized for climate prediction. To identify the most relevant climate change KPI that impacts switches and crossings, we have followed Delphi approaches considering various failure modes.

To identify climate change KPIs, five different failure modes have been selected in collaboration with the experts and the data analysis outcomes. For this task, we interviewed six experts in 3 rounds. In this group, the temperature and precipitation was selected as the first two important climate factors, see Table 4. In the assessment, the climate factor selection is based on the lowest rank after aggregation of the stakeholder's views. Finally, those factors with a ranking index of less than 10 have been selected for the next analysis. In this analysis, we emphasize temperature-related KPIs and their impacts on railway infrastructure asset.

3.3.2 Modelling the natural hazard risks

Let us consider some railway infrastructure that is exposed to natural hazards X caused by climate change impacts. Based on the outcome from Delphi approach, the extreme temperature impacts, cold (L) and hot (H) have been selected for this study, i.e., $X \in \{H, L\}$. These hazards can lead to a certain failure $\Phi^{(X)}$ that may occur via a range of specific exposure scenarios, $\pi^{j}_{\Phi(X)}$, $j = 1, \ldots, n_{\pi}^{\Phi(X)}$, where $n_{\pi}^{\Phi(X)}$ is the total number of scenarios for the occurrence of failure $\Phi^{(X)}$ due to hazard X. Scenarios may be defined, for instance, as the period of time that the infrastructure is exposed to a specific hazard. The set of failure types and scenarios are elicited from experts.

Since the established scenarios are mutually exclusive, the probability of occurrence of failure $\Phi^{(X)}$, can then be obtained using the total law of probability, as given by Eq. (1),

$$\mathrm{P}\left(\Phi^{(X)}\right) = \sum_{j \in \pi_{\Phi(X)}} \mathrm{P}\left(\Phi^{(X)} \middle| \pi^{j}_{\Phi(X)}\right) \mathrm{P}\left(\pi^{j}_{\Phi(X)}\right) \tag{1}$$

Further, let us consider that failure $\Phi^{(X)}$ can lead to some consequence $C_{\Phi(X)}$, which can be expressed as a weighted arithmetic average of damage to the infrastructure and capacity loss, denoted by $C^{I}_{\Phi(X)}$, cost of damage to the environment, denoted by $C^{E}_{\Phi(X)}$, and costs related to the safety and health consequences for the public, denoted by $C^{S}_{\Phi(X)}$:

$$C_{\Phi(X)} = \omega^{I} C^{I}_{\Phi(X)} + \omega^{E} C^{E}_{\Phi(X)} + \omega^{S} C^{S}_{\Phi(X)} \tag{2}$$

where ω^{I}_{C}, ω^{E}_{C} and ω^{S}_{C} are the normalised weighting factors for consequence categories of infrastructure, environment, and safety, respectively, in such a way that $\sum_{x \in \{I,E,S\}} \omega^{x}_{\mathrm{C}} = 1.$

In practice, quantifying the values of $\mathrm{P}\left(\Phi^{(X)} \middle| \pi^{j}_{\Phi(X)}\right)$ and $C_{\Phi(X)}$ is rather complex and associated with large uncertainties. Thus, one may use qualitative ranks for the likelihood of the occurrence of failure $\Phi^{(\mathrm{X})}$ given scenario $\pi^{j}_{\Phi(X)}$, denoted as $\gamma\left(\Phi^{(X)} \middle| \pi^{j}_{\Phi(X)}\right)$, and for its associated consequences, denoted by $\psi\left(C_{\Phi(X)}\right)$. If such ranks are given in linear scales, one can define the level of risk by adding the ranks of the likelihood of

Table 4 Selection of climatic KPI and its ranking based on the aggregation of TRV and InfraNord expert's opinion

Short name	Climate parameter	Climate index	Final
TX	Temperature	Daily maximum temperature	1
TN	Temperature	Daily minimum temperature	7
DTR	Temperature	Diurnal amplitude (warmest minus coldest)	2
Warmdays	Temperature	Hot days/high summer days (Maximum temperature > 20 °C) *	9
Conwarmdays	Temperature	Heat wave (consecutive days with maximum temperature > 20ºC)	3
Vegseasondayend-5	Temperature	Length of the growing season (average temp > 5ºC)	5
Colddays	Temperature	Cold days (maximum temperature < -7ºC)	2
PRRN	Precipitation	Total rain	5
PRSN	Precipitation	Total snow	5
PR7Dmax	Precipitation	Highest rainfall during 7 days	4
Prgt25days	Precipitation	Extreme precipitation > 25 mm/day	1
Drydays	Precipitation	Dry days (with precipitation < 1 mm)	7
Lnstdrydays	Precipitation	Longest dry period (with < 1 mm/day)	10

