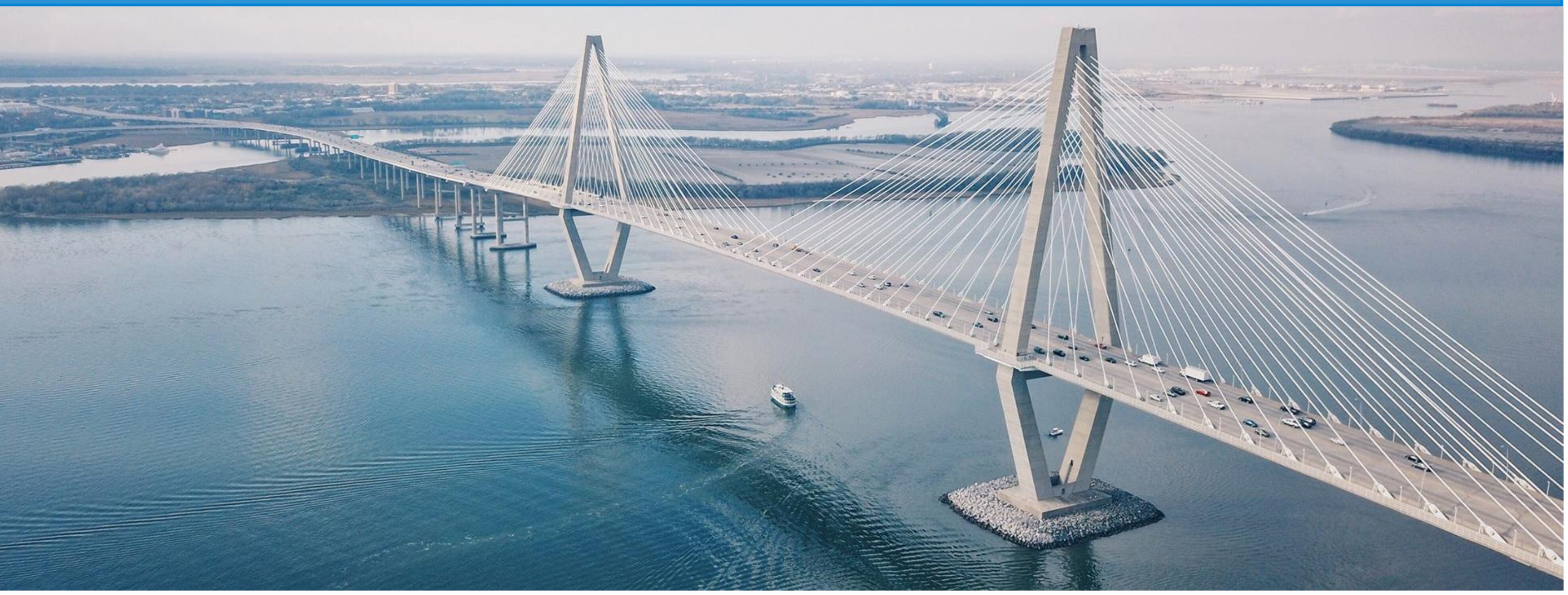
SIRMA
STRENGTHENING INFRASTRUCTURE RISK MANAGEMENT IN THE ATLANTIC AREA



Transportation infrastructure risk-based management

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Territorial risks

SIRMA

STRENGTHENING THE TERRITORY'S RESILIENCE TO RISKS OF NATURAL, CLIMATE, AND HUMAN ORIGIN

Application Code: EAPA_826/2018

Transportation infrastructure risk-based management

WP 6 — Risk & Resilience-Based Decision-Making procedure for Transportation Infrastructure

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Lead partner	**University of Minho (UMinho)**
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SIRMA Project Synopsis

SIRMA

Territorial risks

SIRMA aims to develop, validate, and implement a robust framework for the efficient management and mitigation of natural hazards in terrestrial transportation modes in the Atlantic Area, which consider both road and railway infrastructure networks (multi-modal). SIRMA leads to significantly improved resilience of transportation infrastructures by developing a holistic toolset with transversal application to anticipate and mitigate the effects of extreme natural events and strong corrosion processes, including climate change-related impacts. These tools will be deployed for critical hazards that are affecting the main Atlantic corridors that are largely covered by SIRMA consortium presence and knowledge. SIRMA's objectives will address and strengthen the resilience of transportation infrastructures by:

- Developing a systematic methodology for risk-based prevention and management (procedures for inspection, diagnosis and assessment);
- Implementing a decision-making algorithm for better risk management;
- Creating a hierarchical database (inventory data, performance predictive models, condition state indicators and decision-making tools), where information can be exchangeable between entities and across regions/countries;
- Developing a real-time process for monitoring the condition state of transportation infrastructure;
- Enhancing the interoperability of information systems in the Atlantic Area, by taking account of data normalization and specificity of each country.

SIRMA
STRENGTHENING INFRASTRUCTURE RISK MANAGEMENT IN THE ATLANTIC AREA

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Executive Summary

This Deliverable report (D6.2), summarizes the work developed in the context of working package 6 "Risk & Resilience-Based Decision-Making procedure for Transportation Infrastructure".

This WP aims to develop a resilience-based decision-making tool for transportation infrastructure in the Atlantic region. It is divided into three Actions:

(i) Risk-based model for transportation infrastructure;

(ii) Risk mitigation measures on transportation infrastructures;

(iii) Resilience-based decision-making.

Action 1 integrates data obtained from sensor system, developed at WP5. Additionally, the developed model considers the climate change effects on the likelihood and impact of extreme events, obtained from WP4.

Action 2 is divided into two parts: (i) collecting data about risk mitigation measures, not only in the Atlantic region but also out of it; (ii) incorporating such data on a risk-based predictive model (Action 1). In the end, a database with the most relevant risk mitigation measures will be obtained.

Action 3 addresses the development of a real-time decision-making framework, necessary to define: (i) risk-based predictive model (Action 1); (ii) risk mitigation measures (Action 2); (iii) optimization algorithm. In the end, a decision-making tool based on resilience will be delivered.

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1. Introduction

1.1 Climate trends and future projections for Europe

In the recent years, the environmental debate has to a large extent been influenced by the growing realisation of the threat posed by climate change. Climate change is quite evident in Europe and continues to threaten Europe's economy and society (IPCC, 2013). In fact, some of the observed climate changes have established records in the past few years. Since the mid-20th century, Europe has witnessed an increase in the annual mean temperatures as well as the frequency and duration of heatwaves. However, across Europe, climate change impacts vary based on the geographical and socio-economic conditions. To elaborate, while northern and north-western Europe has faced an increase in precipitation, it has been observed that southern Europe has had a decrease in precipitation. Figure 1 shows the map of Europe with the key observed and projected climate changes. Since vulnerability is country-specific, each European country is bound to experience varying effects of climate change. Overall, future projections state that climate change is anticipated to lead to further increases in the intensity and frequency of precipitation and extreme temperature events. Therefore, it appears that no European country is safe from climate change and its resulting consequences (EEA, 2012; IPCC, 2013, EEA, 2019).

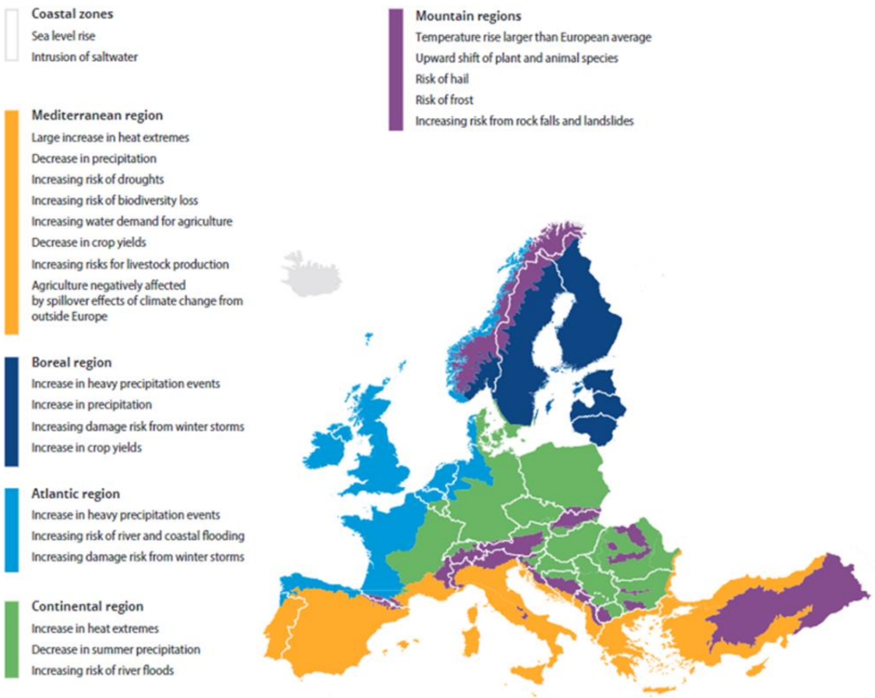

Figure 1. Observed and projected climate changes in Europe (EEA, 2019)

In terms of increased temperatures, Europe is seen to be warming faster as compared to the global average according to European climate projections. Based on EURO-CORDEX5 projections, more than 2°C of warming is expected in Europe. This is anticipated even if the

Paris Agreement are met. This expected increase could reach up to 4°C, in the scenario of an increased warming in Europe. However, it is worth mentioning that the consequences of such increased temperatures will vary depending on the different European regions. South-eastern and southern Europe are expected to have the highest number of seriously affected domains and sectors with becoming the hotpot regions. On the contrary, northern, and central Europe are expected to face milder winters as compared to the past with consistent average temperature rises in summer. Also, as mentioned earlier, these trends shall exacerbate under scenarios of increased warming (EEA, 2017; 2019).

Concerning precipitation levels, a similar trend can be observed in the projected changes in the summer and winter. While an overall decrease in precipitation is predicted in the summers for all regions apart from Eastern Europe and Scandinavia, an increase is expected over most of the northern and central Europe (EEA, 2017; 2019). The risk of river flooding is likely to increase in several parts of Europe, with the exception being north-eastern Europe. Further, the sensitivity to river floods has been intensified by climate exposure, the establishment of several new urban areas and assets accumulation in low-lying areas close to rivers. Figure 2 illustrates the map of Europe showing the likelihood of low-lying urban areas from being potentially threatened by river flooding for the current period as well as the projected future (2071-2100) in a 100-year river flood event. It must be noted that these projections demonstrated by Figure 2 do not consider subsequent changes in the urban land or the adoption of any adaptation measures which may reduce the risk (Rojas et al., 2012, 2013; EEA, 2017).

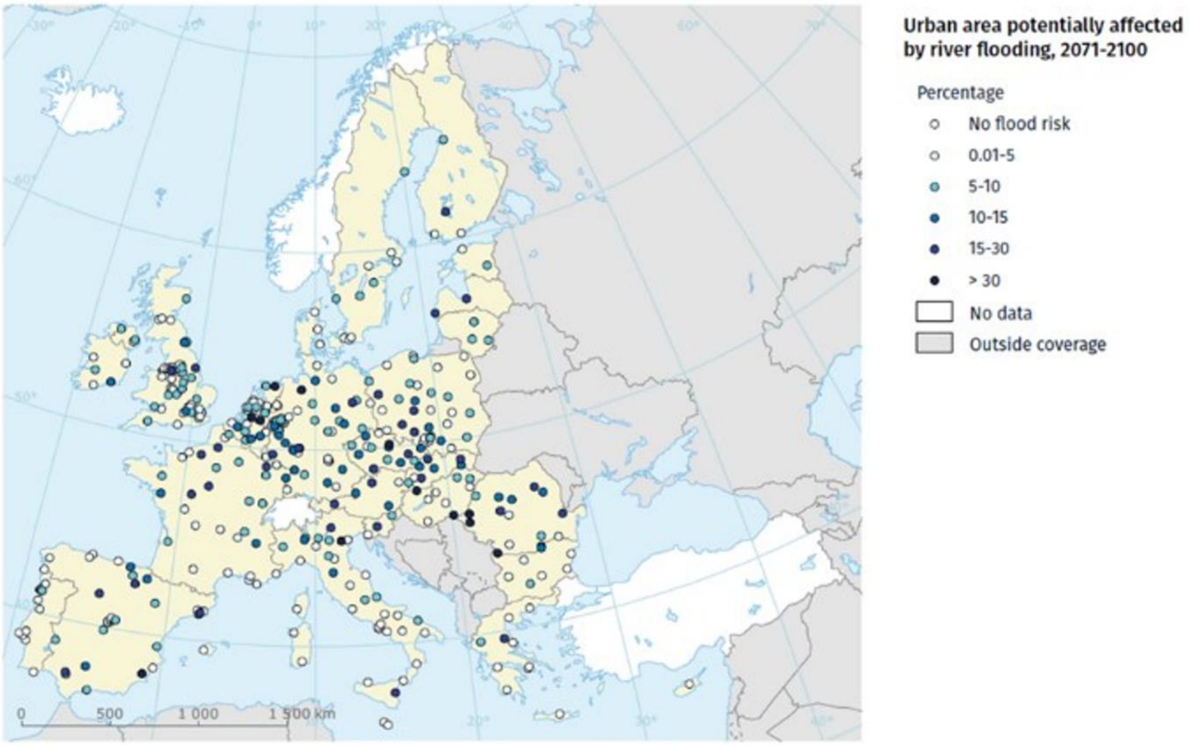

Figure 2. European urban areas potentially at risk of river flooding (EEA, 2017)

Altogether, the frequency of extreme weather events such as river and coastal flooding and heat and cold waves is likely to increase. Increased number of extremely hot days, high overall temperatures along with wind variability and low humidity will surely cause a rise in the number of fires. This includes particularly wildfires and forest fires. Presently, in Europe, river floods and windstorms appear to be the most damaging climate hazards. However, this scenario is projected to change in the upcoming years. By the end of the century, heat waves and droughts will account for 90% of the climate hazard damage. Even though the exposure will be country specific, such events will have an impact on all regions. Also, it appears from the raging fires of 2019 summer in Sweden that in spite of models and projections, no European country is protected by extreme weather events. Nevertheless, coastal regions along with mountainous areas are particularly at risk (EEA, 2017).

Over the recent decades, the risk of forest fires in several domestic areas has increased due to the mingling wild land and urban areas because of urban sprawl with low-density housing. Figure 3 depicts the European urban areas at risk of forest fires against two indices (percentage and seasonal severity rating index). According to the map shown in Figure 3, it appears that the southern European countries are the most vulnerable to fire. Residential areas in all Portuguese cities are at an increased risk of direct fires (with >16% chance). Similar patterns are visible in southern France and Greece, while the situation seems to be more variable in southern Italy (Camia et al., 2008; EEA, 2017; JRC, 2022).

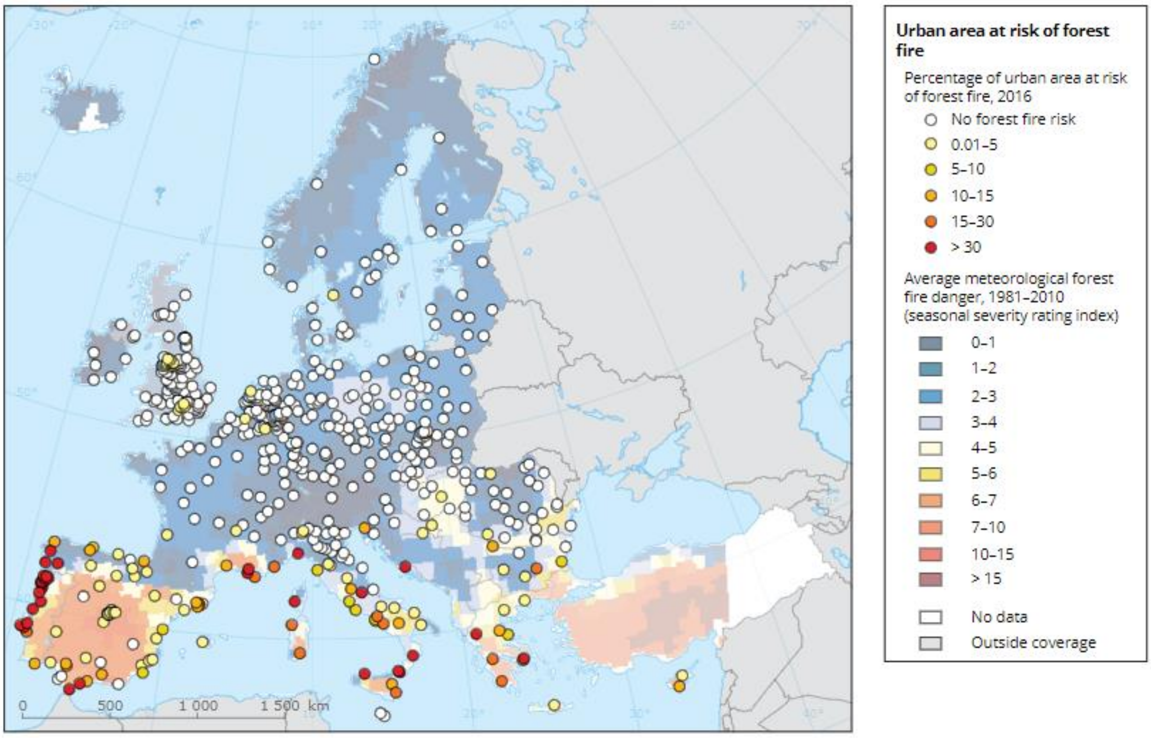

Figure 3. European urban areas at risk of forest fire (EEA, 2017)

1.2 Climate change and the transport sector

Climatic changes such as increasing sea levels and temperatures along with growing intensity and frequency of extreme weather events (such as flooding and heatwaves) are threatening to compromise European transportation services as well as infrastructure. Such impacts on the transportation sector can have destructive consequences, especially for Europe's society and economy (EC, 2013). Extreme weather conditions such as extreme temperatures and extreme precipitations are expected to cause serious consequences for the physical environment (Nemry and Demirel, 2012).

Air pressure, temperature and precipitation are the three main climate change determinants from which the following effects are derived (Doll and Sieber, 2010):

i) Heat periods, droughts, and wildfires;
ii) Heavy precipitation, floods, and mass movements;
iii) Extreme winter conditions;
iv) Storms, storm surges and combined events

1.2.1 Roads (including bridges and slopes)

In transport system design, factors such as weather disaster risks and weather contribution to the common wear and tear of transportation infrastructures play a key role. Extreme weather events such as heavy rainfalls can impact transport operations greatly. For roads and road infrastructure (including bridges), the following climatic events could be potentially damaging:

- ✓ Summer heat
- ✓ Extreme precipitation and floods
- ✓ Extreme storm events
- ✓ Winter conditions

In Europe, summer heat can have the following impacts on roads:

- ✓ Expansion/buckling of bridges;
- ✓ Increase in wildfires that can damage road infrastructure;
- ✓ Reduced life of asphalt road surfaces (such as surface cracks);
- ✓ Melting tarmac;
- ✓ Pavement deterioration and subsidence

On the contrary, extreme precipitation and flooding can have the following effects on roads:

- ✓ Damage of road infrastructure (such as pavements, road washouts);
- ✓ Coastal erosion to coastal roads;
- ✓ Instability of embankments;
- ✓ Risks of landslides;
- ✓ Overstrained drainage systems;
- ✓ Underpass flooding;
- ✓ Scouring of structures;
- ✓ Road submersion

In terms of operations and services, climatic changes can lead to disruption of goods delivery, road safety hazards or road closures, speed reductions, welfare losses, and higher maintenance and reparation costs. While these risks are projected to occur between 2025 to 2080, an increase in severity (highly negative impacts) is likely with time (EEA, 2014).

Floods, particularly flash floods which commence and progress swiftly due to intense precipitation events, are the main reason for weather influenced disruption to the transportation sector (DfT, 2014). These events are likely to continue with time (Dawson et al., 2016). Road networks in urban areas are particularly sensitive to these problems because of the increased number of impermeable surfaces which inhibit water infiltration into the soil. In the event of heavy precipitation, drains tend to exceed their capacity due to overland flow. This in turn increases the chances of drains becoming clogged by debris, much before the authorities can provide flood warnings (Suarez et al., 2005; Koetse and Rietveld, 2009; Tsapakis et al., 2013; Hooper et al., 2014; Pyatkova et al., 2015; Pregnolato et al., 2017). For coastal roads, climatic pressures such as heavy precipitation events, extreme storm events and rises in sea-levels can be very damaging. Overall, any kind of disruption to the transport system can seriously hinder its performance. It has been proven that the road transport system is one of the most critical infrastructures (Giunipero and Eltantawy, 2004).

1.2.2 Railways (including bridges and slopes)

Based on the UK Climate Impacts Programme 2002 (UKCIP02), which provides a set of climate projections derived from a series of climate modelling experiments, the following three climate change groups can be identified:

- ✓ hotter, drier summers;
- ✓ warmer, wetter winters;
- ✓ increased frequency of extreme storms

In the discussion of climate change and its effects, these three groups can provide a useful framework. Climatic changes can have significant impacts on railway operations (Baker et al., 2010). For the current and future railway industry, the following main effects are likely to be of concern (RSSB, 2003):

- ✓ Effects of high temperatures on tracks (buckling);
- ✓ Effects of high rainfall on earthworks;
- ✓ Effects of extreme precipitation levels on current drainage systems;
- ✓ Effects of extreme winds on the overhead system

These effects can be linked to the climate change groups identified earlier. Further, RSSB (2003) has identified rises in sea levels as being critical for coastal railway infrastructures.

On the European railway system, dry hot summers can have the following impacts (RSSB, 2003):

- ✓ Increased wildfires that can damage infrastructure
- ✓ Increased rail buckling
- ✓ Desiccation of track earthworks
- ✓ Material fatigue
- ✓ Increased instability of embankments
- ✓ Greater need for air conditioning systems
- ✓ Increased ventilation problems on underground railway systems due to equipment overheating

Such risks are likely to take place between 2050 to 2080, where most of the Europe will be impacted by them.

