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Additional Information

Risk of increasing temperature due to climate change on high-speed rail network in
Spain

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Abstract

With more than 3,200 km of track, the Spanish high-speed rail network is the longest network in Europe and the second largest in the world after China. Due to its geographical location in southern Europe, the entire network is exposed to periods of elevated temperatures that can cause disturbances and severe disruptions such as rail deformation, or in the worst case, lateral track buckling. In this study, the vulnerability of the current Spanish high-speed rail network is analysed in terms of track buckling failures with a Monte Carlo simulation. Downscaled temperature projections from a range of Global Climate Models (GCMs), under three Representative Concentration Pathways (RCP4.5, RCP6.0 and RCP8.5), were forced in a buckling model and particularized for different segments of the network. With that, the proposed methodology provides the number of rail buckles expected per year by assuming current

maintenance standards and procedures. The result reveals significant increase in the occurrence of buckling events for future years, mainly in the central and southern areas of mainland Spain. However, relevant variations are found in different climates and time horizon scenarios in Spain. The anticipated buckling occurrences highlight the vulnerability of the Spanish rail network in the context of global warming scenarios. Overall, the proposed methodology is designed to be applicable in large-scale railway networks to identify potential buckling sites for the purpose of understanding and predicting their behaviour.

Keywords

Climate change; track buckling; railway infrastructure; risk assessment;

1. Introduction

Railway track systems across the globe play an important role in modern society and their operation, repair and maintenance is essential in reaching a long-term sustainable transport system (Eddington, 2006; Molemaker and Pauer, 2014). According to data provided by the Spanish Railway Infrastructure Administrator (ADIF), the rail network comprises more than 15,000 km of metric, standard and Iberian gauge, with more than 2,700 km of high-speed lines under construction or planned. Indeed, in 2010 Spain became the second country in the world after China in terms of number of kilometres of high-speed lines in operation, thus generating development and improving communications and people's quality of life (López et al., 2009; Mendiluce and Schipper, 2011).

To operate and maintain this extensive network, ADIF needs to ascertain that rail tracks and their elements can cope with and adapt to different loads and weather conditions. To accomplish this task, large investments are expected in years to come in order to adapt to climate change (IPCC, 2014).

Although rails tracks are robust transport infrastructures, the conjunction of mobility growth and climate change predictions can potentially lead to severe disruption, resulting in train delays, speed restrictions and equipment or infrastructure failures such as track buckling events (Liu et al., 2012; Ford et al., 2015). High-speed tracks uses continuous welded rails (CWR) by removing expansion joints in order to improve riding comfort and to achieve high speeds. Specifically, during railway construction as well as repair and maintenance track operations, modern rails are welded and fixed at the so-

called rail neutral temperature at which rails are unstressed axially. As a result, if the temperature is extremely high, rail expansion can quickly exceed several centimetres, which may cause track damage due to large lateral misalignments (Kerr, 1976; Esveld, 2001; Chapman et al., 2007; Navarro et al., 2015; Villalba et al. 2018).

According to the European Union Agency for Railways (ERA), in 2016 track buckles and other track misalignments were the principal causal factor of rail accidents with more than 6,000 events in the European Union (EU) in 2018, observing a pattern between the track buckles and the maximum temperatures registered in EU (Fig. 1). In fact, temperatures in Europe show a clear warming trend over the last four decades, for both annual and seasonal averages. In this sense, 2018 was one of the three warmest years on record for Europe - together with 2014 and 2015 - with an anomaly of around +1.2°C.

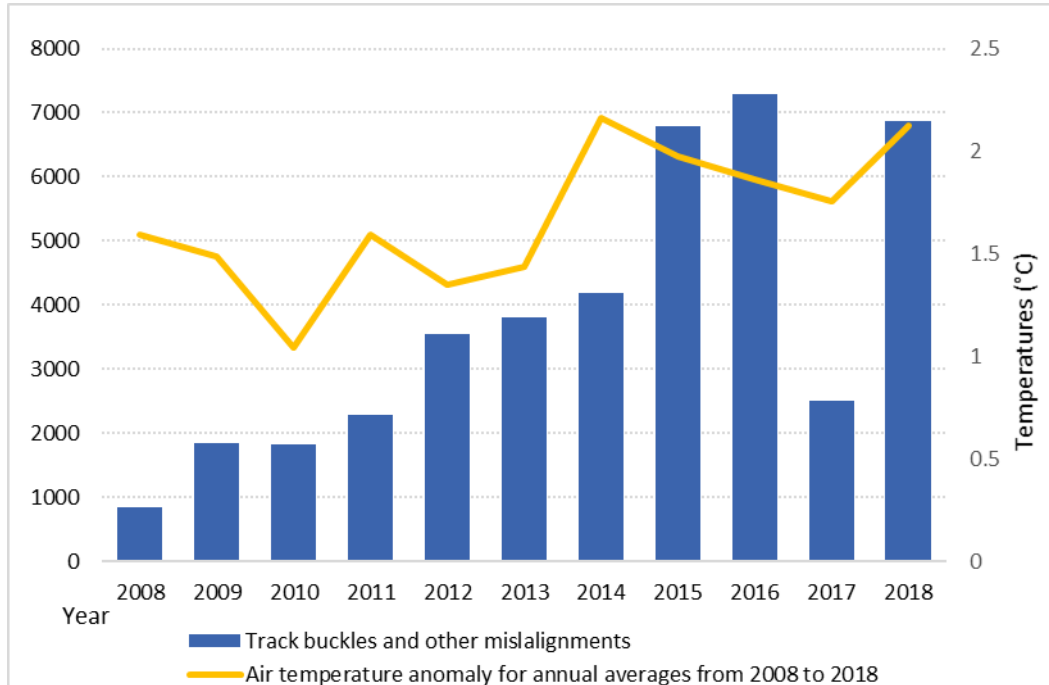


Fig. 1. Total precursors of accidents with track buckles and other misalignments and global temperatures, EU 28, 2008-2018.

To reduce vulnerability, a few rail companies have begun to develop a strategy to adapt their activities and operation, such as reducing maximum speed of the trains, in order to reduce the stress on rails during heat wave events (Chagnon, 2006). In fact, the complexities of climate predictions and the particular conditions across every area covered by a railway network affect how these strategies are devised, especially regarding the magnitude and frequency of these extreme heat conditions and how they affect track stability.

This paper proposes a reliability assessment on the buckling phenomenon across Spain's high-speed rail network. Therefore, the question addressed in this study is to what extent could these buckling events increase through to the end of the century. In order to address that concern, Monte Carlo simulations could contribute to determine buckle events expected per year in the study area by integrating probability distributions for climate variables and track parameters. Given a particular critical threshold, these impact distributions can be used to estimate the likelihood of threshold exceedances, and subsequently, provide guidance on the need for risk treatment actions in order to adopt standards for new and existing infrastructure to the effects of climate change.

