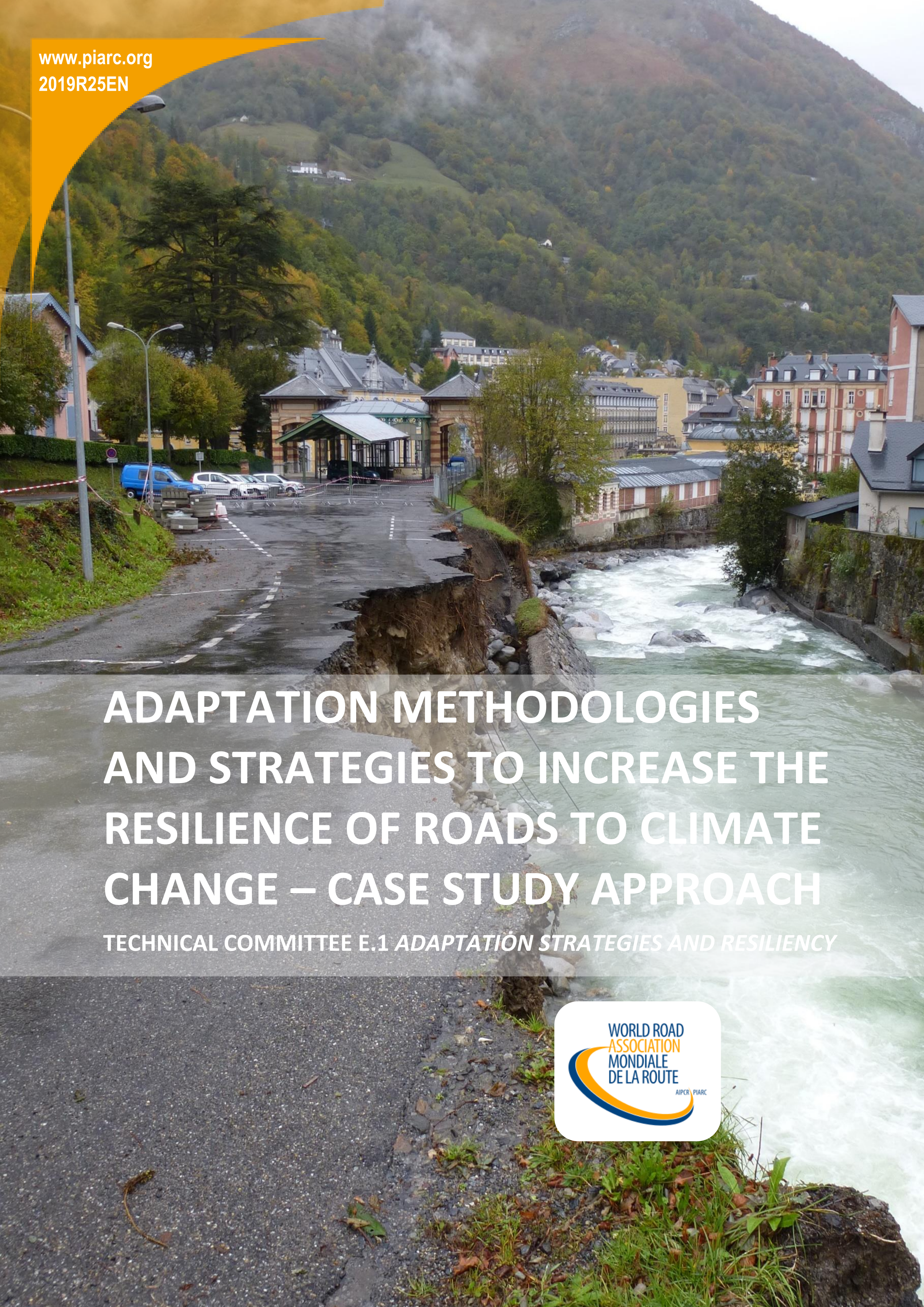

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2019R25EN

ADAPTATION METHODOLOGIES AND STRATEGIES TO INCREASE THE RESILIENCE OF ROADS TO CLIMATE CHANGE – CASE STUDY APPROACH

TECHNICAL COMMITTEE E.1 *ADAPTATION STRATEGIES AND RESILIENCY*

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
AIPCR PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2016– 2019and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

This report is available from the internet site of the World Road Association (PIARC): http://www.piarc.org

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TECHNICAL COMMITTEE E.1 *ADAPTATION STRATEGIES AND RESILIENCY*

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EXECUTIVE SUMMARY

2019R25EN

ADAPTATION METHODOLOGIES AND STRATEGIES TO INCREASE THE RESILIENCE OF ROADS TO CLIMATE CHANGE – CASE STUDY APPROACH

Climate Change is anticipated to have a significant impact on the design, construction, maintenance and operation of global road infrastructure. The IPCC Climate change projections[1] indicate that the earth will become warmer, some regions will become wetter and some will become drier, sea levels will rise and storm surge height will increase, snow cover and extent of sea ice will reduce, and the frequency and severity of extreme weather events will increase. This in turn will result in significant global and regional challenges related to climate change in both the short and long-term [1].

The *PIARC International Climate Change Adaptation Framework for Road Infrastructure* [4] guides road authorities through the process of increasing the resilience to climate change of their networks and assets. It takes users through four stages: Identifying scope, variables, risks and data (Stage 1); Assessing and prioritising risks (Stage 2); Developing and selecting adaptation responses and strategies (Stage 3); Integrating findings into decision-making processes (Stage 4).

Within PIARC Technical Committee E.1, two Working Groups were established.

Working Group 1 (WG1) had the task to undertake a state-of-the-art case study analysis of adaptation strategies to increase the resilience of road infrastructure at the policy, strategic, system level and project specific level. This includes consideration of:

- data requirements regarding climate change adaptation of road infrastructure
- assessment of the vulnerability and criticality of road infrastructure
- adaptation measures with regard to possible threats resulting from climate change; and
- cost-benefit analysis of climate change adaptation.

The WG1 Report provides the methodological detail supporting each stage of the refined PIARC International Climate Change Adaptation Framework for Road Infrastructure, by referring to state-of-the-art case study examples.