For most European railway systems, the increased frequency of warm wet winters can result in the following undesirable effects (RSSB, 2003):

- ✓ Increased flooding of the network and strain on drainage systems;
- ✓ Damage to earthworks; failure of saturated embankments;
- ✓ Track circuit problems

A rise in the incidence of extreme storms and particularly severe rainfall and strong winds is predicted by the UKCIP02. In such cases, similar effects will be observed as highlighted above. However, there may be more dramatic effects (Baker et al., 2010). Overall, climate-related events, specifically floods, are already amongst the issues causing frequent railway disruptions (Lindgren et al., 2009; Doll et al., 2014).

Generally, climatic pressures as well as the occurrence of extreme events can result in potential issues and trigger impacts much beyond the affected areas. Reduction in safety, increased costs for maintenance and reparation, and disruption of delivery of goods and passengers are amongst some of these issues (EEA, 2014). For instance, severe flooding that occurred in the spring of 2013 in Europe, had a significant impact on many countries. These include Germany, Czech Republic and Austria. The transportation sector and the supply chains were critically disrupted. One of the main railway bridges in Germany, which passed across the river Elbe was affected and had to remain closed for a couple of months. This had an impact on important high-speed services and in fact led to disruptions on the whole railway network. The Austrian railway system also faced similar issues where closure of rail services resulted in significant disruptions on long-distance trains from Germany to Italy that passed through Austria. Furthermore, high water levels meant that various waterways had to be closed. These included important sections of the Rhine and Danube. Consequently, supply chains were severely disrupted, mainly due to a halt in the operations of merchant ships (EEA, 2014).

The 2013/2014 winter in the UK was quite exceptional in terms of the weather. Severe winter storms culminated in critical coastal damage and extensive flooding. The transportation infrastructure was the most severely affected during this exceptional weather phase with facing several consequences. These consequences included cancellation or suspension of transport services, closure of railway lines, and serious damage to rail and road infrastructure due to flooding. Figure 4 shows the damage to the main line railway at Dawlish, Devon, UK. The coastal section of the southwest main line railway was damaged severely and normal operations at this section of the line could not be restored for two months. Also, the affected section had to be cut off from the remaining railway network for these two months (EEA, 2014).

Overall, it is understood that extreme weather events can result not only short-term delays but also long-term interruptions where detouring is needed in case the infrastructure is destroyed. Coastal areas are always at a higher risk mainly due to threat posed by rises in sea levels and storm surges, which can jeopardize transport infrastructure as well as services in these places. Also, as evident by the case shown in Figure 4, it appears that some disturbances may extend beyond the affected area, mainly due to the connectedness of transportation systems, thus affecting their performance (Giunipero and Eltantawy, 2004).

Increases in the frequency and intensity of heat waves as well as heavy precipitation events are some of the climatic changes which have already been observed. As a result, there appears to be an increased risk of more frequent, intense, and longer-lasting heat waves in a warmer future climate. In addition, a warmer future climate also indicates that there will be a rise in the risk of floods in several major river basins. This is linked to an increase in future intense storm-related precipitation events leading to flooding events. Modelling studies performed as part of major meteorological research works have demonstrated evidence that future tropical cyclones could become more severe, with greater wind speeds and more intense precipitation. In fact, an eastward extension of the Atlantic storm-track into Europe is also projected with a probable increase in precipitation events, as discussed earlier.

Figure 4. The Dawlish railway damage of February 2014 (Smith, 2022)

The transport system has a particular role in society and economy. However, constant climatic changes pose serious problems to the transportation sector. It is historically well known that persistent heavy rains, river floods as well as flash floods can lead to immense damages to different transport sectors such as the railroad industry. Overall, floods amongst different weather events, generate some of the largest amounts of economic damages and fatalities (Doll and Sieber, 2011).

2. Mitigation and Adaptation

Generally, while the occurrence of some high-impact extreme weather events cannot be attributed solely to climate change, progress is being made in this area (IPCC, 2013). Nevertheless, based on the predicted increases in the intensity as well as frequency of extreme weather events, it is crucial to prepare adequately for such unavoidable circumstances (EEA, 2014). Activities that reduce or eliminate the chances of an extreme incident taking place are often referred to as mitigation measures. Mitigation actions or measures are essentially policy orientated in comparison to the preparedness phase and are normally a form of crisis management (Papanikolaou et al., 2011). As discussed in earlier research works (FEMA, 1992), mitigation activities have the following characteristics:

- ✓ Involve physical or engineering steps along with procedural or situational measures (for instance, altering work methods or informing transport passengers on self-protection procedures);
- ✓ Encourage the use of special managerial as well as technical skills to the methodical identification and hazards control through the lifecycle of a program, vehicle, or facility;
- ✓ Confirm the security and safety of civilians during day-to-day activities;
- ✓ Restrict vulnerability of public authorities to the consequences of natural and human-caused catastrophes.

Future global Greenhouse Gas Emissions (GHG) are partially going to be responsible for the rate and magnitude of climate change. Accordingly, a range of GHG mitigation policies have been and are continuing to address the immense need for global mitigation action to lessen the GHG emissions. The transport sector is identified as one of the major contributors to GHG emissions. Therefore, mitigation measures are needed for this sector in order to deal with the climate change. However, due to climate inertia and past emissions, climate change can be expected to continue for several decades, even if global GHG emissions were ceased now (EEA, 2014). Therefore, it is necessary to adapt to the currently experienced climate changes and to the possible future projected scenarios as well.

During the past decade, an increasing amount of attention has been paid towards the issue of societies needing to adapt to climate change. While mitigation policies are aimed at reducing global greenhouse gas emissions, adaption measures – that are a focus of this chapter – relate to activities and initiatives that can assist in decreasing the vulnerability of transport systems to changing climate. As stated by the Intergovernmental Panel on Climate Change (IPCC), adaptation refers to “adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects which moderate harm or exploit beneficial opportunities” (Parry et al., 2007). Adaptation can be proactive and anticipatory (i.e. prior to an impact), spontaneous and autonomous (i.e. the unplanned response to an impact) or planned (i.e. depending on thoughtful policy decisions and general perception of changing conditions) (Lindgren et al., 2009).

The term adaptation in this chapter refers to measures and activities that respond to the current and future climate change impacts and vulnerabilities withing the continuing and projected social changes. This also includes taking into consideration the climate variability factor which takes place in the absence of climate change. Adaptation actions in the transport sector are intended to protect the transport systems against negative impacts of climate change, while also developing resilient infrastructure (EEA, 2014). Therefore, while adaptation activities deal with unavoidable impacts, mitigation measures deal with the source of the problem. Planning towards future transportation infrastructures requires considering both mitigation and adaptation to climate change (Doll et al., 2014).

3. Development of Database

3.1 Methodology

One of the aims of this work package involved developing a database with the most relevant risk mitigation (adaptation) measures. The overarching aim of the development of this database was to review and analyse past extreme weather events (mainly in European countries/regions) and their effects on the different transportation and related infrastructures. The database seeks information on two major events: floods and wildfires (including heatwaves) and their impact on roads, railways, bridges, and slopes. It reviews the adaptation strategies and policies, proposed, or adopted, to respond to those extreme weather events. The methodology adopted in developing the database is presented in Figure 5.

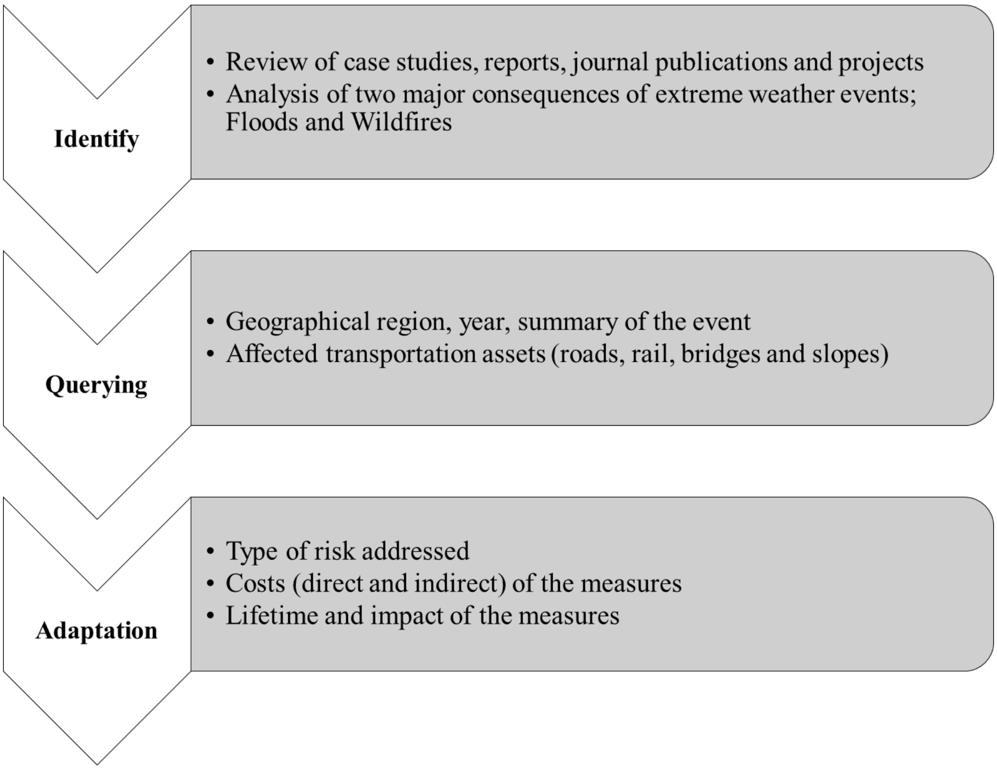

Figure 5. Methodology for developing the database

Review of several different data sources such as case studies, international panel reports and journal publications has demonstrated that over the last few decades, weather extremes leading to floods and wildfires have led to a major disruption on the transportation systems in Europe and around the rest of the world. For the creation of the database, most of these major weather events were identified as case studies. Useful European resources such as the WEATHER (WEATHER, 2022), EWENT (CORDIS, 2022a) and MOWE IT (CORDIS, 2022b) project deliverables were utilised for extracting vital information for the database. In addition, a vast majority of data was obtained from various online sources such as Copernicus (Copernicus, 2022) and The European Climate Adaptation Platform Climate-ADAPT (Climate ADAPT, 2022).

Information was obtained on the meteorological events in terms of the geographical regions that were affected, the timeline of the event and the general summary of what happened. Next, the affected transport infrastructure was identified, if possible. Once the significance of a single event was realised through the vulnerability factor, which considered the level of damages to the society and transport, the next step involved understanding the learning outcomes from the occurrence of that particular event. An in-depth analysis was performed on the adaptation measures that were decided after the event. This included reporting not only adaptation measures but also the emergency management strategies adopted along with the governance structures and policies implemented. The database was then further developed to include vital information on these adaptation measures by reporting the implementation costs of these options and their expected lifetime. Finally, wherever possible, the database also provided information on the suitability of the measure by reviewing any future events that reoccurred at the same geographical location. This included understanding how sustainable and successful were the improvements implemented.

As the database was developed, identified adaptation measures were assessed using a Multicriteria Analysis. The criteria used to assess these adaptation measures were: the component of the risk which the measure will be able to mitigate, the general magnitude of the costs (budget allocations, rebuilding cost that would be required if the asset fails and benefits of the measure); the lifetime of the measure before it needs maintenance or even replacement, and the effectiveness of the measure in terms of reducing risk levels. A complete and accurate database with a set of risk mitigation measures, including a brief explanation in what circumstances these should be used, with what time frequency, effects and costs is provided in the appendix of this report.

Table 1 includes the criteria and rating scale used to evaluate each adaptation measure in Table 2 and Table 3, which present simplified versions of the database for the two major events, floods and wildfires (including heatwaves), respectively. Table 2 and Table 3 provide a summary of the adaptation measures identified for each event.

Along with the simplified tables, the following sections discuss in detail the different adaptation measures proposed. However, it must be noted that the identified adaptation measures are mostly generic goal-type measures that would require further consideration in order to be developed into specific actions that have to be taken either solely by relevant departments or together with cooperation of governmental and private sector bodies. In addition, factors such as costs and impacts are provided based on previous case studies and available data. These may differ for different countries and regions, based on weather and climate predictions.

Another aspect which must be considered while planning and designing adaptation actions in the transport sectors such as the railway sector is that the impacts of potential goal conflicts must be assessed carefully. Implementing counter-productive measures that may have a negative effect on the changing climate in the long-term must be avoided. Thus, it is very important to investigate and exploit the possibility of creating synergies with environmental goals and climate mitigation goals.

Overall, it must be noted that some of these measures are important initial steps but will have limited impacts unless acted upon. Also, while these steps act as crucial first steps, the proposed measures will be sometimes effective for new infrastructure but due to relatively long lifespan, it will require a relatively long time to effectively mitigate system risks. Additional analysis is often needed to clarify current practice and assess potential improvements.

Table 1. The abbreviations, criteria and rating scales used in the evaluation of each adaptation measure

Asset	Mitigation of risk component (Miti.)	Costs	Lifetime	Impact
R = Road **Ra** = Railway **B** = Bridges **S** = Slopes	**H** = Hazard **C** = Consequences **V** = Vulnerability	**Low** - can be achieved within existing or planned budget allocation **Moderate** – will need some further funding **High** – will need major additional funding or major capital program	**Short-term** – Measure requires replacing or major updates in just few years or even months **Long-term** – Measure will be able to serve for a long time (usually around 100 years)	**L** = Low - will have a minor effect on the infrastructure during a risk event **M** = Moderate – will have a moderate effect on the infrastructure during a risk event **H** = High – will almost overcome the effects of the risk event on the infrastructure

3.2 Adaptation measures for floods

An increased frequency and amount of high intensity precipitation events along with ineffective infrastructure to cope with such extreme weather conditions may result in an increase in flooding events. This ongoing risk is likely to become critical in the upcoming future and is assessed as having major consequences on the safety of the transport sector and a resulting financial impact on stakeholders. Based on the results presented in Table 2, it appears that quite a few options have proven to be successful adaptation measures. Some of these adaptation measures are discussed here in detail.

Table 2. Summary of adaptation measures for floods

Asset	Measure	Miti.	Costs	Lifetime	Impact
R, Ra, B, S	Flood awareness and alert systems for monitoring and forecasting floods	C	Moderate	Long-term	M

R, B	Set up of an intermodal mobility management and information system website with its traffic cameras monitoring roads and bridges	C	Moderate	Long-term	M
R	Improved road weather information systems and associated outreach/awareness efforts	C	Moderate	Long-term	L
R	Alarm services for private car users informing about severe weather conditions	V, C	Moderate	Long-term	M
R, Ra, B, S	• Fixed barriers (levees, dykes, earth mounds, solid concrete walls) constructed along rivers • Mobile barriers • Other measures such as closures, pumping systems and safety valves in the canalisation network along rivers	H, V	High	Long-term	H
R, Ra, B, S	Allow larger flood detention spaces in barrages	H, V	Moderate	Long-term	H
Ra	Railway control centre on pillars to make it flood-proof	V, C	Low	Long-term	H
Ra	Construction of counterforts at rail tracks to avoid flooding for the time in which the new planned flood protection embankment is not yet ready	H, V	Low	Short-term	M
Ra, S	Construction of flood protection embankments	H, V	Moderate	Long-term	H
R, Ra, B, S	Completion of new sections in flood protection embankment dams	H	High	Long-term	H
Ra, S	Improvement to stability of slopes and embankments	H, V, C	Moderate	Short-term	M

R, Ra, B, S	Reinforcing dykes and quay walls and opening up areas that can flood to protect land along estuaries. Removal of outer defences of polders and reopening areas to the tides	H, V	High	Long-term	M
R, Ra, B, S	Strengthening the weak areas of dykes, restoring the run-off capacities of areas between dykes and creation of temporary reservoirs to protect river basins from flooding	H	High	Long-term	H
R, Ra	Construction of sea walls	H, V	High	Long-term	H
R	Shifting of road alignments beyond areas at risk	H	High	Long-term	L
B	Adequate design and maintenance of bridges	V	High	Short-term	M
R	Proper design and maintenance of drainage	H	Moderate/High	Short-term	M
R	Improved road pavement materials and design standards	H, V	Moderate	Long-term	M
R, Ra, S	Vegetation management along roads, rail tracks and to enhance slope stability	H, V	Low	Long-term	M
R, Ra, B, S	Emergency Plan; documents to assist all authorities, emergency response organisations and other relevant bodies before and during a flood event with informing people about the flood	V, C	Low	Long-term	L
R, Ra, B, S	Initiatives to raise public awareness and preparedness (publications, presentations, websites)	V, C	Low	Long-term	H

3.2.1 Enhanced weather information and monitoring systems

Enhanced weather information systems along with alert systems are excellent initiatives that involve providing more timely and complete information whilst improving the understanding and appropriate response of the public to that information. These measures are a part of the associated outreach or awareness efforts used by a number of European countries. For instance, the European Flood Awareness System (EFAS) is a system for monitoring and forecasting floods across Europe. It provides probabilistic, flood early warning information up to 10 days in advance (Maurer et al., 2012). Quite similarly, in Dresden, Germany, a website known as intermobil was set up that reported the results from traffic cameras installed to monitor Dresden bridges and roads (intermobil, 2022). The website attracted a huge number of visitors who were interested in knowing which routes would be the most feasible to take. Likewise, there are several other websites and projects as well that aim at allowing service staff and public transport users to share multimedia information on emergency situations through the Universal Mobile Telecommunications Services. These kinds of early warning systems appear to be quite successful in reducing the consequences of a risk event as they increase preparedness along with enabling traffic management measures to be considered. In terms of the benefits, it seems that such systems can have benefits of around 400 Euros for every Euro invested (Maurer et al., 2012). Through the establishment and use of early warning systems, the negative impacts of extreme weather events on different transport systems and the whole economy will be minimised. Also, once implemented, such systems are expected to serve for a long time without needing any major updates. In addition, as Enei et al. (2011) discussed, traffic obstructions lead to serious economic consequences, which can be minimised with the installation of monitoring systems. It has also been determined that in the future, monitoring systems will be widely used and will become less expensive as well. When road users receive accurate and timely information on traffic obstructions and alternative routes in a risk event, this will result in significant reductions in the economic consequences as well. Monitoring systems can also assist with detecting malfunctioning infrastructure elements, where proper monitoring of infrastructure assets such as bridges, slopes and roads can help prevent catastrophes. For instance, monitoring systems can support with understanding waterflows and flood levels along with assisting in drainage inspections (Doll et al., 2011).

One more example of an online web service is the Meteoalarm initiative for private car users that embark on cross-border travels. The website informs authorities and public regarding severe weather conditions in more than 35 European countries by integrating all important weather information originating from the official National Public Weather Services. This is done through consistent presentation of colour-coded maps and weather symbols that demonstrate what the weather might look like in different parts of Europe. Meteoalarm service is a long-term innovative solution that has already proved successful through its daily access rates reaching 12 million per day during warning situations. It is expected that more countries will participate in this initiative where the services then shall expand and perhaps provide information on weather warnings through emails, messages and even real-time images from users (Leviäkangas et al., 2011; Meteoalarm, 2022; GEOBENE, 2022).

Overall, it is deemed vital to monitor transportation systems in order to detect and quantify climate change vulnerabilities as well as improve the effectiveness of adaptation strategies.

Road Weather Information Systems comprise of sensor stations, communication networks, weather and pavement temperature model systems, traveller information and maintenance decision support systems. These can all assist with the long-term monitoring of impacts on road transportation during extreme weather conditions while also contributing directly to mitigating risks through the provision of real-time warnings and notifications of weather conditions to various road transport stakeholders (Papanikolaou et al. 2011; Andrey et al. 2001; Boon and Cluett 2002). Quite similarly, for railway tracks and slope failures, an adaptation example that is quite successful in mitigating the consequences of a flood event is the detection of events by local of slopes with sensors. Such a measure can enable safe operations and rapid recovery with reduced impacts (Collins et al., 2014).

Comparably, another noteworthy example for enhancing the resilience of railway transport is demonstrated by the Austrian Federal Railways (ÖBB Infra AG). To address existing and predicted risks from climate related hazards, the ÖBB Infra AG utilises a series of structural protection measures along with a railway-specific weather monitoring and early warning system as part of its risk reduction strategy. This is because complete protection from structural measures is not possible in some areas, such as the alpine environment, and due to a continuously changing risk profile because of climatic changes. An interactive web portal system is developed that collects information from different weather stations, satellites, radars, and weather projections for the complete railway network. The system then offers an assessment carried out on some of the important meteorological parameters such as precipitation levels. The system not only provides individualised and route-specific warnings, but it can also be used for identifying different weather conditions in advance that can possibly cause large disruptions to railway operations. Such alert systems which can issue warning notifications allow for a plan of procedures to be implemented in times of an extreme weather event being detected. This includes the establishment of temporary mitigation measures, specific route closures, imposing speed restrictions and other operational safety precautions. Overall, such functioning weather monitoring and warning systems are effective tools that can be referred to as a flexible risk management solution for addressing future changes in the intensity as well as frequency of climate change events (Climate ADAPT, 2017).

3.2.2 Technical flood protection measures

With future climate projections showing the likelihood of more intensive precipitation events, flood control becomes an important task. In a typical flooding event, it is expected that serious damages will be incurred by different infrastructure elements. In 2002, Prague experienced a severe flooding episode with total damages of 1 billion Euro. This event was recognised as one of the most expensive weather-related disasters in the history of the city with heavy damages on infrastructure, housing and environment. In order to achieve improved flood control, some adaptation measures that have proved successful in the past include the installation of fixed barriers. This includes construction and establishment of levees, dykes, protective walls and in some cases mobile barriers along rivers. Transporting and installing mobile barriers to areas potentially affected by floods is often part of the flood management plans devised. In terms of the costs associated with such projects, it was observed in Prague that implementation of flood protection measures that included fixed and mobile barriers along with closures, pumping systems and safety valves had a total estimated cost of 146 million Euros which was spent from 1997 to 2012. A cost breakdown analysis showed that the realisation costs for the flood control system amounted to around 144 million Euros, installation costs per event were 0.65 million Euros and the overall storage and maintenance costs per annum were 0.89 million Euros. These measures can be utilised for a long-term with a lifetime of approximately 80 years and are quite effective. Further, the implemented flood protection system proved successful in the 2013 flood event, where the system helped protected a great part of the area at threat and only very minor parts of the area were found to be flooded. Also, any weak points such as the capacity of the pumping station were identified and have been planned to be enlarged (Climate ADAPT, 2016a).