2. Climate change impact on rail networks

As mentioned, planning, design, construction and operation of rail infrastructures is essential to maintain an efficient and reliable transport system, even under adverse or emergency conditions. To provide a better service and satisfy users, railway companies try to achieve a more regular and reliable train service. However, adapting the transport system to the impact of climate change presents some difficulties. In fact, rail transport

can be vulnerable to many different climate impacts and their effects vary between geographical locations, which results in severe consequences for rail infrastructure and operations.

In the latest years, only a few research projects have been developed to determine the influence of climate change on rail infrastructure. In order to investigate relationships between climate change and railway operations, Rossetti (2002) examined statistics for the period 1993-2002 from the Federal Railroad Accident (FRA) database. Factors such as extreme winds, high temperatures and track obstructions (snow, ice, mud, rock) are the most common cause of service disruptions. Thornes and Davis (2002) suggested that unfavourable weather conditions might be responsible for up to 20% of unplanned delays in United Kingdom. Duinmeijer and Bouwknecht (2004) showed that these climatic factors cause between 5% and 10% of all rail infrastructure failures in the Netherlands. Koetse and Rietveld (2009) presented a survey of the empirical literature in which several patterns can be observed, but the net impact of climate change is uncertain and ambiguous.

Recently, Dobney et al. (2009, 2010) quantified the effects of heat-related delays and buckles due to climate change on the United Kingdom's railway network, if the track is maintained to current standards. The results obtained demonstrate that the annual average cost for predicted climate change scenarios reach up to £9.2 million. Baker et al. (2010) considered the issues surrounding climate change through two different perspectives. In 2012, a track buckle derailment on the Queensland rail network costs up to \$1.2 million in superstructure repairs and rolling stock recovery (Simpson, 2012).

On the one hand, they analyse the potential of railways to reduce greenhouse gas emissions as a support for the effort to mitigate global temperature increase. On the other ~~hand~~, they consider the effect of climate change to improve their resilience.

Françoise and Hande (2012) analysed trends about weather-induced degradation and damages costs, considering that the climate dimension must be included in cost-benefit analysis. An approach based on Monte Carlo method was taken by Nguyen et al. (2012) to assess track buckling, but this study was developed to describe and interpret past buckling incidents. Palin et al. (2013) developed novel procedures to combine regional climate data with railway industry knowledge, assessing the changes in climate-related hazards for decision-making.

In recent years, Ferranti et al. (2016) used database failure information to examine heat-related incidents in Southeast England. The results showed a strong correlation between high temperatures and the number of buckling events. Saadin et al. (2016a, 2016b) conducted some studies on extreme weather events that can lead to asset system failure, degraded operation and delays with respect to the Singapore-Malaysia high-speed rail system, which is still in its planning stage. Considering the economic costs of delays, Chinowsky et al. (2017) pointed out that delays due to fluctuations in temperature could cost between \$25 and \$45 billion cumulatively through year 2100, considering a low greenhouse gas scenario. However, these costs could be reduced if modern technologies and maintenance strategies are integrated for optimised track management. Recently, using logistic regression, Fu and Easton (2018) develops a logistic regression analysis, addressing the underlying causes of weather-related

incidents on the on the Great Britain railway's Anglia Route. Finally, Chapman and Bell (2018) highlighted the opportunities that the Internet of things can bring to improve the resilience of rail infrastructure and minimize climate impacts.

As pointed out above, previous studies in the research area focus on techniques and procedures that mainly evaluate climate impacts in terms of train delays and track maintenance costs, but rarely on the likelihood of occurrence. There are very few studies that identify the means to understand vulnerabilities at a local level nor is there any evidence of region-wide or strategic analyses for the Spanish rail network, despite being the second largest high-speed rail network in the world. In addition, little data is found isolating the effect of temperature increase. The objective of this work is to predict the number of buckling events in different climate regions across the entire Spanish territory and for different climate models.

3. Methodology

Maximum temperatures trends, as projected for the proposed scenarios and climate models until the year 2100, represent the most important climate data for rail track buckling analysis. Thus, quantifying the potential for track buckling includes two aspects: determining increases in maximum temperatures and estimating its respective buckling failure probabilities. To accomplish this task, this study provides a methodology to estimate the number of buckling events in Spain as a function of different climate projections.

3.1. Study area

The study area is continental Spain, located in the south west of Europe at 36°–44° N and between 10° W and 3°, which spreads over 490,000 km². Its geographical position and complex orography causes high variability in the spatial distribution of temperature. In fact, there is a difference of about 4°C between northern and southern areas and of about 2°C between the two central plateaus (Font Tullot, 2000).

Spatial heterogeneity of climate conditions provide significant differences in frequency and magnitude of extreme heat conditions in Spain. On the other hand, temperature projections on a daily and local scale are required to investigate the phenomenon of buckling. To address this challenge different global and regional climate change projections have been produced over the last decades. Nowadays, Earth System Models (ESMs) are one of the best methods for obtaining future projections of atmospheric variables, but they are unable to project the extreme temperature behaviour of local daily series (Brands et al., 2013, Keellings and Waylen, 2015, Yue et al., 2015). In addition, Regional Circulation Models (RCMs) neither guarantee an adequate reproduction of extreme temperatures. For instance, Vautard et al. (2013) analysed the RCM projections driven by ERA-Interim to simulate heat waves at the regional scale of Europe, concluding that the climate models have overestimated temperature extremes in Mediterranean regions.

Specifically in Spain, the continental region was divided into different areas characterized by solar radiation atlas, provided by the EUMETSAT Satellite Application Facility on Climate Monitoring (Climate Monitoring-SAF; CM-SAF). Therefore, the first one represents the zone situated in the south-eastern part of the country (zone 1), with

a semi-arid climate. The inland areas of the Iberian Peninsula, on the Central Meseta (zone 2) are characterized by cold winters and warm summers. The Mediterranean coast (zone 3) covers coastal areas located in the eastern part of Spain, with very mild winters and long warm to hot summers. Finally, zones 4 and 5 are located in the northern half of Spain and Atlantic slopes, both located in the northern part of the country (Fig. 2).

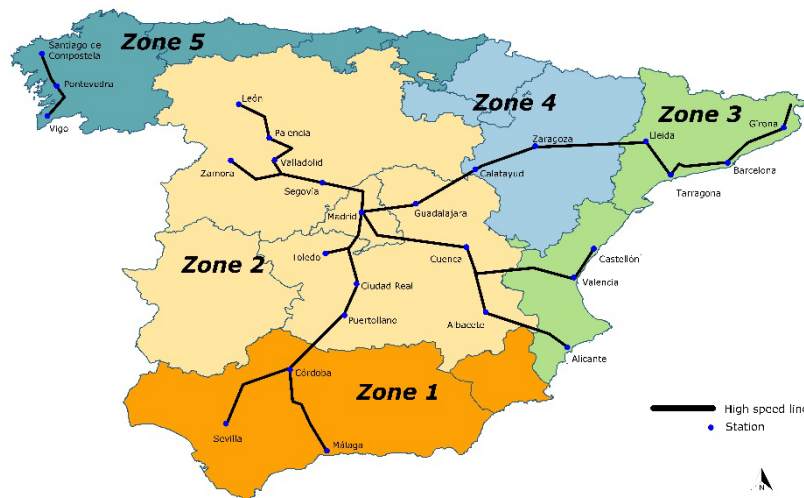


Fig. 2. Main high-speed lines in Spain in 2019 (with maximum speed above 200 km/h) and climate zones.