Working Group 2 (WG2) had the task to review the collected case studies and other relevant experience and propose refinements of the original edition of the International Climate Change Adaptation Framework for Road Infrastructure. The Framework has systematically been implemented in only two places, Mexico and Queensland, Australia. The experience from this implementation, together with a comparison with other existing frameworks, provided input to the contents of the steps of the Framework, and how they can be clarified.

In addition, WG2 investigated possibilities for adjusting the Framework to broaden its applicability. One reason for this was that the Framework appears to be demanding for countries that have not

[1] IPCC Intergovernmental Panel on Climate Change, www.ippcc.ch

already carried out some adaptation work. A number of short-cuts in the procedures are, therefore, proposed to accommodate an initial vulnerability assessment, and a risk assessment in the planning phase of a road project.

Another reason for wanting to broaden the applicability of the Framework is the fact that some countries already apply a methodology for risk assessment, which is different from the one incorporated in this Framework. Some adjustments are, therefore, proposed so that countries can benefit from the structure of the Framework and combine it with their own established methodologies for risk assessment.

The WG1 Report provides the methodological detail supporting each stage of the refined PIARC International Climate Change Adaptation Framework for Road Infrastructure, by referring to state-of-the-art case study examples. The WG2 Report investigates possible applications of the Framework and discusses needs and options for its refinement.

The work on the two WG tasks was based on 59 collected and classified case studies that were analysed and classified by a dedicated Technical Committee (TC) internal Task Force. Further to this, by making available more than 100 case studies in total, the work of TC E.1 represents a comprehensive consolidation of state-of-the-art concepts applicable to climate change adaptation for roads. These detailed references can also be used as reference points for other world-wide projects being undertaken. It is crucial that PIARC's products represent significant added value for owners and operators of road infrastructure and have a unique selling point. This is achieved by making available a wide range of case studies of state-of-the-art practice world-wide.

There is capacity to extend the work developed by TC E.1 into formulating a new edition of the PIARC Framework. It is acknowledged that the work of TC E.1 is highly interrelated between cycles whereby it builds from the previous cycle, and can be extended to the next PIARC cycle for 2020-2023. Therefore, there is a need for consistency in transferring knowledge across three consecutive cycles.

CONTENTS

1. INTRODUCTION

Transport networks are fundamental to our society. Transport provides the services of mobility and accessibility, and aims to provide consistent and predictable services. However, the transport network is vulnerable to the impacts of many external factors which can hinder its ability to provide its intended levels of services.

It is necessary to identify the vulnerability of transport infrastructure in order to improve the resilience of the transport network. According to the Realising European RESILiencE for Critical INfraStructure, EU-Research Project, "Resilience" is defined as the ability to survive in the face of complex, uncertain and an ever-changing future. It is a way of thinking about both short-term cycles and long-term trends. As a result, a resilient system should encompass the notion that the disaster-resilience of society equals the society's ability to reduce:

- failure probabilities of infrastructure
- direct or indirect consequences of failures, in terms of lives lost, damage, and negative economic and social consequences
- time to recover (restoration of a specific system or set of systems to their "normal" level of functional performance) [2; in 3].

Reducing the vulnerability of infrastructure (and increasing its resilience) is of fundamental importance to current and future transport planning. Guidance is required on how to assess the impacts that projects may have on reducing the vulnerability of key parts of networks and the trade-offs involved. This involves developing more resilient infrastructure which can better withstand all types of hazards. This will also help to support the continued provision of essential services (largely provided by infrastructure that is critical) to businesses, governments and the community, as well as to other sectors.

During the 2012-2015 cycle of the Strategic Plan of the World Road Association, in 2014 Technical Committee (TC) 1.3 "Climate Change and Sustainability", developed a proposal for a 'Special Project' to create an international framework for climate change adaptation. The PIARC International Climate Change Adaptation Framework for Road infrastructure [4] (referred to in this report as the "PIARC Framework') was developed to guide road authorities through identifying relevant assets and climate variables for assessment, identifying and prioritising risks, developing a robust adaptation response and integrating findings into decision-making processes. Additionally, this Framework provides a life-cycle and iterative approach to climate change adaptation [4].

As part of this current cycle, Technical Committee E.1 (TC E.1): *Adaptation Strategies and Resiliency* has intensively dealt with the following questions in accordance with the requirements of the PIARC Strategic Plan:

- Investigation and dissemination of information about current adaptation strategies to increase the resilience of road infrastructure (Working Group 1).
- Refinement of the Climate Change Adaptation Framework (based on the "Special Project" developed in the 2011-2015 cycle) and follow-up of its implementation (Working Group 2).

The work on these two issues was based on 59 case studies that were analyzed and classified by a dedicated TC internal Task Force. By the end of this cycle, more than 100 case studies were available.

This report consolidates the findings of this internal Task Force. It is, however, acknowledged that due to the high volume of case studies collected, not all could be represented in this report. Therefore, this report displays as many of these relevant case studies as possible. Further reference can be made to the Task Force report regarding other case study examples.

The purpose of this report is to articulate the task of WG1 and highlight a state-of-the-art case study analysis of adaptation strategies to increase the resilience of road infrastructure at the policy, strategic, system level and project-specific level. It has been developed in parallel with the task of WG2, which was to refine the PIARC Framework and build from the work developed in the previous cycle. This report outlines the methodological detail supporting each stage of the PIARC Framework; hence both the outcomes of WG1 and WG2 are highly related. This report for WG1 includes coverage of state-of-the-art case study examples of the four main areas in the PIARC Terms of Reference for TC E.1:

- Data requirements regarding climate change adaptation of road infrastructure.
- Vulnerability and criticality of road infrastructure assessment.
- Adaptation measures with regard to possible threats resulting from climate change.
- Cost-benefit analysis of climate change adaptation.

These abovementioned areas have been presented in this report by way of state-of-the-art case studies on adaptation strategies and resilience.