Table 5 Ranks for the likelihood of occurrence of failure per scenarios

Likelihood rank $\gamma\left(\Phi^{(X)}\middle|\pi^{j}_{\Phi^{(X)}}\right)$	Linguistic variable	Probability of occurrence of failure $\Phi^{(X)}$ given scenario $\pi^{j}_{\Phi^{(X)}}$ (%)
1	Very low	Around 10
2	Low	Around 30
3	Moderate	Around 50
4	High	Around 70
5	Very high	Around 90

the occurrence of the conditional failures and the ranks of their associated consequences, as given by Eq. (3),

$$r^{\Phi^{(X)}} = \frac{\sum_{j\in\pi_{\Phi^{(X)}}} \gamma\left(\Phi^{(X)}\middle|\pi^{j}_{\Phi^{(X)}}\right) \times \mathrm{P}\left(\pi^{j}_{\Phi^{(X)}}\right) + \psi\left(C_{\Phi^{(X)}}\right)}{2} \tag{3}$$

where $r^{\Phi^{(X)}} \in \{1,\dots,5\}$ is the level of risk. The likelihood rank $\gamma\left(\Phi^{(X)}\middle|\pi^{j}_{\Phi^{(X)}}\right) \in \{1,\dots,5\}$ is given in Table 5. In addition, Tables 6, 7 and 8 present the rank of the consequence severity for different attributes, whose weighted linear combination is used for the rank of the total consequences, i.e., $\psi\left(C_{\Phi^{(X)}}\right) \in \{1,\dots,5\}$. In Eq. (3), $P\left(\pi^{j}_{\Phi^{(X)}}\right)$ can be obtained using historical data on natural hazards or extracted from meteorological databases.

3.3.3 *Expert judgments for risk estimation*

Let $\lambda^{(e)}$ denote the value of parameter λ that is elicited from expert $e = 1,\dots,M$, where M is the total number of experts. In order to account for the uncertainties associated with expert opinions, one can use the probability mass function of parameter λ, which can be obtained by counting the number of experts who assign $\Lambda = \lambda$ divided by the total number of experts, given by Eq. (4),

$$P(\Lambda = \lambda) = \frac{\textit{Number of expets who assign } \Lambda = \lambda}{M} \tag{4}$$

Table 7 Ranks for the severity of the consequences of the failures in terms of damage to the environment

Consequence severity rank $\psi\left(C^{E}_{\Phi^{(X)}}\right)$	Linguistic variable	Environment
1	Negligible	Less than 10% of total damages
2	Minor	Between 10–20% of total damages
3	Major	Between 20–30% of total damages
4	Critical	Between 30–50% of total damages
5	Catastrophic	More than 50% of total damages

Thus, if one elicits expert opinions on likelihood rank $\gamma\left(\Phi^{(X)}\middle|\pi^{j}_{\Phi^{(X)}}\right)$ and consequence severity rank $\psi\left(C_{\Phi^{(X)}}\right)$ corresponding to failure $\Phi^{(X)}$ conditional on scenario $\pi^{j}_{\Phi^{(X)}}$, $j = 1,\dots,n^{\Phi^{(X)}}_{\pi}$, the probability distribution of the rank of risk $r^{\Phi^{(X)}}$, denoted by $F_R\left(r^{\Phi^{(X)}}\right)$, can be obtained using Eq. (5),

$$F_R\left(r^{\Phi^{(X)}}\right) = \frac{\sum_{j\in\pi_{\Phi^{(X)}}} F_\Gamma\left(\gamma\left(\Phi^{(X)}\middle|\pi^{j}_{\Phi^{(X)}}\right)\right) Freq\left(\pi^{j}_{\Phi^{(X)}}\right) + F_\Phi\left(\psi\left(C_{\Phi^{(X)}}\right)\right)}{2} \tag{5}$$

where $F_\Phi\left(\psi\left(C_{\Phi^{(X)}}\right)\right)$ can be obtained a composite distribution of the ranks of consequence attributes, as given by Eq. 6,

$$\begin{aligned} F_\Phi\left(\psi\left(C_{\Phi^{(X)}}\right)\right) &= \omega^{I} F^{I}_{\Phi}\left(\psi\left(C^{I}_{\Phi^{(X)}}\right)\right) \\ &\quad + \omega^{E} F^{E}_{\Phi}\left(\psi\left(C^{E}_{\Phi^{(X)}}\right)\right) + \omega^{S} F^{S}_{\Phi}\left(\psi\left(C^{S}_{\Phi^{(X)}}\right)\right) \end{aligned} \tag{6}$$

In Eq. (5), $F_\Gamma(\cdot)$ and $F_\Phi(\cdot)$ are the probability distributions of ranks γ and ψ. $F_\Phi\left(\psi\left(C_{\Phi^{(X)}}\right)\right)$ and $F_R\left(r^{\Phi^{(X)}}\right)$ can be obtained using a Monte Carlo simulation technique without loss of generality. One should note that, Eq. (5) gives the distribution of the rank of the risk of failure $\Phi^{(X)}$.