The five zones include key sections of the Spanish high-speed railway network, servicing the major cities of Madrid, Barcelona, Valencia and Sevilla, among others. The interdependent nature of the Spanish railway network and their radial scheme means that one incident can quickly propagate throughout the entire rail network causing delays, reducing passenger satisfaction and important cost considerations compared to that of the original fault itself.

3.2. Assumptions

In order to investigate relationships between climate change and track buckling, certain track characteristics were considered. The Spanish high-speed network, in which high-speed trains can circulate at commercial speeds up to 350 km/h, is built as a typical ballasted track composed of ballast layer, sleepers, fasteners and rails (Fig. 3). The minimum thickness of the ballast layer is 30 cm. The monoblock pre-stressed concrete sleepers are AI-04 type and the distance between these elements is equal to 60 cm. Further, rails are continuously welded UIC 60-type with a mass of 60 kg/m³ and thermal expansion coefficient $\alpha = 12 \times 10^{-6} \text{ m/m}^\circ\text{C}$, fixed to the sleepers via SLK-1 Vossloh clips.



Fig. 3. Ballast track superstructure in Spain.

Finally, the lateral resistance, defined as the reaction offered by the ballast layer against lateral displacement, is one of the most important parameters to prevent track buckling. Its behaviour is determined for any given combination of rail, fasteners, sleepers and ballast layer (Samavedam et al. 1991, Emdal, 2007). From this perspective, the lateral resistance is influenced by the frictional resistance of the sleeper-ballast interface and can be measured most conveniently by a single-tie-push-test (STPT) method, which mobilizes a single sleeper in the ballast layer, recording the load-deflection response (Bakhtiary et al. 2015, Esmaeili et al. 2015). Thus, the shape of the load-deflection response obtained from a STPT test is linear until a maximum value is reached, after

which the track structure becomes unstable and buckles (Fig. 4). Recently, Estaire et al. (2018) experimentally studied the resistance of ballast layer in the CEDEX Track Box testing facility developing a series of STPT tests for the Spanish case. Based on the results of the STPT tests, the maximum lateral resistance was 12.5 KN/sleeper, considering the characteristics of high-speed rail track in Spain.

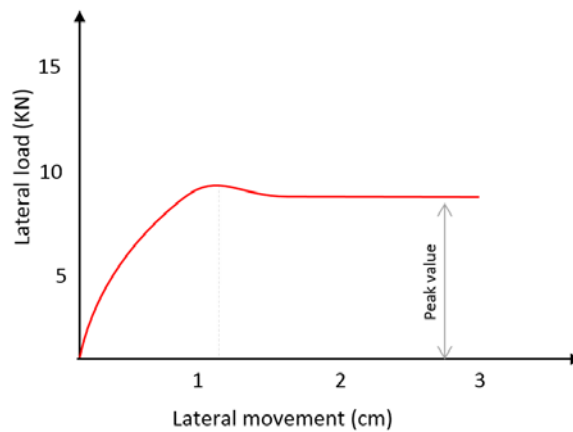


Fig. 4. STPT test response.

3.3. Buckling model

It should be noted that the resolution of the thermal instability problem of a railway tracks is quite difficult due to the uncertainty associated with mechanical and geometrical properties along the line. Moreover, there is no established or standardized method to determine the compressive stress that exceeds track resistance.

Taking these considerations into account, the compressive force in rails due to the rise in temperature has long been a concern. In fact, a number of theoretical mathematical models have been developed over the last decades, but these generally suffer from the lack of physical verification and quantification of some key parameters.

Firstly, compressive forces in rails due to constrained thermal expansion can be calculated using the well-known formula defined in Eq.(1):

$$F_T = \alpha EA(\Delta T) = \alpha EA(T_{rail} - T_{SFT}) \quad (1)$$

where F_T = compressive load due to temperature change, α = steel thermal expansion coefficient, E = Young modulus, A = area of steel rails, T_{rail} = rail temperature, T_{SFT} = stress free temperature.

In order to predict the rail temperature at which the track may buckle, Bartlett (1960) developed a model based on experimental data. It quantifies the relative importance of rail, fastenings and ballast, providing a reasonable predictive tool for assessing the likelihood of the track becoming unstable. The formula gives an estimated longitudinal force in the rail that would be required to overcome the track resistance, as expressed in Eq.(2).

$$F_{max} = \left(\frac{\pi^2 EI}{L^2} + \frac{\pi^2 c}{16D} \sqrt{\frac{\pi L}{q}} + \frac{W_{max} L^2}{\pi^2 q} \right) \quad (2)$$

where, F_B = longitudinal force required to buckle the track (kN), E = Young modulus (MPa), I = moment of inertia of the two rails put together in the horizontal plane (mm⁴), L = distance between the points of contraflexure of the buckled track, c = torsional coefficient for the given type of fastening, D = sleeper spacing, q = misalignment of the track over length, W_{max} = maximum lateral ballast resistance (kN/m).

Therefore, buckling temperature represents the temperature rise over stress free temperature that initiates track buckling on a given track structure. For a given track conditions, buckling temperature can be determined by using Eq.(3).

$$\Delta T_{max} = T_{buckle} - T_{SFT} = F_{max} / \alpha EA \quad (3)$$

where T_{buckle} is the maximum allowable temperature.

In accordance with structural stability, if rail temperature exceeds the maximum allowable temperature, the energy required to buckle the track will be zero and the track will buckle spontaneously.

3.4. Climate projections

The concept of railway vulnerability to climate change is approached under the perspective of identifying foreseeable extreme climate trends. To simulate the seasonal and longer-term behaviour of the climate system, in 1995 the Working Group on Coupled Models (WGCM) established the Coupled Model Intercomparison Project (CMIP), providing a community-based infrastructure in support of climate model projections under standardized boundary conditions. In 2008, 20 climate-modelling groups developed a new set of climate models under the fifth phase of the CMIP (CMIP5), providing a set of global climate models (GCMs) in a medium to long-term horizon.

While GCMs provide the latest and most accurate version of future climate trends, it is also important to keep in mind that they are limited when it comes to describing regional and local details. This becomes particularly important on the Iberian Peninsula, whose particular topography produces different meteorological patterns. To resolve the scale discrepancy between GCMs and the resolution required for impact assessment for Spain, the data from GCMs are downscaled by the Spanish State Meteorological Agency (AEMET) within the framework of the National Plan of Adaptation to Climate Change (PNACC).

