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# Natural Hazard Management in Railway Infrastructures Considering a Climate Change Scenario

## The North Line: Alfarelos-Pampilhosa Section

**Dissertação de Mestrado Integrado em Engenharia Civil, na área de Especialização em Geotecnia, orientada pelo Professor Doutor Paulo Alexandre Lopes Figueiredo Coelho e pela Professora Doutora Maria da Conceição Morais de Oliveira Cunha e apresentada ao Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.**

Fevereiro de 2021

Faculdade de Ciências e Tecnologia da Universidade de Coimbra
Departamento de Engenharia Civil

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# NATURAL HAZARD MANAGEMENT IN RAILWAY INFRASTRUCTURES CONSIDERING A CLIMATE CHANGE SCENARIO

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Thank you all for believing in me, even in the moments I struggled the most.

**Confissão**
Nuno Júdice (1994)

*De um e outro lado do que sou,*
*da luz e da obscuridade,*
*do ouro e do pó,*
*ouço pedirem-me que escolha;*
*e deixe para trás a inquietação,*
*a dor,*
*um peso de não sei que ansiedade.*

*Mas levo comigo tudo*
*o que recuso. Sinto*
*colar-se-me às costas*
*um resto de noite;*
*e não sei voltar-me*
*para a frente, onde*
*amanhece.*

# ABSTRACT

It is practically undisputable that the climate on planet Earth is changing, resulting in weather events which may trigger severe consequences. In Portugal, as all over Europe, there have been some examples of natural hazards increasingly affecting different assets, and it is essential to consider possible weather changes when designing or retrofitting a structure.

The railway network is a vital way of transportation, not only for passengers in a train, but also because of freight activity since it is a quick and efficient way to move goods within a country or even a continent. Considering its inherent features, the railway infrastructure is highly vulnerable to weather events. When assessing risk of a certain railway, it is of the utmost importance to understand how meteorological conditions may directly or indirectly impact it, so as to define measures to reduce risk or mitigate the threats of climate change.

The current thesis aims to give information about rail vulnerability and exposure by considering climate change in risk assessment procedures. By understanding the impact of temperature, rainfall, wind or storms on the railway, it is possible to define a set of measures which may avoid or reduce the effects of weather events, thus diminishing disruptions or delays and avoiding additional costs in maintenance or repair works, which may be significant and have different natures.

The case study presented here includes a section of the North Line, located in Portugal. This section lies between Alfarelos and Pampilhosa (near the city of Coimbra) and besides the problems caused by high temperature, strong winds and rainfall, it is particularly affected by floods, due to its proximity to the Mondego River.

Even though the solutions presented herein may not solve all the problems, they aim at offering a starting point to avoid or reduce some of the challenges posed to this railway infrastructure in a climate change scenario using cost-effective approaches.

**Keywords**: railway infrastructure; climate change; risk assessment; asset vulnerability.

# RESUMO

É praticamente indiscutível que o clima no planeta Terra está em modificação, causando eventos meteorológicos que podem despoletar consequências severas. Em Portugal, tal como por toda a Europa, registaram-se alguns exemplos de ameaças naturais a diferentes componentes estruturais, e é essencial considerar estas alterações, ao projetar ou adaptar determinada estrutura.

A rede ferroviária é uma forma vital de transporte, não só para os passageiros, mas também devido ao transporte de mercadorias, visto que é um modo eficiente e rápido de deslocar bens dentro de um país, ou mesmo de um continente. Considerando as suas características inerentes, a infraestrutura ferroviária é extremamente vulnerável aos eventos meteorológicos. Ao avaliar o risco numa determinada linha ferroviária, é fundamental perceber como as condições meteorológicas a podem afetar direta ou indiretamente, com o intuito de definir medidas para reduzir o risco ou mitigar as ameaças das mudanças climáticas.

Esta dissertação pretende fornecer informação sobre vulnerabilidade e exposição ferroviária, considerando as alterações climáticas na metodologia de avaliação de risco. Ao compreender o impacto da temperatura, da precipitação, do vento ou das tempestades nas linhas férreas, é possível estabelecer um conjunto de medidas que podem evitar ou reduzir os efeitos do clima, diminuindo as perturbações ou atrasos e evitando custos adicionais nos trabalhos de manutenção ou reparação, que podem ser significativos e ter naturezas diversas.

O estudo de caso aqui apresentado refere-se a um troço da Linha do Norte, localizado em Portugal, que se situa entre Alfarelos e Pampilhosa (perto da cidade de Coimbra). Além dos problemas causados pela temperatura elevada, os ventos fortes ou a precipitação, este troço é particularmente afetado pelas cheias, devido à proximidade ao rio Mondego.

Apesar de as soluções aqui apresentadas não resolverem todos os problemas, estas pretendem fornecer um ponto de partida para evitar ou mitigar alguns dos desafios colocados a esta infraestrutura ferroviária, através de abordagens economicamente viáveis.

**Palavras Chave**: infraestruturas ferroviárias; mudanças climáticas; avaliação de risco; vulnerabilidade das estruturas.

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# 1. INTRODUCTION

The transport sector, particularly the railway segment, plays a key role in the economy and the society of a given country. The rail network embodies the transportation of goods and supplies across Europe, as well as a way of public transportation for people. Consequently, routes connecting important locations should be looked after, in order to avoid disturbances that have negative social consequences and large financial costs.

Considering its inherent features, the railway infrastructure, as other transport infrastructures, strongly depends on weather conditions and the subsequent physical impacts. Even though weather conditions have always been considered in infrastructural design, they were frequently disregarded in detriment of other constraints. In addition, what used to be a predictable regular climate has changed throughout the years, demanding for new ways to address this issue. In fact, it is now widely accepted that today’s weather is highly influenced by the recognized phenomenon of climate change, which has abruptly altered average weather conditions, leading to extreme meteorological events, for which transport infrastructures were not prepared for, setting a new level of risk for the transport network. In order to face these climate threats, new and envisioning design approaches considering future climate conditions are required.

The objective of this thesis is to determine how railway infrastructures are affected by weather events, especially the ones potentially intensified by climate change. Isolated assets need to be considered and thoroughly inspected in order to develop risk assessment procedures enabling the identification of the level of gravity of each individual asset, thus prioritising the one(s) to be retrofitted, indicating measures that will improve the resilience of the railway as a whole.

To fully understand the problem addressed, the first step was to collect information related to climate change, how it has been gradually changing, and how extreme events became more frequent and intense. It was also important to understand how it could affect the railway and to find evidence of this transport network being disrupted by extreme events.

To better understand risk terminology, the next step involved research on the topic of risk assessment. Once the effects of climate change on the railway and risk concepts were consolidated, the research focused on to how to mitigate the effects derived from natural hazards on the railway and if these measures were suitable for all situations.

Afterwards, the case study required a profound knowledge of the meteorology of the region, the features of the North Line and how weather events have impacted it in the recent past.

Besides the information gathered about the rail section, a more substantial analysis was conducted, and visual records were taken, making possible to identify situations presenting higher vulnerability and, therefore, greater risk. Additionally, a risk assessment methodology was developed, which eases the complexity of combining multiple concepts, such as probability of occurrence, exposure and vulnerability in one single matrix. Based on the results obtained, some measures were suggested to reduce the vulnerability of the highlighted situations, bearing in mind the research conducted in the previous chapter of the thesis.

After this introduction, the thesis contains three main chapters. Chapter two describes how climate conditions have changed drastically, and evidence is given to sustain the issue of climate change and the extreme weather events deriving from it. Afterwards, the effects of such events and their correlation with railway infrastructures are explored, with supporting examples from what has already been observed across the world. The third section of this chapter is dedicated to explaining the concept of risk and what is involved in risk assessment. The final section considers measures to avoid or mitigate natural hazards in a climate change scenario.

The third chapter englobes the case study – a detailed analysis of the rail section between Alfarelos and Pampilhosa. It starts by providing some general information about the setting of the section at study and the rail network in Portugal. The following sections offer a more specific analysis of the meteorology of the region and how the railway section has been affected by it. Vulnerability of the assets in the rail section is assessed through a comprehensive analysis of the railway and detailed information about past events in the region. To conclude the chapter, a semi-quantitative risk assessment methodology is proposed and, finally, measures to reduce vulnerability in the railway section are suggested.

Chapter four contemplates the findings in the thesis, raising some questions about the importance of natural hazard management in railway infrastructure. It also includes some discussion on the challenges faced in this research work and suggests further studies.

By identifying real situations of railway vulnerability, this thesis unveils how climate change has transformed the future of railway infrastructure. Such a transformation requires preparing for future climate conditions and promoting the use of risk assessment methodologies in order to determine the level of gravity of an asset and define the relevant measures to avoid or mitigate the risks involved.

*“Climate change involves both a shift in mean values and a change of pattern in the frequency and magnitude of extremes. Without a change in coping range through adjustment and adaptation, the system will become more vulnerable.”*

Lindgren et al, 2007

# 2. LITERATURE REVIEW

This chapter begins by presenting some relevant information concerning climate change and its impact around the world, focusing particularly on what concerns its effect on railway infrastructures. The following section intends to describe most of the components of railway infrastructures and to what extent they can be affected by climate change, considering some documented events observed around the globe. Afterwards, there is essential information on how to assess railway risk, considering infrastructural characteristics, hazardous natural events, with particular emphasis on those more involved with climate changes, and their consequences. Finally, there is a section focusing on the measures to avoid or mitigate those consequences and discussing the need to analyse the issue from a different perspective.

## 2.1. General considerations regarding climate change

The definition of climate, according to the Intergovernmental Panel on Climate Change (IPCC), is presented as “the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years” (IPCC, 2007). Such variability may occur without any significant influence in the short term. Nevertheless, more than ever, the perception of climate change is unequivocally recognised by most scientists and members of the international community and may seriously affect many long-lived civil engineering infrastructures.

Therefore, despite the controversy surrounding the issue, one could assume that the effects caused by climate change in the previous few decades could be the result of natural climate fluctuation. However, such climate fluctuation, at the present day, reveals an unparallel frequency and intensity when faced with later years in the same periods. This abnormal behaviour leads to the irrefutable conclusion that today’s climate is highly influenced by an anthropogenic factor: “today, it is considered a fact that human activities have altered the environmental conditions on earth to such an extent that this phenomenon warrants defining a new geological time unit known as the Anthropocene” (ILF Consulting Engineers, 2018), when human activity started to have a significant impact on the planet’s climate and ecosystem, changing it to such a degree that it may have permanent consequences which will affect not only the planet, but everybody living on it.

The threats posed by a shifting climate will not be identical around the globe since these might be different from place to place and may include the rise in the sea level (resulting in coastal floods), storms which are getting more frequent and more intense, severe droughts, and heat waves, among other problems (IPCC 2014; apud Schenk, 2018). The information presented in this section aims to display some important facts related with the issue at study.

For instance, according to the World Meteorological Organization (WMO), the year of 2019 was the second warmest year on record, only after the year of 2016 (WMO, 2020). Furthermore, "since the 1980s, each decade has been warmer than the previous one" demonstrating an intensification of the global warming phenomenon. In other words, human behaviour has fuelled the natural fluctuation of climate.

In order to attain a better understanding of the issue, a closer look at the graph in figure 2.1 displays the previously described trend of a global rising temperature, which is expected to "continue because of record levels of heat-trapping greenhouse gases in the atmosphere" (WMO, 2020), even when considering five different data sets.

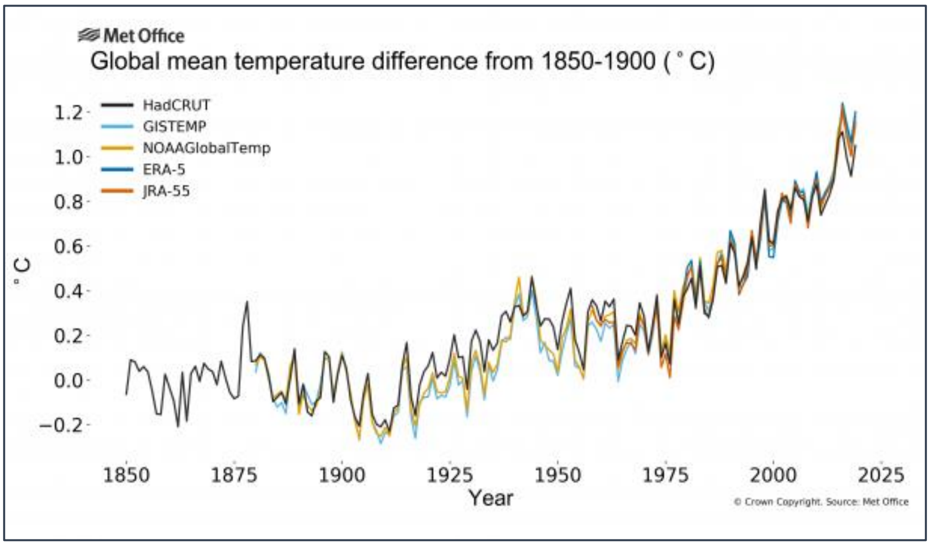

Figure 2.1 – Global mean temperature difference after 1850 to 1900 (WMO, 2020)

Not only has the atmosphere warmed but the oceans as well, due to a reduction in the ice caps, leading to a rise in the sea level (IPCC, 2014). According to IPCC, in the past 100 years, global sea level has risen nearly 178 mm, which may cause significant floods in coastal areas, resulting in loss of resources, human lives and the degradation of ecosystems. The magnitude of the problem is getting worse every year, with catastrophic results, which might get even more serious in the following decades.

Another example of climate change is in the patterns of the average precipitation. According to Merzdof (2019), a warming climate leads to extreme global precipitation trends: "wet areas will become wetter, and dry areas will become drier." According to figure 2.2, in terms of annual precipitation, we witness "an increasing of up to 70 mm per decade in north-eastern and north-western Europe, and a decrease of up to 90 mm per decade in some parts of southern Europe." Moreover, summer precipitation has significantly decreased "by up to 20 mm per decade in most of southern Europe, while significant increases of up to 18 mm per decade have been recorded in parts of northern Europe" (EEA – European Environment Agency, 2017a).

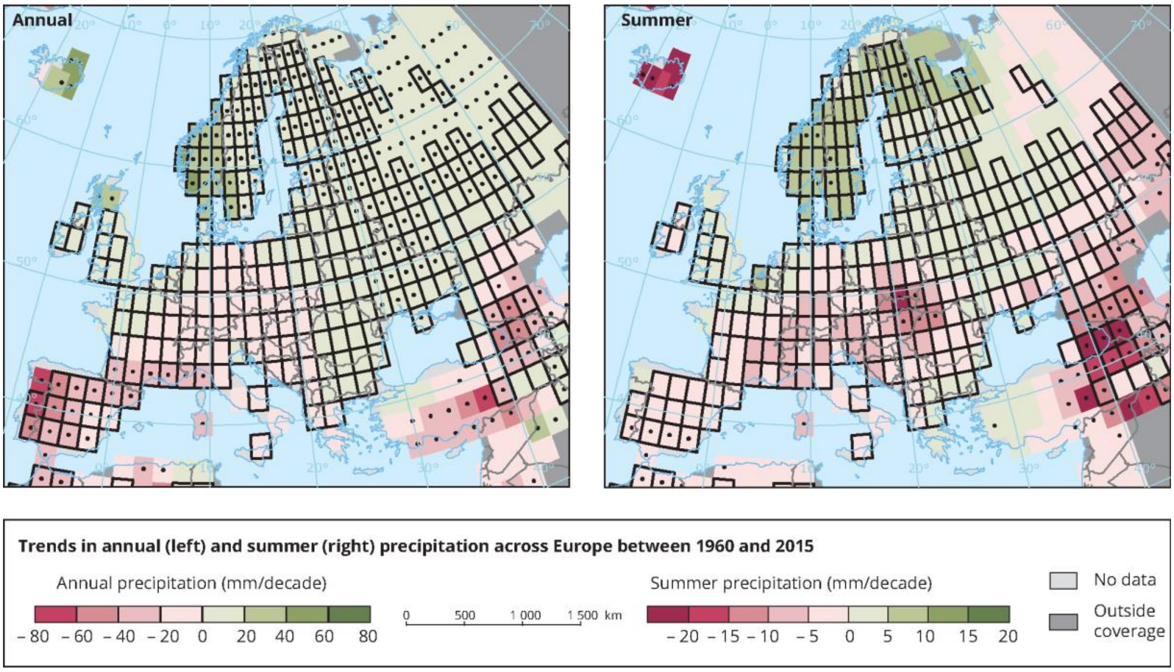

Figure 2.2 – Trends in precipitation in Europe: 1960 to 2015 (EEA, 2017a)

On the one hand, according to a study by Melillo et al (2014), heavy precipitation will lead to an amount of runoff that exceeds the capacity of storm drains and levees, causing flooding events. On the other hand, drought may be a potential factor for wildfires since the absence of rain and low humidity dry out vegetation, which can ignite fires. "In these conditions, a spark from lightning, electrical failures, human error or planned fires can quickly get out of control" (Merzdof, 2019). Another effect of the increase or decrease in precipitation is felt on river flows, which may overflow causing floods, or dry and contribute to droughts, as it is happening in southern Europe (EEA, 2016).