Table 6 : Ranks for the severity of the consequences of the failures in terms of damage to the infrastructures

Consequence severity rank $\psi\left(C^{I}_{\Phi^{(X)}}\right)$	Linguistic variable	Infrastructure
1	Negligible	The damage to infrastructure and loss of capacity are less than 1MSEK;
2	Minor	The damages is valued between 1–5 MSEK
3	Major	The damages is valued between 5–10 MSEK
4	Critical	The damages is valued between 10–25 MSEK
5	Catastrophic	The damages is valued more than 25 MSEK

Table 8 Ranks for the severity of the consequences of the failures in terms of safety and health

Consequence severity rank $\psi\left(C^S_{\Phi(X)}\right)$	Linguistic variable	Safety
1	Negligible	No injuries
2	Minor	Minor injuries and no loss of life
3	Major	Injuries and loss of less than 5 lives;
4	Critical	Many injurers/and loss of 5–10 lives;
5	Catastrophic	Major injurers/and loss of 5–10 lives or more

3.3.4 Operationalising the risk model

Let us consider rail infrastructure asset located in a certain geographical region. To estimate the risks due to failure $\Phi^{(X)}$ occurring as a result of natural hazard X for a given period of time τ. The distribution of the risk rank of the infrastructure due to $\Phi_i^{(X)}$ as a result of natural hazard $X \in \{H, L\}$ can be obtained by following the step-by-step framework proposed in Fig. 7.

3.4 Step 4: Remedy actions

In order to maintain the safety and functionality of the railway infrastructure, adapting to extreme temperatures is essential. Here the following are some of the strategies that can be used to adapt to extreme temperature scenarios:

1. Track design: The use of materials that can withstand temperature changes with an acceptable range of thermal expansion.
2. Expansion joints: Installing expansion joints allows the track to expand and contract with temperature changes, preventing buckling or misalignment.
3. Heat-resistant coatings: The effects of extreme temperatures can be reduced by applying heat-reflecting or heat-absorbing coatings to tracks and infrastructure. In Italy, white rail coatings are already in use. Their evaluation is promising.
4. Insulation: The use of insulating materials around critical components such as signals, switches and control systems helps to maintain their functionality during temperature fluctuations.

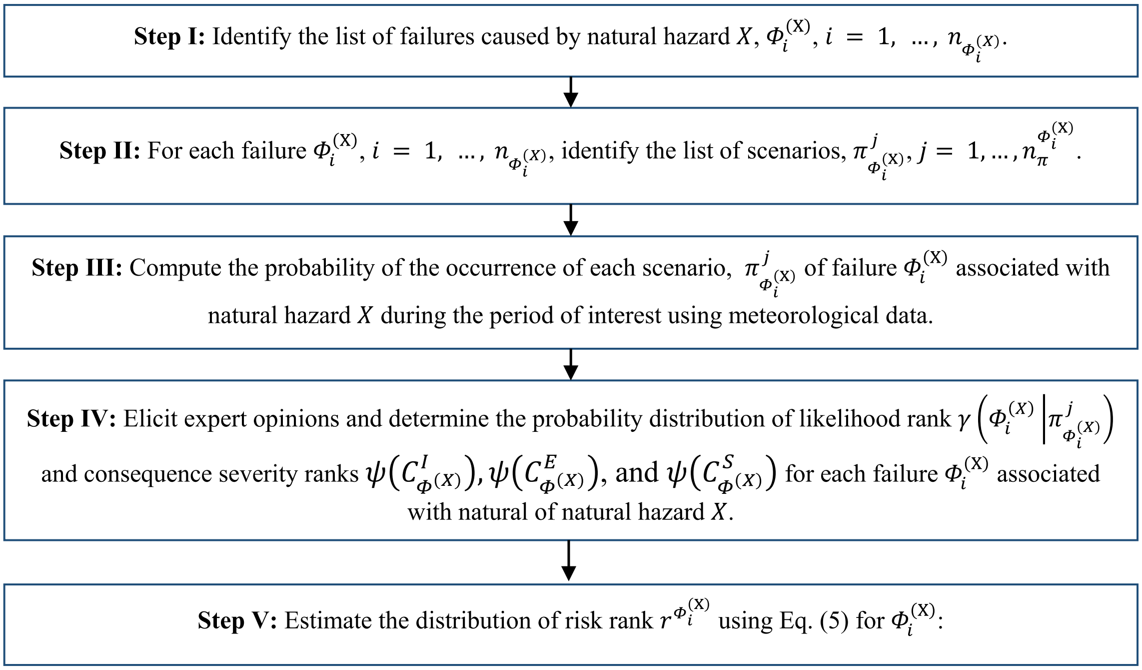


Fig. 7 Estimating the distribution of risk associated with rail infrastructure due to failure $\boldsymbol{\Phi}^{(\mathbf{X})}$ occurring as a result of natural hazards $\boldsymbol{X}$ for a given period of time