2. PURPOSE OF THE REPORT

The World Road Association (PIARC) Strategic Plan is divided into five themes, one of which is Strategic Theme E: Climate Change, Environment and Disasters. The goal of this Strategic Theme is to increase resilience and protect investments in transportation infrastructure from the impacts of climate change events while, at the same time, lessening the impact of road transportation on the environment. This Strategic Theme includes three Technical Committees, one of which is Technical Committee E.1: *Adaptation Strategies and Resiliency*.

The activities of TC E.1 were divided into two working groups and a Taskforce. The Work program addressed two issues:

- Working Group 1 (WG1) – Investigate and disseminate information about current adaptation strategies to increase the resilience of the road infrastructure – report based on case studies
- Working Group 2 (WG2) – Refine the International Climate Change Adaptation Framework for Road Infrastructure (based on the Special Project developed in the 2011-2015 cycle) and follow-up its implementation – report based on case studies.

A TC Internal Task Force was also developed, which collected case studies that provided insight into climate change adaptation for roads.

This report details the output of WG1. It directly complements the refinement of the Framework investigated by WG2, whereby the WG1 report provides the methodological detail supporting each stage of the refined International Climate Change Adaptation Framework for Road Infrastructure.

3. STRUCTURE OF THIS REPORT

This report is structured according to the main sections of data requirements for exposure assessment, vulnerability and criticality assessments for roads, adaptation measures and economic approaches of assessing which adaptation measures provide the most cost-effective responses. Additionally, other sections are discussed which provide a connection between this work and the PIARC International Climate Change Adaptation Framework for Roads and E.1 Case Study Taskforce.

Section 4 provides an overview of the PIARC International Climate Change Adaptation Framework for Roads and identifies the main stages of the Framework. This includes linkages with WG2.

Section 5 details the information collection process needed to develop this report. It outlines the methodology and results of the TC Internal Task Force, which was an important component in providing the case study information for this report. Additionally, the methodology used for integrating these case study results into each section of this report is provided.

Sections 6 and 7 identify the information requirements and context for applying this document in reference to the PIARC Framework. Section 6 sets out the identification of the objectives and the scope when implementing the PIARC Framework. Then, Section 7 outlines the concept of exposure assessment, from the selection of climate hazards and climate change scenarios to the exposure scoring.

Section 8 provides the detailed techniques and case study examples when undertaking vulnerability and criticality assessments, and Section 9 covers the application of risk assessments through top-down approaches, indicator-based approaches and quantitative and probabilistic approaches.

Sections 10 highlights case study examples for identifying, selecting, monitoring and evaluating adaptation measures and responses related to the infrastructure, to traffic and/or hazard management, and to maintenance, operation or planning.

Section 11 then defines ways of including adaptation measures within project appraisal and evaluation. This includes economic methodologies such as cost-benefit analysis or life-cycling assessment, and also prioritisation of resilience options analysis. This Section also describes how to develop an adaptation action plan and to verify the benefit realisation and integration of climate change adaptation into decision-making processes. All sections within the report are supplemented by descriptions of state-of-the-art practices or relevant examples from the large number of case studies analysed for the development of this report.

4. OVERVIEW OF THE INTERNATIONAL CLIMATE CHANGE ADAPTATION FRAMEWORK FOR ROADS

According to the Intergovernmental Panel on Climate Change (IPCC), it is acknowledged that global mean temperatures will continue to rise over the 21st century if greenhouse gas emissions continue unabated, and also that impacts will not be regionally uniform. Additionally, long-term global precipitation will increase: global mean surface temperature and annual surface evaporation is projected to increase as global temperatures rise over most of the ocean. It is projected to change over land following a similar pattern as precipitation. The IPCC note that projections of climate change are uncertain, primarily because they are dependent on the scenarios of future anthropogenic and natural forces that are uncertain. There are also inconsistencies because of incomplete and imprecise models of climate systems and the existence of internal climate variability. It is however possible to understand future climate change using models to characterize outcomes and uncertainties under specific assumptions about future forcing scenarios [1].

The key IPCC Climate Change projections are anticipated to have significant impacts on the design, construction, maintenance and operation of global road infrastructure. These projections estimate that the earth will become warmer, some regions will become wetter overall and some will become drier, sea levels will rise and storm surge height will increase, snow cover and the extent of sea ice will reduce, and the frequency and severity of extreme weather events will increase.

As discussed in Section 1, taking into account those climate change risks and opportunities, the World Road Association (PIARC) developed a Framework to guide road authorities through identifying relevant assets and climatic variables for assessment, identifying and prioritizing risks, developing a robust adaptation response and integrating assessment findings into decision-making processes.

The PIARC International Climate Change Adaptation Framework for Road Infrastructure guides road authorities through the process of increasing the resilience (climate change only) of their networks and assets through the following stages:

- Stage 1 - Identifying scope, variables, risks and data
- Stage 2 - Assessing and prioritizing risks
- Stage 3 - Developing and selecting adaptation responses and strategies
- Stage 4 – Integrating findings into decision-making processes.

Stage one has four main components: establishing assessment scope, aims, tasks and a delivery plan; assessing vulnerability and adaptive capacity; assessing climate change projections and scenarios; and the outcome. Typically, the key aim and driver behind the delivery of any type of climate change adaptation assessment is to ensure and enhance the resilience network, asset, operation or service to the effects of climate change and extreme weather. This will be achieved by assessing exposure, assessing sensitivity, calculating vulnerability levels, assessing adaptive capacity, and assessing climate change projections and scenarios. The outcome is that road authorities will have a defined scope, aims, tasks and a plan for delivery and will have identified which assets, locations and operations are most vulnerable, determined the key climate effects and will have knowledge on how to apply climate change scenarios and projections.

Stage two has four main components: assessing impact probability; assessing impact severity; establishing risk scores and risk register; and the outcome. This stage will enable authorities to understand, and where possibly to quantify, the risks posed to their networks and assets in a simplistic, accessible, iterative and yet robust and holistic way following risk assessment principles. Road authorities will be able to rank their assets, locations and operations according to the level of risk probability and/or severity associated with climate change and extreme weather. For the purpose of this framework, risk is considered to be a function of probability and severity. The outcome will be that road authorities will have developed a ranked list of risk according to their probability of occurrence and their severity. The highest scoring risks should be taken forward to stage three, which outlines how adaptation responses to address these risks can be identified, selected and prioritised.