The outputs from the PNACC plan are used to determine temperature projections at a daily and local scale that influences the high-speed rail network. However, to be able to apply future climate projections to regional impact studies, the appropriate GCMs should be selected based on several approaches. For this study, five different GCMs for each Representative Concentration Pathways (RCP) were chosen (Table 1), ensuring that the subset captures a large range of the variability in climate outcomes (Chinowsky et al. 2017, Khan et al., 2018).

Those models are based on new reference scenarios for the change in radiative forcing, referred to as Representative Concentration Pathways (RCP) of the changes in the concentration of greenhouse gases, ozone and aerosol precursor gases. The four RCPs, namely RCP2.6, RCP4.5, RCP6.0, and RCP8.5 provide a quantitative illustration of concentrations of the pollutants and gases in the atmosphere over time, as well as their radiative forcing until the year 2100. However, RCP2.6 seems a rather unfeasible scenario that will be exceeded over the next few years. Therefore, it seems reasonable

to use RCP4.5, RCP6.0 and RCP8.5. Thus, the novelty of the study is to use of various RCPs to cover a wide range of potential outcomes. The years analysed were 2025, 2050, 2075 and 2100 and were chosen as representatives.

RCP	Model	2025	2050	2075	2100
RCP 4.5	MPI,ESM,LR	0.2	0.5	5.1	1
	MRI,CGCM3	0.4	2.4	2.3	2
	MIROC5	2.1	3.5	3.7	4.6
	ACCESS1,0	1	2.5	5.3	4.8
	bcc,esm1,1	2.7	1.4	4.5	4.9
RCP 6.0	bcc,esm1,1	2.4	1.4	2.7	3.4
	MRI,CGCM3	0.2	0.9	1.6	4.1
	bcc,esm1,1	2.6	3.4	3.3	4.7
	MIROC5	3	2.7	4.1	4.8
	IPSL,CM5A,MR	2.5	2.2	3.8	4.9
RCP 8.5	inmcm4	1.8	2.5	2	4.7
	MRI,CGCM3	2.2	2	3.9	5
	BNU,ESM	1	2.6	4.5	8.8
	HadGEM2,CC	2.8	5.4	8.6	9.2
	CMCC,CM	0.4	3.2	6	9.5

Table 1. Change in average maximum summer temperature (°C) for the Iberian Peninsula.

3.5. Reliability assessment

According with UIC code 720 (UIC, 2005) a risk-based safety assessment is performed for all relevant buckling parameters. To accomplish this task, the Monte Carlo simulation method was used to produce a comprehensive quantification of buckling events due to increases in temperatures. This method was implemented using Matlab for programming an algorithm with different probability distribution for some of the variables involved. By combining the distributions and randomly selecting values from them, it calculates the model bringing out the probability of the output with long simulation runs.

As applied to a track buckling, Monte Carlo simulations generate inputs from random variables represented by their corresponding probability distribution functions. From a practical point of view, it is desirable to minimize the number of parameters needed for their description. These principal parameters have a significant influence on buckling temperatures and are also the parameters to control buckling safety. Thus, focusing on the formulation proposed previously, the most important parameters/conditions influencing CWR track buckling analysis could be drawn:

- The first requirement relates to the segmentation of the track network. Numerical models (Lim et al., 2003; Yang and Bradford, 2016) and rail accident investigations have shown that the mean rail length subject to single-buckling mode, which corresponds to the total length of the track misalignment after the occurrence of buckling, has a length of around 10 meters (Allen and Fry, 2016, Yang and Bradford, 2016). As a result, and considering that the Spain's high-speed network covers over 3,000 kilometres of track, the division generates 300,000 segments, with an average segment length of 10 meters.
- The relationship between air and rail temperature is conditioned by a variety of factors, including track orientation, sunny weather, wind, air humidity, rain, etc. The rail temperature is higher than the air temperature due to the high thermal conductivity and diffusivity of rail steel. Thus, an empirical approach proposed by Hunt (1994), which considers that rail temperature is 1.5 times air temperature, provides a simple approach. While the best practice is to measure track temperature at multiple locations under different climate conditions, the

amount of track is substantial, which has made the widespread use of temperature sensors difficult from a cost-benefit perspective. However, a track section was instrumented during 12 months by using a rail and a handheld digital thermometer (Fig. 5).



Fig. 5. Rail thermometer at the site.

With the data obtained, the factor provided by Hunt's equation was adjusted according to the field observations, as shown in Eq. (3).

$$T_{rail} = 1,65 T_{ambient} \quad (3)$$

where T_{rail} and $T_{ambient}$ are the rail and air temperature.

- It is therefore assumed that the maximum air temperature follows a normal distribution, obtained from a subset of GCMs models selected for RCP4.5, RCP6.0 and RCP8.5 scenarios downscaled by AEMET for the Spanish continental region.
- The appropriate rail neutral temperature is usually determined by the administrator of railway infrastructures above the midpoint between the highest and lowest temperature of the rail temperature range in that specific region. However, while the actual neutral temperature of the rail for each zone or track segment would be the best value, it is generally not available, unless taken by

field measurements through cutting the rail and measuring its expansion or other complex techniques that cannot be applied for the entire network. Therefore, for each zone the SFT was calculated by taking the difference between maximum and minimum air temperatures, according to ADIF normative NAV 7-1-4.1 and expressed as follows:

$$T_{SFT} = \frac{T_{air.max} - T_{air.min}}{2} + 5 \quad (4)$$

where $T_{air.max}$ and $T_{air.min}$ are the maximum and minimum air temperatures recorded for the past 5 years.

- Track misalignments play an important role in triggering track buckling. For high-speed traffic, the allowed misalignment is approximately 1 to 4 mm. Taking this into account, it is assumed that track misalignments follows a normal distribution with a mean value of 2 mm and a standard deviation of 0.5 mm.
- Finally, the misalignment wavelength is the total length of the track after the occurrence of buckling. Experiments and field observations have shown that the magnitude of the buckling wavelength is typically large, approximately 8 to 20 m. In this analysis, it is assumed that the distance between the points of contraflexure of the buckled track follows a normal distribution with a mean value of 10 m and a standard deviation of 2.5 m.

Variable	Distribution	Descriptive statistics
Rail temperature	Normal distribution	Modified Hunt's equation

Maximum air temperature	Normal distribution	Obtained from a subset of GCMs models for RCP4.5, RCP6.0 and RCP8.5 scenarios
Stress free temperature (SFT)	Deterministic	Obtained from maximum and minimum air temperatures in each zone
Track misalignment	Normal distribution	Mean: 2 (mm) Standard deviation: 0.5 (mm)
Misalignment wavelength	Normal distribution	Mean: 10 (m) Standard deviation: 2.5 (m)

Table 2. Parameters for the Monte Carlo simulation.

