Conférence Européenne
des Directeurs des Routes

Conference of European
Directors of Roads

ICARUS

Improve the uptake of Climate change Adaptation in the decision making processes of Road aUthoritieS

Baseline report on determining impacts and risk due to climate change

Deliverable D1.1 Final version

30-11- 2022

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CEDR call 2022: Climate Change Resilience

Deliverable D1.1 Final version

Baseline report on determining impacts and risk due to climate change

30-11-2022

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Summary

This report aims to set the baseline for research in Work Package 1 of the ICARUS project. Work Package 1 focusses on impacts and risks due to climate change. For this purpose, an overview has been made of the State of the Art (SoA) (also a State of Practice (SoP)). For each of these issues, literature analysis, stakeholder engagement and knowledge of the ICARUS consortium was used.

This report is built using a simple and straightforward methodology including a literature review of the state of the art and the state of practice. Conclusions and gaps are described in section 6, while in Annexes 1, 2 and 3 overviews, projections and a living glossary for ICARUS are included for an easy and detailed reading. Definitions are based on current insights but may change due to new insights in the remainder of the proposal.

This deliverable 1.1 introduces the principles of climate risk in the road sector and presents the elements that structure the Impact Chains. These correspond to the core components of risk (hazard, exposure and vulnerability).

This report is linked to two other baseline reports of the ICARUS project:

D2.1: Baseline report on minimum service levels and resilience evaluation

D3.1: Report on the current evidence-base of using cost-benefit analysis for assessing road

The terminology and goals of these reports are consistent with the current report. Though, it should be noted that all baseline reports have been produced at the start of the ICARUS research. Terminology and approaches are likely to change due to evolving insights in the remainder of the project.

It should be noted that the terminology used, and the approaches proposed in this document are based on a series of concepts with a markedly negative meaning: risk, vulnerability, damage, etc. Climate change may also imply positive trends for the road sector in specific activities and locations. For example, in some areas it would be possible to expect a reduction in the investments necessary to guarantee winter viability. Despite the fact that these "positive impacts" and opportunities can be analysed from the approaches proposed in this document, for consistency with the most widely used terminology, these terms that focus on negative impacts are maintained even when sometimes are not intuitive to address an evaluation of the opportunities associated with climate change.

The ICARUS project, framed within the CEDR Transnational Road Research Programme, aims at developing knowledge products for the integration of climate resilience into decision-making processes, as well as implementing existing resilience thinking and research into practice within the NRAs.

Definitions are based on current insights but may change due to new insights in the remainder of the proposal. All definitions are under development and may be changed when new insight appear in the project.

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1 INTRODUCTION TO CLIMATE CHANGE

This section includes a brief description of the causes of climate change and the challenges that it poses for the European road sector.

1.1 Climate change and its main effects on the road network

From a top-down perspective, the origin of climate change is the overall increase of the greenhouse effect (Figure 1.1):

- earth absorbs solar radiation as part of its natural warming process;
- part of this radiation is reflected to space by atmosphere, oceans, lakes, ice …;
- before leaving to space, part the long wave or infrared radiation is absorbed by clouds and greenhouse gases in the atmosphere and reflected back towards earth. This represents more steam accumulation in the atmosphere, which is causing more precipitation in the planet;
- the problem emerges in this phase, because in the last 150 years the layer of greenhouse gases effect has thickened, causing more radiation reflected to earth, increasing the global average temperature. The raise in global temperature has a number of effects on the climate system, known as climate change.

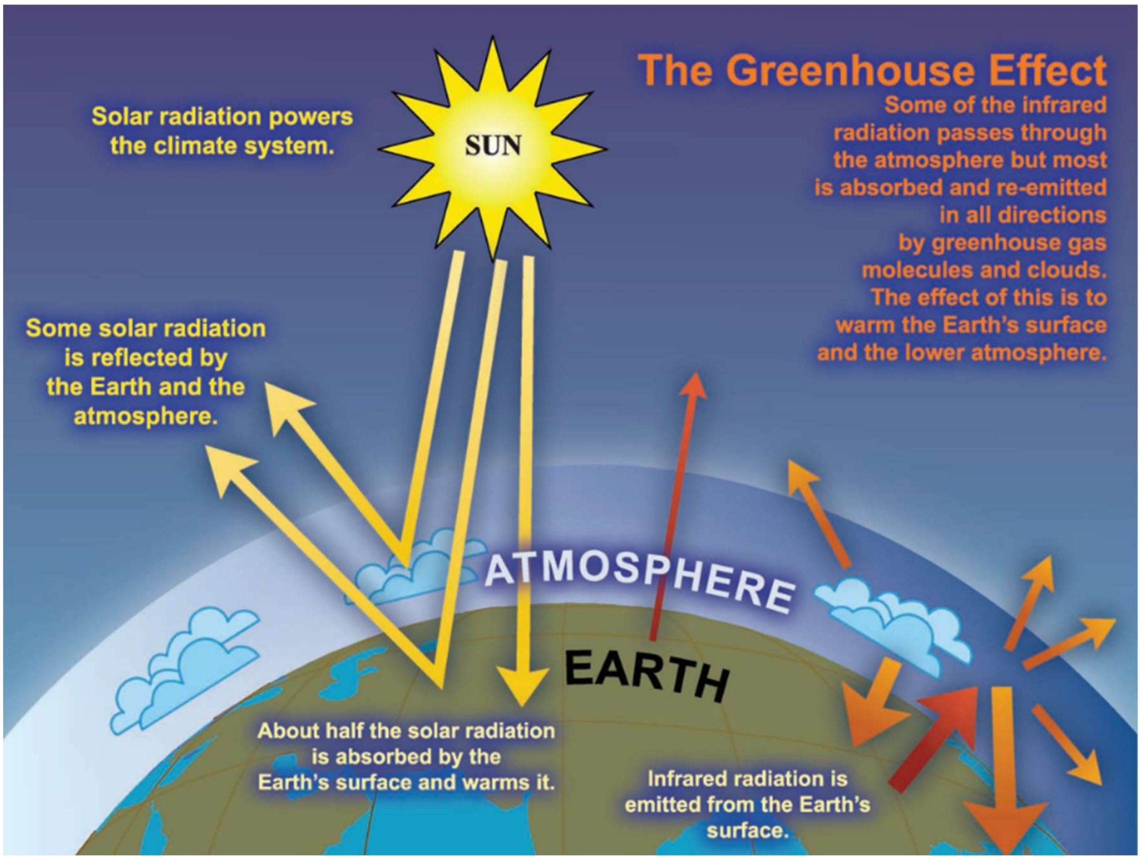

Figure 1.1 An idealised and simplified model of the natural greenhouse effect (IPCC, 2007a). See text for explanation

As a result of climate change, the Earth system adjusts in several ways that have direct and indirect impacts on both the marine and terrestrial environment. Global warming alters all the climate system, affecting the magnitude and distribution of other variables as precipitations, winds, heat, drought, flooding, etc. These changes, globally known as "climate change", have multiple impacts on all natural and human systems, and, of course, on the road sector.

The impacts of climate change on European roads are impossible to be predicted accurately, but different organisations have already started different research initiatives such as the Adaptation to Climate Change – Task Group under CEDR. According to their evaluations (Petkovic, 2012) some of the foreseeable impacts are:

- more flooding and erosion - a challenge for drainage systems and erosion protection and for the design and maintenance of culverts and bridges;
- landslides and avalanches: occurring more frequently, at new locations and with a higher share of "wet" landslide types such as slush avalanches and debris flow.
- droughts and high summer temperatures may represent problems for the asphalt surfacing, due to softening, but also for runoff conditions, roadside fires, increased soil subsidence, due to lower permeability.
- risk of wildfires may also increase in the northern regions, like the Netherlands or UK, and the southernmost region.
- deterioration of roads and pavements - as expressed by the service life and rutting, mostly in cases where the drainage is insufficient. Additionally, this represents a risk for road users because the water stays on the surface causing an aquaplaning effect for the cars provoking traffic accidents.
- effects of sea level rise for coastal stability and sufficient elevation for roads, quays, and bridges, as well as entrance levels for sub-sea tunnels.
- heavy snowfall in mountain areas of northern Europe causing trouble for winter maintenance and operation under difficult conditions.
- risk management and efficient procedures for initiating remedial actions after an unwanted event occurs - due to the fact that the present protective measures may not be sufficient and that the planning of remedial measures requires time.

ICARUS will provide, as a result of the project, a new mapping exposure combining assets, lifecycle and Climatic Impact Drivers as explained in section 4 of this Deliverable following the IPCC AR6 approach briefly introduced in section 3.

1.2 NRA's perspective

In the previous section, the impact of climate change has been described from a top-down perspective, that is, starting from the impacts that can be expected at a global and sectoral level. But, before delving into the information available in this regard, it is also interesting to consider a bottom-up approach, seeking to put oneself in the shoes of the key agents for the adaptation of the sector.

There is a constant need for decisions and development of the road transport system, and it is understood that a change in climatic conditions may have significant effects. Road authorities need to evaluate the effect of climate change on the road network and take remedial action concerning the overall lifecycle of the road network. The prioritization of measures to maximize resilience to climatic conditions with reasonable costs is one of the most important tasks of the NRAs.

Basically, the main questions of road owners and operators are:

- Is climate change really affecting roads?

This question is probably already answered by most of the road operators and owners in Europe. It is generally accepted that climate change is affecting road infrastructure or the level of service, in one way or another.

- How and where will climate change affect road transport?

The underlying question here is about the vulnerability to extreme weather conditions. For road owners and operators, it is important to know which unwanted events might happen in the future in their jurisdiction due to climate change, but also today the weather poses a risk to road transport.

- How likely is it to happen? And if it does happen, what are the consequences?

When knowing which unwanted events might occur on a road network, it is important to know the likelihood and consequences to gain insight in the risk profile. Already in the current climate conditions large uncertainties are present that make it difficult to estimate the probabilities and consequences of unwanted events into the infrastructure and the services it enables. When projecting into the future the uncertainties will increase even further. The uncertainties make a risk-based approach a worthwhile approach.

- What should be done to mitigate the risks and when (before, during and/or after)?

If unwanted events are present with an unacceptable risk profile, mitigation actions need to be taken. Road owners and operators need a methodology that assists in the prioritization of measures and track their effectiveness.

Given the high uncertainties of climate change, there is no straightforward answer to those questions that is valid in all circumstances. On top of this, uncertainties also exist in changing demands for road infrastructure, originating in socio economic developments and changing technologies. In situations with high uncertainties a risk management approach is generally accepted as a way to stay in control.

That’s why in the next points current practice in risk assessment according to different recommendations and accepted frameworks are presented.

2 CLIMATE RISK IN THE ROAD SECTOR

The concept of risk has been established in recent years as a key to planning adaptation to the impacts of climate change. This section first presents the different frameworks and approaches to address climate risk analysis, both general and specific to the road sector in order to bridge the gap between climate change adaptation practice and road design, development and operation (a key objective of ICARUS). Then, it describes the risk management framework applied to the road environment and finally, it discusses how to move from climate risks to climate resilience describing the interactions between the concepts shown in the section.

2.1 Climate risk assessment frameworks

Climate risk assessment provides an understanding of the impacts of climate change (such as infrastructure systems, organizations, natural systems, among others), and how to best tackle the adverse consequences in order to inform the prioritization and implementation of adaptation measures.

2.1.1 IPCC's risk assessment reports (IPCC, 2014; 2021)

Nowadays, the most accepted framework comes from the Intergovernmental Panel on Climate Change (IPCC). As defined by the IPCC's Fifth Assessment Report (AR5, IPCC, 2014a), and maintained in AR6 (IPCC, 2021a), the concept of risk is defined as the potential for adverse consequences for human or ecological systems. This concept is located at the centre of the framework and arises from the interaction of climate-related hazards, the exposure and vulnerability of the potentially affected human and ecological systems. Thus, it makes risk more relevant to climate change adaptation and replaces previous approaches that placed greater emphasis on vulnerability (e.g., the IPCC's Fourth Assessment report approach (IPCC, 2007b) (Figure 2.1).

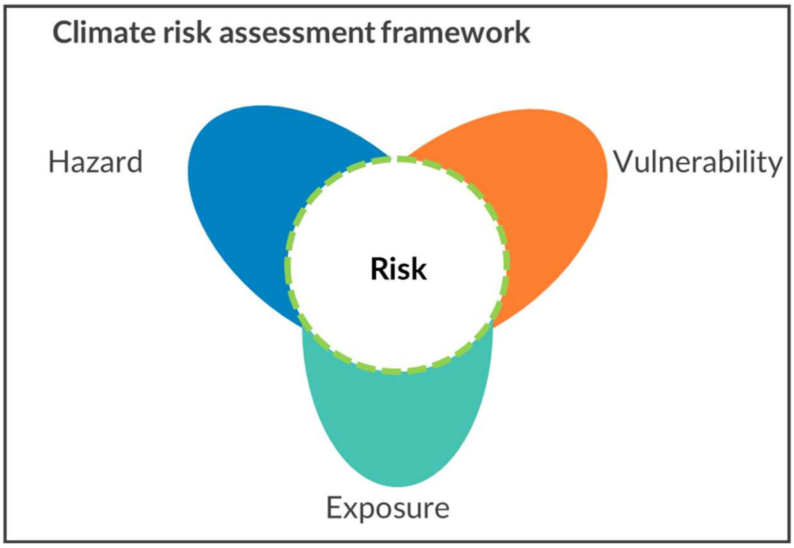

Figure 2.1 Risk assessment framework according to the (IPCC, 2021a)

2.1.2 The RIMAROCC and ROADAPT guidelines (CEDR, 2010)

In the road transport system environment, there is still no formal methodology of risk assessment but good-practice guidelines (Comité technique, 2016). The RIMAROCC (Risk Management for Roads in a Changing Climate) (CEDR, 2010) project, developed by CEDR, presented an overall approach to perform a climate change assessment for roads in a changing climate, which did not maintain the interactions of the IPCC AR6 risk components where risk is taken as a function of hazard, vulnerability and consequences.

Following this, the ROADAPT (CEDR, 2012) project provided a set of guidelines:

A. Guidelines on the use of climate data for the current and future climate

B. Guidelines on the application of a QuickScan[1] on climate change risks for roads

C. Guidelines on how to perform a detailed vulnerability assessment

D. Guidelines on how to perform a socio-economic impact assessment

E. Guidelines on how to select an adaptation strategy

All the ROADAPT guidelines can be used individually but should be seen as interdependent and fitting within the broader RIMAROCC framework. The guidelines are primarily written for National Road Authorities to gain insight into the steps to take for a climate change risk assessment on roads. Within ROADAPT (Figure 2.2), risk is a function of likelihood (determined by combining information on hazard and effect) and impact (determined by combining information on the effect and the socio-economic impact), which is in line with the ISO standards and PIARC recommendations.

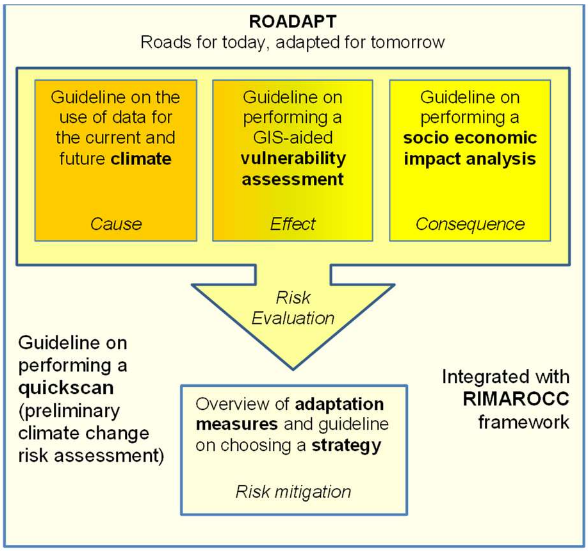

Figure 2.2 The ROADAPT risk evaluation scheme (CEDR, 2012)

2.1.3 PIARC and European Commission guidelines (PIARC, 2015; EC, 2021a)

The adaptation framework in road infrastructure has also been addressed by the World Road Association report (PIARC). The International Climate Change Adaptation Framework for Road Infrastructure project (PIARC, 2015) developed a guide to identify the most relevant assets and climate variables for the assessment of risks and develop a robust adaptation response. The proposed scheme is in line with the framework recently published by the European Commission described in detail below.

Recently, the European Commission provided a technical guidance (European Commission, 2021a) on climate proofing of infrastructure with the aim of identifying and investing in infrastructure for a climate-neutral and climate resilient future. This guidance is similar to the one proposed by the PIARC, 2015) and divides the framework in two phases: (i) a screening phase (phase 1) to describe the vulnerability of infrastructures and (ii) a detailed analysis phase (phase 2) to assess risks.

[1] It is a methodology to quickly and easily determine the effects of climate change on infrastructure.

Phase 1 (screening) identifies the most relevant hazards and analyses vulnerability for a given project, combining the sensitivity of project asset type and their exposure to hazards occurring now and in the coming years (Figure 2.3) for the selected location. The approach is in line with the 4th Assessment Report (AR4) of the IPCC, which places greater emphasis on vulnerability (for specific project type →sensitivity; at selected location→ exposure). However, it should be noted that the AR4 has been updated, and today vulnerability as well as exposure are underlying components of risk (Figure 2.3).

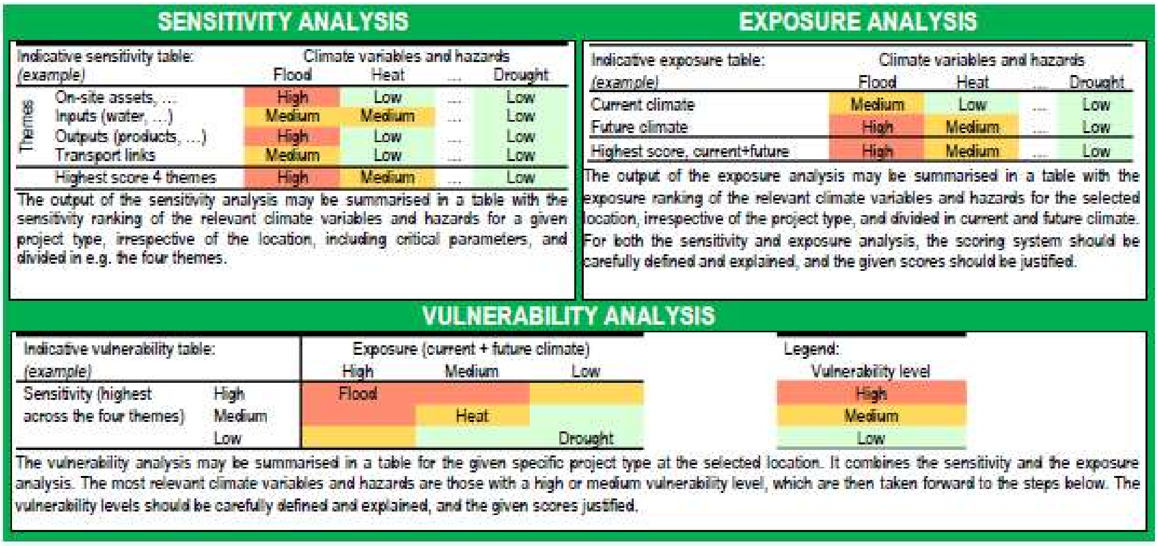

Figure 2.3 Overview of the vulnerability analysis according to the European Commission, 2021a).

Phase 2 (detailed analysis) is based on risk matrices and consists of estimating and ranking the impacts and probabilities of hazards, in a similar way as promoted by ISO standards (e.g. ISO 14091) (Figure 2.4). For any combination of impact and likelihood, a risk level ranging from low to extreme is determined. This categorisation requires judging what is an acceptable level and this may constitute one of the most challenging steps of the process. Thus, whatever level is set must be followed by a clear and defendable explanation (Figure 2.4).

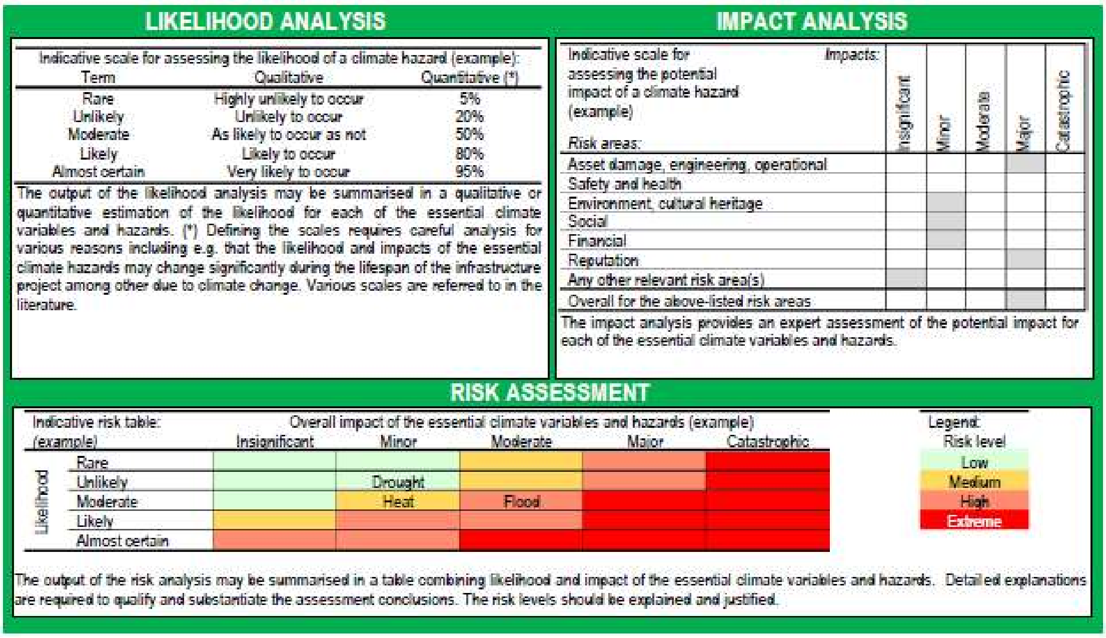

Figure 2.4 Overview of the risk assessment approach according to the European Commission, 2021a)

2.1.4 Conclusions on the comparison of the presented methodological frameworks

Figure 2.5 illustrates a synthesis of the main methodological frameworks used for vulnerability and risk assessment. As it can be seen, the relationships between the different components that compound the concept of risk are nuanced. In three of the four methods (AR5, AR6 and classic approach) a central role and a probabilistic view is assigned to the risk, and this is calculated by considering not only the magnitude of the possible impacts and effects of climate change on the systems, but also including changes in slow-onset processes and climate extreme events.

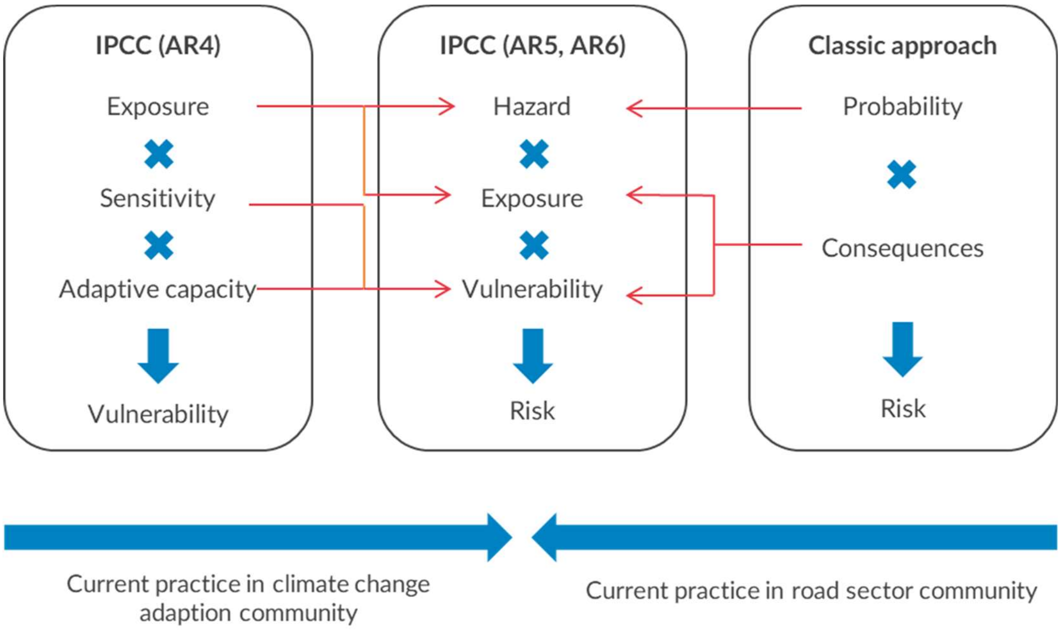

Figure 2.5 Comparison between the methodological frameworks and concepts used for risk assessment. The methodological approaches of the IPCC AR4, the IPCC AR5 and the "traditional" risk analysis (adapted from CAF, 2020)

Following the IPCC framework, the AR6 defines hazard as "the potential occurrence of natural and human-induced event and trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources".

The PIARC has identified the potential hazards (i.e. natural and human-induced hazards) affecting the road network in several reports (PIARC, 2016a; PIARC, 2019a), which gives an overview of the main stressors affecting road projects during the last years. However, the terminology used to classify these hazards slightly differs from the one used in the IPCC (i.e. the natural hazards described in the PIARC classification do not differentiate between those that are attributable to natural climate variability and those that are due to human-induced climate change). This is because the terms of PIARC are adopted from the Disaster Risk Reduction (DRR) field, while the IPCC's terms come from the Climate Change Adaptation (CCA) perspective.

On the other hand, the classification of PIARC does not include slow-onset processes and trends due to climate change (e.g. increasing temperatures, increasing/decreasing precipitation, among others), which are hazards in themselves and lead to changes in the magnitude, duration and frequency of extreme events. In addition, it ignores certain non-climate-related hazards, such as land degradation, and considers human-induced hazards (such as, terrorism, war, vandalism, accidents) that are not specified in the IPCC (see section 3 for more details).

The exposure in IPCC AR6 is defined as "the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected". In the road system environment, this exposure component refers to the presence of transport that could be subject to potential adverse impacts; it therefore depends on its location and not on the type of the transport asset.

The vulnerability is defined in the IPCC AR6 as the "propensity or predisposition to be adversely affected and encompasses the combination of sensitivity and adaptive capacity". It depends on the hazard, as well as on the intrinsic factors of the infrastructure itself (design and current state of the asset), varying its ability to withstand the impacts derived from climate change.

The risk assessment methodology developed in ICARUS is based on the latest report of the IPCC (AR6) and combines the classical approach of the multicriteria impact and likelihood analysis.

2.2 Risk assessment approaches

When it comes to assess the previously described risk components, It is necessary to select an approach. General approaches of risk assessment can be divided into quantitative, semi-quantitative, qualitative and hybrid approach (Table 2.1). These approaches should be context specific with the aim of responding local risks and informing for decision making and planning in the context of climate change. The selection of a particular approach depends on several factors, such as the level of detail of the risk assessment, the complexity of the risks to be analysed and the available resources (e.g. time and data available, model expertise, access to technology, among others). All approaches have an uncertainty in characterising risk (e.g. the climate impact may be uncertain, the threshold at which impacts occurs may be uncertain, the selected indicators may not adequately characterise risk, etc) (GIZ and UNDRR, 2021).

Table 2.1 Strengths and limitations of the main risk assessment approaches

Type of approach	General description	Strengths	Shortcomings	Examples applicable to road system
Quantitative	Estimates risk in tangible terms, providing, for instance, economic consequences, number of claims/fatalities/accidents or loss of capacity of the infrastructure. Based on current or historical observations or on models of physical, socioeconomic and biophysical impacts (e.g., empirical water-depth-damage functions, vulnerability functions, flood inundation modelling). Risk assessment can be made spatially explicit and conducted within a geographical information system (GIS) environment.	Can be visualized on maps.	Requires human expertise in many disciplines. Computation capability for physical impacts modelling. The scale is conditioned by data availability. Data are not always available at the appropriate scale, are not always georeferenced	(Twerefou, 2015; Qiao, 2015)

Type of approach	General description	Strengths	Shortcomings	Examples applicable to road system
			or freely available.	
Semi-quantitative	Based on indicators, which can be calculated in GIS. Risk assessment can be made spatially explicit and conducted within a GIS environment.	Applicable at various spatial scales. Can involve a participative process. Can be easily visualized on maps.	Requires subjective decisions on the selection of indicators. Massive amount of information and data is managed about hazards, exposure and vulnerability. Data are not always available at the appropriate scale, are not always georeferenced or freely available.	(Blest et al., 2016; Oliveira, 2016; The World Bank, 2019; Le Roux, 2019)
Qualitative	Based on expert and stakeholders' judgement. The approach is required when non-quantifiability and high uncertainty are involved in risk assessment.	Simple and can be easily implemented at any scale. Requires limited data. Can involve a participative process.	Requires subjective decisions. Limitations in the replicability. Cannot be visualized on maps.	(Cox, 2013; USAID, 2016)
Hybrid	It combines previous approaches. The approach is required when non-quantifiability and high uncertainty are involved in risk assessment. Risk assessment can be made spatially explicit and conducted within a GIS environment.	Capable of assessing complex risks. Can involve a participative process. Can be easily visualized on maps.	Requires human expertise. Requires subjective decisions on the selection of indicators.	

2.3 Complex climate change risks

The climate change related risks are characterized by their complex nature. Although a coherent definition and framework for assessing the complex risks of climate change has not been achieved between the climate change research community, the term complex is usually used to refer to the diversity of interactions between sectors and systems that can reduce or increase climate change risks (Rinaldi, 2001; Harrison, 2016) (GIZ and UNDRR, 2021). In the last decade, these interactions have been analysed on the basis of the concept of "system of systems" (SoS) approach. Applying a SoS approach a better understanding of network effects even across unrelated systems, before the impact (Cavallo and Ireland, 2014).

There exist multiple terms to describe complex climate change risks (e.g., compound risk (IPCC, 2019), emergent risk (IPCC, 2014b), cascading risk (Rinaldi, 2001), multi-risk (Terzi, 2019), among others). These concepts are evolving and the definition between them is still fuzzy. Simpson, (2021) proposed a recent classification, which included complex risks associated with climate change and related to other drivers:

- Aggregate: occurs when risks share its own set of drivers (i.e., hazard, exposure, vulnerability, and responses) with other risks.
- Compound: can be unidirectional or bidirectional and occurs when interactions between risks are combined.
- Cascade: occurs when one risk triggers other risks in a progression of interactions. This type of interaction is commonly used when assessing critical infrastructures since the condition of one affects the condition of the other.

In the same way that climate change is a trend that clearly has to be considered in the planning, design and operation of road transport, it is equally true that the world is facing a series of environmental and social changes of great magnitude that must be considered in any long- and medium-term analysis. The international research community is moving towards a significantly more expansive framework that looks at global societal and environmental change in the context of global sustainability challenges – that considers, for instance, the interconnections among climate change, energy security and transition, population growth, economic and social developments, etc. As an example, it can be noted that in the analysis of risks linked to the hydrological cycle, it is not uncommon to consider, together with the foreseeable change in precipitation and other climatic variables, aspects such as changes in land use, resource demands, etc. The understanding of the interactions between climate and land use change is improving but continued scientific investigation is needed.

In the State of the Practice of the road sector, there are few studies that have developed risk assessments considering such interactions and networks. Among the three types of risk, cascading interactions have been analysed to a greater extent. The Table 2.2 shows examples found in the scientific literature for each type of interaction.

Table 2.2 Compilation of risk studies applicable to the road system that evaluate the three types of risk interactions

Type of interactions	Examples applicable to road system
Compound	Dunant et al., 2021; Dong et al., 2022;
Cascade	Rehak et al., 2018; Dong et al., 2020; Hu et al., 2022;

2.4 Risk management. Case studies in transport infrastructure projects

According to the IPCC, climate risk management refers to plans, actions, strategies or policies to reduce the likelihood and/or consequences of risk or to respond to consequences. In other words, it includes not only risk assessment, but also risk mitigation measures to avert, minimise, and address losses and damages as well as decision making and implementation.