Another example of extreme weather events is observed through the common occurrence of storm surges in the North Sea, which has significantly increased since the 1950s. With future projections showing potential rise in sea levels, storm surges pose a major threat to Antwerp, a city in Belgium, where one of the estuaries narrows considerably at a particular point, resulting in raising high water levels. To protect the city, the Hedwige-Prosper polders project was launched for improving flood protection by mainly providing extra space to the Scheldt River for flooding. In addition, new estuarine intertidal areas are also created to provide space for tides. The project expects that opening the two polders can offer storage for storm surge waters, decreasing the water levels of the city and thus enhancing the safety in the urban and industrial areas. Further work includes moving dyke protection inland, deploying a system of creeks that will be dug in the polders. An economic analysis on this project revealed that investments on such projects is more cost-effective in safeguarding urban areas as well as economic activities from flooding as compared to constructing large storm surge barriers. The cost for this depoldering project was estimated as 25.8 million Euros in Belgium while a similar project in Netherlands is expected to cost between 40 to 49 million Euros. Regardless, the benefits of such a project are vast, including the major protection to the Belgian territories and it is anticipated that with consistent and continuous maintenance and upkeep, the project should be able to offer its protection abilities for several decades (Climate ADAPT, 2020a).

Not only road infrastructure but other transport related infrastructures are also likely to be seriously damaged due to floods. Thus, to achieve proper flood control, it is important to realise necessary adaptation measures such as regulation of rives, retention areas, adjusting protective walls and levees for controlling floods, even in constant climatic conditions. Furthermore, to protect cities and regions from flooding, it is also often seen that a combined effect of different adaptation measures is utilised by implementing several measures that can reduce the risks of flooding while working on increasing the future resilience of the areas affected. For example, the Tisza River Basin experiences a serious challenge of flooding due to a series of landscape changes. To address this challenge, work is being done on enhancing river defences, restoration of flood plains and creation of temporary reservoirs that can contain flooding and protect cities and the various infrastructure built along the river. The total cost for such a project was around 260 million Euros but with regular maintenance, such measures are expected to last for up to 100 years (Life Tree Check, 2022).

Adaptation measures specifically intended for railway infrastructures are usually aimed at enhancing the resilience of the railway assets. Several different technical adaptation measures have been reported in the past for addressing precipitation and flood events. Most of these technical measures are usually supplementary constructions to protect the infrastructure which is already in place. For example, in 2006, subsequent bursting of two dams due to heavy rainfalls, led to flooding of an important rail link in Prague. Damages included flooding of a railway control centre. To address this issue, a permanent measure was taken where the new control centre building was put on pillars, making it flood-proof. While the costs associated with this task were around 30,000 Euros, this is considered as a long-term and effective solution. In a similar fashion, pile construction is utilised for protecting buildings such as railway control centres with technical equipment necessary for the functioning of the railway system and with rather high investments costs against floods. Since these types of buildings are usually small structures in size, constructing them on piles is feasible. Approximately 5000 Euros are needed per pile, but the operational and maintenance costs are usually similar to a building which is not on piles. The benefits include a reduction in damage costs in case an extreme weather event occurs and consequently an assurance that crucial services by the railway control centre will be provided continuously to deal with the event (Doll et al., 2011; Maurer et al., 2012).

For railway tracks, constructing counterforts is an additional measure that is used at times to prevent the flooding of tracks. This temporary measure, which is used several times per year, can act as a substitute when a flood protection embankment is either being made or not there in place. A long-term adaptation solution is the construction of flood protection embankments that can protect railway tracks from flooding. To elaborate, in 2006, flooding resulted in huge damages to railway tracks in Lower Austria, where there were significant breakages of the flood protection embankments. The reconstruction process started with first the closures of breakages which costed around 3.6 million Euros. This was then followed by reconstruction of embankment dam sections which costed around 14 million Euros for a total length of 10.7 km. The remaining reconstruction works in this case costed a total of 82 million Euros for several long sections (Maurer et al., 2012). While the associated costs for this are quite high, this is a highly effective and a long-term solution where protection systems must be maintained regularly. Also, stability of slopes and embankments must be guaranteed to prevent catastrophic events.

In 2013/2014 winter, a run of winter storms culminated in severe coastal damages and widespread flooding in the United Kingdom. Amongst the various affected elements of infrastructure, the transport system was the most severely damaged. There were significant flooding damages to the road and rail infrastructure, railway lines had to be closed and services had to be suspended. During this period, a coastal section of the Southwest main railway line at Dawlish, Devon was severely damaged, where the line was cut off from rest of the railway network for two months. Damages due to huge waves were witnessed by the Dawlish railway station, stretch of the sea wall and foundations beneath the tracks which resulted in leaving the track unsupported. Following this critical event, in the long term, some options were considered. These included retaining the coastal route, building a second line and thereafter re-routing the main line. The adaptation measures included the installation of a temporary sea wall to prevent further damages, rebuilding and fortifying the breach with larger amounts of concrete and steel to further strengthen the structure, removal of collapsed cliff sections and then considering the building of a new higher and wider seawall in front of the existing seawall. Strong winds along with high waves frequently damage the railway station and tracks. Therefore, a 36.5 million Euros package of improvements was announced for this project, which included examining each option available for ensuring the resilience of the route. Construction of a new, higher and wider structure is expected to enhance resilience from waves, floods and other weather-related events while also taking predicted rising sea levels into account. This appears to be an excellent example of an adaptation option where the current infrastructure is adapted while work is being done on creating new infrastructures. Also, the new raised sea wall is protected from the sea and provides great protection to the railway line against strong winds and rain at Dawlish (Network Rail, 2014; Network Rail, 2019; BBC, 2020).

The Timmendorfer Strand coastal flood defence strategy also a similar example of such an initiative. Due to climate change, Timmendorfer Strand, a municipality in Germany is threatened significantly from impacts due to rising sea levels and storm floods. Therefore, the adaptation measures implemented included the construction of a sea wall that can provide a high degree of protection against coastal flooding and erosion. It has also been identified that sea walls require less space requirements as compared to other coastal defences such as dykes and can be heightened to face sea level rises. While construction costs of such a sea wall can be relatively high, these structures need low maintenance and are a much cheaper as compared to other options such as jetties. In terms of costs, these depend on the shape, volume, crest level, foundation level, wave loading and other characteristics of the sea wall. For example, in the Netherlands, a sea wall is estimated to cost 300 to 500 Euros per square metre of concrete whereas jetties related costs are estimated to cost 10,000 to 20,000 Euros per running metre. Overall, walls are long-term investments with lifetime of around 100 years. The estimated benefits are between 4 to 8 times higher than the estimated costs (benefit-cost ratio) (Climate ADAPT, 2015; Climate ADAPT, 2016b).

3.2.3 Adoption of adequate design standards, materials and maintenance of infrastructure elements

Adopting appropriate design standards and maintenance protocols for infrastructure elements is a common approach for mitigating risks due to extreme weather events. For instance, designing higher dimensions of road drainage systems to tackle future weather conditions such as precipitation events is highly recommended. As part of flood protection and management options, some commonly used adaptation measures include the construction of extensive sewerage and flood protection works for collecting the superficial runoff and maintenance of lengthy flood protection works to collect water runoff and for enhancing the overall flood protection of cities. To prevent slope failures, slopes can be re-engineered to change grade, drainage can be improved, or stabilisation can be provided in order to reduce vulnerability through robustness (Smethurst et al., 2017). Furthermore, due to a changing climate and an increase in the frequency of extreme weather events, maintenance works need to be done frequently. Comparing predicted impacts of future extreme events to past and current design codes is also important to prevent major disasters. It is also suggested that rising water tables must be considered in the designing process while maintenance can be easily achieved through self-flushing drains that can be inspected effortlessly. Most experts state that proper and scheduled maintenance of drainage can help prevent flash floods. Also, drainage upgrading measures should be adopted in those regions where intense precipitation events are likely to occur more frequently (Doll et al., 2011).

Quite similarly, for roads and bridges, proper design and maintenance of these infrastructures including pavements is recommended where pavement monitoring can be carried out along the whole length of motorways and at least once a year to reduce the vulnerability of roads. In addition, the service life of pavements can be prolonged with adequate maintenance. Adaptation measures on improving the stability of slopes and embankments also involve proper drainage measures, use of adequate construction materials and appropriate maintenance. While the costs of these measures depend on the techniques used and the maintenance works needed, it is expected that the costs for improving design methods are generally low, as compared to their possible advantages. Also, in terms of construction materials, these are usually chosen taking into account cost effectiveness (Doll et al., 2011; Tegethof, 2011). For adapting railway infrastructures to climate change and extreme weather events, maintenance measures are also quite relevant.

3.2.4 Vegetation management as a flood protection measure

Vegetation acts as a nature-based solution for effectively adapting to rising flood risks. Vegetation management has a huge scope as it can be used for roads as well as railways. Vegetation management can also be used to enhance slope stability and is an effective measure in reducing vulnerability. For roads, vegetation management actions involve cutting down trees that may be problematic, selecting proper vegetation, removing vegetation close to pavements and planting of vegetation to stabilise soil. Such measures can assist with reducing traffic obstructions and stabilisation of slopes. Vegetation management along railway tracks has several effects on railway infrastructure. For instance, protection forests, built at a distance to the rail tracks to avoid trees falling directly on the tracks, can help decrease the chance of landslides due to heavy rain as the ground is better stabilised by the trees and their roots. However, vegetation also may act as a risk for the rail infrastructure where storms may result in trees falling. Also, it may take up to 100 years to avail full benefits and protection of plantation. Regardless, such measures are easily implemented, and the investment and maintenance costs seem to rely on the required vegetation type. A normal low vegetation initiative near the rail tracks that requires regular cutting to safeguard railways against floods is expected to cost much lower as compared to a protection forest, where the latter can cost 100 Euros per hectare for forest management and 50000 Euros per hectare for recultivation of damaged protection forests (CCSP, 2008; Lindgren et al., 2009; Doll et al., 2011).

3.2.5 Reviewing and updating emergency management plans

Adaptation measures also include management options which are focused on providing solutions when an extreme weather event occurs, resulting in transport infrastructure disruption. Such options help reduce negative impacts of extreme events while making sure alternative railway and road routes as well as efficient emergency transport management schemes are available when needed. Reviewing and updating emergency management plans is an effective adaptation measure that can help prepare for increased frequency of extreme weather events. Emergency plans are usually an approach for regulating the information chain if there is a flooding threat. These plans can provide assistance to all authorities, emergency response organisations and all other relevant stakeholders before and during a flood event by informing people about the floods, arranging all necessary control measures and combating floods in an efficient manner. This measure can also involve improving and increasing the preparedness for flood events that may happen at locations that are yet to be upgraded. These measures can be easily implemented, are able to serve for a long time and require very low costs. However, the associated effectiveness is also expected to be low (Maurer et al., 2012).

3.2.6 Incentives and other initiatives to implement adaptation measures

Incentives and regulations must be developed and imposed for increasing the resilience of transport infrastructures to extreme weather events. Implementation of relevant adaptation measures along with carrying out their maintenance can help reduce the risk of floods and thus incentives and regulations can act as an important step towards the realisation of necessary adaptation measures. In addition, such incentives and regulations can also assist with decision making process for new infrastructure projects leading to the construction of more economic, efficient and useful infrastructure with reduced vulnerability in the future. In terms of the costs, such incentives and regulations are expected to not cost much. Overall, regulation schemes are considered as crucial as physical adaptation measures are. Thus, it seems that providing incentives to stakeholders to adopt adaptation measures is very important.

Plans can also be developed to reduce the flooding impacts due to heavy rain. One example of such an initiative is the Cloudburst Management Plan that has been adopted in Copenhagen, Denmark. In the past, Copenhagen was impacted by several major rainfall events that resulted in serious and extensive damage where repair was very expensive. Since the occurrence of such events is anticipated to become more frequent and intense, the plan developed includes the cost assessment of different adaptation options (i.e. new options compared to traditional measures), cost of damages with or without the implementation of adaptation measures and the resulting impact on the financial health of the impacted stakeholders. The outcome of such an activity clearly demonstrated that a societal loss would be experienced if there is a continued focus on traditional sewage systems rather than on alternative and innovative solutions. The latter includes measures that look at draining and storing excess water at ground level. The overall Cloudburst Management Plan comprises of pipe-based and surface solutions that include designing retention areas and roads for storing, detaining, or transporting large amounts of water (EEA, 2018).

Initiatives to raise public awareness and preparedness are also an excellent approach that can be implemented ahead of time through sharing knowledge and coaching the public that can assist with identifying hazards and risks, taking action to build safety and resilience, and reducing future hazard impacts. Usually, individuals and communities are willing to take part and ownership in this. In addition, public education and public awareness for risk reduction can encourage and motivate societies to participate in reducing future suffering. These initiatives are applicable to all transport infrastructure assets and can help reduce the vulnerability as well as consequences of the risk. The costs associated with such practices are expected to be low while the vision and benefits can be long-term. Public education and awareness can be approached through campaigns, participatory learning, informal education and formal school-based interventions (DEFRA, 2011; IFRC, 2011).

3.3 Adaptation measures for wildfires

As discussed earlier, extreme heat increases the risk of catastrophes where heat can exacerbate drought, hot and dry conditions that can result in wildfires. Climate change and extreme weather events are making heatwaves more intense, especially in European countries where different transport infrastructures are now at a constant threat posing a further risk to people, ecosystems and economy. Based on the findings presented in Table 3, which presents a summary of the adaptation measures identified for heatwaves and wildfires, it seems that there are various strategies that can be implemented to build transport resilience to extreme heat and resulting wildfires. Some of these adaptation measures and strategies are discussed here in detail.

Table 3. Summary of adaptation measures for wildfires

Asset	Measure	Miti.	Costs	Lifetime	Impact
Ra	• Automatic monitoring, modelling and forecasting systems • Establishment of early warning systems	V, C	Moderate	Long-term	M
Ra	Operational and maintenance measures for ensuring climate-resilient railway infrastructure	H, V, C	Moderate/High	Long-term	H
Ra	Installation and improvement of cooling signals and fans	H, V, C	High	Long-term	M
Ra	Upgrading of track: tracks should be replaced as part of normal maintenance	V, C	Moderate/High	Short-term	M
Ra	Painting railway tracks with white colour	H	Low	Short-term	M/H
Ra	• Pre-stressing of steel, • Deployment of heat resistance material	H, V, C	Moderate/High	Long-term	M/H
R	Polymeric pavement materials and fibre-reinforced concrete overlays	V	Moderate	Long-term	M/H
Ra	Selection of suitable vegetation along rail tracks to reduce the risk of fires	H, V	Low	Short-term	M

R, Ra, B, E	Fire prevention additional staff	H, V, C	High	Long-term	M
R, Ra, B, E	• Fire prevention programs and technical assistance • Forest monitoring and mapping	H, V, C	Moderate	Long-term	L/M
R, Ra, B, E	Wildfire management: To exchange information and technical details for wildfire management	H, V, C	High	Long-term	M

3.3.1 Monitoring, modelling, forecasting and early warning systems

Monitoring, modelling and forecasting, and early warning systems are a commonly employed adaptation measures that aim to increase preparedness and enable different management measures to be taken in advance. By means of providing early warning systems, it is expected that the negative impact of extreme weather events - particularly heat waves leading to wildfires - on transport systems and the whole economy will be minimised.

To ensure smooth operations of trains during high temperatures, one adaptation measure that is often used involves the installation of automatic remote monitoring systems that can intensively monitor the temperatures of railway tracks. As part of calculating rail temperatures, railway infrastructure managers also install probes to obtain instant alerts when track temperatures rise (Network Rail, 2015). The system can send notifications to railway operators informing them about the section of the track which may be expanding too much and could result in further consequences. This warning triggers an early reaction where local speed restrictions are introduced as slower trains would cause lower forces and impacts on the track, which further reduces the chances of rail bucking (Network Rail, 2022a). Therefore, in periods of extreme heat, automatic monitoring systems can help detect instances that can cause rail buckling and help prevent further damages to tracks, infrastructures, trains and people due to issues such as train derailment, cancellations, blockages and several others (Doll et al., 2011). In terms of the costs, these are dependent on the type of monitoring systems. Monitoring systems for track temperatures can be a very cost-efficient measure. However, an increase in the investment costs can be expected as automation increases in monitoring procedures, but with lower running costs. Costs are also dependent on the area being monitored. Indeed, monitoring the conditions of the railway tracks of a whole network will be expensive and an extensive job as compared to monitoring areas that only exist along critical parts of the network.

In situations where hazards are going to be expected frequently, it can be beneficial to have an Early Warning System. For an effective system, a few considerations have to be taken into account, this includes community participation, education, awareness and emergency preparedness. These systems need to be developed with practical and scientific data and also need to be inclusive of the different community requirements and the relevant risk factors. Such systems should primarily comprise of:

1. Expansive risk knowledge to ensure nothing is overlooked,
2. Prompt monitoring and warning capabilities,
3. Resilient dissemination and communicative methods and.
4. Ability to respond and act respectively.

It is not required to develop these systems from the ground up, and the knowledge can be borrowed from regions where these are in place or experience high hazard frequency.

As a region which has a few different systems in place, Europe has in place mainly:

1. Meteoalarm - a collective effort from The Network of European Meteorological Services (EUMETNET) that provides extreme weather event alerts,
2. Copernicus Climate Change Service (C3S) provides high-quality data tailored to the requirements of various socio-economic sectors and
3. Risk Data Hub of the Disaster Risk Management Knowledge Centre (DRMKC) that provides curated EU-wide data utilizing hosting datasets connected to national platforms.

There are also smaller scale operations or systems such as in:

1. Austria - applied to railway transport.
2. North Macedonia - applied to heatwaves and national heatwave preparedness.
3. Tatabanya (Hungary) - urban heatwaves and forest fires.
4. Emilia Romagna (Italy) - as a regional Weather Alert Web Portal developed in conjunction with real-time hydro-meteorological monitoring technologies.

It is predicted that Europe will experience an increased frequency of heat waves, which will grow in intensity according to RCP scenarios, every 2 years in the second half of the 21st century. As a tactic, countries using Early Warning Systems and rely on EuroHEAT in Europe which is an information and decision-making tool.

Fire risk also plays a significant role as it is dependent on a multitude of factors such as climate change, vegetation, socio-economic factors and forest management. As it impacts Southern Europe more than other parts of Europe, the European Forest Fire Information System (EFFIS) plays a key role in providing support year-round through various services and information. It is based on a module which generates a map anywhere between 1-9 days forecasting fire danger using numerical weather simulations (Climate ADAPT, 2019a).

3.3.2 <u>Operational and maintenance measures</u>

Maintenance measures must be implemented and increased in places that witness excessive heat periods. Maintenance can include many different options to reduce the vulnerabilities of transport infrastructure in undesirable weather conditions.

Heat waves can result in distortion of railway tracks. To tackle this issue, most Southern European countries such as Italy adopt a simple adaptation measure which involves painting the railway tracks in white colour to combat the distorting effects of heat on metal. However, in some places such as further North in Austria, such measures are not (Molarius, 2012).

Further, in 2018, this technique of painting railway tracks was tested by in the eastern Switzerland canton of Graubünden by the Rhaetian Railway External link with the aim of keeping the metal tracks from buckling or deforming in the heat. White paint has been observed to show a positive impact in strong sunlight (SWI, 2018). As the painted rail has a higher reflectance and lower heat absorption than a normal (brownish) rail. Quite similarly, in 2019, a national railway company of Germany, Deutsche Bahn, also painted a section of their railway tracks with white paint with the goal of preventing the serious issue of overheating rails and warped tracks during heatwaves. Their tests indicated a reduction of up to -7 Kelvin in temperature by painting rails with white colour when compared to normal conditions (Railway Technology, 2019). The rails reflected more light and thus became less hot than their conventional counterparts. In 2022, Network Rail, a leading infrastructure manager of most of the railway network in Great Britain also implemented this measure of painting certain parts of the rail white so that less heat is absorbed by the rails which would result in reduced expansion. It was reported that a painted rail is usually 5°C to 10°C cooler (Network Rail, 2022b). In terms of lifetime, this measure requires regular repainting and repair works depending on usage, but the associated costs can be expected to be low. Overall, such an adaptation measure can help mitigate the hazard of wildfires on the railway tracks.

Installing and improving cooling signals is a technical adaptation measure that can be implemented to prevent overheating of signals and other railway infrastructures in countries expecting very high temperatures during summer months. This measure is expected to be rolled out in the entire Europe if temperatures continue to rise until 2050. Since signals require regular standard maintenance, such a technology can be easily installed. However, due to a large number of signals and budget restraints, it might be expensive to implement such a measure and would require regular maintenance and perhaps upgrading will be needed. Nevertheless, costs are also dependent on the number of signals and other electronic equipment that has to be cooled as well as the number of days per year when cooling is needed. Regardless, the measure can perform for a long-term where cooling signals and fans can assist with keeping some equipment functional during extreme heat periods. The prevention and reduction of overheating of critical railway infrastructure can help ensure smooth operations on the rail infrastructure with several benefits. Reduction in malfunctioning of signals and other vital electronic equipment can assist with reducing delays in heat periods. In terms of flexibility, adapting to changing conditions is easy with this measure as the cooling systems can react accordingly based on changing temperatures in the future (Doll et al., 2011).