Every year, there are reports of unprecedented wildfires, with impacts on humans and wildlife, and the destruction of assets, releasing even more carbon dioxide into the atmosphere and contributing to the increase of the greenhouse effect. The EEA (2019) mentions that "the unprecedented forest fires in several European countries in 2017 and 2018 coincided with record droughts and heatwaves in these years." According to the EEA, the issue of wildfires is particularly serious in southern Europe (EEA, 2019). Figure 2.3 shows the evolution of the burnt area in southern Europe, and even though there is a reduction trend, there is still a huge burnt area in Portugal, confirming that the measures to prevent wildfires have not been successful. As it is possible to verify, Mediterranean countries have deeply suffered with the impact of wildfires, which might possibly be the outcome of climate change in Southern Europe. The situation is even worse in Portugal (and Spain). A closer look at recent years, and mainly at the year 2017, shows that even though there are already some preventive measures being applied in Portugal, these have not been capable of diminishing the impact of wildfires and the burnt area, therefore suggesting the problem will continue in the future.

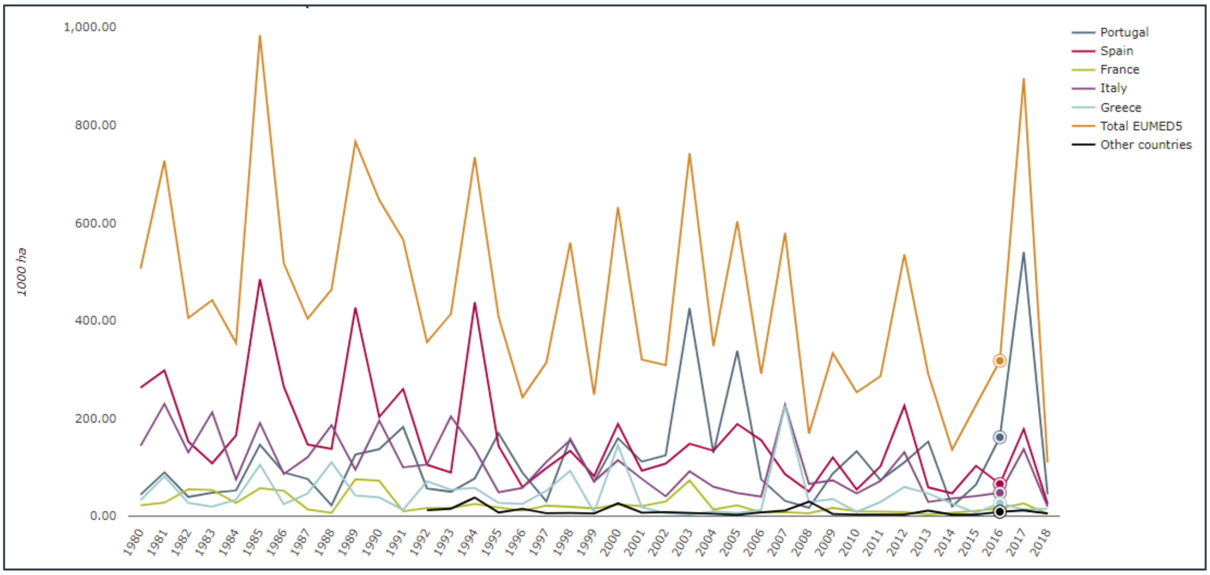

Figure 2.3 – Burnt area in European countries: 1980-2018 (EEA, 2019)

Heat waves and extremely high temperatures may lead to wildfire events, resulting in the spikes seen in the graph. Such events, despite being irregular, have huge consequences for society, since the destruction caused by fires is hard to recover from and has elevated social and financial costs. Consequently, climate change should not be considered only in terms of average weather variations experienced throughout the past decades, but also of extreme episodes.

Comparably to the rainfall, there are other threatening phenomena such as winter storms and extreme winds. According to Munich Re, winter storms are as dangerous as hurricanes. In fact, even if wind speeds do not reach those of cyclones, the storm front can be over 1,000 km long, sweeping across half a continent. In addition, it is expected that this type of meteorological events will increase all over Europe in the following decades (EEA, 2017b).

Overall, the intensification of climate change due to anthropogenic origins is on the rise and the future projections indicate a continuous escalation of the already known effects. Climate change is strengthening already existing threats (Lindgren et al, 2009), leading to extreme conditions and events, “such as storms, floods, droughts or landslides” (ILF, 2018). The Climate Change Synthesis Report (IPCC, 2014) states that even considering different emission scenarios, temperatures will rise, and heat waves will become more intense and last longer, as will happen with extreme precipitation. “The ocean will continue to warm and acidify, and global mean sea level to rise” (IPCC, 2014).

The projections of a future climate, as confirmed by the EEA (2020) after analysing a set of different studies, are that severe droughts will be more frequent in southern Europe and that their frequency will also increase in central and western Europe. As for changes in heavy rain, the EEA (2020) predicts a 35% increase for central and eastern Europe, and an increase of 25% in heavy rain in southern Europe. This may intensify the episodes of floods which are already felt in some parts of Europe.

When it comes to wildfires, the EEA (2020) predicts, in a high-emission scenario, an increase of more than 40% in weather-driven wildfires. For the same scenario of high emissions, “European coasts would experience mean sea level rise between 0.4 m and 1 m,” causing more frequent coastal flooding in the next 100 years. According to the EEA (2017b), “the risk of severe winter storms, and possibly of severe autumn storms, will increase for the North Atlantic and northern, north-western and central Europe over the 21st century.”

Nevertheless, climate projections are filled with uncertainty and, as mentioned by IPCC (2012), apud Olsen (2015), the main sources of uncertainty in the projections are caused by the natural variability of climate, the inaccuracy in climate model response or sensitivity to anthropogenic and natural factors, and, lastly, the uncertainty in the projections of future emissions and other natural and anthropogenic climate drivers.

Scientists and governments around the world are concerned about this situation and trying to avoid the hazardous consequences of climate change. Besides changing human action on the planet, it is of the utmost importance to study different scenarios and build climate models which can anticipate the future and predict climate changes, so that some perilous outcomes can be averted. Considering the existing data, it is reckless to ignore proven facts and disregard climate models which may help preventing what has been happening. It is crucial to design new structures or retrofit old ones able to withstand the changes in the weather, thus mitigating the risks.

## 2.2. Railway infrastructure – the effects of climate change

A railway is comprised of components and assets meant to have a long-life span, being constantly used by trains that transport people and products on a daily basis, without major disruptions. Typically, the actual life span of a railway infrastructure, at full capacity, is close to a 60-year period (Pyddoke, 2002, apud Lindgren et al, 2009). However, "the lifetime of different installations can be substantially longer, up to 100 years for culverts and bridges" (Swedish Commission on Climate and Vulnerability, 2007, apud Lindgren et al, 2009).

### 2.2.1. The components of the railway

According to the Network Rail (the British company operating railway infrastructure), the railway track is the whole structure where trains run on. As seen in figure 2.4, this structure includes rails (lengths of steel welded together), sleepers (supports for the rails), switches and crossings (moveable sections of track that guide trains from one track to another and allow them to cross paths) and sets of points (mechanical systems that move the switches and crossings).

Figure 2.4 – Railway track (AGICO Group, 2020)

In order to give support, load transfer and drainage to the track, ballast is placed in different layers beneath that structure (see figure 2.5 and additional photographs in Appendix C).

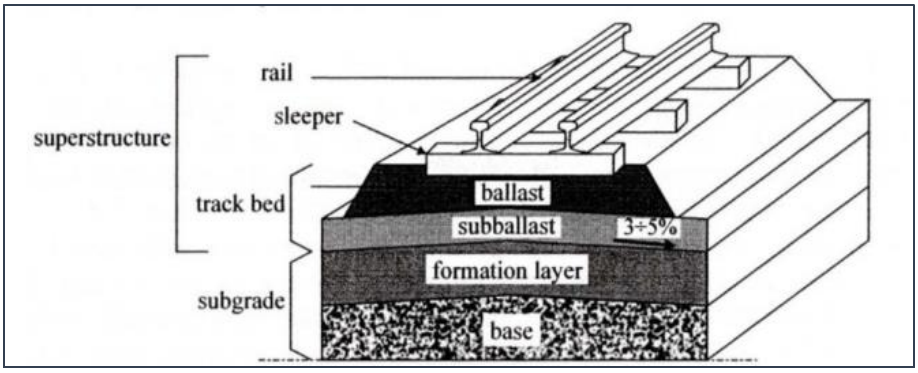

Figure 2.5 – Railway track with ballast (Profillidis, 2006)

The assets that complement the track are bridges, tunnels and viaducts, which help to shorten the path, and earth assets, such as embankments, which allow the railway lines to pass at an acceptable level and gradient over low lying ground, soil cuttings (excavation that allows railway lines to pass at an acceptable level and gradient through the elevated surrounding ground that is composed predominantly of soil), and, finally, rock cuttings (excavation that allows railway lines to be at an acceptable level and gradient through the elevated surrounding ground that is composed entirely or predominantly of rock) (Network Rail, 2020b). Figure 2.6 shows examples of a tunnel, an embankment, a cutting and a bridge.

Figure 2.6 – Earth assets: a. Tunnel; b. Embankment; c. Cutting; d. Bridge
(a. and c. Network Rail, 2020b; b. Keenan et al, 2019; d. Douro, 2020)

### 2.2.2. The effects of natural hazards on the railway

The number of passengers on railway and the number of freight activity has increased over the last decades (World Bank, 2020), and the projections are to increase even further (IEA, 2019), since travelling by train could be an efficient way to reduce greenhouse gas emissions, moving people and goods across great distances in a fast, safe and sustainable way. As such, societies depend on railway infrastructures, and it is critical to avoid disruptions caused by maintenance, repairs or rebuilding, or delays forced by inefficient systems, which may even force scheduled trains to remain stationary.

In order to provide a resilient railway, many of the assets and components have to be managed and replaced. Some examples of this work are the redistribution and compaction of the ballast, the smoothing and cleaning of the rail head and monitorization of infrastructure so as to identify flaws in the rail that need to be fixed (Network Rail, 2020b).

According to an article written in the Joint Research Centre (JRC) by Nemry and Demirel (2012), rail assets and components reliability “could be affected by one or several simultaneous changes in the climate conditions, including hot summers, extreme precipitation events, increased storminess and sea level rise.” Thus, it is vital to take into account the vulnerability of the railway since “transport delays and interruptions have high social costs. The ability of the transport sector to respond rapidly to climate change is constrained by its reliance on long lasting infrastructures” (Eisenack et al, 2011).

Adapting the railway infrastructure is inevitable and will lead to changes in its design, and “how we fund and manage it over time and think of the various infrastructures as interconnected systems of systems” (Bollinger et al, 2014, apud Schenk, 2018).

As mentioned before, the impacts from climate change on the railway infrastructure could derive primarily from high temperature, drought or decreased precipitation, extreme precipitation, storms and extreme winds, storm surges, and seasonal changes. Some of these may be trigger events (primary or initial events) which may result in other weather-related events (secondary events), such as the change in river flows and river floods, wildfires or even toppled trees.

- **Extreme high temperature**

Although it is not easy to quantify the notion of extreme temperature, the IPCC considers all extreme events as something which shows a significant variation within the values of a region, in a specific season (Seneviratne al, 2012).

As such, events of "higher average temperature and more frequent extreme high temperatures […] can potentially enhance the risk of rail track deformation" (Nemry and Demirel, 2012). According to the authors, this deformation effect on the track is also known as buckling and defines a lateral misalignment of the track that is serious enough to cause a derailment. This phenomenon happens when extreme temperatures force the track to expand along with "the disturbance caused by a train that is a common contributor" (Dobney et al, 2008). Figure 2.7 below recalls an incident caught on video of a train almost derailing due to buckling on the track (Nguyen et al, 2012). This happened in Melbourne (January 2009), during a heatwave.

Figure 2.7 – Railway track buckling, Australia (Nguyen et al, 2012)

Moreover, due to extreme high temperatures there are risks associated with the "sag of overhead line and risk of dewirement" as mentioned in the Climate Change Adaptation Report (2015) referred by Network Rail (2015).

- **Drought**

Seneviratne et al (2012) define drought as "a period of abnormally dry weather long enough to cause a serious hydrological imbalance." A common consequence derived from periods of decreased rainfall is the "desiccation of embankments resulting in track geometry faults and failures in supported lineside equipment" (Network Rail, 2015). It is also relevant to add that, in some types of soil, droughts contribute to episodes of flash floods, since the dry, hard ground makes it difficult for water to penetrate it (AllTraIn Consortium, 2015).

- **Extreme precipitation**

One more side effect that derives from climate change is the change in the pattern of precipitation trends, namely the intensity and frequency of rainfall. According to Mills and Andrey (2002), “increased precipitation may affect the frequency of landslides and slope failures that could damage road and rail infrastructure.” Landslides and slope failures impact the railway “when soil, rocks and earth fall onto and either wholly or partially block the track” (Network Rail, 2020b). Henceforth, the stability of embankments and slopes is affected by the increased precipitation.

Nevertheless, slope stability is not the only problem. As mentioned by the AllTraIn Consortium (2015), rainfall could be the initial event for soil liquefaction, debris flow and shallow landslides. “Intense precipitation events may lead to overloading drainage systems, [the foundation resistance will be affected because] soil moisture levels may also increase” mainly on constructions on expansive clays (Olsen, 2015). Moreover, subgrade and ballast may be affected from the increased annual precipitation, namely the successful use of the ballast “as strength and stiffness of the materials reduce, there is a risk of degradation of bearing capacity” (RAIB, 2003).

A tangible demonstration of the flooding consequences in the railway is noticeable in figure 2.8. The photos refer to a fast flood that happened on 26th October 2019, in the line between Abergavenny and Hereford, UK. According to the Network Rail, “the flash flooding went on to wash away the railway foundation stone leaving sections of track suspended” (Network Rail, 2019). This event caused the railway to remain closed for a week, while 500 tonnes of ballast and 300 tonnes of foundations were being replaced (BBC, 2019).

Figure 2.8 – Flood in a railway, UK (BBC, 2019)

Olsen (2015) states that bridges and culverts "are often designed for floods of a given return period" but with climate change, the frequency and intensity of floods will most likely increase and so "the design flood will be exceeded more often than planned." Even though flooding is the most visible and significant impact of precipitation, the disruption continues long after the floodwaters subside since the damage needs to be repaired (Standley et al, 2009; apud Chapman, 2014).

This year, 2020, on 12th August, a landslide in Stonehaven, UK, caused a train to derail. BBC (2020b) mentioned that, according to a report from RAIB, "the train had turned backwards towards Aberdeen after a report of a landslip further down the track." It is also stated that the train "had travelled more than a mile when it was derailed […] after hitting a separate landslip" (RAIB, 2020; apud BBC, 2020b). Furthermore, a news article in The Guardian states that the accident happened after intense rainfall and reports of flooding (Topham, 2020). This incident was particularly serious since the train hit the landslip "at almost the maximum speed for the stretch of track" causing the death of three people and the disruption of the track from August to November. Topham (2020) also mentions that repairs took a long time, namely "the laying of more than 500m (546 yards) of replacement track, […] 400m of telecom cables, […] along with extensive improvements to drainage systems." In figure 2.9, it is possible to confirm the severity of the incident.

Figure 2.9 – Train derailment caused by a landslide, UK (Topham, 2020)

River floods and similar hydrological hazards may be a secondary result of intense rainfall surpassing the "infiltration capacity of the soil, or by rain falling on saturated ground" (Arnerl et al, 2014). When "a flood exceeds the design water level, including the freeboard of an embankment dam, levee or dike (herein the embankment), embankment overtopping and breaching can occur" (Picket et al, 2011). Such a phenomenon has effects like the "overflow of bridges, embankments and cuttings and also damage road pavement and rail tracks […] [leading to] bridge collapse by direct impact or by erosion of the bridge supports" (AllTraIn Consortium, 2015).

In 2020, a river flood in the Murmansk region, in Russia, destroyed a railway bridge across the Kola river. After the river overflew its banks and washed away one of the five pillars supporting the bridge, leading to its collapse, the whole structure fell down (High North News, 2020). As told by Russian Railways to the Reuters agency, that route was essential since it was the only one in the area. As such, after the loss of the bridge, a temporary ban was imposed on the loading of all goods to the Murmansk transport hub (Reuters, 2020). In figure 2.10, a photograph of the collapsed bridge over the Kola river can be seen.

Figure 2.10 – Railway bridge damaged by river flood, Russia (Reuters, 2020)

- **Storm surges**

Storm surges are another phenomenon to consider when the issue at hand is the effects of the weather on railway infrastructures. A storm surge is a temporary rise, at a specific site, of the height of the sea because of extreme meteorological conditions (low atmospheric pressure and/or strong winds) (IPCC, 2014). The storm surge refers to the excess above normal sea level, considering tidal variation, at a given time and place.

According to the AllTraIn Consortium (2015), storm surges are the primary event that leads to floods: they state that "a storm surge can obstruct roads and railways by flooding.

Infrastructures can be damaged by hydro-mechanical pressure or erosion forces. Tunnels can be damaged by hydro-mechanical pressure on the lining. Water ingress at the tunnel portals can lead to obstruction and damage operational equipment."

Figure 2.11 recalls an incident which took place in 2014, in the UK. "A section of the sea wall in Dawlish, Devon, collapsed and left the railway to Cornwall suspended mid-air" (BBC, 2014). The obvious destruction in this incident was the immediate result of a storm surge, leading to the closure of the train lines and its replacement over a period of six weeks, causing disruptions and additional costs, according to the same source.