In the last decade, several risk management tools/methodologies have been introduced and employed to manage and minimize the uncertainty and threats realization to the organizations. Although a unique or prevalent approach and framework does not exist, all existing project risk management methodologies includes the following main steps (summarized from Miller, 2013; PMI, 2013; WSDT, 2014), which are consistent with the general Risk Management approach of ISO 31000:

- Risk Management Planning: It constitutes the preliminary activity required to determine the methodology and the focus of the Risk Management activities to be conducted and communicated. Just like every other project activity, Risk Management should have budget and resources allocated consistently with its scope of work. Level of details of the work to be conducted should reflect project complexity and general risk exposure. This process should be initiated as soon as the project is conceived and should be completed in the early stages of project planning.
- Identification of Risks: In this phase, any risk that may affect the project during the various stages of the life cycle is identified and described. This is an iterative process that should be conducted continuously during the whole project life cycle, as new risks may emerge or evolve as the project progresses. The specific cause of each risk and the phases of the project affected by each risk shall be identified. During this process triggers, which are symptoms or warning signs that a hazard has occurred or is about to occur, will also be identified.
- Qualitative & Quantitative Analysis of Risks: The priority of identified risks is assessed by providing a qualitative estimate of the relative probability of occurrence and the corresponding impact on project objectives. From this data, various techniques can be used to prioritize risks determining which are the most urgent to deal with. Moreover, the quantitative analysis provides quantification of risk severity, both in terms of likelihood and potential impact. This analysis provides more accurate results than the Qualitative counterpart, but it also requires a greater effort to be conducted. For these reasons, quantitative analysis is typically limited to most relevant risks, determined through a preliminary Qualitative Analysis. In general, during the Planning phase it should be defined whether to conduct Quantitative Analysis and if yes, to which extent.
- Risk Response Planning: develops options and actions to improve opportunities and reduce threats to project objectives. It includes the identification of necessary actions to be performed to mitigate the risks. These actions are assigned to a specific responsible (the "risk response owner"). Responses to planned risks should be tailored to the importance of the risk, profitable in relation to the target to be met, realistic within the context of the project, agreed upon by all parties involved and should also be timely. Typically, more the one response exists for every risk and a choice among different options must be made.
- Monitoring and Control of Risks: This activity, that should be carried out throughout the whole infrastructure life cycle, consists in monitoring of identified risks, monitoring of residual risks, identifying new risks, executing risk response plans and evaluating their effectiveness. Responses to planned risks included in the project management plan are executed during the project life cycle, but the whole project must be continuously monitored for new risks, risks

changes (including those becoming obsolete). The monitoring and control makes use of techniques, such as analysis of variation and trends, which require the use of performance information gathered during project execution.

In the transport infrastructure sector, there is not a standard risk approach able to consider the "risk-related" aspects for the whole lifecycle of the road. Most of the studies and research are sector specific and referred to single stages of the transport infrastructure life cycle[2]. Several approaches have been proposed from different authors in order to better manage risks during the single stages of evaluation (e.g., Ye and Tiong, 2000; Salling, 2008; Salling, 2009), appraisal (e.g., Miller, 2013) construction (e.g., Ashley, 2006), and operation & maintenance.

In the following subsections a review of the most widely adopted frameworks, as well as different real and successful risk management case studies and practices are presented which are limited in the literature. Those populated, are not in general specific for climate change and they integrate it as a one of many. Additional details about each case study can be obtained in the references provided.

2.4.1 "Risk analysis and management for projects" (RAMP)

RAMP (Risk Analysis and Management for Projects) is a working methodology developed by the Institution of Civil Engineers in UK (ICE) and the Institute and Faculty of Actuaries. Its latest version (Third Edition) was published in 2014 (Institution of Civil Engineers and Institute and Faculty of Actuaries, 2014).

RAMP serves as a framework for analysing and managing the risks involved in projects, both large and small. This methodology aims at ensuring the effective identification of risks, its analysis and control. Among its intended purposes, the most emphasized is that of allowing an early detection of risks in order to allow for preventive mitigation and a prompt response if they occur.

RAMP focuses on the strategic and financial aspects of civil projects, resulting an effective tool for planners, engineers, accountants, actuaries, lawyers, project managers, public administrators and anyone else who concurs to a project's success.

Some of the benefits associated to the implementation of RAMP include:

- Avoidance of wasted work, because of the iterative nature of the process;
- Consideration of opportunities as well as threats;
- Improvement of the credibility of the business case for the project;
- Consistency with approaches to Enterprise Risk Management (ERM) in the project sponsor's organisation;
- Greater confidence for those who decide on whether projects should proceed;
- Tracking of "lessons learned".

In this framework, risk is defined as the potential impact of all the threats (and opportunities) which can affect the achievement of the objectives for an investment. This concept of risk is associated to six concepts used for the evaluation of risk:

[2] In UK a very high-level assessment at options phases is applied, then a more detailed assessment at preliminary design/planning phases. LA114 methodology for individual projects is applied and also strategic assessments at an organisational level.

- Overall risk: the combined effect of all individual risks or sources of uncertainty in a situation.
- Risk event: a possible occurrence which could affect (positively or negatively) the achievement of the objectives for the investment.
- Likelihood: the chance (or probability) of the risk event occurring within a defined time period.
- Impact: the value of the effect of the risk event on one or more objectives if it occurs.
- Expected value: a best estimate of the average outcome, i.e. all possible outcomes weighted by their probabilities.
- Risk efficiency: a state achieved when the downside risks have been sufficiently mitigated and the upside risks have been optimised.

The RAMP methodology (Figure 2.6) is divided into thirteen steps grouped into four activities: process launch, risk review, risk management and process close-down.

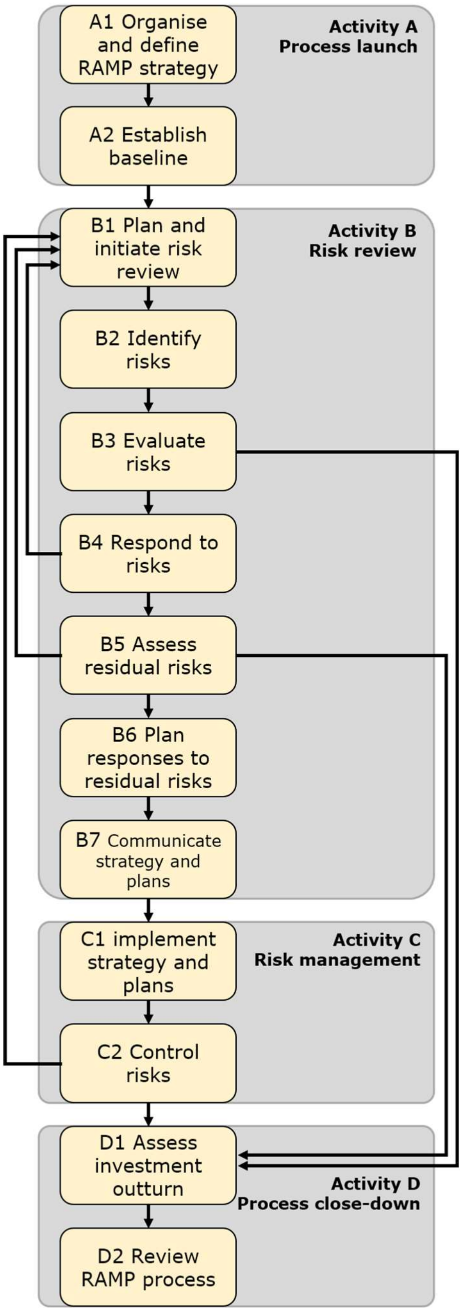

Figure 2.6 Flowchart of the overall RAMP process (ICE, 2015)

2.4.2 "Infrastructure procurement route map"

The UK Government, jointly with Infrastructure UK, the University of Leeds, the Institution of Civil Engineers (ICE) and the Infrastructure Client Working Group, developed this route map in 2013 (HMT, 2013). This publication aims at improving the capability of sponsors and clients to plan, execute and operate major infrastructures.

The route map developed is not a prescriptive process. It describes some questions to be asked and the correct time to ask them to effectively and timely identify risks. Some of the benefits foreseen in the application of this route map consists in improving value, avoiding unnecessary costs, increasing the projects potential in terms of revenue and developing a tailored best practice toolkit (Figure 2.7).

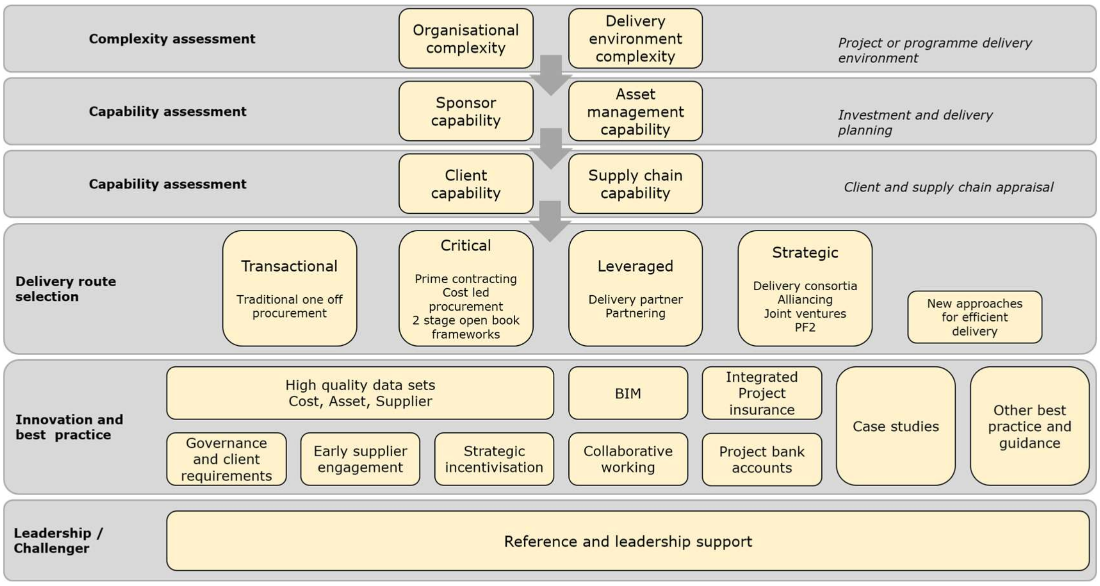

Figure 2.7 Methodology overview (HMT, 2013)

The main four components of the route map are:

- Complexity assessment of the organisation and the project or program delivery environment and associated pipeline;
- Capability assessment of the procuring authority and project or program delivery partner and the supporting supply chain;
- Delivery route/procurement option selection and implementation; and
- Innovation and best practice resources (building on existing guidance and tools where appropriate).

The route map has been applied with success to some relevant projects such as London's Crossrail, the Environment Agency's Thames estuary, High Speed 2 railway and London Underground's station stabilisation program.

2.4.3 "Improving infrastructure delivery: Project initiation route map"

The Project Initiation Route map is a product of government working collaboratively with industry and the University of Leeds, through the Infrastructure Client Group. This route map aims at offering support on strategic decision-making during project initiation based on the latest thinking and knowledge acquired from delivery of Major Projects applied in a series of structured exercises. It enables sponsors and those responsible for project delivery to properly align complexity with the necessary capabilities and other enhancements to ensure a more successful outcome.

The route map is an aid to strategic decision-making (Figure 2.8). It supports the alignment of the sponsor and client organizations' capability to meet the degree of challenge during initiation and delivery of a project.

The route map contains detailed checklists to use during the initial assessment steps, advice on how to conduct the gap analysis, and advices about what to include in plans for an enhanced project environment. It provides an objective and systemic approach to project initiation founded on a set of assessment tools that help determine:

- Complexity and context of the delivery environment;
- Capability of current and required sponsor, client, asset manager and market;
- Key considerations to enhance capability where complexity-capability gaps are identified.

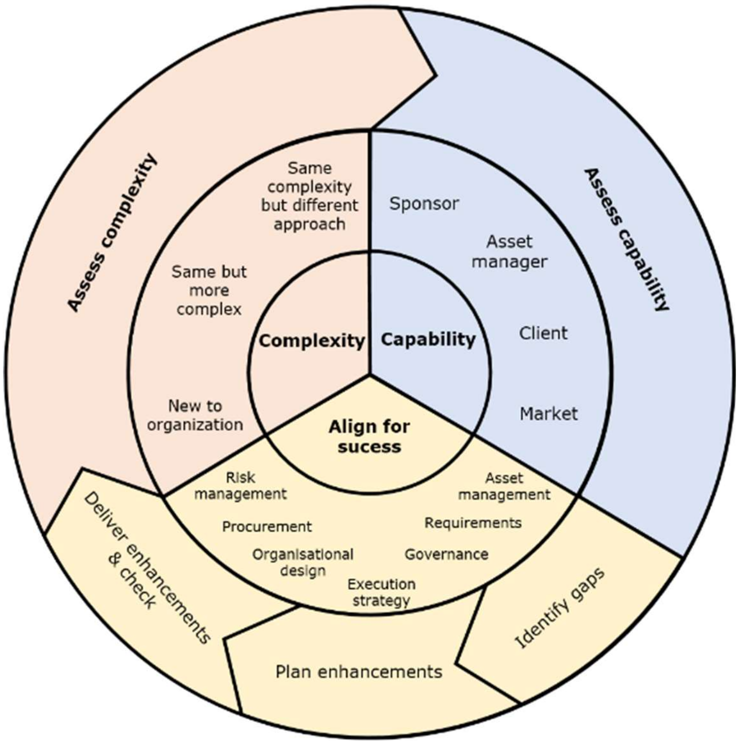

Figure 2.8 Methodology main core (Infrastructure and Projects Authority, 2013)

2.4.4 "Managing risk and uncertainty in infrastructure projects"

This report (Infrastructure Risk Group, 2013) arises from research undertook by the Infrastructure Risk Group (IRG) on behalf of Infrastructure UK, a unit within the UK Treasury. Major infrastructure owner operators and the Institute of Risk Management also participated on it.

The report was published in 2013, aiming at influencing, sharing and improving leading practice on infrastructure projects, looking for a more economic and public resources efficiency. The report is addressed to anyone who can exert influence on sharing and improving leading practice on major infrastructure projects.

The report is divided into three sections: Part A, focusing on a preliminary review and some recommendations; Part B, detailing guidance and improvement tools and methods; and Part C, with supporting material.

The research looked at the risks associated with cost management and uncertainty throughout the project life cycle. The report gives 9 key recommendations, guidance for improvement and case studies.

- Cost and risk estimation:

1. Present risk exposure as a range, to promote more informed decisions and communications (particularly at a strategic level)
2. Leading organisations to underpin early-stage risk allowances with both reference-class forecasting, and risk analysis, rather than Optimism Bias-based uplifts
3. Consider cost and risk estimates side-by-side, for completeness and to combat double counting

- Active risk mitigation and management:

4. Incentivise risk mitigation to ensure risk actually gets managed in the face of other behavioural influences (c.f. London 2012 Olympics delivery programme and London Underground's Ring-Fenced risk model)
5. Adopt informed and rapid contingency draw-down processes (e.g., as for the Olympics)
6. Different organisations to cooperate on risk and contingency management of interfacing programmes, to enhance mitigation and avoid duplicating contingencies

- Enabling and supporting activity:

7. Use a common vocabulary and develop a generic risk profile
8. Set up a UK-wide body to collect and share data
9. Establish a UK forum to share good practice

2.4.5 "Project Risk Management Guide - Guidance for WSDOT Projects"

The "Project Risk Management Guide - Guidance for WSDOT Projects" (WSDOT, 2014) is a document published by the Development Division of the Washington State Department of Transportation (WSDOT).

This document offers guidance to managers, teams, and all other staff involved with project risk management. It provides:

- Uniformity in project risk management activities.
- Techniques and tools for project risk management.
- Data requirements for risk analysis input and output.
- The project risk management role in overall project management.
- Guidance on how to proactively respond to risks.

The project risk management process is divided into six different steps, as shown on Figure 2.9.

- Risk management planning: deciding how to approach, plan, and execute risk management activities throughout the life of a project.
- Identify risk events: determining which risks might affect the project and documenting their characteristics.

- Qualitative risk analysis: assessing the impact and likelihood of the identified risks and developing prioritized lists of these risks for further analysis or direct mitigation.
- Quantitative risk analysis: estimating numerically the probability that a project will meet its cost and time objectives.
- Risk response: developing options and determining actions to enhance opportunities and reduce threats to the project's objectives.
- Risk monitoring & control: tracking identified risks, monitors residual risks, and identifies new risks—ensuring the execution of risk plans and evaluating their effectiveness in reducing risk.

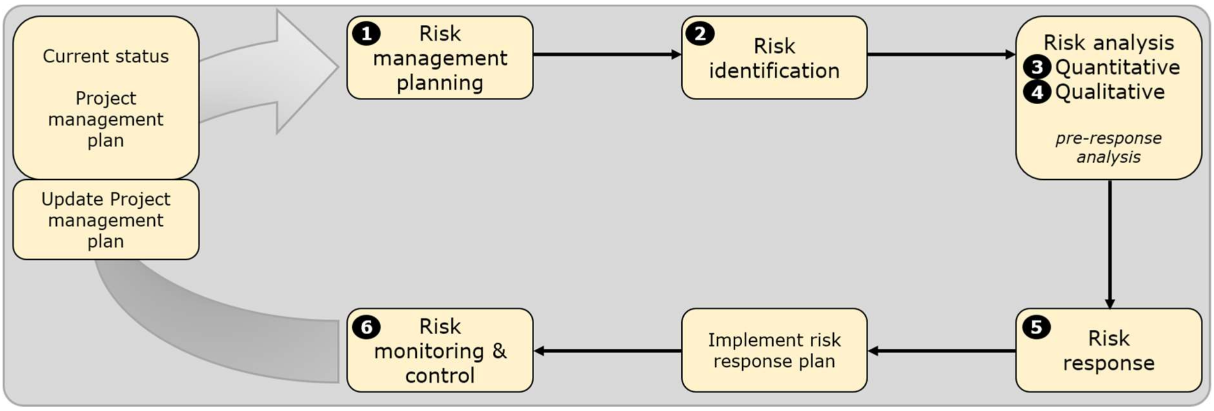

Figure 2.9 Project Risk Management Planning (WSDOT, 2014)

2.4.6 World Road Association (PIARC) risk management guidelines

The World Road Association (PIARC) has published two documents that analyse the management of risk in road projects. These publications are "Towards Development of a Risk Management Approach" (PIARC, 2010) and "Managing Operational Risks in Road Organization" (PIARC, 2012).

Both guidelines provide a review of different existing methodologies at national level, state of art about risk management, a general risk framework applied to road projects, examples of implementations and case studies, and finally some recommendations.

The risk framework proposed by this organization is detailed in Figure 2.10 and it is divided into seven steps:

- Define the context.
- Identify risks.
- Analyse risks.
- Evaluate risks.
- Treat risks.
- Monitor and review.
- Communicate and consult.

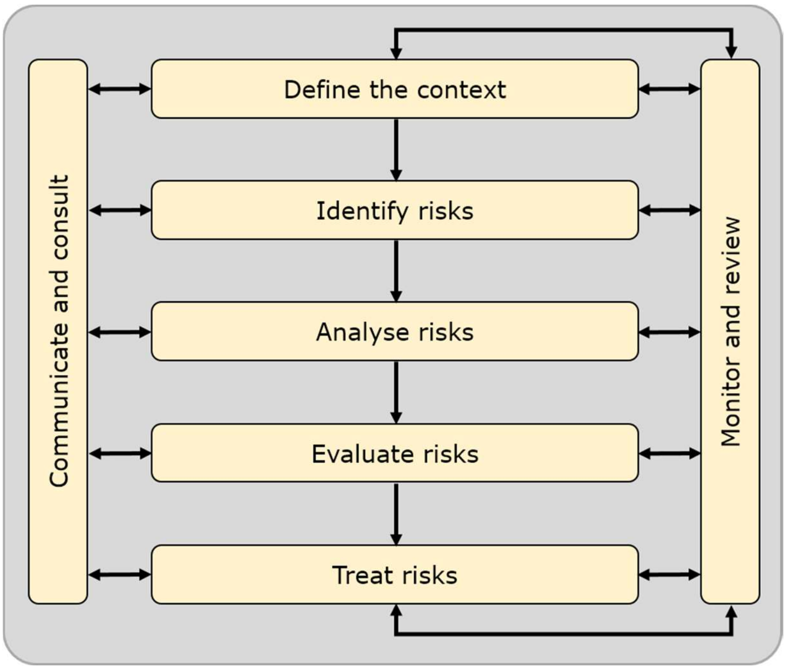

Figure 2.10 Risk management process (PIARC, 2010)

2.4.7 "PMBOK® Guide and Standards"

The "Project Management Body of Knowledge" (PMI, 2013) is a set of standard terminology and guidelines for project management developed by the Project Management Institute (PMI). This knowledge has been in constant evolution over time, and in 2013 the fifth edition of the book "A Guide to the Project Management Body of Knowledge" was presented.

The core of this book is dedicated to project management, project life cycle, integration, control, quality, human resources or time and cost management. There is also an entire chapter (#11) specifically focused on risk management.

Project Risk Management includes the processes of conducting risk management planning, identification, analysis, response planning, and controlling risk on a project. The objectives of project risk management are to increase the likelihood and impact of positive events and decrease the likelihood and impact of negative events in the project.

Project Risk Management activities (Figure 2.11):

- Plan Risk Management: The process of defining how to conduct risk management activities for a project.
- Identify Risks: The process of determining which risks may affect the project and documenting their characteristics.
- Perform Qualitative Risk Analysis: The process of prioritizing risks for further analysis or action by assessing and combining their probability of occurrence and impact.
- Perform Quantitative Risk Analysis: The process of numerically analysing the effect of identified risks on overall project objectives.
- Plan Risk Responses: The process of developing options and actions to enhance opportunities and to reduce threats to project objectives.

- Control Risks: The process of implementing risk response plans, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating risk process effectiveness throughout the project.

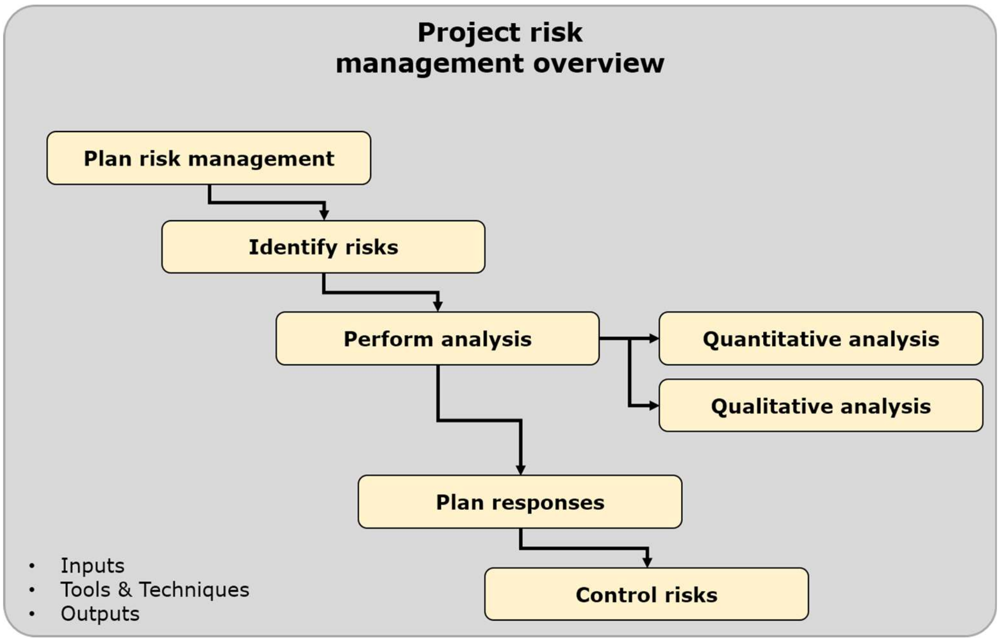

Figure 2.11 Risk management overview (PMI, 2013)

2.4.8 The Millau Viaduct (PIARC, 2010)

The Millau Viaduct was built to create a new link between Paris and South of France, and more generally Northern Europe and Spain. Its construction ended in December 2004 after a very short construction period of 38 months. This structure of exceptional dimensions is easily identifiable thanks to its 2460 meters total length and above all by its world record height, 245 meters for P2 pier).

Risks related to technical aspects, especially stability under strong wind conditions and difficulties resulting from building a road infrastructure at such a height, played a key role in the design choices of this exceptional mega-project.

Indeed, after a certain number of preliminary studies made by the French State technical services, it was finally decided to set a very unusual design process consisting in an international architectural/engineering competition, and to pass a 75 years concession contract with a private company for the construction and operation of the new infrastructure. The chosen architectural solution corresponds to the vote of a 20 persons committee made of the French director of roads, technical experts, public finance specialists and local and regional representatives. During the planning and construction phases great attention was paid to environmental aspects, and significant communication campaigns enabled to explain project issues, design choices, to describe mitigation measures and make road users and local inhabitants accept this new infrastructure. The overall great Millau Viaduct mega-project from preliminary studies to construction was deeply influenced by considerations related to risk analysis. During the operation phase, most of those risks, particularly foundation technical risks, bad-ageing risk and risks related to users' security, were subjected to specific control and monitoring: deformation measurement, cable-stayed vibration control, corrosion control, ice detectors installed in the pavement structure, anemometers, video surveillance. Even more than the technical risks, financial risks and social/political aspects seemed to be very critical for the completion of this mega-project and was therefore kept under control.

2.4.9 The Stockholm South Link (PIARC, 2010)

The Southern Link in Stockholm is another relevant case study for project risk management. Based on this example, the interfaces of risk management with the project sponsor, the project management, the product, and external stakeholders will be illustrated.

A checklist for project risk management has been provided:

- Decide on a plan for the project's risk management;
- For larger projects appoint a coordinator for risk management;
- Those best qualified to deal with the risk should undertake it;
- Project's top 10 ranking risks delivered to the next phase with suggestions for measures;
- Requirements in the contract for the contractor's own risk management;
- Perform risk analysis based on the 2 perspectives:
    - Contractor phase;
    - Road using phase;
- During construction always prioritize safety, working environment, and environment along time-cost-function;
- Keep the analysis up to date.

2.4.10 A risk-management approach to a successful infrastructure project. McKinsey Working Papers on Risk. (Beckers, 2013)

In 2011, a major transportation-asset operator and developer embraced a life-cycle approach to manage its large project pipeline (Figure 2.12). Top management committed to reduce its risk-related provisions by one-third; better risk management was identified as a core driver of profit and loss, value creation, and competitiveness.

At the outset, there was a lack of a single risk definition or risk taxonomy across projects, project stages, and departments. In addition, there was no systematic formulation of how risk management added value to the company, for example, in deriving risk-management objectives from a corporate value framework, or demonstrating how risk management could lead to better decisions. The organization's focus was on the mitigation of project-schedule and cost overruns, but not on risk optimization.

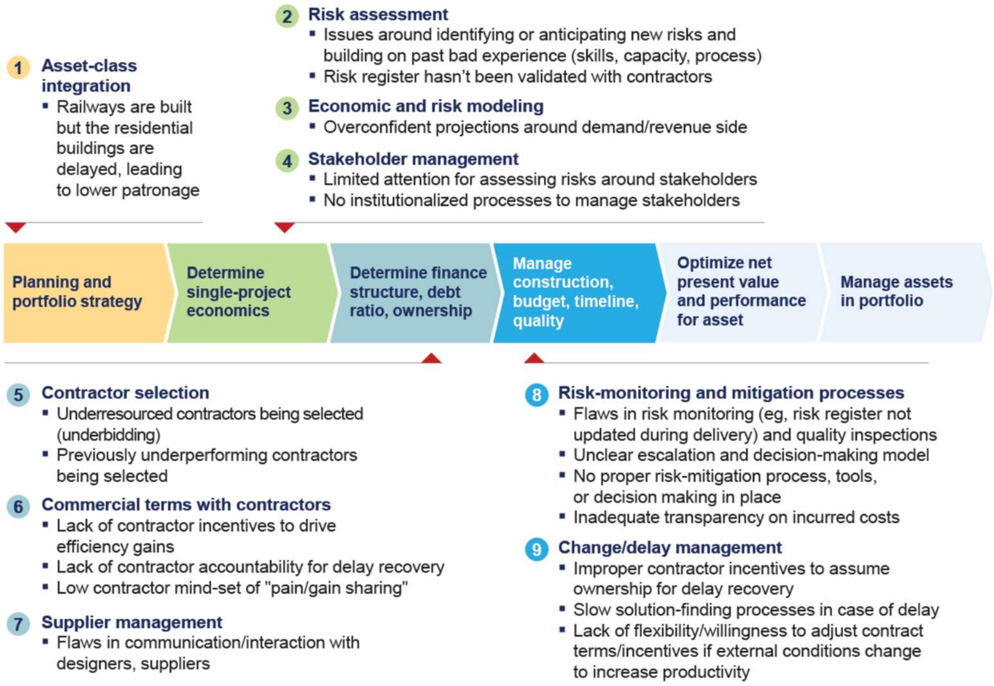

Figure 2.12 Uncertainties and complexities found along the project life cycle (Beckers, 2013)

Senior management decided to embrace a systematic step change to enhance institutional risk-management capabilities, from daily employee practices and behaviours to mind-sets and corporate culture. An integrated life-cycle approach was put in place to address many of the problems outlined above.

Management needed to formulate a clear business case for the value of risk-management activities and to devise a risk strategy that was tightly linked to the business. The appropriate transparency on risk, cost and the key drivers and sources of risk then had to be established, along with a much clearer understanding of what risk-management levers and instruments were available. Having established this at the top of the organization, it was then vital that effective risk-management governance, organization, and processes were put in place and that a strong risk culture and awareness was driven throughout the organization (Figure 2.13).

Reliable and transparent communication is vital to the success of any project, so it was crucial that an improved system of communication was put in place between top departmental teams involved in any infrastructure project. This enabled cross-divisional cooperation and ensured alignment of goals and processes. Proper interaction with, and performance tracking of, contractors was established to help monitor and evaluate risk on a timely basis, and there were clear directions from the top of the organization to operating levels that cascaded risk-management awareness downward. This approach also required on-site “shop floor” risk transparency to be further advanced, as well as a move from ad hoc reactive risk mitigation to proactive risk anticipation.

Figure 2.14 shows how far reaching this effort was across the organization; it involved people processes, management practices, governance, approval processes, and day-to-day behavioural norms at every level.

Issues	Essence of best-practice approach	Possible tools
Lack of communication between top teams of civil and engineering/maintenance	▪ Major risks and solutions regularly discussed in a structured way, involving relevant areas ▪ Key decisions always incorporate risk insights along the project life cycle ▪ Continuous and focused risk transparency	▪ Risk-input template for key decisions ▪ Top-management risk dashboard ▪ Regular senior-management discussions on risk
Insufficient interaction between client's and contractor's top teams	▪ Early transparency about risk ownership and consequence management ▪ Regular interaction on operational and top level to align on status and anticipation of risks	▪ Report on allocation of risks ▪ Contract with risk-transfer chapter ▪ Regular risk dialogue with contractor
Failure to cascade risk-management awareness from top levels to lower levels	▪ Risk-mitigation actions are clearly articulated and compliance mechanism in place ▪ Organization has a risk-conscious culture enforced by consequence management ▪ Clear change-order management in place to allow fast resolution time	▪ Risk dashboard for site manager ▪ Internal process enforcing mitigation ▪ Change-order routes defined ▪ Dedicated project risk team and local risk champions
Lack of on-site transparency	▪ Risk-anticipation and mitigation actions are emphasized on the ground via simple, practical tools that are used daily ▪ Bottom-up escalation routes are clear, trigger points are predefined	▪ Daily check-in/out meetings ▪ On-site visual management ▪ Daily contractor-compliance monitoring ▪ On-site change-request handling
Ad hoc risk management instead of proactive risk anticipation	▪ Risk discussion/reporting less focused on status checking, rather used as navigation tool for upcoming risk-event anticipation ▪ "Raising the alarm" is preferred to "blaming the bad news courier"	▪ War room/control tower with regular "look ahead" sessions ▪ Checklists for on-site risk anticipation ▪ Trigger-event checklist for escalation

Figure 2.13 Day-to-day risk management improvement actions and tools (Beckers, 2013)

	Findings following risk-culture diagnosis	Initiatives
People processes	▪ Several **gaps in risk training** ▪ Risk criteria insufficiently taken into account in **promotion and compensation**	▪ Introduction of **risk orientation** for lateral hires ▪ Introduction of **risk training** for upper tenure as **prerequisite for promotion** ▪ **Letter to newly appointed managing directors,** making clear that leadership review committee considered individual risk behavior
Management practices	▪ **Lack of systematic consideration of how business strategy affects risk** position (eg, no clear view on consolidated country exposure given business-expansion plans)	▪ **New function on corporate level set up** to monitor high-level risk topics across the corporation
Governance	▪ Each **division has different practices on risk management**; some are more formal, others less so	▪ Design of a more **harmonized set of divisionally led risk committees** to strengthen direct risk mitigation and informal risk dialogue
Approval processes	▪ **Multiple systems for management approvals** with partial overlaps and with lack of consistent audit trail	▪ **Multiple adjustments of management approval** for more consistency
Norms	▪ **Hero** in the organization seen as the person that can **sail close to the wind** and get projects through	▪ **Symbolic actions put in place** to increase the impact of risk-culture initiatives and emphasize new approach to risk across the organization ▪ **Make risk norms highly visible** to reinforce desired risk behaviors via posters, screen savers, intranet pages, brochures

Figure 2.14 Specific initiatives to improve risk culture (Beckers, 2013)

Professional risk management can not only significantly improve results in public procurement processes; it can also attract and mobilize additional private financing. Given the scale and scope of emerging infrastructure projects, there is a strong case for embracing risk management throughout the life cycle of individual projects and also at the portfolio level.