Furthermore, railway tracks must be upgraded on a regular basis as part of normal maintenance to tackle catastrophic issues such as wildfires. Depending on the type of upgrade, the cost of this activity can vary where replacing a railway track can range from £0.25 million to £1.6 million per kilometre (Doll et al., 2011). Some common maintenance activities include checking the stability of the track and strengthening any weak parts before the start of summer. In addition, when tracks are constructed of short rails bolted together, small gaps are left in between each one to allow for expansion (Network Rail, 2022b). Other activities commonly carried out by infrastructure managers include replenishing the ballast that surrounds the sleepers, and re-tensing (stretching) continuously welded rails before the summer period arrives. Also, any construction or management works that may hamper the stability of the tracks resulting in an increased risk of buckling are avoided in summers. Sprinkler systems are also introduced to cool rail temperatures at key junctions and investigative tests on this technique have demonstrated that temperatures may reduce by four degrees in ten minutes using the sprinklers (Network Rail, 2015).

In terms of transport infrastructures such as bridges, one maintenance activity that is highly recommended is the frequent inspection of these infrastructures to check for weather-related issues (especially corrosion) to reduce the risk of further damage and destruction. For bridges, adequate design and maintenance is also very important. One of the main climate change concerns relevant to design, construction and management of existing bridge structures is the increased occurrence of temperature fluctuations. Current standards for bridge structures exhibit significant resistance to such effects; nonetheless, the research on new climate-proofed standards is ongoing (Climate ADAPT, 2019b). To avoid infrastructure damages in the future, it is recommended to compare the predicted impact of future extreme weather events such as heatwaves to current and past design codes.

3.3.3 Materials

Currently, some commonly adopted technical adaptation measures adopted to protect against the main risks of extreme heat include endless welding of rails, deployment of heat resistance material and pre-stressing of steel. Usually, endless welding of rails is done when new tracks are built, and it is expected that this technology will be implemented in the future as well for the construction of new tracks. However, for existing tracks this is not possible at least 2050 due to the high costs associated with upgrading. Deployment of heat resistant materials is also done as a measure to avoid rail buckling and resulting delays and cancellations of trains, as well as derailments in worst case (Doll et al., 2011). In the UK and several European countries, rails are pre-stressed to withstand higher temperatures. In this process, when steel rails are installed, a process called stressing is carried out to protect rails against buckling. The rails have a specified stress-free temperature, most likely the equivalent of the mean summer rail temperature of the country (i.e. the range of temperatures the track can comfortably cope with). As temperatures continue to rise in most parts of Europe, this seems to be an obvious solution, however, this measure may also result in certain issues. Stressing rails to cope with high temperatures in summer would make them less resilient to low temperatures during winter. For example, if Britain's rails are stressed to the same degree as those in very hot countries, there may be a risk of increased tension on the rails in winter (Network Rail, 2022c). Thus, there must be a right balance to make the network as resilient as possible all year around. In terms of cost savings, one study estimated that approximately £10k could be saved per stressing operation of a track renewal item. In a yearly program of work, where rerailing is part of the process, implementing the stressing operation could lead to savings of £9 million per annum (ORR, 2008). Also, such a measure is expected to serve for a long-term and is capable of mitigating or reducing all components of risks to the railway tracks from heatwaves.

For roads, polymeric pavement materials and fibre-reinforced concrete overlays is an adaptation measure that is carried out to mitigate or reduce the risks caused due to heat. This includes the use of new, heat-resistant paving materials and polymer-modified bitumen. Pavement technology is also improved as part of this measure where polymeric grids are used to prevent rutting and overall adjustments of structural designs of the pavement are made. In addition, materials that can reflect solar radiation are used on surfaces along with materials that have high thermal conductivities. The road surface reflectance can be increased through the use of bright, coloured elements on the road or by coating road surfaces with reflective materials. Other activities in this measure include treatments with polymeric and other non-conventional aggregates, addition of rubber to asphalt, use of new additives for asphalt pavements, fibre reinforcement and use of porous salt. Often, concrete is also used in higher quantities due to its increased temperature resistance abilities and other advantages such as lower need for maintenance, possibility of increased load and longer lifetime. The design of concrete pavements may also be changed to reduce the water quantity needed. Also, a simple measure to cool road pavements would involve using water (Climate ADAPT, 2019b).

Overall, these materials and technologies can be used in almost all of European regions, but the proper construction materials should be selected based on cost effectiveness. Also, the measures are expected to serve for a long time with various benefits (Doll et al., 2011).

3.3.4 Adaptation of fire management plans

Emergency plans for natural disasters such as fires, floods, earthquakes, and other events need to tackle specific items to be effective. This includes outlining the specific area or region responsible for implementation and execution of the plan. The goal of any effective plan is to prevent the hazard, followed by reducing the vulnerabilities and eliminating consequences with the highest risks. When referring to a fire management plan, it can include the following:

- ✓ Prevention of fires by implementing a system that can reduce or eliminate the factors
- ✓ Protecting people, properties such as land and buildings and forests from fires
- ✓ Using controlled fire systems to accomplish forest management and other land uses.

For a plan to be executed effectively, it needs to be tailored to the needs of the community or the area of impact, a good knowledge interpretation of past events, sustainable number of resources like staff, equipment, vehicles and technology. Similarly, an effective fire management plan will depend on the involvement of all relevant stakeholders. Specifically, some common and suggested mitigation measures are as follows (Climate ADAPT, 2020b):

1. Additional staffing - due to the uncontrolled nature of forest fires and rapid expandability, staff or crew members required to operate equipment can be a major challenge. It is estimated that it can cost 8 million Euros per year for hiring 4000 seasonal and permanent staff members (Maurer et al., 2012). While this is a significant cost, it has a very high impact on the ability to tackle fire-related events. It would be a program that can be implemented long-term and expanded making it a worthwhile investment.
2. Modern quality forest monitoring and mapping systems - data that can be collected easily and monitored well in advance to track the development of fires and create plans in response can prevent large scales fires from developing and significantly improve firefighting capabilities. This is estimated to be an expensive system to implement and will depend on the level and area of execution, however, can have a significant impact. Running a program like this can be permanent.

3. Information exchange and collective development for wildfire management - this can be quite complex to implement, as it requires various stakeholders to agree, the quality of data has to be standardised, and the exchange of information has to be prompt to maintain relevance.

On the whole, a fire management plan will require high investment costs as fire management activities must be a part of the national or local spatial plans and thus have a long lifetime (up to decades). However, the benefits are significant as well, being related to prevention of fire risks, improved monitoring capacities, enhanced response in case of fire events and rehabilitation of damaged infrastructures.

3.3.5 Land and vegetation management

Promoting the recovery of native vegetation and habitat is an adaptation measure that can confer resilience to future climate or fire disturbance in several places. Such activities of planting fire-adapted native plant species can be done before or after a fire event. After a wildfire event, active planting or seeding of native species can boost the regeneration rate and/or competition with disturbance-adapted invasive species. However, post-fire revegetation in an entire burned area may be unrealistic and unnecessary. In such cases, the focus of revegetation should be on small target areas (Sample, 2022).

Vegetation along roads can contribute to environmental protection as well as have an adaptation function. For instance, roads can be protected from direct sunlight and thus heat. However, improper vegetation along roads can be a huge risk factor for traffic disruption in the events of extreme weather while also influence road safety. Therefore, in line with building climate resilient roads, it is recommended to replace mature trees with hedges and planting vegetation at sufficient distances from the roads (Climate ADAPT, 2019b).

Similarly, for railway infrastructure as well, vegetation management is very important. While vegetation can protect rail infrastructures against mass movements, wild vegetation can also pose a fire hazard as the brush and leaves on the tracks are flammable. Wildfires are often caused near railway lines due to weather conditions and grassy areas with dry or dead vegetation where such areas can be easily ignited by sparks from the brakes of railway vehicles. With global warming and a rise in surface temperatures expected, vegetation fires can be expected to occur frequently in the future. To deal with this issue, vegetation management can be carried out along with monitoring activities to identify hotspots that can be used to mitigate or reduce the risks of fires (Nezval, 2022).

In terms of costs, the investment as well as finances depend upon the type of vegetation which is required and thus are based on the vegetation function with respect to the infrastructure protection. Regardless, this adaptation measure requires frequent maintenance but if managed properly, it should be able to reduce the risk of fires to a certain extent.

An example of a place implementing land and vegetation management actions as adaptation measures against wildfires is the county of Dorset in southwest England. Following a large fire in 2011 that destroyed more than 50 hectares of heathland, the country identified that fire risks are likely to increase with a changing climate and due to increased temperatures and frequent dry conditions. Therefore, the measures adopted include adaptation of fire management plans and integrated land use planning along with adaptive management of natural habitats. To do so, existing recreational sites are improved along with developing new recreational infrastructure, lands are purchased as an alternate open source, more wardens and rangers are provided, monitoring equipment is purchased, land management is carried out to reduce fire loads and fire risks and firefighting equipment is purchased while developing other firefighting instruments as well. In addition, for managing fires, the county has updated maps that are readily available on mobile data terminals to fire wardens and other related staff to show fire access routes. Social media platforms and messaging applications are used for circulating information about fire incidents to land managers. Finally, an on-line platform known as Firewise UK is also launched for raising awareness on ways to reduce fire risks to nearby areas (DWFire, 2022). Regarding costs of implementing all these exhaustive measures, it was identified that only marginal costs are required for administrative works of the measures. In 2015, a total expense of 5.1 million Euros was estimated as the cost of the measures to mitigate the impacts of urban development on heathland in Dorset. While the costs may seem high, the benefits include a reduced risk of fires, preservation of biodiversity, contributions to reducing sensitivity to a changing climate and assurance that the heathlands integrity will not be further diminished by steady increases in urban pressures. However, quite recently, in 2021, large wildfires broke out in Dorset heathland where almost 13 hectares of forestry plantation was destroyed. This shows that the adaptation measures will need to be carefully assessed and properly implemented with requiring several updates every few months (Climate ADAPT, 2020c).

Another city addressing the impacts of urban heatwaves and forest fires is Tatabánya in Hungary. Hungary is known for its continental climate that is characterised by hot summers where temperature extremes peak up to 42°C with overall low humidity levels. Over the last couple of decades, heatwave events have become more frequent, longer and intense with future climate projections indicating that these trends will persist in the upcoming decades. Heatwaves and wildfires are the two main climate-related risks which will continue to hit Tatabánya. Therefore, to deal with these issues, the city has developed a mix of soft measures. These include:

- ✓ a local heat- and UV- alert system: a heatwave and UV protocol is set in action during extreme hot weather predictions,
- ✓ warnings for heatwaves or high UV radiation are issued by meteorological service and national health office to local authorities, followed by citizens receiving alerts and advice on how to prepare
- ✓ improving the capacity of the fire brigade

Overall, the adaptation options implemented in this case involved:

- ✓ Monitoring, modelling and forecasting systems
- ✓ Establishment of early warning systems
- ✓ Heat health action plans
- ✓ Capacity building on climate change adaptation
- ✓ Adaptation of fire management plans
- ✓ Awareness campaigns for behavioural change

The costs for this plan were funded through the municipal budget aimed at environmental education and climate change which provided approximately 15,000 Euros. In terms of the success of this plan, it was observed that the heat alert system was activated several times already in the last 10 years where an average of three to five alerts were issued yearly in the city. In addition, the UV alert system has been activated once every year. Also, the inhabitants are now more aware of what needs to be done during a heatwave or UV radiation alert. Furthermore, through a well-managed emergency response system and excellent fire management plans which include providing specialist training and equipment, improving the road network, providing systems to detect fires early, and using a fire weather index system, Tatabánya has enhanced the capability of fire brigades to fight forest fires efficiently. The plan should be able to serve for a long-term with constant revisions needed (Climate ADAPT, 2020d).

4. General recommendations and survey outcomes

To develop a decision-making procedure based on resilience, it was considered necessary to collect information on risk mitigation measures to be incorporated into a risk-based predictive model. To this end, a questionnaire was developed to obtain feedback from specialists dealing with transport infrastructure management on the effectiveness, costs, and time-frequency of the most common risk mitigation measures. The survey intended to collect responses on a list of the most relevant risk mitigation measures that can be adopted for extreme natural hazards, namely floods and wildfires. This section provides the survey outcomes and recommendations for some generic adaptation measures that have been used to adapt different transport related assets and to increase their resilience. It must be noted that there were 19 survey respondents and the data collected is anonymous and confidential. It is used exclusively for the purpose of this research project.

The survey was designed to collate the possible mitigations that can be employed to reduce the risk to different infrastructure assets from floods and wildfires. Each risk mitigation is further subcategorised into the Hazard, Vulnerability and Consequence elements that are used in risk calculations. Therefore, based on the two risk events studied, the Hazard can be mitigated by changes that reduce either the frequency of the risk event at a site, or reduce the intensity of that risk event at a site, while the Vulnerability of an asset can be mitigated by changes that reduce its exposure or increase its resistance to damage and the Consequence of damage can be mitigated by removing people from danger or improving the ability to recover afterwards.

The results are obtained in terms of effectiveness, costs and lifetime of the provided adaptation measure. The effectiveness criterion requires ordering the measures from the most effective (1) to the least effective (total number of measures) in terms of the effect the risk event will have on the respective infrastructure asset. For costs, these are assessed based on the estimated cost compared to the rebuilding cost that would be required if the asset fails. The costs are categorised as:

- ✓ Little cost (<25% rebuild cost)
- ✓ High cost (50%-75% rebuild cost)
- ✓ Very high cost (>75% rebuild cost)
- ✓ Moderate cost (25%-50% rebuild cost)

The final criterion requires a value to be input for the predicted lifetime (frequency of application of the measure) of the proposed adaptation measure.

4.1 Floods

4.1.1 Bridges

Changing channel characteristics, or installing sub-infrastructures such as dams, gates and bypasses, are some adaptation measures to control and manage flood flows and can assist with mitigating the hazard to bridges. The survey results indicated that all technical adaptation measures proposed for mitigating the hazard of floods to bridges are moderate in terms of their effectiveness and are predicted to have a lifetime of more than a decade or even two decades in some cases. However, the costs associated with such measures can be towards the moderate to high side. In terms of controlling vegetation and other materials on site, such a measure is more of a management option and thus while it is moderately effective, it has little associated cost but will need regular maintenance every year.

In terms of the mitigations to vulnerability of floods for bridges, both, technical as well as management options are proposed, and the outcomes of the survey demonstrated that all these measures are moderately effective, where costs can vary from being moderate to high. However, for measures such as relocating the infrastructure to another site, these are considered as very high-cost measures. Regardless, all measures have a lifetime of nearly a decade or even more in some cases.

Mitigations to the consequence of floods for bridges are usually management options. The survey proposed measures such as closing the asset to protect users and evacuation plans. Such measures are considered not very effective and have respective low costs and lifetimes.

Table 4. Mitigations to Hazard of floods for bridges

Measure	Effectiveness	Costs	Lifetime
Increase the width or depth of the channel	3	Moderate	11 Years
Install a dam or weir upstream to control the flow	3	High	2 Decades
Install a bypass channel that diverts flood flow around the site	3	High	14 Years
Install a weir or channel gates to control sea storm surge	3	Moderate	17 Years
Control of vegetation, litter and other materials at site	3	Little	1 Year

Table 5. Mitigations to Vulnerability of floods for bridges

Measure	Effectiveness	Costs	Lifetime
Relocate structure to another site	3	Very high	2.5 Decades
Install drainage to remove pluvial extreme rainfall	3	Moderate	9 Years

Raise the height of the structure	3	High	17 Years
Protecting bridge elements (piers, wing walls, ...) with riprap (rock armor)	3	Moderate	8 Years

Table 6. Mitigations to Consequence of floods for bridges

Measure	Effectiveness	Costs	Lifetime
Close the asset to protect users	2	Moderate	7 Years
Evacuation plans to remove people from danger	2	Little	5 Years
Insurance against flood damage costs	3	Moderate	2 Years

4.1.2 Slopes

Similar to bridges, the survey results indicated that adaptation measures such as changing channel characteristics or installing sub-infrastructures can be moderately effective in mitigating the hazard of floods to slopes. However, these measures are suggested to require moderate to high costs but can serve for close to a decade.

Further, the survey results demonstrate that measures to mitigate the vulnerabilities of floods for slopes such as installing drainage to remove pluvial extreme rainfall water or installing flow channels can be moderately effective measures which would require moderate costs as well and can serve for a decade at least. Measures such as resurfacing with the use of resistant materials or replacing the slope infrastructure with alternative structures can be costly measures that are not very effective in reducing the vulnerabilities. Regardless, these are also expected to serve for more than a decade.

With regards to mitigating the consequences of floods for slopes, measures such as closing the associated road/rail asset and implementation of evacuation protocols seem to be effective and cost-effective options but ones that will require regular updating.

Table 7. Mitigations to Hazard of floods for slopes

Measure	Effectiveness	Costs	Lifetime
Increase the width or depth of the channel	3	Moderate	7 Years
Install a dam or weir upstream to control the flow	3	High	12 Years

Install a bypass channel that diverts flood flow around the site	3	High	1 Decade
Install a weir or channel gates to control sea storm surge	3	Moderate	7 Years

Table 8. Mitigations to Vulnerability of floods for slopes

Measure	Effectiveness	Costs	Lifetime
Install drainage to remove pluvial extreme rainfall	3	Little	1 Decade
Install flow channels to avoid erosion of slope	3	Moderate	11 Years
Strengthen the structure with soil pinning or geotextile	3	Moderate	8 Years
Resurface with resistant material (concrete/steel)	4	High	15 Years
Replace with alternative structure (wall)	4	High	12 Years
Protect the asset using mass retaining system: riprap or gabion stone	3	Moderate	13 Years

Table 9. Mitigations to Consequence of floods for slopes

Measure	Effectiveness	Costs	Lifetime
Close the associated road/rail asset to protect users	2	Moderate	5 Years
Evacuation plans to remove people from danger	2	Little	5 Years
Insurance against flood damage costs	3	Moderate	3 Years

4.1.3 Road pavements

For road pavements and roads, the survey responses demonstrate that all technical adaptation measures for mitigating hazards of floods are moderately effective with lifetimes of more than a decade, but the costs may vary from moderate to high, depending on the measure. Vegetation and debris management is a low-cost measure that can be effective to a certain extent if carried out properly and regularly.

In terms of mitigations to vulnerabilities, relocating the infrastructure to another site may be a highly effective and long-term option but is expected to be a costly measure. Other measures such as installing substructures or changing the characteristics of the infrastructure such as raising the height of the road may be moderately effective and long-term options with moderate to high costs required to implement such measures. Management options such as regular cleaning and maintenance plans are inexpensive measures that can be moderately effective too.

During flood events, any flood related consequences can be reduced effectively through closure of roads and implementation of strong action plans such as evacuation protocols to remove people from danger. Insurance options also help protect against flood damage costs. However, while these measures seem to cost moderately, they may require regular updating and thus are short-term options.

Table 10. Mitigations to Hazard of floods for road pavements

Measure	Effectiveness	Costs	Lifetime
Increase the width or depth of the channel	3	Moderate	13 Years
Install a dam or weir upstream to control the flow	3	High	16 Years
Install a bypass channel that diverts flood flow around the site	2	High	14 Years
Install a weir or channel gates to control sea storm surge	3	Moderate	11 Years
Control of vegetation, litter and other materials at site	3	Little	1 Year

Table 11. Mitigations to Vulnerability of floods for road pavements

Measure	Effectiveness	Costs	Lifetime
Relocate road to another site	2	Very high	13 Years
Install drainage to remove pluvial extreme rainfall	3	Moderate	1 Decade

Raise the height of the road	3	High	13 Years
Increase size of culvert to manage flow	3	Moderate	1 Decade
Periodic drainage systems and culvert cleaning maintenance plan	3	Little	1 Year

Table 12. Mitigations to Consequence of floods for road pavements

Measure	Effectiveness	Costs	Lifetime
Close the road to protect users	2	Moderate	4 Years
Evacuation plans to remove people from danger	2	Moderate	5 Years
Insurance against flood damage costs	3	Moderate	2 Years

4.1.4 Railway Tracks

For railway tracks, the survey responses demonstrate that technical adaptation measures to mitigate hazards of floods are moderate to less effective options while being long-term options but ones requiring high costs.

Technical measures proposed for mitigating vulnerabilities such as relocation of the asset or adjusting the characteristics of the infrastructure and related sub-infrastructures are also suggested to be moderately effective and long-term options with varied costs, mainly depending on the activity type.

Flood related consequences can be mitigated effectively through closure of railway tracks and implementation of strong action plans such as evacuation protocols. However, it is understood that emergency plans can be improved at the margins but will not make a huge difference. Overall, all such measures are short-term options that require consistent management.

Table 13. Mitigations to Hazard of floods for railway tracks

Measure	Effectiveness	Costs	Lifetime
Increase the width or depth of the channel	3	High	11 Years
Install a dam or weir upstream to control the flow	4	Very high	1 Decade

Install a bypass channel that diverts flood flow around the site	3	High	1 Decade
Install a weir or channel gates to control sea storm surge	4	High	9 Years
Control of vegetation, litter and other materials at site	3	Little	1 Year

Table 14. Mitigations to Vulnerability of floods for railway tracks

Measure	Effectiveness	Costs	Lifetime
Relocate railway to another site	3	Very high	13 Years
Install drainage to remove pluvial extreme rainfall	3	Moderate	7 Years
Raise the height of the track	3	High	11 Years
Increase size of culvert to manage flow	3	Moderate	9 Years

Table 15. Mitigations to Consequence of floods for railway tracks

Measure	Effectiveness	Costs	Lifetime
Close the railway line to protect users	2	Moderate	2 Years
Evacuation plans to remove people from danger	3	Moderate	4 Years
Insurance against flood damage costs	3	Moderate	2 Years

4.2 Wildfires

4.2.1 Bridges

The survey responses indicate that management measures such as controlling vegetation, materials and possible sources of ignition are moderately effective in mitigating the hazard of wildfires for bridges. Such measures are suggested to have little to moderate costs but as expected with any management options these will be required to be updated regularly on an annual basis.

For mitigating vulnerabilities associated with wildfires, measures such as fire control systems and replacement of flammable elements are also suggested as high to moderately effective options with moderate costs required. While fire control systems are recommended to have a lifetime of only a few years, the other option of replacing flammable elements can serve for more than a decade.

Evacuation plans as well as insurance options are effective measures for mitigating the consequences of wildfires where the former has lower costs while insurance options may cost moderate. Regardless, these measures can perform for a few years before requiring updating.