With the previous assumptions, the buckling load is a function of the difference between the rail temperature and the neutral temperature. Furthermore, the buckling strength is determined by track components and misalignments. Accordingly, for each iteration, Monte Carlo simulation randomly selects the input values for the maximum air temperature, track misalignment and wavelength to evaluate track stability for each segment in which the entire network is divided (Fig. 6). In order to make the quantification comprehensible, the number of buckle events are presented in yearly average for the three emissions scenarios considered.

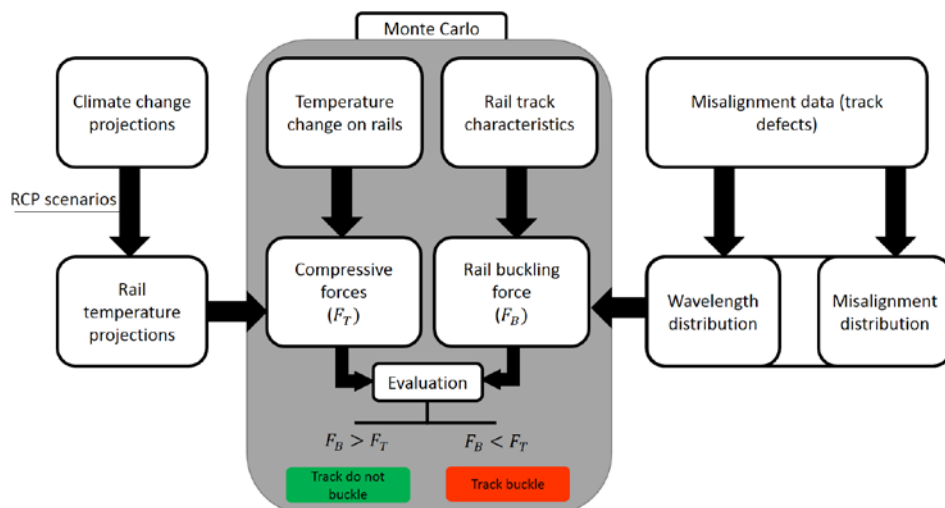


Fig. 6. Flowchart of calculation process.

In order to progressively adjust the proposed methodology, further work can be performed by comparing the expected number of buckling events from the proposed assessment to the effective number of incidents reported with the aim to understand better the impact of temperature in terms of both understanding as well as prediction of buckling incident occurrence.

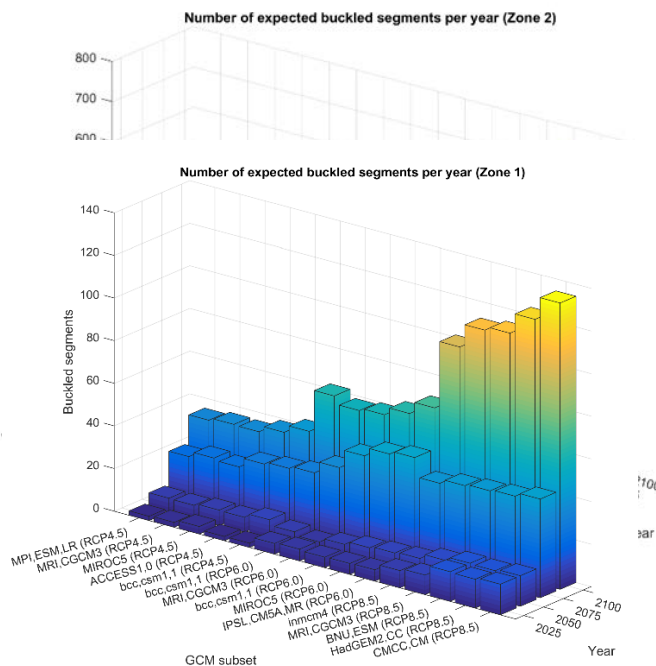
4. Results and discussion

This analysis provides several new and potentially important insights into the analysis of rail buckling under future climate change on the Spanish high-speed network. First, the assessment of rail track buckling in the Spanish railway network for the next century requires a set of climate models. The main tracks are used to provide a case study analysis of the potential impacts of climate change on track buckling and to indicate the needs for policy changes in terms of track asset maintenance programs under different climate change scenarios. However, it should be noted that results were obtained for the current high-speed network in Spain. Hence, the extent of the current transportation network and the other second or third order effect were not considered.

Considering that the accuracy of a Monte Carlo simulation is a function of the number of realizations, a sensitivity analysis can be used to deal with the number of runs. Thus, the results of the Monte Carlo simulation in terms of number of buckled segments and their variance for a confidence level of 95% and error bound of 5% shows that the number of iterations needed is around 10,000. Therefore, the computer time for simulating a sample size of ten thousand runs was less than 90 seconds. Because of the large amount of data, bar plots represent the expected number of buckled segments for each GCM subset, as a result of the Monte Carlo simulations. Thus, values are reported as the average number of buckled segments and grouped together for each zone in order to estimate the certainty or uncertainty in climate projection impacts.

Fig. 7. The average annual buckled segments on the rail system per era in zone 1.

Fig. 7 represents the expected total number of buckling events in the south of Spain (zone 1) from the five climate models and three RCPs scenarios in the years 2025, 2050,



2075 and 2100. The data in Fig. 7 shows that there is considerable uncertainty in the range of predicted effects from temperature change. In the short-term projection, such

as 2025, the average annual numbers of potential buckling events are similar for the three types of scenarios and are kept within reasonable levels. In the long-term projection, such as 2100, the annual number of potential buckling events would be from 35 to 42 in RCP4.5 scenarios, from 62 to 70 in RCP6.0 and from 100 to 135 in RCP8.5. Between 2025 and 2100, the projected changes in temperature under the CMCC, CM in the RCP8.5 scenario were the most extensive, obtaining the greatest number of buckles. This variability is indicative of the uncertainty associated with the different climate scenarios and reflects the importance of viewing the data over the ensemble of scenarios to determine an appropriate adaptation scenario.

Fig. 8. The average annual buckled segments on the rail system per era in zone 2.

Fig. 8 shows the trends of the average annual buckled segments for the Central Meseta (zone 2). As shown, buckled segments range from 7 to 35 in 2025, but the greatest impacts from climate change in terms of expected number of buckled events are projected for all the RCP8.5 models. This will have a significant effect on the number of failures as well, which suggests that extreme temperature events tend to have a significant disruption on rail transport. Thus, the overall trend is similar to the previous area, but the effects are really more pronounced. In the case of RCP4.5 models, maximum values are generally achieved during the 2050s, which is consistent with the assessment of projected emissions for this emission scenario (Meinshausen et al., 2011).

