Effect of climate change on railway maintenance: a systematic review

Saeed Mohammad khah

ISISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal. E-mail: mohamadkhah.sa@gmail.com

Joaquim Tinoco

ISISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal. E-mail: jtinoco@civil.uminho.pt

José Campos e Matos

ISISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal. E-mail: jmatos@civil.uminho.pt

Abstract: According to international reports and publications, the effects of climate can cause rail failures and consequently leading to disrupt travel schedules and unforeseen delays. Extreme heat, cold and snowfall are among the most important climate changes conditions that affect the normal railway operation. Thus, in order to determine the appropriate maintenance strategy that reduce the social and economic impact of the repair interventions, it is fundamental to identify and predict in advance the potential points of failure. This paper compares and analysis different published studies related to railways failures by measuring the effects of weather on rail defect.

Keywords: climate change, railway maintenance, performance, railway infrastructure.

Special Session Topic: Probabilistic vulnerability estimation, lifetime assessment and climate change adaptation of existing and new infrastructure.

1. Introduction

Uncertainty over weather conditions has become a significant problem around the world and is a social, economic, and political problem. The reasons for climate change can be attributed to destructive human activities, environmental processes, and increased greenhouse gas emissions (Kaewunruen, Li and Sakdirat 2019).

The need for society to adapt to changing climate conditions has been an issue that has always been considered over the past decades. Increasing concentrations of greenhouse gases have caused global warming over the past century. According to weather forecasting models, the average annual temperature will increase by 1 to 5.5 °C, which will be associated with the possibility of heavy rainfall in the north and reduced rainfall in the south. However, the intensity of daily rainfall will increase with these climate changes on Earth (Oslakovic, Maat and Hartmann 2013).

On the other hand, one of the most important infrastructures of human society that must be adapted to climate change is the transportation sector. Transport networks are very important for social functioning and support the movement of passengers, goods, and services in any community. One of the most important transportation systems that, in addition to being environmentally friendly, can help reduce greenhouse gases, is the rail transportation system. Railways are a vital part of advanced societies, accounting for about 5 to 8.9 percent of GDP (Gross Domestic Product) in Europe and the United States (Greenham, et al. 2020).

Climate change has increased the frequency of severe phenomena, so the rail transport system, which is exposed to severe environmental conditions, may be directly affected by these extreme changes. Severe weather can lead to rail failures, rail buckling, landslides, as well as accidents, and out-of-schedule delays in the transportation sector, causing severe financial and human losses to the system. Therefore, by maintaining its operational strength, it can be maintained in time to achieve a stable and long-term transportation system (Kaewunruen, Li and Sakdirat 2019).

To maintain the efficient operation of rail transport, it is necessary to ensure that the rail network, in addition to withstanding the pressures, is also able to continue working in different weather conditions. According to the European Railway Agency (ERA), in 2016, extreme heat was one of the main causes of rail breakdowns and accidents, and according to the report, in 2018, with more than 6,000 reported cases, severe weather effects can be observed on the rail system (Sanchisa, Francoa and Fernándeza 2020).

In this paper, we have tried to systematic review the existing papers and researches on the effects of climate change on the railways, the rate of breakdowns and delays in different weather conditions, and to determine the important lessons of each region and practical operations. Hence, this paper can be useful for developing an appropriate and sustainable strategy for policymakers, officials, and scientists around the world.

2. Research Method

In this paper, in order to extract papers related to the impact of climate change on railway maintenance management, a search was conducted using the keywords: climate change, railway maintenance, performance, railway infrastructure in the Google Scholar search engine. The criterion for collecting papers was the use of publications that were published in scientific journals, conferences, and organizational and local technical reports between 2000 and 2021.

108 papers were compiled and analyzed with the keywords: review, selection, coding, sorting. In the next step, the abstract of the papers was studied and irrelevant papers were removed from the system. After a thorough study and review of the remaining papers and their screening, the number was reduced to 20 final papers. Figure 1 shows a framework of different steps for sorting papers.