Stage three also follows a process of four steps, including: identification of adaptation responses and strategies; the selection and prioritisation of adaptation responses and strategies; the development of an adaptation action plan or strategy; and the outcome. Identification of adaptation responses and opportunities occurs through professional judgement, expertise and knowledge of the road network – authorities should be able to produce a list of potential adaptation responses suited to their particular assessment and road network. Selection and prioritisation of adaptation responses and opportunities occurs through two common methods; cost-benefit analyses (CBA), and Multi-Criteria Analysis (MCA). At this stage of the assessment, road authorities will have a list of potential adaption responses to the key risks facing their network assets, operations and locations. The outcome of this stage is that road authorities will be able to develop a prioritised list of adaptation responses which can be accompanied by an action plan to facilitate the delivery of these activities. Stage four then outlines how each of these outcomes can be incorporated into decision-making, education, awareness and training through effective communication.

Stage four similarly has four main steps: incorporating recommendations into decision-making processes; education, awareness, training and effective communication; developing a business case;defining future planning and monitoring; and the outcome. Climate change must be considered as one of the many risks requiring attention in transportation decision-making, rather than as a separate standalone issue. Road authorities may be able to incorporate climate change vulnerability assessment results into: asset management plans, inventories and policies; landscape strategies; traffic management strategies; investment plans; design standards and specifications; emergency and risk management processes; hazard mitigation plans; transportation planning project selection criteria; or environmental reviews and strategies. The outcome of this stage is effective integration of assessment findings into decision-making activities, communication plans, business case activities and ongoing planning and operational procedures.

In summary, the PIARC Framework was developed through extensive research and consultation with road authorities globally and synthesises evidence of state-of-the-art practice and knowledge available internationally. Furthermore, this is a direct effective and useable tool for any road authority, irrespective of geographical, climatic, economic or environmental condition and it is applicable at any scale (such as national, regional, local or asset specific).

4.1. Implementing the PIARC Climate Change Adaptation Framework in Mexico

After the publication of the PIARC Framework, the Secretariat of Communications and Transportation in Mexico carried out the implementation of this work within the network of Federal highways throughout five States of the country.

According to the stages of the Framework, in Stage 1 the objective was established, including assessing the risk of the road network against extreme hydrometeorological phenomena associated with climate change. The scope included the entire toll-free road network in these areas. Intermediate activities and deliverables were established, including a guide for the use of the Framework. This involved certain adjustments to the PIARC Framework, particularly in the thresholds to determine the levels of vulnerability and risk, as well as a detailed report of the vulnerability of the network of roads by State, and a geo-referenced database of risk sites.

In terms of the identification of sites, a procedure of work in field and formats of registry was developed. Once the sites were identified and registered, the vulnerability levels across all sites was determined according to their exposure and sensitivity, based on hazard maps and expert criteria of the engineering experts.

Once the levels of vulnerability were determined, sites with a high or very high value continued to the risk prioritization process in Stage 2 of the Framework, where the probability of the impact, and its severity, was evaluated to determine the level of risk.

According to the risk rating, those sites that were determined to be the highest risk, then continued to Stage 3 of the Framework. Additionally, for each site at risk, its adaptation measure was determined. It was required that each measure be evaluated through a MCA using established criteria into the Framework to prioritize the adaptation responses.

Finally, a plan for the implementation of the adaptation actions was developed, which included the continuous application of the Framework to the state road network, the incorporation of the measures within the road conservation programs, and continuous training. Training on the use of the Framework in Mexico was carried out through various Workshops, attended by personnel from the road dependencies, consultants, universities and other stakeholders of interest.

The Framework includes other activities in Stage 4, in addition to training and communication, which have not yet been implemented in Mexico, such as the monitoring of adaptation measures and the development of a business model.

4.2. Implementing the PIARC Climate Change Adaptation Framework in Australia

A recent project is being undertaken by the Department of Transport and Main Roads (TMR), Queensland under a National Asset Centre of Excellence (NACoE) program together with the Australian Road Research Board (ARRB), relating to the implementation of the PIARC Framework. This project emerged from the PIARC International Technical Workshop ”International adaptation strategies and increasing the resilience of infrastructure”, hosted by TMR in Brisbane in May 2017, where the PIARC Framework was presented.

The purpose of this project is to develop a consistent climate change framework for TMR (which is also applicable to industry) based on the findings of existing projects. This involves integrating the existing PIARC International Climate Change Adaptation Framework for Road Infrastructure, and other approaches into current TMR practice. Additionally, this project is connected to PIARC TC E.1 / WG1 by integration of Queensland case studies into this current document and is an example of how this international framework can be applicable in Australia and elsewhere. Further details are provided in the PIARC WG2 report.

4.3. Implementing the PIARC Climate Change Adaptation Framework in Paraguay

As a result of the updating of the Road Design Manual, the Paraguayan Road Association sought to include adaptation to climate change into the design criteria and standards for the future roads in Paraguay.

In order to facilitate this process, through the World Road Association and the Mexican Institute of Transportation, a workshop was held on the experience of Mexico in applying the Framework.

The workshop included relevant topics such as terminology for adaptation to climate change, an overview of the impacts that occur on roads and best adaptation practices, as well as the use of tools that can help identify the impacts of climate change, and how can they be taken into account to select their possible adaptation responses.

The Paraguayan Road Association will include in its new Manual an Annex guide on the PIARC Framework, to enable users to apply it in the design and conservation of roads in Paraguay.

5. OVERVIEW OF THE INFORMATION COLLECTION PROCESS

5.1. CASE STUDY COLLECTION FROM THE TC INTERNAL TASK FORCE

The goal of the TC Internal Task Force was to collect case studies that provided insight into climate change adaptation for road infrastructure. Case studies from across the world were collected by conducting a survey, with the purpose of providing case studies to the Working Groups for a technical review. The Task Force aimed to reduce the efforts of the Working Groups by the collation and provision of case studies collected within the survey. Being able to access case studies in a direct way, enabled WG1, for example, to focus on identifying state-of-the-art practices, both at the network and project level. The survey was conducted recognising that climate change and its impacts on transportation are expected to vary between world regions. Therefore, a global survey covering different regional settings is advantageous, especially when reviewing strategies and state-of-the-art practices of climate change adaptation. This ensured the application of a wide range of case studies for use by WG1 and WG2.