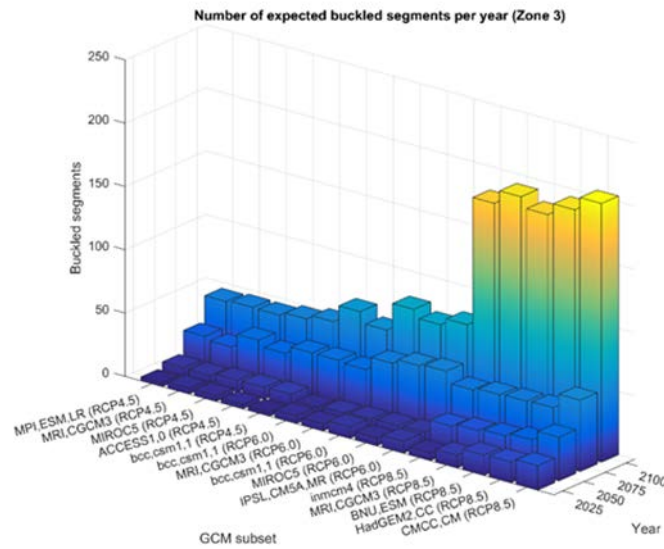


Fig. 9. The average annual buckled segments on the rail system per era in zone 3.

Fig. 9 shows the evolution of the expected buckled events per year in the Mediterranean coast (zone 3). For RCP 4.5 buckled events increases approximately linearly until the end of the century, while RCP8.5 models strongly increases in the last period (2075-2100). By 2100, results obtained shows an average of 45 to 52 buckle events per year are

expected in the study area under RCP4.5 scenario and between 181 to 204 under RCP8.5 scenario.

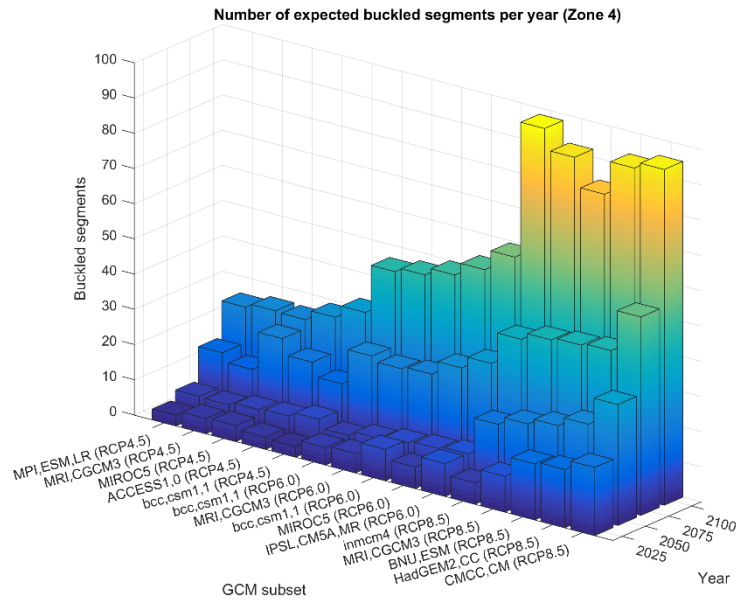


Fig. 10. The average annual buckled segments on the rail system per era in zone 4.

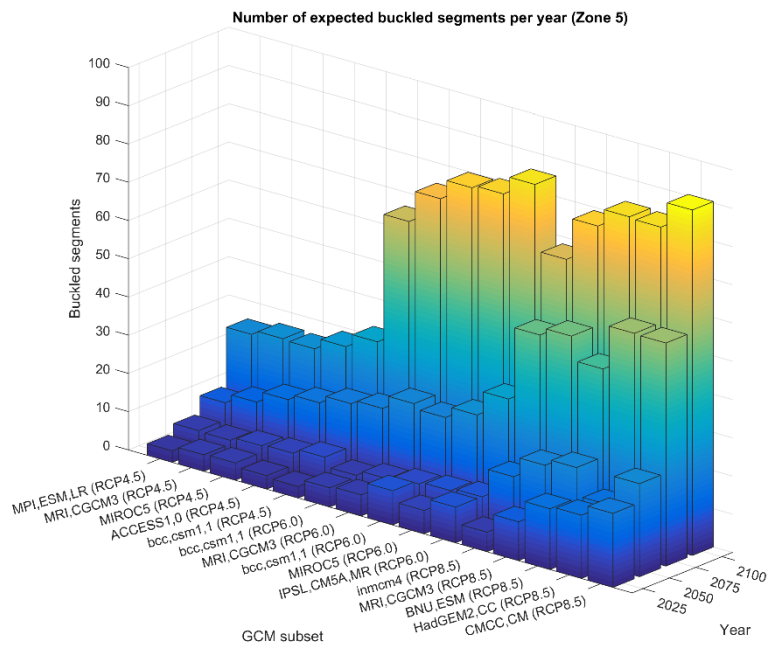


Fig. 11. The average annual buckled segments on the rail system per era in zone 5.

Fig. 10 and Fig.11 show the estimated number of buckled events for areas located in the northern slope sector. These areas are anticipated to experience the smallest temperature increases due to climate change in Spain (Castro et al. 2005) and, accordingly, the number of future buckle events are quite limited when comparing them with those of previous geographical areas. It can also be seen from Fig. 11 that future projections reveal that under the lower emission scenario (RCP 4.5) the number of expected buckled segments will increase only slightly from 5 to 25 events by 2025 and 2100 respectively. However, under the higher emission scenario (RCP 8.5), buckled events will undergo a large increase from 10 to 80 in the year 2100.

The foregoing results illustrate that the proposed approach can be useful in dealing with statistical variability in the track parameters and climate scenarios to evaluate the anticipated annual number of buckles in a given territory. Results obtained represent how temperature affects the rail track in each region for different climate models. Analysing results in a temporal context, it is clear that expected impact grows throughout the study period, especially under the higher emission scenario (RCP 8.5). In addition, differences between the three RCPs increase over time, which is an indicative value of the uncertainty associated with climate scenarios. In the spatial context, specific regions including the Central Meseta and the South are anticipated to experience the greatest impacts for all climate models considered.

4.1 Limitations

This study is designed as a high-level assessment of the vulnerability—in terms of number of buckle events—of the existing high-speed rail network in Spain from the impacts of climate change through 2100. A main source of variability comes from the

climate data used for analysis. Indeed, future climate modelling is uncertain, but authors seek to reduce this inconvenient as much as possible by employing a wide variety of available models that are approved by the IPCC and AEMET to provide a range of analysis for future climate changes. However, depending on the climate scenario selected, the projected impacts can range from a few to several hundred of buckled segments, which represents the uncertainty related to selecting different GCM models. The potential to use existing scenarios from alternative sources should not be discounted.

A key limitation of the modelling approach used in this study is the assumption of actual maintenance procedures for projecting the expected number of buckles. It is highly unlikely that the actual maintenance and safety practices remains unchanged for a prolonged period of time.

Another limitation is related to the lack of information about the rail accidents and incidents in Spain. Further analysis and discussions are intended to take place in order to perform better reporting of the precursor's events. Accordingly, more predictor variables can be included so as to result in a more realistic rail track model.