5. Shade structures: Reducing direct exposure to sunlight and extreme snowfall by installing shelters or galleries along the tracks.
6. Monitoring systems: Implementing advanced monitoring systems that detect changes in temperature and track conditions in real-time can enable proactive maintenance and timely intervention.
7. Cooling technologies: Implementing cooling systems, such as water sprays or embedded cooling pipes along the track, can help regulate temperatures during extreme heat.
8. Weather-responsive operations: Implementing weather-responsive operating protocols allows adjustments to speed limits, track inspections and maintenance schedules during extreme temperature conditions.
9. Vegetation Management: The management of vegetation in the vicinity of tracks can prevent the obstruction of air flow and reduce the heat island effect that contributes to higher temperatures around railway infrastructure.
10. Community awareness: Awareness raising through education and demonstration of the impact of extreme events can be a catalyst for co-operation.

Combining these strategies can enhance the resilience of railway infrastructure against extreme temperatures and mitigate hazards associated with heat-induced deformations or malfunctions.

4 Framework validation

The aim of the proposed framework is to map the risk of railway assets posed by climate change. Therefore, an illustrating case from Luleå railway station in northern Sweden has been selected. In the first step, the infrastructure asset data, including failure date, type of failures, train interruption by failure, maintenance duration, and asset location, are collected from the Ofelia and BIS datasets. In this research, we have focused only on the hourly temperature feature which is extracted from SMHI open databases. The temperature data for 18 years from 2001 until 2018 from Luleå-Kallax Airport weather station, as the closest weather station to the asset, is extracted.

Two scenarios for the temperature have been defined, including:

1. Temperature greater than 27 ℃
2. Temperature less than – 20 ℃.

Thereafter, the exposure times of the asset have been divided into four different categories:

Table 9 Selected failure modes of railway infrastructure asset due to extreme temperature

Hazard	Induced failure
High temperature,H	$\Phi_1^{(H)}$, “Track, switches-crossing” buckling
	$\Phi_2^{(H)}$, Vegetation fire
	$\Phi_3^{(H)}$, Supportability loss
Low temperature,L	$\Phi_1^{(L)}$, Rail defect and breakage
	$\Phi_2^{(L)}$, Supportability loss

Table 10 Frequency of scenarios for H(High temperature), and L(Low temperatures) hazards

Hazard H: High temperatures for all failures ($i = 1, 2, 3$)	Hazard L: Low temperatures for all failures ($i = 1, 2, 3$)
Scenario S1, $\pi^1_{\Phi_i^{(H)}}$: 0.380952381	Scenario S1, $\pi^1_{\Phi_i^{(L)}}$: 1.954545455
Scenario S2, $\pi^2_{\Phi_i^{(H)}}$: 0.142857143	Scenario S2, $\pi^2_{\Phi_i^{(L)}}$: 0.727272727
Scenario S3, $\pi^3_{\Phi_i^{(H)}}$: 0.19047619	Scenario S3, $\pi^3_{\Phi_i^{(L)}}$: 0.863636364
Scenario S4, $\pi^4_{\Phi_i^{(H)}}$: 0.19047619	Scenario S4, $\pi^4_{\Phi_i^{(L)}}$: 4.272727273

1. Exposure time less than 1 h (S1)
2. Exposure time less than 2 h (S2)
3. Exposure time between 2 and 5 h (S3)
4. Exposure time greater than 5 h (S4)

For instance, consider hazard $X = H$ (i.e., High-temperatures). Three different failures may occur due to this high-temperature hazard, as given in Table 9, ie., “Track, switches-crossing” buckling $\Phi_1^{(H)}$,Vegetation fire $\Phi_2^{(H)}$, and Supportability loss, denoted by $\Phi_3^{(H)}$.

There are four different exposure scenarios:

1. $\pi^1_{\Phi_i^{(H)}}, i = 1, 2, 3$: High-temperature exposure for less than 1 h.
2. $\pi^2_{\Phi_i^{(H)}}, i = 1, 2, 3$: High-temperature exposure between 1 and 2 h
3. $\pi^3_{\Phi_i^{(H)}}, i = 1, 2, 3$: High-temperature exposure between 2 and 5 h.
4. $\pi^4_{\Phi_i^{(H)}}, i = 1, 2, 3$: High-temperature exposure for more than 5 h.