A case study to be discussed in this point should be the one included in '[Climate risk assessment for UK motorways and trunk roads: application of the LA114 standard]' that has been carried out under the LA114 methodology described in earlier comments. This document sets out the requirements for assessing and reporting the effects of climate on highways (climate change resilience and adaptation), and the effect on climate of greenhouse gas from construction, operation and maintenance projects.

2.5 From climate risk to climate resilience

A climate change risk assessment provides the necessary base to identify and reduce risks and define adaptation measures with the aim of strengthen the road system resilience under multiple climate-related risks (Figure 2.15).

Climate related risks in the road environment arise from the interaction between climate change, road infrastructure and Nature-Based Solutions (NBS). Climate change affects road infrastructure and NBS, giving rise to potential adverse consequences because of their vulnerability and exposure to certain hazards. Road infrastructures can adapt to climate change to reduce losses and damage caused by climate change. However, they could also maladapt, increasing their risk to adverse climate-related outcomes. NBS (considered in ICARUS as green road infrastructures) are impacted by both transportation infrastructure and climate change. However, they can adapt and mitigate these impacts, as well as provide ecosystem services to road infrastructure, such as regulatory services which prevent soil erosion and protect them from floods (Figure 2.15a).

Reducing climate risks and building resilience in the road system requires a transformation that strengthens the resilience of ecosystems and the sector's own infrastructure. Recognition of climate risks can reinforce adaptation and strengthen adaptation and mitigation actions by reducing the risks and foster the transformation towards resilience. This transition is enabled by governance, finance, knowledge, capacity building and technology (Figure 2.15b).

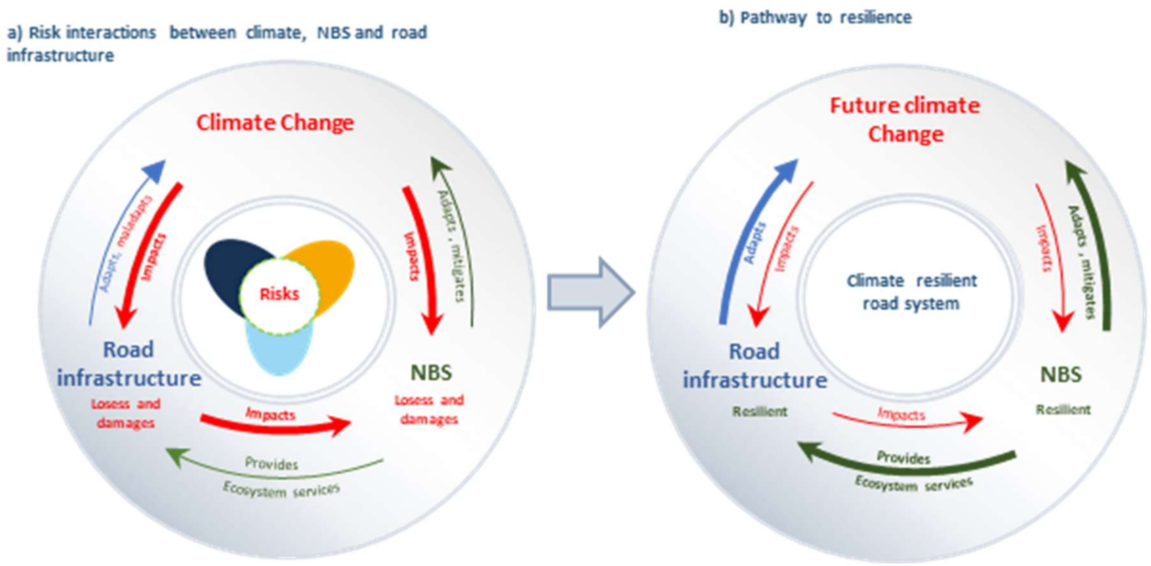

Figure 2.15 From climate risks to a climate resilient road system. a) Interactions of climate change risk assessment; b) pathway to resilience

Resilience term in the literature has a wide range of meanings with disparate approaches as it has been applied in many disciplines. When communicating about resilience, it is necessary to be sure that everyone has the same understanding of what is trying to be achieved.

According to the IPCC (IPCC, 2019a), resilience is defined as "the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation".

In the road environment, the CEN-CENELEC (European Commission, 2021b) has tailored the term of resilience to the assessment of resilience of transport systems and defined as the "ability to continue to provide service if a disruptive event occurs".

Similarly, the Resilience Shift (RS) established in 2016 that resilience (Reeves, 2019) is the ability to withstand, adapt to changing conditions, and recover positively from shocks and stresses. Resilient infrastructure will therefore be able to continue to provide essential services, due to its ability to withstand, adapt and recover positively from whatever shocks and stresses it may face now and in the future.

Other definitions of resilience that are used in the road environment are the following:

- "Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event" (UK Cabinet Office, 2011)
- "Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (FHWA, 2014).
- "Resilience planning is not just about the physical resilience of the highway infrastructure but also about how disruption is managed and the speed of recovery. Climate change and other rising risks may increase the frequency with which Highway Authorities will have to respond to severe weather emergencies (UK Roads Liaison Group, 2016)

In general, all these definitions agree that improving resilience constitutes both increasing the ability of infrastructure to withstand potential threats and also the capability of the system to rapidly recover from disruptive events. Besides, these terms include aspects of withstanding change; however, the IPCC definition goes further by describing not only the ability to maintain essential function, identity and structure, but also the capacity for transformation.

A more detailed explanation can be found in D2.1 Baseline report on minimum service levels and resilience evaluation Chapter 3.1.

3 IDENTIFYING CLIMATIC IMPACT-DRIVERS

From the road sector "impact" is almost always referred to a negative consequence in the infrastructure due to a hazard or extreme weather event (in Annex 2 Projected changes in climatic impact-drivers are linked to performance indicators for road sector), impact-drivers have another meaning.

In fact, the Climatic Impact-Driver (CID) concept is developed in the IPCC Sixth Assessment Report (AR6). CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems (Swiss Re, 2021).

The CID framework includes seven categories, thirty-three climate factors, and each factor can be assessed using different evaluation indices for different affected sectors. The major features of CIDs include their time scale variety and irreversibility, mutation and tipping points, the time of emergence, compoundness, and their dependence on affected system elements.

The CID framework is helpful for making more objective, neutral and comprehensive assessments on the impacts and risks of climate change.

Based on this, this section builds from the state of the practice and examines the most significant climate-impact drivers affecting road and transport system. It starts by introducing key concepts regarding climate scenarios and providing a brief guidance on scenario selection. Then, it follows with the identification of the most significant climate-impact drivers impacting the road and transport systems and concludes with an overview of past and projected changes in Europe's most climate hazard indices and with robust evidence-based approaches.

As summarized in sections 2, risk analysis and risk management based on probabilistic quantitative methods have been widely proposed and adopted in the transport sector for dealing with foreseeable and calculable stress situations. During decades, the road sector has made a massive use of climate data records on planning, design and maintenance of roads. However, climate change makes it impossible for us to continue basing our risk analysis methods on stationarity (Miully, 2008). As it is indicated in Figure 2.7, in this situation, the use of climate projections is of great value for planning and designing road assets, especially those of long live, as platform, bridges, embankments and earthworks, etc. This section summarizes how these projections are generated and how they can be used in the road sector.

It must be borne in mind that the use of the data generated by climate projections, necessarily implies the use of past observations. Although in this section these sources of information are not going to be analysed, historical records from meteorological stations, reanalysis (ECMWF), gridded observations and other "classic" climate products are, without a doubt, valid and necessary data sources for road resilience.

3.1 Climate scenarios and projections

The terms "climate change" usually refers to global warming, the ongoing increase in global average temperature and its impacts on Earth's climate system. Climate change scenarios or climate scenarios are projections of how the climate might change in future depending on the societal choices made, policies committed to and resulting climate forcings (mainly, GHG concentrations in the atmosphere). Climate scenarios shouldn´t be considered a prediction or a forecast. As we can't predict the future, they are "only" possible evolutions of the climate system depending on the actions and development trajectories that humanity chooses in the coming years. These scenarios are extremely useful for road sector, as they allow to explore possible futures, the assumptions they depend upon, and the courses of action that could bring them about. In this section it is explained how they are generated and how they can be used.

Climate scenarios are created using Global Climate Models, which use mathematical equations to replicate the physics of the Earth's systems. The characteristics of this models have evolved greatly in the last decades, gaining resolution, simulating an increasing number of processes, etc. but all of them simulate the whole global climate system. There are run by different research organizations about the globe, but in a set of coordinated exercises or experiments that make use of a common set of scenarios that are explained in the next paragraphs. The most recent experiment is CMIP6.

Climate change is primarily caused by greenhouse gases (GHG) added to the atmosphere by human activities (IPCC, 2018), most importantly carbon dioxide (CO2) and methane, but also from other gases and other drivers or "climate forcings" as changes in the albedo, etc. Different levels of GHG emissions and other climate drivers are added into the GCM runs to output various scenarios of the Earth's climate.

This climate forcings (mainly GHG concentrations) are generated using Integrated Assessment Models and considering the Shared Socioeconomic Pathways or SSP. SSP were developed by the IPCC to explore how the global society and economy may evolve in the coming decades. They comprise five narratives and a set of driving forces. SSP scenarios quantify energy and land-use developments and associated uncertainties for greenhouse gas and air pollutant emissions (Figure 3.1).

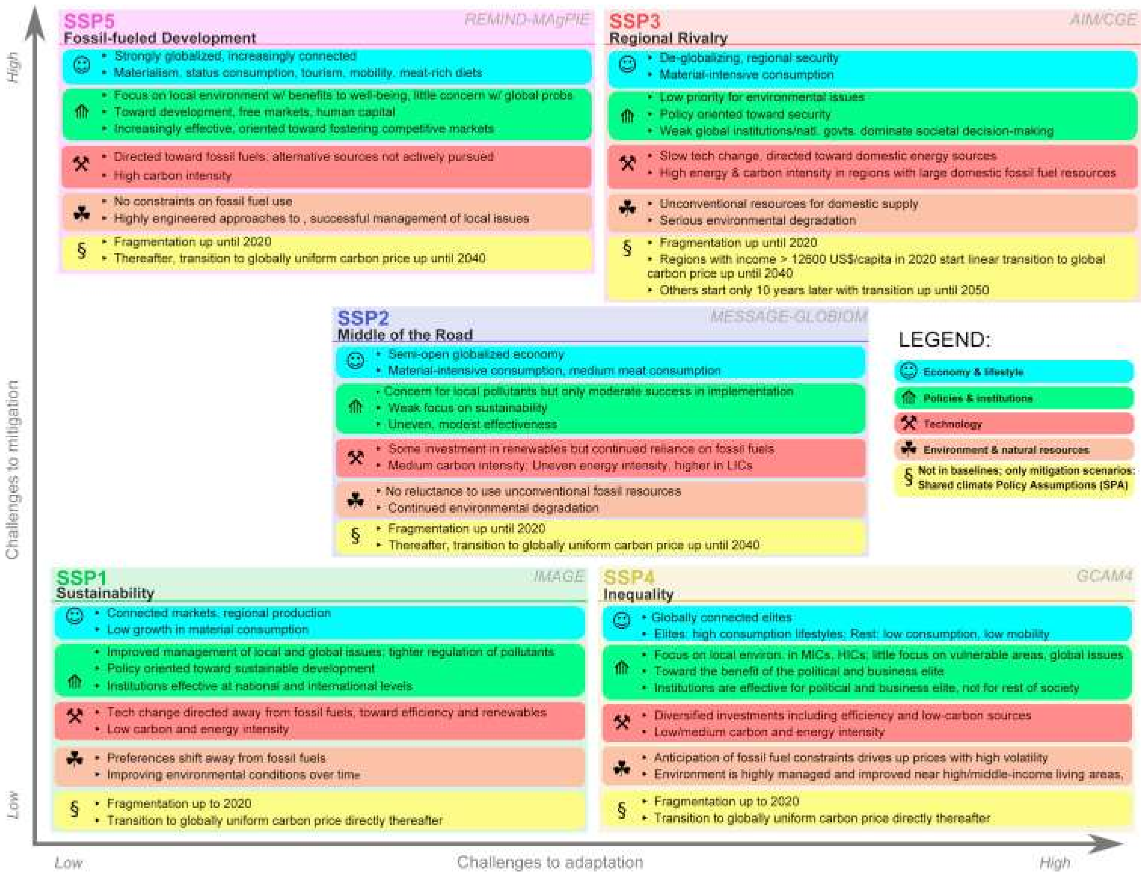

Figure 3.1 Summary of the SSP narratives (Bauer, 2017)

With this information GCM are run, considering different levels of greenhouse gases. The Representative Concentration Pathways or RCPs were developed by the IPCC to describe a common set of scenarios with different levels of greenhouse gases (GHGs) in the atmosphere. However, they are not expressed in terms of GHG concentrations. As the amount of GHG increases, more energy is trapped in the global climate system, and it is imbalanced. The RCPs scenarios are expressed as the difference between energy inputs and outputs in the earth system. RCP 8.5 is a scenario with a radiative forcing (expressed in Watt per square meter) of 8,5 W/m2 in 2100. On the other hand, there are other scenarios which are summarized in Figure 3.2.

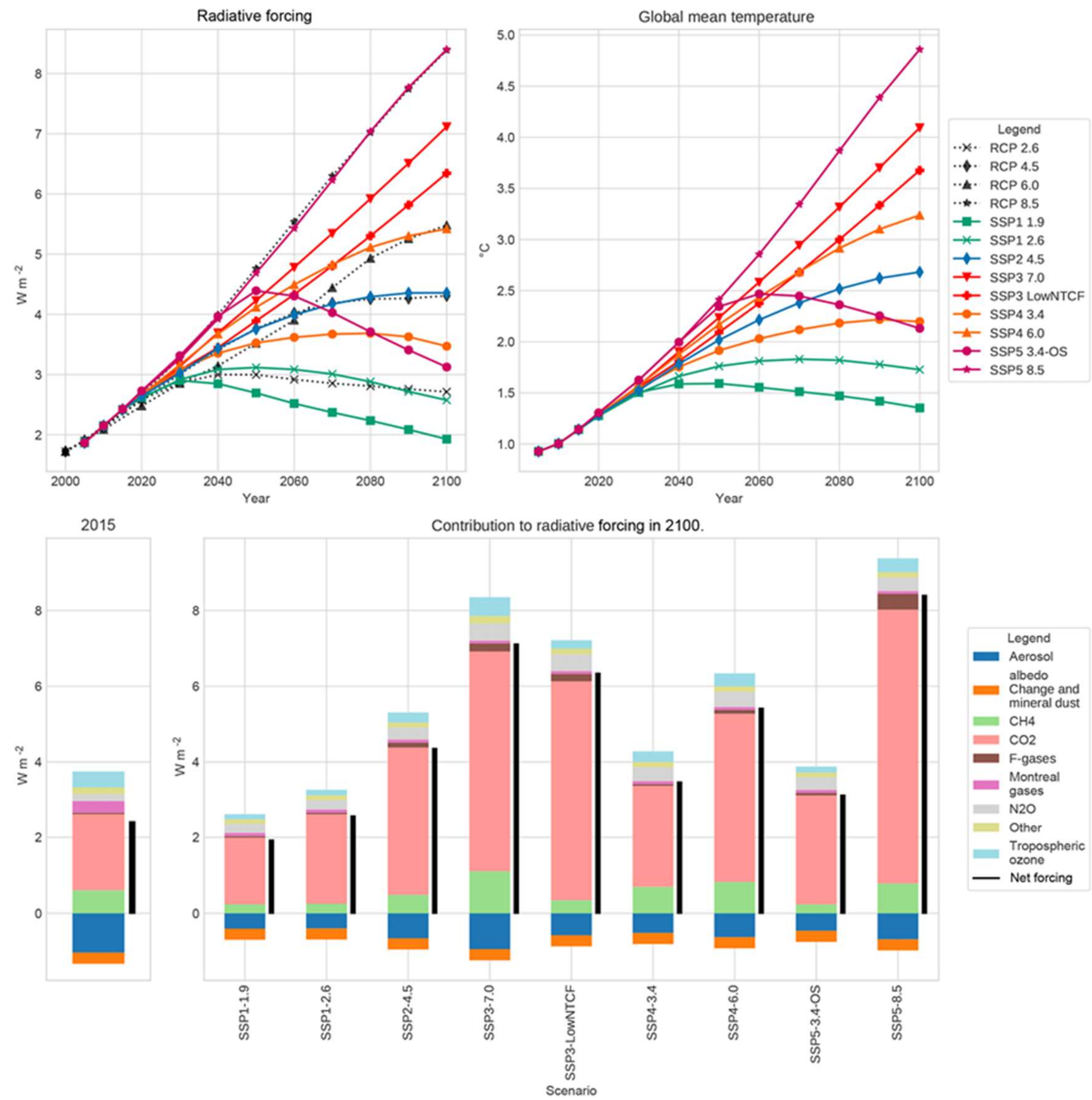

Figure 3.2 Radiative forcing and changes in the global mean temperature from SSP (Gidden, 2019)

Ideally, all SSP scenarios can be combined with all RCP scenarios, but it is accepted that some combinations of socioeconomic development matches with emission scenarios quite well, and that others are more unlikely (e.g., a low emission world represented by RCP 2.6 doesn´t match with the fuel-intensive development proposed by SSP5). The most used combinations are presented in Figure 3.2.

Global climate models are powerful tools for studying climate change trends, but usually they are not considered of resolution enough to perform risk assessment and adaptation planning at local level. Therefore, limited area models or Regional Climate Models (RCM), that only simulates part of the earth system, are run nested to GCM simulations. The most complete experiment in this regard is CORDEX, that coordinates the simulation of several institutions around the globe. The current outcomes already available from this initiative are usually based on CMIP5 GCM models, so in the current situation, for performing climate change risk assessment a decision should be made between using the most modern global models runs from CMIP6 or using RCM with higher resolutions from the CORDEX initiative but having in mind that they are nested ton CMIP5 model outputs.

3.2 Guidance on selecting climate scenarios

Considering how climate data are generated, it is possible to use the next kinds of scenarios:

- Synthetic scenarios: particular climate elements are changed by a realistic arbitrary amount, for example, adjustment of global surface temperature by +1, +2, and +3°C from a reference state, without the use of climate models.
- Analogue scenarios: using a temporal analogue (using past climate record) or a spatial analogue (e.g., Madrid's climate in 2050 will resemble Marrakech's climate today) to represent the possible future climate.
- Climate model-based scenarios: use outputs from Global Climate Models (GCM) or Regional Climate Models (RCM). They usually are constructed by adjusting a baseline climate (typically based on regional observations of climate over a reference period) by the absolute or proportional change between the simulated present and future climates.

Evaluating the climate risk of different components of road assets requires the consideration of a defined set of scenarios. To facilitate comparison and generation of coherent results, it is interesting to use this set to evaluate the risk of all assets and considering all hazards. It is interesting to define a time horizon that allows to evaluate the life spam of all assets. If this includes only the next few decades, the differences between several RCP/SSP are not very relevant, but in the long term (end of the decade), the differences between an RCP2.6 scenario and a RCP8.5 scenario are usually very significative. In all cases is recommended to use outcomes from several models, in order to capture our imperfect knowledge and capacity to simulate the global climate (Figure 3.3).

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Figure 3.3 Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered (IPCC, 2021b)

3.3 Transforming climate scenarios into valuable information for road sector

How can data from GCM and RCM be used for road resilience? Much of the documentation around climate data is tailored specifically for the climate modelling community and is often not accessible to those from a different background without considerable prior reading.

An ideal workflow for climate data is shown in Figure 3.4. It is based on the basic workflow suggested by the climate4impact project. An important part of these activities is intended to generate additional resolution and remove the existing bias in climate models outcomes. For doing so, the use of observation data is always required.

The core of this process (grey boxes) will require programming skills, understanding of climate dynamics, etc. But knowledge of what variables will drive impact and risk is required at the start of the process and, for the final calculations. It is important to ensure that every stage is tailored towards the needs of the specific application / user. The final steps usually imply the connection to impact models, but sometimes other techniques can be applied (expert judgment, qualitative risk assessment, design considering climate parameters, etc.)

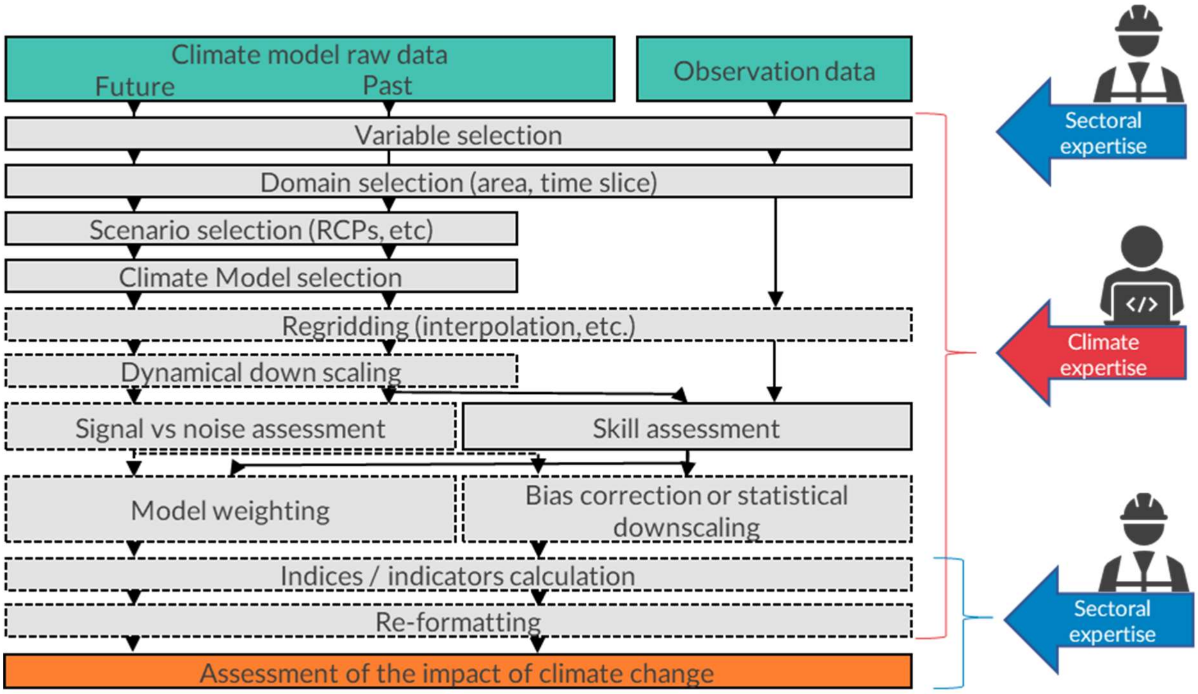

Figure 3.4 Diagram of a suggested workflow for climate model and observation data use (dashed boxes are optional). Based on (Climate4impact)

These steps can allow to transform the outcomes of the climate models into actionable information for climate risk assessment. Variables as temperature, precipitation, etc. can be applied to risk assessment with the limitations of the own climate models to simulate such variables and processes. For this, usually the time series generated by climate models are integrated generating indices that are indicators of the process or impact we are studying. As an example, extreme temperatures can be assessed generating 50-year return periods of the maximum temperature, and this is an index that is applied for calculating thermal actions (such as the elongation of a bridge) (Figure 3.5).

However, there are other climate variables and processes that cannot be simulated correctly by global and regional climate models. As an example, even though climate models perform a simplified simulation of hydrological cycle, due to its resolution their outcomes cannot be used to evaluate the foreseeable evolution of water resources, floods, etc. In the same way, climate models are not intended to provide local conditions for agriculture or plant grow simulation, detailed simulations of winds in areas of complex orography, etc. To generate simulations for some evaluations additional models should be run using the outcomes of climate models. These models are usually referred as "impact models". Hydrological models, agricultural models, local climate models, etc. are some of the most common, but any model requiring climate variables as an input could be a sort of impact model. So, in a broad sense, simulating the elongation of a bridge considering temperature provided by climate projections could be an impact model (Figure 3.5).

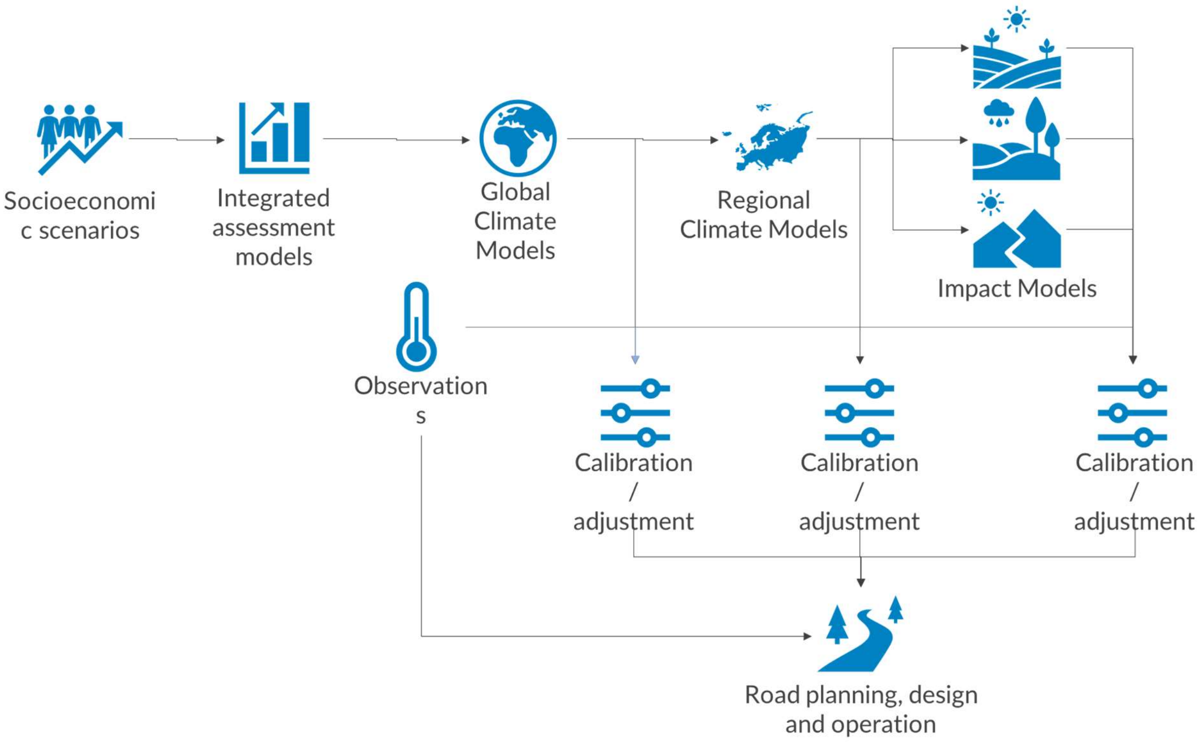

Figure 3.5 Summary of relevant information sources of climate data and their transformation into useful information for road adaptation and resilience

3.4 Uncertainty management

Due to the complex, diverse, and context-dependent nature of climate change adaptation, it is currently recognised that there is no single approach for transforming raw climate information into actionable information about climate change induced hazards (Reinhard Mechler, 2019). The most common approach, for evaluating climate change induced hazards at local level (known as "top-down" or "science drive approach"), involves, among other tasks, the consideration of different climate forcing or emission scenarios, the generation of an ensemble of global climate model or GCMs, usually an ensemble of regional climate models nested to the GCMs, statistical downscaling and/or bias correction and the use of hazard or impact models forced with climate change projections (Climate4impact).

So, the assessment of future impacts of climate change is associated with a cascade of uncertainty linked to the modelling chain employed in assessing local scale changes and the techniques and scenarios assumed (Wilby, 2010) (Figure 3.6). Impact modelers typically "dictate" the approach for climate change related hazard assessment, with decision-makers; then, facing difficulties when interpreting the results of ensemble experiments and translating the uncertainty into actionable information for decision-making (Smith, 2018). As a consequence, several authors are proposing to strengthen the participation of the decision makers in the design and development of the impact assessments (this is referred as the "D approach" by Smith (2018)) or changing the approach to the generation of selected storylines that combine different climate scenarios with other trends (as suggested by Shepherd (2018)).

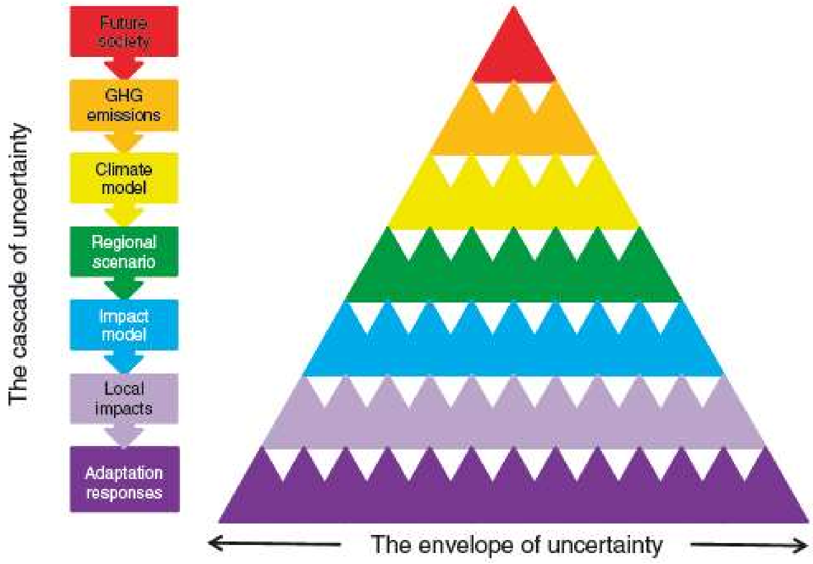

Figure 3.6 Graphical representation of the uncertainty associated to climate risk assessment and definition of adaptation options. Source: (Wilby, 2010)

In any case, uncertainty is intrinsic to the climate impact modelling chain. The use of climate projections and scenarios to plan, design and operate road assets implies that it should be considered and managed. ClimateAdapt (ClimateAdapt) propose different approaches for dealing with this uncertainty. At this stage of the project, the next approaches are considered of interest:

- Scenario Planning: A comparison of how well alternative designs and decisions perform under these different future conditions is proposed. In addition to providing a useful description of uncertainty, scenarios can also bring clarity regarding the trade-offs made within the decision-making process.
- Adaptive Management: selection of strategies that can be modified to adapt to the changing evolution of climate are encouraged. Adaptive design, is proposed by other sources as an interesting approach for infrastructure planning and design (e.g., OECD, 2018), American Society of Civil Engineers ASCE, 2015), etc.)
- Robust or Resilient Strategies: This approach first identifies a range of possible future circumstances that a project might face, and then identifies strategies that will work reasonably well across that range of possible futures. A robust strategy can be defined as one that performs well over a very wide range of alternative futures.
- Options that minimize implementation costs and maximise benefits: This includes low-regret or no-regret actions, win-win actions, for example those that deliver wider benefits, soft strategies, reversibility, flexibility and safety margins, etc.