A final limitation of this study is that analysis was limited to looking at incremental changes in climate (maximum temperatures) on existing rail infrastructure. It therefore does not account for other weather impacts sea level rise, flooding or storm surge.

5. Conclusions

Adapting effectively and efficiently to the inevitable consequences of climate change should be part of modern rail management. The current study gives a general overview

about potential vulnerability of the Spanish high-speed rail system to projected temperature increases. The aim of this work is to provide to managers and infrastructure planners tools that support adaptation-planning strategies to reinforce the resilience of their infrastructures and networks to increasing temperatures.

Thus, extreme high temperatures are associated with increased incidences of rail buckles. In particular, the impact of high temperatures on rails differs between geographical locations and the appropriate assessment requires a more detailed analysis of the particular rail network. To accomplish this task, Monte Carlo simulations are used to estimate the number of future buckling events by using results from 15 GCM models under three RCP scenarios (RCP 4.5, RCP 6 and RCP8.5) until 2100. The use of data from multiple models allows some of the uncertainty in the analogue locations to be included. Uncertainties of the effective buckling lengths, rail temperature and track misalignments have also been taken into account.

Overall, higher temperatures due to climate change are set to have a significant impact on the high-speed network in Spain. In fact, buckle events were projected to increase in frequency under all climate change scenarios compared to the present day. However, results from the proposed methodology have shown that buckle events in Spain vary substantially both spatially and temporally. The two medium scenarios (RCP 4.5 and RCP6.0) reveal that effective strategies for mitigating anthropogenic carbon emissions could significantly reduce the negative impacts of high temperatures on rails.

Considering impacts on a geographic, the northern sections as well as the coastal areas have lower average temperatures and thus have a lower vulnerability to temperature increases. By contrast, central and southern regions are forecasted to incur the greatest absolute increases in summer temperatures also incur the largest increases in buckling events. This variability represents an important challenge in achieving effective mitigation or adaptation strategies for addressing climate change. However, maintenance operations can be prioritized to minimize the annual buckling probability on the basis of track conditions and the anticipated rail temperatures. Procedures like ensuring the track is thoroughly maintained greatly reduce the vulnerability of the rail during high temperatures.

Finally, there is significant capacity to improve the modelling and methodologies used in the proposed approach. The relationships between temperatures and disruption on the Spanish railway network have not been validated due to the quality or consistency of the reporting of these events. Thus, verifying relationships between temperatures and buckling events would increase the confidence in making projections of quantities dependent on these relationships. Moreover, an on-going calibration of the model with more precise climate scenarios would enable a more detailed estimation of future performance and hopefully increase confidence in the results.

Bibliography

1. Allen, D.H., Fry, G.T., 2016. Finite element formulation for thermal buckling of rails, CRR Report No. 2016-02, Texas A&M University.

2. Baker, C.J., Chapman, L., Quinn, A.D. Dobney, K., 2010. Climate Change and the Railway Industry. Proc. IMechE, Part C: J. Mechanical Engineering Science, 224, 519-528.
3. Bakhtiary, A., Zakeri, J.A., Fang, H.J., Kasraiee, A., 2015. An experimental and numerical study on the effect of different types of sleepers on track lateral resistance. Int. J. Transp. Eng., 3 (1), pp: 7-15.
4. Bartlett, D.L., 1960. The stability of long welded rails, Civil Eng. and Public Works Review, Vol. 55, No. 649, Parts I-IV.
5. Brands, S., Herrera, S., Fernández, J., Gutiérrez, J.M., 2013. How well do CMIP5 earth system models simulate present climate conditions in Europe and Africa? Clim. Dyn., 41, pp: 803-817
6. Castro, M., Martin-Vide, J., Alonso, S., 2005. The climate of Spain: past, present and scenarios for the 21st century. A Preliminary General Assessment of the Impacts in Spain Due to the Effects of Climate Change. 1-62.
7. Chagnon, S.C., 2006. Railroads and Weather: From Fogs to Floods and Heat to Hurricanes, the Impacts of Weather and Climate on American Railroading. American Meteorological Society, Boston, MA.
8. Chapman, L., Thornes, J.E., Huang, Y., Cai, X., Sanderson, V.L., White, S.P. 2007. Modelling of rail surface temperatures: a preliminary study Theor. Appl. Climatol., 92 (1-2) pp: 121-131.
9. Chapman, L., Bell, S.J., 2018: High-Resolution Monitoring of Weather Impacts on Infrastructure Networks Using the Internet of Things. Bull. Amer. Meteor. Soc., 99, 1147–1154. <https://doi.org/10.1175/BAMS-D-17-0214.1>
10. Chinowsky, P., Helman, J., Gulati, S., Neumann, J., Martinich, J., 2017. Impacts of climate change on operation of the US rail network, Transport Policy, 2017.

11. CMSAF. <http://www.cmsaf.eu> (accessed on 30 January 2019).
12. Dobney, K., Baker, C.J., Quin, A.D., Chapmann, L., 2009. Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east Kingdom, *Meteorological Applications* 16, 245-251.
13. Dobney, K., Baker, C.J., Chapman, L., Quinn, A.D., 2010. The future cost to the United Kingdom's railway network heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change. *Proc Inst Mech Eng F—J Rail Rapid Transit* 224 (1), 25-34.
14. Duinmeijer, A.G.P. & Bouwknecht, R., 2004. *Betrouwbaarheid Railinfrastructuur 2003 (Reliability Rail Infrastructure 2003)*. Prorail, Utrecht.
15. Eddington, R., 2006. The Eddington transport study: the case for action. In: Harrison, P.A., Butterfield, R., Downing, T. (Eds.), 1995, *Climate Change and Agriculture in Europe: Assessment of Impacts and Adaptations*, Research Report No 9. Environmental Change Unit, University of Oxford.
16. Emdal, A.E., Priol, G., Grimstad, G., Lohren, A.H., 2007. Numerical analysis of the effect of sleepers on the lateral displacement of railway track. *Numerical Models in Geomechanics*.
17. Esmaeili, M., Nouri, R., Yousefian K., 2015. Experimental comparison of the lateral resistance of tracks with steel slag ballast and limestone ballast materials. *Rail and Rapid Transit. Proc IMechE Part F* 231 (2), pp: 1-10.
18. Estaire, J., Cuéllar, V., Pardo de Santayana, F., Santana, M., 2018. Testing railway tracks at 1:1 scale at CEDEX Track Box. *360 high-speed magazine*, Nº 5 - June 2018, pp. 191-217.
19. Esveld C. *Modern railway track*. Second ed. The Netherlands: MRT Productions, 2001.