4.1 Risk of extreme high/low temperature to railway

For the period 2001–2022, the number of weather incidents in which temperature is above 27 ℃ and below – 20℃ have been identified according to the predefined exposure scenarios S1-S4 for the asset located at Luleå. The frequency of occurrence of each scenario, as presented in Table 10, is estimated for month July as the hottest month for the high-temperature hazard, and for February as the coldest month of the year for the low-temperature hazard.

4.1.1 *"Track, switches-crossing" buckling failure due to high temperatures*

To illustrate the Probability Distribution Functions (PDF) of the likelihood of failures and their consequences, we present the detailed results for the failure $\Phi_1^{(H)}$, "Track, switches-crossing buckling". The likelihood of failure occurrence under scenarios S1-S4 are asked from the experts as described in Table 5. We also elicited expert opinions on the severity ranks of three different consequences related to the failure occurrence using the descriptions in Tables 6–8. For this specific example, 15 experts provided their opinions. The distribution of the ranks given by the experts is presented in Fig. 8 for the failure $\Phi_1^{(H)}$, "Track, switches-crossing buckling".

In the next step, the likelihood of the occurrence of each failure, considering the probability of occurrence in all exposure scenarios, is estimated using the total law of probability. Figure 9 shows the probability density function of the likelihood of the occurrence of failure $\Phi_1^{(H)}$, "Track, switches-crossing" buckling. The Mean of the failure occurrence frequency and consequence severities of extreme hazards H and L temperatures associated with different failure modes are presented in Table 11. The Mean for track buckling is 0.63 times per month due to high-temperature effects.

Furthermore, the severity of failure consequences is estimated using Eq. (6). As an example, Fig. 10 shows the distribution of the severity ranks for the combined consequence of $\Phi_1^{(H)}$, "Track & switches-crossing" buckling. It should be noted that we have aggregated three different consequence attributes, i.e., damage and capacity loss, the consequence for the environment, and the safety consequence, using weighted arithmetic methods, with weighting factors [0.4 0.2 0.4], respectively.

4.1.2 *Risk matrix for extreme temperature hazards*

The risk matrix, presented in Table 12, maps the failure modes of hazards at high and low temperatures. Here, the first row is associated with the consequences as C1: Negligible, C2: Minor, C3: Major, C4: Critical, C5: Catastrophic).

5 Conclusion

This study assessed climate risk associated with extreme hot and cold temperatures on railway assets. We gathered