Figure 2.11 – Railway incident caused by a storm surge, UK (BBC, 2014)

- **Strong wind, storms and lightings**

Wind is another climate phenomenon which may lead to harmful consequences. According to the Met Office (2020), the Beaufort Scale "is an empirical measure for describing wind intensity based on observed sea conditions" and the scale goes from Beaufort level 0 to Beaufort level 12, where 0 describes the wind as 'calm' and 12 describes the wind as a 'hurricane'. Even though it is considered a typical weather event, one could speak of extreme winds, when they exceed speeds higher than 75 km/h (corresponding to a Beaufort number above 8). Unlike other events, wind is not usually considered individually, but in association with other events such as storms or cyclones (Seneviratne et al, 2012). These authors mention that "extreme wind speeds pose a threat to human safety, maritime and aviation activities, and the integrity of infrastructure."

In a paper for the RSSB, written by Eddowes et al (2003), this phenomenon might "increase the incidence of dewirements […] and snagging of overhead lines" and cause "instability of rail vehicles at speed.” This instability happens as railway traffic “can also be directly affected by strong winds that can induce accidents or disruption of the service” (AllTraIn Consortium, 2015), due to wind-blown objects, including but not limited to trees (Eddowes et al, 2003). Furthermore, “some structural types of bridges are very sensitive to strong winds (e.g., suspension bridges), which can induce large displacements and vibrations, leading to temporary bridge closure” (AllTraIn Consortium, 2015).

In 2012, an incident in Littleport, UK, took place resulting from the loss of contact of the pantograph, an apparatus assembled on the top of an electric train, which collects power when in contact with the overhead line equipment (OLE). An investigation by the Rail Accident Investigation Branch (RAIB) concluded that “the pantograph head lost contact because the overhead line was deflected from its intended position due to a combination of long-term movements of the line support mast foundations and the force of the wind at the time of the accident” (RAIB, 2013). Figure 2.12 displays the support structure hit by the pantograph.

Figure 2.12 – Structure hit by the pantograph, UK (Railways Archive, 2013)

Despite the evident effects of winter storms, quite frequently they have even more repercussions than floods. Other secondary effects triggered by winter storms are the possibility of trees falling, which may disrupt the railway, or even “the adverse effect of higher wind speeds on overhead line equipment (OLE)” (Network Rail, 2007).

In February 2020, storm Ciara caused major disruptions on the railway as “heavy rain and flash flooding washed away railway foundation stone and blew trees and debris onto overhead power lines and tracks across the North West & Central region between London, the West Midlands, North West and Cumbria” (Network Rail, 2020a). Figure 2.13 shows one of the trees that blocked the railway – in this case, a tree blocking all lines in Four Ashes, Staffordshire.

Figure 2.13 – Railway blocked by tree, UK (Network Rail, 2020a)

Another threat which may have a serious impact on railways are lightnings. A lightning could be defined as “the occurrence of a natural electrical discharge of very short duration and high voltage between a cloud and the ground or within a cloud” (Earthnetworks, 2020). Thunderstorms may include lightnings, which consequently lead to explosions, fires, wildfires, toppled trees and blackouts (AllTraIn Consortium, 2015). This phenomenon may have a particular influence on the railway due to the fact that lightning damages the electronic equipment, according to RSSB - Rail Safety and Standards Board (Marteaux, 2016), and “destroyed transformer stations for railway power supply can take months to replace” (AllTraIn Consortium, 2015), which is unacceptable in a transport infrastructure.

- **Wildfires**

Wildfires are not a primary weather event, even though they might be triggered by a reasonable number of weather events. These events may be caused by extreme temperatures, droughts, wind, storms or lightnings, or may be intensified even when the origin was human activity (Seneviratne et al, 2012). One of the consequences of extreme high temperatures is the propensity to wildfires and, according to Lindgren et al (2009), “rail traffic is one the main causes of forest fires.” Still, whereas extreme high temperatures may be the trigger that first comes to mind when the subject ar wildfires, there are some other causes such as droughts, lightnings, sparks from rock falls and even spontaneous combustion.

According to the AllTraIn Consortium (2015), the difference between a regular fire and a wildfire is the fact that a wildfire is distinct in “its extensive size, the speed at which it can spread from its source, its ability to change direction unexpectedly and to jump gaps such as roads, rivers and fire breaks.” Moreover, the main consequences of wildfires are the destruction of power and control communication lines and the smoke and flames descendant from the wildfire that can block railways, tunnels and bridges, compromising structural integrity of railways, bridges, embankments, among others (AllTraIn Consortium, 2015).

In the summer of 2020, in August, a large wildfire took place in Chobham Common, UK. In the amidst of the wildfire, trains were disrupted since it was right next to the track (BBC, 2020a), as shown in figure 2.14.

Figure 2.14 – Wildfire next to the railway track, UK (Network Rail, 2020b)

- **Considering weather and weather-related events collectively**

These events (primary or secondary) should not be considered in an isolated way, since they are usually connected, and one may result from the others and/or they may happen at the same time. Even though intense winds may happen as an isolated phenomenon, they are usually accompanied by rainfall or even a storm. Floods are caused by increased precipitation, but they may be intensified by drought, which may also be a consequence of extreme high temperature. Wildfires can be the result of lightning, high temperature, drought, or even wind and storms.

Furthermore, the effects on the railway may be the result of one or more weather events. In order to clarify this idea, two examples are offered: dewirements and derailments. The first may be the consequence of extreme high temperature, but also of strong winds or storms; the latter could be caused by buckling due to high temperature, ballast problems due to extreme precipitation, or even toppled trees due to strong winds.

The diagram in figure 2.15 shows a logical proposal for establishing how primary or trigger weather events (which may lead to other weather-related events) have an impact on infrastructural assets, thus causing local or global consequences (in this figure, the effect of heavy rainfall, leading to debris flow).

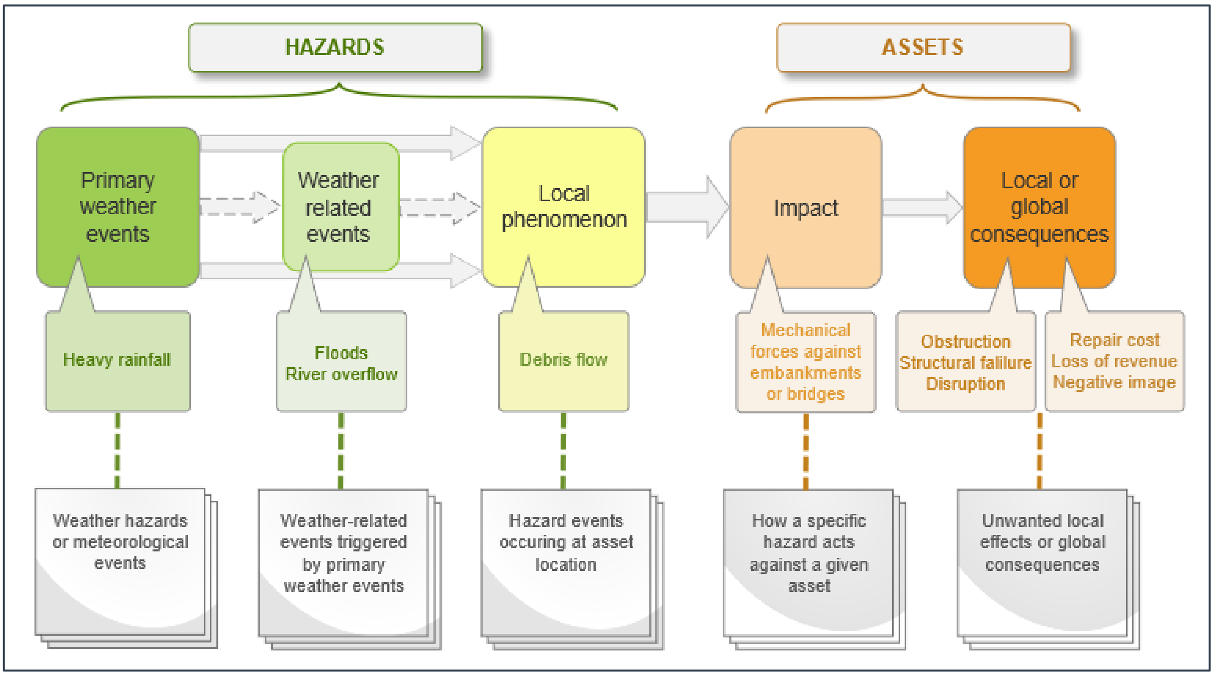

Figure 2.15 – The chain sequence of rainfall (adapted from AllTraIn Consortium, 2015)

This sums up the idea that it is essential to consider climate change and all driven events when assessing rail infrastructure risk. These threats to railway infrastructures may lead to different types of impacts and consequences, such as damage (obstruction and structural impact) and disruption of services (operational impact), which require additional amounts of money to be repaired or replaced, or even to detour the disrupted service. As such, it is of the utmost importance to check infrastructure vulnerability to weather or weather-related events and to retrofit assets and mitigate risks.

### 2.2.3. Assessing railway infrastructural risk

Transport infrastructure is one of the pillars of modern society and a “reliable transport infrastructure is one of the backbones of a prosperous economy” (Koks et al, 2019). Railways are a major contributor for the transport network, and they are extremely important for a sustainable future. The World Bank states that “railways are a climate-smart and efficient way to move people and freight.” By boosting economic growth while reducing the emissions of greenhouse gases, they are a clean and efficient way to move millions of passengers and goods across countries and continents (World Bank, 2020).

As discussed in the previous section, railways do tend to be vulnerable to certain hazards, namely man-made and natural phenomena. Man-made events, such as the ones derived from technological failure or accidents, were not considered  for the purpose of this thesis. On what concerns natural phenomena, only the ones resulting from climate change are subject to a deeper analysis, since the wide spatial distribution of the whole transport infrastructure increases exposure and vulnerability of transport assets to natural hazards (Koks et al, 2019), and, as already mentioned, climate change generates a significant number of natural phenomena. Hence, the importance of railway infrastructure and its vulnerability to these phenomena should not be undermined, and even more so, should be looked after so as to guarantee its functionality.

- **Risk definition and assessment**

As a result, in order to guarantee such functionality, risk assessment is essential. Risk assessment, as mentioned by the United Nations International Strategy for Disaster Reduction (UNISDR), is a "methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend" (UNISDR, 2009).

According to the European Commission (EC, 2010), it includes the overall process of risk identification (finding, recognizing and describing risks), risk analysis (comprehending the nature of risk and determining its level), and risk evaluation (comparing the results of risk analysis with the terms of reference in order to determine whether the risk magnitude is acceptable or tolerable). Therefore, assessing risk is not a straightforward task since it involves a set of procedures to be carried out so as to identify the causes, determine the level and whether it may or may not cause unacceptable disturbance.

Having in mind risk assessment, some other definitions should be established a priori, namely risk, vulnerability and exposure. According to a working paper by the European Commission (EC, 2010) and the ISO 31010, "risks are the combination of consequences of an event or hazard and the associated likelihood of occurrence," whilst "consequences are the negative effects of a disaster expressed in terms of human impacts, economic and environmental impacts, and political/social impacts."

Moreover, in natural hazards the magnitude of the impact has influence on the probability of occurrence, which means there is interdependency. This happens when the impacts are influenced by preparedness or preventive behaviour. Thus, "impacts are often expressed in terms of vulnerability (V), defined as the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard", whereas "exposure (E) is the totality of people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses" (EC, 2010). Thereby, risk is given by:

$$Risk = f(p \cdot E \cdot V) \tag{1}$$

As such, “risk is a function of the probability of occurrence of a hazard, the exposure (total value of all elements at risk), and the vulnerability (specific impact on exposure)” (EC, 2010). This is consistent with what is known as Crichton’s Risk Triangle, shown in figure 2.16 below (Crichton, 1999).

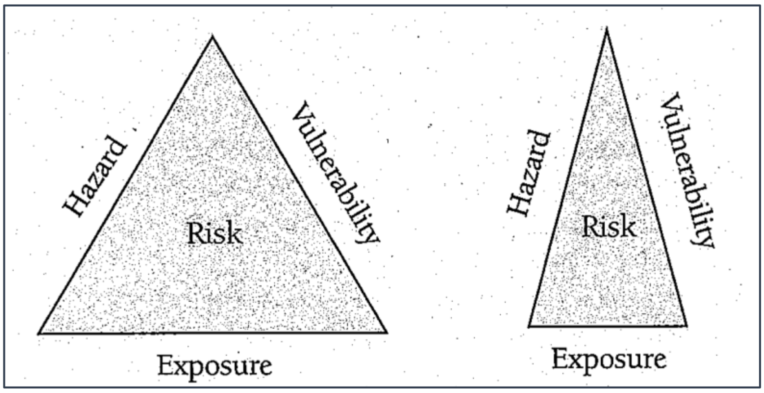

Figure 2.16 – Crichton’s Risk Triangle (Crichton, 1999)

Crichton (1999) developed the Risk Triangle for the insurance area. Nevertheless, the same concepts are bridged and discussed here. Crichton says that risk corresponds to the area of the triangle. Therefore, by applying simple geometry, we can infer that risk depends on the size of each of the three sides of the triangle. Moreover, Crichton explains that “if we can reduce exposure, […] we reduce the area of the triangle, so reducing our risk”. Likewise, by reducing or increasing vulnerability or the probability of occurrence, the area of the triangle subsequently increases or reduces, thus increasing or reducing risk. Even so, it is important to emphasize that such an assessment suggests a perception of risk but not an absolute value.

Crichton also gives some examples to reduce the risk of natural hazards. On the one hand, one could reduce exposure by discouraging the development of housing and industry in areas where hazard is particularly high, such as floodplains, since the assets would be less exposed to flood. On the other hand, one can reduce vulnerability by having appropriate resilient building standards and designs and a suitable contingency plan to help to a rapid recovery, i.e., flood defences (Crichton, 1999).

Misconceptions of these terms are frequent, as mentioned by Cardona (2004), who denotes that “many references are made to the word vulnerability as if it were the same thing as risk.” To enlighten these concepts, the same definitions for Vulnerability and Exposure presented in the AllTraIn Consortium (2015) are adopted herein:

Exposure: the significance of the infrastructure that is affected by the impacts of the phenomenon or hazard.

Vulnerability: the percentage of the Exposure that is expected to be lost derived from the impacts of the phenomenon or hazard.

The adopted definition for vulnerability implies that the same “is considered a fraction of the exposure that is likely to be lost” (AllTraIn Consortium, 2015) denoting that they are connected. Nevertheless, in one of the four major findings from the World Bank, it is stated that “the exposure to hazards will rise in cities, but greater exposure need not increase vulnerability” (World Bank, 2010).

The AllTraIn Consortium (2015) states that these definitions “consider that the risks associated to a particular hazard are inexistent if either the exposure or vulnerability of the elements at risk is null,” which is coherent with the Risk Triangle, as mentioned by Crichton (1999), “if any one component or side of the triangle is zero, then there is no risk.” However, that is rarely the case in railway infrastructures, which means that there is always some risk involved.

Should infrastructure designers and decision-makers have a deeper knowledge of these concepts and their relationship and apply the findings on railway infrastructure, there would be a smaller inherent risk to the existing infrastructure, ultimately preventing consequences such as the ones described in section 2.2.2.

- **Infrastructure assets categorization**

In order to assess the risk of the infrastructure, an asset division has to be carried out, since “functionality of the whole system may depend on the vulnerability in the lower priority parts of the system” (Lindgren et al, 2009). As such, for the purpose of accurately measuring vulnerability in transport networks, an appropriate categorization of attributes and influences in terms of structure, nature and traffic should be considered (Husdal, 2004). The structural factors have to do with the built infrastructure and its design specifications, the natural factors are associated with the environment surrounding where the infrastructure is built and, finally, the traffic factor is related to the traffic on the infrastructure that may influence the non-structural effects (AllTraIn Consortium, 2015).

When analysing railways, and all the problems brought up in section 2.2.2, one could say (for the purpose of the current thesis) that some of the most vulnerable assets affected by climate change derived phenomena are bridges, embankments, cuttings and tunnels.

### a) *Bridges*

Bridges are infrastructures built to overcome the physical obstacles, such as rivers, lakes, valleys, or roads, allowing the passage over them, without closing the way underneath (Yaghoubi, 2018). Their life span exceeds a period of over 100 years (Nemry and Demirel, 2012).

Considering its life span and functionality, the AllTraIn Consortium (2015) suggests assessing the physical vulnerability of bridges considering "the construction type, the major geometric features (span, height and length), the structural condition, the location of pillars, the foundation system, the type of track or pavement and also the existence of any auxiliary structure." These specifications may change bridge exposure and increase or decrease vulnerability.

Bridges are susceptible to strong winds since these might induce large displacements and vibrations, ultimately leading to bridge closure; to river floods that might overflow them or cause bridge scour by erosion of the bridge supports; and to wildfires (possibly ignited from lightning) that can cause structural damage to bridges located above them (AllTraIn Consortium, 2015).

As stated by the USAID (United States Agency for International Development, 2015), "scour is a process involving the erosion of streambed or bank material due to flowing water at or around piers and foundations" and it causes instability of the foundations as stabilizing material moves away from the bridge substructure. Moreover, scour "tends to occur gradually over time and is not normally associated with a single flooding event" (Dikanski et al, 2016).

However, flooding leads to another problem for bridges, namely carrying debris, such as boulders and trees that create dams behind bridges or that directly impact the footings of the bridge, and "if the impact doesn't damage the bridge immediately, the weight of the pilled-up debris combined with the force of flowing water pushing on it can cause the bridge to collapse" (USAID, 2015).

Repeated events of extreme rainfall and flooding increase the vulnerability of bridge structures, leading to a higher risk, which may result in severe consequences for the structure or even its collapse. Bridges naturally result in great exposure since they provide passage and overcome obstacles that other infrastructures could not or would struggle to, meaning they retain a huge importance in everyday life for people and effective transportation. Furthermore, bridges over rivers have higher vulnerability when compared to others in different geographical positions, for river floods affect them and make them more vulnerable. Hence, with a great level of exposure, and even higher level of vulnerability, risk increases substantially.