Table 16. Mitigations to Hazard of wildfires for bridges

Measure	Effectiveness	Costs	Lifetime
Control of vegetation, litter and other materials at site	2	Little	2 Years
Ignition controls to prevent fire starting	3	Moderate	1 Year

Table 17. Mitigations to Vulnerability of wildfires for bridges

Measure	Effectiveness	Costs	Lifetime
Fire control systems around structure	3	Moderate	4 Years
Replacement of flammable elements	2	Moderate	11 Years

Table 18. Mitigations to Consequence of wildfires for bridges

Measure	Effectiveness	Costs	Lifetime
Evacuation plans to remove people from danger	2	Little	4 Years
Insurance against fire damage costs	2	Moderate	3 Years

4.2.2 Slopes

The survey responses obtained for slopes are quite similar to the responses received for bridges, perhaps due to similar measures suggested. The results demonstrated that control of vegetation and debris on site is a highly effective measure for mitigating the hazard of wildfires and these measures are suggested to have little to moderate costs with requiring annual updates.

In terms of reducing the vulnerabilities with relation to wildfires, the survey concluded that control systems around existing and new structures are highly effective. Respondents also stated that the costs can be expected to be fairly moderate with most suggested that these systems are expected to be in place for at least 5 years.

Similarly, for mitigating consequences, the survey responses concluded that having emergency or evacuation plans can be implemented with very little investment and can be both highly effective in nature with a need to update the plans every 5 years. Having an insurance plan around the affected areas can help assure that costs are covered by fair parties involved and everyone is compensated fairly. This can also be very effective, with moderate costs as these can vary, and can last 2 years at a time.

Table 19. Mitigations to Hazard of wildfires for slopes

Measure	Effectiveness	Costs	Lifetime
Control of vegetation, litter and other materials at site	1	Little	1 Year
Ignition controls to prevent fire starting	2	Moderate	2 Years

Table 20. Mitigations to Vulnerability of wildfires for slopes

Measure	Effectiveness	Costs	Lifetime
Fire control systems around structure	2	Moderate	5 Years

Table 21. Mitigations to Consequence of wildfires for slopes

Measure	Effectiveness	Costs	Lifetime
Evacuation plans to remove people from danger	2	Little	5 Years
Insurance against fire damage costs	2	Moderate	2 Years

4.2.3 Road pavements

For road pavements, the survey responses demonstrate that mitigation measures for hazards of wildfires such as controlling vegetation and other debris on site, controlling ignition for fire prevention and livestock grazing close to roads are all high to moderate effectiveness. These measures require low to moderate costs and have a short lifetime.

For mitigations to vulnerability of wildfires for road pavements, the survey presented several measures. These included building fire control systems and use of less flammable materials for road pavements. Both measures were classified as moderately effective options with requiring moderate levels of investments. Other measures such as use of water tank trucks to spray water on the work area before maintenance tasks, deploying fire extinguishers on maintenance works area and avoiding road maintenance works in summer with tools that can increase the risk of fires were assessed as moderately effective measures requiring low costs. Overall, all these measures are suggested to have a short lifetime of around 4 years.

For mitigation of consequences of wildfires for road pavements, the results of the survey showed that evacuation plans to remove people from danger and setting up insurance policies against fire damage costs are effective options where evacuation plans will require relatively low costs with a lifespan of 4 years. Insurance options are suggested to have moderate costs as these can vary and can last 2 years at a time.

Table 22. Mitigations to Hazard of wildfires for road pavements

Measure	Effectiveness	Costs	Lifetime
Control of vegetation, litter and other materials at site	2	Little	2 Years
Ignition controls to prevent fire starting	2	Moderate	2 Years
Livestock grazing on fields close to roads	3	Little	2 Years

Table 23. Mitigations to Vulnerability of wildfires for road pavements

Measure	Effectiveness	Costs	Lifetime
Fire control systems around structure	3	Moderate	4 Years
Use of less flammable pavement materials	3	Moderate	4 Years
Use of water tank trucks to spray water (about 600 liters) on the work area previous to maintenance tasks	3	Little	4 Years
Avoid road maintenance works in summer (yellow or orange alerts) with tools that can cause fires, such as blowtorches in the	3	Little	4 Years

installation or removal of safety barriers for repair works			
Deploy of fire extinguishers on maintenance works area	3	Little	4 Years

Table 24. Mitigations to Consequence of wildfires for road pavements

Measure	Effectiveness	Costs	Lifetime
Evacuation plans to remove people from danger	2	Little	4 Years
Insurance against fire damage costs	2	Moderate	2 Years

4.2.4 Railway Tracks

Possible mitigations to hazard of wildfires for railway tracks includes controlling vegetation and other debris on site as well as controlling ignition for fire prevention. These measures have a high to moderate effectiveness, require little to moderate costs and would need to be updated annually.

Vulnerability of wildfires for railway tracks can be mitigated through fire control systems which are highly effective, require moderate levels of investments and have a lifespan of 4 years. Other measures include replacement of flammable elements that can be moderately effective and serve for at least a decade but will be very costly to implement. Fire-resistant cabinets for electrical systems are another viable mitigation measure that is moderately effective and requires moderate levels of investments while being able to perform for up to 7 years.

For mitigation of consequence of wildfires for railway tracks, the results of the survey showed that evacuation plans to remove people from danger and setting up insurance policies against fire damage costs are effective options where evacuation plans will require relatively low costs with a lifespan of 3 years. Insurance options are suggested to have moderate costs as these can vary and can last 2 years at a time.

Table 25. Mitigations to Hazard of wildfires for railway tracks

Measure	Effectiveness	Costs	Lifetime
Control of vegetation, litter, and other materials at site	2	Little	1 Year
Ignition controls to prevent fire starting	3	Moderate	1 Year

Table 26. Mitigations to Vulnerability of wildfires for railway tracks

Measure	Effectiveness	Costs	Lifetime
Fire control systems around structure	2	Moderate	4 Years
Replacement of flammable elements	3	High	1 Decade
Fire-resistant cabinets for electrical systems	3	Moderate	7 Years

Table 27. Mitigations to Consequence of wildfires for railway tracks

Measure	Effectiveness	Costs	Lifetime
Evacuation plans to remove people from danger	2	Little	3 Years
Insurance against fire damage costs	3	Moderate	2 Years

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SIRMA

STRENGTHENING THE TERRITORY'S RESILIENCE TO RISKS OF NATURAL, CLIMATE, AND HUMAN ORIGIN

Territorial risks

Application Code: EAPA_826/2018

Transportation infrastructure risk-based management - Appendices

WP 6 Risk & Resilience-Based Decision-Making procedure for Transportation Infrastructure

Deliverable ID	**D6.2**
Deliverable name	**Risk Mitigation Measures on Transportation Infrastructures**
Lead partner	**UMinho**
Contributors	**University of Birmingham (UBirmingham)**

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Appendices Contents

Appendix 1. Database Risk Mitigation Measures

Project	Country or region	Event	Year	Any other hazards? (mentioned in this document)	Summary (What happened?) & Impacts on transport sector	Affected mode of transportation	Adaptation measures (Long term)	Mitigation directed at	Mitigation type (to)	Overall/Expected implementation costs of the long-term mitigation measure / (Benefit/Cost [B/C])	Frequency (How often we can apply this?) (How long can the measure be applied for [permanent or temporary])?	Impact of the measure (Success stories?)	Sources/Links
Weather-D6_Case studies	Europe (Flood of 2002 in Eastern Germany)	Flood	2002	Heat waves, hurricanes, heavy snow	Caused by over a week of continuous heavy rains ravaging Europe, killing dozens, dispossessing thousands, and causing damage of billions of euros in the Czech Republic, Austria, Germany, Slovakia, Poland, Hungary, Romania and Croatia, as well as in Russia. The flood was of a magnitude expected to occur roughly once a century. In Saxony 740 km roads, 466 bridges and 20% of the railway network were destroyed, and in whole Germany 400 km railway tracks had to be repaired or replaced. In Saxony, the traffic sector encountered damages of around 2 billion Euros, with road infrastructure (1 billion) and rail infrastructure (0.8 billion) being the largest parts.	All	European Flood Awareness System (EFAS) European system monitoring and forecasting floods across Europe. It provides probabilistic, flood early warning information up to 10 days in advance.	All	Consequences	B/C: 400:1 The benefits are of the order of 400 Euro for every 1 Euro invested.	Permanent		Maurer, H.; Rudzikaite, L., Kiel, J., et al. (2012): WEATHER Case studies – Synthesis Report; (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework programme of the European Commission. Project co-ordinator: Fraunhofer-ISI. Karlsruhe, January 2012. Pregnolato, M., Ford, A., Wilkinson, S. and Dawson, R., 2017. The impact of flooding on road transport: A depth-disruption function. Transportation Research Part D: Transport and Environment, 55, pp.67-81. https://en.wikipedia.org/wiki/European_Flood_Awareness_System Pappenberger, F., Cloke, H. L., Parker, D. J., Wetterhall, F., Richardson, D. S. and Thielen, J. (2015) The monetary benefit of early flood warnings in Europe. Environmental Science and Policy, 51. pp. 278-291. ISSN 1873-6416 doi: https://doi.org/10.1016/j.envsci.2015.04.016 Available at: http://centaur.reading.ac.uk/40264/
							The website of intermobil with its traffic cameras monitoring Dresden's bridges gained increasing number of visitors to the site, who wanted to know which bridges are cleared at the moment.	Roads, Bridges	Consequences	-	Permanent		Dresden 2011: Hochwasser 2002: Chronik der Ereignisse, official website of Dresden, http://www.dresden.de/de/08/03/053/03/c_06.php
							The independent commission proposed following measures [Kirchbach 2003]: • Allow larger flood detention spaces in barrages • Analysis of the technical flood prevention system • On-line status information for emergency managers • Concentrate responsibilities for dams and barrages in one general office	All	Hazard	-	Permanent	In spring 2006, from February to April 2006 melting snow in combination with heavy rain caused long lasting flooding of a large region in Central Europe by the rivers Elbe and Danube. This event was a practical test of all administrative reorganisation and flood protection measures. A three-shift-operation plan was set up for the flood information centre and an on-call duty proved to be useful for 24 h service of flood alert and prediction services. However, duration of the flood made great personal, organisational and technical demands. Further lessons learned from flood 2006 in Saxony-Anhalt: • There should be enough trained personnel to use new technologies such as GIS mapping. • Expert advisers for dykes supported decisions for and against emergency measures. • The flood report plan should be adapted with regard to the findings of the flood of 2006. • Flood tourism should be reduced. • A part of the emergency services should be equipped with mobile communication devices which can send and receive e-mails and fax in order to provide flood coordinators with current information. • Monitoring of the water body should be improved during flood events with additional measurement sites and a defined measurement plan which is jointly prepared by involved institutions. All in all, it can be stated that the flood event could be managed better than in 2002. Gained knowledge was used for improvement of the emergency services. Priorities set when defining the reconstruction plan for dykes proved to be right. In August 2010 a similar meteorological situation like the one in 2002 caused flooding at the Polish/German/Czech border. In the aftermath, a commission was set up to analyse the alert system. The report [Jeschke 2010] showed that the system set up after 2002 is feasible to cope with such situations. However, there are still open points to improve the system fundamentally. Only after a quarter of the foreseen time span, MobiKat proved to be a useful tool to monitor emergency cases like floods of the river Elbe [DNN 2006].	Kirchbach 2003: Kirchbach et al.: Bericht der Unabhängigen Kommission der Sächsischen Staatsregierung – Flutkatastrophe 2002, Hauptband, http://www.schlaudi.de/hw/Kirchbachbericht.pdf
							After the flood of 2002 Saxon laws concerning flood protections have been revised. The new flood protection strategy of Saxony reduces damage risks through: • Individual precaution (inform the public on risks, possible flood adapting construction techniques and area usage) • Planning (define flood areas, flood protection concepts, flood protection action plans) • Reduce flooding by using natural areas • Increase flood protection levels by technical measures, e.g. accumulation lakes, absorption basins and dykes, Since 2004 flood protection concepts for all first order water courses and the river Elbe exist [SMUL 2010] and are implemented at the moment.	All	Hazard, Vulnerability, Consequences	-	-		SMUL 2010: Claußl, Christiane: Antwort auf: Kleinen Anfrage der Abgeordneten Dr. Jana Pinka, Fraktion DIE LINKE, Drs.-Nr. 5/2861, Thema: Hochwasserschutz-Aktionsplan für Sachsen. Sächsisches Staatsministerium für Umwelt und Landwirtschaft. http://edas.landtag.sachsen.de/viewer.aspx?dok_nr=2861&dok_art=Drs&leg_per=5&pos_dok=2
							Some measures taken until 2009 as consequences of the events in 2002 were [IKSE 2009]: • Implementation of the European Flood Alert System • Update and improvement of Czech and German flood forecasting models including snow melting models • Reorganisation of flood alert systems (e.g. flood information centres, implementation of new siren systems) • New measurement equipment, including an ombrometer network for Saxony (can lengthen forecasting horizon 2.5 times) • Initiatives to raise public awareness and preparedness (publications, presentations, websites)	All	Consequences	-	-		IKSE 2009: Internationale Kommission zum Schutz der Elbe: Zweiter Bericht über die Erfüllung des „Aktionsplans Hochwasserschutz Elbe" im Zeitraum 2006 bis 2008. Magdeburg, 2009. http://www.ikse-mkol.org/fileadmin/download/APHWS/2_Bericht/IKSE_Zweiter%20Bericht-HWS_2006-2008.pdf
							• MobiKat: The MobiKat system, developed by Fraunhofer IVI, is a decision support system, which enables relief units to efficiently plan and execute protection and rescue measures [FhG IVI 2009], which is at the moment being enlarged to a Czech – German cooperation now called MobiKat-COSMOD [COSMOD 2009]. MobiKat, was started in the end of 2005. MobiKat® was developed in cooperation with end-users as a modular system for operational command and the management of resources. It is used for effective situation management and to save human lives during natural disasters, large-scale technical breakdowns, extreme weather conditions, major events and others. • Easy.GO: Easy.GO is part of the traffic research project, "Mosaique", which enables service staff and public transport users to share multimedia information on emergency situations via UMTS technology. The information is gathered in order to provide updated traveller information depending on the current network situation. • SMART-WAY: The Easy.GO approach has been developed further during the EUproject SMART-WAY, which designs a navigation system for public transport users taking delays, disruptions and changing connections due to emergency situations during a trip into account [SMART-WAY 2011].	All	Consequences	-	-		FhG IVI 2009: MobiKat project http://www.mobikat.net/en/index.html DNN 2006: Gefahrenabwehrsystem MobiKat hat seine Feuertaufe im Hochwasser bestanden. In: Dresdner Neuste Nachrichten, 10.04.2006, p. 14. COSMOD 2009: Informations- und Entscheidungsunterstützungsplattform für Großschadenslagen. http://www.mobikat.net/dokumente/Projektinformation_Mobikat-Cosmod_D.pdf https://www.vvs.fraunhofer.de/en/members/fraunhofer-institut-fuer-verkehrs--und-infrastruktursysteme-ivi.html
							The International Commission for the Protection of the Elbe River (ICPER) published a joint Czech- German action plan for flood protection Elbe in 2003 with following goals: • Increase water retention capacity • Technical measures for endangered areas • Flood risk maps to reduce damage potentials • Improve flood forecast and flood alert systems • Inform the public and increase flood risk awareness	All	Hazard, Vulnerability, Consequences	-	-		
							• Allocation of land for flood areas • Install mobile flood barriers • Training of governmental emergency teams • Improvement of communication and organisation structures • Set up of digital communication technologies • Increase the number of experts available for advise regarding water issues • Set up of area-wide siren systems for alarming the public	All	Hazard, Vulnerability, Consequences	-	Permanent		Bericht der Unabhängigen Kommission der Sächsischen Staatsregierung - Flutkatastrophe 2002 (Kirchbach-Bericht) Leitstelle Wiederaufbau: Augusthochwasser 2002 - Schadensausgleich und Wiederaufbau im Freistaat Sachse. Starke &Sachse, Großenhain, 2003 Hünerkoch, D.: Die Bahn kommt wieder - Die Deutsche Bahn und der Wiederaufbau nach dem Hochwasser 2002. Druckerei Vetters, 2002 Arbeitsgruppe Hochwasser (Sachsen-Anhalt): Hochwasser 2002 im Land Sachsen-Anhalt - Auswertung des Katastrophenschutzmanagements. Magdeburg, 2003 Boden, M.; Kühnert, C.: Die Veränderungen des Liniennetzes des Öffentlichen Verkehrs zur Jahrhundertflut 2002 im Stadtgebiet von Dresden, 21. Verkehrswissenschaftliche Tage, Technische Universität Dresden, 2007 IKSE: Dokumentation des Hochwassers vom August 2002 im Einzugsgebiet der Elbe. Magdeburg, 2004 Marschner, J. et al. (Red.): Die Jahrhundertflut - Das Jahr danach. Druckhaus Dresden, 2003 Moch, G. and Dallmann, A. (Red.): Jahrhundertflut in Dresden. Dresdner Druck- und Verlagshaus, 2002 Müller, U.: Hochwasserrisikomanagement - Theorie und Praxis. Vieweg & Teubner, 2010 http://undine.bafg.de/
Climate Adapt (Realisation of flood protection measures for the city of Prague)	Prague	Flood	2002	-	In 2002, Prague experienced severe flooding with total damage of 24 billion CZK (1 billion euro). This event was recognized as one of the most expensive weather-related disaster in the history of the city with heavy damages on infrastructure, housing and environment.	All	To protect the city, its inhabitants and the priceless historical heritage from such great floods there was a need for grey infrastructure. Green and blue infrastructure would only serve as some kind of additional support to the flood barriers and can be very useful for example to tackle flash floods caused by extreme precipitation. Greener strategies or approaches have not been realised along the Vltava River. However, these approaches are implemented when revitalizing smaller streams in the city, like for example Rokytka. The specific adaptation measures implemented to control Vltava river floods include: • Fixed barriers (levees, dykes, earth mounds, solid concrete walls) constructed along the Vltava River. • Mobile barriers which are mainly used in the old historical centre, and partly in the surrounding areas. The transport and installation of mobile barriers to the areas potentially affected by flooding is based on the Flood Management Plan of the Prague City. In Dubeč, a training area for training of mobile barriers installation is built. • Other measures, as closures, pumping systems and safety valves in the canalisation network along the Vltava River.	All	Hazard, Vulnerability	The estimated total cost amounts to 145.94 Million euro (2013) and includes: total cost of the realisation of the flood control system (144.4 Million EUR, 2013), installation costs per event (0.65 Million euro, 2013), annual maintenance and storage costs (0.89 Million euro, 2013).	The flood protection measures were constructed from 1997 to 2012. The implementation of these measures was rather long-term including design, project preparation and construction of the particular measures. Life Time: Approximately 80 years.	The success of the implemented flood protection system was proved during 2013 flood event, when great part of the city along Vltava River was protected and only very minor parts were flooded. On the other hand, the 2013 flood event highlighted the "weak points", such as the capacity of the pumping station on Rokytka creek that is planned to be enlarged based on this flood event.	https://climate-adapt.eea.europa.eu/metadata/case-studies/realisation-of-flood-protection-measures-for-the-city-of-prague
European Floods Directive (2007/60/EC) (Douka, A)	-	Flood	2007	-	Structural measures	-	Designation of water retention areas used for controlled flooding Widening of the river bed Creation and management of controlled water levels through dams	All All All	Hazard Hazard Hazard, Vulnerability	-	-	-	Douka 2020
					Non-structural measures		Detection of natural flooding areas, land use limitations in flood hazard areas, updating of local plans, relocation of elements at risk, flood forecasts and early warning systems, and flood surveillance services [10] (p. 74).	All	Hazard, Vulnerability, Consequences				
Netherlands' vision 2053		Flood			Structural measures		by building earth dunes and beaches in front of existing coastlines instead of constructing higher dikes that can be weakened against the power of sea waves [10] (p. 26).	All	Hazard, Vulnerability				
EWENT WP5	Germany, Finland	Flood	Up to 2010	Extreme snowfall, strong winds, heat waves, cold waves, low visibility	Heavy rainfall may lead to situations when roads have to be closed for safety reasons. In case of long lasting heavy rainfall, flooding may occur and cause damage to road structures. In Finland heavy rain over 100 mm per day may cause local disorders, as the intensity of rain can be locally very hard. 150 mm per day can cause erosion damage, and also flooding, if the drums do not carry the water away and the waters nearby flow to the road area. Gravel roads are particularly sensitive to the increase of winter precipitation: the surface structure affected by water saturation weakens the road bed structure and decreases the winter carrying capacity. This is especially harmful for agriculture and forestry.	Road	Common gravel road network in Finland is still about 27 000 km (in addition to 200 000 km of private roads), and part of the lightweight coated roads will be changed back to gravel roads. Some of the local environmental centers have already been demanding larger culverts. Road underpasses pumping capacity can be exceeded, but even greater problem is the potential of power failures. Technical design of the road transport infrastructure is based on drainage systems that are not over sized as standardization committees which take regional meteorological long term studies into consideration say there will be no increase in heavy precipitation in Austria.	Roads	Vulnerability	-	-	-	Molarius et al., 2011: "Weather hazards and vulnerabilities for the European transport system – a risk panorama" EWENT Project Deliverable 5. Available at: http://virtual.vtt.fi/virtual/ewent/Deliverables/D5/Ewent_D51_FINAL.pdf

