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Risk of increasing temperature due to climate change on operation of the Spanish rail network

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Abstract

The rail network in Spain is around 16.000 km of Iberian, standard and narrow gauge, connecting the main population cities and hubs of transport. Due to its geographical location in southern Europe, during the summer months the entire network is subjected to high temperatures variations, including heat wave events, where temperatures become exceptionally elevates. With the use of continuous welded rails and the absence of expansion joints, temperature changes in rails results in significant compressive stresses. Moreover, climate models considers that extreme temperatures are going to become more frequent and intense in the next decades. Thus, understanding the nature of buckling events is required to identify potential causes and develop adaptation strategies and safety procedures. However, the impact in the railway infrastructure in Spain have not been fully addressed due to the differences in local environmental parameters and track characteristics, among others.

In this study, the issue of potential impacts of temperatures on the Spanish railway network are analyzed in terms of average track buckling failures until 2030. The approach addresses the frequency of future buckling events considering the spatial and temporal distribution to establish trends between climate projections and track buckling events. Therefore, this work is of significant importance for planning, design and maintenance, providing a predictive track maintenance regime in order to assist the decision-making process.

Keywords: Rail transport, buckling, temperatures, climate change, risk assesment

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1. Introduction

Railway track system plays an important role in the modern society, and its maintenance is essential to reach a sustainable transport system. Nowadays, rail research attempts to determine from a technical and operational point of view practices that aim to improve the overall efficiency of the rail system.

In the case of Spain, their network connects practically the whole country by train and is characterized by the coexistence of two different track gauges. The first one, the Iberian gauge (1,668 mm) was adopted in 1955 and is the most extensively track gauge, with more than 11,000 km. The second one, the standard track gauge (1,435 mm) was introduced in the 1992 and employed in all high-speed lines. Nowadays, the Spanish high-speed rail network comprises more than 3,000 km, being the second-largest high-speed network in the world after China.

Although rail network is a robust infrastructure, increasing temperatures caused by climate change could accelerate their deterioration. The consequence of increasing extreme weather events due to climate change could be a related loss of network availability and subsequent reduction of transport reliability and accessibility. Despite climate change posing serious challenges to rail infrastructure, the complexities and temperature trends have introduced an additional measure of uncertainty for railroad operators. In general, climate change vulnerability refers to the state of susceptibility to damage from exposure to climate hazards. Concerning the effect of temperature, there is a growing consensus that over the next century, global mean temperature and local climate variations are going to undergo significant change. In particular, not all European regions or countries will experience the same degree of rise in average temperatures, and differences will increase somewhat in summer.

In particular, projected temperatures will have a tendency to increase more than thus projected for the rest of the European countries. With the use of continuous welded rails (CWR) in the majority of modern railways, temperature changes produce important compression stresses that, under certain circumstances, can led to dangerous lateral track displacements and track buckling (TRB 2008, Nemry and Demirel 2012, EC 2013, Palin et al. 2013).

With these premises, the present paper aims to investigate the undefined risk due to temperature increases in the Spanish rail network. Understanding the nature of these buckling events is of clear importance for Spanish railway administrator and for the passengers who use the railway network. Finally, the risk and consequences will be reviewed and analyzed.

2. Climate change and rail buckles

From the beginning, rail transport have faced weather conditions that expose transport to multiple risk situations. Thunderstorms, tornadoes, river floods, rock and mudslides, avalanches, extreme precipitations or temperatures and other adverse climate conditions could provoke severe delays and track disruptions. During the latest decades, the impact and severity of weather and climate change has increased around the world, highlighting the vulnerability of this mode of transport to weather events.

Accordingly, climate models suggest changes in regional distributions of rainfalls, storms and increases in global temperatures during the next decades. Particularly, the Intergovernmental Panel on Climate Change (IPCC), which includes more than 1,300 scientists from all over the world, forecasts a temperature rise of 2.5 to 10 degrees over the next century. These changes also includes increases in the number and intensity of extreme events.