Additionally, extreme high temperatures are also a problem to consider, due to the thermal "expansion of swing bridges" (Marteaux, 2016). Bridges are frequently affected by the variation in the average daily temperature causing them to extend or shorten, which in the long term reduces their service life, and increases the costs of bridge inspection, maintenance and repair (USAID, 2015).

Finally, wildfires "can cause structural damage to bridges located above them" (AllTraIn Consortium, 2015) leading to its collapse. The occurrence of this phenomenon needs to be considered in bridges located near areas usually affected by fires.

### *b) Embankments*

Embankments are fundamental assets for the railway. According to the Network Rail, these represent "a construction that allows railway lines to pass at an acceptable level and gradient over low lying ground." This asset is susceptible to extreme precipitation since it may cause landslips and earthwork failure due to increased pore pressure that ultimately leads to a greater instability and, therefore, a reduced safety factor (Highways England, 2016). In case of flooding, the consequence is the scour of the embankment material (Network Rail, 2015).

In case of embankments subjected to cycles of drought and extreme precipitation, the action of drying and shrinkage leads to volume changing and surface cracking during dry periods. Quite frequently, these cracks will allow water into the embankment, thus accelerating the re-wetting process, and consequently reducing the number of cycles required to reach failure by progressive means (Hughes et al, 2009).

The AllTraIn Consortium (2015) considers, for the assessment of physical vulnerability of embankments, the "construction type, the major geometric features and drainage systems as structural factors. The type of track or pavement and the existence of any auxiliary structure for railway system are also considered."

Embankments are extremely valuable assets in a railway infrastructure since they provide safety to the track and are constantly exposed to weather events. As a result, it is essential to consider factors which might impact them, leading to complications that may affect railway transportation.

### *c) Cuttings*

Cuttings, much like embankments, are important means of physically forming the trafficked surface of transport infrastructure. They provide passage for traffic and are essentially excavations in existing ground, with side slopes that help to maintain the required vertical alignment (Perry et al, 2003). Similarly to embankments, cuttings are affected by extreme precipitation that could lead to excessive moisture and increased pore pressure causing instability and ultimately their collapse (Eddowes et al, 2003).

The AllTraIn Consortium (2015) considers for the assessment of physical vulnerability of cuttings the "construction type, the major geometric features (lateral slopes and depth), the drainage system and support structure. The structural condition, the type of track or pavement and the existence of any auxiliary structure are also considered."

Therefore, cuttings are assets which allow the passage of rail transportation, by removing soil or rock, thus bringing the track to a lower level. However, due to their features, they are extremely susceptible to weather events, increasing the risk and eventually causing safety issues and long interruptions of the railway track.

*d) Tunnels*

The purpose of a tunnel is, in a way, similar to bridges since both are used to overcome different barriers, only tunnels are excavated below the surface, typically in mountains or urban areas. Tunnel vulnerability is related to extreme rainfall since it affects cuttings and leads to failure of the retaining walls located around the tunnel portals (Eddowes et al, 2003). In case of flooding, water entry at the tunnel portals can lead to obstruction and damage operational equipment (AllTraIn Consortium, 2015). Finally, due to storm surges "tunnels can be damaged by hydro-mechanical pressure on the lining (AllTraIn Consortium, 2015).

To assess the physical vulnerability of tunnels, the AllTraIn Consortium (2015) considers its "construction type (construction system and cross-section), the major geometric features (length, cross-sectional area and cover depth)." Depending on ground conditions, length and diameter, and the depth of a tunnel, they may be extremely vulnerable to weather events (namely floods), as the impacts could result in major disruptions for railway transportation.

### 2.2.4. Measures to mitigate infrastructural hazards

In a world where transportation is responsible for a substantial share of pollution and environmental problems, using a train has obvious advantages over other forms of transport. However, the absence of continued action could diminish this competitive superiority (Network Rail, 2007) if measures are not taken to address the challenges imposed by climate change. Therefore, there is a need to "reduce their [railways] vulnerability by modifying actions and internal processes of the organization, aiming to achieve a future state that is resilient to change and does not compromise the system" (Bustos and Vicuna, 2016).

In order to reduce delays and disruption time, one must reduce risk. This can be done by conducting risk assessment to identify the risks and the potential consequences resulting from natural hazards. This procedure makes it possible to identify likely weaknesses, highlighting where it is most pressing to reduce asset vulnerability. So as to reduce it, adaptation and mitigation strategies need to be considered, which recalls for an investment for the future resilience of the railway.

The measures included could be an adaptation, i.e., “an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities;” or of the mitigation kind – “the lessening or limitation of the adverse impacts of hazards and related disasters” (UNISDR, 2009). Both measures, may they be adaptive or mitigative, refer to the purpose of preventing or mitigating hazards or their impacts, or in other words, they aim to avoid damage to the infrastructure and disruption of the service (AllTraIn Consortium, 2015).

These measures may come in the form of general and specific measures or in the development of alternative and more suitable methodologies for each problem, asset and hazard in question.

- **General measures**

Some measures, such as traffic redundancy, land use planning, maintenance procedures and weather information systems, may be accommodated by all considered assets in a general way.

*a) Traffic redundancy and speed restrictions*

Traffic redundancy is the capability of a certain structure to maintain service, even if providing a lower service level, which minimizes the disruption of the service (AllTraIn Consortium, 2015). This is achieved by using existing services which are already in place and reducing some of the services which can be non-essential.

Regarding speed restrictions, this could be useful in days of extreme high temperatures that can potentially enhance the risk of rail track deformation effect, where speed limit restrictions minimize forces resulting from stresses induced in a constrained rail by temperature above the ‘stress-free’ temperature (the temperature at which the rail is installed) or from mechanical sources (braking, rolling friction and wheel flanging on curves) (Nemry and Demirel, 2012).

According to the U.S. Climate Change Science Program (2008), during the installation, the rail is prestressed to a target neutral temperature. Due to the fact that the track is more stable when the rail is in tension, at temperatures below the neutral temperature, the target neutral temperature is usually 75 percent of the expected maximum temperature of the region. This has significant influence for the track to withstand a reasonable temperature range and the expansive forces originated by the extreme temperatures (Dobney et al, 2008).

Nevertheless, a rail subjected to extreme high temperatures will rarely buckle spontaneously. In fact, it is the disturbance caused by a train that is a common contributor, and so, to overcome this, speed restrictions should be implemented (Dobney et al, 2008). For this reason, the adaptation of the stress-free temperature, in accordance with the new temperature profiles, could be an option to reduce rail buckle vulnerability and, ultimately, the need for speed restrictions (Nemry and Demirel, 2012).

Speed restrictions are also important to consider when track resistance could be compromised due to ballast missing from the track, especially in curves where it provides adequate lateral strength, or when ballast strength and stiffness performance reduce due to the increase in annual precipitation (Eddowes et al, 2003).

Despite the effectiveness of this measure, as far as rail track deformation is concerned, speed restrictions result in longer transit times, higher operating costs, shipment delays, reduced track capacity and they may affect passenger schedules (Nemry and Demirel, 2012), only highlighting relevance for the need to have a proper stress-free temperature of the rail track.

#### b) *Land-use planning*

Land-use planning is associated with the attempt to control the use of land efficiently and ethically, taking into consideration the needs to accommodate both population and economic growth during the planning period. A plan is developed in order to provide necessary public facilities and services, to designate suitable areas for further development and to preserve environmental resources (AllTraIn Consortium, 2015).

Some examples of how land-use may come in handy are the continued mapping of current and future climate vulnerabilities, as well as their consequences. It could become a significant instrument to guide the implementation of adaptation measures. This measure has the potential to transform the strategies for climate change adaptation from event-driven (reactive) to a more proactive and preventive adaptation. Furthermore, systematic mapping of climate threats, vulnerabilities and their consequences will help prioritising efforts to reduce vulnerability (Lindgren et al, 2009). Additionally, it is possible to use flood mapping to better define the areas at risk of flooding incidents (Eddowes et al, 2003) or the use of temperature maps to better reflect the true mean temperatures (Lindgren et al, 2009), helping to define the stress-free temperature per region, as suggested above.

### *c) Maintenance*

On what concerns maintenance procedures, there are activities or repair works that railway owners and operators are compelled to undertake regularly to extend infrastructure functionality during its life span. The objective of this procedure is to maintain the transport network in a proper condition or to perform repairments in case of infrastructure failure (AllTraIn Consortium, 2015).

Maintenance procedures should not be overlooked as these play a key role in ensuring transport infrastructures durability and serviceability. For instance, cold winter conditions and heat stress induce deterioration, which needs to be routinely repaired due to the fact that such deterioration affects the performance of the infrastructure and, consequently, repairing of the track and ballast are of the upmost importance (Nemry and Demirel, 2012).

According to the RSSB (Eddowes et al, 2003), climate change will affect boundary structures of the railway structures, such as fences, noise barriers and walls, since the deterioration rate of stone, brick and timber might induce the need for maintenance. Therefore, it is extremely important for railway management to pay attention to the deterioration of such materials since they could compromise the whole structure.

Furthermore, the Network Rail states that “maintenance of assets, particularly vegetation and drainage, is of key importance to reducing the number and duration of weather-related incidents. Regular, targeted, maintenance is required in high risk areas and those with a history of impacts in order that the impact be minimised” (Network Rail, 2017).

On the one hand, drainage maintenance is vital since “some infrastructure may become inadequate when climate change alters the frequency and severity of extremes, for example, an increase in rainfalls may affect the capacity and maintenance of storm water, drainage, and sewerage infrastructure” (IPCC, 2012), an idea which is reinforced by Lindgren et al (2009): “there are also indications that the present ability to cope with normal climate variation has been reduced […] especially as regards drainage systems.”

On the other hand, maintenance of corridor vegetation is frequently used as buffer-zones to shield residential areas. With variations in the climate, the existing vegetation may become unsuited for the new conditions and perish, also leading to the instability of cuttings and embankments. Such a condition is reinforced by the seasonal changes and the growth rates of leaf fall, that causes low adhesion to the track or ineffective braking (Eddowes et al, 2003). Even further, the most effective way to prevent toppled trees is to remove all those classified as ‘highly vulnerable’ or ‘diseased’ (AllTraIn Consortium, 2015). The improvement of both drainage and vegetation management will make earthworks, such as embankments and cuttings, more resilient to the current climate change variability (Network Rail, 2017).

To sum up, maintenance of transport infrastructure is fundamental to keep integrity and serviceability. Nevertheless, to fully avoid weather-induced deterioration of the infrastructure is not economically feasible (Nemry and Demirel, 2012) for it would represent remarkably high costs, and in a situation of economic crisis such as the one we are facing nowadays, it is usually not considered by decision makers.

### d) *Weather information systems*

Lastly, weather information systems encompass automatic weather stations installed along the transport infrastructures. These stations are able to measure real-time atmospheric, pavement, sub-ground, water level conditions and visibility. Such systems can provide forecasts and warnings for the infrastructure users, owners and operators, creating the opportunity to take the real-time decisions mentioned before (AllTraIn Consortium, 2015).

According to Network Rail (2015), the fact that weather stations provide real-local time information, enables the improvement of operational response and reduces delays through better decisions, for example, when to place speed restrictions in high wind conditions.

A particularly important measure, which may be considered common to all assets and hazards, is analysing historical data. The process of “identifying meteorological, climatic, and other hazards is one that may start with a review of historical experience to indicate the types of incidents that are of primary concern” (Quinn et al, 2017). This process identifies the hazards based on the analysis of data from past delays and disruptions of train operation, technical failures related to signalling, catenary, drainage systems and other structures, which is then correlated with data from the nearest weather station, allowing to define the most critical weather events (Oslakovic, 2013). According to the Network Rail (2015), the analysis of historical data enables each route to understand local weather conditions, to distinguish adverse and extreme weather, in terms of asset performance, and to explore the frequency in which these are experienced. Furthermore, it allows to establish weather thresholds for the assets through the connection between weather events and delays or failures from the different assets.

- **Specific measures**

Measures towards more specific hazards need to be accounted for as well. These measures include increasing drainage capacity, keeping low maintenance vegetation, elevating the assets, analysing historical data, the use of secondary lining and others that will be detailed below, with particular emphasis on those related to hazards more prone to climate change effects.

### a) *Drainage system and slope geometry*

As mentioned before, the present capability to deal with current climate fluctuation, more precisely with extreme rainfall, might not be sufficient. For instance, the drainage system (including gutters, pipes, spillways, and others) should enable water to flow through the railway from points of entry to points of exit in such a way to allow earthworks, track and assets to perform efficiently (Network Rail, 2016). If the existing capacity of the drainage system demonstrates the inability to deal with current extreme precipitation and originates flooding, then its capacity could be improved.

As an example, the Network Rail has added 20% to estimated requirements for drainage capacity. This measure could be added only on flood-prone areas and will help avoiding disruption of the rail caused by flooding events and will contribute to the non-instability of earthworks (Network Rail, 2017). In order to assist drainage systems, implementation of small meandering water courses could buffer high water levels better than the drainage systems (Lindgren et al, 2009).

To deal with landslides, the options are modifying slope geometry, creating a better drainage system, building a retaining structure or applying internal slope reinforcement (Popescu, 2009). The author states that modification of slope geometry is an efficient method for deep seated landslides and consists of removing material from the area driving the landslide (which may be replaced by lightweight fill material), adding more material to the area that helps maintaining stability (it works as a counterweight) and reducing the slope angle. Drainage is essential in slope stabilization due to the important role that pore pressure plays in shear strength and it is a very cost-effective measure. It is possible to apply surface drainage to divert water from slipping into the sliding area, vertical drainage with pumping or self-drainage, or even horizontal drains. The retaining wall approach is more adequate for areas with high loss potential or restricted sites and is also a more expensive solution. Finally, internal slope reinforcement concerns solutions such as rock bolts, soil nailing (it avoids the need to open the cutting contrasting with the retaining wall), anchors or grouting (Popescu, 2009).

### b) *Vegetation*

Some may suggest the use of tree-free zones around the track, and despite being a good idea, as no trees would fall onto the rail track due to extreme winds, nor there would be fuel for wildfires (avoiding a great number of disruptions), it is also true that the lack of corridor vegetation could result in increased vulnerability to heat and temperature variations (Lindgren et al, 2009). The solution for this contradictory argument could be the selection “of low maintenance vegetation to act as buffer zones, whilst not hindering the growth of other vegetation" (Eddowes et al, 2003).

Moreover, the use of vegetation helps slope stability by 'reinforcement' of the soil through tree roots as they extend across potential failure planes and increase shear strength (working as an anchor for weak masses of soil). Vegetation also helps reducing pore water pressure within the soil from direct absorption and evaporation of rainwater making up for the reduction of soil strength caused by wet soil (Macneil et al, 2001).

### *c) Asset elevation*

Another measure that could prevent disruption of the railway or even the deterioration of the ballast, due to flooding, is elevating the assets (Olsen, 2015). Regarding infrastructure located in low coastal regions or floodplains, this measure could prove to be very useful not only to avoid track disruption due to flooding, but to prevent further degradation of strength and stiffness of the ballast. This measure has been applied in the Netherlands, where "track has been elevated" in locations prompt to flooding (Quinn et al, 2017).

### *d) Rip rap*

To prevent bridge scour or even embankment erosion, rip rap is a method to consider. As mentioned before, bridges are affected by scour around the supports caused by river flooding, and embankments are susceptible to erosion caused by extreme precipitation. Rip rap consists of a layer of a variety of rocks and it is placed around the pillars and abutments of a bridge in order to prevent scour, or on embankments to defend them from water erosion (AllTraIn Consortium, 2015). Figure 2.17 demonstrates this technique.

Figure 2.17 – Rip rap technique in a bridge over the Guadiana river, Serpa (Google Maps)

e) *Secondary lining*

A suggestion to deal with water-related hazards in tunnels, such as floods due to an increase in the water table originated in extreme precipitation, is the use a secondary lining. Tunnels typically consists of a primary line (sprayed concrete) and an inner (secondary) lining. Between the primary and secondary linings there is a waterproof membrane (Jiang, 2016). The waterproof membrane is bonded to both the primary and secondary lining, and so water has to find a path through a crack in the primary lining, then a tear in the membrane followed by a crack in the secondary lining, always considering that these failure zones need to occur in the same spot because water cannot migrate along the membrane and primary or secondary linings (ITAtech, 2013).

f) *Painting rails or installing concrete slabs*

Finally, the measures to deal with extreme temperatures are painting the rails in white or the installation of concrete slabs. On the one hand, painting the rails white makes them absorb less heat and therefore expand less (a white painted rail could be 5º C to 10º C cooler) (Network Rail, 2020b). On the other hand, with knowledge of where the rail track is the most prompt to buckling, concrete slabs should be considered, at the expense of sleepers or ballast. This adaptation prevents rail buckling since the rail track is capable of sustaining much higher forces (AllTraIn Consortium, 2015).

- **Applying general and specific measures**

The measures presented above intend to lessen asset vulnerability to infrastructural assets. Obviously, assets suffer from a variety of hazards, so a different set of measures should be applied, considering adaptative or mitigative ones. This way, reminiscing the concept of Crichton's Risk Triangle, vulnerability is reduced, thus causing the area of the triangle to diminish at the same time, which means that the risk of failure of the asset decreases.