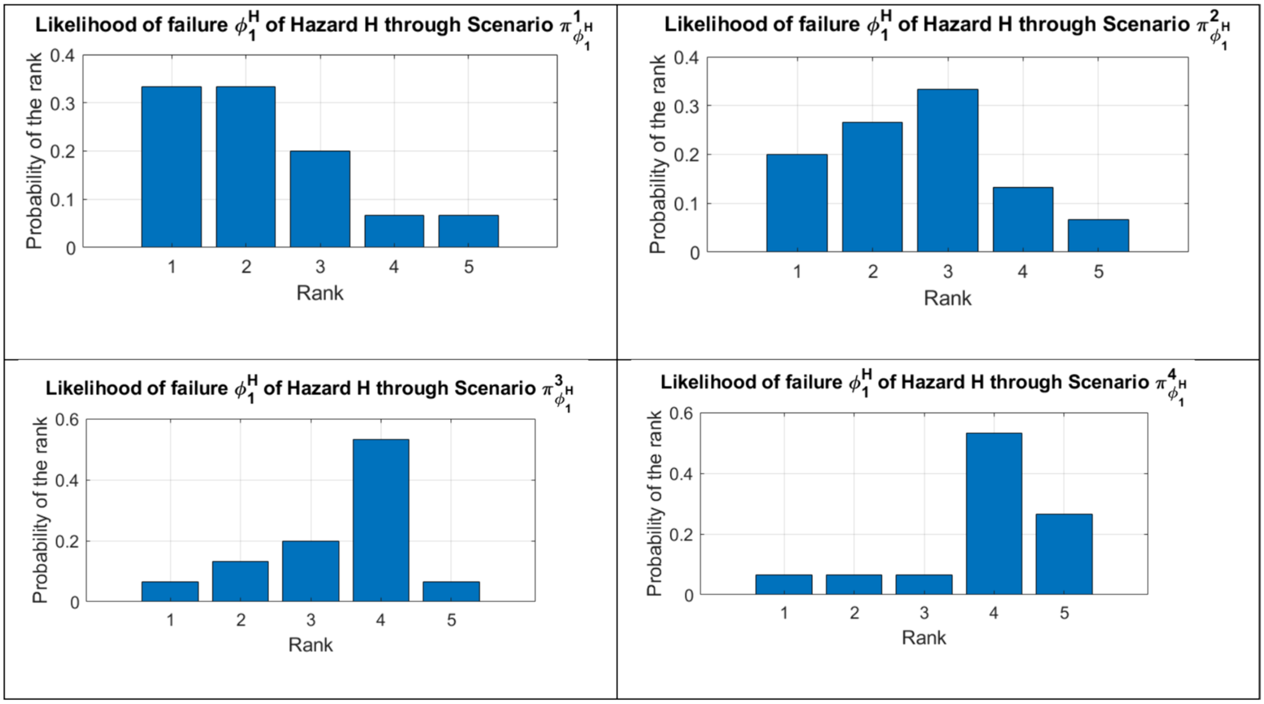


Fig. 8 Distribution of the ranks of the likelihood of failure $\boldsymbol{\Phi}_1^{(H)}$, "Track switches–crossing" buckling due to high temperature hazard, under different exposure scenarios

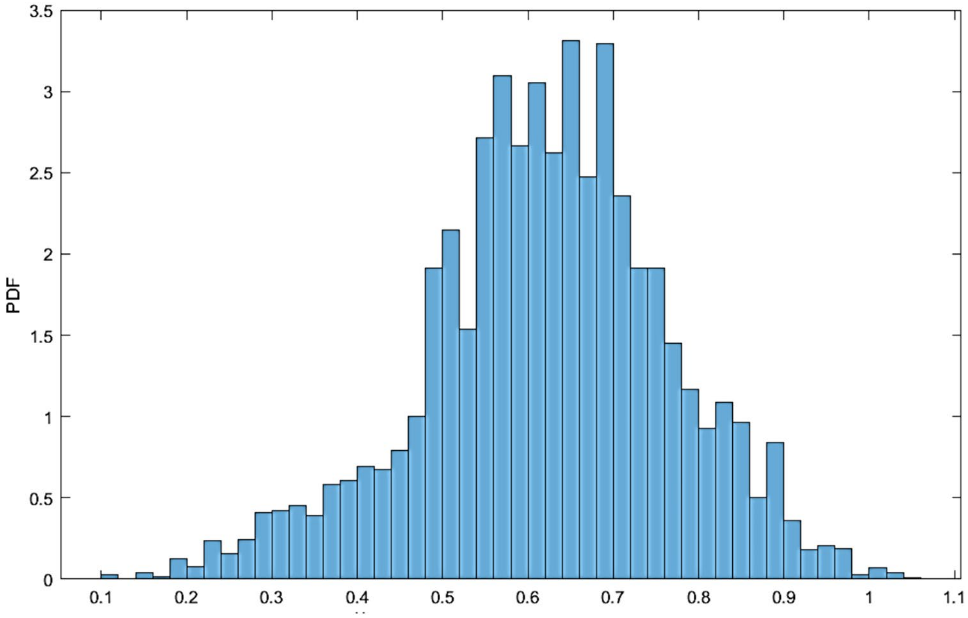


Fig. 9 PDF of the frequency of "Track, switches-crossing" buckling considering different exposure scenarios, Mean = 0.71

Table 11 Mean of failure occurrence frequencies given all four scenarios for high-temperature, and low-temperature hazards

Hazard	Induced failure	Mean of failure occurrence frequency, given all four scenarios	The Mean of consequence severity ranks
High- temperature,H	$\Phi_1^{(H)}$, Track, switches-crossing buckling	0.63	3.04
	$\Phi_2^{(H)}$, Vegetation fire	0.71	2.75
	$\Phi_3^{(H)}$, Supportability loss	0.59	2.70
Low-temperature,L	$\Phi_1^{(L)}$, Rail defect and breakage	3.24	2.83
	$\Phi_2^{(L)}$, Supportability loss	3.60	2.47

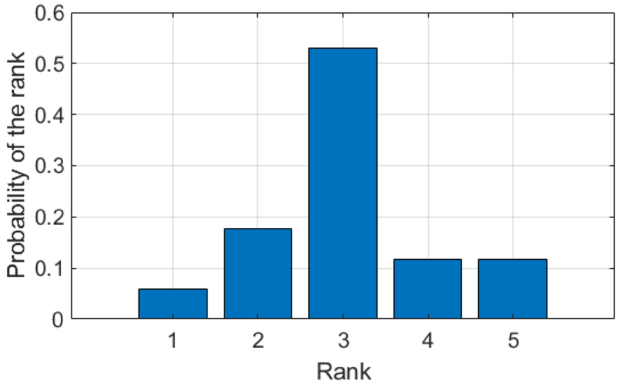


Fig. 10 Aggregation of consequence for "Track, switches-crossing" buckling- consequence scale (Negligible, Minor, Major, Critical, Catastrophic), Mean (consequence) = 3.04

data through expert interviews, questionnaire studies, and exploration of multiple databases sourced from Trafikverket and the SMHI. Subsequently, we developed a framework to identify vulnerable assets by considering various climatic parameters.