5.2. TASK FORCE METHODOLOGY

The approach to the survey was developed in collaboration with the two Working Groups of TC E.1. With its main purpose being to support both WG1 and WG2, the Task Force was not required to prepare an additional work plan. To better coordinate the conduct of the survey, a draft structure of the Task Force and an internal work plan was prepared and updated as work progressed. The survey was based on the following approach with five main steps:

- Development of a matrix template for the categorization of case studies.
- Distribution of a questionnaire by email to ask for case studies.
- Categorization of case studies provided to the Task Force using the matrix template.
- Analysis of the completed matrix templates for the set of case studies categorized.
- Provision of the case studies and the results of the analysis to the Working Groups.

A key element of this approach is a matrix template which outlines the priorities of the work programs for WG1 and WG2. In addition to the matrix template, which was used to categorize case studies provided to the Task Force, a questionnaire was distributed to PIARC TC E.1 members to ask for case studies. The questionnaire was also sent to the United Nations Economic Commission for Europe (UNECE) Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes and the Conference of European Directors of Roads (CEDR) Task Group on Climate Change. This approach enabled the collection and categorization of case studies relevant to a technical review by the Working Groups.

5.3. TASK FORCE RESULTS

In the survey, 59 relevant case studies from 19 countries were identified (Figure 1). Most of the case studies were from Europe and North America. Whilst this geographical pattern might not represent the availability of case studies globally, it could be related to the limitation of the survey being in only four languages and the specific channels used to distribute the questionnaire. Therefore, the results have to be treated carefully, bearing in mind that they are based on an incomplete set of case studies. Furthermore, it has to be mentioned that the structure of the matrix template, especially the option for multiple choices in one section, was a limiting factor for statistical analysis and interpretation. Therefore, the anlalysis provided a qualitative description of the results only.

Several documents were also provided by Japan, but as only abstracts were available in English, the results are not included in the present report. They will be analysed within the next PIARC cycle in 2020-2023 with the latest case studies received.

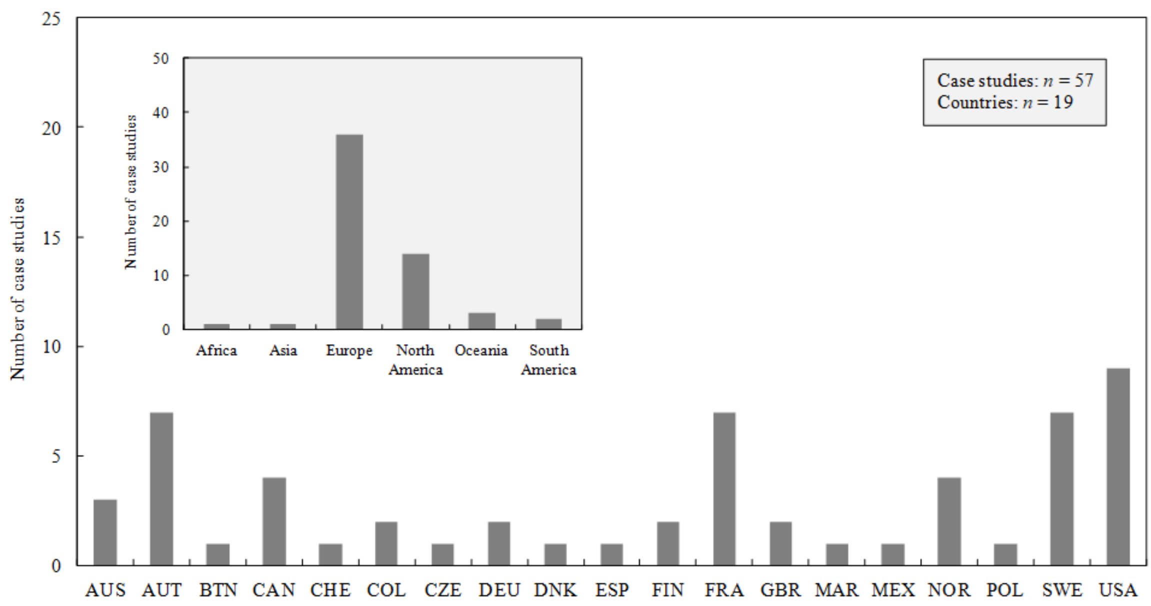


Figure 1: Task force summary of case studies collected by country. Source: Klose, M, BASt

5.4. Approach to identifying case studies

In order to develop this report for WG1, a state-of-the-art case study matrix was produced to connect each stage of the Table of Contents proposed for this report, to the case study database prepared by the TC Internal Task Force. The matrix also included additional studies presented at workshops and seminars, and presentations provided at all TC E.1 meetings throughout the 2016-2019 cycle.

The identified case studies were then transferred into this report, and any gaps where further information was required, were discussed with the Working Group 1 members.

6. INFORMATION REQUIREMENTS AND CONTEXT FOR GUIDELINES APPLICATION

As identified in Section 2, the objective of WG1 was to undertake a state-of-the-art case study analysis of adaptation strategies to increase the resilience of road infrastructure at the policy, strategic, system level and project-specific level. This includes consideration of data requirements, vulnerability and criticality of road infrastructure assessment, adaptation measures and economic methodologies required to analyse climate change.

These aspects are directly connected with the main steps provided within the PIARC Framework, including further details on the case study approaches to support the Framework. The outputs from this report were therefore closely related to the refinement of the Framework as outlined in the report compiled by WG2, and outlined the underpinning methodologies and state-of-the-art practice to support the PIARC Framework.

This section of the report defines the objectives and scope of a holistic risk assessment using examples of world-wide approaches.