Whilst some of these adaptation and mitigation measures can be implemented generally in the whole infrastructure (traffic redundancy, land-use planning, more regular maintenance of assets, the use of weather stations and historical data), some other measures have particular effectiveness if applied to a certain natural hazard, on a specific asset of the infrastructure (for example, increasing capability of the drainage system only makes sense to react to extreme precipitation consequences).

Both general measures and more specific asset-related measures should be implemented in an articulated way, so that they complement each other, increasing asset resiliency and ultimately creating a railway which is fit for the future.

## 2.3. The need for a new approach

The transport sector, particularly the railway network, embodies a major role in economic and social functions. This means that the social and economic sectors rely on the efficiency and effectiveness of the infrastructure as a whole. Since the railway is comprised of several assets, such as embankments, cuttings, tunnels, bridges, and others, it is vital to prevent failure of any of the described assets, for the resilience of the railway is as strong as its most vulnerable asset.

The current state of climate change demands for a different approach from the one taken by some project managers and decision makers up to this point. Most of the built infrastructure is designed to last for a long-life span. However, the rate at which climate has been fluctuating, increasing the frequency of phenomena and the intensity of the very same, shows that the future design cannot be based on past knowledge alone. This means that future designing, as a long-term commitment, should consider data from past weather events and account for predicted changes in terms of climate variability.

As such, climate change has an impact on the aforementioned assets, and when an asset is compromised, the whole infrastructure is disrupted, causing economic losses, transport disruptions and delays. To a certain extent, all the assets comprising the railway infrastructure demonstrate a degree of exposure and vulnerability to external factors [natural hazards] and the relationship between these three concepts [exposure, vulnerability and occurrence of hazard] creates more or less risk, which is something that should be thoroughly considered.

The methodologies to address this issue come in the form of varied approaches, each with its down and upsides. One could start by enhancing resilience of infrastructures, after considering risk and defining what the acceptable level of performance is (given the available information), making sure the capacities to withstand and recover from shocks are in place (OECD, 2014).

Another way of dealing with the current climate change problem could be something known as ‘low-regrets strategies and robust design.’ This method is useful when the uncertainty of the problem cannot be quantified and, therefore, a method that accounts for doubt may be employed, in this case, robust decision-making. This approach identifies alternatives that are efficient across a large range of possible future conditions (Olsen, 2015). Ultimately, the infrastructure would do well both under current climate and future uncertain climate conditions. However, such alternative demands a high cost and is rarely adopted to address the problem.

A whole different way of dealing with uncertain future climate fluctuation is the Observational Method (OM), well known to Civil Engineers, especially to those in the geotechnical field, since it is widely used in the excavation tunnels. In this method, the conditions considered do not represent the worst possible scenario, but instead the most probable situation. The Observational Method (OM) consists of "a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate" (Olsen, 2015). To use the OM, the engineer must preselect a course of action for each and every unfavourable circumstance that might by revealed during the period of observation and constant monitoring. Applying this method means that it is essential to define different courses of action for different scenarios.

One more different approach to tackle the problem is through flexible, adaptive engineering. Since engineers cannot anticipate every possible scenario for the future infrastructure, the design itself should be flexible. This means "the ability to change size and/or functions in the future" (Olsen, 2015). This way of addressing the problem includes an adaptive infrastructure, with the appropriate monitoring system in order to analyse the assets' performance over time, and the flexibility "so projects can later easily be adjusted to a range of future scenarios" (ILF, 2018), as demonstrated in figure 2.18. The figure shows that this approach allows the preparation for multiple scenarios, and when compared to the non-adaptable solution, the advantages are the flexibility and adaptability along the life span of the infrastructure, to either reach the same investment of the fixed solution or to stop before reaching that same point.

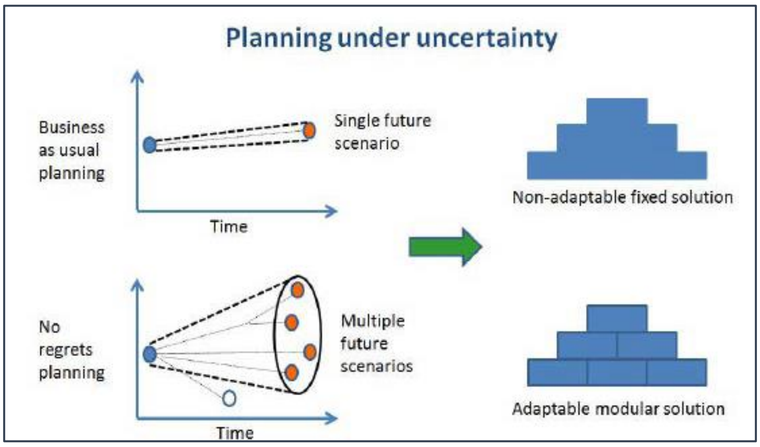

Figure 2.18 – Non-adaptable vs adaptable modular solutions (ILF, 2018)

As it is possible to conclude, there are several methods to address the issue. Their use depends on specific characteristics, which need to be analysed under different situations. Nonetheless, considering the weather has a certain degree of unpredictability, planning for different scenarios when designing an infrastructure could result in far more flexible and cost-effective solutions when faced with severe weather events. This type of methodology is still in an early stage, in a way that there is little work that explicitly addresses field situations.

# 3. CASE STUDY

The case study presented in this chapter includes an analysis of a section of the North Line (Alfarelos - Pampilhosa), considering the impact of climate change on the railway infrastructure (by giving examples of registered events or by identifying situations where asset vulnerability appears to be higher, according to information given previously), suggesting a risk assessment methodology, and proposing some measures to mitigate the effects driven from climate events.

## 3.1. Defining the case study

### 3.1.1. Geographical location

Portugal has around 90.000 km$^2$ and is located on the southwest of Europe. According to the latest census (2019), it has slightly over 10.000.000 inhabitants (INE, 2020) and a higher demographic density in the western part of the country, namely between the capital city, Lisbon, and its second city, Oporto (PORDATA, 2019).

Its coastline has an extension of more than 1.400 km, bathed by the Atlantic Ocean, meaning that Portugal is one of the main entrances and exits of goods for Europe, which supports the relevance of a resilient and sustainable transport network for people and goods (INE, 2007).

The weather is typically Mediterranean – temperate climate, with dry summers and rainy winters, with a strong Atlantic influence and prone to winter storms, with episodes of strong winds (INE, 2007). Temperatures usually range from 4º C in winter to around 30º C in summer. Despite some episodes of severe rainfall, drought has become more intense, especially during the summer months.

Coimbra is the biggest city in the centre of the country, half-way between Lisbon and Oporto. It is mainly a university city, with a considerable number of students moving to the city during the academic year. The river Mondego flows through the city. It is the longest national river, and it drains into the Atlantic Ocean, in Figueira da Foz.

### 3.1.2. The rail network in Portugal

The first train journey in Portugal happened in 1856, between Lisbon and Carregado (Fernandes, 2016). The same author mentions that it “was initially built in standard gauge, which only later was substituted by Iberian gauge due to developments registered in Spain.”

IP - Infraestruturas de Portugal (Portuguese Infrastructures) is a state company, formed in 2015 after the fusion between the company that controlled the railway network (REFER – Rede Ferroviária Nacional) and the one controlling the road network (EP – Estradas de Portugal). This merger eased the implementation of a joint strategy for all transportation infrastructures in the country, creating an entity that is responsible for managing and controlling the network, and building and maintaining infrastructures (IP, 2021).

In 2019, "the national railway network was 3620.7 km in length," without a significant difference from the previous year (INE, 2020). According to the same source, it had "377 traction vehicles, 2684 wagons and 1008 vehicles for the transport of passengers." On what concerns infrastructures, in 2019, there were 1836 bridges, 79 tunnels, 549 stations and 834 railroad crossings.

Portugal has active railway lines crossing the country north to south, and west to east (see map in Appendix A). The rail lines connect most major cities, with different types of trains: regional, interregional and fast trains, and international trains. Freight activity is also extremely important, even though there has been a reduction in activity in the previous years.

This year, there was a record reduction in both passenger and freight transportation, due to the Covid-19 pandemic. As such, figures and facts regarding 2020 will not be considered in this text. According to statistics mentioned in INE (2020), the number of passengers in railway mode showed an increase of 18,9% since 2018, with over 175 million passengers a year, or 5 billion passengers/km. Comparing with other European countries, this variation is one of the highest, only surpassed by Greece. Out of the 175 million passengers a year, 158.3 million occurred at an urban level, 16.8 million were long-haul passengers, and 230 thousand were international passengers (see figure 3.1 below).

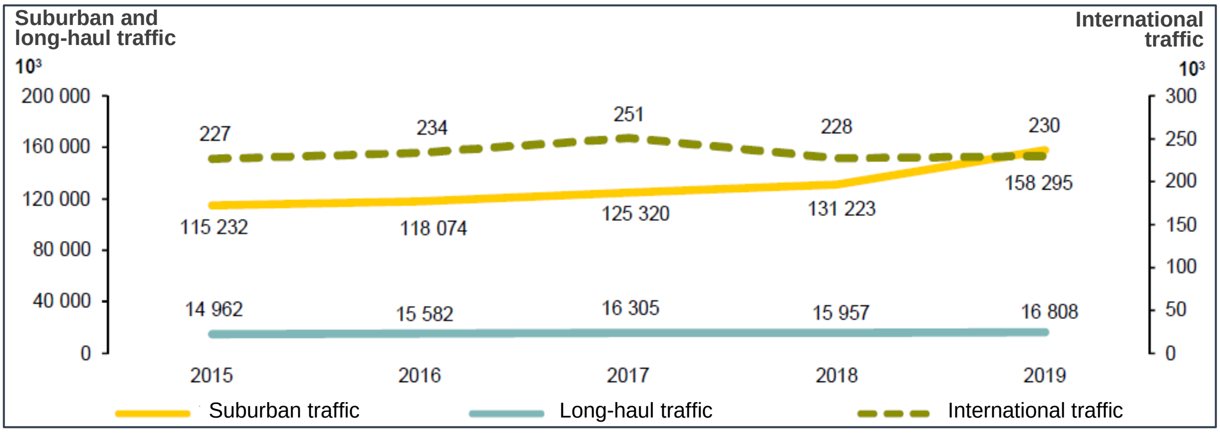

Figure 3.1 – Railway passengers according to type of traffic: 2015-2019 (INE, 2020)

"In 2019, goods moved by railway transport (9.7 million tonnes) registered a variation of -8.4% (-0.5% in 2018). In terms of transport volume, there was a decrease of 10.4% (+0.5% in 2018), which mirrored the 2.2% decrease in the average distance travelled by each tonne (255.6 km)" (INE, 2020). The graph in figure 3.2 shows the evolution of freight activity from 2015 to 2019. The type of goods more frequently carried was metal, corresponding to 13,1% of the total.

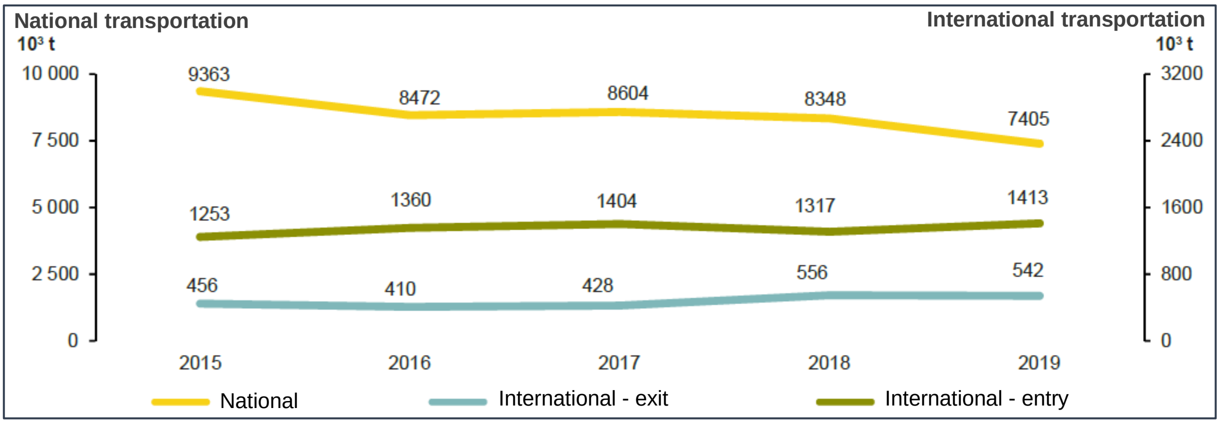

Figure 3.2 – Freight activity: 2015-2019 (INE, 2020)

Portuguese railway lines run on Iberian gauge – it refers to the distance between the inside edges of the rails forming the track. Although there is an international track gauge size (1435 mm), the Iberian Peninsula has its own gauge size, wider than the regular standard (1668 mm) – see figure 3.3 below. This is justified with the complex orography, which demands greater stability, achieved by the increased distance between rails (Bilogistik, 2016).

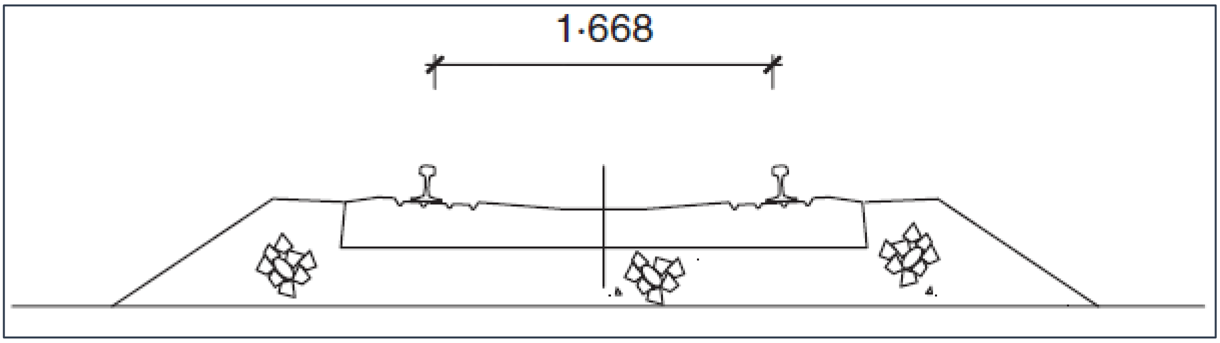

Figure 3.3 – Iberian gauge – dimension in mm (adapted from Gonzalez et al, 2008)

Currently, it is unanimously accepted that the Portuguese railway requires a process of modernisation which will benefit it, making it more suitable to meet the current requirements and preparing it for the future. The foremost pressing constraints are the level of deterioration of the infrastructure, which forces trains to reduce their speed; the technical obsoleteness and lack of uniformity regarding signalling systems and electrical supply; the existence of parts of the railway which are still not electrified; restrictions to the maximum length and weight of the trains; faulty connections with main ports and logistics centres in Europe; and cargo restrictions in parts of the network with the highest demand (Fernandes, 2016).

In order to address these constraints, strategic national plan Ferrovia 2020 (based on PETI3+, Infrastructure and Transportation Strategic Plan – 2014-2020) was implemented. The plan consisted of the requalification of the national railway network, contemplating a global investment of 2000 million euros. Its main objectives were the increase of railway capacity, the improvement of quality and safety services, the replacement of outdated equipment and the reduction of operational costs in order to contribute to financial sustainability (IP, 2021).

The country is connected with Europe through the Atlantic Corridor, which runs through Portugal, Spain, France and Germany. This project connects 6200 km of railway, 15 ports and 44 terminals in Europe. As it is possible to see in figure 3.4, it is “a main artery of the European railway network that combines 11 different corridors to connect all stakeholders, transport markets and services through seamless international rail freight transportation, in a collective push to qualify and increase performance on track” (Atlantic Corridor, 2020).

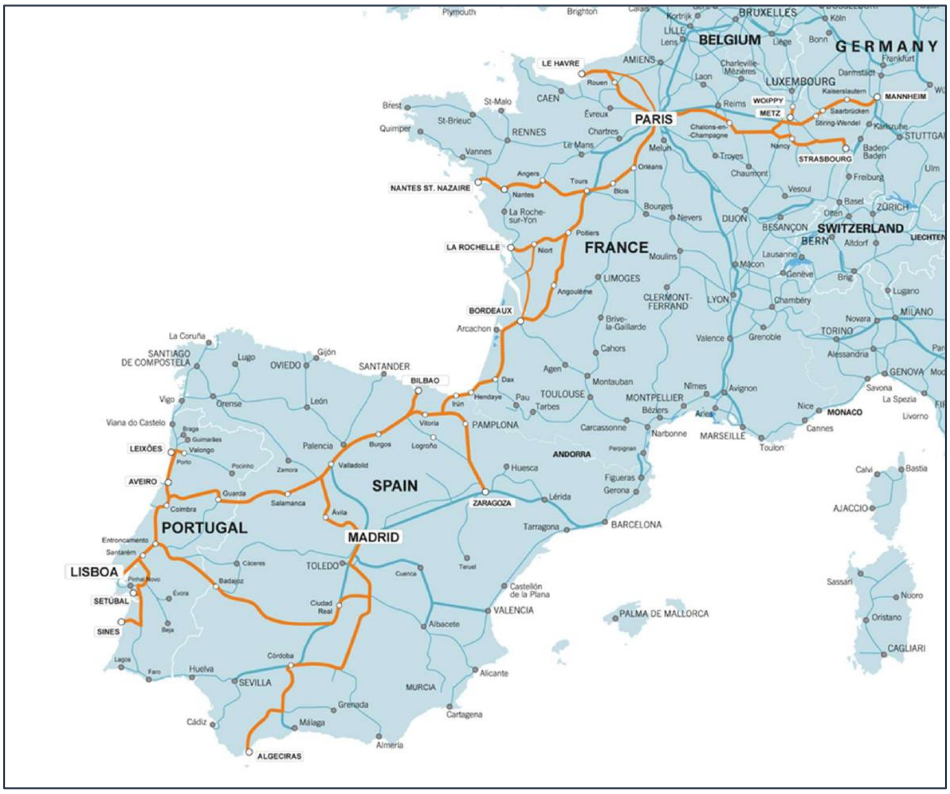

Figure 3.4 – Map of the Atlantic Corridor Railways (Atlantic Corridor, 2020)

### 3.1.3. The North Line

From all the rail lines in Portugal, the most important one is probably the North Line, connecting Lisbon and Oporto, as shown in figure 3.5. Besides linking the two most important cities, it also runs through Aveiro, Coimbra, Santarém and Vila Franca de Xira, it is linked with other rail lines, and it has two relevant connections with rail lines that transport passengers and products to Spain, in Pampilhosa and Entroncamento, to the north and the south of Coimbra, respectively.