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Climate-ADAPT	Austria	Flood	1998-2007	Ice and snow, debris flows, rock falls, avalanches or landslides	Austrian Federal Railways (ÖBB Infra AG) are very important due to their provision for the accessibility of lateral alpine valleys. Alpine topography and limited space availability means railway lines often follow floodplains and are located along steep and unsteady slopes. This considerably exposes them to flooding and in particular to alpine hazards, such as debris flows, rock falls, avalanches or landslides. As a result, railway infrastructure and operation has been repeatedly impacted by alpine hazards. For instance, several coaches of an intercity train derailed at the Masonbach torrent (Vorarlberg) on 11th August 1995, following a debris flow event that had destroyed a bridge. Three people were killed, 17 people were heavily injured and the track had to be closed for almost one week. Also in June 2013, floods and debris flow events caused substantial damage to the railway infrastructure. The national railway operator ÖBB Infra AG reported losses of about €75 million to its railway network. In the future, the risk from Alpine hazards could increase considerably due to climate change.	Railways	On the one hand, risk from Alpine hazards is reduced by implementing structural protection measures. ÖBB Infra AG is mainly responsible itself for constructing and maintaining protective measures, such as dikes or debris sheds.	Railways	Hazard	-	Structural protection measures such as dikes or debris flow barriers usually have a lifetime of several decades.	-	https://climate-adapt.eea.europa.eu/metadata/case-studies/building-railway-transport-resilience-to-alpine-hazards-in-austria
							On the other hand, risk from Alpine hazards is reduced by improving preparedness for response and emergency management. A key element of ÖBB's risk reduction strategy is the weather monitoring and early warning system called infra:wetter, which is jointly operated by ÖBB and the private weather service UBIMET GmbH. This interactive web-portal available to the ÖBB staff combines data from own and external weather stations of the ZAMG (Zentralanstalt für Meteorologie und Geodynamik - Central Institute of Meteorology and Geodynamics), radars, satellites as well as local and global weather projections with detailed information on the complete railway network in Austria. It provides a calculation of important meteorological parameters like temperature, wind speed, precipitation, snowfall, and the snow line at a local level.		Consequences	-	Permanent	-	
							Besides providing individualized and route-specific warnings to approximately 1,500 users, infra:wetter is also used to identify so-called critical meteorological conditions (CMCs) in advance: weather conditions that potentially lead to larger disruptions of train traffic and thus require coordinated action by the Natural Hazards Management Department of the ÖBB Infra AG.		Consequences	-	Permanent	In case a critical meteorological condition is detected with sufficient pre-warning time, a weather warning is issued and a plan of procedures is implemented. This can include the installation of an incidence command that decides about operational safety precautions, such as speed limits, track closures or temporary mitigation measures. For instance, in the case that heavy snowfall is predicted, measures such as a revised planning of human resources and provision of winter services, or preheating of switch points can be undertaken to ensure the operability of the network.	
EWENT WP5	Southern European countries	Heat waves (Fires)	Up to 2010	Snow, strong winds, traffic, cold waves	Heat waves lead to distortion of the tracks.	Railways	Railway carriages and buildings have been equipped with air conditioning. To prevent heat distortion of the railway tracks, tracks are painted with white colour in southern European countries.	Railways	Hazard	-	Will need repainting and repair works often depending on usage	DB pursued the idea of painting rails white after promising results were obtained from an experiment to evaluate the effect of the white paint on a test track at Königsborn. The rails were shown to reflect more light and therefore become much less hot than their conventional counterparts. A study by the Swiss Federal Technology Institute ETH Zurich showed that white paint had a positive impact in strong sunlight.	Molarius et al., 2011: "Weather hazards and vulnerabilities for the European transport system – a risk panorama" EWENT Project Deliverable 5. Available at: http://virtual.vtt.fi/virtual/ewent/Deliverables/D5/Ewent_D51_FINAL.pdf https://www.railway-technology.com/features/solution-to-overheated-rail-tracks/ https://www.swissinfo.ch/eng/extreme-heat_swiss-railway-field-tests-white-paint-to-keep-tracks-from-buckling/44287044
EWENT WP6	Austria, Belgium, Croatia, Czech Republic, Greece, Ireland, Iceland, Italy, Germany, Lithuania, Luxembourg, Denmark, Netherlands, Spain, Serb Republic, Norway, Finland, Portugal, France, Sweden, Switzerland, United Kingdom, Hungary, Cyprus, Slovakia, Poland, Romania, Slovenia (30 European countries)	Flood	Up to 2010	Warnings for coastal sea areas, avalanches, forest fires, extreme temperatures, thunderstorms, fog, snow/ice, wind, rain	Based on the identified extreme phenomena and the probabilities of extreme weather in Europe along with the consequences of the harmful weather events, different measures and strategies of adaptation and mitigation are highlighted for negative impact reduction, control and monitoring in short and long-term periods.	All	Alarm services. For private car users embarking on cross-border travels, an online web service has been developed, known as **Meteoalarm.** It is an initiative by EUMETNET, the public European weather services network within the World Meteorological Organization. The service is available on http://www.meteoalarm.eu informing public and authorities about severe weather conditions in 30 European countries. On Meteoalarm, weather symbols and color-coded maps of Europe show at a glance where the weather might be, or soon become, dangerous.	Roads	Consequences	-	Permanent	The daily access rates reach 12 million per day during warning situations. In the future the website will be expanding. Probably more countries will be participating. It is foreseen to connect with information providers and to disseminate weather warnings through SMS and email. A feedback feature with the possibility to present photographs from users might be a further step.	Leviäkangas et al., 2011: "Extreme weather impacts on European networks of transport" EWENT Project Deliverable 6.(Available at: http://virtual.vtt.fi/virtual/ewent/Deliverables/D6/Ewent_D6_SummaryReport_V07.pdf https://ec.europa.eu/echo/files/civil_protection/civil/prote/pdfdocs/1_pres_meteoalarm.pdf https://geo-bene.project-archive.iiasa.ac.at/node/2113.html
							Extension of the forecast period to 5 days on the MeteoAlarm.	All	Consequences	Total cost: € 303.700, EC: € 227.7775	Permanent		
							Ideas from stakeholder interviews and EWENT Innovation Seminar: Weather hazard skill management certificate that would be required for transport operators and infrastructure managers. Fog alert system combining weather and navigation data.	Roads	Hazard	-	Permanent	-	
Weather-D6_Case studies	Southern Europe (Greece)	Fires (Heat)	2007	Windstorm, heavy snow, inland shipping affected by heat	Fire events in the region of Peloponnese. Strong winds and lack of precipitation in the area further increased the intensity of the blazes and supported the propagation of the event. The local and national road networks were affected.	Roads	• Fire prevention additional staff	All	Hazard	8 million Euros per year (assuming 1,000 Euros per month per fire fighter for 4000 seasonal and permanent personnel for 2 extra months in their contracts)	Permanent	The 2021 Greece wildfires are multiple wildfires burning in Greece since early August 2021, which have caused a lot of damage. Climate experts say these wildfires that razed 100,000 hectares (247,000 acres) of Greek forest are only a small sampling of the environmental and economic devastation the country will face due to a warming planet this century. The fires came in the wake of a heatwave, repeating a pattern seen in two other nationwide conflagrations in 2007 and 1987; and the phenomenon is worsening.	Source 1: Agricultural University of Athens, Rehabilitation and development study for the agricultural sector, the forests and the environmental protection of the 2007 fire stricken areas, Athens, 2007 Source 2: European Forest Fire Information System, Forest fires in Europe, Report No 8, JRC Scientific and Technical Reports, 2007 Source 3: General Secretariat of Civil Protection, General Plan for facing emergency situations because of forest fires, 2011 Source 4: StatheropoulosM., A data file of the big forest fires in Greece during summer 2007 – how early warning systems can be used as a shield of protection from forest fire smoke impacts, Athens Summit, Global Climate and Energy Security, 2008 Source 5: United States Agency International Development, Annual report for fiscal year 2007, Office of U.S. Foreign Disaster Assistance, 2007 Maurer, H.; Rudzikaite, L., Kiel, J., et al. (2012): WEATHER Case studies – Synthesis Report; (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions)
							• Fire prevention programs and technical assistance • Forest monitoring and mapping		Hazard	-	Temporary		
							• Wildfire management: To exchange information and technical details for wildfire management.		Hazard	1.6 million Euros	Temporary (2 years)		
Weather-D6_Case studies	Prague	Flood	2006	Heat waves, hurricanes, heavy snow	Subsequent bursting of two dams due to heavy rainfalls, leading to flooding of important rail link	Railways (freight and passenger) and road	New railway control centre on pillars. The new building was made on pillars to make it flood-proof.	Railways	Vulnerability, Consequences	30000 Euros	Permanent	Maintenance of protections systems is highly recommended otherwise protection cannot be guaranteed although protection system is constructed for high risk events (dam that broke was constructed for a 100 year event, flood was a 100 year event, due to non optimal maintenance dam has broken, new dam is again for 100 year event).	ÖBB: recovery report (Hochwasser Sprik&Partner (2007): Hochwasser March 2006, ÖBB Infrastruktur Bau, Stecke 114, Wien Nord - Bernhardstal nach Staatsgrenze, km 40.5 - 53.3 Schadens- und Sanierungsbericht Bezirksfeuerwehrkommando Gänserndorf (2006): Einsatzdetailbericht Marchhochwasser 2006 Riocom (2008): Hochwasser-Alarmplan March für die ÖBB-Nordbahnstrecke Angern bis Hohenau http://www.stillfried-grub.at/ff/extrablatt.pdf www.hochwasserschutz-march.at Interview with ÖBB infrastrcuture - department for natural desaster management Interview with OMV - gas hub Baumgarten Interviews with representatives of the affected communities Maurer, H.; Rudzikaite, L., Kiel, J., et al. (2012): WEATHER Case studies – Synthesis Report; (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework programme of the European Commission. Project co-ordinator: Fraunhofer-ISI. Karlsruhe, January 2012.
							Construction of a counterfort at rail tracks. It is a measure to avoid flooding for the time in which the new planned flood protection embankment is not yet ready. It should protect Stillfried against flooding during that time. One part of the counterfort is an installation directly on tracks which doesn't influence train operations. In case of emergency further parts of the counterfort which are stored in a container near the tracks, will be installed on the track installation.	Railways	Hazard, Vulnerability		Temporary (may still be in use). Local action force train the installation of counterfort several times per year.		
							Reconstruction of flood protection embankments for sections with a total length of 10.7 km	Railways	Hazard	14 million Euro	Permanent		
							Completion of new flood protection dams' sections	All	Hazard	82 million Euro	Permanent		
							ÖBB-Emergency Plan; a document for regulating the information chain if a there is a flooding threat. It is valid for a specific endangered track section. It should assist all authorities, emergency response organisations and other relevant bodies before and during a flood event with informing people about the flood, arranging all the necessary control measures and fighting against the flood in an effective manner. This plan ties in with the alarm plan of the public authorities.	All	Consequences	About EUR 13 million were needed for the rebuilding of the railway station Dürnkrut which include costs for base structure, rail system and overhead catenary wires well as costs for building construction, railway crossings, defence electronics, transmission lines and lighting. Rebuilding for the section Angern an der March to Dürnkrut cost about EUR 24 million. Costs for base structure, rail system, overhead contact line, railway crossings, transmission lines and lighting are included in the rebuilding costs. Around EUR 1.5 million occurred for the upgrading of the formation. For construction measures of the section Dürnkrut to Drösing about EUR 2.5 million were needed. Costs accrued for base structure, rail	Permanent		
Weather_D2_Appendix--B	Scotland	Flood			Railtrack Scotland has identified adverse weather as a key business risk. Flooding is considered as one of the main climate sensitivities.	Railways	Railtrack Scotland identifies sites that are vulnerable to flooding and thereafter installs pumps and/or culverts	Railways	Vulnerability	-	-	-	Kerr, A.; McLeod, A. (2001): Potential adaptation strategies for climate change in Scotland, University of Edinburgh, Scottish Executive Central Research Unit. Doll, C. and N. Sieber (2011): Vulnerability Assessment for Road Transport. Contribution to Deliverable 2: Transport Sector Vulnerabilities within the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project co-
							Railtrack Scotland works with the National Farmers Union (Scotland) to encourage actions on land adjacent to railways that reduce flood risk	Railways	Hazard	-	-	-	

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Weather-IP_AU (Bushfire, Heat Wave and Flooding Case Studies from Australia)	Australia	Fires	2009	Heatwaves	One of the most extreme and protracted heatwaves ever for the Australian state of Victoria. Multiple bushfires ignited throughout the state and fires increased greatly causing a large number of deaths.	Railways, Roads, Bridges	The pre-existing Wildfire Management Overlay (WMO) detects areas where the strength of wildfire is considerable and probable to cause a danger to life and assets. WMO's intention is to make sure development in areas subject to high fire risk includes appropriate fire protection measures. The WMO was revised to improve safety as recommended by the Royal Commission and is now called the Bushfire Management Overlay (BMO). The BMO requires that new developments implement appropriate bushfire protection measures including where the building is located on the site, emergency access and fire-fighting water supply. The BMO includes a statutory provision in Planning Schemes for high risk areas where the provisions apply to specific land.	All	Hazard, Vulnerability, Consequences	$465 million were contributed by the Australian Government towards the reconstruction and recovery efforts to address the psychosocial, economic, infrastructure, and environmental impacts (Australian Government, 2009).	Permanent	In January 2018 a 10km section of the Hume freeway literally melted. And extreme temperatures can cause train tracks to buckle, overhead power lines to sag, and motors to overheat, meaning trains need to either go very slowly or they can't run at all.	Victorian Bushfires Royal Commission (2009) Conditions on the day, Available at: http://vol4.royalcommis sion.vic.gov.au/index.php?pid=1 Chhetri, P., A. Hashemi, F. Basic, A. Manzoni and G. Jayatilleke (2012) Bushfire, Heat Wave and Flooding - Case Studies from Australia. Report from the International Panel of the WEATHER project funded by the European Commission's 7th framework programme. Melbourne, March 2012. https://environmentvictoria.org.au/our-campaigns/safe-climate/victoria-heatwaves-climate-change/
							A new Rail Operations Management System (ROMS) is established with the ability to undertake simulations of a number of scenarios across rail network, including the loss of individual carriages and lines and to assist in the areas of fleet management, timetabling and staff management.	Railways	Vulnerability		Permanent		
							• Codes of practice – ensure all roads operated by VicRoads adhere to 1985 Codes of Practice • Operation and management plans – development of Rail Operations Management System • Condition licenses – introduction of Bushfire Management Overlay • Fitness for purpose obligations – a State Planning Policy for Bushfire Prone Regions	All	Vulnerability		Permanent		
Weather-IP_AU (Bushfire, Heat Wave and Flooding Case Studies from Australia)	Australia (Queensland and Victoria)	Flood	2010/2011	Heatwaves	The Queensland Floods are viewed as one of the most expensive disasters in Australia's history. Brisbane's entire public transport system was affected. Excessive rainfall across much of eastern Australia together with record cyclone activity resulted in severe flooding and damage to transport as well as other infrastructure.	All	Development of Bruce Highway Upgrade Strategy (BHUS), Brisbane to Cairns, to improve efficiency, safety, reliability and flood immunity. This highway provides critical linkages for east-west freight movements, to 11 coastal ports and between inland production areas and towns / will deliver improved flood resilience, improved highway safety and remove existing constraints on connectivity to key gateways.	Roads, Bridges	Vulnerability, Consequences	Estimated Project Cost:$20 million Australian Government Contribution:$20 million	The program commenced on 1 July 2013, with a rolling program of upgrade projects up and down the highway, to be completed by June 2028.	As at December 2020, 23 major projects had been completed under the program including the delivery of:	Victorian Floods Review (2012) Available at: www.floodsreview.vic.gov.au https://www.tmr.qld.gov.au/projects/programs/bruce-highway-upgrade-program Queensland Floods Commission of Inquiry (2011) 'Government response to the Floods Commission of Inquiry Interim Report' Chhetri, P., A. Hashemi, F. Basic, A. Manzoni and G. Jayatilleke (2012) Bushfire, Heat Wave and Flooding - Case Studies from Australia. Report from the International Panel of the WEATHER project funded by the European Commission's 7th framework programme. Melbourne, March 2012.
							Adaption strategies Of the four options open to government they have been applied as follows: • Codes of practice – ensure safeguarding of existing transportation and logistics infrastructure through the Victorian Flood Management Strategy 1998, the Water Act 1989 and the Emergency Management Act 1986, Dam Safety Management Guidelines, and Australian Government Emergency Management Planning (Floods). • Operation and management plans – improve management of roads, bridges and dams by reviewing and updating existing guidelines, and provide assistance to local governments to enhance their ability to cope with extreme weather events • Condition licenses – state road and water authorities to enhance and clearly define roles and responsibilities. • Fitness for purpose obligations – authorised government agencies to provide timely information to the public and communities in preparation for floods, and to improve public awareness and education of those in risk areas.	All	Vulnerability				
WEATHER-IP_BG-Karagyozov_pub	Bulgaria	Flood	2005	Fires on technical fault, landslides, floods, snowdrifts, icing, frosts, other natural disasters, serious road accidents with motor vehicles	As a result of the action of natural forces such as torrential rains, melting snow or damaged hydraulic structures (dams, etc.) large areas of land were flooded and transportation infrastructure was destroyed.	All	A new body, Crisis Headquarters, was formed to address the flood damages. Affected households were granted funds for urgent domestic needs	-	Consequences	4601610 Euros	One-time	-	Karagyozov, K. (2012) Impact of Natural Disasters on Transport Systems – Case Studies from Bulgaria. Report from the International Panel of the WEATHER project funded by the European Commission's 7th framework programme. Sofia, April 2012.
							The government approved the membership of the National Institute of Hydrology and Meteorology (NIHM) in Mid-term European Forecasting Center and decided that NIHM should submit weather forecast four times a day	All	Consequences	-	4 times/day	-	
							Policies and strategies developed: • creation of the Ministry of State Policy for Disasters and Accidents (MSPDA) • carry out specific policies for effective crisis management • the Regulations of Disaster Management Policy were ratified by subsequent structural changes and the State Civil Defense Agency was restructured to operate under the auspices of the Ministry • two laws were drafted and approved by the Council of Ministers - one for amending the Act on Crisis Management and the other is the new Act on Disaster Protection.	All	Consequences	-	-	-	
							National Programme for Disaster Protection: • Preventive action in defence of port infrastructure from flood (51129 Euros) • Preventive activities in disaster by heavy rains, blizzards and ice on the rail infrastructure and equipment (214742 Euros); • To build a protective dike destroyed with the bridge of the Iskar river on the second major railway line Sofia-Gorna Oryahovitsa-Varna. • To make safe the steep earthy and rocky slopes by forcible overthrow using an alpine method of activated landslide processes and landslip caused by flooding (330942 Euros)	All	Vulnerability, Consequences	596812 Euros (cost breakdown provided under long term measures)	-	-	