6.1. DEFINITIONS

A key step towards determining the adaptation of a given project, initiative or programme is to develop an understanding of what is meant by terms such as risk and vulnerability, as these can vary significantly. This section sets out the definitions used in this report.

Vulnerability is defined as “any weakness that can be exploited by an aggressor to make an asset susceptible to change” (HB167:2006 also FEMA 452 / January 2005). According to this definition “Vulnerability” and “Risk” are different things. A weakness (vulnerability) in combination with exposure to a possible hazard can lead to certain likelihood and severity of consequences. For example, in the PIARC Framework, vulnerability is used to prioritize the assets to be included in the risk assessment. Here, vulnerability is scored and the score applied in the calculation of the total risk score. According to PIARC (2015), vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed (exposure); and the degree to which something is affected, either adversely or beneficially, by climate related stimuli (sensitivity). Therefore, exposed and sensitive assets are also considered as vulnerable assets.

In RAINEX the following approach in Figure 2 shows the interrelationship between vulnerability, exposure, hazards, risk and criticality.

Figure 2: Relation of hazard, criticality, exposure and vulnerability in rainex. Source: http://www.rainex-project.eu/

In the context of risk, the following definitions have been obtained from the ISO Guide 73:

- 3.4.1 Risk assessment— the overall process of risk identification (3.5.1), risk analysis and risk evaluation (3.7.1).
- 3.5.1 Risk identification—the process of finding, recognizing and describing risks (1.1). Risk identification involves the identification of risk sources (3.5, 1.2), events (3.5,1.3), their causes and their potential consequences (3.5, 1.3). Risk identification can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder's (3.2, 1.1) needs.
- 3.6.1 Risk analysis—the process to comprehend the nature of the risk (1.1) and to determine the level of risk (3.6, 1.8). Risk analysis provides the basis for risk evaluation (3.7.1) and decisions about risk treatment (3.8.1). Risk analysis includes risk estimation.
- 3.7.1 Risk evaluation— the process of comparing the results of risk analysis (3.6.1) with risk criteria (3.3, 1.3) to determine whether the risk (1.1) and/or its magnitude is acceptable or tolerable. Risk evaluation assists in the decision about risk treatment (3.8.1).

Whilst these definitions are referred to in this report, the aim is to provide case study methodologies relating to the phases of the PIARC Framework. Where terms differ, alternative information is provided.

6.2. DEFINING OBJECTIVES AND SCOPE OF A HOLISTIC RISK ASSESSMENT

In order to begin a risk assessment (where "risk assessment" is defined as the holistic process as outlined in Figure 3), a road authority sets its aims and objectives and defines precisely the territory and/or the network(s) to be studied. In particular, this step determines the choice of the human and economic resources to be deployed, the most suitable assessment methodology, the required data, the level of detail, etc.

Figure 2 outlines how exposure, vulnerability and sensitivity are related as part of a holistic risk assessment process[2]. It is, however, noted that this process can also be identified in other sources as an overall adaptation framework, e.g. the PIARC Framework. This is where a framework will consider the identification of the scope, variables, risk and data, then a separate vulnerability assessment to identify the exposure, sensitivity and adaptive capacity. Following this step an assessment and prioritisation of risks is then undertaken to assess the likelihood or consequence, and risk score; followed by the development of adaptation responses and integration of prioritised options into decision-making processes.

The process outlined in Figure 3 demonstrates “the overall process of risk identification, risk analysis and risk evaluation”, according to the ISO definition for Risk Management.

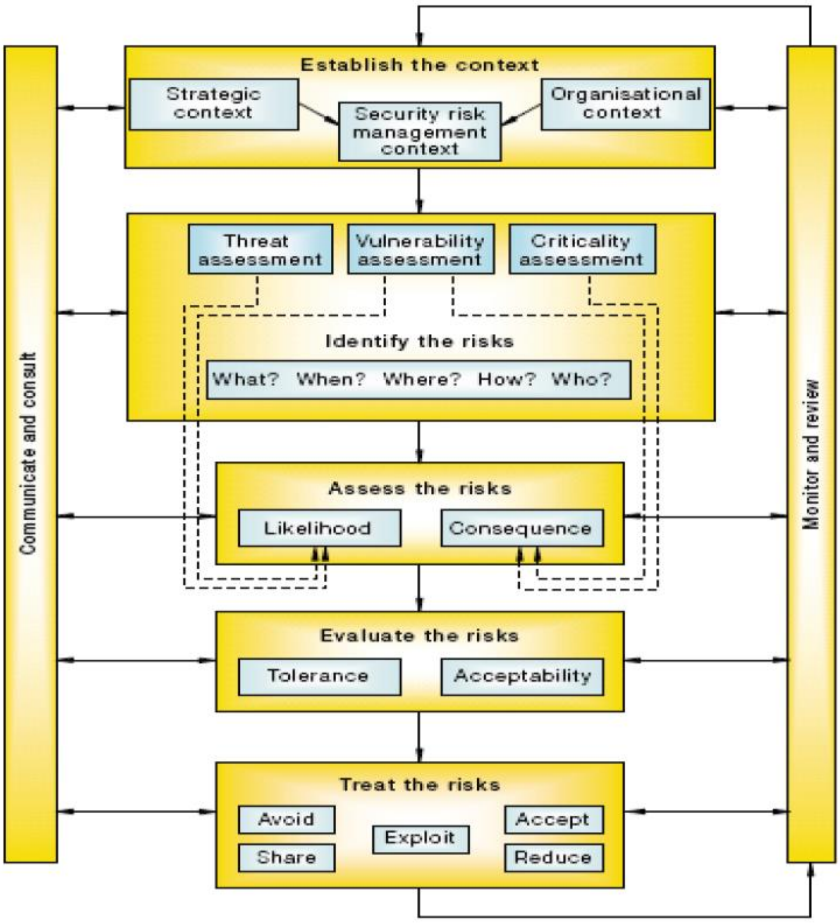


Figure 3: General risk management process. Source: HB167:2006 Security Risk management; ISO 31000:2009

The aim of the process identified in Figure 3 is to determine:

- how will the results be used to prioritize the investments and modify, if necessary, the network management e.g. To reinforce a specific asset e.g. bridge?
- what is the availability of economic and social resources?