3.5 Other time scales of climate data

Meteorological forecasts, which can provide more and more precise information about the climatic variables for the coming days, are used intensively for preparedness in advance of snow event, heavy rains, etc. Seasonal forecasts (CCCS) (forecasts of average seasonal conditions over a region that are made many months in advance due to slowly changing parts of the climate system) are an increasing area of interest in infrastructure management, and, in some conditions are expected to inform decisions in a longer term (weeks to months). Annual to decadal projections (WMO) should be also mentioned as an emerging product of interest.

These climate products are usually generated with climate models that share the characteristics of those used for generating multidecadal projections, but they are reinitialized every year. Thanks to this characteristic, they provide a prediction about the evolution of the main variables (temperature, precipitation, etc.) in the coming months and years. In a broad sense, these products are more suited to projection of surface temperature, but their confidence in forecasts of precipitation and atmospheric circulation is limited (Smith, 2019).

3.6 Sources of climate data.

The sources of climate data of interest for climate risk assessment of roads can be summarized as the following:

Global Share Socioeconomic Pathways (SSP) Database: Usually the outcomes of IAMs are, in general terms, of little interest for road resilience. While some data can be obtained from these simulations and the SSP scenarios, usually they are of complex application for the evaluation of specific projects. In any case, the most interesting point to access this data is the SSP Database (SSP Database).

National socioeconomic scenarios. Global SSP have the main goal of supporting the climate modelling community, so they deliver the essential variables demanded by this community and present a resolution that in some cases only include great regions in the globe. However, several countries have found interesting to generate national scenarios with higher spatial granularity and a wider scope (e.g., including technological prospections, etc.). They can provide a coherent set of socioeconomic variables that can complement the climate risk assessment. Some examples are the United Kingdom (UKCRP), Finland (SYKE), Netherlands (WLO), etc. These sources of socioeconomic data don´t provide acute climate data, but will provide, as an example, population growth rate coherent with low/medium/high emission climate scenarios that would allow to estimate coherent traffic flow increases.

Earth System Grid Federation: The Earth System Grid Federation (ESGF) Peer-to-Peer (P2P) enterprise system is a collaboration that develops, deploys and maintains software infrastructure for the management, dissemination, and analysis of model output and observational data. It is integrated by a set of nodes, operated by different institutions. The most interesting data that can be accessed through this system for road resilience are:

- CMIP6 and CMIP5: Coupled Model Intercomparison Project Phases 5 and 6, the main intercomparison project on global climate models.
- CORDEX: Coordinated Regional Climate Downscaling Experiment. This is the most relevant initiative of regional climate modelling. Currently, most of the simulations are nested in CMIP5 Global models.
- Bias-adjusted CORDEX simulations: this dataset provides bias corrected outcomes of regional models, using different techniques and reference data. They are visible on all ESGF index nodes worldwide under the "CORDEX-Adjust" project but the full support for all CORDEX search options is only provided by some nodes, including:
    - NSC/LIU-SMHI, Sweden (https://esg-dn1.nsc.liu.se)
    - DKRZ, Germany (https://esgf-data.dkrz.de/)
    - IPSL, France (https://esgf-node.ipsl.upmc.fr)

ESFG is the great and vast repository of climate simulations, but downloading, processing and using its data requires some capacities that usually are scarce in the organizations involved in road adaptation and resilience. The following data sources provide an easier access to climate data.

Global climate atlas. Different sources provide climate data in portals with intuitive interfaces to consult and access climate data. Among these sources, the next ones can be used as examples:

- IPCC AR6 WGI Interactive Atlas (IPCC): this portal could be highlighted and recommended as a first entry to consult climate projections for different reasons. First, it includes an important and updated catalogue of data (CMIP5, CMIP6, CORDEX, observations, reanalyse, etc.). It also includes functionalities that facilitate the access of non-expert users to climate data. It includes the possibility of consulting data using two types of scenarios: degrees above the preindustrial era (and other baselines) and combination of RCP/SSP and temporal horizons (e.g., Medium Term, 2041-2060) considering the SSP2-RCP4.5 pathways).
- KNMI Climate Atlas (KNMI): This atlas includes an accessible interface, but it doesn´t include information such as CMIP6.
- World Bank Climate Knowledge Portal (WB). This tool allows to visualize and download data. As with the previous one, the information provided is still based on the previous generation of climate models (CMIP5).
- GFDRR ThinkHazard! Tool (GFDRR): This portal combines outputs from climate data with other sources to provide different information about risks. It focuses on providing a score, evaluation more than on the provision of quantitative values of the variables.

National climate scenarios and portals. Several countries (i.e. UK) have developed their own climate scenarios. Usually, these national scenarios or projections are derived from CORDEX simulations (regional models), but in some cases, they are complemented with new simulations of high-resolution models (DMI, 2014). In each country, the national projections have different characteristics, but in relation to the global information these sources provide some of the following characteristics:

- Increase of spatial resolution (usually through statistical approaches).
- Bias correction combining model outputs with local observations. It should be noted that in this activities, national exercises may use national databases, improving the outcomes in reference to continental or global bias corrected datasets, that usually use global reanalysis and observations of lower resolution.
- Integration of the time series for generating climate indexes, synthetic information, etc.
- Facilitate visualization through an atlas.
- Data download in formats that usually are more accessible than the outcomes of the models (e.g., txt or csv vs netCDF or GRIB respectively).

It is not possible to present here a list of all the national atlases, but they are generally provided by the national meteorological services or the ministries in charge of climate change adaptation. This is also an important aspect, because they can be mandatory for some activities, or at least an authoritative reference, in their respective countries. In 2021 the EEA published an overview of the National and transnational climate atlases in Europe (EEA, 2021) that summarizes their main characteristics.

In addition to the national initiatives, in some countries it is also possible to find regional and other sub-national scenarios and atlases (e.g., in Spain, the autonomous government of Andalusia (Junta de Andalucía), Basque Country (Ihobe), etc. also provide climate data).

Copernicus Climate Change Service (C3S). This service provides information about the past, present and future climate, as well as tools to enable climate change. The core of the service is the Climate Data Store, that comprise a huge and growing catalogue of climate data. This data includes climate projections (CMIP6, CMIP6, CORDEX, etc.), reanalysis, gridded observations, seasonal forecast, sectorial impact data (projections of river flow, sea level rise, wind energy potential, etc.) direct observations, etc. It also provides the tools to make use of this data, as the CDS toolbox, that allows to process these datasets using C3S computational resources. However, in comparison with global atlases and national scenario portals the information is harder to be acquired by non-trained personnel.

It should be noted that C3S is constantly improving the service and adding new datasets and features. Additionally, to climate projections (outcomes from climate models), it provides impact data elaborated with different simulation chains. Some examples of datasets that can be found in the C3S and are not usually provided by national atlases are river flow projections (C3Sb and C3Sc), soil erosion indicators (C3Sd),

Commercial services providing risk assessment. Due to the increasing demand of risk evaluations under an uncertain climate, different companies and organization are providing services that allow to evaluate climate risks. These services include different added value on top of climate projections, as probabilistic analysis of climate scenarios, damage functions, etc. Some examples are:

- MSCI: Real Estate Climate Solution (MSCI)
- XDI: EasyXDI (XDI)
- GRESB Climate Risk Platform (GRESB)

Figure 3.7 summarizes this landscape of sources of climate information considering the processing chain exposed in previous sections and their spatial resolution.

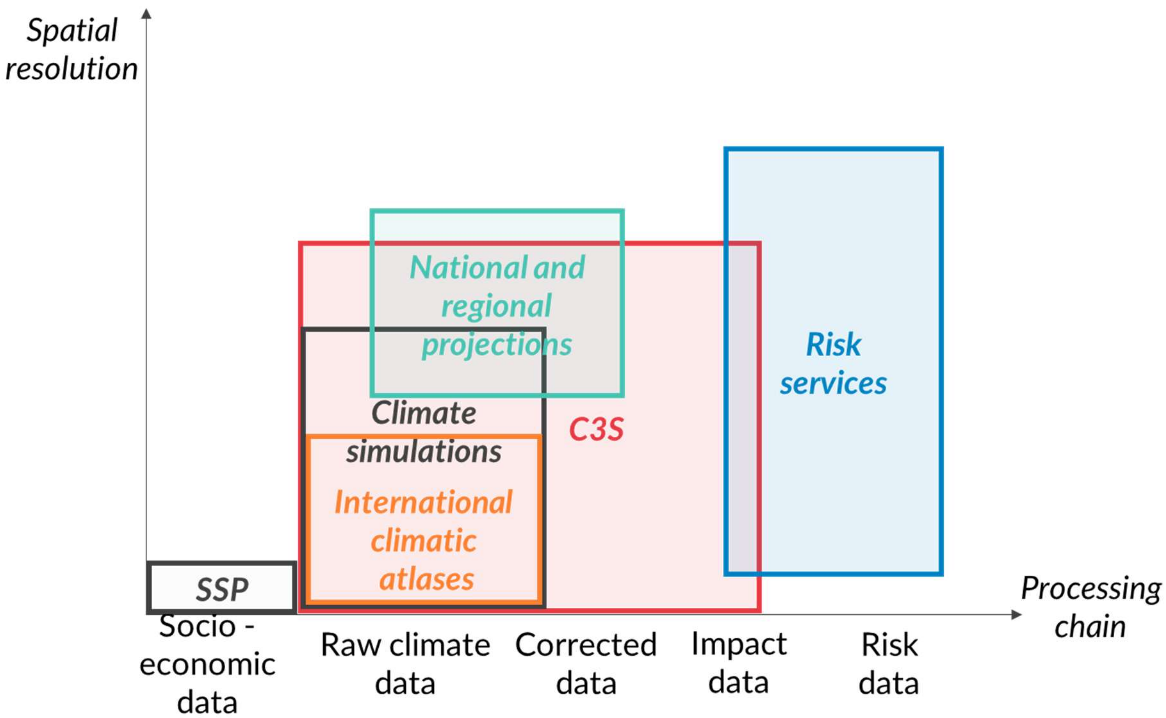

Figure 3.7 Summary of sources of climate data and scenarios relevant for climate risk assessment

On the left, the SSP are included. These socioeconomic data are generated with integrated assessment models that usually include a simplified climate model, so while they provide overall temperature increase and other basic variables, their outcomes cannot be used in impact and risk modelling. SSP provides the climate forcing to GCM, that allows to evaluate how different socioeconomic scenarios alter the climate patterns. RCM are nested to GCM providing better spatial resolution. Sources as ESGF provides the outcomes of this simulations. On top of that, national atlases usually provide better resolution and derived information (indexes, bias corrected data, etc.). The C3S has become the huge repository of global and European data. It usually don´t provide the level of resolution provided by the national atlases, but provides other timescales, impact data, etc. Finally, a new set of risk services and visors focus on the probabilistic impact of climate related hazards on individual assets.

3.7 Identification of climate-related hazard indices (CIDs)

The identification of hazards is one of the primary steps when analysing climate risk assessment. The aim of this step is to specify which climate hazards are relevant to the specific project type at the planned location now and in the future.

The Annex 2 describes a set of 23 climate-related hazard indices not only applicable for adaptation planning at the European and national level, but also relevant to road sector. These indices are available in the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S) and are also available through the European Environment Agency's interactive climate hazards report (EEA, 2021).

The framework in which these indexes are presented adopts the six main categories introduced by the IPCC AR6 WG1 (IPCC, 2021a) entitled Climatic Impact-Drivers (CID) ("Heat and cold", "Wet and dry", "Wind", "Snow and ice" and "Oceanic") and links to the already existing classification in the Implementing regulation 2020/1208 adopted by the European Commission (Annex 1) (European Commission, 2020), which splits climate related hazards into:

- Extreme events (acute) are extreme deviations that vary from minutes to seasons and can be described by their duration, magnitude and frequency as they have a start and an end.
- Slow-onset processes or trends (chronic) are long-lasting monotonic changes and can be described by their change rate.

The table below presents the climatic impact drivers and indices applicable to road and transport system for both types of climate related hazards.

Table 3.1 Climatic-related hazard indices that mainly impact road and transport system based on the CID framework developed by IPCC, 2021a)

	Climatic Impact-Driver (CID)					
	Heat and cold	Wet and dry	Wind	Snow and Ice	Coastal and oceanic	Others: radiation, subsidence
Extreme events	Extreme heat	River flood	Severe wind speed	Heavy snowfall and ice storm	Coastal flood	
	Cold spell	Heavy precipitation and pluvial flood	Tropical cyclone	Hail	Coastal erosion	
	Frost	Ground water flooding	Sand and dust storm	Snow avalanche		
		Landslide				
		Hydrological drought				

		Wildfire conditions				
Slow-onset processes and trends	Mean air temperature	Mean precipitation	Mean wind speed	Decreasing glaciers, ice sheet, permafrost	Sea level rise	Radiation at surface
					Ocean and lake acidity[3]	Subsidence

Figure 3.8 presents the direction of the projected changes of the previously described CIDs for different scenarios and for the four main regions of Europe (Mediterranean, Western and Central Europe, Eastern Europe and Northern Europe). The level of confidence of the direction of projected changes depends on the climatic impact driver, being higher for those related to temperature and to sea level rise.

In general, there is a high confidence that mean air temperature as well as extreme heat will rise in all the regions of Europe and as a consequence of this warming, there will be a reduction in cold spells and frost. In the Mediterranean region, there will also be an increase in other CIS (e.g., aridity, hydrological drought and droughts), while in Western and Central Europe, Easter Europe and Northern Europe those related to extreme precipitation will increase (e.g., river floods and heavy precipitation and pluvial flood).

Regarding coastal and oceanic climatic impact drivers, all of them (relative sea level, coastal flood, coastal erosion, marine heatwave and ocean acidity) will increase in almost all regions of Europe, excepting the Eastern Europe.

[3] Corrosion damage activation.

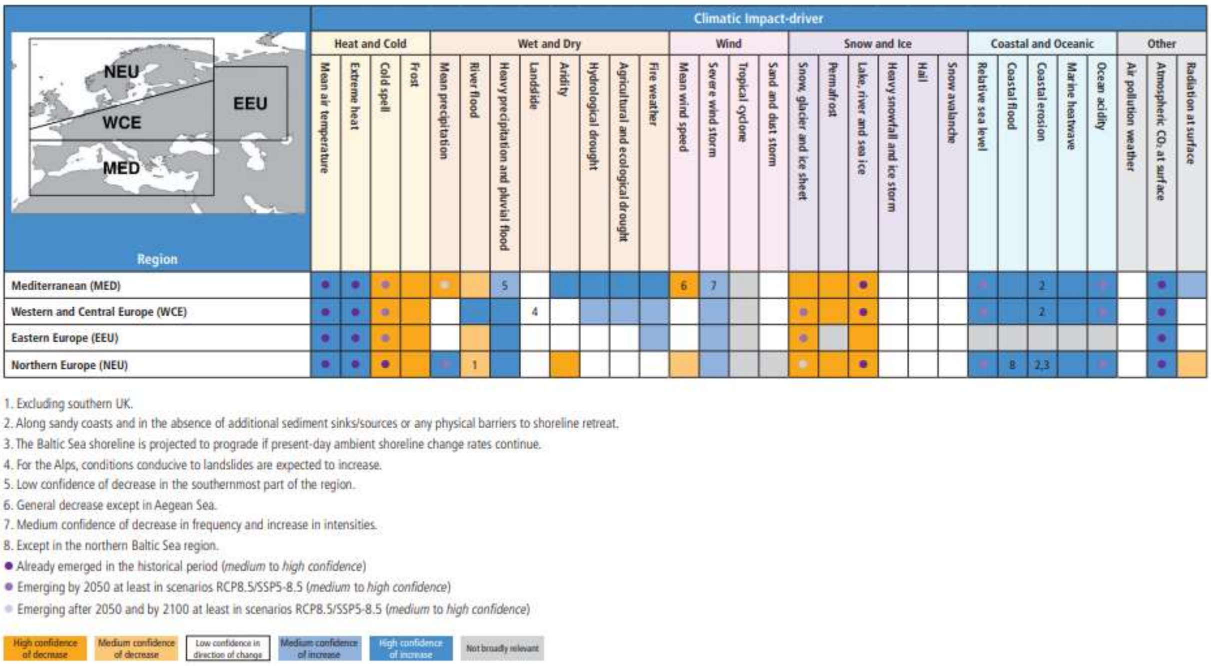

Figure 3.8 Summary of confidence in direction of projected change in climatic impact-drivers in Europe (IPCC, 2021)

Annex 2 provides a more detailed literature review of CID changes along the next decades, based on the ETC-CCA Technical Paper 1/2020 (Crespi, 2020) and the contribution of Working Group I to the IPCC Sixth Assessment Report (WG1 AR 6). The former compiles information from international organizations, European projects, national authorities and scientific literature, while the latter builds on national and international scientific literature. Furthermore, European data sources of each index, including CDS datasets whenever available are included, and reanalysis and projection datasets are also reported for index computation.

4 MAPPING EXPOSURE

Exposure describes if the asset type is subject to one or more climate CID and subject to loss. This assessment should include all relevant road assets to conceptualize direct and complex impacts (i.e., aggregate, compound and cascade). Besides, it should address the asset life cycle and evolve over time considering factors (e.g., temporal variations, changes and/or deterioration of the asset during its life) that may lead to the degradation of its performance.

Based on this, the section starts by introducing the highway asset types according to CoDEC's classification of road entities. Then, it follows by describing the basis for a proper exposure mapping, which involve the combination of climatic impact drivers and specific asset types. Finally, it highlights the importance of addressing exposure along the road project cycle.

4.1 Highway asset type categorisation

CoDEC is a project funded by the CEDR (Conference of European Directors of Roads) Transnational Research Programme Call 2018 aiming to understand, in a very practical way, the key means for successful implementation of Building Information Modelling (BIM) principles within the European highways industry, in particular with regards to freeing and enriching data flow to and from Asset Management Systems (AMS).

Considering CoDEC's classification of road entities, highway asset types can be categorized as the table below.

Table 4.1. Asset types according to CoDEC's classification of road entities

Entity Class (CODEC)	Asset (ICARUS)	Component
Road Entities	Road Section	Kerb and traffic separation Lanes Pavement Layer Pavements Road studs Soft shoulders Traffic signage and marking
Structures	Bridge	Substructure Bridge deck system Mechanical connections Pylon Reinforcement and Pre-stressing Maintenance Access Retaining wall systems Drainage and wastewater collection

Entity Class (CODEC)	Asset (ICARUS)	Component
	Tunnel	Tunnel Supporting structures Reinforcement and Pre-stressing Electromechanical Fire-fighting system
	Earthworks Embankments Cuttings Reinforced earth retaining wall	Earthworks Embankments Cuttings Reinforced earth retaining wall
	Culverts	Pipe culvert, pipe arch culvert, box culvert, arch culvert, bridge culvert
Electrical power and lighting functions	Roadway lighting systems	Streetlights Column Lantern housing Lamp Interface cabinet Drainage
Drainage and wastewater collection	Drainage and wastewater collection	Drainage Pipe Open drain Manhole Catch pits Outfalls

Although a more in-depth decomposition could be made (from Component level to Subcomponent level) this baseline document does not provide a detailed list. In the next "Deliverable 1.2", the ICARUS Consortium will reach an agreement in the definition of the level of detail according to Impact Chains needs.

4.2 Combination of climatic impact drivers and asset types

Mapping exposure, which involves the combination of spatial and temporal coincidence of assets and climatic impact drivers, provides a better understanding of which hazards are relevant at the asset location. Current exposure should be based on available current and past climate hazard maps and data of asset location or asset alternative locations, while future exposure should focus on climate model projections.

One of the objectives of ICARUS is to identify the most relevant climatic impact drivers for each of the assets with the aim of facilitating the exposure mapping when assessing road resilience. The Table 4.2

provides an example of the main climatic impact drives affecting the road entity (i.e., road section, cycle pathway and footpath) after internal discussions within the consortium.

During the next phases of the project, stakeholders' input will be considered to fulfil this exercise and provide a better context for exposure mapping. This mapping will not only adequate the development of a risk assessment, but also will tailor adaptation needs for a future climate change (e.g., identifying where the technological challenges for improvement lie and which standards need to be reviewed). All analysis are under development and may be changed when new insight appear in the project.

Table 4.2 Tentative CID for Road entity identification based on IPCC 2021,a. To be developed in next deliverables.

Road entity						
	Heat and cold	Wet and dry	Wind	Snow and Ice	Coastal and oceanic	Others: radiation and subsidence
Extreme events	Extreme heat	River flood	Severe wind speed	Heavy snowfall and ice storm	Coastal flood	
	Cold spell	Heavy precipitation and pluvial flood	Tropical cyclone	Hail	Coastal erosion	
	Frost	Landslide	Sand and dust storm	Snow avalanche		
		Hydrological drought				
		Wildfire conditions				
Slow-onset processes and trends	Mean air temperature	Mean precipitation	Mean wind speed	Decreasing glaciers, ice sheet, permafrost	Sea level rise	Radiation at surface
					Ocean and lake acidity	Subsidence

4.3 Mapping exposure along road project cycle

As previously mentioned, road infrastructure includes a wide range of asset types such as road pavement, bridges, retaining walls, tunnels, earthworks and slopes, gantries, drainage, ITS (Intelligent Transport Systems), depots and so on. Infrastructure cannot be separated from the other aspects of the operation and governance of the road network and the interdependencies with other sectors (i.e. forestry and urbanisation can change the run-off of water and after the road flooding and erosion risk). It is the resilience of the system as a whole which is important to the user.

Table 4.3 Typical Infrastructure value chain (Reeves, 2019) consistent with Deliverable 3.1

Diagnose and Conceive			Design and Deliver			Operate and Maintain		
Diagnose	Options	Procure	Design/Plan	Finance	Implement	Operate	Maintain	Dispose/Reuse

Exposure should be addressed considering all these assets along the road project cycle. Table 4.3 depicts a typical value chain of a large infrastructure project, showing the different project stages from proposal to delivery. Decisions are made at each stage, which influence the resilience of the infrastructure and involve working in collaboration with different stakeholders.

- Initial proposal stage - decision-making is centred around the policy need and how best to meet this. This includes the case for investment, the benefits expected from the project and the major options available e.g., on alignment. These types of decisions are normally made by national and local government and are influenced by local communities' groups and businesses. It is more effective if resilience is fully integrated in a project from the start, for example by inclusion in the project objectives and being considered in alignment options, so this is an important stage in the value chain.
- Appraisal stage - options are further developed and then evaluated in terms of their economic, social and environmental impacts. This is normally carried out by the infrastructure owner in conjunction with government and follows national appraisal guidelines. The resilience of both the infrastructure being built/ upgraded and the impact the project has on the resilience of other infrastructure and communities should be considered.
- Planning and detailed design – planning consent often involves public consultation, so any group or individual is able to influence the project. Is carried out on the selected option, with decisions being made on design and materials by the infrastructure owner and (depending on the type of procurement) supplier. Procurement decisions are also made by the infrastructure owner in terms of procurement type, supplier requirements and supplier selection. Resilience can be embedded by using more robust materials and design better able to withstand different hazards, by incorporating features which make it easier to repair if damaged, or update if conditions change, and by including it in procurement processes.
- During construction - the planned design and materials may need to be adjusted by supplier, with the agreement of the infrastructure owner, to fit the actual conditions. When complete, the infrastructure owner signs-off the new asset and it enters into use. Although, most major decisions have been made by this phase of the project there are still opportunities for modifying designs and selecting products to increase resilience. Care must also be taken that the aspects included in the design to increase resilience are not eroded due to pressures on time and budget.
- Maintenance and operation - decisions relating to the maintenance of deteriorated infrastructure and the operation of the network are made by the infrastructure owner and their supplier. Resilience can be included in prioritisation of maintenance and improving response to incidents.

Evaluating exposure to the variety of hazards facing road networks requires decision-making at all points of the infrastructure lifecycle and involves the contribution of different types of organisations to these decisions (see Annex 3. Glossary). The interactions between these stakeholders are particularly important for determining resilience.

During the next phases of the project, stakeholders' input will be taken into account to fulfil this exercise and provide a better context for exposure mapping considering life-cycle phases. This mapping will not only facilitate the development of a risk assessment, but also will tailor adaptation needs for a future climate change (e.g., identifying where the technological challenges for improvement lie and which standards need to be reviewed). All analysis are under development and may be changed when new insight appear in the project.

Table 4.4 Example of tentative CID for Diagnose and Conceive phase. To be developed in next deliverables.

Diagnose and Conceive						
	Heat and cold	Wet and dry	Wind	Snow and Ice	Coastal and oceanic	Others: radiation & subsidence
Extreme events	Extreme heat	River flood	Severe wind speed	Heavy snowfall and ice storm	Coastal flood	
	Cold spell	Heavy precipitation and pluvial flood	Tropical cyclone	Hail	Coastal erosion	
	Frost	Landslide	Sand and dust storm	Snow avalanche		
		Hydrological drought				
		Wildfire conditions				
Slow-onset processes and trends	Mean air temperature	Mean precipitation	Mean wind speed	Decreasing glaciers, ice sheet, permafrost	Sea level rise	Radiation at surface
					Ocean and lake acidity	Subsidence

It would be expected that during the initial stages of a project, the hazards that will change the conceptual design (location, asset type, …) are most important. That is why it can be identified flooding and landslides/avalanches and maybe extreme wind as the most important. Others CID will be dealt with at the design and deliver phases of the project and some others at operation and maintenance.

5 VULNERABILITY OF THE ASSETS

The definition of Vulnerability explained in section 2.1 has also been adopted by the CEN Working Group on Resilience (European Commission, 2021a), however multiple definitions exist, and in various contexts, which can lead to inconsistencies in how infrastructure is assessed (National Academies of Science, 2021). The National Academy of Science 2021 Report uses the NRC definition of Vulnerability, which is "*Potential for harm to system functionality due to disruption caused by a hazard. Vulnerability is a function of the characteristics—scale and scope— of the hazard and the location, design, and condition of the infrastructure asset*" (National Research Council, 2012). This definition differs slightly from the IPCC definition, in that the scale of the hazard is considered, in addition to the condition of the asset are considered.

Different organisations use different definitions of vulnerability in their assessments. For example, Risk Analysis and Management for Critical Asset Protection (RAMCAP) models define vulnerability as the likelihood of damage to an asset, whereas the Federal Highway Administration's (FHWA's) Vulnerability Assessment Scoring Tool (VAST) use vulnerability to refer to an asset's sensitivity to hazards or events (National Academies of Science, 2021). In broad terms, vulnerability may be defined as the level of sensitivity to a hazard (National Academies of Science, 2021; National Research Council, 2012). Understanding vulnerability of an asset is an essential step in identifying weaknesses in a network and can help prioritise areas for resilience improvement.

Considering this, the section will present the factors affecting infrastructure vulnerability, then a review about how vulnerability is assessed in practice. How vulnerability is assessed over the life cycle is then presented, followed by ways in which Nature-based Solutions may be used to decrease vulnerability.

5.1 Factors influencing infrastructure vulnerability

There are many factors affecting an asset or network's vulnerability. There are those factors pertaining to the hazard, the condition of the asset, as well as those affecting the capacity of the asset/network to adapt.

Hazard:

1. Type of hazard
2. Likelihood of damage occurring

Asset Sensitivity:

1. Condition of asset
2. Location of asset[4]

Capacity to adapt:

1. Availability of repair products and services
2. Availability of financial resources
3. Availability of human resources

[4] NRC considers location to be a function of vulnerability. Nevertheless, according to IPCC reports, exposure is an independent component (not a function of vulnerability).

4. Availability of additional services in response to disruption (e.g., redundancy in network)
5. Dependence on other assets in the network or services

5.2 Vulnerability Assessments in Practice

Research on infrastructure resilience and vulnerability have been ongoing for several years now, with increased emphasis on assessment since the turn of the century. With increasing numbers of extreme weather events as highlighted in Section 3 and Annex 2, along with cyber-attacks and other hazard events, it is becoming essential for infrastructure owners and managers to ensure their assets are resilient in order to provide continued safe operation.

There are a number of vulnerability assessments that have been developed for road and rail authorities, including those published by the UN (United Nations, 2021), the US National Academies of Science (National Academies of Science, 2021), as well as other scientific researchers (Sventekova, 2021). A description of a selection of these assessments follows in this section.

5.2.1 UN Handbook

The UN Handbook on Managing Infrastructure Assets for Sustainable Development (United Nations, 2021) provides a simple vulnerability assessment tool for local and national governments which uses qualitative definitions to determine the level of exposure and adaptive capacity. In this guide, exposure refers to the degree to which a given system may be directly or indirectly affected by a hazard, while adaptive capacity is a measure of a system's existing resilience to shocks or changes. A higher exposure score results in higher vulnerability, while a higher adaptive capacity score results in lower vulnerability. Therefore, these values should not be multiplied together as in a risk assessment, however, the scores may be used to determine the level of vulnerability with the vulnerability matrix. This matrix serves as a guide only, and the handbook advises users to adapt the matrix by changing the cells to suit their assets if desired.

5.2.2 Slovakia case study

Researchers in Slovakia developed a vulnerability assessment for rail infrastructure based on qualitative and quantitative information and applied it to a case study in Slovakia (Sventekova, 2021). Consistent with the definition used in this report for vulnerability, vulnerability assessment of rail infrastructure in their study consisted of an assessment of their level of sensitivity and also the ability to restore functionality following a hazard. The authors developed an 11-step process to assess vulnerability as shown in Figure 5.1. The process connects safety of the element or asset, condition of the asset itself, and identification of vulnerabilities.

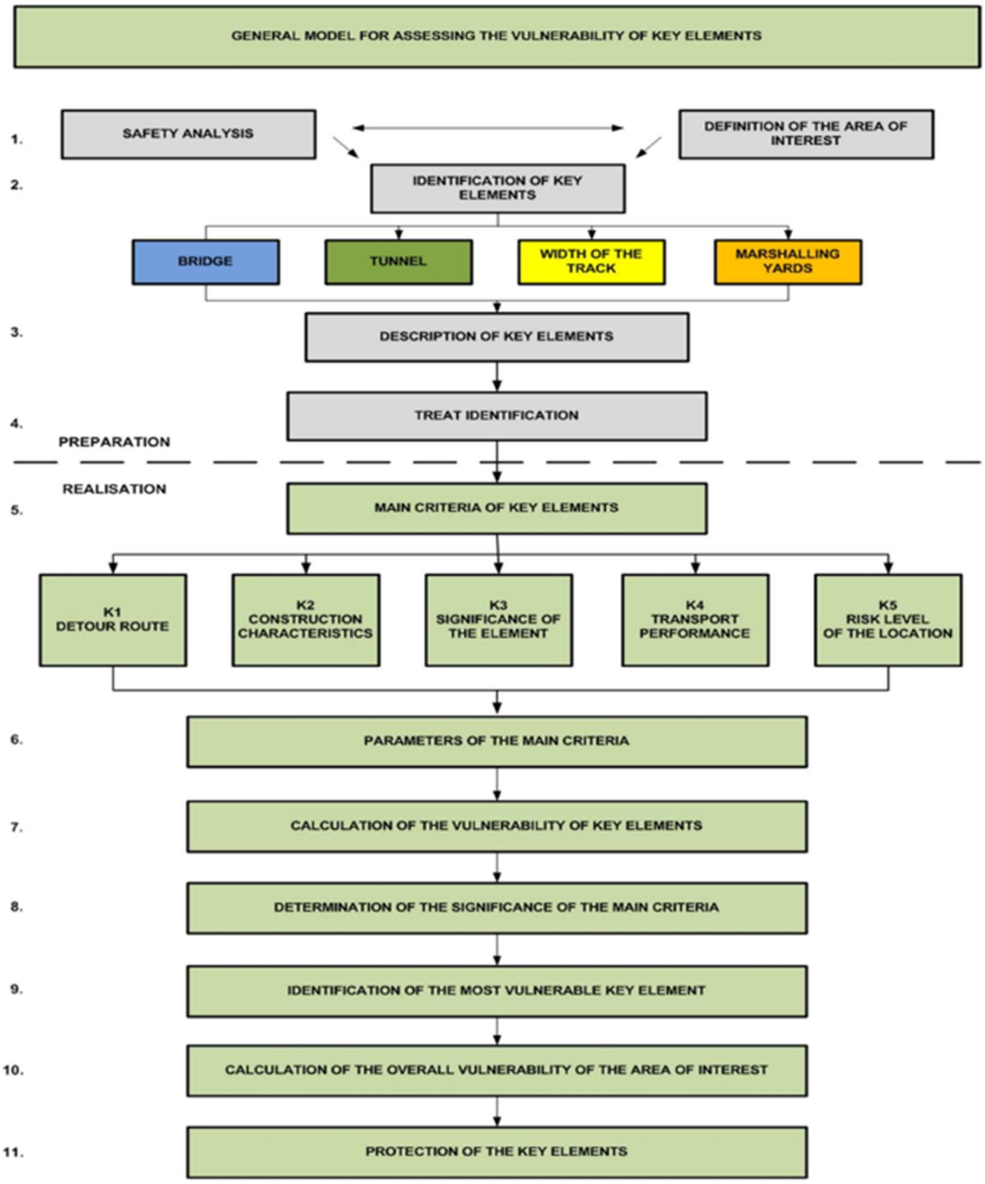

Figure 5.1 20 step process for assessing infrastructure vulnerability as developed by (Sventekova, 2021)

5.2.3 Federal Highway Administration (FHWA)

The Federal Highway Administration (FHWA) published the "Vulnerability Assessment and Adaptation Framework" in 2017 (FHWA, 2017) which offers guidance to transportation agencies on how to assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects. The Framework offers a number of methods to assess vulnerability, again considering the asset's exposure to a hazard, the asset sensitivity including damage to the asset, and adaptive capacity. The methods are:

- Stakeholder Input: Relies primarily on institutional knowledge to identify and rate potential vulnerabilities based on experience of local agency staff, engineers and emergency responders for example.
- Indicator-Based Desk Review: Relies on available data to score and rank assets. Available data may include information on the hazard and/or asset.