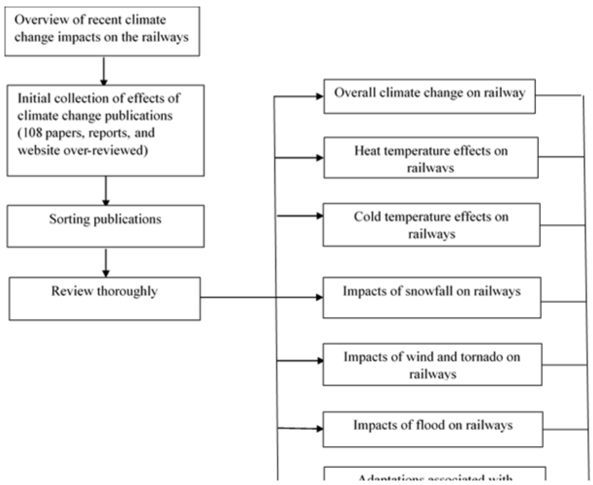

Figure 1. Flowchart of the literature screening methodology used in this review

Because transportation systems, especially railways, are one of the most important infrastructure systems of human society, any damage to this sector can disrupt the daily life of society. Therefore, evaluating and understanding the reactions and possible consequences related to disruptions in the rail transport sector is very important, and in recent years, special attention has been paid to it. Therefore, in this paper, a systematic review of the existing publications with a focus on the effects of weather on railways, as one of the most important causes of disruption in the railway network, is discussed. Table 1 lists the reviewed papers.

Table 1. List of reviewed manuscripts, year, and their domains.

no	Literature	Aim
1	Sarah Greenham, Emma Ferranti, Andrew Quinn,Katherine Drayson (2020) The impact of high temperatures and extreme heat to delays on the London Underground rail network: An empirical study	In this study, the effects of heat intensity on rail failure and its effects on train arrival delay have been investigated using a regression model.
2	Tianni Wanga , Zhuohua Qub, Zaili Yangc, Timothy Nicholb, Delia Dimitriue(2020) Impact analysis of climate change on rail systems for adaptation.	In this paper, by preparing a questionnaire and receiving information from railway organizations, the amount of weather effects on the railway was collected and these responses showed that almost one third of these organizations take preventive measures and then using Fuzzy Bayesian Reasoning is a case study in the UK.
3	Ignacio Villalba Sanchisa, Ricardo Insa Francoa, Pablo Martínez Fernándeza (2020) "Risk of increasing temperature due to climate change on high-speed rail network in Spain"	In this paper, using the buckling formula of the rails, and considering the temperature of the rails and the air temperature and the temperature forecast until 2100, a forecast based on the buckling of the rails in different parts of Spain is presented.
4	Edwar Forero-Ortiz, Eduardo Martínez-Gomariz,, Manuel Cañas Porcuna,, Luca Locatelli and Beniamino Russo(2020) "Flood Risk Assessment in an Underground Railway System under the Impact of Climate Change—A Case Study of the Barcelona Metro"	In this study, it combines data related to the Barcelona Metro with hydraulic models, provides historical data on floods, and uses it to estimate the risk of climate change.
5	Ignacio Villalba, Ricardo Insa Franco (2019), Impacts of climate change on operation of the Spanish rail network"	In this study, using air temperature and rail temperature and a formula in this case, the buckling rate of the rail has been obtained and according to the weather forecast until 2100, this trend has been estimated in different regions of Spain.

Table 1. List of reviewed manuscripts, year, and their domains (Continued).