[2] A holistic risk assessment process is defined in this report as to refer to the whole processes (sensitivity assessment, criticality assessment, assessment of the risks, evaluation of risks and risk treatment).

- what type of data is available and required regarding the infrastructure (current condition, etc.) and what are the functionalities of the network (traffic, etc.)?

This selection of an appropriate process, as outlined above, directly refers to the purpose of the study being undertaken. For example, does the transport authority wish to lead an overall vulnerability assessment or even a risk assessment of its network? Or does the transport agency wish to focus on one part of the network/asset facing one specific hazard?

The case studies identified in this report covered a large panel of aims, objectives and scope of risk assessment. These varied from large-scaled assessment, such as:

- assessment of the assets and functions of different networks most at risk from climate change hazards [5; 6]
- assessment of the most appropriate adaptation options of roads facing climate change in regards to costs and benefits [7]

to very precise analysis, e.g.:

- assessment of the impact of submersion or erosion on the network functions in a context of climate change [8]
- analysis of the exposure and vulnerability of road sections and drainage systems to flooding in a context of climate change [9; 10; 11; 12; 13].

An example of a large-scaled assessment methodology can be found in the framework developed in the transport section of the French national climate change adaptation plan [14].

6.3. Practical advice to lead a holistic risk assessment

Many case studies (e.g. [6; 14]) involved the establishment a group of experts to conduct a risk assessment, including:

- transport specialists (e.g. people in charge of the operation, maintenance, development and technical strengthening of the networks) who are able to provide information either on the assets, on the functionalities of the networks (e.g. traffic), or on economic and financial issues
- climate specialists, able to provide information on past weather events and the expected climate change, or people able to understand and use climate information;
- those who have a good knowledge in the area of study, e.g. past climate hazards or local issues even if they are not directly related to the network (e.g. isolated population due to lack of road networks)
- other specialists, involved in the development of the needs and the objectives of the risk assessment, e.g. specialists in economics, energy, communication networks, land and urban planning, geology, hydrology etc, as identified for the the inter-American Development Bank (IDB) [15].

It is important that specialists frequently interact and that meetings be carefully planned to allow the preparation of a list of climate hazards, scoring scales, and indicators of vulnerability. For example, Cerema (France) has led a risk assessment of the road network “DIR Mediterranée” [6], which is a state-owned network with over 750km of roads and many engineering works. It has set up a working group comprised of: the road operator (DIR Méditerranée, which is also in charge of the maintenance), the transport owner (The French Ministry of Environment, which is in charge of the national roads), and specialists in climate change, data and GIS, road infrastructures and of road functionalities.

Additional examples of where information is shared and coordinated are identified in Boxes 1 and 2.

Box 1: Australian Government's Trusted Information Sharing Network for Critical Infrastructure

Critical infrastructure delivers essential services such as food, water, healthcare, electricity, communications, transportation and banking. Without these services, Australia's social cohesion, economic prosperity and public safety are threatened. The resilience of critical infrastructure is therefore integral to a strong economy and a vibrant business sector. It is also vital to the resilience of our communities to disasters.

The Trusted Information Sharing Network (TISN) for Critical Infrastructure Resilience was established by the Australian Government in 2003. It is Australia's primary national engagement mechanism for business-government information sharing and resilience building initiatives on critical infrastructure resilience. The TISN provides a secure environment for critical infrastructure owners and operators across eight sector groups to regularly share information and cooperate within and across sectors to address security and business continuity challenges.

In May 2015, the Critical Infrastructure Resilience Strategy was developed. The strategy consists of a policy statement and a plan for practical implementation, and aims to ensure the continued operation of critical infrastructure in the face of all hazards. More resilient critical infrastructure will also help to support the continued provision of essential services (provided by critical infrastructure) to businesses, governments and the community, as well as to other critical infrastructure sectors.

Source: Commonwealth of Australia, Critical Infrastructure Resilience Strategy Policy Statement (2015), https://www.tisn.gov.au/Pages/default.aspx

Box 2: BMVI Network of Experts, Germany

On the 1st January 2016 the BMVI Network of Experts was established to provide solutions and guidance for transport challenges of today and the future. The objective of the BMVI Network of Experts is to place existing competences on a broad common basis, networking intensively with each other and thereby promoting the transfer of knowledge and technology across disciplines. This networking and mutual exchange furthermore focus on the dialogue between experts from areas of science and research, politics, industry and economy. The main topics being addressed by collaborative research and knowledge transfer are:

- Topic 1: Adapting transport and infrastructure to climate change and extreme weather events
- Topic 2: Designing environmentally friendly transport and infrastructure
- Topic 3: Increasing the reliability of transport infrastructures
- Topic 4: Consistently developing and using digital technologies
- Topic 5: Enhanced development of renewable energy in transport and infrastructure.

For more information on the BMVI Network of Experts see *www.bmvi-expertennetzwerk.de*

Source: BASt, Germany

6.4. OVERVIEW OF METHODOLOGIES TO ASSESS CLIMATE CHANGE SCENARIOS

The next Sections (specifically Section 7 and 8) detail different approaches to assess data availability and requirements and exposure. It is relevant to first consider the general data availability for each of these assessments, as set out in the aims of the Strategic Plan for WG1. Qualitative approaches may be used if no quantitative data is available, or as a first rapid approach. These approaches are often based on expert judgement, and are a result an initial qualitative classification, e.g. low/medium/high sensitivity/exposure/risk. Sometimes, more detailed information is available that could be translated into classes of intensity, occurrence, impact degree; or scored by a relative scale. In this case, a semi-quantitative approach may be used. Quantitative approaches are usually based on models using databases or precise measures, which might be expensive and time-consuming. Moreover, it is noted that databases or measures may not always be available.

According to PIARC [4], vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed (exposure); and the degree to which something is affected, either adversely or beneficially, by climate related stimuli (sensitivity).