With the previous considerations, rails must adapt their infrastructures and operations to the new, more stringent climate conditions in the short, medium and long term. In particular, heat-related of climate change can affect motor engines, sagging of overhead lines and the failure of electrical equipment, but the most important consequence of higher temperatures is a buckled rail. Rail buckling is defined in Ellis (2006) as a "*sudden, short and un-designed bend in the track caused by a lack of lateral resistance, poor track maintenance and (generally) high rail temperatures*". Thus, as longitudinal expansion is highly constrained in CWR, temperature forces expands the metal, curving and misaligning rails.

In order to reduce the risk of track buckling, rails are normally fixed to the sleepers at the so-called stress free temperature (SFT), at which the net longitudinal forces in rails are zero. Theoretically, well maintained track should not be vulnerable to buckling up to ambient temperatures. However, railway networks are associated with an increased occurrence of rail buckling during moderately high temperatures. In fact, the European Union Agency for Railways (ERA) registered in 2016 more than 5,000 incidents, in which the principal precursors were track buckles and other track misalignments. To avoid the problems caused by buckled rails, some rail administrators imposes speed restrictions when certain temperature thresholds are passed in order to reduce the risk of buckling and, consequently, train derailment (Chagnon, 2006). In those cases, resulting delays impact negatively in the passengers as well as the entire economy.

In order to reach an efficient and reliable transport system is essential to predict the occurrence of buckling events, considering that the entire rail transport infrastructure will be significantly impacted by climate change. On the basis that there will be significant impact from climate change and considering that all eventualities cannot be catered for, this work aims to determine the impact of temperature increases on the Spanish rail network and propose some adaptation measures to alleviate the impact.

3. Methodology

The study methodology incorporates a model-based approach that combines projections of climate change for the 21st century regionalized over Spain and corresponding to different emission scenarios with current track characteristics. Thus, the current rail network is stressed with future climate projections to determine the potential vulnerabilities in terms of buckling events.

The modeling approach encompasses the next steps:

- Estimate rail track characteristics for different railway tracks.
- Determine climate scenarios to span a range of future outcomes.
- Calculate projected future climate risks in terms of buckling events.
- Develop risk maps by plotting the frequency of a buckling risk.

As mentioned before, the Spanish rail system is characterized by the coexistence of two principal track gauges. Despite different track characteristics and configurations are present along the entire network, it has been considered that the entire network is composed of ballast layer, mono-block pre-stressed concrete sleepers at a distance of 60 cm and UIC 60-type rails. Under the previous conditions, the lateral resistance between a simple mono-block concrete sleeper and the ballast was obtained from laboratory test in Spain (Estaire et al. 2018), showing a peak resistance around 12.5 KN/sleeper.

The second step is related with climate models. Projections used in the current work are downscaled using statistical procedures by the Spanish State Meteorological Agency (AEMET) within the framework of the National Plan of Adaptation to Climate Change (PNACC). Three different Representative Concentration Pathways (RCP) are employed which are identified by their approximate total radiative forcing in the year 2100, relative to year 1750: 8.5 W/m^2 (RCP8.5), 6.0 W/m^2 (RCP6.0) and 4.5 W/m^2 (RCP4.5). These climate scenarios are the most commonly used in climate change analysis and cover a range of different possible situations, providing some information about the potential benefits of climate change mitigation.

With the track characteristics and climate models, the next procedure includes the buckling model. As mentioned, high compressive forces caused by thermal and mechanical sources have been considered as the most critical factors of buckling. Thus, buckling temperature represents the temperature rise over SFT that initiates track buckling. For a given track conditions, buckling temperature can be determined by Schramm's, as showed in equation 1:

$$\Delta t = \sqrt{\frac{4.35\, wI}{\alpha^2 E A^2 f}} \tag{1}$$

where Δt=increase above SFT required before buckling (°C), w= resistance of track to transverse displacement (kN/m), I= second moment of inertia of one rail about vertical axis (mm^4), α= coefficient of expansion of rail steel (=0.0000115/°C), E= Young's modulus of elasticity for rail steel (215GPa), A= cross sectional area of one rail (mm^2), f=assumed initial misalignment (mm).