6	Dan Li and Sakdirat Kaewunruen (2019), Effect of Extreme Climate on Topology of Railway Prestressed Concrete Sleepers	In this paper, the effects of weather on concrete sleepers are analyzed
7	Study on climate change impact assessment for the design, construction, maintenance and operation of Rail Baltica railway 2019.	The purpose of this report is to identify the breakdowns and the impact of weather conditions on the railways of the Baltic, which provides preventive and repair solutions in the face of these conditions.
8	Berg Heinz-Peter (2017), Risks and consequences of weather hazards on railway infrastructure	Provide a flowchart to calculate the vulnerability of the rail network to floods. Temperatures in the UK are projected to be 1.5 degrees warmer in winter and 2.5 degrees warmer in summer by 2050. Preventive measures to prevent floods or the dangers of rising levels.
9	Emma Ferranti, Lee Chapman (2017), "The hottest July day on the railway network: insights and thoughts for the future"	In this paper, information is obtained from railway companies based on existing reports and the effect of excessive heat is related to the amount of delays and buckling using an expert system and sample studies.
10	Dawson D, Shaw J, and Gehrels W (2016) Sea-Level Rise Impacts on Transport Infrastructure	They used a semi-empirical model to define the effects of sea-level rise on the rail system of England
11	David Jaroszwesk, Elizabeth Hooper (2014) , "The impact of climate change on urban transport resilience in a changing world"	In this paper, the effects of various climates such as the intensity of high temperature snowfall and wind intensity on railway failure have been investigated by reviewing the existing literature.
12	Johanna Ludvigsen , Ronny Klæboe (2014), Extreme weather impacts on freight railways in Europe	In this paper, the relationship between temperature and reported delays for freight trains has been investigated using a regression model.
13	Christian Trinks, Michael Hiete,(2013), "Extreme weather events and road and rail transportation in Germany"	In this paper, by preparing a questionnaire, the opinions of experts have been sought and the number of breakdowns and the most weather effects and the method of repair and preventive measures have been presented.
14	Irina Stipanovic Oslakovic, Herbert ter Maat, Andreas Hartmann(2013) "Risk Assessment Of Climate Change Impacts On Railway Infrastructure"	In this paper, the ratio of the number of failures with temperature (high, low and snowfall) is obtained first, then using correlation and regression models until 2050, the amount of failures and delays is predicted.
15	K Dobney,C J Baker, Chapman, and D Quinn (2009), "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"	This paper deals with the effects of high temperatures on the number of breakdowns and delays in the UK rail network and discusses the cost in the future of the UK rail network.
16	Mark J. Koetse , Piet Rietveld (2009), "The impact of climate change and weather on transport: An overview of empirical findings"	In this study, the existing experimental literature examines the conditions of rail network failures with climate change
17	C J Baker, L Chapman, A Quinn, and K Dobney (2009), Climate change and the railway industry: a review	In this study, by examining the experimental literature, the effects of weather and damages to the rail, such as heat, rising sea level, etc., cause the buckling of the rail and cause delays, financial losses and traffic in the rail network.
18	Johan Lindgren, Daniel K. Jonsson, Annika Carlsson-Kanyama (2009), Climate Adaptation of Railways: Lessons from Sweden	In this paper, using a questionnaire and a case study, the amount of failure in the Swedish railway network is examined and evaluated.
19	Brian P. Arkell, Geoff J. C. Darch (2006), Impact of climate change on London's transport network	In this paper, by examining 4 case studies and accidents caused by tides, very hot temperature and flooding in the subway, it presents and offers preventive methods.
20	Michael A. Rossetti (2003), Potential Impacts of Climate Change on Railroads	The purpose of this paper is to identify and evaluate the destructive effects on the railways and to describe the effects of the weather on the railways on a time scale.

3. Impact of Climate Change on the Rail Transport System

Climate change has increased the occurrence of extreme phenomena in recent years, so climate change may have a direct effect on the efficiency of railway infrastructure exposed to harsh environmental conditions (Kaewunruen, Li and Sakdirat 2019). The rail network is impacted by both extremely hot and cold climate changes, as shown in Figure 2. Pavement failure, rail buckling, landslides, as well as collisions, and out of schedule delays, can all be characterized by excessive weather.

Safety and reliability as the two main parameters of rail transport quality are considered. Strong weather may affect these operations, disrupting the level of rail transport services or causing unforeseen delays in the system. The most important climatic effects that affect the railway lines are extreme temperature, snowfall and ice, storms and strong winds, and flood (Leviäkangas, et al. 2011). Table 2 summarizes the findings of papers and research in this field and includes climatic phenomena, their important parametric values, and the effects and consequences reported on the railway. In this table, the study area and the source of the study are also mentioned for further research.