- Engineering-Informed Assessment: This is a more detailed engineering assessment that includes multiple assets, and evaluates risks to transportation assets in response to climate stressors.

The first two methods, stakeholder input and indicator-based desk review presented by the framework focus on a network or region level analysis, while the third method, engineering-informed assessment, may be used for assessment of an asset. However, a combination of methods may be used depending on the agency's priorities or information available. An example of an Indicator-Based Desk Review is shown in Figure 5.2.

Variable	Value of Asset	Range of value across all assets		Scaled value for Asset (0-100)	Variable Weight	Score
		Low	High			
Sensitivity						
% change in design flow required for overtopping	-18%	-78%	2375%	98	60%	58.5
Channel condition rating	6	-	-	50	15%	7.5
Culvert condition rating	5	-	-	50	15%	12.5
					Sum of sensitivity variable scores:	78.5
					Sensitivity weight:	33%
					Final Sensitivity Score	25.9
Exposure						
Stream velocity	7.01	0.74	37.53	17	20%	3.4
Previous flooding issues	1	0	1	100	35%	35
Belt width to span length ratio	3.68	0.32	209.24	2	10%	0.2
% forest land cover in drainage area	1.85%	0%	91.23%	2	10%	0.2
% of drainage area not lakes and wetlands	99.91%	97.71%	100%	96	10%	9.6
% drainage area urbanized land cover	4.00%	0%	53.52%	7	15%	1.1
					Sum of exposure variable scores:	*49.5*
					Sensitivity weight:	*33%*
					Final Exposure Score	16.3
Adaptive Capacity						
Average annual daily traffic	5,700	90	49,200	11	35%	4
Heavy commercial average daily traffic	610	5	5,900	10	25%	2.6
Detour length	0.6	-0.37	20	4	35%	1.3
Flow control regime	0	0	1	0	5%	0
					Sum of adap. cap. variable scores:	7.8
					Sensitivity weight:	33%
					Final Adaptive Capacity Score	2.6
					OVERALL VULNERABILITY SCORE	45

Figure 5.2 Example of Indicator-Based Desk Review: MnDOT scaled and weighted indicators of sensitivity, exposure, and adaptive capacity of assets under study to create vulnerability scores. This allowed MNDOT to group assets into vulnerability tiers

5.2.4 United Nations Conference on Trade and Development (UNCADT)

The United Nations Conference on Trade And Development (UNCADT) also assesses vulnerability under the headings of sensitivity, exposure and adaptive capacity (disruption) as shown in Figure 5.3 (UNCTAD, 2017) and provides guidance on when to use qualitative, quantitative or a hybrid assessment.

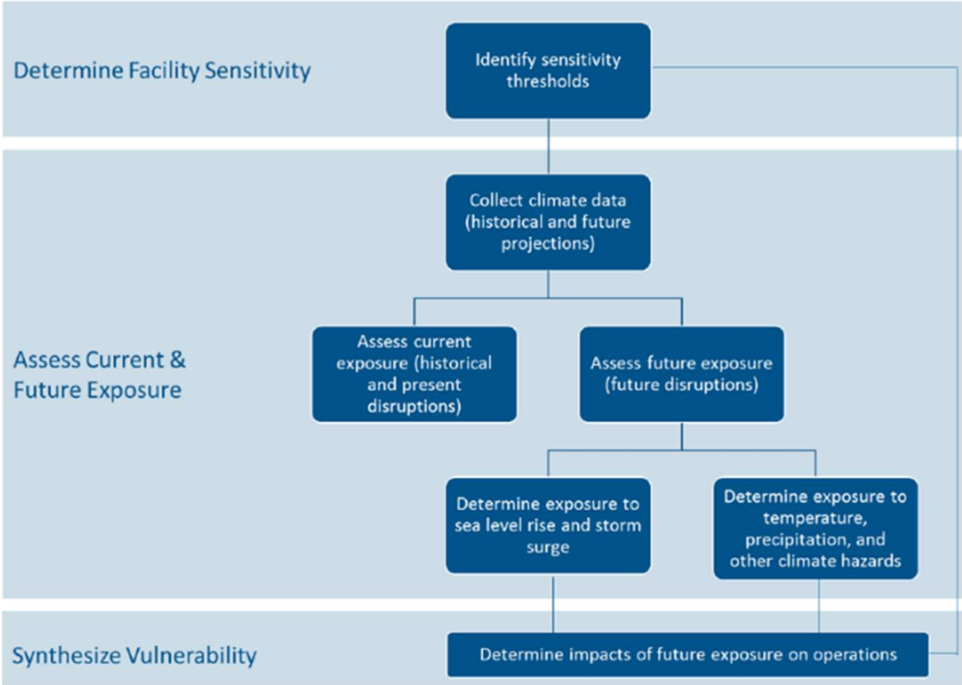

Figure 5.3 UNCADT Sensitivity Threshold Methodology for Vulnerability Assessment (UNCTAD, 2017)

5.2.5 Vulnerability Assessment Scoring (VAST) Tool

The US Department of Transportation (DoT) developed the Vulnerability Assessment Scoring Tool (VAST) in 2015 to assist transportation agencies and other organisations perform a quantitative, indicator-based vulnerability assessment of their assets to climate related hazards (US Department of Transportation, 2016). Similar to other tools presented in this report, the VAST tool considers vulnerability to be a function of exposure, sensitivity, and adaptive capacity and produces a dashboard which reflects the scale of threats and mitigation measures. A vulnerability score may be calculated for each asset as follows:

$$Vulnerability = f(Exposure, Sensitivity, Adaptive\ Capacity)$$

A large amount of data may be input to the tool including detailed asset data (e.g., age, location, replacement/repair costs), exposure indicator data (e.g., changes in temperature and precipitation over time), and sensitivity indicator data related to adaptive capacity of the asset. Data may be sought from interviews with staff, maintenance or repair records, or monitored data. Finally, VAST assesses future scenarios considering a small amount and larger amount of climate change over time and calculates a vulnerability score from 0 to 4, with 4 representing the most vulnerable, allowing users to identify vulnerabilities in their networks.

5.2.6 National Academy of Sciences

The National Academy of Sciences Report (National Academies of Science, 2021) with contributions from the Transport Research Board (TRB) presents a variety of resilience tools being used by Transport agencies throughout the USA. One of the most popular types is the Risk Analysis and Management for Critical Asset Protection (RAMCAP) Tool which was developed by the American Society of Mechanical Engineers (ASME), and includes a vulnerability analysis as part of the assessment. However, in this context, the term vulnerability refers to the likelihood of damage occurring. Calculation of the vulnerability in RAMCAP involves analysing the existing capabilities, countermeasures and mitigation strategies and their effectiveness in reducing the probability of a successful attack.

In summary, several vulnerability assessment tools have been developed and are in use by transportation agencies. The majority assess vulnerability as a function of asset exposure, sensitivity to damage, and adaptive capacity, and allow a combination of qualitative and quantitative data to be used in the assessment.

5.3 Assessing vulnerability over the life cycle

There are many aspects of vulnerability that can change over an asset or network's life cycle: climate hazards changing over time, additional redundancy built into network, asset condition deteriorating, traffic loading increasing, etc. It is therefore important that a vulnerability assessment is re-visited and updated throughout an asset's service life.

A number of agencies have recommended infrastructure monitoring and long-term data collection in order to monitor vulnerability and resilience over time. Back in 2012, the National Research Council Report on Disaster Resilience recommended that "*Monitoring vulnerability and resilience requires long-term systematic data collection to capture for place-based human and environmental changes*" (National Research Council, 2012). FHWA (2017) advises long term monitoring and re-visiting the vulnerability assessments as climate change evolves. The assessments may be updated with monitoring data from indicators, as well as new climate data to revise the vulnerability assessments.

5.4 Measures to influence vulnerability

There are many types of measures to influence vulnerability, depending on the infrastructure type and hazard. Measures may include building new assets or replacing existing ones, adapting existing assets to accommodate climate-induced changes in demand, increasing network redundancy, or adapting existing policies, plans, and operations and maintenance practices to increase resilience (United Nations, 2021).

Over the last decade or so, nature-based solutions (NbS) have gained attention as sustainable resolutions for infrastructure struggling to cope with an increasing number of extreme weather events and climate-related hazards. The European Environment Agency (EEA) published a report in 2015 exploring the possibility of using NbS (or green infrastructure), rather than concrete and steel, to mitigate the impacts of weather and climate change-related hazards on infrastructure (EEA, 2015). In the report, suggestions were made on ways to implement NbS to mitigate against adverse effects of landslides, avalanches, flooding, storm surges and carbon destabilisation by ecosystems. One of the key points, as summarised in IPPC AR6, is that both people and biodiversity benefit, whilst contributing to achieving other sustainable development goals (IPCC, 2022).

The Nature-based Solutions (NbS) Initiative define NbS as "*working with nature to address societal challenges, providing benefits for both human well-being and biodiversity. Specifically, they are actions that involve the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands such as croplands or timberlands; or the creation of novel ecosystems in and around cities.*" (Nature-based Solutions Initiative, 2022). In a similar vein, a commonly used definition from the World Conservation Union (IUCN), is that NbS are "*actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (Cohen-Shacham, 2016).

NbS offer new opportunities under climate change. ICARUS will analyse in D1.3 how these solutions may impact the road system to mitigate the impacts and thereby enhance resilience.

5.4.1 Examples of Nature-Based Solutions

Nature-based Solutions (NbS) can help to address climate change issues that we face, and help to reduce infrastructure vulnerability and thus increase resilience. The Global Program on Nature-Based Solutions (NBS) for Climate Resilience have suggested several ways in which NbS may be used to improve infrastructure resilience along our coastlines, in our cities, and around rivers (Global Program on Nature-Based Solutions for Climate Resilience, 2020). Examples include:

- Coastlines: restore ecosystems such as mangrove swamps and marshes to reduce the impact of waves and storm surge
- Cities: wetlands, green roofs or nature-based stormwater system can alleviate flooding from heavy rains, improve water and air quality
- Rivers: Managing and restoring watersheds and rivers can regulate water flow and improve water quality

Similarly, the World Bank published a Catalogue of Nature-based Solutions for Urban Resilience (WB, 2021) outlining multiple examples of NbS for 14 different environments. These are Urban Forests, Terraces and Slopes, River and Stream Renaturation, Building Solutions, Open Green Spaces, Green Corridors, Urban Farming, Bioretention Areas, Natural Inland Wetlands, Constructed Inland Wetlands, River Floodplains, Mangrove Forests, Salt Marshes and Sandy Shores.

5.4.2 Implementation of Nature-Based Solutions

More recently, a number of projects implementing NbS have been trialled. In Barcelona, researchers surveyed users of the Besòs riverside park, a locally managed NbS area, to understand their perspectives towards a NbS (Ramírez-Agudelo (2022). Their findings showed that the area had a positive impact on the users lives, with many of the users frequenting the area for social, cultural, recreational benefits and for health-related purposes.

Highways England are making funding available to farmers and landowners near Manchester through a Natural Flood Management programme in order to “reduce flood risk on sections of the strategic road network known to be particularly vulnerable to flooding”. The funding programme enables landowners to slow or store water in the landscape through natural processes, reducing flooding in downstream areas. Examples of measures include buffer strips, increasing soil health, water storages features such as ponds and swales, in-channel structures and other approved innovations that the landowners may create. (Highways England, 2022)

A number of NbS which have been implemented in Bangladesh were reviewed by Smith et. al (Smith, 2021). They found that short term trade-offs with local needs were required in order to maximise NbS benefits in the long term. They also recommend that support for NbS should be included in government policies, all stakeholders should be included in the implementation, transparent governance required, and provision of secure finance and land tenure.

5.4.3 Summary

In summary, nature-based solutions (NbS) can play a very positive role in increasing resilience and reducing vulnerability of infrastructure, particularly related to water infrastructure, whilst also contributing to other sustainable development goals. However, they need to be carefully implemented and managed in order for them to be used successfully by communities.

6 CONCLUSIONS

This document provides the basic knowledge to understand the impacts and risk of climate change on roads. It introduces the elements (hazard, vulnerability and exposure) that structure impact chains (concept to be developed in D1.2) providing a literature review of the state of the art and the state of practice. It consists of a report that serves as a basis for the development of D1.2.

The conclusions drawn from this study are summarised below.

Climate change knowledge for roads

Europe's climate is changing. Climate change is expected to increase the frequency and magnitude of extreme weather events, cause sea level rise and changes in the timing of events such as snowfall. These changes can have significant effects on transportation infrastructure and systems (e.g. more frequent extreme events can mean there is less time for infrastructure owners to recover between events); however, it is still unclear how these climatic changes will impact on infrastructure as many weather-related failures are complex, with multiple risk factors in addition to climate.

Climate data and information to understand and plan for these changes is needed to reduce risks, adapt and build climate resiliency. Whilst climate models provide an indication of the types of changes to be expected, there is still a high range of uncertainty in climate projections especially in the longer term.

The generation of usable climatic variables at the local level with the resolution required by designers and decision makers in the road sector is in a very diverse situation. For variables whose trends can be simulated with quality by climate models, such as temperature, precipitation, etc. national portals are often the most interesting source of data. These sources usually provide higher resolution than international sources, easier access to data, derived information as indexes, bias corrected data, etc. However, some of the variables of interest for road design are not provided by national sources (river flows, extreme values of precipitation, land and snowslides, etc.).

To generate projections of these variables, it is generally convenient to couple the climate model outputs with other models that simulate different bio-physical processes for the area of interest (or basin, etc.). C3S provides some of these information, but, usually, it should be evaluated and/or corrected considering local data. Besides, the generation of these projections involve the use of different scenarios, models, approaches, etc. generating and spread of results that are a proxy of their uncertainty. This uncertainty is intrinsic to the process of generating projections of the variables involved in road design and management, and, without the application of techniques that are generally complex for professionals in the road sector, it is generally convenient to make decisions considering the full range of possible futures that they describe to us.

Risk management principles, frameworks, and approaches

The risk term has a wide range of meanings with disparate approaches, frameworks, etc. as it has been applied in many disciplines. In climate change adaptation, the most accepted framework comes from the IPCC, where risk is taken as a function of hazard, vulnerability and exposure. However, in road transport system environment, although there is still no formal methodology to assess risks, most of them consists of estimating and ranking the impacts and probabilities of hazards, which also provide a central role and a probabilistic view to the risk.

The characterisation of the components of risk differs slightly in both perspectives, mainly regarding the definition of hazard. Generally, in the road sector, hazards are referred to those that are usually assessed in the DRR field. Thus, they normally include certain anthropic hazards (such as, terrorism, war, vandalism, accidents) that are not usually considered in the CCA perspective. However, other types of climate hazards related to slow-onset processes and trends due to climate change (e.g. increasing temperatures, increasing/decreasing precipitation, among others) are neglected. In this sense, it is recommended their consideration in road risk assessment guidelines as they are hazards in themselves and lead to changes in the magnitude, duration and frequency of extreme events.

In terms of risk assessment approaches, a multitude of both qualitative and quantitative methodologies have been proposed and coexist, with no significant dominance of one over the other. It is recommended that the choice of approach should consider the level of detail to be provided in the risk assessment, the complexity of the risks to be analysed and the resources available. On the other hand, it should be kept in mind that every kind of risk analysis - whatever method is finally used - is a more or less simplified model relying on preconditions and assumptions and can never totally reflect reality. Nevertheless, assessment models provide a much better understanding of risk-related processes than merely experience-based concepts can achieve.

Similarly, there is no clear predominance of the different frameworks regarding climate risk management. Although they are usually in line with the general Risk Management approach of ISO 31000, they are sector specific and refer to single phases of the transport infrastructure life cycle. Therefore, a proper consideration of risk management is needed at all stages of the project life cycle.

Climate Impact Drivers and use in the context of roads

The CID framework is helpful for making more objective, neutral and comprehensive assessments on the impacts and risks of climate change. This framework, proposed in the latest IPCC report (AR6) and recognized by the European Environment Agency, is composed of 6 general categories and include a variety of climate-related hazard indices that affect an element of society or ecosystems. The main characteristics of CIDs are their time-scale variety and irreversibility, mutation and tipping points, time of occurrence, composition and their dependence on the elements of the system affected.

In this report a full spectrum of climate-related hazard indices affecting transport sector have been defined. They correspond with hazards that are normally assessed in this sector (i.e. extreme events such as river floods, landslides, pluvial floods), but also with other hazards adopted in the CCA perspective (i.e. slow-onset processes and trends, such as sea level rise). With climate change, extreme events will superimpose and interlink with slow-onset processes; thus, it is recommended that they no longer be considered stationary.

The proposed CID framework applicable to the transport sector is currently in line with climatic data sources available at the European level, which provides insight into its behaviour in the coming decades. The available datasets in the Climate Data Store of the Copernicus Climate Change Service offers reanalysis and projection data for each climatic index and provides additional climatic variables for the calculation of those that are not available. Similarly, European Environment Agency's interactive climate hazards offers a big picture and a detailed information on the evolution of these indices, which is necessary for smarter decision-making to prevent the worst impacts of climate change across Europe's road sector.

Mapping exposure over the road project cycle

The Mapping Exposure could provide fundamental data, skills and tools at-risk communities need to make planning decisions along the whole life cycle of the asset, connection, or network. Using these maps, governments can better understand and communicate climate change risk to local communities and put/remove or refine adaptation plans in place.

To reach that goal, future work could employ dynamic and adaptative modelling frameworks to incorporate the spatio-temporal extent and depth of CID during an event, and also land use. This kind of framework could be used in near and long-term forecasting applications.

As explained in point 4 this baseline document does not provide a detailed list. In the next “Deliverable 1.2”, the ICARUS Consortium will reach an agreement in the definition of the level of detail according to Impact Chains needs.

Vulnerability of the assets

There are a number of definitions for vulnerability in the literature and many road authorities have published their own vulnerability assessments which are used in practice. Most assessments consider the hazard itself and the potential damage which may be caused by the hazard, as well as the condition of the asset. However, others also consider the capacity of the asset to adapt and restore functionality following the hazard.

Although limited data exists considering the assessment of vulnerability over an asset’s life cycle, it is recommended to update the vulnerability assessment throughout an asset’s life, due to changes in asset condition that may occur.

One way to decrease an asset’s vulnerability, would be to adopt a Nature-based solution (NbS) to help prevent damage to infrastructure during climate events. NbS may be implemented to improve local areas for communities, as well as providing benefits during extreme events, however, they need to be carefully implemented and managed in order for them to be used successfully by communities. Nevertheless, NbS are not always the only solution.

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8 ANNEX 1. OVERVIEW OF CLIMATE RISK ASSESSMENT AND RESILIENCE METHODOLOGIES[5]

	General description	Strengths	Limitations
UKGBC (2022)	The guidance presents a methodology for addressing climate-related physical risks at building scale.	Provides a detailed framework and methodology to assess climate change risks.	The proposed methodology is not specific to road sector. Includes data sources mainly for the UK.
European Commission (2021)	It provides a technical guidance for project promoters and experts involved in the preparation of infrastructure projects on climate proofing.	Describes in detail the steps of a risk assessment in the context of climate change. Methodology can be applied to assess the infrastructure of any sector (e.g., transport, energy, urban development, water and information and communication technologies).	The proposed methodology is not specific to road sector. The interaction between the components to assess risk assessment deviates from the latest report of the IPCC (AR 6).
European Commission (2021a)	This document is focused on the resilience of transport systems to specified events. For any organization that is interested in measuring resilience regardless of size or extent of infrastructure, including multimodal.	For explicitly or implicitly modelling of the transport system in space and time, including cascading events. How to define the service being provided by a transport system as a precursor to the assessment of resilience.	Does not provide specific information on the organisational requirements to assess resilience.

[5] A specific annex for conducted risk assessment for climate change risks in the road sector will be provided in D2.2.

	General description	Strengths	Limitations
PIARC (2021)	This Literature Review provides general insight on how the concept of resilience is currently being considered among the academic and technical community.	This literature review presents all relevant information, under appropriate subcategories, namely complex systems, infrastructures and assets.	It was concluded that resilience is not a well-established or extensively studied concept and, therefore, an unambiguous definition valid for every technical field of interest does not exist. No specific consideration to earth structures was found in reference documents when addressing the concept of resilience
GIZ and UNDRR (2021)	It provides a guidance on how to address climate change risk assessment. It targets experts, decision makers, stakeholders operating in the field of disaster risk reduction and climate change adaptation.	Describes in detail the steps of a risk assessment in the context of climate change. The guidance can be customized for any country and project. Provides key concepts regarding climate change risk assessment (e.g., an understanding of disaster risk reduction and climate change adaptation, concepts of impacts chains, cascading and compounding hazards, etc.)	The proposed methodology is not specific to road sector. Methodology might be complex when conducting multi risks analysis.

	General description	Strengths	Limitations
IEMA (2020)	This guide provides a framework for the effective consideration of climate change resilience and adaptation in the Environmental Impact Assessment process, originally aligned with the 2014 European Union (EU) Directive and later updated to include developments in practice	It considers the key stages of the Environmental Impact Assessment and analyse the linkage with climate adaptation and resilience. Step by step process is provided. It considers a limited level of detail for the assessments, proportional to the scientific evidence available, avoiding undue burdens to developers and regulators.	It is not specific to road sector. It was prepared to help UK developers. Examples provided focused on UK.
PIARC (2019a)	General risk catalogue to be used as a starting point by project and risk managers in the field of road/transport infrastructure in any country to mitigate project related risks.	The case studies were gathered from Germany and the USA while the typical risks are applicable in all countries. Since the low- and middle-income countries (LMIC) are likely to be in the early stages of implementing risk management, the risk catalogue and case studies would be of great assistance. Includes an excel spreadsheet tool with all risks divided into risk categories with examples/suggestions of preventative and mitigating measures	It is highly recommended that others continue to work on further developing the framework for the interaction of project risk with program and enterprise risk for better organizational management of risk. Also, the risk catalogue is recommended to be further developed to improve its user-friendliness and convenience for road organizations. Real-life examples from PIARC members (LMIC and non-LMIC) should be considered for further incorporation into the risk catalogue.

	General description	Strengths	Limitations
PIARC (2019b)	Examples of practices and relevant case studies using information from different countries.	Includes international survey conducted with respect to best practices in information management and disaster management with stakeholders.	Good practices in Emergency (natural disasters, infrastructure failures, attacks,...) planning. Evaluation and adaptation of road infrastructure for emergency situations. Management of emergency information through Big Data and social networks. Financial aspects of emergency management and recover
TCFD (2018)	Its objective is contributing to laying the foundations for a common conceptual framework and a standard set of metrics for reporting physical climate risks and opportunities, also identifying the needs for guidance, research and development.	It contributes to the standardization of the assessment and disclosure of physical risks and opportunities. It encourages and guides not only the disclose of risks but also opportunities.	First attempt to standardization that will evolve over time. The proposed guidelines are not specific to road sector.
German Federal Government (2017)	The guideline provides the framework and steps to execute a sectoral and cross-sectoral climate impact and vulnerability assessment.	It identifies the key aspects of climate impacts and vulnerability. It includes a clear definition of steps for vulnerability assessment.	The proposed methodology is not specific to road sector. It is based on an outdated IPCC framework. It includes data sources mainly for Germany.

	General description	Strengths	Limitations
PIARC (2015)	Framework to guide road authorities through a series of steps to identify potential impacts of climate change on their networks, evaluate the level of potential risk and vulnerability, understand how to respond to these risks effectively, and direct them towards appropriate and useful resources, evidence and supporting information.	The purpose of this framework is to collate and synthesise the best practice and knowledge available internationally into an effective and useable tool that can be applied within any road authority. The framework is also designed to be applicable to road authorities operating under any geographical, climatic, economic and environmental condition. It is applicable to all road and network types and for road authorities at any stage of understanding and responding to climate change and extreme weather risks.	
PIARC (2016a)	It deals with methodologies and tools for risk assessment and management applied to road operations including managing risks in relation to the climate change.	Promotes a web-based Risk Management Manual/RM-Manual, which is a useful knowledge database designed to introduce road risk management technologies and their practices in the world.	Further detailed study is necessary to improve the rating of the likelihood of hazards and their consequences.
PIARC (2016b)	It discusses the integration of risk-based analyses into the bridge management systems of several countries.	Gives examples of formal methods of risk-based analyses on certain types of structures.	Consequences of climate change is currently limited by the difficulty in assessing the increase of natural hazards (scour, flooding, wind, extreme temperature) due to climate change.

	General description	Strengths	Limitations
CEDR (2015)	The approach addresses cause, effect and consequence of weather-related events to identify the top risks that require action.	Includes mitigation actions.	These mitigating measures of road owners are not to be confused with climate change mitigation which aims at the reduction of climate change itself by for example minimizing greenhouse gas emissions.
CEDR (2010)	Risk Management for Roads in a Changing Climate.	The project developed several case studies and a Guidebook that illustrate possible uses of the RIMAROCC method at different scales: structure (e.g. bridge or short road section), section (a longer section of roadway), network (over 1000 km of interconnected roads), and territory (a road network and its associated territory).	Vulnerability and socioeconomic impact assessments, and selection of adaptation strategies need to be developed. This project links to ROADAPT.

9 ANNEX 2. PROJECTED CHANGES IN CLIMATIC IMPACT-DRIVERS

This chapter provides a better insight about changes in each of identified climatic impact-drivers (CID). These CIDs are organized in the six general categories described in chapter 0. Each one encompasses the future behaviour of the main climate-related hazard indices that occur or will occur in European road transport based on European Climate Databases. Furthermore, it provides the most relevant climate risk indexes for the road sector.

Heat and Cold

Mean air temperature

The mean annual temperature over Europe has increased faster than the global average. In the last decade, the mean air temperature has been 1.94 to 2.01 °C warmer than the pre-industrial period, being particularly warming over eastern Europe, Scandinavia and eastern part of Iberian Peninsula.

Warming is projected to increase in the upcoming years. Projections from the CMIP6 (CMIP) suggest that mean temperature will increase at a higher rate than the global average, with a warming rate depending on the emissions scenarios and socio-economic pathways. Under the forcing scenario SSP1-2.6, mean temperature will rise by 1.2 -3.4 ° C, while under the SSP5-8.5 scenario projected warning will range between by 4.1 and 8.5 °C (by 2071-2100 and compared to 1981–2010).

The highest warming is expected across north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, while the lowest warming is projected in western Europe, especially in the United Kingdom, Ireland, western France, Benelux countries and Denmark (EEA, 2022).

Figure 9.1 shows observed trends and projected changes in annual mean temperatures.

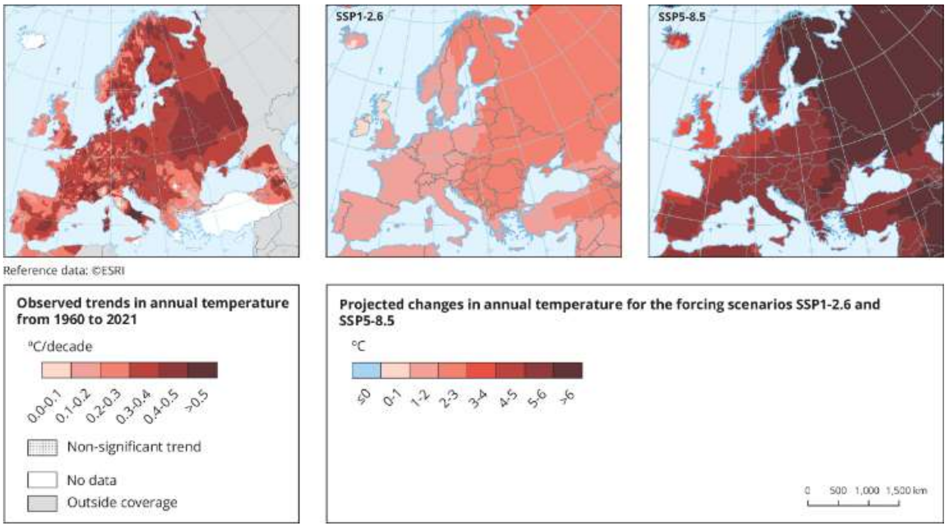

Figure 9.1 Observed trends from 1960 to 2021 and projected changes in annual mean temperature for the forcing scenarios SSP1-2.6 and SSP5-8.5 (EEA, 2022)

A warming of the temperature will increase the heat island effect and, as a consequently, several risks may occur, such as melting asphalt, asphalt rutting increase due to material constraints, thermal expansion on bridge expansion joints and paved surfaces.

This warming trend could require modification in road pavement design and maintenance, changing, for instance, asphalt properties and updating construction and maintenance standards. According to Nemry, 2012), upgrading asphalt to warmer climate conditions will vary from 35 to 135 million €/year by 2040-2070 over the different climate scenarios, representing 0.1% to 0.5% of current road maintenance costs.

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.1 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Mean air temperature	
Definition	It represents the average air temperature for a given time scale (e.g., seasonal or annual).
European data source of the index	European Environment Agency: Observed annual mean temperature trend from 1960-2021 and projected 21st century temperature change under different SSP scenarios in Europe. European Climate Data Explorer: Daily mean temperature – Monthly statistics, 2011-2099
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Truck Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Presence of Bus Routes, Past Experience with Temperature. Use of Polymer Modified Binders, Travel Time, Intervention Costs, Accidents

Extreme heat

Hot extremes are commonly characterized by their intensity and frequency and are normally assessed by analysing changes in the magnitude of extreme day/night temperatures, the number of warm days/nights, and the number of heatwave days.

Even though with significant regional variation, much of Europe has experienced intense heatwaves since 2000, in the form of hotter days, higher night-time temperatures and an increasing number of hot days, tropical nights and humid heatwaves. High maximum temperatures show increases in magnitude and frequency across Europe, including central and southern regions. In Northern Europe, a strong increase in extreme winter warming events has been observed.

In the future, it is expected an increase in hot extremes, even faster than mean temperatures. Heat stress due to both high temperature and humidity is projected to increase across Europe under all emission scenarios and global warming levels by the middle of the century, with prolonged waves of extreme heat and duration of extreme humid heat conditions, especially in southern region. Under a high-emissions scenario:

- The number of hot days may increase fourfold in Europe by the end of the century, with the largest absolute increases in southern region.