With that simplified equation, buckling occurs when the rail temperature exceeds the buckling temperature. Based on empirical equations, rail temperature can be obtained as expressed in equation 2:

$$T_{rail} \approx {}^{3}/_{2}\, T_{ambient} \tag{2}$$

Thus, buckling occurs when rail temperature exceeds the maximum temperature, verifying equation 3:

$$T_{rail} - T_{SFT} > \Delta t \tag{3}$$

With the previous equations, the risk of buckling should consider the probability of main factors influencing the track stability. In order to establish correlation between ambient temperatures and buckling occurrence, a Monte Carlo simulation was employed. To accomplish this task, the Spanish railway network assumed to contain 1,6 million segments of steel rail tracks (considering that the entire rail network comprises around 16,000 km of rail tracks, the network is divided into segments of 10 meters). With all, this method selects randomly the input values for the maximum air temperature from climate models, track initial misalignment (f) and lateral resistance (w) by using normal distributions for each parameter. For each rail segment, occurrence of buckling failure was determined according to equation 3. To obtain the distribution for the number of failed rail segments, a total of 1,000 simulation runs, each with 1,6 million segments, were then carried out. The proposed probabilistic approach determines the probability of buckling at a given ambient temperature across the Spanish territory.

Finally, in order to give a more comprehensive overview the buckling risk are presented in yearly average in a map for the three emissions scenarios considered, providing an indication of when these impacts will occur in the span of the study.

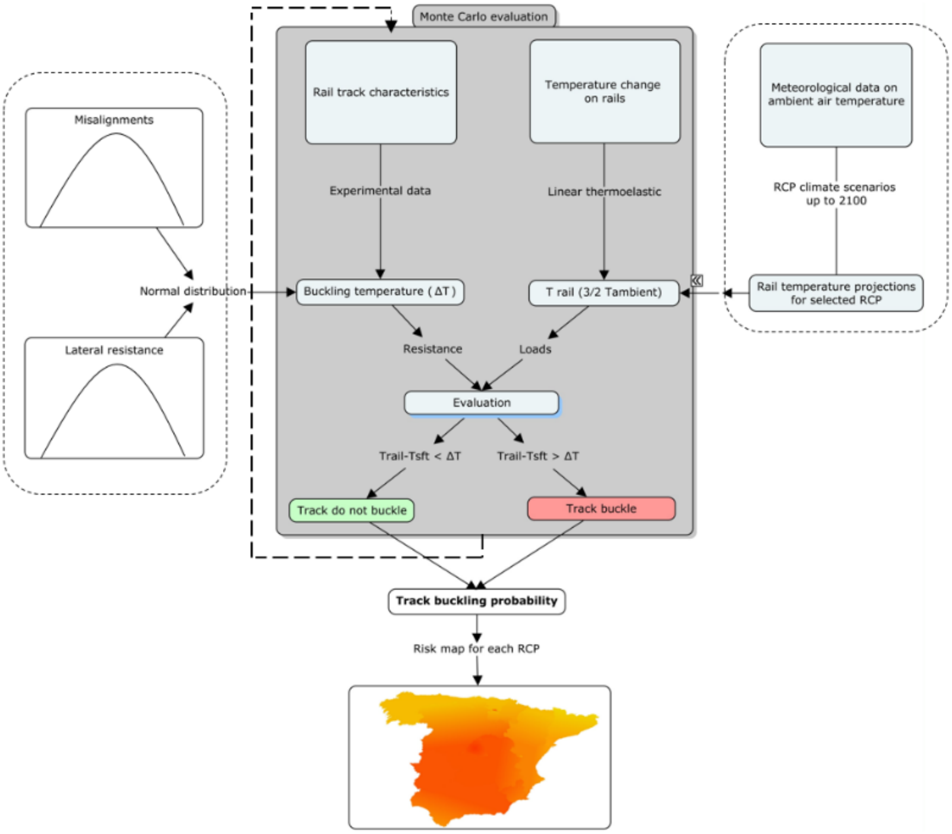

Fig. 1. Scheme for the proposed methodology.

4. Results and discussion

As mentioned, the assessment of rail track buckling in the Spanish railway network requires a set of climate models able to characterize the spatial distribution of surface temperature changes. Putting results in a geographical and temporal context provides an overview of when these impacts will occur in the span of the study. Thus, emission scenarios run thought four different time horizons: 2025, 2050, 2075 and 2100.

Figure 2 illustrates the potential impact of climate change for 2100 based on RCP4.5 scenario. For an RCP4.5 scenario by 2100, the yearly mean temperature range over Spain is estimated between 8°C to 36°C, and its change ranges from 2°C to 8°C.