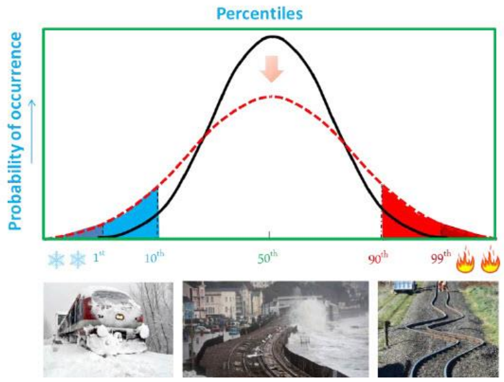

Figure 2. The threshold of extreme event percentiles and potential impacts (Kaewunruen, Li and Sakdirat 2019)

Table 2. Weather phenomena, critical parameter values and reported impacts.

Extreme temperature: cold			
Temperature (C)	Impacts on Railways system	Validity area	Source
T > -4.5°C	• Damage to rail switches. • The probability of delay is less than 33%	Netherland	(Oslakovic, Maat and Hartmann 2013)
-9°C <T< -4.5°C	• The probability of delay is between 33% and 66% • Freezing of switches, blocking of railway yard and equipment	Netherland	(Oslakovic, Maat and Hartmann 2013)
T < -12°C	• Frost cracking, freezing of equipment and structures on track • The probability of delay is over 66% • Damage to rail track	Netherland	(Oslakovic, Maat and Hartmann 2013)
T < -29°C	• First affect can produce rail contraction that can cause gaps and misalignment in the track • Rail signals freeze • Switches fail • Incidence of accidents	Swedish-U.S- Baltic	(Study on climate change impact assessment for the design, construction, maintenance and operation of Rail Baltica railway 2019)- (Lindgren, et al. 2009)- (Rossetti 2003)
Extreme temperature: heat			
Temperature (C)	Impacts on Railways system	Validity area	Source
T < 15°C	Problems with signals with the possibility of burning the fuse	England	(Greenham, et al. 2020)
20°C < T < 25°C	• Start of breakdown and delay in train movement • 33% probability of delay	England - Netherland	(Greenham, et al. 2020)- (Oslakovic, Maat and Hartmann 2013)
T > 25°C	Rail buckling, the possibility of the train derailing, delay in rail traffic	England	(Greenham, et al. 2020)- , (Dobney, et al. 2009)
T > 42°C	Most reported delays, Rail equipment failure, rail track buckling, Overhead line sag	England - Spain	(Greenham, et al. 2020)- (Villalba and Franco 2019)- (Ferranti, et al. 2017)- (Jaroszweski and Hooper 2014)- (Ludvigsen and Klæboe 2014)

Table 2. Weather phenomena, critical parameter values and reported impacts (Continued).

Snowfall			
Snowfall (mm/day)	Impacts on Railways system	Validity area	Source
	• Flooding • Freezing • Damage to cables • Loss of electricity • Blowing snow • Blocking tracks and yards	Baltic Swedish	(Lindgren, et al. 2009)- (Study on climate change impact assessment for the construction, maintenance and operation of Rail Baltica railway 2019)
Snowfall > 50 mm/day	Rail switches fail	Netherland	(Oslakovic, et al. 2013)
Flood			
	Impacts on Railways system	Validity area	Source
	• Damage to railway embankment and slope • Water on track or in underground structures • Damage to rail track • Other material damage to equipment and infrastructures • Delay	England Spain	(D, Shaw and Gehrels 2016)- (Forero-Ortiz, et al. 2020)- (Arkell and Darch 2006)- (Koetse and Rietveld 2009)- (Wanga, et al. 2020)- (Heinz-Peter and Berg 2017)
Wind and Tornado			
	Impacts on Railways system	Validity area	Source
	• Changes in sea level; flooding • Damage to cables • Falling trees • Loss of electricity • Freezing	Germany	(Trinks and Hiete 2013)

3.1 Snowfall

Winter storms cause heavy snowfall in northern and central Europe and are one of the main reasons for the disruption of the rail transport network and train delays. Heavy snowfall freezes the rail points and disrupts the operation of rail switches, causing accidents due to reduced visibility, slippery rails and the possibility of poor brake performance (Leviäkangas, et al. 2011).