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WEATHER-D4	Europe	Heat & drought	Until 2050	Ice & Snow Storm	For heat and drought different **technical** measures (a lot of for cooling of signals and improvement of steel) and some maintenance measures have been found in literature.	Railways	Improvement of cooling signals and installation of fans to keep some equipment functional during periods of extreme heat and to avoid overheating and ensure smooth operations on the rail infrastructure (South Europe currently)	Railways	Vulnerability	Costs depend on number of signals (and other relevant electronic equipment that has to be cooled) of a railway network and number of days per year where cooling is necessary.		Reduction of malfunction of signals and other electronic equipment leads to reduction of delays in heat periods; on average 600 signals per 100km rail network, but not all signals need a cooling (due to different sensibility against heat) increased electronic power consumption due to cooling	Arbeitspapier zur Vorbereitung des Stakeholderdialogs zu Chancen und Risiken des Klimawandels – Verkehrsinfrastruktur – Dialoge zur Klimaanpassung Verkehrsinfrastruktur, 2009 Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase O – U.S. Climate Change Science Program Synthesis and Assessment Product 4.7, 2008
		Heat & drought Rain & Flood			-		Selection of suitable vegetation along rail tracks to reduce the risk of fire and floods		Hazard	Investment and maintenance costs depend on the kind of vegetation that is needed and therefore depends on the function that the vegetation has with respect to the infrastructure protection. A protection forest has higher life circle costs than a —normal low vegetation that only has to be cut regularly to protect the railway against storms.		Depends on the measure – planting new vegetations has positive effects on nature, but cutting trees along railway lines can lead to a reduction of natural tree inventory. There should be a balanced planting of trees in other places. Protections forest can also protect other infrastructures.	DB-Netz, ÖBB-Infrastructure, SBB Climate Adaptation of Railways: Lessons from Sweden – Johan Lindgren, Daniel K. Jonsson, Annika Carlsson-Kanyama, 2009 Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I – U.S. Climate Change Science Program Synthesis and Assessment Product 4.7, 2008 Adaptation Investment Strategy for existing road network: presentation at the 3rd weather workshop – Michel Ray; May 2011 Österreichische Bundesforste, Bericht zum Geschäftsjahr 2002
		Heat & drought			-		• Pre-stressing of steel, • Deployment of heat resistance material to avoid rail buckling and therewith delays and cancellations of trains, as well as in worst case derailments.		Hazard, Vulnerability, Consequences	One study estimated that approximately £10k could be saved per stressing operation of a track renewal item. In a yearly program of work, where rerailing is part of the process, implementing the stressing operation could lead to savings of £9 million per annum.	Long-term	Helps avoid rail buckling and therewith delays and cancellations of trains, as well as in worse case derailments.	http://www.weather-project.eu/weather/inhalte/adaptation-workshop-may-2011.php Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase O – U.S. Climate Change Science Program Synthesis and Assessment Product 4.7, 2008 Impacts of Climate Change on Transport and Adaptation in Asia – Madan B. Regmi and Shinya Hanaoka, 2009 Doll, C., S. Klug, J. Köhler, I. Partzsch, R. Enei, V. Pelikan, N. Sedlacek, H. Maurer, L. Rudzikaite, A. Papanikolaou, V. Mitsakis (2011): "Adaptation Strategies in the Transport Sector" Deliverable 4 of the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project coordinator: Fraunhofer ISI, Karlsruhe.
					Maintenance measures		Upgrading of track: tracks should be replaced as part of normal maintenance, upgrades to handle increased traffic volumes, or replacement due to storm surge or other catastrophic events. The cost to upgrade track can vary depending upon the type of upgrade, the slope and curvature, as well as the number of bridges and tunnels.		Vulnerability, Consequences	Costs to replace track range from $0.3 million to $1.9 million per kilometre, excluding any additional right-of-way expenses	-	-	Doll, C., S. Klug, J. Köhler, I. Partzsch, R. Enei, V. Pelikan, N. Sedlacek, H. Maurer, L. Rudzikaite, A. Papanikolaou, V. Mitsakis (2011): "Adaptation Strategies in the Transport Sector" Deliverable 4 of the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project coordinator: Fraunhofer ISI, Karlsruhe.
		Heat & drought Rain & Flood					Installation of automatic monitoring systems: Intensive monitoring of track temperatures for early reacting (with speed limits and shorter trains for a shorter braking distance and lower loading capacity for lower impacts on tracks) to avoid possible rail buckling and therewith damages on rail tracks, trains and peoples due to derailment, cancellation of trains, blockade of track sections etc. Therefore, buckling of rail tracks caused by extreme heat (in many cases in connection with old and poor maintained infrastructure) can be detected in time Drains and embankments not working probably anymore and therefore not giving enough protection against heavy rains and flood can be detected in time		Vulnerability, Consequences	Costs strongly depend on the kind of monitoring system. The more automatic monitoring procedures are possible the higher are investments costs but the lower are running costs. Costs also depend on what is monitored. Monitoring the condition of the rail track of the whole network is more extensive than monitoring dams that do only exist along critical parts of the network.	-	-	Railways facing the challenges of climate change and extreme weather conditions, presentation at the 3rd weather workshop – presentation at the 3rd weather workshop – Alex Veitch, Enno Wiebe, May 2011
		Heat & drought					Increase of maintenance activities due to excessive heat Maintenance includes many different possibilities to reduce infrastructure vulnerability that is caused by infrastructure in bad condition. Some examples: • Maintenance of rail track (including replacement in time) reduces rail buckling during heat periods. • Maintenance of embankments and drains guarantees the functioning of these systems if heavy rains or floods occur. • Frequent inspection of bridges (especially corrosion) reduces damage and destruction risk due to heavy rains		Vulnerability	Costs depend on the infrastructure (or part of infrastructure) to be maintained and the level of maintenance that is actually in use. Rail infrastructure maintenance is driven by the passenger/freight ratio, the number of tracks, the number of trains per period, the geographical situation and other factors. An average estimation is rather not possible	-	The whole European transport infrastructure network; reduced malfunction of the infrastructure system, reduced destroyed infrastructure due to extreme weather events	Natural Disasters in Australia – Reforming mitigation, relief, and recovery arrangements; A report to the Council of Australian Governments by a high level officials' group, August 2002 Impacts of Climate Change on Transport and Adaptation in Asia – Madan B. Regmi and Shinya Hanaoka, 2009 Climate Adaptation of Railways: Lessons from Sweden – Johan Lindgren, Daniel K. Jonsson, Annika Carlsson-Kanyama, 2009 Adaptation Investment Strategy for existing road network: presentation at the 3rd weather workshop – Michel Ray; May 2011 Railways facing the challenges of climate change and extreme weather conditions: presentation at the 3rd weather workshop - Alex Veitch, Enno Wiebe, May 2011]
		Heat & drought					Updating of temperature maps in order to reflect the true mean temperatures		Vulnerability, Consequences		-	-	http://www.weather-project.eu/weather/inhalte/adaptation-workshop-may-2011.php
							Pile construction (for buildings with technical equipment such as railway control centre)	-	Vulnerability, Consequences	€ 5.000,. /pile investment costs Operation and maintenance costs are rather similar to a building not constructed on piles. Additional costs of a building on piles depend on the dimension of the building (the bigger the building the more piles are necessary). Railway control centres (for them such pile constructions are most relevant) are rather small – therefore additional investment costs are rather low per control centre. Total Costs also depend on number of control centres of a railway network.	Piles have there fixed high. If flood probability decreases piles are still there and if expected height of flood increases, piles have to be rebuilt completely. For new buildings this measures is very easy to implement. Existing building need to be rebuilt.	Reduction of damage costs, speed up of reconnection if rail track is only destroyed insignificantly.	Spirk & Partner (2007): Hochwasser March 2006, ÖBB Infrastruktur Bau, Strecke 114. Wien Nord – Bernhardstal nach Staatsgrenze, km 40,5 –53,3 Schadens- und Sanierungsbericht, Stand 31.10.2007
		Flood			-	Roads	Shifting of road alignments beyond areas at risk. For roads in endangered areas it is one option to find another route, so that the road alignment can be shifted over middle or long term. For planning of new road, the element of local vulnerability to weather extremes need to be considered within a life cycle cost benefit analysis.		Vulnerability	High costs if the considered space is rare and expensive in urbanised areas	Difficult to shift a road, which already exist; only in case of new planning	-	Heck, H.-M., Bobinger, R. (2006): Netzentwurf und Netzoptimierung,
							Road alignments with less land consumption and more effective utilisation of existing infrastructure. Generally, infrastructures such as roads, has to be designed in an efficient way for maximal capacity utilisation by occupying least space. In case of damage, less investment is necessary to rebuilt the infrastructure.	Roads	Vulnerability, Consequences	Compared to standard planning, this measure would cause no extra direct costs	-	Little effect on reducing the hazard	
							Concepts of removing the hard surfaces that are covering the ground/ land rehabilitation program. Urban areas are sealed with concrete and asphalt to a large extent including the roads. This accelerates the dangers of flooding in urban areas. Not all of the roads need to be constructed with high building standards, and land rehabilitation programs and foresting measures could also help to slowdown the water by infiltration. However, there is little leeway to remove the hard surfaces in higher density urban areas.		Hazard	Costs depend on what extent this measure would be implemented (Mid-level costs)	Quite difficult to implement, because most settlement areas and roads need to be covered with hard surfaces	-	Geiger, Wolfgang; Dreiseitl, Herbert; Stemplewski, Jochen (2010): Neue Wege für das Regenwasser. Handbuch zum Rückhalt und zur Versickerung von Regenwasser in Baugebieten. 3. Auflage. Oldenbourg Industrieverlag.
		Rain and Flood				Roads	Improvement to stability of slopes and embankments. Stability of slopes and embankments has to be guaranteed to avoid catastrophes. The stability of slopes can be improved by protective vegetation, proper drainage, usage of adequate construction materials, and appropriate maintenance.	Roads, Slopes (Embankments)	Hazard, Vulnerability	Depending on the technique used for stabilisation	-	-	Tegethof, U.; Klimawandel – Anpassunsstrategien für die Straßenverkehrsinfrastruktur; Journal „Straße und Autobahn— p. 89-93 (2011). NRC - National Research Council of the National Academies (2008): Potential Impacts of Climate Change on U.S. Transportation. Transportation Research Board Special Report 290
		All					Vegetation management along roads: Reduction of traffic obstructions, stabilisation of slopes. The most important aspects of vegetation management are: - cutting down of trees that may pose a problem - choosing the proper vegetation - removing of the vegetation close to the pavement - planting of vegetation to stabilize soil.	Roads, Slopes and Pavements	Hazard, Vulnerability	-	Vegetation has normally a long grow phase. For this reason it is not easy to react to changing conditions.	-	-
		Heat & drought Rain & Flood					Adequate design and maintenance of bridges. Increase of impact of extreme events has to be considered. It is possible, that due to climate change, maintenance works will have to be done more frequently. To avoid catastrophes, it is recommended to compare the predicted impact of future extreme events to current and past design codes.	Roads, Bridges	Vulnerability, Consequences	-	Due to climate change, maintenance works will have to be done more frequently	The entire European road network will benefit	Tegethof, U.; Klimawandel – Anpassunsstrategien für die Straßenverkehrsinfrastruktur; Journal „Straße und Autobahn— p. 89-93 (2011).
		Flood					Proper design and maintenance of drainage. According to most experts, flash floods can be avoided through proper and scheduled maintenance of drainage. In some regions, where intensive precipitations are likely to increase, an upgrading of drainage should be considered. However, according to [Schmitt 2006], the upgrading is not always necessary.	Roads	Vulnerability	Depends on drainage system needed	Drainage system is designed normally for more than 20 years.	The entire European road network will benefit	Hanson, K. (2010): The Blue Spot Concept: methods to predict and handle flooding on highway systems in lowland areas. SWAMP; Summary Report Nr 1. Hellman, F. (2010): Inspection and Maintenance: guide for reducing vulnerability due to flooding of roads. SWAMP; Report Nr 4.
MOWE-IT Railway-Guidebook	Europe	Flood	2005	Wind/Storm Hard winter	Flooding across a number of countries including Switzerland, Austria, Romania and Germany. Many railway services had to be suspended as lines were undermined or destroyed by landslides and bridges were washed away. Total damage was estimated to cost around €2.7 billion in Austria and CHF 3 billion in Switzerland.	Railways	(Long-term preparation) • Have flood response plans in place - prioritise use of limited resources during flood events • Use improved flood prediction models incorporating better weather forecasts and much more detailed information on topography, infrastructure, geology and hydrology • Enhance flood resilience of infrastructure where necessary or provide movable flooding walls. Work together with local authorities to have general local flood defence. Use inflatable dams) • Improve and maintain drainage network along the rail network • Clean drainage especially after autumn (in Essen there was flooding on the roads in November 2010 after some days normal rain due to clogged drainage by leaves) • Incorporate climate change projections into the design of drainage to cope with predicted future flooding frequency and magnitude • Consider infrastructure interdependencies. This especially applies to ensuring energy supply • Explore relocation of important infrastructure to higher elevations and areas of lower flood risk • Develop tailored plans for flash flooding and seasonal flooding (Immediately before event) • Flood warnings should be given in plenty of time • Monitor drainage and solve problems quickly • Deploy trouble shooting teams (drainage, bank repair teams) • Install flood protection walls or inflatable walls • Prepare water pumps for affected areas • Interrupt operations before events occur	All	Hazard, Vulnerability, Consequences	-	-	It was observed during the Alpine flooding of 2005 that Southern Bavaria was more prepared than other regions because of prior experience with the Whitsun flooding incidents of 1999.	Silla, A., Jaroszewski, D., Quinn, A., Baker, C., Hooper, E., Kochsiek, J., & Schulz, S. (2014). Guidebook for Enhancing Resilience of European Rail Transport in Extreme Weather Events. European Commission EC. https://silo.tips/download/guidebook-for-enhancing-resilience-of-european-rail-transport-in-extreme-weather

Project	Country or region	Event	Year	Any other hazards? (mentioned in this document)	Summary (What happened?) & Impacts on transport sector	Affected mode of transportation	Adaptation measures (Long term)	Mitigation directed at	Mitigation type (to)	Overall/Expected implementation costs of the long-term mitigation measure / (Benefit/Cost [B/C])	Frequency (How often we can apply this?) (How long can the measure be applied for [permanent or temporary]?)	Impact of the measure (Success stories?)	Sources/Links
Attica Tollway (Dimitris Mandalozis)	Athens, Greece	Climate change	-	Extreme maximum temperatures, reduction of annual rainfall, extreme rainfall and storms, hot/cold variability	The project discusses the consequences of a climate change on road infrastructure and thereafter discusses adaptation measures & requirements to prevent impacts of climate change on road networks	Roads	**1. Flood protection and management** • Construction of extensive sewerage and flood protection works for collecting the superficial runoff (few remaining natural receptors) • Maintenance of 67km-long flood protection works to collect water runoff and improve the overall flood protection of the city of Athens • Areas that used to be threatened by floods before Attica Tollway are now protected. Tollway is also protected. **2. Pavement Maintenance** • Pavement measurements and characteristics: • Falling Weight Deflectometer • Laser Profiler • Grip Tester • Ground Penetrating Radar • Use of pavement monitoring data •Pavement monitoring is carried out along the whole length of the motorway and at least once a year. • Skid resistance and texture, as they are sensitive functional characteristics, are measured twice a year, to obtain data regarding both the winter season, as well as the summer season. • Historic data has been collected from the start of operation of the tollway, allowing to check indicator values and variability throughout the years and to identify potential sources of concern and trends. **3. Meteorological stations** • There are 3 meteorological stations located along the length of Attica Tollway, providing real-time data regarding the prevailing weather conditions. • Information can be used to prepare operator, as well as users of the tollway, regarding extreme weather conditions. **4. Proactive Management / Action Plans/ Monitoring / Inspections** • Inspection and Monitoring (Day-to-day operation, Extreme events) • Action Plans (Maintain strength and durability at minimal cost) • Resilience (Adapt to changes, Maintain operating standards, Ensure user safety and comfort) • Risk Assessment (Costs, Projected Risks, Studies, Research) • 5th Generation Roads: The resilient road: Fully adaptable to extreme weather conditions	Roads	Hazard, Vulnerability Vulnerability Consequences Vulnerability, Consequences	EUR 1300M (This budget includes Project Development Costs)	Permanent Temporary Permanent	This construction of extensive sewerage and flood protection works for collecting the superficial runoff resulted in great improvement for the overall flood protection of the city of Athens, since there are few remaining natural receptors. During operation of the motorway, this extensive system is maintained thoroughly, to ensure that it continues to protect the capital from flooding. - - -	Mandalozis, D., Halkias, B., Tyrogianni, H. and Kafla, N., 2012. The Carbon Footprint of Attica Tollway. Procedia - Social and Behavioral Sciences, 48, pp.2988-2998. https://unece.org/DAM/trans/doc/2012/wp5/06__Mr_Mandalozis.pdf https://www.academia.edu/18141745/Operating_in_Green_The_case_of_Attica_Tollway_in_Athens_
European Climate Adaptation Platform (The economics of managing heavy rains and stormwater – The Cloudburst Management Plan)	Copenhagen, Denmark	Heavy rains and stormwater	2011-2016	Droughts, extreme temperatures, flooding, sea level rise, storms, water scarcity	Copenhagen experienced four major rainfall events, resulting in severe damage that was expensive to repair. These types of events are expected to be more intense and more frequent as a result of climate change.	Roads	The city has drawn out a Cloudburst Management Plan that aims to reduce the impacts of flooding due to heavy rains. The plan included an assessment of the costs of different measures (traditional vs new options including adaptation measures), the cost of the damage despite the measures and the resulting financial impact. The results showed that continuing to focus on traditional sewerage systems would result in a societal loss compared with the alternative solution. The alternative adaptation measures aim to store or drain excess water at ground level. The plan consists of four surface solutions as well as pipe-based solutions, including: • stormwater roads and pipes that transport water towards lakes and the harbour, e.g. in the built-up area of central Copenhagen; • retention roads for storing waters; • retention areas to store very large water volumes, e.g. parks that could turn into lakes during flood events; • green roads to detain and hold back water in smaller side streets	Roads	Hazard, Vulnerability	The traditional sewerage system was estimated to cost DKK 20 billion (EUR 2.6 billion) compared with DKK 13 billion for the alternative solution. Despite capital investments in the traditional sewerage system, financial losses from flooding would remain high (net loss of DKK 4 billion). On the other hand, the chosen combined solution — consisting of expanding the sewer network and surface projects focusing on water retention and drainage — would result in a net saving of DKK 3 billion.	The Cloudburst Management Plan was developed during 2013 and includes 300 surface projects. The projects have started to be implemented at around 15 projects per year for the next 20-30 years. The projects are prioritised according to the level of flood risk, a socio-economic assessment and the availability of co-benefits.	The plan is also likely to contribute to a growth in property values, increased employment, upgrade of urban spaces and increased tax revenues.	https://climate-adapt.eea.europa.eu/about/climate-adapt-10-case-studies-online.pdf
European Climate Adaptation Platform (Financial contributions of planning applications to prevent heathland fires)	Dorset, United Kingdom	Fires	2011	-	A large fire on 9 June 2011 destroyed 56 hectares of Dorset heathland. The risks of fire are likely to increase with climate change, because of higher temperatures and more frequent dry conditions.	Roads	• Adaptation of fire management plans • Adaptive management of natural habitats • Adaptation of integrated land use planning To protect its remaining heathland from fire, the county of Dorset has implemented a planning regulation to fund measures to help reduce the risk. Due to changes in agricultural practice, conifer planting, scrub encroachment, urban expansion and road building, the extensive area of heathlands (50000 ha) has been reduced to about 8000 ha. The Dorset Heathland Planning Framework Supplementary Planning Document (SPD) seeks to secure financial contributions from developers who want to build in the area, to fund the implementation of a package of alleviation measures to offset the adverse effects of residential development. The contributions are applied to all new housing that results in a net gain in dwelling units within a zone between 400 m and 5 km from designated European wildlife sites. The framework does not allow any development within a 400 m buffer zone around heathland sites. These fees are applied to fund a number of measures to mitigate the impact of urban development on heathlands that can contribute in reducing heathlands sensitivity to climate change induced effects, as in particular to increased fire risk. Mitigation measures include: (i) improvement of existing recreational sites and development of new recreational infrastructure to divert the recreational pressure from the most valuable and sensitive heathlands; (ii) land purchased as alternative open space; (iii) provision of more rangers and wardens; (iv) purchasing monitoring equipment; (v) land management to reduce fire load and risk of fires; and (vi) purchasing firefighting equipment and develop other firefighting instruments. Concerning this latter point, 2019 measures included: • Update of maps showing fire access routes for heathland sites; these maps are provided to fire appliances on their mobile data terminals. • Use of WhatsApp to circulate information about fire incidents as they occur to land managers who will support each other as required. • Launch of Firewise UK, an on-line platform raising awareness on how to reduce risk of fire to homes close to areas at risk from wildfire.	All	Hazard, Vulnerability, Consequences	The measure itself requires only marginal costs for administrative work. The budget for the financial year 2019 -2020 was £203,241.41, funded by Local Planning Authority Partners from developer contributions collected from development within 5 km of any heathland site. The cost of measures to mitigate the impact of urban development on heathland in south east Dorset was estimated at £4.3 million (November 2015 prices) and these should be brought up by the charges on house owners as a result of the measure.	The first Dorset Heathlands Planning Framework Supplementary Planning Document' (SPD) was introduced in 2007 and has been updated several time since now. The current Dorset Heathlands Planning Framework Supplementary Planning Document' (SPD) is proposed until 2025.	The benefits are the assurance that the integrity of the heathlands will not be further eroded or diminished by a steady increase in urban pressures due to additional development; the reduced risk of fires; the preservation of biodiversity; and the contribution to reducing the heathlands' sensitivity to climate change. However, quite recently, in May 2021, large wildfires broke out on heathland in Dorset. At least 12.7 hectares (31 acres) of forestry plantation has been destroyed in the blaze, the fire service said.	https://climate-adapt.eea.europa.eu/about/climate-adapt-10-case-studies-online.pdf https://climate-adapt.eea.europa.eu/metadata/case-studies/financial-contributions-of-planning-applications-to-prevention-of-heathland-fires-in-dorset-uk/#adapt_options_anchor https://www.bbc.co.uk/news/uk-england-dorset-56977310
European Climate Adaptation Platform (A transboundary depoldered area for flood protection and nature: Hedwige and Prosper Polders, Belgium)	Hedwige and Prosper Polders, Belgium (Flanders coast)	Flood	2005	Sea Level Rise, Storms	The Hedwige and Prosper Polders are low-lying areas of reclaimed land that are located just before the Scheldt estuary reaches Antwerp. Storm surges threaten the Flanders coast, including the city of Antwerp. The occurrence of storm surges in the North Sea has increased significantly since the 1950s, and sea-level rise is projected to further raise this threat in coming decades.	All	The Hedwige-Prosper Polder project is part of the wider Sigma Plan. The Sigma Plan is designed to reinforce dikes and quay walls, and open up areas that can flood to protect land along the Scheldt estuary. The project aims to remove the outer defences of the two polders and reopen these areas to the tides. This 'depoldering' process involves moving dike protection inland to provide room for water during tidal surges. The new dikes constructed inland will provide flood protection for the low-lying hinterland, and a system of creeks will be dug in the polders to simulate the natural wetland. This project (465 ha), combined with the adjacent Saeftinghe wetlands area, will create a large, cross-border, brackish intertidal area of approximately 4 100 ha. Waterwegen en Zeekanaal completed the new inland dike on the Belgian side, the Prosper Polder, in 2015. Works in the Hedwige Polder are expected to be completed in 2023.	All	Hazard, Vulnerability	A cost-benefit analysis for the Dutch government studied several project alternatives and indicated that the selected project option for depoldering the Hedwige polder in the Netherlands would cost between 40.0 to 49.3 million Euros (The costs for depoldering the Prosper polder in Belgium was estimated at 25.8 million Euros).	Final completion of the works, after the optimization of the channel system within the polder to allow Scheldt to properly flow inside, is expected to be completed in 2023. The lifetime of the project has not been indicated; with regular upkeep and maintenance, it is expected to remain in place for many decades. As noted above, sedimentation could affect its nature and flood protection functions.	Benefits from the project taken into account in the cost-benefit analysis include: improvement of water quality, increase in natural area, provision of new recreational opportunities, improvement of air quality due to a reduction in fine dust originating from ploughed fields (reduction of 30 tonnes per year PM10), reduction in pesticide use and reduction in water level during storm surges.	https://climate-adapt.eea.europa.eu/metadata/case-studies/a-transboundary-depoldered-area-for-flood-protection-and-nature-hedwige-and-prosper-polders https://www.sigmaplan.be/en/projects/hedwige-prosper-project/
European Climate Adaptation Platform (Temporary flood water storage in agricultural areas in the Middle Tisza river basin, Hungary)	Hungary	Flood	1998-2014	-	Between 1998 to 2001, four serious of floods occurred in the Tisza River Basin, including a rupture to dike flood defences which caused flooding in areas that should have been protected. This demonstrated that the dikes, walls along the river that hold back water, were not high nor strong enough to protect the basin from flooding.	All	To protect the cities of the river basin and reduce the risk of flooding, cost-effective adaptation measures were adopted. From 2007, weak areas of the dikes which had never been strengthened in previous attempts were improved, while to complement the dike flood protection system, the run-off capacity of areas between dikes was restored, and temporary reservoirs were created in agricultural areas that could be flooded when the river flow was high. In this way, more of the basin is protected from flooding and the areas chosen as reservoirs can still be used for agriculture at other points during the year, while during extreme rainfall the flooding frequency has been significant reduced. The temporary flood water storage in reservoirs on agricultural land works by giving the river room to flood specific areas with water during extreme flooding events. The reservoirs have a total capacity of 1 – 1.5 km3 and are used for agriculture in normal periods. During extreme rainfall events, the reservoirs provide a buffer for water flow, and reduce flood wave propagation by temporary allowing the river to flood them during emergencies. The plan for implementing the reservoirs was supported by a new Act in 2004, which has the following objectives: Increase flood safety (partly) by the reactivation of former floodplain territories, the management of the water surpluses, the development of the regions with most disadvantageous status and the improvement of living conditions in these regions.	All	Hazard, Vulnerability	The overall cost of around EUR 260 million has been paid with contributions from the European Regional Development Fund and the Cohesion Fund.	The lifespan of the measures implemented is expected to be 100 years. From an engineering perspective the strategy proved to be successful, however maintenance is required with respect to environmental damages within reservoirs. This has not yet been addressed in the project.	For example, in 2010, one of the reservoirs was successfully used during a flood event. By combining a mix of strategies, a balance was found between reducing the costs of the measures and avoiding taking too much land away from agriculture and other uses.	https://www.lifetreecheck.eu/en/Databaze/2020/Temporary-flood-water-storage-in-the-Middle-Tisza https://climate-adapt.eea.europa.eu/about/climate-adapt-10-case-studies-online.pdf http://www.feem-project.net/epiwater/docs/epi-water_DL_4-2.pdf
Incorporating climate change risks in planning the modernization of the railway corridor in Slovakia	Slovakia	Flood	2019	Extreme temperatures, Ice and Snow, Storms	Natural conditions of Slovakia are very diverse in terms of topography, climate, vegetation and economic activities. The southern part of the country is mostly lowland, i.e. warmer and drier, while the mountainous north has a cooler and humid climate. This diversity is one of the reasons for a wide range of natural risks induced by climatic events affecting rail transport, which are likely to be exacerbated by climate change. Along with global warming, the occurrence of climate extremes, including heavy storms, torrential rains, strong winds and heatwaves, will likely increase. Weather extremes are potentially the most dangerous manifestation of climate change for the transportation sector and for rail transport in particular, causing damage to the railway infrastructure and disruption of traffic. Major impacts include flooding.	Railways	• Monitoring, modelling and forecasting systems • Establishment of early warning systems • Operation and construction measures for ensuring climate-resilient railway infrastructure Proposed adaptation measures can be grouped in three categories: • Technical options, increasing resilience of essential railway infrastructure to extreme weather events and climate change trends. These measures, which are aimed at preventing disruption of infrastructure availability, include: increased capacity of the drainage system, such as culverts able to cope with higher quantity of water and improved drainage of railway subgrade, tunnels and bridge structures; increased railway alignment above the limit of potential flood (betweenQ100 to Q1000 depending on the on-site situation); resistant bridge structures and deep bridge pillars; use of highly water resistant building materials for railway subgrade and other components; flexible way of mounting rails, which significantly reduces the deformation of rails due to extreme temperatures; installation of structural protection systems (e.g. windbreaks, retaining walls, embankments). • Management options, providing solutions when extreme weather events occur and infrastructure disruption takes place. These options help minimize negative impacts of extreme events and include: (i) increased maintenance and control of sections at risks, e.g. equipping switches, rails and catenaries with detectors monitoring temperature; (ii) provision of substitute bus service in the event of temporary interruption of rail transport; (iii) ensuring alternative railway routes and efficient emergency transport management; (iv) measures pertaining to environmental management (e.g. river basin reforestation). • Early warning system, monitoring and forecasting, aiming to increase preparedness and enable traffic management measures to be taken in advance. This typology of measures relies on the implemented and operative monitoring, forecasting and alerting system of Slovak Hydrometeorological Institute (SHMI); it deals with a "railway tailored" monitoring and forecasting system which focuses on the events particularly harmful for railway. By means of providing early warning system, the negative impact of extreme weather events on rail transport system and the whole economy will be minimized. Adaptation measures include: measures to ensure flood protection up to Q500 flood level, drainage of the railway subgrade, and retaining walls reinforcing slopes with high risk of instability. All bridges and tunnels are designed to withstand floods and torrential rainfall (e.g. through isolated bridge decks, resistant bridge pillars) and must be tested for static and dynamic load before they are put in regular operation.	Railways, Bridges	Vulnerability, Consequences	The main funding instrument of all phases of the railway modernization project (preparatory, design and implementation) is the Operation Programme Integrated Infrastructure 2014-2020 (OPII), preceded by the OPII for the period 2007–2013. The total allocation of OPII 2014–2020 Priority axis 1 - focused on railway infrastructure within TEN-T core network - is € 853,9 million, out of which € 725,8 million provided by the European Commission through the Cohesion Fund and the remaining € 128,1 represented by national co-financing from the State budget. Further economic resources shall be also ensured by the OPII foreseen of the next 2021–2027 programming period. Given this overall figure, the total financial costs for the modernization of the entire corridor cannot be quantified yet, as the majority of its total length is still in the preparatory phase. The financial figures are available only for the corridor sections which have been already modernized or are under construction. For instance, the total budget of the construction work carried out in the section Púchov - Považská Teplá currently under construction is € 365 million. In this case, the contribution from OPII 2014–2020 is € 361 million. However, the cost of technical measures increasing climate change resilience of railway is not available separately, as they represent an integral part of the overall construction works.	The studies carried out within the preparatory phase of the modernization project (feasibility study, impact analysis, vulnerability analysis, proposal of adaptation measures) are currently ready almost for the entire length of the railway corridor. Their preparation took between several months to approximately two years according to the extent and complexity of the specific railway section considered. Implementation started and is on-going on some section of the corridor. Modernization work of the Bratislava - Žilina section of approximately 200 km length is almost completed; climate-proofing of the railway is an integral part of constructions works. Due to a large number of influencing factors, the date of completion of the entire corridor cannot be defined yet. The technical measures increasing climate resilience of railway have a lifetime of several decades, depending on the level of maintenance. Railway infrastructure lifetime is also very long in the order of tens of years up to 100 years or even more, if well maintained and continuously monitored.	Main overall expected benefits of the railway modernization project include: attractive, faster and more comfortable railway transport; less transport emissions compared to road transport; better competitiveness of SME; health benefits due to lower air pollution and lower noise pollution still compared to road transport. As far as adaptation to climate change is concerned, the project is expected to increase the resilience of the railway transport system and ensure operation also during extreme meteorological events.	https://climate-adapt.eea.europa.eu/metadata/case-studies/incorporating-climate-change-risks-in-planning-the-modernization-of-the-railway-corridor-in-slovakia
Tatabánya, Hungary, addressing the impacts of urban heatwaves and forest fires with alert measures	Tatabánya, Hungary	Fires	1961-2010	Droughts, Extreme Temperatures, Heatwaves and forest fires	Hungary has a continental climate, characterized by hot summers (temperature extremes are about 42°C) and low overall humidity levels. The average yearly rainfall is approximately 600 mm but showers and cold to frigid snowy winters are frequent. Heatwave events, especially in summer, have become more frequent, longer and intense over the period 1961-2010. In addition, drought frequency, duration, and severity increased in the past decades. Climate projections based on RCP4.5 and 8.5 scenarios indicate that these trends (increases in heatwaves and drought) will persist in the future decades, thus impacting Hungarian landscape and society. Tatabánya has and will continue to face two major climate-related risks for which adaptation measures are required: heatwaves (including the connection to urban heat island effect) and wildfires. These two risks, caused by extreme temperatures and droughts, threaten the surrounding region and the health of the population (including through air pollution). In addition strong rains and floods are currently increasing.	All	• Awareness campaigns for behavioural change • Monitoring, modelling and forecasting systems • Establishment of early warning systems • Adaptation of fire management plans • Capacity building on climate change adaptation • Heat health action plans	All	Consequences	In 2009, a budget of HUF 4,000,000 (approx. EUR 15,000) was made available by the Environmental Education and Climate Change Department and a full-time climate manager was assigned for the implementation of the Action Plan. This budget remained approximately constant through the years: 4-6,000,000 HUF have been provided yearly by the Municipality of Tatabánya, while additional contributions have been made available by other organizations involved.	Approximately 1.5 years were needed to develop the Local Climate Change Strategy and Action Plan. The implementation of the measures started in 2008 and is on-going, with measures already implemented still active.	The heat alert system has been activated several times already: in the last 8 years (up to 2020) an average of 3-5 alerts were yearly issued in Tatabánya. The UV alert system was activated once every year, except in 2012 when it was activated twice. According to the Mayor's Office, an increasing number of inhabitants are now aware of what they should do during a heatwave or UV radiation alert.	https://climate-adapt.eea.europa.eu/metadata/case-studies/tatabanya-hungary-addressing-the-impacts-of-urban-heat-waves-and-forest-fires-with-alert-measures