- The number of tropical nights may increase up to 100 per year by the end of the century in southern Europe.
- The warmest 3-day mean temperature is projected to increase by 6.5 °C (by 1.5 °C in low-emissions scenario).
- It is virtually certain that the length, frequency and intensity of heat waves will increase in the future.

Figure 9.2 shows observed trends and projected changes in annual hot days.

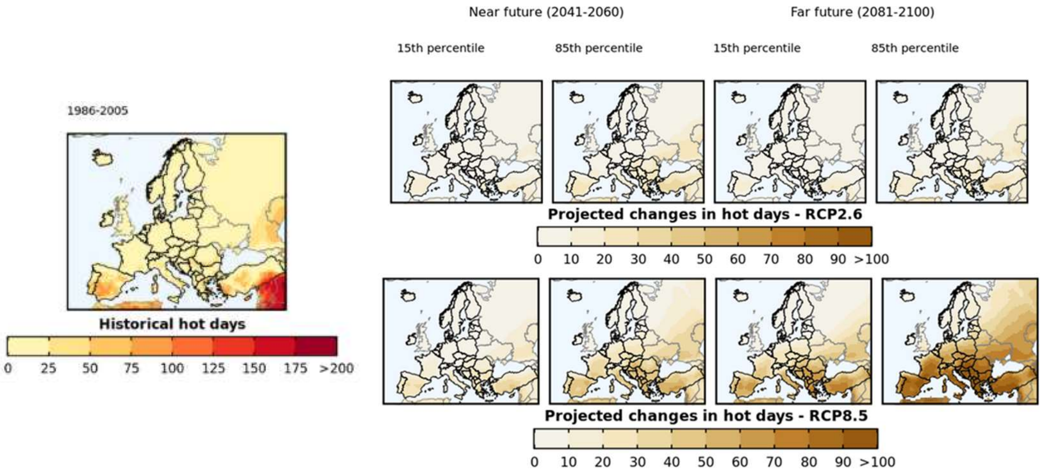

Figure 9.2 Observed trends from 1986 to 2005 and projected changes in annual hot days for RCP2.6 and RCP8.5 in near and far future (EEA, 2022a)

Extreme heat is particularly relevant for road pavement. This weather stress contributes to initiate or accelerate some negative impacts in asphalt and concrete pavement, such as increasing levels of rutting and spalling, as well as softening and expanding the pavement. During summer 2022, severe heatwaves affected Europe and brought record-breaking temperatures to several countries (France, Portugal, Spain and UK). As a result of the heatwaves, road pavements were softened in England (Dillon, 2022) and water was poured on the road to prevent pavement from melting in France (King, 2022).

In the rail sector adverse consequences were also recorded during the summer of 2022 . Network Rail was forced to warn passengers in England and Wales to travel only if absolutely necessary from Monday 18 July to Tuesday 19 July, due to the forecast of high temperatures. Besides, Network Rail was forced to introduce speed restrictions on railway lines across the country to ensure the safety of trains. Journeys were much longer and there were cancellations, delays and last-minute changes.

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.2 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Extreme heat	
Definition	Episodic high surface air temperature events potentially exacerbated by humidity. It can be described using different climate indices: hot days (maximum daily temperatures above 30°C), tropical nights (minimum night temperature of at least 20°C), warmest 3-day period (highest daily mean temperature in a year averaged over a 3-day window), heatwave days based on

	apparent temperature (number of heatwave days per year), climatological heatwave days (number of days per year within prolonged periods of unusually high temperatures).
European data source of the index	European Environment Agency: Heat and cold — extreme heat — European Environment Agency (europa.eu) European Climate Data Explorer: Tropical Nights, 2011-2099 — English (europa.eu)
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Truck Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Presence of Bus Routes, Past Experience with Temperature. Use of Polymer Modified Binders, Travel Time, Intervention Costs, Accidents

Cold spells and frost

Even though year-to-year variability is considerable, Europe has observed a decrease in the number of frost days since the 1980s, being northern region the one showing the fastest absolute decline.

This trend is projected to continue in the future. It is very likely that the frequency of cold spells and frost days will keep decreasing over the course of this century. The number of frost days may decline by about half during the 21st century under the high-emissions scenario (RCP8.5). Moreover, it is likely that, at the of the century, cold spells will virtually disappear.

Figure 9.3 shows observed trends and projected changes in annual frost days.

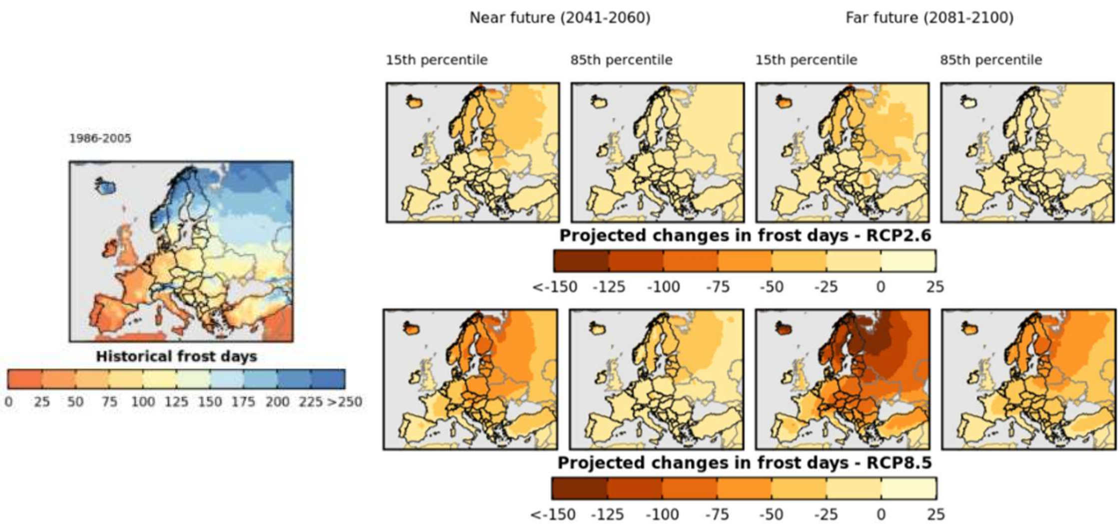

Figure 9.3 Observed trends from 1986 to 2005 and projected changes in annual frost days for RCP2.6 and RCP8.5 in near and far future (EEA, 2021a)

The consequence of milder winters as a result of a reduction in the frequency of cold spells and an increase in the number of freeze/thaw cycles on the roads will lead to a more brittle structure (CERD, 2012a). Transportation scheduling may also be altered due to reduced frost and mid-winter thaws. However, they will bring economic savings as during warmer winters less maintenance operations will be required and could mean less frost control for transport departments and safer travel conditions for passengers.

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.3 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Frost days	
Definition	Cold spell are episodic cold surface air temperature events potentially exacerbated by wind. Frost can be described as freeze and thaw events near the land surface and their seasonality. Frost days index provides the number of days in a year with a daily minimum temperature below 0 °C.
European data source of the index	European Environment Agency: Heat and cold – frost days – European Environment Agency (europa.eu) European Climate Data Explorer: Frost Days, 2011-2099 – English (europa.eu) Copernicus: Heat waves and cold spells in Europe derived from climate projections (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Truck Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Presence of Bus Routes, Past Experience with Temperature. Use of Polymer Modified Binders, Travel Time, Intervention Costs, Accidents

Wet and Dry

Mean precipitation

During the last decades, north-eastern and north-western Europe have experienced an increasing trend, with increases of up to 70 mm per decade in annual precipitation and up to 18 mm per decade in some parts of the region. In Southern Europe the trend has been the opposite, with decreases of up to 90 mm per decade in annual precipitation in some parts of the region and up to 20 mm per decade in mean summer precipitation in the most of them. Conversely, no significant changes have been registered in Mid-latitudes. These observed trends are observed below.

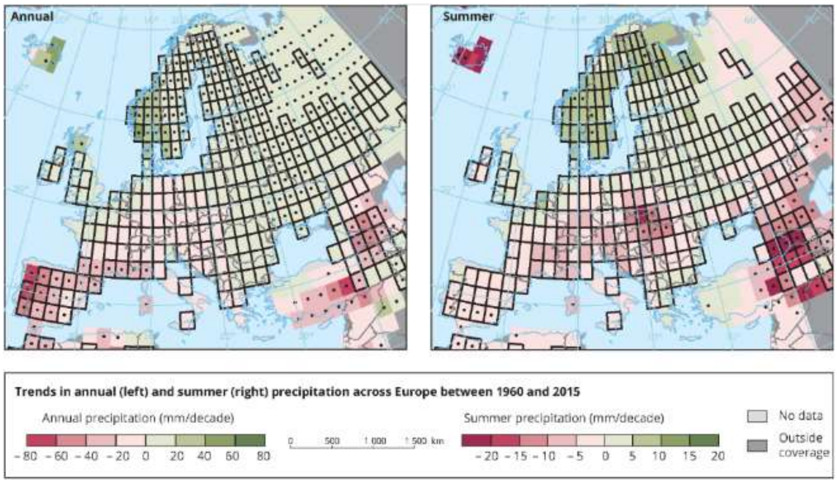

Figure 9.4 Observed trends in annual and summer precipitation across Europe between 1960 and 2015 (EEA, 2021b)

Regarding projected changes, there will be a substantial variation across regions and seasons. Annual precipitation projections are expected to increase in northern Europe and decrease in southern Europe, being this reduction stronger in the summer. Figure 9.5 shows projected changes in annual and summer precipitation.

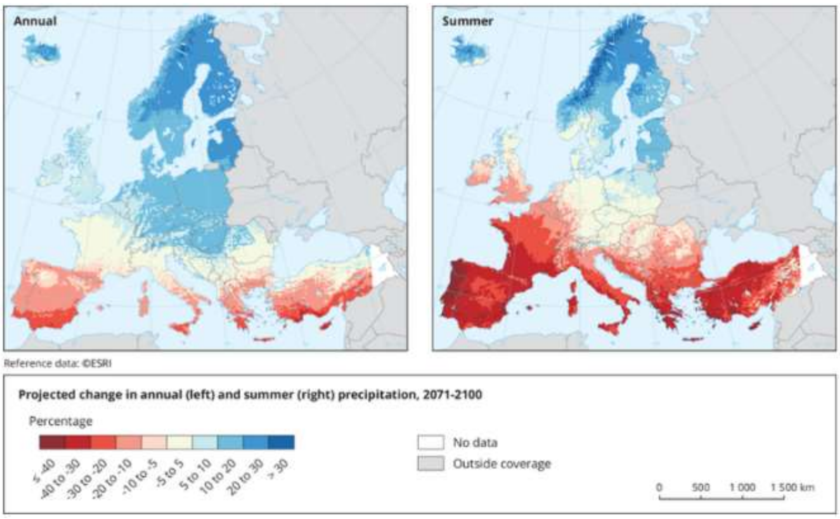

Figure 9.5 Projected changes in annual (left) and summer (right) precipitation (%) in the period 2071-2100 compared to the baseline period 1971-2000 for the forcing scenario RCP 8.5 (EEA, 2021c)

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.4 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Mean precipitation	
Definition	It represents the changes in annual and seasonal precipitation. Total precipitation index represents the total amount of precipitation over a given period (e.g., a whole year or a season).
European data source of the index	European Climate Data Explorer: Mean precipitation (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — mean precipitation — European Environment Agency (europa.eu); Mean precipitation — European Environment Agency (europa.eu); Trends in annual and summer precipitation across Europe between 1960 and 2015 — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Change in Total Seasonal Precipitation, Travel Time, Intervention Costs, Accidents

River flood

Over the period 1960-2010, annual river floods increased in north-western and parts of central Europe as a consequence of increasing autumn and winter rainfall. The trend was the opposite in southern and north-eastern Europe, caused by decreasing precipitation and increasing evaporation in the first case and decreasing snow cover and snowmelt in the second one. These trends can be observed in Figure 9.6.

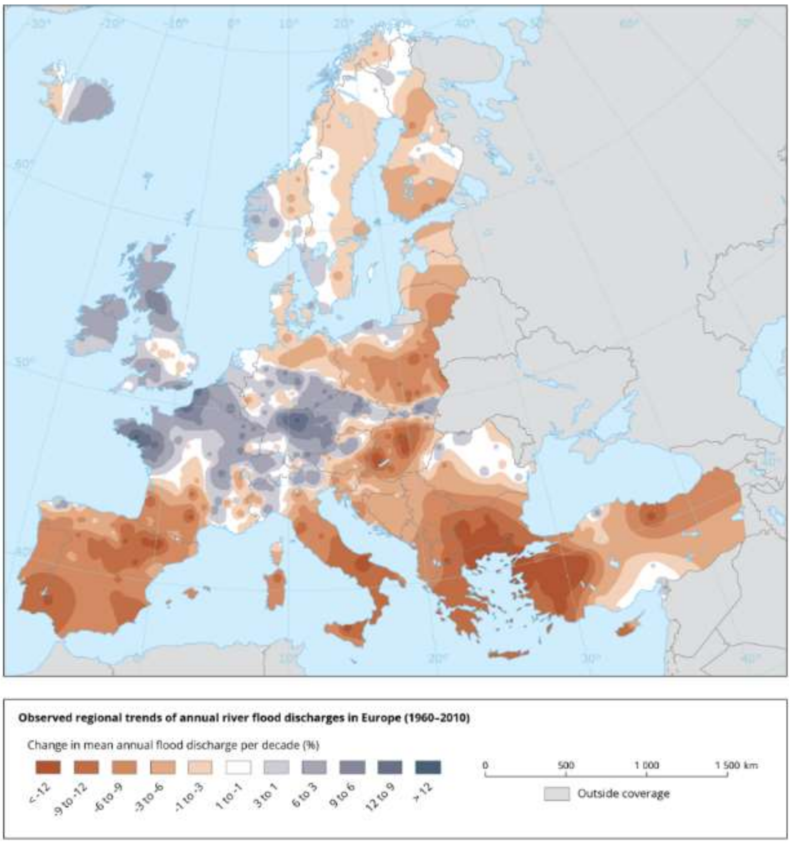

Figure 9.6 Observed trends from 1960–2010 in annual river flood discharges in Europe (EEA, 2021d)

In the future, the occurrence and frequency of 100-year river floods is projected to increase in most of the regions of Europe. The largest increases are expected in central and central-eastern Europe, while in the northern Europe, southern Spain and Turkey maximum 100-year daily river discharge is expected to decrease. On the other hand, the 3 °C global warming scenario will exacerbate these trends causing three times the direct damages if additional adaptation actions are not implemented. Figure 9.7 summarizes projected changes in maximum 100-year daily river discharge for two global warming levels.

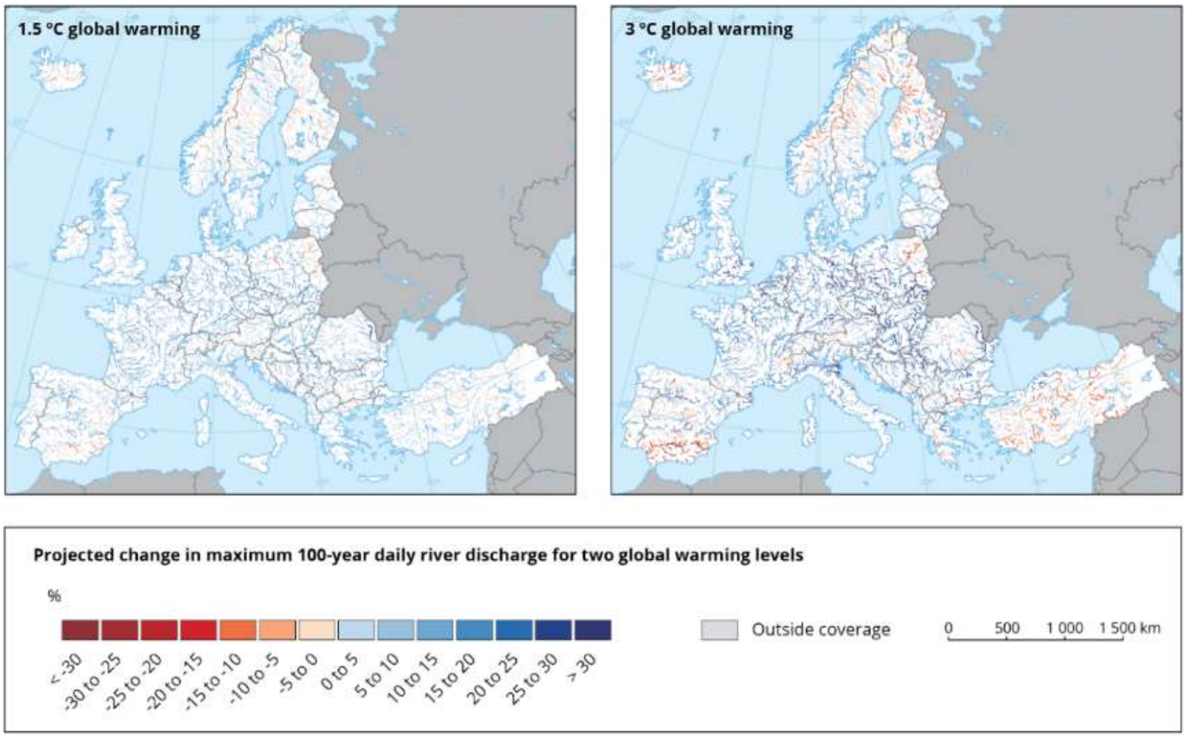

Figure 9.7 Projected changes in maximum 100-year daily river discharge between the reference period (1981–2010) and 1.5°C and 3°C global warming levels (ensemble mean of model simulations) (EEA, 2021d)

Flood effects can cause severe disruptive impact on the road network with significant socio-economic consequences. This is the case of the floods that occurred in July 2021 in multiple regions across central and western Europe (Hallegatte, 2019; Wang, 2019). For instance, in the German Ahr Valley, extreme rainfall caused catastrophic flooding and damaged many roads and almost all bridges, hampering crisis response, reconstruction work, and economic recovery of the region. According to several studies (Kreienkamp, 2021), the occurrence of such event has become 1.2–9 times more likely today than in the 1.2 °C cooler pre-industrial climate.

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.5 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

River flood	
Definition	River floods are episodic high-water levels in streams and rivers driven by basin runoff and the expected seasonal cycle of flooding. It represents the maximum river discharge for a given return period (e.g., 50 or 100-year period).

European data source of the index	Climate Data Store: River flow (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — heavy precipitation and river floods — European Environment Agency (europa.eu); River floods — European Environment Agency (europa.eu) Copernicus: Water quantity indicators for Europe (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	Extreme floods, Location in 100-Year Flood Zone, Location in 500-Year Flood Zone, Location in 10-Year Floodplain, Location in 25-Year Floodplain, Travel Time, Intervention Costs, Accidents

Heavy precipitation and pluvial floods

Pluvial floods and flash floods are triggered by intense local precipitation events and also influenced by non-climatic factors (e.g., land use, changes to river basins, urban planning).

Since the 1950s, the frequency and magnitude of unusual precipitation events (precipitation exceeding the 99th percentile of daily precipitation values) has increased in Europe as a whole, with clearer increases in northern and central Europe. No significant changes are observed in southern Europe.

Figure 9.8 shows observed trends in maximum annual 5-day consecutive precipitation in winter and summer.

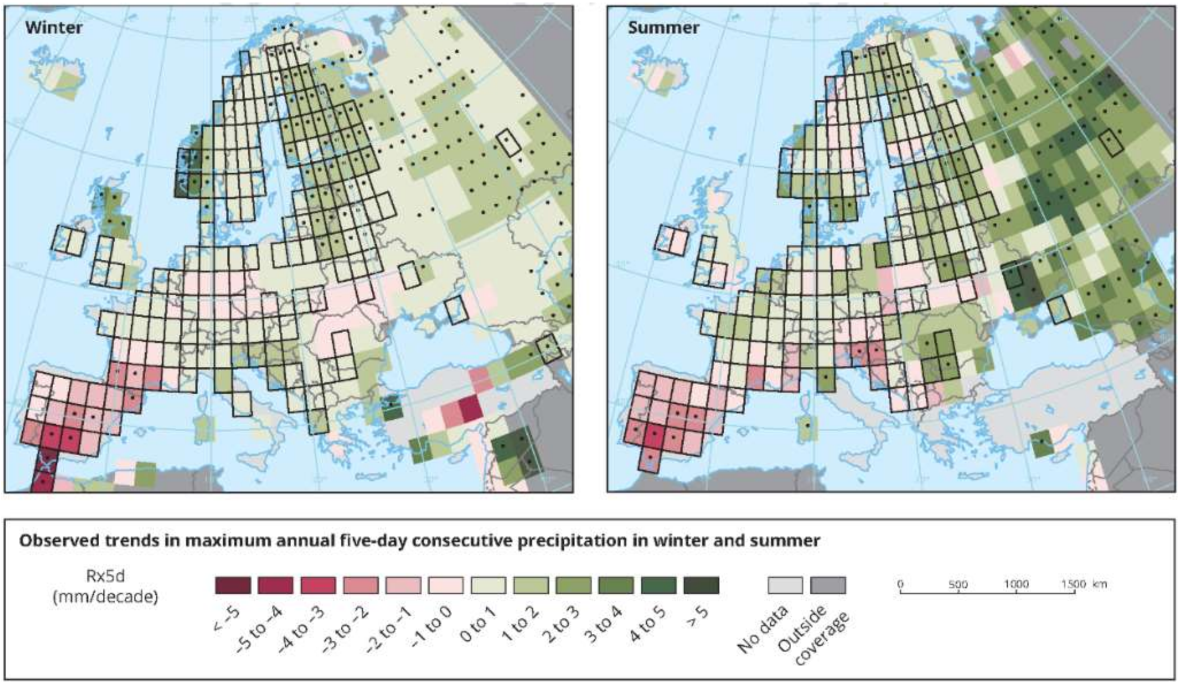

Figure 9.8 Observed trends in maximum annual 5-day consecutive precipitation in winter and summer across Europe between 1960 and 2018 (EEA, 2021e)

The same trend is projected for the future, with the largest increases projected in frequency and intensity of extreme precipitation in northern Europe and smaller increases in central Europe, continuing without significant changes in southern Europe. The strongest changes are projected in Scandinavia and eastern Europe in winter.

Figure 9.9 summarizes observed trends and projected changes in extreme precipitation total.

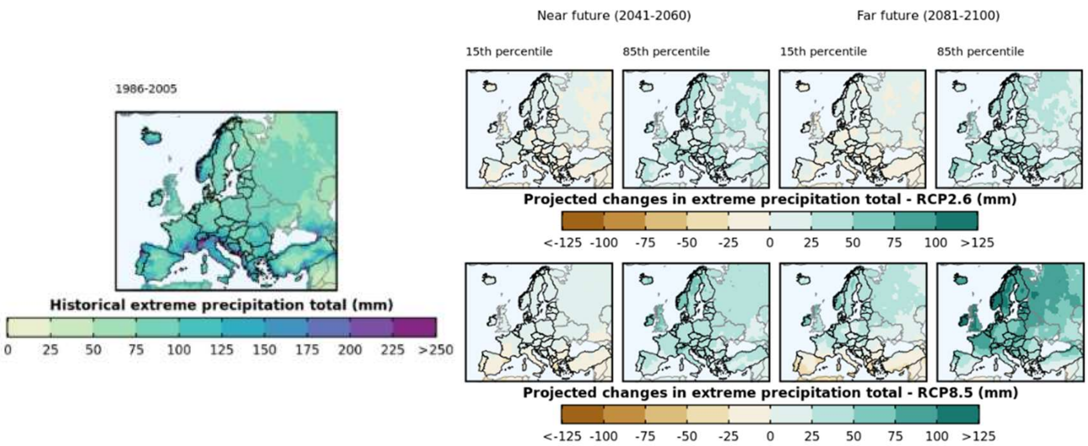

Figure 9.9 Observed trends from 1986 to 2005 and projected changes in extreme precipitation total for RCP2.6 and RCP8.5 in near and far future (EEA, 2021f)

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.6 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Heavy precipitation	
Definition	High rates of precipitation can result in episodic, localized flooding of streams and flat lands. Heavy precipitation can be described using different indices: maximum consecutive 5-day precipitation (greatest precipitation total over five consecutive days in a year), extreme precipitation total (total precipitation on all days with heavy precipitation) and frequency of extreme precipitation (number of days in a year with extreme precipitation).
European data source of the index	European Climate Data Explorer: Heavy precipitation (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — heavy precipitation and river floods — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents

Landslides

Climate models cannot resolve these complex slope failure processes, so most studies rely on proxies or conditions conducive to slope failure.

Too much rain falling too fast not only can trigger floods, but also landslides. The spatial and temporal patterns of precipitation, the intensity and duration of rainfall, and antecedent rainfall are important factors in triggering shallow landslides. Climate indices analysed in previous section are also relevant for the assessment of landslide and erosion risks. But climate and landslides act at only partially overlapping spatial and temporal scales, complicating the evaluation of the climate impacts on landslides. Moreover, landslide susceptibility is not only related to climate conditions, but also to three spatial criteria: terrain gradient (e.g., slope), shallow subsurface lithology, and land cover.

Quantification of possible trends in the frequency of landslides is difficult due to incomplete documentation of past events, especially those that happened before regular satellite observations became available. The projected increase in intensity and frequency of rainfall events and extreme precipitation events is expected to have an effect in landslides in some regions. Where the frequency and/or the intensity of the rainstorms will increase, shallow landslides, including rock falls, debris flows and debris avalanches, and also ice falls and snow avalanches in high mountain areas, are also expected to increase. In Central Europe, rainfall periods are projected to increase by mid-century: by up to 1 more period per year in flat areas in low altitudes and by up to 14 more periods per year at higher altitudes. By the end of the century, they are projected to become even more evident.

Landslides are projected to increase by up to +45.7% and +21.2% by mid-century under both RCP4.5 and RCP8.5 in Southern Italy (Calabria region) and by up to 40% in Central Italy (Umbria) during the winter season. in the Peloritani Mountains in Southern Italy, a decrease is projected by mid of the century under both RCP4.5 and RCP8.5. In the Eastern Carpathians, the Moldavian Subcarpathian and the northern part of the Moldavian Tableland, a slight increase (10-year return period) is projected in landslides, while higher increase is projected in the western hilly and plateau areas of Romania (100-year return period).

Figure 9.10 shows landslide susceptibility for weather induced landslides according to ICG and JRC models. Red circles show possible hotspots while white represents regions without landslide hazard.

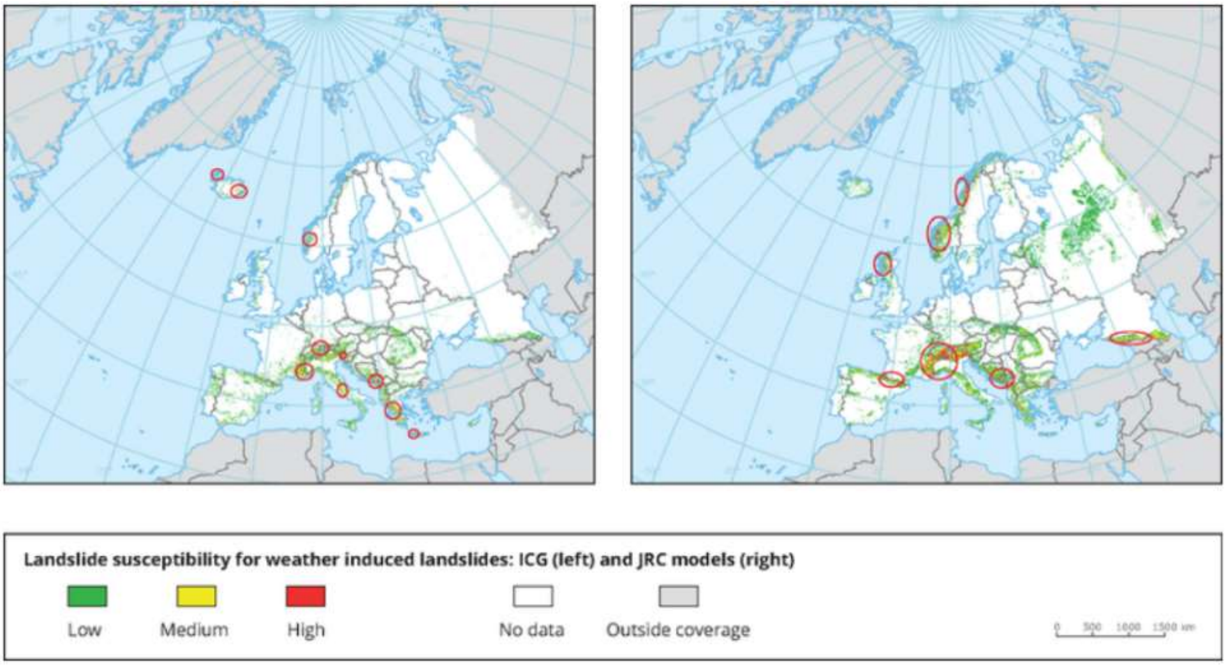

Figure 9.10 Landslide susceptibility for weather induced landslides: ICG (left) and JRC models (right). (EEA, 2017)

Figure 9.11 provides the expected variations in abundance of four types of climate change driven landslides.

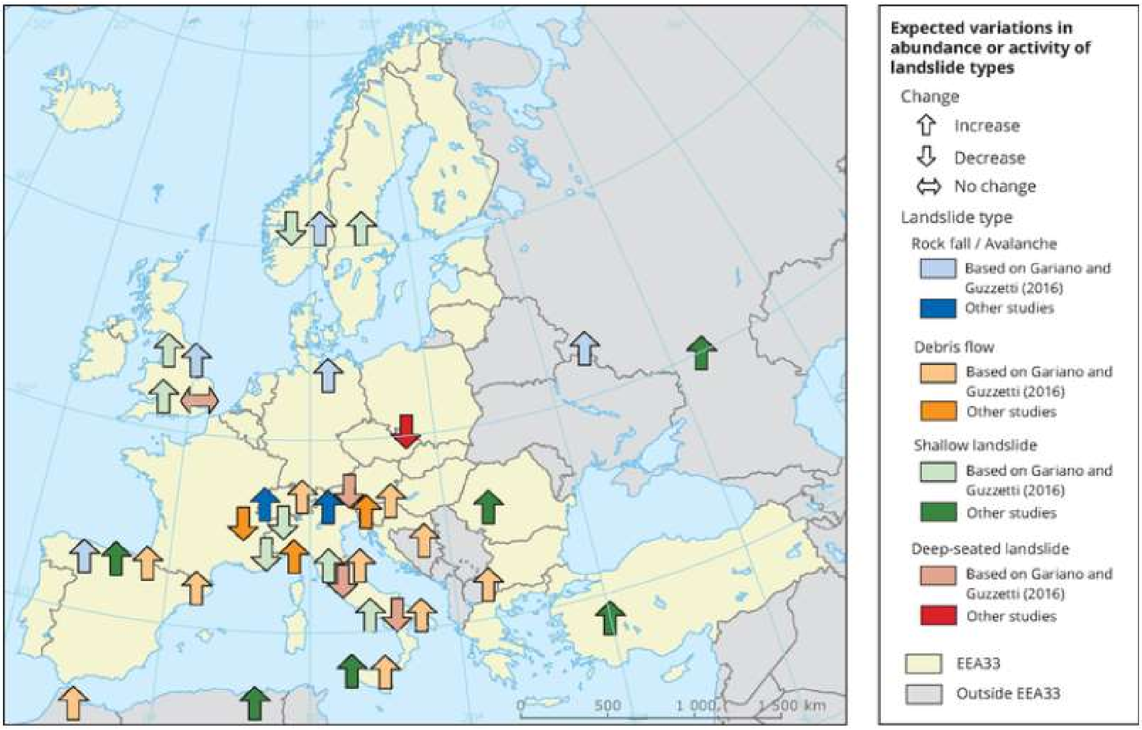

Figure 9.11 Expected variations in abundance or activity of four landslide types, driven by the projected climate change (EEA, 2017a)

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.7 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Landslides	
Definition	Ground and atmospheric conditions that lead to geological mass movements, including landslide, mudslide, and rockfall.
European data source of the index	European Climate Data Explorer: European Environment Agency: Landslide susceptibility for weather induced landslides: ICG (left) and b) JRC models (right) — European Environment Agency (europa.eu); Expected variations in abundance or activity of four landslide types, driven by the projected climate change — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Erosion, Tilting and bulging, Overflow, Settlement, Earthquake induced landslide, Earthquake induced rockslide, Earthquake induced failure of Anchors, Earthquake induced damage to concrete wall, Material defects or degradation, Concrete degradation (carbonation, alcali-silika reaction, chlorine ingress), Rebar corrosion, Loss of tension, Anchor corrosion, Excessive Settlement, Cracking (mm), Damage to geotextile, Cracking (mm), Overload, Travel Time, Intervention Costs, Accidents

Hydrological drought

Drought has been a recurrent feature of the European climate. An increase in severity and frequency of both, meteorological and hydrological droughts, has been observed in parts of Europe, being greater in southern region in accordance with drought indices. With regard to hydrological drought, southern and most of central Europe regions have suffered a decrease in minimum runoff and river low flows, whereas those have increased in northern Europe.