The study shows that hot temperature impacts, which cause track bucking and vegetation fire, have received a medium level of risk, while supportability losses are not an issue for the asset located in North Sweden. However, supportability lost in the same area due to extreme cold environments is identified as high risk. In addition, extreme cold temperatures lead to rail defects and breakage with a medium level of risk in Luleå area. In addition, the risk analyses were performed for four different exposure scenarios; however, we aggregated the predefined scenarios to simplify the analyses. Impact analysis helps infrastructure managers and maintenance entrepreneurs to identify and

Table 12 Risk matrix for high/low-temperature hazards for the asset located in Luleå, Sweden(A.H.S Garmabaki, 2023)

Failure frequency\ Consequences	C1	C2	C3	C4	C5
Less than 0.1 times per month					
Between 0.1–1 times per month		Supportability losses (H)	Vegitation fire (H)		
Track buckling(H)					
Between 1–3 times per month					
More than 3 times per month		Rail defect breakage (L)	Supportability losses (L)		

prioritize climate risks. This will help decision-makers identify appropriate climate adaptation measures and actions to cope with future climate change effects.

6 Future research

We are working to implement different future scenarios to map climate risks and hazards for all railway switches and crossing assets, considering the geographical location and exposure factors. In addition, we are extending our research domain to assess the extreme wind and extreme precipitation, including rain snow and windstorms.

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Declarations

Conflict of interest There are no conflicts of interest declared by any of the authors.

Human participants and/or animals Human Participants and/or Animals are not involved in this research.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

A.H.S Garmabaki, M. N., Johan Odelius, Matthias Asplund, Javad Barabadi, Gustav Strandberg (2023), Risk assessment of climate change on Railway infrastructure asset, 7th International Congress and Workshop on Industrial AI and eMaintenance

Andersson-Sköld Y, Thorsson S, Rayner D, Lindberg F, Janhäll S, Jonsson A, Moback U, Bergman R, Granberg M (2015) An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. Clim Risk Manag 7:31–50

Boyle J, Cunningham M, Dekens J (2013) Climate change adaptation and canadian infrastructure, international institute for sustainable development (IISD): winnipeg. MB, USA

Calle-Cordón, A., Jiménez-Redondo, N., Morales-Gámiz, J., García-Villena, F., Peralta-Escalante, J., Garmabaki, A., Famurewa, S. M., Duarte, E., & Morgado, J. (2018). Combined RAMS and LCC analysis in railway and road transport infrastructures. 7th Transport Research Arena TRA 2018, Vienna, 16–19

Carter JG, Cavan G, Connelly A, Guy S, Handley J, Kazmierczak A (2015) Climate change and the city: building capacity for urban adaptation. Prog Plan 95:1–66

Ciscar, J.-C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A. (2014). Climate impacts in Europe-The JRC PESETA II project.

Cooke RM, Shrader-Frechette K (1991) Experts in uncertainty: opinion and subjective probability in science. Oxford University Press, England

Eklund, A., Axén Mårtensson, J., Bergström, S., Björck, E., Dahné, J., Lindström, L., Olsson, J., Simonsson, L., Sjökvist, E. (2015). Sveriges framtida klimat: Underlag till Dricksvattenutredningen. SMHI.

Forero-Ortiz E, Martínez-Gomariz E, Cañas Porcuna M, Locatelli L, Russo B (2020) Flood risk assessment in an underground railway system under the impact of climate change—A case study of the barcelona metro. Sustainability 12(13):5291

Forzieri G, Bianchi A, e Silva FB, Herrera MAM, Leblois A, Lavalle C, Aerts JC, Feyen L (2018) Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environ Change 48:97–107

Gao J (2016) Analysis and assessment of the risk of snow and freezing disaster in China. Intern J Disaster Risk Reduct 19:334–340

Garambaki A, Thaduri A, Seneviratne A, Kumar U (2016) Opportunistic inspection planning for railway emaintenance. IFAC-PapersOnLine 49(28):197–202

Garmabaki AHS, Marklund S, Thaduri A, Hedström A, Kumar U (2020) Underground pipelines and railway infrastructure–failure consequences and restrictions. Struct Infrastruct Eng 16(3):412–430