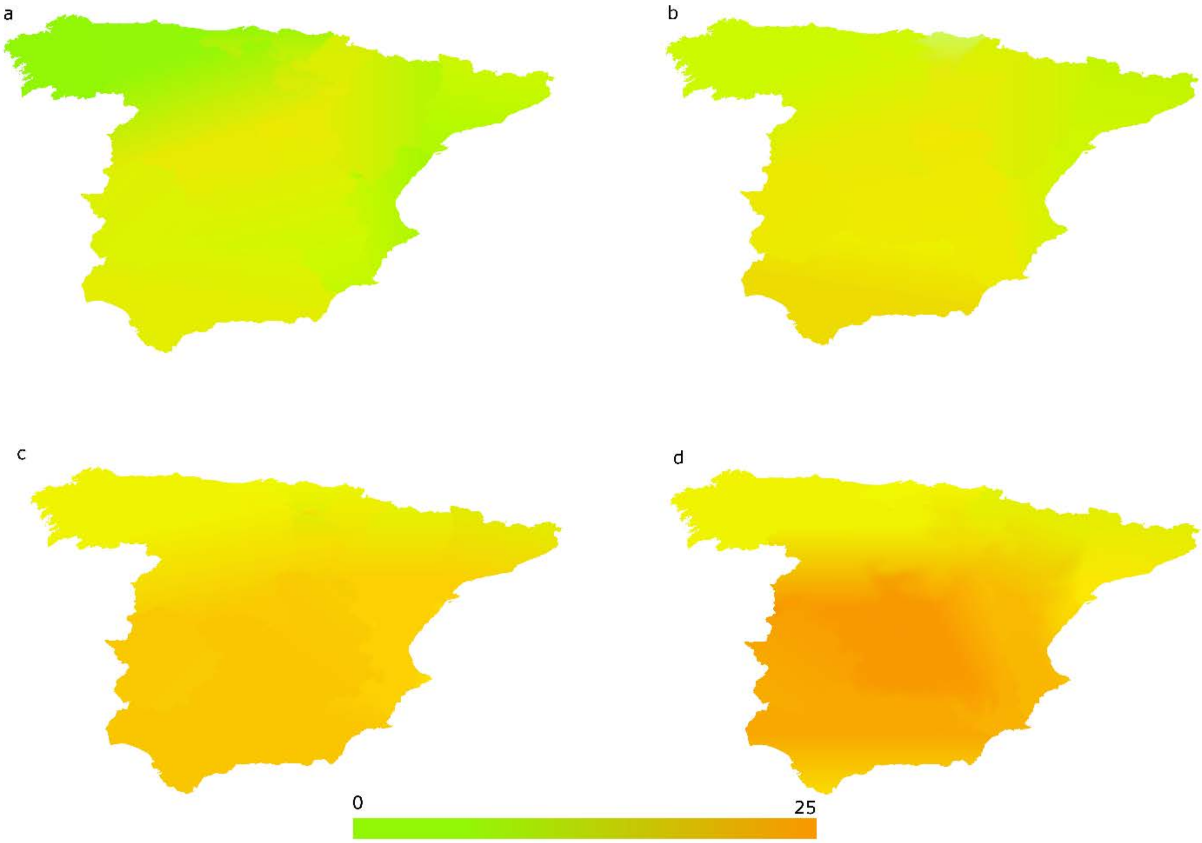

Fig. 2. Buckling events for the RCP4.5 scenario. (a) 2025; (b) 2050; (c) 2075; (d) 2100.

As illustrated in Fig. 2, the majority of the system is impacted in the year 2100. For the 2025s if it is assumed all track is of good quality reduced number of buckle events are seen. However, specific regions including the south and middle of Spain are anticipated to experience the greatest impacts. The northern sections as well as the coastal areas have lower sensitivity to temperature changes and thus have a lower vulnerability. Therefore, the areas with the greatest impact lie where the ambient temperatures are in the milder or greater range. In particular, the maximum number of expected events for the year 2100 vary from 20 to 25 for the central area.