Even though the magnitude of droughts varies strongly from year to year, future projections under higher emissions scenarios show a small drop in northern Europe, substantial increases in central regions and the largest increases in southern ones, where drought magnitude could potentially be tripled the by the end of the century. Focusing on river flows, most European regions are projected to suffer increasingly severe river flow droughts, with the exception of central-eastern and north-eastern Europe. Longer drought periods are projected in southern regions and central Europe, the former already in medium-emission scenarios and the latest in the highest emissions scenarios.

Figure 9.12 shows observed trends in runoff of driest month in Europe and Figure 9.13 provides projected changes in 10-year river water deficit between the reference period and the end of the 21st century in two emission scenarios.

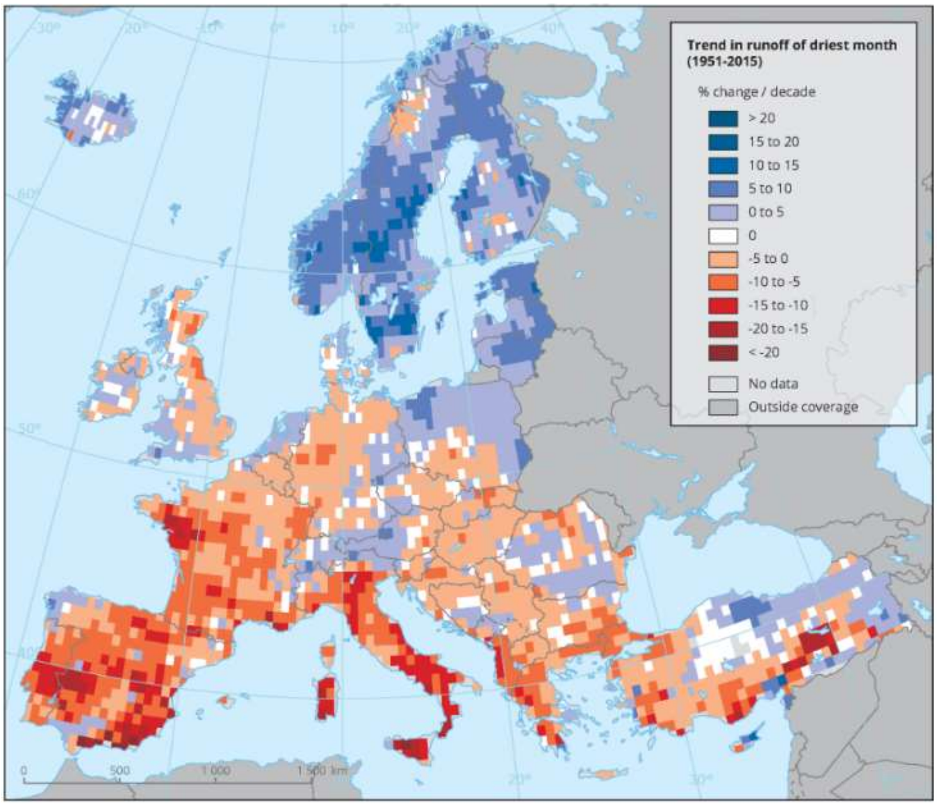

Figure 9.12 Observed trends in runoff during the month with the lowest river flow of the year in Europe (1951-2015) (EEA, 2021g)

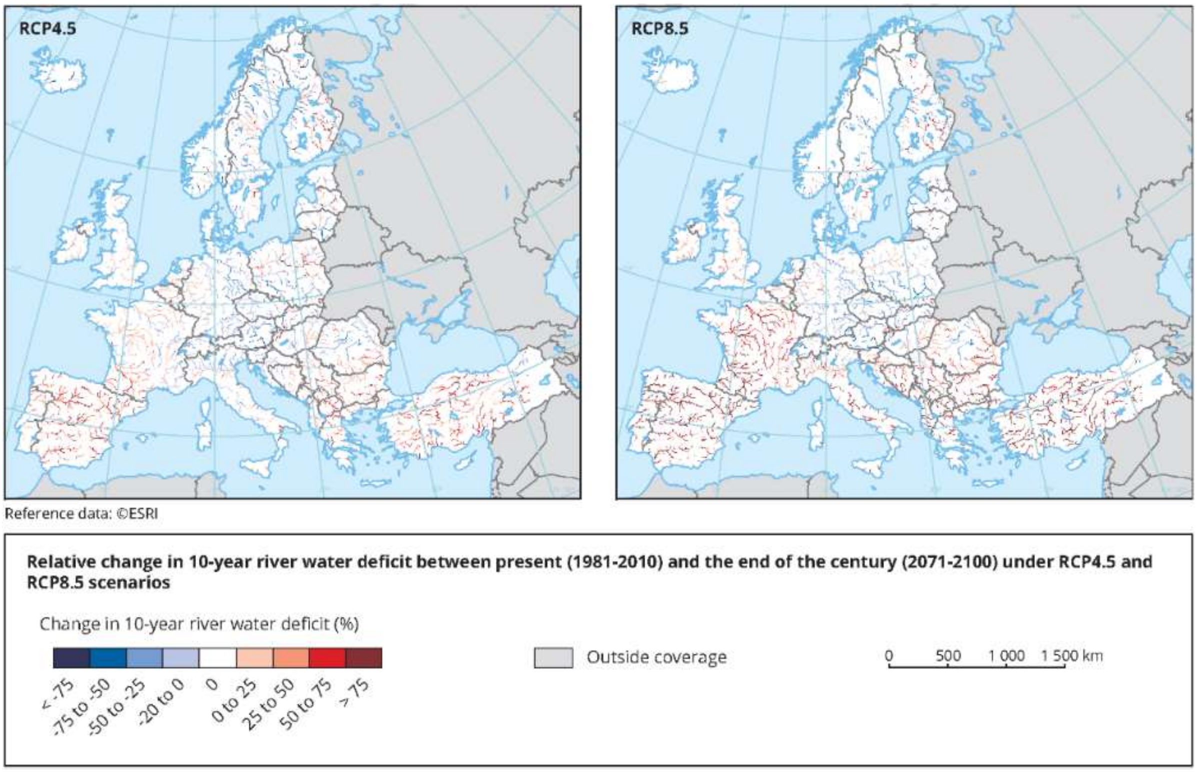

Figure 9.13 Projected change in 10-year river water deficit between the reference period (1981-2010) and the end of the 21st century, 2071-2100) in Europe, under RCP4.5 and RCP8.5 emission scenarios (EEA, 2021g)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.8 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Hydrological droughts	
Definition	Hydrological and ground water drought is defined as surface and sub-surface water deficit. It combines runoff deficit and evaporative demand that led to dry soil.
European data source of the index	European Climate Data Explorer: Meteorological and hydrological droughts (no further updates) — English (europa.eu) European Environment Agency: Wet and dry — drought — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Flood level and stability, Channel modification, Scour, Settlement, Piles (Active), Backfill (Passive), Yielding point, Flexural Mechanism, Shear Mechanism, Tilting, Drift ratio δ/h, Curvature φ, Rotation ϴ, Displacement δ, Travel Time, Intervention Costs, Accidents

Fire weather

Many factors can have an impact on fire risk, including not only climatic conditions but also vegetation, forest management practices and other socio-economic factors. To monitor trends in forest fires, the number of fires and the burnt area are usually reported.

Forest fires have been observed to largely affect southern Europe, although regions not typically prone to fires in central and northern Europe are being increasingly affected in recent years, coinciding with record droughts and heatwaves. In the Mediterranean region, the burnt area has increased from 1980 to 2000, but a decrease has been observed thereafter.

Future trends, in a warmer climate, show more severe fire weather, resulting in an expansion of the fire-prone area and longer fire seasons across Europe, being particularly strong in southern Europe (Portugal, Spain and Turkey) and under higher-emissions scenarios. Nevertheless, increases are also being projected for central Europe. Regarding northern Europe, despite large forest fires have recently occurred in this region, they are not projected to occur frequently.

Next figure shows observed trends and projected changes in forest fire danger under two climate change scenarios.

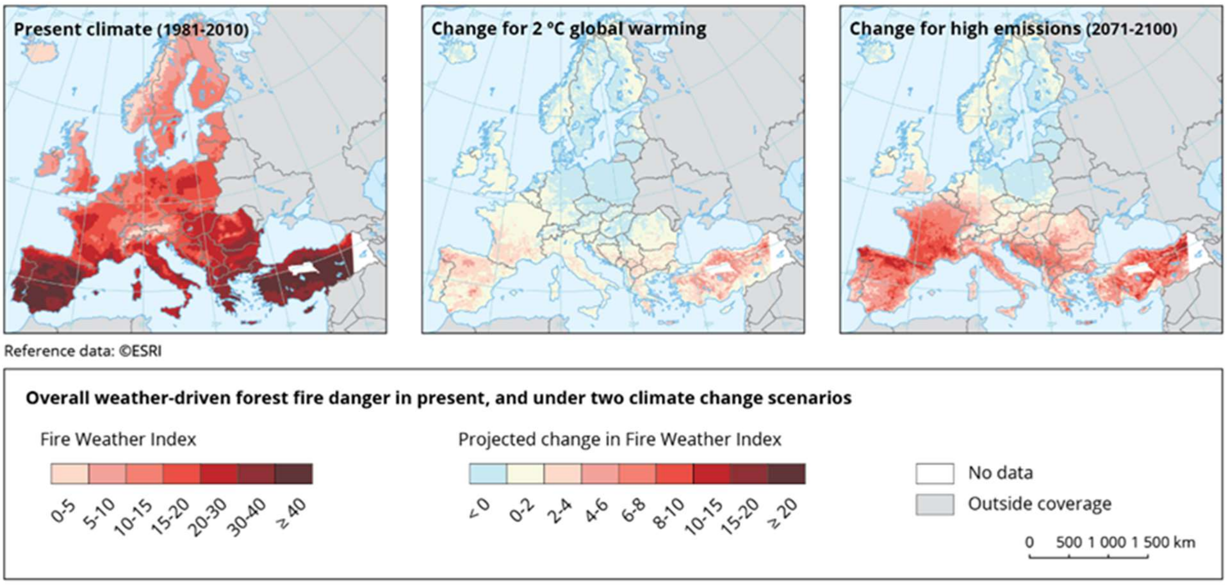

Figure 9.14 Observed trends from 1981 to 2010 and projected changes in forest fire danger under 2°C global warming scenario and far future high emissions scenario (EEA, 2021h)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.9 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Fire weather	
Definition	Total number of days per year with a critical level of fire danger (exceeding a threshold), where fire danger is normally based on the Canadian Fire Weather Index (FWI).
European data source of the index	European Climate Data Explorer: Forest fires in Europe — English (europa.eu); Fire Weather Index - Monthly Mean, 1979-2020 — English (europa.eu); Fire Weather Index - Days With High Fire Danger, 2011-2099 — English (europa.eu) European Environment Agency: Wet and dry — fire weather — European Environment Agency (europa.eu) Copernicus: Fire danger indicators for Europe from 1970 to 2098 derived from climate projections (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	ARFF Cost per Firefighter, ARFF Employees Who Are Not Active Firefighters, Firefighters – Number of, Fires – Number of, Hours per Firefighter per Week, Number of fire incidents, Travel Time, Intervention Costs, Accidents

Wind

Mean wind speed

Over the past four decades, mean surface wind speed has decreased in Europe, with a change to an increasing trend in the last decade but without fully consistency across studies. Northern Europe and the coastline usually register higher annual mean wind speed in comparison to southern regions and inland.

Despite past data or model projections did not provide firm evidence of major changes in mean wind speed, more recent CMIP6 projections suggest moderately decreasing wind speeds in southern and northern Europe. Subregional patterns show increases in wind speeds in the Aegean Sea and in the northern Adriatic Sea.

Figure 9.15 shows observed trends and projected changes in mean wind speed.

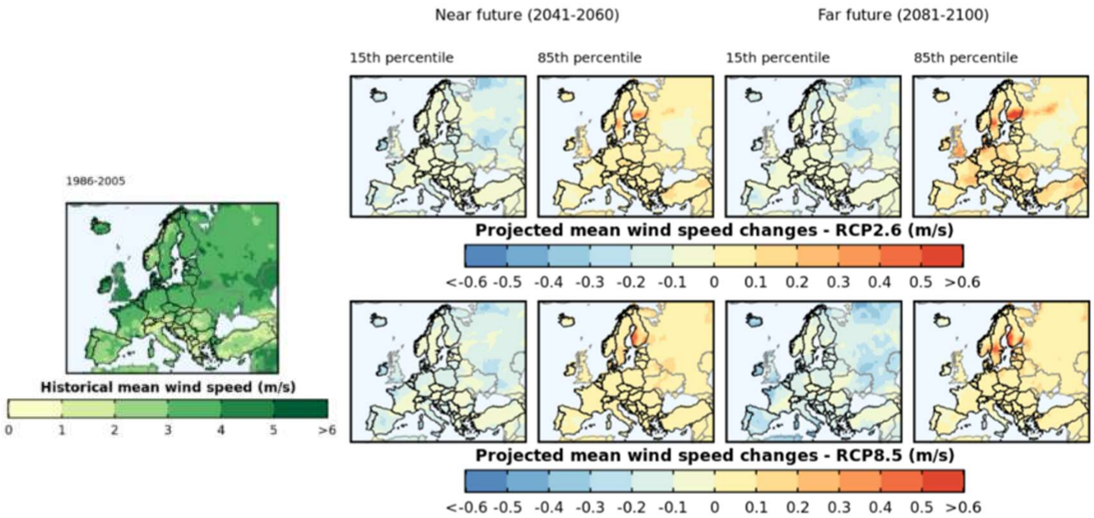

Figure 9.15 Observed trends from 1986 to 2005 and projected changes in mean wind speed for RCP2.6 and RCP8.5 in near and far future (EEA, 2021i)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.10 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Mean wind speed	
Definition	Average values of wind speed at 10-m height over relatively long timescales (e.g., seasonally or annually).
European data source of the index	European Climate Data Explorer: European Environment Agency: Wind — mean wind speed — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Modelled Wind Speed, Observed Wind Speed Records, Past Experience with Wind. Roadway Signal Density, Past Experience with Wind. Wind Design Speeds, Past Experience with Wind. Proximity of Trees to Power Lines, Past Experience with Wind. Efficacy of Tree Trimming Maintenance, Past Experience with Wind. Building Density, Past Experience with Wind. Presence of Overhead Utility Lines, Past Experience with Wind. Sign Support Strength, Past Experience with Wind. Height and Size of Road

	Signs, Past Experience with Wind. Length of Support Arms, Past Experience with Wind. Number of Signals/ Signs or Major Crossings, Past Experience with Wind. Presence of Aerial Signal Lines, Past Experience with Wind. Height and Size of Road Signs, Travel Time, Intervention Costs, Accidents

Severe wind storm

Severe storms including thunderstorms, wind gusts, derechos, and tornados.

Even though there are large uncertainties in past trends of extreme winds in Europe, a general decrease has been observed in the past decades, with the exception of Artic ocean areas. Over the past century, considerable decadal variability has been observed across Europe in storm location, frequency and intensity such that no significant long-term trends are apparent. Nevertheless, it is likely that Northern Hemisphere storm tracks and intensity have shifted northwards since at least 1970.

Regarding future projections, more uncertainty is associated to extreme wind than for other climate hazards due to the limited data availability and inherent weaknesses in current climate models. Some studies project changes in winter storm tracks, showing an extension eastwards of the North Atlantic storm track towards central Europe and the British Isles. With regard to frequency and intensity of strong winds, storms and extra-tropical storms, IPCC AR6 finds medium confidence in projections that indicate increases in northern and central Europe. According to a recent study, focusing on central Europe, under SRES A1B scenario, frequency could be increased an averaged 21% (in a range between -11% and +44%) and intensity about 30% (in a range between -28% and +96%) by the end of the 21st century. For southern Europe, an increase is expected in storm intensity, but frequency is projected to decrease.

Figure below provides projected changes in extreme wind speed based on GCM and RCM ensembles.

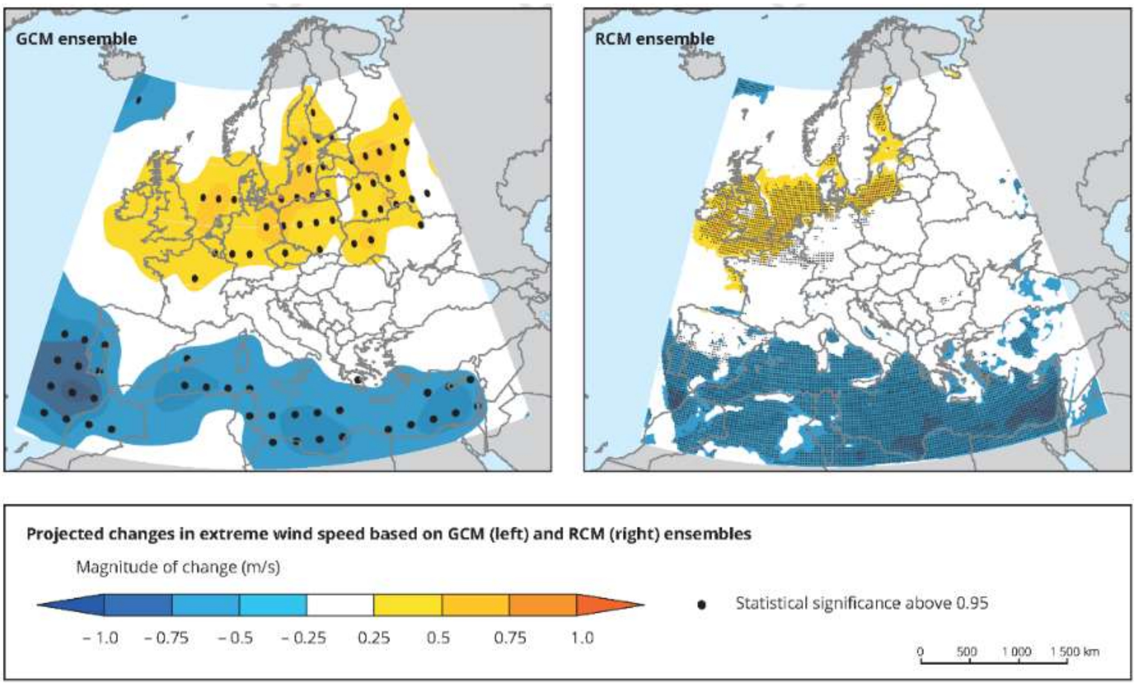

Figure 9.16 Projected changes in extreme wind speed for A1B, 2071–2100) relative to 1961–2000 (EEA, 2021j)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.11 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Severe wind speed	
Definition	Extreme wind speed days index counts the number of days with daily maximum wind speeds above the 98th percentile, computed over the reference period.
European data source of the index	European Climate Data Explorer: Wind storms (no further updates) — English (europa.eu) European Environment Agency: Wind — severe windstorms — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Modelled Wind Speed, Observed Wind Speed Records, Past Experience with Wind. Roadway Signal Density, Past Experience with Wind. Wind Design Speeds, Past Experience with Wind. Proximity of Trees to Power Lines, Past Experience with Wind. Efficacy of Tree Trimming Maintenance, Past Experience with Wind. Building Density, Past Experience with Wind. Presence of Overhead Utility Lines, Past Experience with Wind. Sign Support Strength, Past Experience with Wind. Height and Size of Road Signs, Past Experience with Wind. Length of Support Arms, Past Experience with Wind. Number of Signals/ Signs or Major Crossings, Past Experience with Wind. Presence of Aerial Signal Lines, Past Experience with Wind. Height and Size of Road Signs, Travel Time, Intervention Costs, Accidents, Accidents

Tropical cyclone

Tropical cyclones are complex phenomena, that appear under specific atmospheric and oceanic conditions. These include high sea surface temperatures and low vertical wind shear – a measure of how much winds vary in direction or strength with height. Warming climate suggest that tropical cyclones could become less frequent, but the lack of long-term cyclone data makes this trend difficult to quantify. At the same time, increasing sea surface temperatures give tropical cyclones more energy, increasing their intensity and making them more destructive.

Before the widespread use of satellites in the 1970s, there was a limited availability of high-quality observational data and irregular observed record of tropical cyclones, making more difficult finding long-term trends in cyclone frequency. This lack of longer records of reliable observations makes tropical cyclone modelling challenging and led to different interpretations. Some empirical studies that analysed the intensity of tropical cyclones under higher sea-surface temperatures indicated that an increase was taking place while others claimed the opposite.

With regard to frequency, a recent study (Chand, 2022) shows a 13% decrease in tropical cyclones around the world between 1850-1900 and 1900-2000 (finding a drop from more than 100 tropical cyclones a year in pre-industrial times to around 80 in 2012). However, the researchers find a slight increase in the North Atlantic, driven by a rising trend over recent decades. In particular, in Europe, decreasing trends were found for the period 1979-2008 in the Mediterranean basin in spring while increases have been found in the Mediterranean basin in summer and in Arctic ocean areas.

In general, due to climate change, the risk of intense tropical cyclones could be double by 2050 (Muis, 2022), according to a new study published in Scientific Advances. Maximum wind speeds associated with these cyclones are also projected to increase up to 24%. In particular, in Europe, a slightly increase in frequency and amplitude is projected in Northern, Central and Western regions by 2050 and beyond and for global warming levels of 2°C or more. By the end of the century, RCP8.5 and SRES A1B scenarios show a slightly increasing frequency and amplitude of strong winds and extra-tropical storms in Northern, Western and central Europe and European coasts. On the contrary, in Mediterranean regions, frequency of storms is projected to decrease while intensity is projected to increase by 2050 and beyond for SRES A1B, A2 and RCP8.5 scenarios.

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.12 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Tropical cyclone	
Definition	Strong, rotating storm originating over tropical oceans accompanied by high winds, rainfall, and storm surge.
European data source of the index	European Climate Data Explorer: European Environment Agency:
Variants of the index applicable to the road sector (if existing)	Modelled Wind Speed, Observed Wind Speed Records, Past Experience with Wind. Roadway Signal Density, Past Experience with Wind. Wind Design Speeds, Past Experience with Wind. Proximity of Trees to Power Lines, Past Experience with Wind. Efficacy of Tree Trimming Maintenance, Past Experience with Wind. Building Density, Past Experience with Wind. Presence of Overhead Utility Lines, Past Experience with Wind. Sign Support Strength, Past Experience with Wind. Height and Size of Road Signs, Past Experience with Wind. Length of Support Arms, Past Experience with Wind. Number of Signals/ Signs or Major Crossings, Past Experience with Wind. Presence of Aerial Signal Lines, Past Experience with Wind. Height and Size of Road Signs, Travel Time, Intervention Costs, Accidents

Sand and dust storm

Sand and dust storms erode topsoils and induce problems for transportation, mechanical equipment and built infrastructure corresponding to the magnitude and duration of high winds and particulate matter concentrations. Dust events may be represented as the number of dust hours per dust storm year and by particulate matter (PM) concentrations.

No specific information is available for this CID, but it is connected to trends in extreme wind events analysed in previous subchapters. In this sense, it can be highlighted that slightly increases in frequency and amplitude are projected for Northern, Central and Western Europe by the 2050 and beyond and for global warming levels of 2°C or more. In the Mediterranean region, a decrease is projected in frequency while intensity is projected to increase.

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.13 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Sand and dust storm	
Definition	They can be defined as storms causing the transport of soil and fine dust particles.
European data source of the index	European Climate Data Explorer: European Environment Agency:

Variants of the index applicable to the road sector (if existing)	Cost per employee, Employees Who Are Not Active, Employees – Number of, dust storm – Number of, Hours per employee per Week, Number of sand or dust storm incidents, Travel Time, Intervention Costs, Accidents

Snow and ice

Decreasing glaciers, ice sheet, permafrost

Projections show (high confidence) that glacier ice volume could be reduced in the European Alps and Scandinavia. According to GlacierMIP projections, glaciers in the Central Europe region are projected to lose 63 ± 31% (RCP2.6), 80 ± 22% (RCP4.5) and 93 ± 13% (RCP8.5) of their 2015 mass by 2100. In Scandinavia, the projected lost is 55 ± 33% (RCP2.6), 66 ± 34% (RCP4.5) and 82 ± 24% (RCP8.5). Other simulations bolster this shrink in glaciers.

With regard to permafrost, in Europe, it is found in high mountains and in Scandinavia, as well as in Arctic Islands. Trends in recent decade show that permafrost has been lost and its temperature has increased in the order of 0.2 ± 0.1°C between 2007 and 2016 as a consequence of accelerated warming at high altitudes and latitudes. In the future, over the 21st century, increasing thaw and degradation of permafrost is projected, being virtually certain its decrease in extension and volume.

Permafrost thawing is projected to affect the frequency and magnitude of high-mountain mass wasting processes. By 2100, even the lowest emissions scenarios show (medium confidence) the disappearance of most of the Northern Europe periglacial processes. Moreover, debris-flow season may last longer in a warming climate (medium confidence). Quantitative data for the European Alps is highly site dependent.

Infrastructure in circumpolar areas, key to developing sustainable economic models, could be seriously damaged by the middle of this century as a result of thawing permafrost, according to a study published in Nature (Hjort, 2018). Permafrost researchers are analysing the factors driving the rapid change of Arctic coastlines and the implications for humans and the environment.

Specifically, permafrost thaw caused by anthropogenic warming could put 30-50% of "critical circumpolar infrastructure" in the Arctic at risk. Arctic coasts are characterised by sea ice, permafrost and land ice. This makes them particularly vulnerable to the effects of climate change, which is already accelerating rapid coastal erosion. Permafrost in Arctic regions stores nearly 1,700 gigatonnes of frozen and thawing carbon, and global warming, they say, could release an unknown amount of that carbon into the atmosphere. The University of Oulu researchers estimate that by the middle of this century, around 69% of residential, transport and industrial infrastructure in permafrost regions will be located in areas with a "high potential for near-surface thawing". As a result, the cost of degradation of such infrastructure could reach "billions of dollars" during the second half of the century.

In Russia, for example, they estimate that the costs of maintaining the current road network affected by permafrost deterioration between 2020 and 2050 could be as high as $7 billion (about 6.175 billion euros).

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.14 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Decreasing glaciers, ice sheet, permafrost	
Definition	
European data source of the index	European Climate Data Explorer: European Environment Agency: [Snow and ice — snow, glaciers and ice sheets — European Environment Agency (europa.eu)]

Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents

Heavy snowfall and ice storm

Northern Europe and the Alps concentrate the regions with larger amounts of snowfall and longer snow season, together with the Carpathians and other mountain regions in southern Europe, these to a lesser extent. Observed trends show a general reduction in annual snowfall and snow cover extent across Europe and especially at lower elevations. Shorter snow seasons has also been observed in northern, western and eastern Europe as a result of earlier snowmelt in spring. With regard to heavy snowfalls, they have decreased in frequency in the past decades and is expected to continue the dame trend in the future climate (low confidence).

Future projections show the same trend in central and southern Europe, where substantial decreases in snowfall are expected and could almost disappear in many low-elevation regions. In northern Europe, the projected trend on snowfall will depend on the balance between the overall amount of precipitation and the proportion of precipitation falling as snow. Projections depend on the altitude and emissions scenario, but they seem to show an increase in the amount of precipitation and a decrease in the proportion of precipitation falling as snow, in particular at lower altitudes and under the highest emissions scenarios. The length of snow season could also be reduced, in some regions, in more than 100 days by the end of the century.

Climate models are not able to simulate small-scale phenomena such as hail storms, making projections not directly available. On the other hand, observational networks lack homogeneity over long climate periods, making difficult the detection of clear trends. Moreover, limited number of studies are available. Nevertheless, there is some evidence (low confidence, low evidence) on the increase in frequency of hail storm environments (favourable atmospheric configurations) and, in the future, these environments could become more frequent by 2050 and 2100 (medium confidence in 2050-RCP4.5 and more likely than not in 2100-RCP8.5). However, the confidence about the impact of climate change on these ice and snow episodic hazards is low (limited evidence).

Freezing rain is projected to increase in western, central and southern Europe (low confidence).

Figure below shows observed trends and projected changes in annual snowfall at low to medium elevation (500-1400 m).

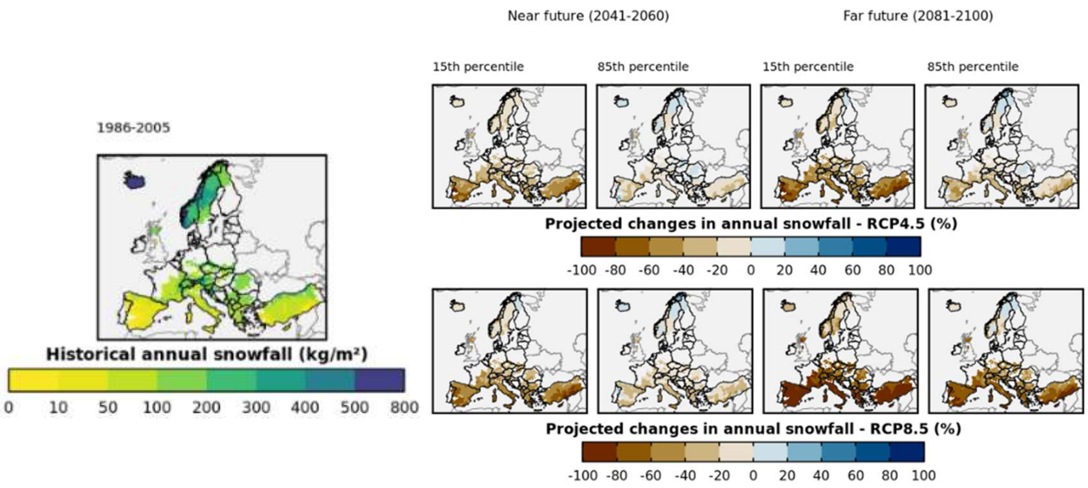

Figure 9.17 Observed trends from 1986 to 2005 and projected changes in annual snowfall at low to medium elevation (500-1400 m) for RCP4.6 and RCP8.5 in near and far future (EEA, 2022b)

To better understand the possible future impacts of this hazard, it is necessary to analyse the climate indices related to this hazard. The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.15 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Snow and ice	
Definition	High snowfall and ice storm events including freezing rain and rain-on-snow conditions.
European data source of the index	European Climate Data Explorer: Snow cover (no further updates) — English (europa.eu); Total Winter Snow, 2011-2099 — English (europa.eu); Days with a High Amount of Natural Snow, 2011-2099 — English (europa.eu) European Environment Agency: Snow and ice — snow, glaciers and ice sheets — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Number of days of snow and/or ice free surface, Customer satisfaction with snow and ice removal, Average time from snow event to bare pavement operations and services, Runway Light Damage per Snow Event, Cost of Damages to road During Adverse Weather Events Other than Snow/Ice, Ground Equipment Damage During Snow/Ice Events, Runway incursions by ground vehicles during snow events, Cost per employee, Employees Who Are Not Active, Employees – Number of, snow events – Number of, Hours per employee per Week, Number of snow and ice incidents, Travel Time, Intervention Costs, Accidents

Hail

Here storms producing solid hailstones are considered. Hailstorms are most common in mid-latitudes with high surface temperature and humidity. Mountainous areas and pre-Alpine regions register the highest number of these events in Europe. Since 1951, hail trends have been showing an increase in southern France and Austria and a decrease in some regions in eastern Europe.