This line is responsible for 70% of national railway traffic, having more than 600 passenger trains per day in all of its multiple sections, allowing for accessibility to logistics platforms, ports and industrial facilities, with approximately 120 freight trains per day (IP, 2021).

Figure 3.5 – The North Line (adapted from IP, 2021)

The line is 336,1 km long, electrified in all its length, and most of it is a double track (305,6 km – 91%), with the remaining part having multiple lines. Some parts of the line allow for maximum speeds from 120 km/h to 160 km/h, while others allow for speeds from 160 km/h to 220 km/h – such restrictions depend upon track geometry deformations or other conditioning in the track. In this line, freight trains are usually around 340 m long, even though in some parts of the line they can reach over 600 m long. It is comprised of 28 stations and 47 station halts, it has electronic signalling controlled from a central unit in 75% of the length and it has an automatic speed control system, operational in the whole length of the line (Fernandes, 2018).

The North line has been going through renovations and improvement work within the scope of the strategic plan Ferrovia 2020, which is still not concluded. As such, 130 km of railway line will be affected, with full renovation of the track, slab and ballast, updating signalling and telecommunication infrastructure and improving the conditions of railway stations and halts. The goals are to reduce the travel duration of long-haul trip, to increase freight train capacity, to increase the overall quality and reliability of the railway, and to reinforce safety and comfort (Fernandes, 2018).

### 3.1.4. Alfarelos – Pampilhosa section of the North Line

The section of the North Line chosen for the case study corresponds to the railway between the train station in Alfarelos and the one in Pampilhosa, as shown in figure 3.6. It has a length of 36 km and a double track for the whole course (IP, 2021). During this course, there are 3 main train stations (Alfarelos, Coimbra-B and Pampilhosa), and in between these, there are 11 other station halts (Formoselha, Ameal, Vila Pouca do Campo, Pereira, Taveiro, Casais, Espadaneira, Bencanta, Adémia, Vilela and Souselas). There is a freight terminal in Alfarelos, able to operate 750m-long trains. The railway does not intersect other railways, except for the access to factories in Souselas. In Alfarelos, the railway continues south or bisects towards Figueira da Foz, connecting to the harbour. In Pampilhosa, the railway continues north or bisects towards the east, following the Beira Alta Line all the way to Vilar Formoso and Spain.

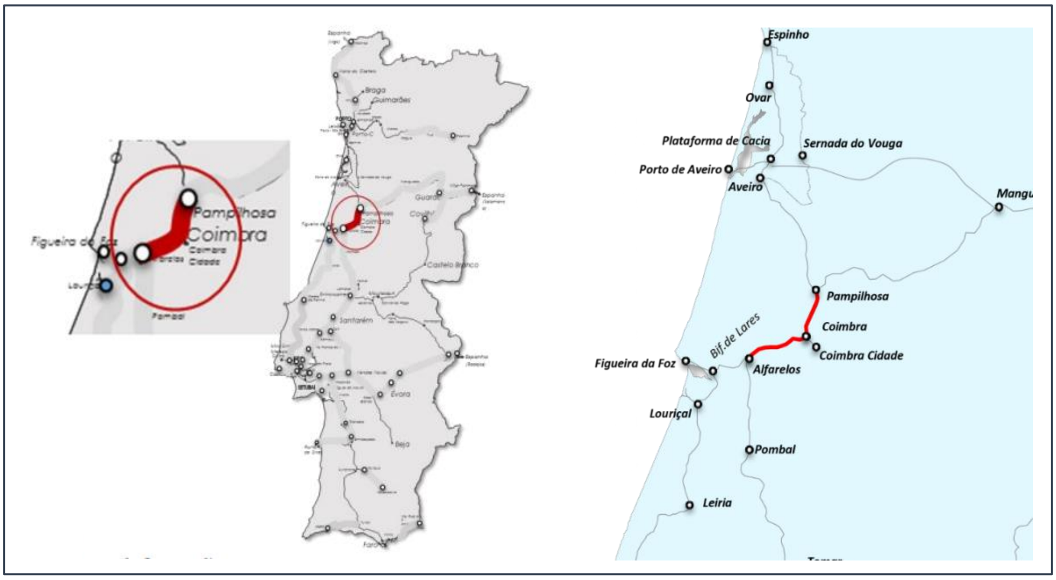

Figure 3.6 – The railway between Alfarelos and Pampilhosa (COMPETE 2020, 2018)

Most of the railway infrastructure between Alfarelos and Coimbra is built in a morphologically uniform terrain, where altitude ranges approximately from 6 m to 26 m above the sea level. The section between Coimbra and Pampilhosa is not as homogeneous, displaying a combination of plain terrain while exposing some more accentuated elevations (Topographic Map, 2020).

When the terrain is unsuitable for the railway, earthworks are put in place, as well as bridges, as it can be seen in figures 3.7, 3.8 and 3.9 below, located near the city of Coimbra.

Figure 3.7 – Cutting to the north of Coimbra (Google Maps)

Figure 3.8 – Embankment to the west of Coimbra

Figure 3.9 – Bridge over the Mondego River

The north side of the railway between Coimbra and Alfarelos is located in the vicinity of the Mondego river, as well as some agricultural fields. On the opposite side, there are some villages and roads that either follow the railway direction or cross it (constituting a vulnerable area for accidents). The railway corridor is sometimes tucked away with undifferentiated vegetation (either trees, reeds or grass), and occasionally it is next to buildings (see Appendix C).

## 3.2. Assessing climate change-related vulnerability in the railway section

Before trying to assess infrastructural vulnerability to natural hazards, particularly to those more closely related to climate changes, and developing risk assessment methodologies and strategies to reduce it, it is pertinent to have a deeper understanding of the weather in the region.

### 3.2.1. Meteorology in the region

Portugal has a Mediterranean type of climate, with hot and dry summers, and cool and wet winters. In addition, the country is no stranger to climate change effects and derived events (fires, hurricanes, floods, long periods of drought, rising of sea level, and so on).

According to data provided by the Portuguese Institute of the Sea and the Atmosphere (IPMA, 2021), air temperature in mainland Portugal shows a tendency towards an increase in the mean annual air temperature (in fact, the year of 2020 was one of the 4 hottest years ever recorded in Portugal). Both minimum average temperature and maximum average temperature display the same rising tendency, registered at a global scale over the past decades. This can be seen in figure 3.10, which shows mean minimum and maximum air temperatures since 1930.

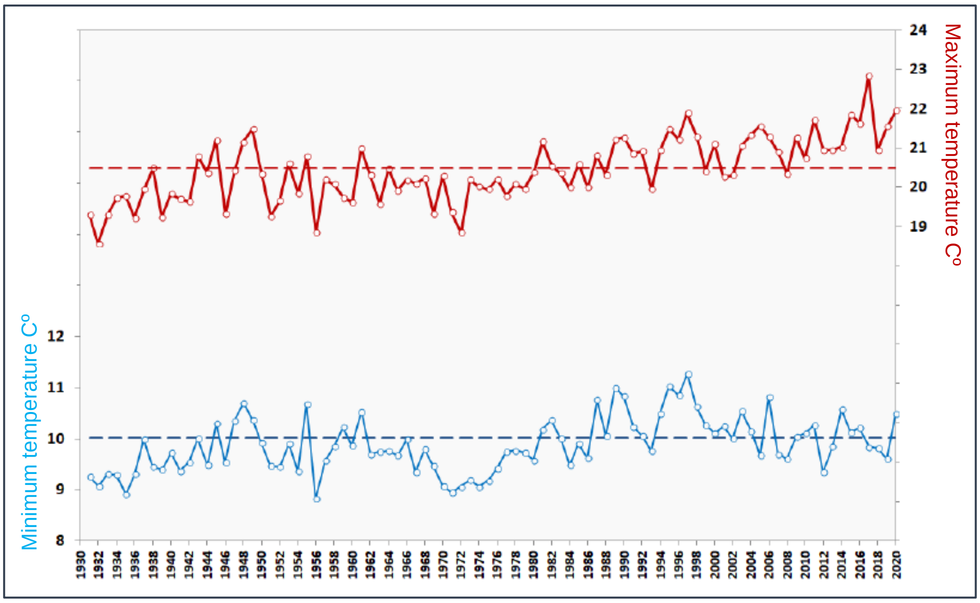

Figure 3.10 – Mean minimum (blue) and maximum (red) air temperatures (IPMA, 2021)
(Portugal – 1930 to 2020)

Moreover, during 2020, the month of February recorded the highest air temperature since 1931; the month of May registered one of the longest heat waves and with the largest territorial extension for that same month (in a total of 7 heat waves during the year); and, finally, the warmest month of July since 1931, with the highest temperature since 1931. The 2011-20 decade was the warmest in Portugal, since 1931, and the second one with less precipitation, after 2001-2010 (IPMA, 2021).

At a regional scale, namely in the area of the case study (Coimbra), a very similar behaviour relatively to near surface air temperature can be seen in figure 3.11. According to data analysed in the SIAM Project (Miranda et al, 2002), from 1910 to 1940, there was a rise in the maximum and minimum average temperatures, estimated in 0.83º C per decade for the maximum, and 0.018º C per decade for the minimum. From 1950 to 1970, there was a decrease of 0.47º C and 0.18º C per decade, respectively. From 1980 to the end of the century, another increase of maximum average temperature and minimum average temperature was registered, evaluated in 0.41º C per decade and 0.78º C per decade respectively (Miranda et al, 2002).

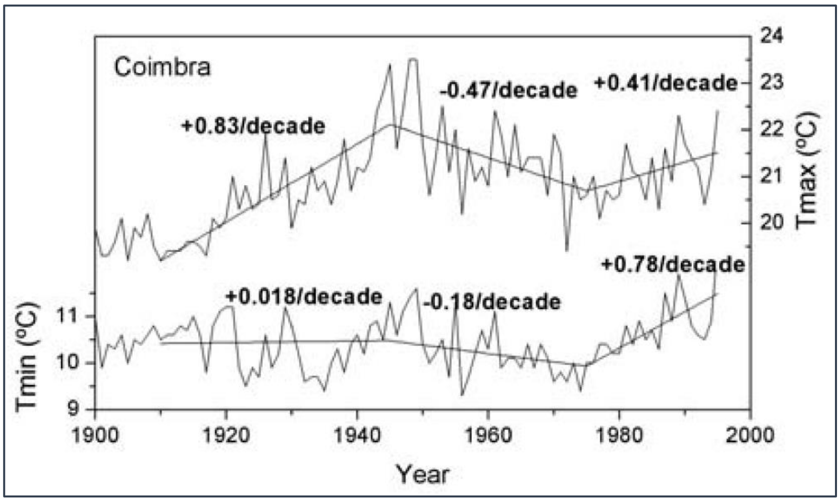

Figure 3.11 – Annual mean min. and max. temperatures: Coimbra (Miranda et al, 2002)

A recent study carried out in Portugal (Carvalho et al, 2020) states that average temperatures in the Iberian Peninsula will increase 2º C or 3º C (or even 4º C or 5º C in some regions) until 2100. The previous study predicts an increase in the number of summer days with a maximum temperature over 40º C. This could lead to droughts, desertification, fires and other environmental and health problems.

This reinforces what is mentioned by the EEA (2020): “in southern Europe, severe droughts are projected to become more frequent,” according to predictions until 2070, considering a medium or a high emissions scenario. In the Iberian Peninsula, droughts will be even more severe.

IPMA (2021) mentions that 2020 was a hot and dry year, as shown in figure 3.12. In fact, most recent years have been hotter and drier than average, which leads to a reduction in soil moisture and contributes to the phenomenon of wildfires which has ravaged the country.

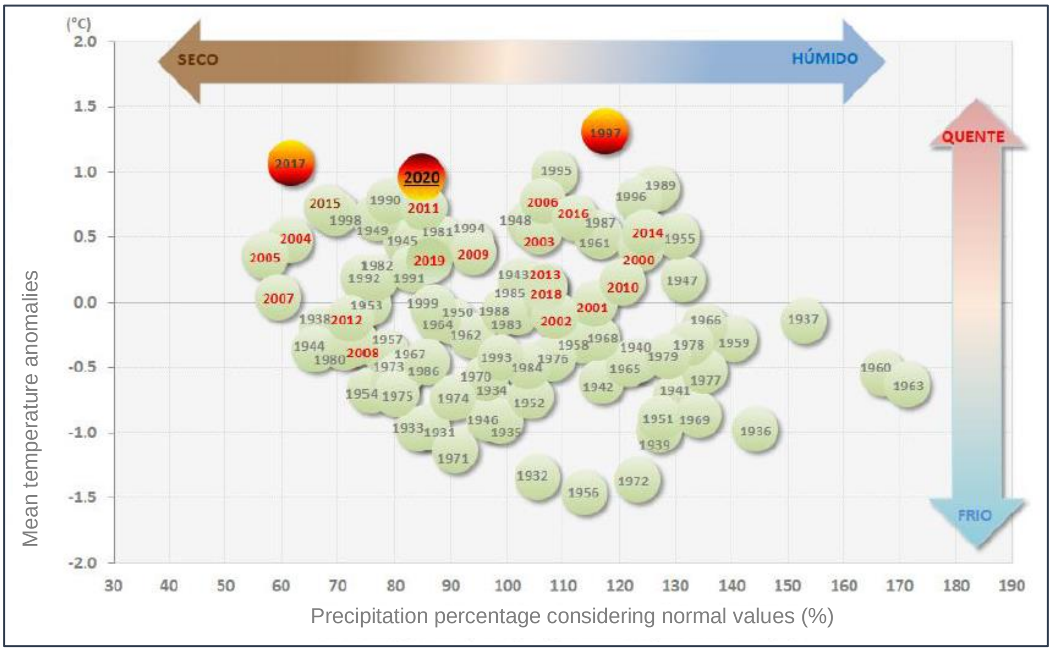

Figure 3.12 – Mean temperature and precipitation anomalies (IPMA, 2021)

Miranda et al (2002) gathered data obtained from different GCM (General Circulation Models) from the IPCC, showing anomalies in temperature in the Iberian Peninsula and forecasting an upward trend of temperature anomalies in the following decades (even when considering different emission scenarios), as seen in figure 3.13 (detailed information in Appendix B).

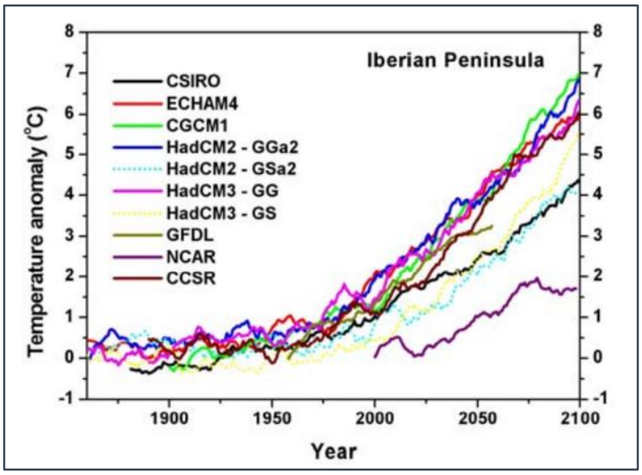

Figure 3.13 – Mean temperature anomalies in the Iberian Peninsula (Miranda et al, 2002)

Nunes et al (2019) corroborate this trend and point out the dangers of wildfires boosted by climate change. Even if fires are not necessarily triggered by climate events, hot and dry weather may intensify them.

Although most climate models predict a reduction in mean precipitation and the duration of the rainy season, there will be events of heavy precipitation and strong winds – “there is also a growing concern that increases in extreme weather events like floods, droughts, severe heat and cold spells may come as a result of global warming” (Miranda et al, 2002). This study predicts an increase in precipitation during the winter months (which may cause floods), and a reduction in the summer months (see figure 3.14).