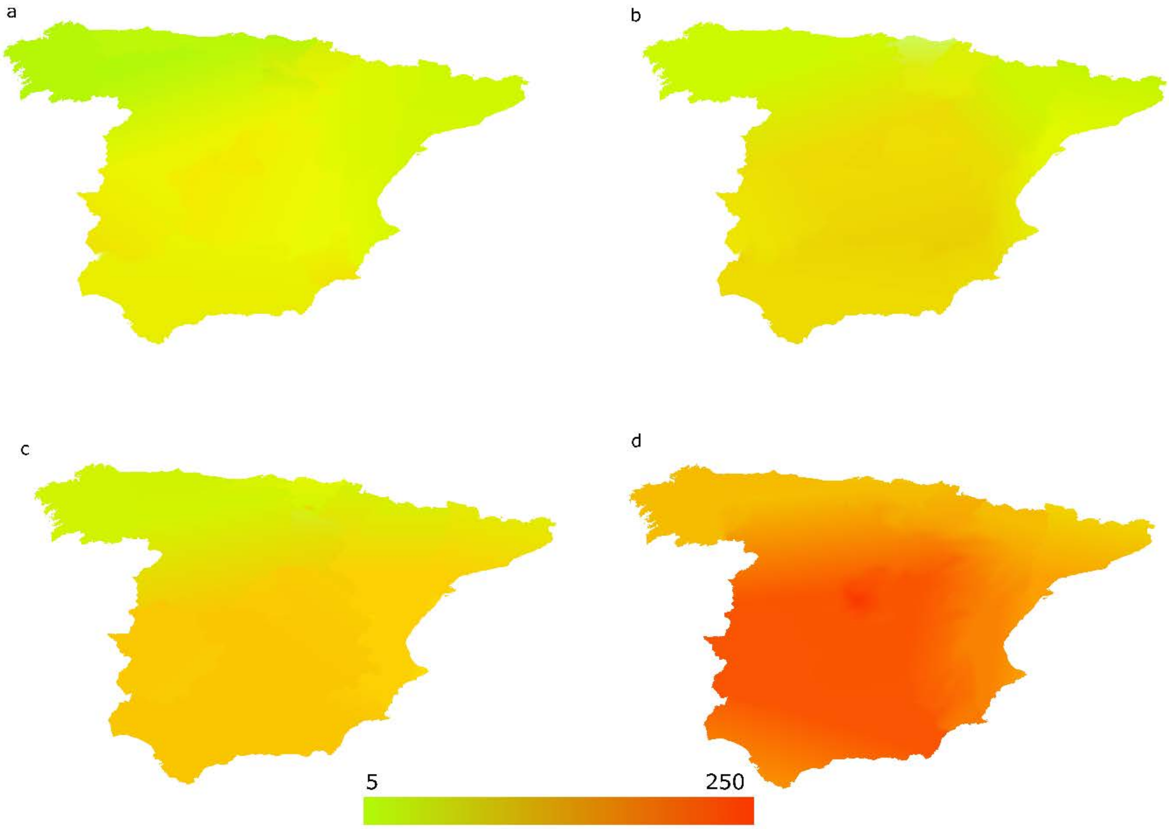

Fig. 3. Buckling events for the RCP6.0 scenario. (a) 2025; (b) 2050; (c) 2075; (d) 2100.

Considering the RCP6.0 emissions scenario, which corresponds with a medium range emission scenario (a peak emissions by 2060), the projected number of buckling events are show in Fig.3. As expected, all time scenarios have a greater impact than their corresponding RCP4.5 scenarios by the end of the century. Particularly, larger central areas experience the most important impacts with more than 200 events per year by 2100. In addition, important impacts are expected in all regions between the years 2075 to 2100, in accordance with rapid temperature increase.