The IPCC Sixth Assessment Report states "low confidence" regarding changes in hail in Europe. Despite the high uncertainty associated to future projections of hail events, some agreement has been found in model-based studies for central Europe that reflect increases in hailstorm frequency in this region. In south-west Germany, an increase between 7% and 15% was projected for the period 2031–2045 (compared with 1971–2000). An increase was also projected in hail probability over most areas of Germany for the period 2021–2050 (compared with 1971–2000).

Observed annual median and trend of the Mean Potential Hail Index (PHI) are shown in Figure 9.18.

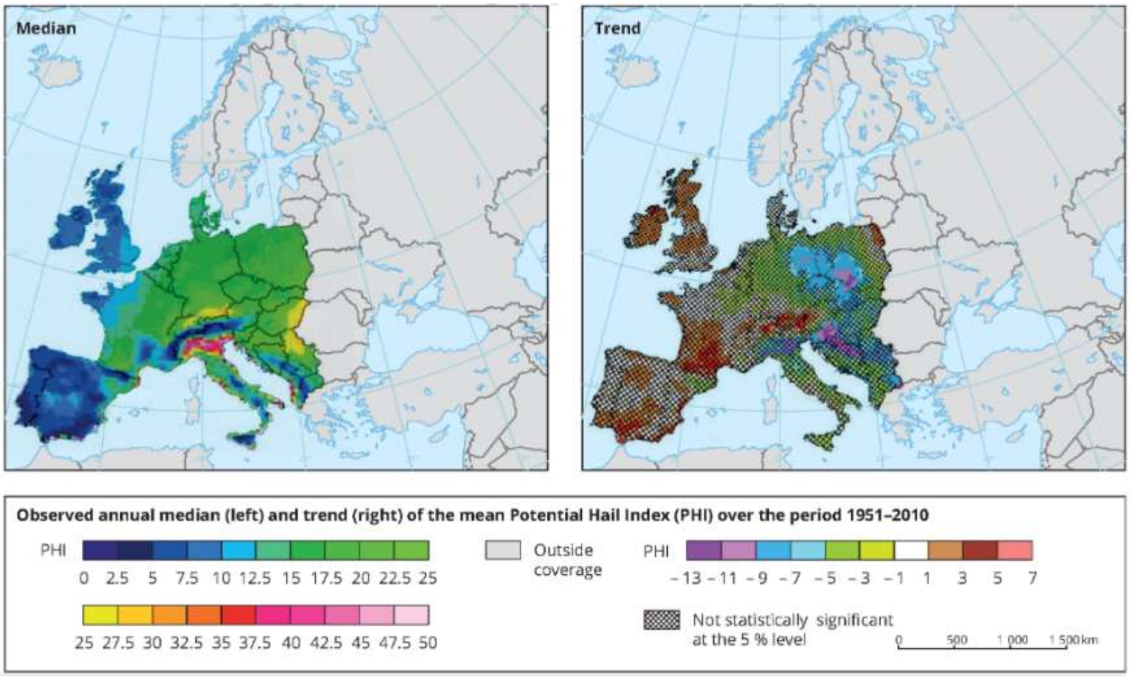

Figure 9.18 Observed annual median and trend of the Mean Potential Hail Index (PHI) over the period 1951-2010 (EEA, 2021k)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.16 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Hail	
Definition	Potential hail index (PHI) quantifies the atmospheric potential for hailstorms.
European data source of the index	European Climate Data Explorer: Hail (no further updates) — English (europa.eu) European Environment Agency: Hail — European Environment Agency (europa.eu); Hail — European Environment Agency (europa.eu); Snow and ice — snow, glaciers and ice sheets — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents

Snow avalanche

Snow avalanches claim an average of 100 lives in Europe every year. The European Avalanche Warning Services (EAWS) defines avalanche danger as a function of snowpack stability, its spatial distribution and avalanche size. It is referred to a specific region of at least 100 km² (not a single slope) and considers a scale of five levels (European Avalanche Danger Scale) based on the likelihood and size of avalanches, from 1 – Low (generally stable conditions) to 5 – Very high (extraordinary avalanche conditions). Five typical avalanche problems were also defined that support avalanche forecasting: new snow, wind-drifted snow, persistent weak layers, wet snow and gliding snow.

Avalanches are local and extreme events, with highly nonlinear responses to snow and weather conditions making they difficult to predict using climate models. Avalanche dynamics depend on complex relationships between temperatures and snow amounts. Major avalanche cycles in mountains on all continents are related to severe winter storms. During storms, precipitation amounts, air temperatures and prior snow stratigraphy affect the frequency and types of avalanches. With ongoing climate change, the frequency and types of snow avalanches may change, but is still unclear whether warmer temperatures will lead to fewer avalanches because of less snow or whether avalanche activity will sometimes be locally more severe because of more intense winter precipitation. Several decades of reliable observations are required to quantify trends in avalanche activity.

Climate change effect on mountain snow cover seems clear at lower elevations but less certain above treeline (where most avalanche starting zones are located, 1800–2200 m in the European Alps). All these mentioned uncertainties together with the lack of complete documentation of past events (especially those that happened before regular satellite observations became available), make it difficult to quantify possible trends. However, some projections are available:

- Medium confidence projections in the recent IPPC special report show that the number of avalanches and runout distances will decrease at lower elevations.
- In high mountain areas, ice falls and snow avalanches are expected to increase in areas where the frequency and/or the intensity of the rainstorms will increase (e.g., the Alps, the Carpathians in Eastern Europe).
- Due to the general increase of the freezing line in winter, higher frequency is projected for rain at higher elevations than at present. With this shift from solid to liquid precipitation, they are expected seasonal snow lines at higher elevations and shorter snow seasons than today
- The proportion of wet-snow avalanches is expected to increase at higher elevations in winter (due to more favourable conditions), but could be decrease in spring and at lower elevations. The first projection predicted a 20–30% reduction in the French Alps from the middle to the end of the 21st century compared to the reference period, 1960–1990 (Strapazzon, 2021).

EAWS publishes “avalanche bulletins” to inform the public about the current snow and avalanche situation in each territory. They are published on a regular basis during the peak winter season and primarily contains a description of the avalanche danger, information on the weather parameters that affect avalanches and information on the structure of the snowpack. Due to the limited data resources, the information provided is often too general for local assessment purposes.

Figure 9.19 provides information on the number of avalanche fatalities registered since 1937 in Europe.

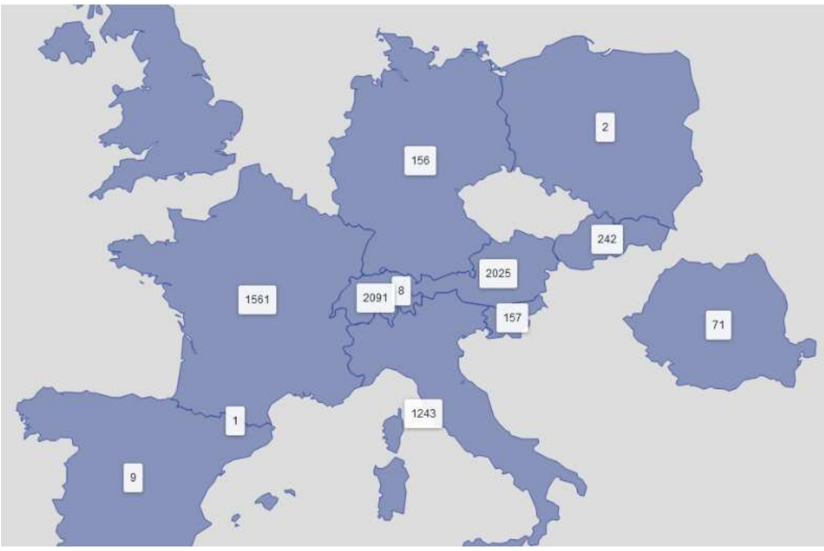

Figure 9.19 Fatalities since 1937 in Europe (EAWS, 2022)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.17 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Snow avalanche	
Definition	EAWS defines as rapidly moving snow masses in volumes exceeding 100 m^3 and minimum length of 50 meters.
European data source of the index	European Climate Data Explorer: Snow cover (no further updates) — English (europa.eu); Total Winter Snow, 2011-2099 — English (europa.eu); Days with a High Amount of Natural Snow, 2011-2099 — English (europa.eu) European Environment Agency: Snow and ice — snow, glaciers and ice sheets — European Environment Agency (europa.eu) EAWS: Home - EAWS (avalanches.org)
Variants of the index applicable to the road sector (if existing)	Travel Time, Intervention Costs, Accidents

Coastal and oceanic

Sea level rise

Mean sea levels have been globally rising for more than a century, suffering an acceleration in recent decades due to warming oceans and melting glaciers and ice sheets. However, regional differences are observed, with decreasing sea levels in some regions such as the northern Baltic Sea coast and, to a lesser extent, the northern Atlantic coast, where land levels continue to rise as a result of post-glacial rebound since the last ice age.

In the future, relative sea level of European seas is projected to continue rising under all emissions scenarios. As an average, under the high-emissions scenario (RCP8.5), most of the European coastline is expected to suffer more than 0.6 meters increase by 2100 with respect to the current level. The main exceptions are the same mentioned above, the northern Baltic Sea and the northern Atlantic coasts, where slower rise or even a decrease could be expected.

Observed trends and projected changes in relative sea level across Europe are shown in Figure 9.20.

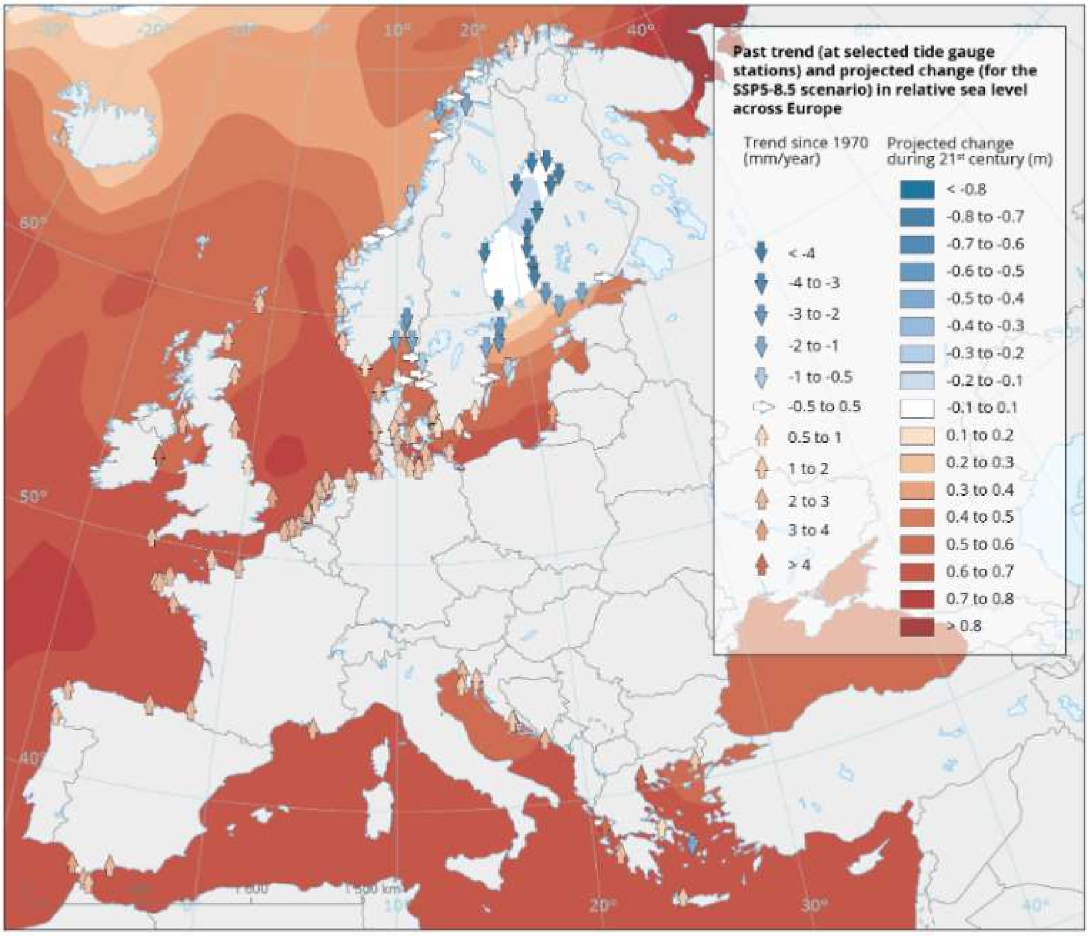

Figure 9.20 Observed trends since 1970 and projected changes in relative sea level for 2081-2100 and high-emissions scenario (RCP8.5) (EEA, 2021l)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.18 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Relative see level rise

Definition	Represents the changes in the height of sea water relative to land with respect to the average conditions over a reference period.
European data source of the index	European Climate Data Explorer: Extreme sea levels and coastal flooding — English (europa.eu); Mean Relative Sea Level, 2070-2100 — English (europa.eu) European Environment Agency: Global and European sea level rise (europa.eu); Coastal — relative sea level — European Environment Agency (europa.eu) Coastal — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Past Experience with Tides/SLR. Adjacent to Areas Exposed to Sea Level Rise, Past Experience with Tides/SLR. Access Roads Vulnerable to Sea Level Rise, Soil Type. Past Experience with Tides/SLR. Height of Drainage Outlets Relative to Sea Level, Travel Time, Intervention Costs, Accidents

Ocean and lake acidity

Ocean acidity[6] was relatively stable for millions of years but, the increase in atmospheric CO2 concentrations during the industrial era, made acidity rise about 30% (from pH 8.2 to 8.1). This pH reduction is similar across the global ocean and throughout continental European seas, except for variations near the coast and larger increases in the northernmost European seas (i.e., the Norwegian Sea and the Greenland Sea).

In the future, models consistently project further ocean acidification worldwide, with pH decreases of between 8.05 and 7.75 by the end of the 21st century, depending on considered emission scenario. The largest projected decline represents more than a doubling in acidity by the end of this century with respect to present conditions under a high-emissions scenario (RCP8.5).

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.19 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

pH level	
Definition	Defined by the concentration of hydrogen ions dissolved in water.
European data source of the index	European Climate Data Explorer: European Environment Agency: Open ocean — ocean chemistry: dissolved oxygen and ocean acidity — European Environment Agency (europa.eu); Oxygen concentrations in coastal and marine waters surrounding Europe (europa.eu)
Variants of the index applicable to the road sector (if existing)	Intervention Costs

[6] Ph has a direct correlation to aggressive ocean environment. As the ocean continues to absorb more CO_2, the pH decreases, and the ocean becomes more acidic with corrosion implications.

Coastal floods

At present, 1-in-100-year coastal floods (extreme total water level, ETWL) is between 0.5-1.5m in Mediterranean (MED) basin; 2.5-5.0 m in the western Atlantic European coasts, around the UK and along the North Sea coast; and 1.5-2.5m along the Baltic Sea coast.

Rising sea levels together with tidal swings and storm surges are driving growing coastal floods along most European coasts, with the only exception of the northern Baltic Sea coast, as a consequence of continued land uplift following the last ice age. By 2100, historical 1-in-100-year coastal floods are projected to happen at least once a year along the Mediterranean and Black Sea coasts, reaching several times a year when high-emissions scenario (RCP8.5) is considered. Along remaining European coasts, at least once a decade is projected, even under a low emissions scenario, and could reach once a year under RCP8.5.

Figure 9.21 shows projected changes in the frequency of historical 1-in-100-year coastal flooding events by 2100.

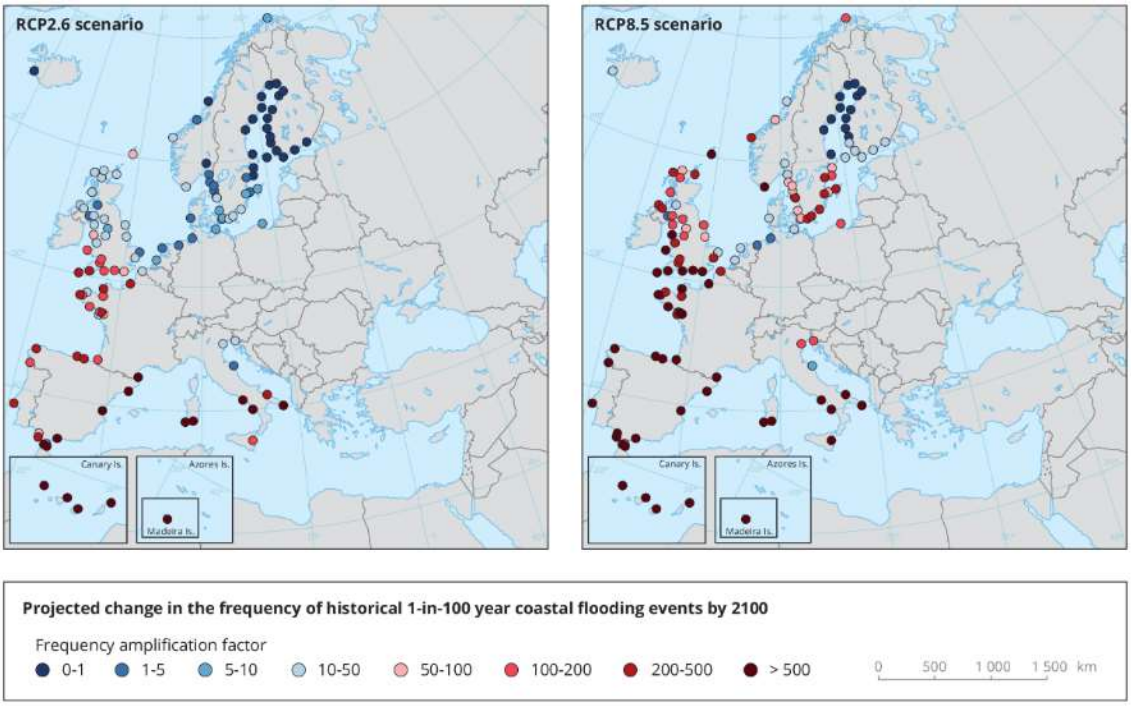

Figure 9.21 Projected changes in the frequency of historical 1-in-100-year coastal floods between 2010 and 2100 under RCP2.6 and RCP8.5 (EEA, 2021m)

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.20 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Extreme sea level	
Definition	The extreme sea level index represents the maximum sea water level along the coast corresponding to a 1-in-100-year coastal flood event.
European data source of the index	European Climate Data Explorer: Extreme sea levels and coastal flooding — English (europa.eu); Annual Highest High Water, 2070-2100 — English (europa.eu)

	European Environment Agency: Coastal — coastal floods — European Environment Agency (europa.eu); Extreme sea levels and coastal flooding (europa.eu) Copernicus: Water level change indicators for the European coast from 1977 to 2100 derived from climate projections (copernicus.eu)
Variants of the index applicable to the road sector (if existing)	Past Experience with Tides/SLR. Adjacent to Areas Exposed to Sea Level Rise, Past Experience with Tides/SLR. Access Roads Vulnerable to Sea Level Rise, Soil Type. Past Experience with Tides/SLR. Height of Drainage Outlets Relative to Sea Level, Travel Time, Intervention Costs, Accidents

Coastal erosion

Coastal erosion is generally accompanied by shoreline retreat, that can occur as a gradual process (e.g., due to sea level rise, changes in river flows and fluvial sediment supply) or as an episodic event due to storm surge and/or extreme waves, especially when combined with high tide.

Estimated changes in shoreline over 1984 – 2015 show retreat rates along the sandy coasts of the Mediterranean and Central European regions (around 0.5 m/year) and in Caspian Sea region in Eastern Europe (around 4 m/year). More or less stable shorelines are shown in Northern Europe.

In the future, projections show this retreat trend is continuing along sandy coasts throughout the continent (except those bordering the northern Baltic Sea) through the 21st century (high confidence). By 2050, median shoreline change projections (CMIP5) along sandy coasts in Central and Mediterranean Europe show a retreat by between 25 m and 60 m relative to 2010 under both RCP4.5 and RCP8.5. In Northern Europe the change seems insignificant under RCP4.5 but not under RCP8.5, where around 40 m retreat is projected. By 2100, median shoreline retreats are projected to be around 50 m (RCP4.5) and 80 m (RCP 8.5) in Northern Europe and Mediterranean and far higher at 100 m (RCP4.5) and 160 m (RCP8.5) in Central Europe. In total, about 12,000 km (RCP4.5) and 18,000 km (RCP8.5) of sandy coasts are projected to retreat by more than a median of 100 m by 2100.

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.21 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Shoreline retreat	
Definition	Long term or episodic change in shoreline position caused by relative sea level rise, nearshore currents, waves, and storm surges.
European data source of the index	European Climate Data Explorer: Extreme sea levels and coastal flooding — English (europa.eu) European Environment Agency: Coastal — European Environment Agency (europa.eu)
Variants of the index applicable to the road sector (if existing)	Proximity to Coastline, Coastal Vulnerability, Past Experience with Precipitation. Proximity to the Coast, Proximity to the Coast. Propensity for Ponding, Proximity to the Coast. Percentage of Impervious Surface, Intervention Costs

Others: radiation

Radiation at surface[7]

Radiation has undergone decadal variations in past observations which are mostly responding to the so-called dimming and brightening phenomenon driven by the increase and decrease of aerosols. For the last two decades or so, brightening continues in Europe.

Future regional shortwave radiation projections depend primarily on cloud trends, aerosol and water vapour trends, and stratospheric ozone when considering UV radiation. An increase is projected in surface radiation in Central Europe (low confidence) and Southern Europe (medium confidence) while decreases are expected over Northern Europe (medium confidence).

The table below presents a detailed information of this climate related hazard index. Besides, it includes the European data source of the index and variants of the index applicable to road sector.

Table 9.22 Detailed information about the index: available European data sources and variants of the index applicable to the road sector.

Radiation	
Definition	Balance of net shortwave, longwave and ultraviolet radiation at the earth's surface and their diurnal and seasonal patterns.
European data source of the index	European Climate Data Explorer: European Environment Agency:
Variants of the index applicable to the road sector (if existing)	Change in Total Number of Days per Year above/below a Threshold Temperature, Change in Longest Number of Consecutive Days per Year above/below a Threshold Temperature, Change in Annual Maximum or Minimum Temperature, Change in Annual Mean Temperature, Past Experience with Temperature. Truck Traffic, Past Experience with Temperature. Temperature Threshold in Pavement Binder, Past Experience with Temperature. Thermal Expansion Coefficient of Concrete, Past Experience with Temperature. Condition of Concrete Pavement Joints, Past Experience with Temperature. Presence of Bus Routes, Past Experience with Temperature. Use of Polymer Modified Binders, Intervention Costs, Accidents

[7] Pavement and concrete absorb and re-emit the sun's heat more than natural landscapes such as forests and water bodies. This CID is linked to heat island effect.

10 ANNEX 3. GLOSSARY

The ambition of this Annex is to be a living glossary for ICARUS project. It will evolve according to the Consortium contributions along the whole life of the project. Definitions are based on current insights but may change due to new insights in the remainder of the proposal. All definitions are under development and may be changed when new insight appear in the project.

Term/Acronym	Definition
AADT	Average Annual Daily Traffic . European Commission (2021a)
Absorb phase	The time extending from the start to the end of the disruptive event. The exact definitions of the start and the end of the event is situation dependent. . European Commission (2021a)
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects. (Commission Notice, 2021)
Adaptation options	The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural. (Commission Notice, 2021)
Adaptive capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. (Commission Notice, 2021)
Carbon dioxide (CO_2)	A naturally occurring gas, CO2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land use changes (LUC), and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a Global Warming Potential (GWP) of 1. (Commission Notice, 2021)
Climate	Climate can be defined as the average weather, normally over 30 years. It is the statistical description of the mean and variability of relevant variables such as temperature and precipitation. (Commission Notice, 2021)
Climate change	A change in the state of the climate that can be identified by changes in the mean and/or variability of its properties and persists for an extended period *(e.g., decades or longer). (Commission Notice, 2021)
Climate change adaptation	The adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. (Commission Notice, 2021)
Climate change mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs). (Commission Notice, 2021)
Climate extreme (extreme weather or climate event)	The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes.' (Commission Notice, 2021)

Term/Acronym	Definition
Climate neutrality	Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate. (Commission Notice, 2021)
Climate projection	A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols or radiative forcing scenarios, often based upon simulations of climate models. (Commission Notice, 2021)
Communities and local businesses	local communities and businesses are affected by travel disruption. they can exert pressure for improvements in resilience. (Reeves, 2019)
Contractors/Suppliers/Operating companies	Private companies are often contacted by the infrastructure owner to manage, maintain, construct and design infrastructure on their behalf. Their responsibilities depend on the type of contract, but they are likely to play a key role in responding to and recovering from incidents. (Reeves, 2019)
CO_2 equivalent (CO_2-eq) emission	The amount of carbon dioxide (CO2) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are several ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO2-equivalent emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for a 100-year time horizon. For a mix of GHGs it is obtained by summing the CO2-equivalent emissions of each gas. CO2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding climate change responses. There is generally no connection between CO2-equivalent emissions and resulting CO2-equivalent concentrations. (Commission Notice, 2021)
Cost-benefit analysis (CBA)	An analytical methodology for the quantification of the positive and negative consequences of a project in monetary terms over a set appraisal period. (Commission Notice, 2021)
Critical Infrastructure	An asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions. (Commission Notice, 2021)
Cultural heritage	Encompasses several main categories of heritage. Tangible cultural heritage includes movable cultural heritage (paintings, sculptures, coins, manuscripts), immovable cultural heritage (monuments, archaeological sites, and so on), underwater cultural heritage (shipwrecks, underwater ruins and cities). Intangible cultural heritage includes oral traditions, performing arts, and rituals. (Commission Notice, 2021)
Disaster	Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environ- mental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery. (Commission Notice, 2021)
Emergency services	In the case of an incident often police, and maybe ambulance and fire services would be involved in its management. Police are often the only organisation with the legal power to close roads (although the Head of Highways may have this power). (Reeves, 2019)

Term/Acronym	Definition
Exposure	The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected. (Commission Notice, 2021)
External funders	Whilst the majority of road infrastructure construction is funded by government or users of the infrastructure via tolls, in low- and middle-income countries there may be investment from external funding organisations such as international development banks or foreign governments. Provision of funding may have resilience requirements associated with them. (Reeves, 2019)
Extreme weather event	An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season). (Commission Notice, 2021)
Global Warming Potential (GWP)	An index, based on radiative properties of GHG, measuring the radiative forcing following a pulse emission of a unit mass of a given greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in causing radiative forcing. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame. (Commission Notice, 2021)
Government Departments/ Ministries	Most countries have a central government department/ministry responsible for transport. The level of influence they have depends on the organisational structure. For example, when there is a federal system, such in the US or Germany, the national government may set general guidelines and individual states may have different standards and regulations. (Reeves, 2019)
Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary GHGs in the earth's atmosphere. Moreover, there are several entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO2, N2O and CH4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). (Commission Notice, 2021)
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. (Commission Notice, 2021)

Term/Acronym	Definition
Impacts (consequences, outcomes)	The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial. (Commission Notice, 2021)
Intervention costs	All costs incurred by the infrastructure manager. . European Commission (2021a)
Local government/ Municipalities	Even when not the road owner, local government is a key stakeholder for any incident that occurs within its boundary. it is also often the planning authority, so able to influence new construction. (Reeves, 2019)
Manage	All activities of infrastructure managers in their effort to ensure that infrastructure provides the expected levels of service, including the planning of maintenance and adaptation interventions. . European Commission (2021a)
Measure	Assess the importance, effect or value of (something). . European Commission (2021a)
Measure of service	A quantifiable unit that gives an indication of the level of service being provided. For example, the amount of time required to travel from A to B is a measure of the service provided by a transport system. . European Commission (2021a)
Mitigation (of climate change)	A human intervention to reduce emissions or enhance the sinks of greenhouse gases. Note that this encompasses carbon dioxide removal (CDR) options. (Commission Notice, 2021)
National Road Administration (NRAs)	The organisations which manage the construction, maintenance and operation of a country's main roads. . European Commission (2021a)
Other Government Agencies	Depending on the type of hazard other government agencies may be involved. For example, for large scale flooding in England the Environment Agency would be a key stakeholder. Metrological organisations, national health service, government departments involved in civil protection could also be involved. For severe incidents government ministers would play a role. (Reeves, 2019)
Owners/ Operators of the infrastructure	These can be a government agency, part of a (national/ regional/ local) government department, a publicly owned company, privately-owned company or the government agency can contract out the operation (and usually the construction) of a section of their network to a private company e.g., a PPP paid for through tolling or virtual tolling. Roads are often divided into different hierarchical categories each often with different ownership. For example, local roads are often managed by local government/ municipalities. (Reeves, 2019)
RCP2.6	One pathway where radiative forcing peaks at approximately 3 W/m2 and then declines to be limited at 2,6 W/m2 in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100). (Commission Notice, 2021)
RCP4.5 and RCP6.0	Two intermediate stabilisation pathways in which radiative forcing is limited at approximately 4,5 W/m2 and 6,0 W/m2 in 2100 (the corresponding ECPs have constant concentrations after 2150). (Commission Notice, 2021)

Term/Acronym	Definition
RCP8.5	One high pathway which leads to > 8,5 W/m2 in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250). (Commission Notice, 2021)
Recovery phase	The time extending from the end of the disruptive event to the moment in time where the transport system is once again providing service as expected. The exact definitions of the end of the event and the moment in time where the transport system is once again providing service as expected is situation dependant. . European Commission (2021a)
Regulators/ Monitors	Depending on the type of infrastructure owner organisation there may be a regulator. For example, the Office of Road and Rail in the UK monitors English strategic trunk roads as these are managed by publicly owned companies rather than directly by the government. In Scotland PAG (Performance Audit Group), a consortium of consultants employed by Transport Scotland, monitor and report the performance of the road operating companies. Transport Focus is a public body which acts as a transport user watchdog for English strategic trunk roads and rail in GB. (Reeves, 2019)
Representative concentration pathways (RCPs)	Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes the fact that not only the long- term concentration levels, but also the trajectory taken over time to reach that outcome are of interest (Moss et al., 2010). RCPs were used to develop climate projections in CMIP5. (Commission Notice, 2021)
Resilience	Ability to continue to provide service if a disruptive event occurs. . European Commission (2021a)
Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence. (Commission Notice, 2021)
Risk assessment	The qualitative and/or quantitative scientific estimation of risks (6) (Commission Notice, 2021)
Risk management	Plans, actions, strategies or policies to reduce the likelihood and/or consequences of risks or to respond to consequences. (Commission Notice, 2021)
Sensitivity	Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise). (Commission Notice, 2021)
Service	Ability to perform an activity in a certain way . European Commission (2021a)

Term/Acronym	Definition
Slow onset events	Slow onset events include, among others, temperature increase, sea-level rise, desertification, glacial retreat and related impacts, ocean acidification, land and forest degradation, average precipitation, salinization, and loss of biodiversity. As regards the statistical distribution of a climate variable (and how it may shift in a changing climate), slow onset events will often reflect how the mean value is changing (whereas extreme events are related to the tail ends of the distribution). (Commission Notice, 2021)
Strategic Environmental Assessment (SEA)	The process of carrying out an environmental assessment as required by Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment. The main steps of the SEA process are preparation of the SEA Report, publicity and consultation, and decision-making. (Commission Notice, 2021)
Target	Level of service or level of resilience that stakeholders would like to have . European Commission (2021a)
Technical advisory bodies	Some countries have publicly owned organisations which offer technical advice on road transport for example BASt1 in Germany. These organisations may not have direct control over the industry, but their advice and guidelines influence government and industry decision-making. (Reeves, 2019)
Users of the infrastructure	Users of road infrastructure include the public, haulage companies, taxis and bus, coach and tram companies. (Reeves, 2019)
Vehicle manufacturers	The designers of road vehicles can influence resilience of the transport system as a whole. (Reeves, 2019)
Vulnerability	Vulnerability [IPCC AR4 ()] is the degree to which a system is susceptible to, and unable to cope with, is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity. Vulnerability [IPCC AR5 (9)]: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. (Commission Notice, 2021)