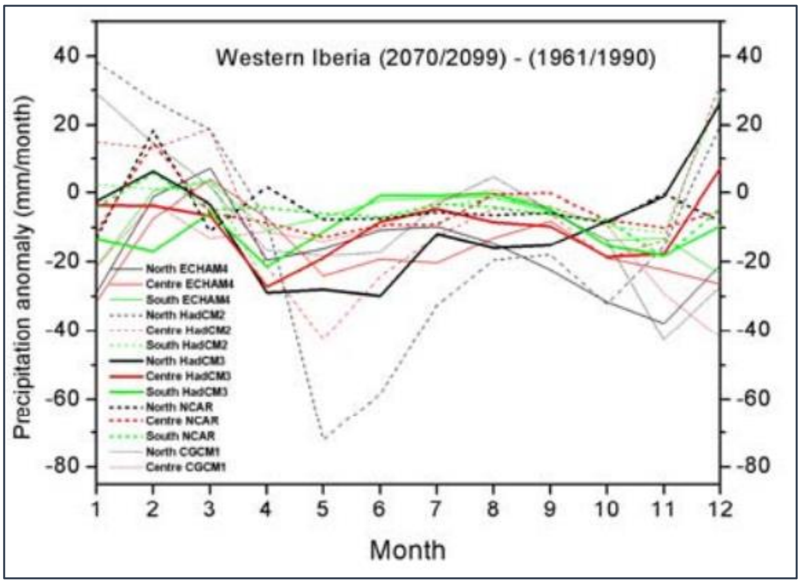

Figure 3.14 – Monthly precipitation anomalies in Western Iberia (Miranda et al, 2002)

Building climate models entails a lot of uncertainty, since the data available have numerous variables and the process depends on emissions scenarios. Nevertheless, the previous decades show a tendency which could hardly be disregarded.

### 3.2.2. Infrastructure vulnerability to natural hazards in a climate-change scenario

As mentioned before, railway infrastructures can be extremely vulnerable to weather events. The centre of Portugal, namely the area surrounding the city of Coimbra, has suffered with some meteorological occurrences, such as storms, rainfall, strong winds and even wildfires.

The railway section studied here crosses river Mondego in the city of Coimbra and follows it southwest, towards Alfarelos. This section is located close to the river, ranging from a little over 1 km of distance to 100 m or even 50 m from the river (near Alfarelos), so there is higher risk (the map in figure 3.15 shows the distance from the railway to the river).

Figure 3.15 – Distances from the railway to the river at different locations
*(distance measured using Google Maps)*

There are several reports of recent weather events, showing the problems caused by flooding. In December 2016, excessive rainfall led to the partial flooding of the North Line, near the train station in Alfarelos. Figure 3.16 shows the train station flooded during this event. Consequently, it forced speed restrictions in the trains, in some sections of the North Line, and even to the disruption of the train service between Figueira da Foz and Alfarelos, and between Pombal and Coimbra. In order to overcome the disruption to Figueira da Foz, arrangements were made to provide buses that transported people from and to Coimbra and Figueira da Foz (TVI, 2016).

Figure 3.16 – Alfarelos train station flooded after rainfall, 2016 (TVI 24, 2016)

Two years later, in 2018, tropical storm Leslie took place, causing a path of destruction on its way, affecting especially the district of Coimbra. The aftermath of the storm in the railway, particularly in the North Line, caused the interruption of train traffic between Pombal and Pampilhosa. Winds reaching 176 km/h caused the interruption of train activity as trees or other objects carried out by the strong winds occupied and/or damaged the track (SIC, 2018), as shown in figure 3.17 below.

Figure 3.17 – Destruction caused by tropical storm Leslie, 2018 (CM Jornal, 2018a)

Furthermore, train circulation between Alfarelos and Figueira da Foz was disrupted since the strong winds damaged power supply and both stations and stations halts (Correio da Manhã (2018b).

Very recently, in 2019, two storms hit Portugal in December – first storm Elsa, followed by storm Fabien. The consequence was, once again, the disruption of train circulation in the North Line since the track was underwater between the section that connects Alfarelos and Ameal (JN, 2019), as it is possible to see in figures 3.18 and 3.19.

Figure 3.18 – Alfarelos train station flooded, 2019 (Cunha, 2020)

Figure 3.19 – North Line flooded between Alfarelos and Ameal, 2019 (Liberato, 2020)

Moreover, according to IP (2020b), the Alfarelos Branch, which connects Alfarelos station to Bifurcação de Lares halt, was also damaged. This connection is an important and strategic connection between the North Line and the West Line, mainly for goods transportation into two important paper factories settled in Figueira da Foz. A further and detailed explanation provided by IP (2020b) stated that due to Elsa’s impact and the rise of the water level of the Mondego and the Arunca rivers, one of the slopes of Marujal Bridge (over the Arunca river) was damaged, causing the suspension of rail circulation in the branch connecting to Alfarelos.

This happened because the rise of the water level led to the collapse of one of the earthworks meant to hold the river (levee), and ultimately collapsed the bridge slope, along with the rails and overhead line equipment. The disruption of that branch lasted for 10 days, and when train circulation was finally allowed, there were still speed restrictions for at least 18 more days (IP, 2020b). Some of the damage caused may be observed in figure 3.20.

Figure 3.20 – Damaged slope located between Ameal and Alfarelos (IP, 2020b)

Some other reported events mention the flooding of the railway track near Pampilhosa, leading to service disruption. Some trees fell on the overhead line equipment on the track, in Anadia, also causing circulation disruption (RR, 2019).

In April 2017, a derailment took place in Adémia (to the north of Coimbra), in the North Line, which encompassed and damaged 250 m of the double track (Trainspotter, 2019). According to the same source, the analysis from the Office for the Prevention and Investigation of Civil Aviation and Rail Accidents (GPIAAF) acknowledged the existence of 9 m of track, starting immediately before the derailment point of origin, with irregularities in the longitudinal alignment of the rails. Furthermore, two sections with 3 m where detected exceeding maximum admissible values of vertical misalignment. This misalignment was caused by the surface of clay particles that clogged the voids between ballast rocks. These clay particles are sized below 0.002 mm and have a high capacity of retaining water, as well as an adjustable physical behaviour, evidencing great stiffness when dry, and great plasticity and elasticity when wet.

According to GPIAFF (Trainspotter, 2019), clay particles were forced to surface due to pressure imposed by the train, since the soil was wet from intense rain two weeks prior to the derailment, filling the spaces between the rock ballast, reducing the draining capacity of the railway, as well as the support capacity provided by the ballast. With a reduced support capacity, the geometrical deformation of the track took place and led to an anomaly of -155 mm on a vertical alignment, when the highest acceptable value was of -103.5 mm.

Eventually, this anomaly triggered the lateral instability of the train and the cargo of the train was mostly on top of the left wheels, causing the derailment. This event had an estimated total cost of 2 million euros and the disruption for 54 hours of one of the tracks of the North Line, between Coimbra and Souselas, and 100 hours where the derailment happened (Trainspotter, 2019). Figure 3.21 shows the impact of the derailment.

Figure 3.21 – Train derailment in Adémia, 2017 (Trainspotter, 2019)

A closer look at what happened in Portugal, in 2017, is proof of the problem of droughts and consequent wildfires: in June, 64 people died as a consequence of a wildfire and, in October, 45 people died as a result of another fire. Some of the trains available had to be suspended (affecting more than 750 passengers), including an international train and a fast train which had to stop in Coimbra, in order to avoid the risk presented by the fires (TVI 24, 2017). This was also the outcome of hurricane Ophelia, the biggest one on record on the eastern Atlantic coast.

That year, the burnt area added up to approximately 225.000 hectares. In that same year, the country experienced one of the most demanding droughts in history, with 6% of the territory going through severe drought, and 94% on extreme drought, according to the Portuguese Institute of the Sea and the Atmosphere (IPMA, 2017).

A more detailed examination of the North Line section selected for the case study unveiled several situations that increase railway vulnerability (creating greater risk), especially when climate change is part of the equation. In order to establish a list of assets susceptible to climate events, the section was analyzed and the spots where risk is higher are highlighted below (the photographs in this section were taken by the author or retrieved from Google Maps).

As stated in section 2.2.3., bridges are susceptible to extreme winds since these induce large displacements, but in this particular situation it is also important to consider toppled trees near the bridge or the possible occurrence of wildfires, since the trees are near the track. In addition, one of the most problematic issues with bridges has to do with flooding events and subsequent bridge scour caused by erosion of the bridge supports and carried debris, such as boulders and trees. Figure 3.22 shows Mondego Novo bridge, in Coimbra (June 2020), when large dimension debris was pilled up against the piers, and the presence of several trees near the bridge. The debris was dragged by the floods (December 2019), as reported in previous sections, and could lead to bridge scour which could be prevented by the use of the rip rap technique.

Figure 3.22 – Mondego Novo bridge, Coimbra – piers sustaining debris (Google Maps)

Situations such as slopes facing instability (some more evident than others), which may result in landslides and occupy the track, may become the origin of delays or derailments, and may lead to human life consequences, are frequently found. The evidence of slope instability in cuttings was found multiple times and, in case of extreme precipitation, the risk of landslide is real. Approximately 1 km south of the train station in Pampilhosa, on the right side of the track, there is evidence of slope instability, since some trees are not vertical, clearly indicating that the landslide has already started. Moreover, some piles of soil indicate the same. It is possible to see this in figures 3.23 and 3.24 (and in additional photographs in Appendix C).

Figure 3.23 – Evidence of slope instability with toppled trees (Google Maps)

Figure 3.24 – Evidence of slope instability – piles of soil have slid (Google Maps)

Approximately 2.4 km south of Pampilhosa, a small retaining wall with a large crack can be found, indicating that it could not sustain the lateral forces applied by the cutting (see figure 3.25). If the crack was not proof enough of susceptibility to landslide, comparing the verticality of the trees with the catenary poles demonstrate that, in fact, in case of extreme precipitation, the landslide constitutes a great risk, boosted by the significant height of the cutting. One more concern, in this case, is the presence of tall trees that may fall onto the OLE or onto the track if the landslide does happen, or if extreme wind events affect that area (see figure 3.26).

Figure 3.25 – Cracked retaining wall (Google Maps)

Figure 3.26 – Toppled trees compared with vertical catenary poles (Google Maps)

As far as embankments are concerned, not much evidence of instability was found. An example of a place that appears to be at risk of landslide (figure 3.27) is located 3 km from Pampilhosa station, where some vegetation and trees seem to have slightly rotated and, therefore, may indicate higher vulnerability to extreme precipitation events.

Figure 3.27 – Vegetation on the left may indicate embankment instability (Google Maps)

Regarding wildfires, there are some areas which seem to be more vulnerable. These are neglected areas of dense vegetation and tall trees that not only make it more susceptible to wildfires, due to all the combustible material, but also hinder it to put out the fire. These areas were found for 1 km between Pampilhosa and Souselas (figure 3.28), where the dense vegetation increases predisposition to wildfires (additional photographs in Appendix C).

Figure 3.28 – Railway surrounded by dense forest (Google Maps)

Trees may also fall onto the track causing disruption or damaging the OLE. A clear example of where there is risk for the railway is located between Vilela and Adémia, where tall trees stand too close to the railway. Although other places have been identified as vulnerable to toppled trees (see Appendix C), the situation presented in figure 3.29 stood out from the rest.

Figure 3.29 – Tall trees near the railway (Google Maps)

Another source of risk, mentioned in section 2.2.3, concerns maintenance tasks, which was the most common issue throughout the section from Alfarelos to Pampilhosa. The problem is about drainage maintenance. However, old signalling can also be found in this section. Poorly maintained drainage has consequences on flooding events, and old signalling may be the root for accidents in the railway. Figure 3.30 shows a poorly maintained drainage system, and figure 3.31 shows old signalling (see additional photographs in Appendix C).

Figure 3.30 – Drainage clogged with debris in Casais

Figure 3.31 – Old signalling 5 km south of Pampilhosa (Google Maps)

Finally, various rail crossings for pedestrians, some of which are not even regulated, can be found (see figure 3.32). In addition, there are some roads and houses located remarkably close to the railway (see figure 3.33), which is a source of risk for the railway infrastructure, in case of a car accident (see additional photographs in Appendix C), and increases the potential effects of a train accident.

Figure 3.32 – Non-regulated pedestrian crossing near Pampilhosa (Google Maps)

Figure 3.33 – Road and houses next to the railway

Considering the reports on what has already happened and the examination of the railway section, it seems evident that there may be risk which could be reduced if the proper measures were to be adapted.

### 3.2.3. Risk assessment methodology

As mentioned before, railway infrastructures can be extremely vulnerable to weather events. The centre of Portugal, namely the area surrounding the city of Coimbra, has suffered with extreme events, such as temperature fluctuations, extreme winds, intense precipitation and flooding, droughts, wildfires and storms, which have physical impacts on transport infrastructure assets, such as the closure of bridges and tunnels, the loss of power supply or communication, or they may even trigger local phenomena, like landslides or rockslides, damaging earthworks and ultimately impacting the whole infrastructure. Therefore, there is a unequivocal necessity to improve infrastructure resilience, beginning with the assets.

According to the United Nations, resilience is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner" (UNISDR, 2009). In other words, it is of the utmost importance to prepare infrastructures for future climate events so as to lessen the damage and the disruption time and, at the same time, to speed up the repairment work. As stated by IP, when the subject is climate change, one way of developing methodologies that increase infrastructure resilience is to plan preventive measures to help mitigating risks associated with climate change, namely identifying critical sections and/or assets of the infrastructure (IP, 2019).

When it comes to risk assessment, the suggested approach is one adapted from IP (2020a). In order to determine risk, as mentioned in section 2.2.3, three parameters need to be pre-determined, specifically asset vulnerability and exposure, and the likelihood of occurrence of a given hazard. The assessment suggested here is a semi-quantitative approach and it combines exposure and vulnerability in an isolated table so that it is possible to create a simple interpretation matrix to determine the level of risk of an asset. First, one should characterize the probability of occurrence (P) of the hazard studied, according to table 3.1 below.

Table 3.1 – Criteria to assign hazard probability of occurrence (P)

| **Probability of Occurrence** | **Rare** | **Unlikely** | **Possible** | **Likely** | **Almost Certain** |
|---|---|---|---|---|---|
| **Classification** | 1 | 2 | 3 | 4 | 5 |
| **Description** | Occurrence is practically impossible | Occurrence is low | Occurrence may happen occasionally | Reasonable chance of occurrence | Very high probability of occurrence |
| **Likely frequency of occurrence** | Not predicted to happen | Once every 20 years | Once every 7 years | Once every 3 years | Once every one and a half year |

The next step it to estimate the level of gravity (G) of the hazard in the asset (table 3.2). In this simplified proposal, gravity combines exposure and vulnerability parameters. A particularly important aspect of the gravity assessment criteria is that it is subjective to personal analysis and it can be adjusted to insert components that other companies might find of higher relevance.

Table 3.2 – Criteria to determine level of gravity (G)

| **Level of Gravity** | **Very Low** | **Low** | **Medium** | **High** | **Very high** |
|---|---|---|---|---|---|
| **Classification** | 1 | 2 | 3 | 4 | 5 |
| **Human life** | No impact | Small injuries | Injuries with temporary incapacitation | Injuries with permanent incapacitation | Victim(s) |
| **Financial Gravity (F)** | $F \leq 6.000$ € | €$6.000 < F \leq 30.000$€ | €$30.000 < F \leq 150.000$€ | €$150.000 < F \leq 750.000$€ | $F > 750.000$€ |
| **Disruption time (D)** | No impact | $D < 1h$ | $1h < D \leq 6h$ | $6h < D\ 24h$ | $D > 24h$ |
| **Asset value within the network** | Not important | Small importance | Average importance | High importance | Fundamental |
| **Reputation of the company** | No negative projection | Small negative projection at a regional level, for less than 10 days | Intermediate negative projection at a regional level, for more than 10 days | Negative nationwide projection, for less than 10 days | Negative international projection or negative nationwide projection, for more than 10 days |

Gravity is then calculated, considering the contribution of all components in the first column of table 3.2, according to the expression below:

$$G = \frac{Human\ Life\ Gravity + Financial\ Gravity + Disruption\ Time + Asset\ Value + Company\ Reputation}{5} \quad (2)$$

Then, the level of risk is determined by coupling the level of gravity and the probability of occurrence, as seen in table 3.3 below.

Table 3.3 – Level of risk

| | | **Probability of Occurrence** | | | | |
|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** |
| **Level of Gravity** | **1** | Low | Low | Low | Low | Moderate |
| | **2** | Low | Low | Moderate | Moderate | High |
| | **3** | Low | Moderate | Moderate | High | High |
| | **4** | Low | Moderate | High | High | Very high |
| | **5** | Moderate | High | High | Very high | Very high |

Finally, after the level of risk is assigned, the suggested procedure is described in table 3.4.

Table 3.4 – Reaction to level of risk

| Level of Risk | Measures |
|---|---|
| **Low** | Risk is negligible. In this case, no measures are assigned since the consequences are acceptable. |
| **Moderate** | Risk has some expression. It is obligatory to take some measures to reduce risk, but not urgent to do so. |
| **High** | The level of risk is considerable. It is obligatory and urgent to take measures to reduce risk. |
| **Very high** | The level of risk is extreme. Measures are obligatory and should be applied immediately. |

## 3.3. Measures to reduce vulnerability in the railway section

After the risk assessment of an asset, measures to improve its resilience need to be carried out. As a matter of fact, in the railway section chosen for the case study (Alfarelos – Pampilhosa), some measures have already been implemented, while others are meant for future completion. The strategy to create a more resilient section and to prepare it for the near future was divided into three separate phases. The first phase included the suppression of 19 level crossings, the construction of 13 pedestrian overpasses or underpasses, as well as the implementation of new signalling and communication systems, the rising of passenger platforms, amongst others. It was meant to take place between 2007 and 2015, and the main goals were to diminish accidents, to eliminate restraints to the use of the railway (allowing for faster journey times), and to achieve a higher flexibility in traffic management (IP, 2021).