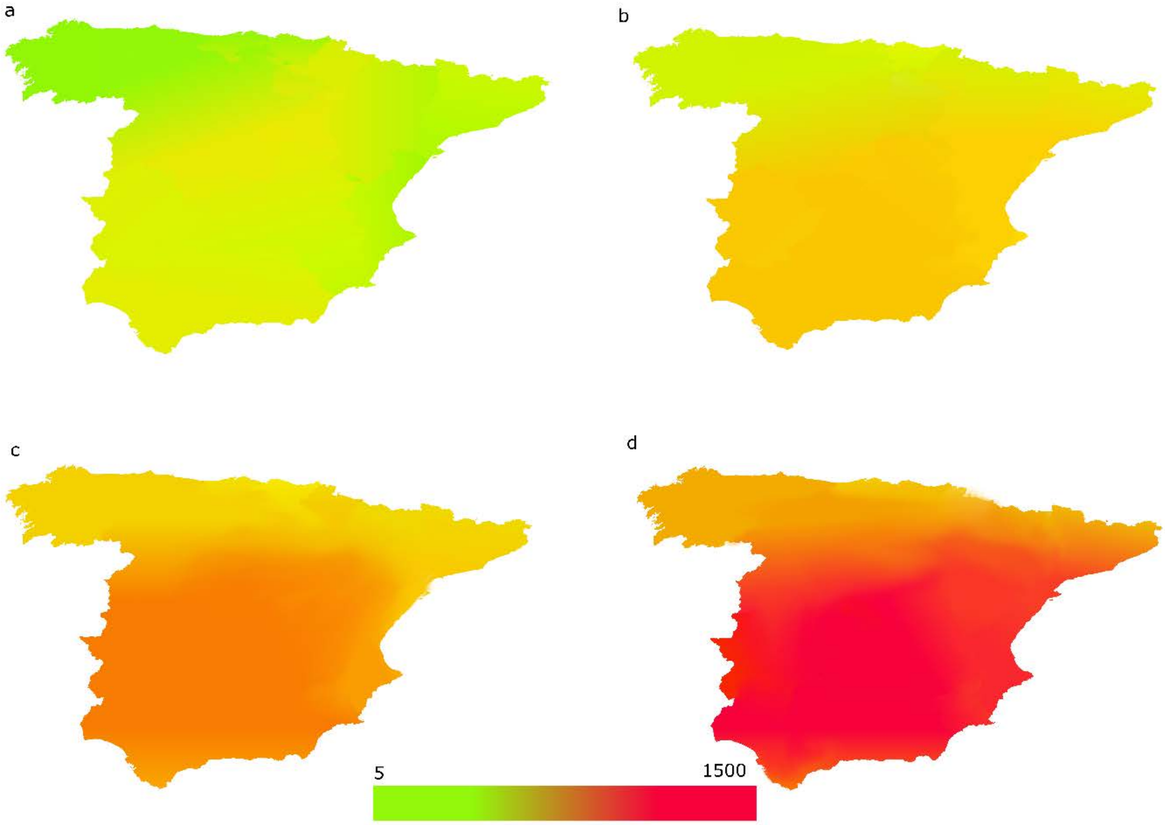

Fig. 4. Buckling events for the RCP8.5 scenario. (a) 2025; (b) 2050; (c) 2075; (d) 2100.

Fig.4 represents buckling events for the RCP8.5 scenario. Comparing results achieved with previous scenarios, the increase in the number of expected buckling events is considerably greater. In fact, the annual number of buckling events could increase to 20 to 90 by the 2050 and to 60 to 550 by the 2075. In the year 2100 the expected number of buckling events reaches, for central areas, more than 1500. These values provides an important information source for, and a step towards the creation of a risk database of, railway authorities.

5. Conclusions and recommendations

The proposed analysis provides a method for estimating the number of future buckle events under climate change. To accomplish this task, spatial temperature data from the State Meteorological Agency AEMET is used under future climate change scenarios. Based on empirical formulation and Monte Carlo simulation, the proposed methodology calculates the number of expected buckle events occurring in one year. Thus, buckle can occur when the rail temperatures exceed the buckling temperature. With that, results are provided for different time horizons, in order to consider impacts in relation to time and space.

As showed, rail buckle events are projected to increase in frequency under all climate change scenarios, specially for central areas of Spain. For the 2025s if it is assumed all track is of good quality reduced damages from buckle events are seen. However, for the 2050s and in the following years, the number of buckle events are considerably.

Given that the Spanish rail network size and are set to increase, there is a real need to increase the resilience to high daily temperatures. This method permits more practical measures for buckling safety assurance through targeted track maintenance operations and train operations. Finally, the focus of this study was on temperature effects, but additional climate change impacts can be considered to determine the cumulative impacts from climate change.

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