Lindgren, et al. In 2009 (Lindgren, K. Jonsson and Carlsson-Kanyama 2009) with an interview and a questionnaire from the Swedish Rail Administration obtained information on the effects of the weather Swedish railway system failures. Based on the gathered information, they found that the Swedish National Railway's adaptation measures against climate change had not been very successful. The case study found that in November 2006, heavy snowfall and severe winter conditions affected much of the rail traffic around Gävle (east-central Sweden) and canceled many itineraries.

Another study by Oslakovic, et al (Oslakovic, Maat and Hartmann 2013) in 2013 in the Netherlands, found similar results. Climatic effects on the Utrecht-Amsterdam and Utrecht-Rotterdam railways, which are considered to be the busiest of the Dutch railways, have been studied. For this purpose, the risk assessment method was used and during a ten-year period from 2000 to 2010, they evaluated about 868 failures due to weather conditions they concluded that as snowfall increased, the probability of breakdowns increased exponentially. According to the results obtained in this study, for snowfall of more than 58 mm per day, the probability of failure will be 100%, and in the rainfall of 9 mm per day, and 22 mm per day, respectively the probability of failure is 33% and 66%.

3.2 *Extreme temperature*

Sunlight and excessive heat in summer can cause heat kinks in the rail system. These kinks may cause train derailment and accidents with the potential for injury, loss of life and severe financial loss, and the release of hazardous toxic substances into the environment due to inconsistencies in the route. In addition, the rail line may undergo uneven thermal expansion because part of the rail is in the shade, thus greatly threatening the risk of buckling. In winter and extreme cold, a similar situation may occur, increasing the risk of rail breakage and cause to train delays. High temperatures cause buckling in the rails and this failure is one of the most important factors in delaying rail performance. At low temperatures, functions of switches and failure of rails are the most important causes of breakdowns and delays in the rail transportation system (Rossetti 2003).

In 2009, Dobney et al (Dobney, et al. 2009) have concluded that the hot summer of 2003 in the United Kingdom would be repeated in the 2050s and 2080s and that the total cost of heat-related delays, in the end, can be doubled and approximately equal to 23 million pounds. In 2003, Rossetti et al (Rossetti 2003) expanded a ten-year study using US Department of Transportation data from 1993 to 2002, screening more than 5,700 accident and breakdown reports. In this study, frost, snow, and storms have been introduced as the most important causes of rail accidents.

3.3 *Flood*

Global warming and climate change are causing icebergs to melt and oceans and seas to rise, and rivers to overflow. This makes adaptation and operational tasks heavier for infrastructure in port areas and along rivers. Floods cause serious damage to embankments and ballasts. Moreover, they also drag the subgrade. In addition, rising groundwater levels can produce serious damage to underground structures such as the subway and cause the soil bed to become wet, which affect the foundation bed by loosen and freeze severely, eventually damaging the rail system. For example, the 2004 floods in the UK closed the westbound route to London for five days (Leviäkangas, et al. 2011).

3.4 *Wind and Tornado*

Strong winds and tornadoes are other environmental factors that may affect the rail transportation system. Tornadoes can cause the train to derail by shaking violently on the train or dropping trees along the track. Severe storms, such as lightning, also damage traffic control systems and safety devices, causing unforeseen delays in the transportation network (Leviäkangas, et al. 2011).