According to IP (2021), 30.5 million euros have already been invested. The 3 phases comprise an estimated investment of 90 million euros, involving works such as the whole renovation of 35 km of double track, the rising of platforms in 3 stations and 5 halts, works to improve slope stability, enhancement of drainage system, the installation of fencing along the section and the setting up of 4 railroad switches that will enable the movement of 750-m long trains (Fernandes, 2018). Phase 2 outlined the stabilization of 6 more slopes and, phase 3 will involve the renovations of the stations in Alfarelos and Coimbra-B and the removal of level crossings (Fernandes, 2018).

However, phase 1 was not remarkably successful as the renovation was not ambitious enough (probably due to budget cuts which prevented the implementation of all that was planned). Since the track itself was not raised, in sections that are known to be vulnerable to floods from the Mondego river, neglecting it is a significant issue, which has been affecting the infrastructure, as previously shown. Phase 1 was completed in 2018 and, in that same year, the North Line was disrupted due to flooding after storm Leslie, proving that the measures taken did not take into consideration weather events which have become more and more frequent. In 2021, IP intends to modernize the train station in Pampilhosa, treat slopes and drains between Souselas and Pampilhosa (which is urgent, as shown before), and replace sleepers near Pampilhosa, according to the Network Statement 2021 (IP, 2021).

Considering the vulnerability of assets highlighted in section 3.2.2, the measures suggested to enhance railway resilience in the rail section between Alfarelos and Pampilhosa are now presented according to the ones proposed in section 2.2.4, considering its adequacy for each of the detected problems.

When contemplating problems of slope stability, the natural course of action is to stabilize the slope of both cuttings and embankments. Such is achieved, for example, by improving drainage system using surface drainage to divert the water, and even horizontal drainage to lower the water table inside the slope, therefore increasing shear strength. Another option could be the use of a retaining wall (a gabion wall, for instance), or anchors. Gabion retaining walls are a good solution since there is material available and it does not imply a huge investment. Figure 3.34 shows a retaining wall out of gabion, close to the halt in Vilela, and figure 3.35 shows a slope with horizontal drainage in Loreto.

Figure 3.34 – Gabion retaining wall in Vilela

Figure 3.35 – Horizontal drains in Loreto

The problem of dense vegetation and inappropriate drainage is related with maintenance and its frequency. Maintenance of the drainage system should be more careful, especially in periods that are known to be of extreme precipitation so that the system may fulfil its job and the railway does not have to be disrupted. Moreover, new drainage systems should be designed looking at future trends of precipitation, which means their capacity should be increased. Figure 3.36 demonstrates a proper drainage, close to the station in Pampilhosa.

Figure 3.36 – Drainage system near Pampilhosa (Google Maps)

Vegetation is a controversial subject, for if on the one hand, vegetation helps creating a buffer zone between the corridor and the outside of the corridor, as well as maintaining a lower temperature on the track, on the other hand, dense vegetation contributes to a higher vulnerability to the wildfire phenomenon. The suggestion here is to preserve the vegetation, maintaining sustainability, helping reducing carbon dioxide emissions, stabilizing slopes with its roots, maintaining a reasonable temperature on the corridor, and serving as a buffer zone, as long as no tall trees are part of the corridor and the vegetation is maintained so as to make it easier to extinguish a fire if one occurs. In figure 3.37, it is possible to see the remaining logs of what used to be two trees that endangered the OLE and the track.

Figure 3.37 – Proper maintenance of vegetation near the railway (Google Maps)

River flooding from the Mondego is a major problem in the rail section of the case study, as reported in section 3.2.2. In Alfarelos and all its flood-prone area, track elevation is an absolute necessity in order to prevent situations like the ones which happened in 2016 and 2019, when a large extension of the track was submersed. The damage to the track is a huge loss and it causes delays or disruption times. In this particular case, the drainage system will not be enough due to the proximity of the Mondego river to the track. The elevation of the track has been mentioned in some plans, but it has not been implemented thus far.

Finally, and despite not being a natural hazard, roads and houses right next to the railway are a major source of vulnerability due to accidents, as well as regulated and non-regulated level crossings. In order to prevent the construction of houses and roads too close to the railway, a restrictive mapping should be established to enforce safe distance and reduce vulnerability. On what concerns level pedestrian crossings, the solution is uneven crossings, allowing for safe passage. A few examples can be seen in Appendix C, showing pedestrian overpasses in Bencanta and Casais (and others are planned).

Besides the measures presented, some other general measures (already presented in section 2.2.4.) could be applied to reduce risk, namely using weather information systems or applying speed restrictions when considered necessary.

# 4. DISCUSSION AND FURTHER STUDIES

Portugal is very vulnerable to climate changes because of its geographical situation. Even if one cannot precisely quantify the expected weather events, the data gathered so far is enough to demand for immediate action. Obviously, the country is facing a significant economic and financial crisis, which makes it extremely difficult to define priorities. Nevertheless, the longer one takes to apply adequate measures, the bigger the effects and consequences of the climate on railway assets.

There is enough evidence of hazards to the railway assets in the North Line, between Alfarelos and Pampilhosa, to cause concern. The measures adopted thus far have solved some of the existing problems, but some were mere temporary work, and the assets under repairment or retrofitting will need additional work in the near future, resulting in more delays, disruptions and extra amounts of money, which could otherwise be avoided if the right strategy was adopted.

It is urgent to assess risk consistently, without disregarding the effects of the climate on already degraded railway infrastructures. Perhaps it is high time to consider the railway as a crucial way of transportation, not only for people, but also goods, and invest now to save in an uncertain future. It is proven that if vulnerability and exposure are reduced, by considering adaptative or mitigative measures, risk will be reduced even if the probability of occurrence of a hazard remains high. It is possible to avoid or reduce damage to railway infrastructures or to prevent disruptions, if maintenance procedures are carried out regularly and measures to address the issue are adopted in designing or retrofitting a structure. Naturally, this solution may require a huge investment, which could lead decision-makers to disregard the whole procedure. Hence, it is recommendable to adopt a risk methodology capable of determining the level of risk and help them make the right choice, considering the natural hazards uncertainty deriving from climate changes.

A few months ago, the new strategic plan for this decade was presented. PNI 2030 (National Investment Programme) includes a great investment in the railway sector (over 10.000 million euros), including the construction of a new railway between Lisbon and Oporto, cutting the travel time to half, which will release the existing North Line for freight activity and regional or suburban transportation. Among the several measures proposed, the programme also intends to consider climate risk and adapting the infrastructures (design, construction, maintenance and operation), to make them more resilient towards extreme weather events (PNI 2030, 2020). Hopefully, this programme will acknowledge the effects and impacts of the climate on the railway infrastructure and suitably incorporate the new design paradigm in new and existing infrastructures.

IP is also participating in a European research project, funded by Horizon 2020, with several other European partners, including the University of Minho, in Portugal. SAFEWAY includes the whole ground transportation network and it “leads to significantly improved resilience of transport infrastructures, developing a holistic toolset with transversal application to anticipate and mitigate the effects extreme events at all modes of disaster cycle” (SAFEWAY, 2020). It intends to assess the impact of natural hazards, considering infrastructure assets. This project englobes 4 case studies (still at study) and one of them is in Portugal, between Santarém and Leiria, an area which is susceptible to floods and wildfires (SAFEWAY, 2020).

This demonstrates the relevance given to the issue and the need to research about the problem in order to find better solutions. This thesis compiles the knowledge on the subject and suggests a different approach, which could help in achieving a more resilient railway. There are some gaps in it since it was intricate to get information about the railway section at study and to gain a full understanding of its situation (especially on what concerns examining the railway, since access to it is overly complex). Nevertheless, after a broad analysis of the railway section, the unpreparedness for future climate change is noticeable and, furthermore, it seems clear that there are measures which could be adopted to reduce the inherent risk.

It would be relevant to study not only a section of the North Line, but the whole line, identifying assets which could benefit from a set of measures to help building a better and safer railway. Moreover, it is also important to check all other lines in the country and examine them in detail.

A resilient and fit railway for future climate change events will lead to a more secure and reliable way of transportation. While on the one hand it is extremely important to reduce delays and disruptions for goods and passengers and so assuring the reputation of the transportation company, there is another silver lining in having a railway that people can trust, namely the contribution for a sustainable future, because being ready for the future is only part of the work.

However, considering the current reluctance of society and governments to invest heavily on large infrastructure developments and taking into account the uncertainly involved with the effects of climate changes, the use of adaptive measures to mitigate the possible future effects of climate change offers an attractive cost-effective solution for creating new railways and/or retrofit existing ones that will perform better in a climate change scenario.

# 5. CONCLUSIONS

It is indisputable that climate change is a reality and will seriously affect human life in the years to come. If the international community and the individual citizens do not radically change their attitude and way of life, emissions to the atmosphere will continue building up and further increase the problem of global warming and climate changes. This problem will most certainly affect the design of engineering structures, especially those with a long-life design such as railways.

This dissertation considers how railway infrastructures can potentially be affected by climate change fluctuation and aims to develop a methodology to assess the level of risk of each asset of the infrastructure, recommending measures to avoid and mitigate inherent vulnerability, either in the railway section of the case study presented, or in similar infrastructures.

A broad diversity of evidence was found all over Europe, showing how the effects of extreme meteorological events have been affecting railway infrastructures, such as track buckling caused by extreme high temperatures; wildfires next to the railway associated with strong winds, long periods of drought and abnormal high temperatures; earthwork landslides due to atypical precipitation; tree falling from gusts; bridge scour around piers and abutments derived from floods; and an overall hastened deterioration of the railway.

It becomes clear that a set of adaptation and mitigation measures is required so as to answer a frequently declared, and yet disregarded, change of conditions in the weather. The measures herein suggested intend to lessen asset vulnerability, therefore diminishing risk. Even though the perfect scenario would be that of an infrastructure that could be resilient to all the possible effects derived from natural hazards, such an infrastructure would not be economically feasible, particularly in a conjuncture of economic crisis such as the one being felt at the moment.

Therefore, a way to prioritise interventions and which assets to repair or retrofit is quite useful. This is done by determining the level of risk of an asset and identifying the ones with a higher level, or priority of intervention. Nevertheless, risk assessment is a subjective evaluation, and a consensus about the level of gravity might be hard to attain. Even so, this subjectivity will not result in great differences, thus being a proper way to define risk and prioritise assets.

On what concerns the advocated measures, some thought was given into suggesting approaches which could be sustainable, such as using wildfire-resistant vegetation in the corridor to lower temperature and serve as a buffer zone, instead of cooling systems in the trains, or even using local natural resources, such as rocks used in gabion walls or around pillars and abutments to prevent bridge scouring.

Although a diversity of studies can be found in European countries, suggesting the inclusion of adaptation and mitigation tools to deal with climate change effects in the railway and its effective implementation, in Portugal, the study of this matter seems to be in an embryonic state. This seems to trigger some apprehension, particularly when one relates the unawareness of such problems to the news of a new rail line between Lisbon and Oporto or even a high-speed train in the near future.

It seems evident that there are quite a few complications associated with extreme weather events in the Portuguese railway, resulting either from poor maintenance or from lack of adaptation to the current climate conditions. Either way, there is room for improvement in the methodology to tackle the risks derived from weather or weather-related events.

This thesis provides a semi-quantitative methodology to assess the level of risk of each asset when facing natural hazards exacerbated by climate change, and it could be adapted to the road transportation network with little effort. The measures herein specified will contribute to the development of solutions that may lead to a more resilient railway, which can be fit for the future. In fact, even if suitable risk management of a railway in a climate change scenario may require more data to support quantitative risk analysis and cost evaluation of traditional and innovative adaptive mitigation measures, the methodology herein proposed sheds some light on the requirements involved in future risk management of railways.

The planning, designing, construction and maintenance of railway infrastructures needs to be done in a responsible way, considering data gathered from past events, but also go beyond it, and ponder the information provided by climate models which can help in identifying risk and defining measures to maintain infrastructures able to perform effectively, over a long period of time.

Future research in this field needs to consider the challenges posed by quantitative risk analysis in general, including combining different effects resulting from different hazards. In addition, the costs and benefits of possible mitigation measures need to be appropriately evaluated, which is an undoubtedly stimulating task if innovative adaptive measures are to be considered.

*Risk analysis and management is the primary approach engineers take*
*to deal with future uncertainty.*
Olsen, 2015

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# 7. APPENDICES

## Appendix A – Active railway network in Portugal

IP (2021)

# Appendix B – Maximum temperature climate model (Portugal)

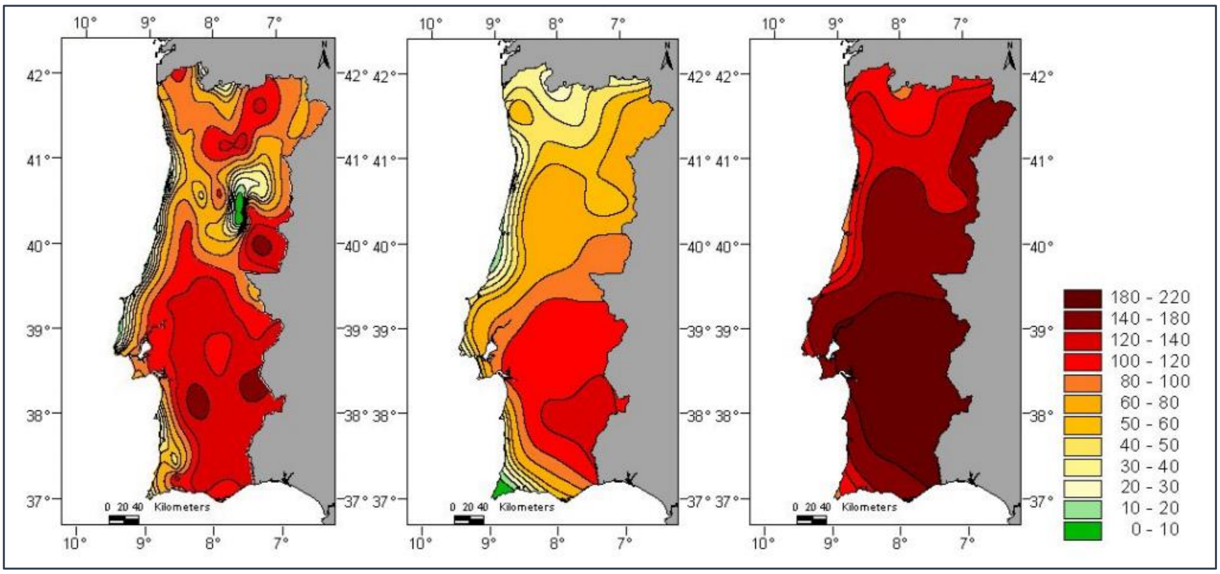

Figure B.1 – Number of days per year with maximum temperature above 25ºC (Miranda et al, 2002)

a- 1961-1990 climatology

b- HadRM control simulation

c- HadRM GGa2 simulation (2080-2100 period)

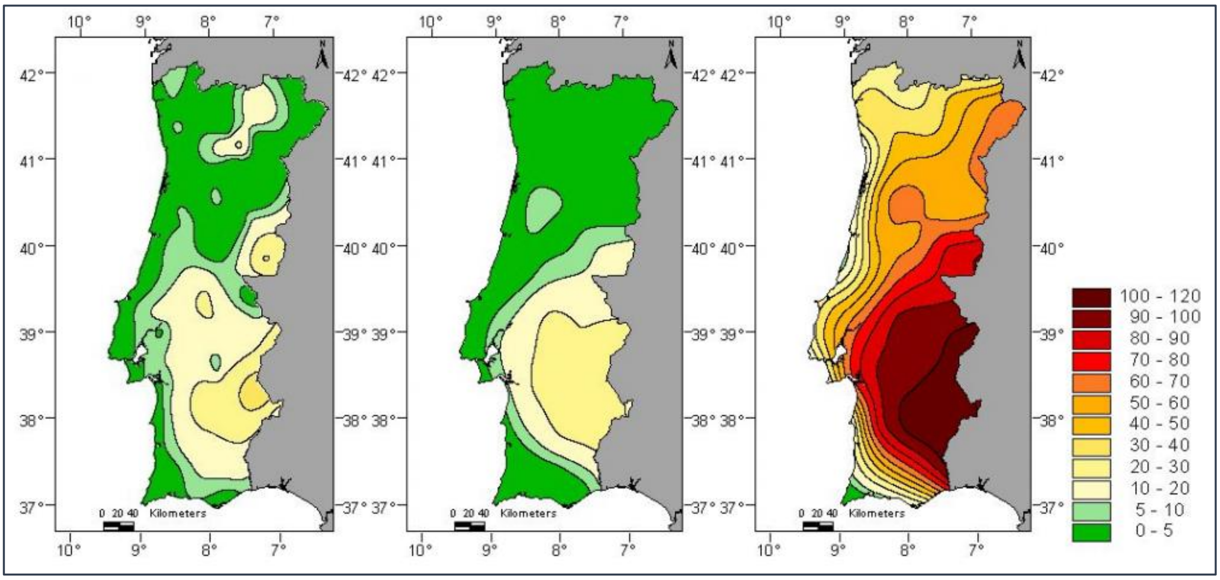

Figure B.2 – Number of days per year with maximum temperature above 35ºC (Miranda et al, 2002)

a- 1961-1990 climatology

b- HadRM control simulation

c- HadRM GGa2 simulation (2080-2100 period)

# Appendix C – Additional photographs: Alfarelos - Pampilhosa Section

- Components of the railway (rails, sleepers and ballast)

- Pedestrian crossings (overpass pedestrian crossings, underpass pedestrian crossing, level pedestrian crossing)

- Houses and road near the railway

- Bridges

- Cuttings and slopes

- Drainage systems

- Undifferentiated vegetation, trees and forest zones near the railway