20. Federal Railroad Administration, Office of Safety Analysis.
<http://safetydata.fra.dot.gov/officeofsafety/>
21. Ferranti, E., L. Chapman, C. Lowe, S. McCulloch, D. Jaroszweski, and A. Quinn, 2016: Heat-related failures on southeast England's railway network: Insights and implications for heat risk management. *Wea. Climate Soc.*, 8, 177–191.
<https://doi.org/10.1175/WCAS-D-15-0068.1>
22. Font Tullot, I., 2000. *Climatología de España y Portugal*. Universidad de Salamanca, Salamanca, p. 428.
23. Ford, A., Jenkins, K., Dawson, R., Pregnolato, M., Barr, S., Hall, J., 2015. Simulating impacts of extreme weather events on urban transport infrastructure in the UK. In: Dolan, T., Collins, B. (Eds.), *International Symposium for Next Generation Infrastructure Conference Proceedings: 30 September–1 October 2014* International Institute of Applied Systems Analysis (IIASA), Schloss Laxenburg, Vienna, Austria. UCL STEaPP, London. pp. 233-238.
24. Françoise, N., Hande, D., 2012. *Impacts of Climate Change on transport: A focus on road and rail transport infrastructures*. EU Joint Research Centre: Institute for Prospective Technological Studies.
25. Fu, Q., Easton, J., 2018. Prediction of weather-related incidents on the rail network: prototype data model for wind-related delays in Great Britain. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 4(3).
<https://doi:10.1061/AJRU6.0000975>
26. Hunt, G. A., 1994. An analysis of track buckling risk. Tech. Rep. RR-TM-013, British Railways, 31 pp.

27. IPCC, 2007. Climate change 2007, the physical science basis. In: Solomon, S., et al. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (996 pp.).
28. IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA, 1132 pp.
29. Khan, N., Shahid, S., Ahmed, K., Ismail, T., Nawaz, N., Son, M., 2018. Performance Assessment of General Circulation Model in Simulating Daily Precipitation and Temperature Using Multiple Gridded Datasets. *Water* 2018, 10, 1793.
30. Keellings, D., Waylen, P., 2015. Investigating teleconnection drivers of bivariate heat waves in Florida using extreme value analysis. *Clim. Dyn.*, 44 (11), pp: 3383-3391.
31. Kerr AD. The effect of lateral resistance on track buckling analysis. *Rail Int.* 1976 (1) pp: 30–38.
32. Koetse, M. J., Rietveld, P., 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, 14(3), 205-221. <http://dx.doi.org/10.1016/j.trd.2008.12.004>
33. Lim, N. H., Park, N. H., & Kang, Y. J., 2003. Stability of continuous welded rail track. *Computers and Structures*, 81 (22-23), pp: 2219-2236.

34. Liu X., Saat M.R., Barkan C.P., 2012. Analysis of causes of major train derailment and their effect on accident rates. *Transportation Research Record: Journal of the Transportation Research Board* 2289(1), 154-63.
35. López, E., Gutiérrez, J., Gómez, G., 2009. Measuring regional cohesion effects of large-scale transport infrastructure investments: An accessibility approach. *European Planning Studies*, 16 (2), pp 277-301.
36. Meinshausen, M., Smith, S.J., Calvin, K. et al. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109, 213. <https://doi:10.1007/s10584-011-0156-z>
37. Mendiluce, M., Schipper, L., 2011. Trends in passenger transport and freight energy use in Spain. *Energy Policy*, 39 (10), pp 6466-6475.
38. Molemaker, R.J., Pauer, A., 2014. The economic footprint of railway transport in Europe. Community of European Railway and Infrastructure Companies (CER), Brussels.
39. Navarro Martinez, J.I., Villalba Sanchis, I., Martínez Fernández, P., Insa Franco, R., 2015. Analytical model for predicting the buckling load of continuous welded rail tracks. *Proc Inst Mech Eng F—J Rail Rapid Transit* 229 (5), pp: 542-552. doi:10.1177/0954409713518039
40. Nguyen M., Wang X., Wang C.H., 2012. A reliability assessment of railway track buckling during an extreme heatwave. *Proc Inst Mech Eng F—J Rail Rapid Transit* 226 (5), pp513–517.
41. Palin, E.J., Thornton, H.E., Mathison, C.T., 2013. *Climatic Change* (2013) 120: 71. doi:10.1007/s10584-013-0810-8

42. Rossetti, M.A., 2002. Potential impacts of climate change on railroads. In: The Potential Impacts of Climate Change on Transportation Workshop, USDOT Center for Climate Change and Environmental Forecasting.
43. Saadin, S.L., Kaewunruen, S., Jaroszweski, D., Dindar, S., 2016a. Operational risks of Malaysia-Singapore high speed rail infrastructure to extreme climate conditions. In: Proceedings of the the 1st Asian Conference on Railway Infrastructure and Transportation (ART 2016), Jeju, Korea.
44. Saadin, S.L., Kaewunruen, S., Jaroszweski, D., 2016b. Operational readiness for climate change of Malaysia high-speed rail', Institution of Civil Engineers. Proceedings. Transport, vol. 169, no. 5, pp. 308-320. : <http://dx.doi.org/10.1680/jtran.16.000>.
45. Samavedam, G., Kish, A., 1991. Continuous Welded Rail Track Buckling Safety Assurance through Field Measurement of Track Resistance and Rail Force. Transportation Research Record 1289, pp: 39-52.
46. Schulz, J., Albert, P., Behr, H.-D., Dewitte, S., Dürr, B., Gratzki, A., Hollmann, R., Karlsson, K.-G., Manninen, T., Müller, R., et al. 2009. Operational climate monitoring from space: The EUMETSAT Satellite Application Facility on Climate Monitoring (CMSAF). Atmos. Chem. Phys. 9, pp: 1687–1709.
47. Simpson, V., 2012. Track Buckle Cost. QR National.
48. Thornes, J.E., Davis, B.W., 2002. Mitigating the impact of weather and climate on railway operations in the UK. Proceedings of the 2002 ASME/IEEE Joint Rail Conference in Washington DC, April 23-25, 2002.
49. UIC 2005. UIC Code 720: Laying and maintenance of CWR Track.

50. Vautard, R., Gobiet, A., Jacob, D. et al., 2013. The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. *Clim Dyn*, 41 (9-10), pp: 2555-2575.
51. Villalba Sanchis, I., Insa Franco, R., Salvador Zuriaga, P., Martínez Fernández, P., 2018. An analytical model for the prediction of thermal track buckling in dual gauge tracks. *Proc Inst Mech Eng F—J Rail Rapid Transit* 232 (8), pp: 2163-2172.
doi:10.1177/0954409718764194
52. Yang, G., Bradford, M.A., 2016. Thermal-Induced buckling and postbuckling analysis of continuous railway Tracks. *Int. J. of Solids Struct.* 97-98, pp: 637-649.
53. Yue, T., Zhao, N., Fan, Z., Li, J., Chen, C., Lu, Y., Wang, C., Xu, B., Wilson J., 2015. CMIP5 downscaling and its uncertainty in China. *Global Planet Change*, 146, pp: 30-37.