4. Adaption and Management Options

Rail networks are heavily dependent on non-rail infrastructure networks that should be used for their activities. Similarly, these networks often rely on rail networks for normal operation. Disruption of the rail network has a sudden impact on external infrastructure networks and other sectors of transport. Major potential disruption to rail traffic will have a wide range of effects on other sectors of transport. For example, road traffic should replace rail traffic and affect local communities through congestion and traffic congestion. Traffic congestion, in turn, has adverse effects on residents who have difficulty accessing schools, offices, as well as emergency services. This volume of traffic can also affect the transportation of fuel resources or emergency transportation systems such as public necessities and medicines, so it is necessary to identify the risk factors and disruptors in transportation and ways to prevent it. (Gardiner, et al. 2009)

4.1 *Extreme Temperature Management Options*

Risks of track buckling in hot weather and train interruptions and rail failure in winter are initially controlled by adjusting the temperature of the rail without stress. At present, the rails are set at a stress-free temperature of 21°C to 27°C. To reduce the risk of rail buckling occurring when the high-temperature threshold is reached, guards should be deployed along the track to monitor for danger signs by monitoring the situation and to apply speed limits to reduce the risk. This can also be done in cold weather. By placing the thermometer in critical areas, the operator can be given the necessary warnings when the temperature reaches the critical points of the upper and lower limits, and by applying speed limits and placing warning signs, the dangerous effects of climate change can be mitigated (Marteaux and Olivier 2016) .

Also, for the design of new infrastructure, rail vehicle design standards specify that rail vehicles should be designed for temperatures between 25°C to 40°C and brakes should be designed for temperatures between -20°C and 35°C. And ensured their proper performance during this period. Also, in overhead railway lines, the design temperature range between -18°C to 38°C should be considered (Marteaux and Olivier 2016).

4.2 *Snowfall Management Options*

Heavy snowfall is another important factor in disrupting the rail network. If the snow depth is 20 cm higher than the rail head, traffic signs should be installed and the train should be prevented from moving so that after snow removal, the situation returns to normal, and the rail system continues to move. Also, in winter, the rolling stock should be equipped with special equipment to fight cold weather (antifreeze for air systems, fuel additives, and coupler bags) (Marteaux and Olivier 2016).

4.3 *Flood Management Options*

In floods and heavy rains, it should be noted that if the level of rainfall and when the floodwater is located between the bottom and top of the rail, the activity of the rail system can be controlled in severe weather conditions by applying a speed limit of 8 km/h. But when the water level on the rail reaches the third rail, it must be stopped immediately to take the necessary action to drain the water (Marteaux and Olivier 2016). In the design of new drainage infrastructure structures, storm events with a return period of 10 to 50 years should be considered to deal with the destructive effects of future weather conditions (Marteaux and Olivier 2016).

4.4 *Wind and Tornado Management Options*

In case of strong winds, the wind speed limit according to which the train is designed should be considered. For new infrastructure structures, the maximum wind speed should be considered for passenger trains 36 meters per second and freight trains 30 meters per second (Marteaux and Olivier 2016).

In general, special inspections should be carried out in severe weather events. Annual inspections should be carried out to identify gradual changes in high-risk areas, and critical areas should be registered as "essential features" in inspection offices, and in extreme weather conditions these areas should be controlled and, train movement is done with the speed limit (Gardiner, et al. 2009).

5. Conclusions

Examining the available literature and papers, it can be said that in general, heavy snowfall, extreme temperature changes, winds, and floods are the most important factors influencing the climate on the railway network. Given the scenario of global warming and greenhouse gas emissions, severe climate change in the coming years will have a more severe impact on human societies. It seems that developed countries should take more efficient measures to reduce greenhouse gas emissions, as well as with rising temperatures and melting ice. As a result, sea levels will rise, which could have a greater impact on flooding in vulnerable areas. An efficient measure to mitigate the effects of climate changes is by considering climate change parameter during the design stage of new infrastructure, and adaptive measures for existing ones.

Acknowledgments

The authors would like to thank ISISE – Institute for Sustainability and Innovation in Struc-tural Engineering (PEst-C/ECI/UI4029/2011 FCOM-01-0124-FEDER-022681). This work was co-financed by the Interreg Atlantic Area Programme through the European Regional Development Fund under SIRMA project (GrantNo. EAPA_826/2018).

REFERENCES

Arkell, Brian P., and G. J. C Darch. 2006. "Impact of climate change on London's transport network." (Municipal Engineer).