Garmabaki AHS, Odelius J, Thaduri A, Famurewa SM, Kumar U, Strandberg G, Barabady J (2022) Climate change impact assessment on railway maintenance. Dublin, Ireland

Garmabaki AHS, Thaduri A, Famurewa S, Kumar U (2021) Adapting railway maintenance to climate change. Sustainability 13(24):13856. https://doi.org/10.3390/su132413856

IPCC6, Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R. A., Betts, R., Kerr, R. B., & Biesbroek, R. (2022). Climate change 2022: impacts, adaptation and vulnerability. https://www.ipcc.ch/report/ar6/wg2/

IPCC. (2022). Climate Change 2022: Impacts, adaptation and vulnerability. https://www.ipcc.ch/report/ar6/wg2/

Jain D, Singh S (2021) Adaptation of trips by metro rail users at two stations in extreme weather conditions: Delhi. Urban Climate 36:100766

Jenkins K, Gilbey M, Hall J, Glenis V, Kilsby C (2014) Implications of climate change for thermal discomfort on underground railways. Transp Res Part d Transp Environ 30:1–9

Kaspersen PS, Halsnæs K (2017) Integrated climate change risk assessment: a practical application for urban flooding during extreme precipitation. Climate Serv 6(55):64. https://doi.org/10.1016/j.cliser.2017.06.012

Lemmen, D. S., Lacroix, J.,and Warren, F. J. (2008). From impacts to adaptation: canada in a changing climate, 2007: synthesis. Government of Canada.

Liljegren, E. (2018). Regeringsuppdrag om Trafikverkets klimatanpassningsarbete.

Marteaux, O. (2016). Tomorrow's railway and climate change adaptation. https://www.rssb.co.uk/Library/research-development-and-innovation/2016-05-t1009-exec-report.pdf

Meyer M, Booker J (1991) Eliciting and analyzing expert judgement: a practical tour. Academic Press, London

Misnevs B, Melikyan A, Bazaras D (2015) Hazard assessment of weather factors for the occurrence of an emergency on the railway. Procedia Comput Science 77:40–47

Naseri M, Barabady J (2016a) An expert-based approach to production performance analysis of oil and gas facilities considering time-independent Arctic operating conditions. Intern J Syst Assur Eng Manag 7(1):99–113

Naseri M, Barabady J (2016b) An expert-based model for reliability analysis of Arctic oil and gas processing facilities. J Offshore Mech Arct Eng 138(5):051602

Nemry, F., Demirel, H. (2012). Impacts of Climate Change on Transport: a focus on road and rail transport infrastructures. European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS).

Norrbin, P. (2016). Railway Infrastructure Robustness: Attributes, evaluation, assurance and improvement Luleå tekniska universitet].

Oslakovic, I. S., ter Maat, H., Hartmann, A., Dewulf, G. (2013). Risk assessment of climate change impacts on railway infrastructure In: Proc. Engineering Project Organization Conference 9–11

Otway H, Winterfeldt D (1992) Expert judgment in risk analysis and management: process, context, and pitfalls. Risk Anal 12(1):83–93

Palin EJ, Stipanovic Oslakovic I, Gavin K, Quinn A (2021) Implications of climate change for railway infrastructure. Wiley Interdiscip Rev Climate Change 12(5):e728

Pregnolato M, Ford A, Glenis V, Wilkinson S, Dawson R (2017) Impact of climate change on disruption to urban transport networks from pluvial flooding. J Infrastruct Syst 23(4):04017015

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SMHI. 2022. Advanced Climate Change Scenario Service. https://www.smhi.se/en/climate/future-climate/advanced-climate-change-scenario-service/

Thaduri, A., Garmabaki, A., Kumar, U. (2021). Impact of climatechange on railway operation and maintenance in Sweden: a State-of-the-art review. Maintenance, Reliability and Condition Monitoring (MRCM).

Wang Z, Ding Y, Zhou B, Chen L (2020) Comparison of two severe low-temperature snowstorm and ice freezing events in China: role of Eurasian mid-high latitude circulation patterns. Int J Climatol 40(7):3436–3450

Ye B, Jiang J, Liu J, Zheng Y, Zhou N (2021) Research on quantitative assessment of climate change risk at an urban scale: review of recent progress and outlook of future direction. Renew Sustain Energy Rev 135:110415

Zhao J, Liu K, Wang M (2020) Exposure analysis of Chinese railways to multihazards based on datasets from 2000 to 2016. Geomat Nat Haz Risk 11(1):272–287

Zhou Y, Yue Y, Gao Z, Zhou Y (2017) Climatic characteristics and determination method for freezing rain in China. Adv Meteorol 2017:1–11. https://doi.org/10.1155/2017/4635280