Project	Country or region	Event	Year	Any other hazards? (mentioned in this document)	Summary (What happened?) & Impacts on transport sector	Affected mode of transportation	Adaptation measures (Long term)	Mitigation directed at	Mitigation type (to)	Overall/Expected implementation costs of the long-term mitigation measure / (Benefit/Cost [B/C])	Frequency (How often we can apply this?) (How long can the measure be applied for [permanent or temporary])?	Impact of the measure (Success stories?)	Sources/Links
How Network Rail 'battles the buckle' during hot weather	United Kingdom	Heat	Currently	Extreme Temperatures	On hot days, rails in direct sunshine can be as much as 20 degrees centigrade above air temperature. As rails are made out of steel, they expand as they heat, and that expansion has to be managed. When Network Rail install tracks, small gaps – called expansion joints – are left between sections of steel rails to safely allow a small amount of expansion during hot weather. If the joints have already fully closed up and the rail continues to expand, then the rail starts to go into what is known as 'compression'. The combined system of rail, sleepers and ballast (the stones on which the rails and sleepers sit) which make up tracks is designed to be able to resist these compressive forces – but in extreme cases the tracks can buckle, making it impossible to run trains. Usually, these repairs can't be done until the temperature of the rails has dropped, causing significant disruption for passengers and freight.	Railways	**How does Network Rail prevents track buckling?** • Each part of the network is risk-assessed so that we know at what rail temperature the risks of track buckling are increased. • Checking the stability of the track each winter and strengthening any weaknesses before the summer arrives; typically this includes replenishing the ballast that surrounds the sleepers, and re-tensing (stretching) continuously welded rails. • Planning to avoid work that will disturb the stability of the track during the summer as this increases the chance of a track buckle, though sometimes it cannot be avoided. • Painting at-risk rails white so they absorb less heat, reducing rail temperatures. Typically, a painted rail will be five to ten degrees cooler than an unpainted rail. • Introducing sprinkler systems to cool rail temperatures at key junctions and during trials these have reduced temperatures by four degrees in ten minutes. • Continually enhancing current measures for calculating rail temperatures, including installing probes that give instant alerts when track temperatures rise. • On very hot days when high rail temperatures are widespread, imposing speed restrictions at vulnerable locations; slower trains exert lower forces on the track, reducing the risk of buckling. **Future solutions** • Benchmarking with other countries to understand how they cope with hot weather. Determined that countries with ballasted track systems, like the UK, have the same challenges. • Some countries use "slab track" where a track is laid on reinforced concrete slabs rather than on sleepers and ballast, preventing tracks from buckling.	Railways	Hazard, Vulnerability, Consequences	Costs depend on measures. Depending on the type of upgrade, the cost of this activity can vary where replacing a railway track can range from £0.25 million to £1.6 million per kilometre. The installation cost of slab track is typically four times that of track laid on sleepers and ballast. Even taking into account the savings in maintenance and disruption costs, it's hard to make a business case for slab track	Short-term. Most measures will require regular maintenance.	Smooth operations on the rail infrastructure with several benefits.	https://www.networkrailmediacentre.co.uk/news/media-briefing-network-rail-battles-the-buckle-during-hot-weather https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/delays-explained/buckled-rail-and-summer-heat/ https://www.networkrail.co.uk/stories/how-we-prevent-tracks-from-getting-too-hot/ Doll, C., S. Klug, J. Köhler, I. Partzsch, R. Enei, V. Pelikan, N. Sedlacek, H. Maurer, L. Rudzikaite, A. Papanikolaou, V. Mitsakis (2011). "Adaptation Strategies in the Transport Sector" Deliverable 4 of the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project coordinator: Fraunhofer ISI, Karlsruhe.
Climate adaptation strategy for the Grimsel area in the Swiss Alps	Grimsel area, Swiss Alps	Flood	2016	Extreme Temperatures, Ice and Snow	Settlements, infrastructure, land use and road connections in the Grimsel area in southern Switzerland are heavily exposed to risks from hydrological and gravitational natural hazard processes, such as rock fall, mudflows, landslides, avalanches, and floods favoured by sedimentation of debris. Permafrost thawing, glacier retreat, and more frequent heavy rainfall events due to climate change are expected to further decrease slope stability and increase likelihood of mass movements. In the Grimsel area, high current problem pressure from mudflows and local flooding in parts of the municipal territories was an important driver for initiating development of the climate adaptation strategy. In their assessment of future challenges, the participating stakeholders concluded that threats caused by a range of hydro-gravitational hazards are likely to increase under conditions of progressing climate change, including an extension of hazard-prone periods into the summer season. The resulting risks directly affect the only cantonal road, which is the main public transport connection in and out of the region and the secondary road system, which is a main economic asset of the region.	Roads, Bridges	• Adaptation of integrated land use planning • Crises and disaster management systems and plans • Establishment of early warning systems • Climate proofed standards for road design, construction and maintenance • Operation and construction measures for ensuring climate-resilient railway infrastructure • Establishment of a steering committee for the "Climate Adaptation Strategy for the Grimsel Area: Constituting a steering group and defining its tasks and terms of reference in order to secure the implementation, monitoring and advancement of measures. • Improving exchange of data and information on natural hazards: Establishing an infrastructure and procedures for exchanging and processing data and information on natural hazards from various sources and for providing them to experts and the public. This shall support regional actors in coping with risks. • Preparing for possible new railway connection: The measure aims at contributing to the recent political discussion on plans to build a new narrow-gauge railway, bundled with a high-voltage power line, in a 20 km long tunnel system passing north-south under the Grimsel pass. The project offers a "climate-proof" alternative to the hazard-prone cantonal road. Possible implications of the project on the region and its exposure to natural hazards shall be evaluated and fed into decision-making. • Improvement of crisis communication for tourism: Elaborating and implementing a tailored communication concept to convey in a more timely, accurate and effective manner information on occurrence of hazard events to touristic user groups. • Marketing of the natural environment and dynamic processes: Developing tourism products that market landscape and the natural environment as regional assets. This shall also contribute to raising awareness of guests for natural hazard processes and to create better understanding for emergency measures such as road closures.	All	Hazard, Vulnerability, Consequences	For each measure defined in the strategy, the benefits and intended outcomes are described and financing needs are characterised in qualitative terms, but neither benefits nor costs have been quantified. Establishment and operation of the steering group did not cause any extra costs, because administration and work time are borne by the regular budgets of the member organisations. It has not been possible to estimate the costs of other measures at the time of drafting the strategy document, because in most cases the financing needs for full realisation of the measures depend on the outcomes of first implementation steps (e.g., clarifying the exact needs of various user groups regarding the planned natural hazard data hub). Accordingly, estimation of cost is sometimes part of the step-by-step implementation plan for measures. Qualitative cost-benefit considerations played an important role in development of the strategy and are at the root of several measures. For instance, protecting the road infrastructure against natural hazards and increasing the quality of traffic access is restricted by the limited availability of public financial resources. The current focus of the public road management regime on monitoring hazard hot spots and preparing recovery measures if damages occur will thus have to be retained, because financing of larger structural protection measures is not feasible. Similar cost-benefit relations in the field of tension between risk prevention (adequate protection levels) and risk tolerance (acceptable risk levels) contribute to many of the challenges that the strategy responds to.	The measures defined in the strategy are predominantly non-structural, but rather process-oriented and aim at shaping conditions and durable processes for climate-resilient, sustainable regional development. As such, their 'lifetime' is not subject to a discrete time range.	Implementing measure 1), the strategy has been structurally anchored in the region by establishing the steering group already in 2016. The steering group is part of a newly created governance arrangement for implementation of the strategy that builds on existing institutional structures in the region and combines central coordination with decentral responsibilities. It is composed of important institutions that participated in the strategy development and chaired by the Regionalkonferenz Oberland-Ost, an institution that is in charge of coordinating regional policy and acts at the interface of municipal, cantonal and federal authorities. The actors participating in the strategy development have committed themselves to implementing the strategy by signing a declaration of intention. By the end of 2018, realisation of further measures is showing a mixed picture, with the state of implementation ranging from finalized to being in progress to facing difficulties. The improvement of data exchange on natural hazards (measure 2) among the region's main infrastructure operators is progressing very well and has yielded substantial outcomes, e.g. regarding the redressing of redundant monitoring structures, common usage of databases run by single operators, and joint	https://climate-adapt.eea.europa.eu/metadata/case-studies/climate-adaptation-strategy-for-the-grimsel-area-in-the-swiss-alps
Installation of road weather information systems as an adaptation strategy	-	All	-	-	It is considered essential to monitor transportation systems in order to detect and quantify climate change vulnerabilities as well as improve the effectiveness of adaptation strategies.	Roads	**Road Weather Information Systems** make an important contribution, because they (1) facilitate the long-term monitoring of climate change in EWCs' impacts on road transportation and (2) contribute directly to the mitigation of risks (e.g., road crashes) by providing real-time warning about crucial weather conditions to road transportation stakeholders (Papanikolaou et al. 2011; Andrey et al. 2001). A RWIS consists of sensor stations, communication network, weather and pavement temperature modelling, tailored weather and pavement temperature forecasts, traveller information and maintenance decision support systems (Boon and Cluett 2002).	Roads	Vulnerability, Consequences	RWIS are profitable investments (B/C = 5)	Permanent	RWIS cannot offer protection against the deterioration of infrastructures as the sudden consequence of weather extremes, such as floods, heat or cold spells. But they do help to address one of the most costly consequences of these events: system performance in terms of user time losses and safety.	Doll, C., Trinks, C., Sedlacek, N., Pelikan, V., Comes, T. and Schultmann, F., 2013. Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria. Natural Hazards, 72(1), pp.63-85. Papanikolaou A, Mitsakis V, Chrysostomou K, Trinks C, Partzsch I (2011) Innovative emergency management strategies. Deliverable 3 of the research project WEATHER. EC FP7. Fraunhofer ISI, Karlsruhe Andrey J, Mills B, Vandermolen J (2001) Weather information and road safety. Institute for Catastrophic Loss Reduction, Paper Series No. 15 Boon CB, Cluett C (2002) Road weather information systems: enabling proactive maintenance practices in Washington State. Washington State Transportation Center, Research Report
Timmendorfer Strand coastal flood defence strategy	Germany	Flood	1999-2011	Sea Level Rise, Storms	Timmendorfer Strand is located at the temperate zone of the Baltic Sea Region and large part of it lays no more than 3 meters above sea level. With respect to climate change, it is mainly threatened from impacts due to sea level rise and storm floods. From a coastal defence perspective, changes in mean and maximum water levels and sea condition caused by climate change are predominantly relevant. Both parameters (water level and sea conditions) are essential basis for the dimensioning of the coastal flood defences.	All	• A seawall provides a high degree of protection against coastal flooding and erosion. It fixes the boundary between the sea and land which can be beneficial if important infrastructure or buildings are located on the shoreline. • Seawalls have a lower space requirement than other coastal defences such as dikes. Seawalls can be heightened to face sea level rise, which requires simultaneously a widening of the foundation. • The high level of security provided by a seawall can favour the development of the hinterland. The crest of the seawall often extends into a stone covered part providing other functions, e.g. road, promenade or parking places.	All	Hazard, Vulnerability	Construction costs are high but these structures usually require low maintenance. Construction costs vary according to the shape of seawall structures: the volume of the seawall depends on the required crest level, the foundation level, the wave loading, and acceptable overtopping rates. In the Netherlands, it has been estimated that a seawall would cost 300-500€ per m^3 of concrete (Deltares, 2014). Costs related to jetties are estimated at 10,000 € to 20,000 € per running metre in the Netherlands; costs mostly depend on the water depth and availability of rock (Deltares, 2014). The estimated benefits are between 4 and 8 times higher than the estimated costs (benefit-cost ratio).	Walls are long-term investments with a lifetime of around 100 years.	-	https://climate-adapt.eea.europa.eu/metadata/case-studies/timmendorfer-strand-coastal-protection-strategy-germany https://climate-adapt.eea.europa.eu/metadata/adaptation-options/seawalls-and-jetties
Reconstruction of the Dawlish railway line in the United Kingdom	Dawlish, Devon, United Kingdom	Flood	2014	Strong winds	Severe damage to a coastal section of the south–west main line railway at Dawlish, Devon during the storms in February 2014. This event saw the railway in the south-west of the United Kingdom cut off from the rest of the railway network for two months. During this period of exceptional weather, the transport system was among the most severely affected elements of infrastructure, with flooding and other damage to rail and road infrastructure, closures of railway lines and suspension of services for commuters, cancellation of flights and ferries, and other consequences.	Roads, Railways	3 long-term options: • Retaining the coastal route • Building a 2nd line • Rerouting the main line. Adaptation measures implemented included: • An installation of a temporary sea wall to prevent further damages • Rebuilding and fortifying the breach with a large amount of concrete and steel • Removing collapsed cliff sections • Building of a new higher and wider seawall in front of the existing seawall.	Railways	Hazard, Vulnerability	A £31 million package of improvements was announced to examine every option to ensure the resilience of this route.	Long-term	Construction of a new, higher and wider structure is expected to enhance resilience from waves, floods and other weather-related events while also taking predicted rising sea levels into account. The new raised sea wall is protected from the sea and provides great protection to the railway line against strong winds and rain at Dawlish.	https://www.networkrailmediacentre.co.uk/news/dawlish-railway-reopens-in-time-for-easter-holidays-as-network-rails-orange-army-wins-its-war-with-the-elements https://www.networkrail.co.uk/stories/five-years-since-we-reopened-dawlish/ https://www.bbc.co.uk/news/uk-england-devon-54297969