D, Dawson, j Shaw , and w Gehrels . 2016. "Sea-Level Rise Impacts on Transport Infrastructure."

Dobney, K, C J Baker, Chapman, and D Quinn. 2009. "The future cost to the United Kingdom's railway network of heat-related delay and buckles caused by the predicted increase in high summer temperatures owing to climate change." *Journal of Rail and Rapid Transit.*

Ferranti, Emma, Lee Chapman, Susan Lee, David Jaroszweski, Caroline Lowe, and Steve McCullochc. 2017. "The hottest July day on the railway network: insights and thoughts for the future." *METEOROLOGICAL APPLICATIONS.*

Forero-Ortiz, Edwar, Eduardo Martínez-Gomariz, and Manuel Cañas Porcuna. 2020. "Flood Risk Assessment in an Underground Railway System under the Impac of Climate Change—A Case Study of the Barcelona Metro." *Sustainability.*

Gardiner, L., D Firestone, G Waibl, N Mistal, and K Van Reenan. 2009. *Climate Change Effects on the Land Transport Network Volume One: Literature Review and Gap Analysis.* NZ Transport Agency Research Report.

Greenham, Sarah, Emma Ferranti, Andrew Quinn, and Katherine Drayson. 2020. "The impact of high temperatures and extreme heat to." *Meteorology & Atmospheric Sciences.*

Heinz-Peter, and Berg. 2017. "Risks and consequences of weather hazards on railway infrastructure." *Polish Safety and Reliability Association.*

Jaroszweski, David, and Elizabeth Hooper. 2014. "The impact of climate change on urban transport resilience in a changing world." *Progress in Physical Geography.*

Kaewunruen, Dan Li , and Sakdirat. 2019. "Effect of Extreme Climate on Topology of Railway Prestressed Concrete Sleepers." *Climate.*

Koetse, Mark J., and Piet Rietveld. 2009. "The impact of climate change and weather on transport:." *Transportation Research.*

Leviäkangas, Pekka, Anu Tuominen, Riitta Molarius, Jari Schabel, Sirra Toivonen, Jaana Keränen, and Jouko Törnqvist. 2011. *Review on extreme weather impacts on transport systems.* VTT Technical Research Centre of Finland.

Lindgren, Johan, Daniel K. Jonsson, and Annika Carlsson-Kanyama. 2009. "Climate Adaptation of Railways: Lessons from Sweden." *European Journal of Transport and Infrastructure Research.*

Ludvigsen, Johanna, and Ronny Klæboe. 2014. "Extreme weather impacts on freight railways in Europe." *Nat Hazards.*

Marteaux, and Olivier. 2016. *Tomorrow's Railway and Climate Change Adaptation: Executive Report.* Rail Safety and Standards Board Limited.

Oslakovic, Irina Stipanovic, Herbert ter Maat, and Andreas Hartmann. 2013. "Risk Assessment Of Climate Change Impacts On Railway Infrastructure." *EPOC 2013 Conference.*

Rossetti, Michael A. 2003. "Potential Impacts of Climate Change on Railroads." *The Potential Impacts of Climate Change on Transportation.*

Sanchisa, Ignacio Villalba, Ricardo Insa Francoa, and Pablo Martínez Fernándeza. 2020. "Risk of increasing temperature due to climate change on highspeed rail network in Spain." *Transportation Research.*

2019. *Study on climate change impact assessment for the design, construction, maintenance and operation of Rail Baltica railway.* Connecting Europe facility of the European union.

Trinks, Christian, and Michael Hiete. 2013. "Extreme weather events and road and rail transportation in Germany." *Emergency Management.*

Villalba, Ignacio, and Ricardo Insa Franco. 2019. "Impacts of climate change on operation of the spanish rail network." Edinburg.

Wanga, Tianni, Zhuohua Qub, Zaili Yangc, Timothy Nicholb, and Delia Dimitriue. 2020. "Impact analysis of climate change on rail systems for adaptation planning: A UK case." *Transportation Research*