In a vulnerability assessment, it is important to consider a wide range of factors in determining which aspects of a network to prioritise; for example, the effectiveness, costs/benefits (in terms of avoided damages or avoided delays), co-benefits, flexibility of design, and implementation barriers should be considered [56]. This step should also include consideration of maintenance objectives and decisions to commission or decommissioned infrastructure [54].

In the context of this report, exposure, sensitivity, criticality and risk assessment (as defined by the PIARC Framework) are set out in Sections 7, 8 and 9. Case study examples are provided highlighting the application of these methods.

7. EXPOSURE ASSESSMENT

In a vulnerability assessment (or risk identification stage as set out in Section 6.2), it is important to consider a wide range of factors in determining which aspects of a network to prioritise; for example, the effectiveness, avoided damage or avoided delays, co-benefits, flexibility of design, and implementation barriers should be considered [56]. This step should also include consideration of maintenance objectives and decisions to commission or decommission infrastructure [55]. Therefore, as identified in the PIARC Framework, vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed (exposure); and the degree to which something is affected, either adversely or beneficially, by climate-related stimuli (sensitivity).

In order to assess the observed conditions and identify risk sources it is important to identify the profile of the network of interest, e.g, assess normal operating conditions in a full intact network, develop an inventory of assets, and initially identify critical locations and components. Following this step is the exposure assessment which is defined in Section 7.1.

7.1. Definition of climate exposure

In the PIARC Framework, exposure is the nature of the climate hazards which a network (and its components) has to cope with, e.g. assessment of the observed conditions and identification of risk sources. Exposure can relate to the entire network, a part of the network, a road section and/or to a specific object. Thus, assessing the exposure of a road network means identifying the hazards that may occur now or in the future an area of the network, and their characteristics:

- Frequency
- Duration
- Intensity
- Localization.

These identified characteristics will depend on the area of study and which transport assets will be assessed. This step should already have been undertaken while defining the scope of the study.

According to the UNISDR, exposure refers to the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. This can include the number of people or types of assets in an area. These can be combined with the specific vulnerability and capacity of the exposed elements to any particular hazard to estimate the quantitative risks associated with that hazard in the area of interest (https://www.unisdr.org/we/inform/terminology). Further to this, RAINEX defines exposure as people, properties, systems or other elements present in hazard zones that are subject to potential losses (e.g. RAINEX only refers to land transport infrastructure).

7.2. Selection of the climate hazards

In order to assess the exposure, the case studies identified in this document generally provide a list of hazards impacting roads according to the following questions:

- What are the current characteristic climate/s of the geographical area/s where the network or the road assets are located, e.g. mean temperature, mean precipitation, wind patterns?

- Which climate hazards have already occurred in this area, and which have or have not impacted the network: flooding, heat wave, freeze-thaw cycle?
- What kind of hazards usually impact a road network/asset (by deteriorating it sooner as expected, destroying it, or causing traffic failure) even if these hazards have not occurred yet in this area, e.g. freeze-thaw cycle, coastal flooding? This can be done with the use of climate analogues, e.g. the WATCH tool (CEDR project, in progress).
- How will all these hazards evolve in the future?
- Will the transport network have to face new hazards in the future, in a context of climate change, e.g. fires (smoke may disrupt the traffic)?

In general, the mean and extreme values in intensity, frequency or duration of the following parameters and hazards may be useful for a risk assessment:

- temperature: extreme hot/low temperature, heat/cold waves;
- precipitation: rain, snow, drought;
- landslides: swelling and shrinking of clay soils, rock falls, mudslides;
- wind: extreme wind;
- flooding: sea elevation, fluvial flooding;
- wildfires; and
- others.

It can also be important to make a distinction between climatic parameters and the climatic hazards, caused by climate parameters. For example, landslides, floods and wildfires are considered as hazards, whereas the others identified above are parameters. Norway has undertaken work to define this distinction further, and has documented a list of hazards. A key aspect of consequence is traffic disruption, as shown in Table 1.

Type of disruption	Reasons for disruption
Bridge closed Tunnel closed Ferry boat is not operating Road closed	Fire (on the road asset or close to the road) Vehicle in the road Drainage failure Accident with dangerous substances Flood Foundation failure Restrictions height – length – width – weight Landslide Quick clay slide Rockfall Avalanche Storm surge Electricity failure Accident point / stretch Wind Adverse weather

Table 1: Summary of the types and reasons for disruption

Another case study showing the identification and definition of hazards is shown in Box 3.

Box 3: Bruce Highway Flood Study

The Bruce Highway Flood Study is a project initiated and managed by the Department of Transport and Main Roads (TMR), Queensland. It utilises a hydrologic technique known as continuous simulation which is being used in a completely new way to assess the long-term flood reliability of the Bruce Highway link from Brisbane to Cairns. The study is looking at the flood performance of the whole Bruce Highway over the last one hundred years using rainfall records to generate stream flows at every crossing (there are over 500 of these) – this data is combined with hydraulic assessment to determine when each crossing is cut from flooding. This procedure effectively simulates the long-term performance of each link of the Highway over the last hundred years. Having established this, the study then looks at upgrading the key segments of the Highway and re-simulating performance to quantify the level of reliability improvement. The level of improvement achieved can be quantified in economic terms (that is, reduced disruption), which then forms the basis of a consistent and transparent upgrade works prioritisation programme. This is the first time a holistic assessment of the Bruce Highway has occurred and is the largest single length of flood link study ever completed in Queensland. This is also relevant to Section 9 in the appraisal of economic implications for climate change events.

Source: Department of Transport and Main Roads, Queensland

7.3. SELECTION OF CLIMATE CHANGE SCENARIOS

It is noted that in order to understand how the future road infrastructure will be affected by climate change, relevant climate change projections needed to be developed or researched. There are four main ways of developing climate change projections:

- Comparing historical events with maintenance and repair needs. It is possible to estimate how well assets may withstand stressors in the future. This then gives rise to the selection of adaptive approaches to make the structure less vulnerable. However, this should also be weighed against the uncertainty of future events and whether an asset/network is exposed to stressors which it is currently not exposed to [49].
- Geographical location to determine key climate change types – the geographical location of an area for assessment plays a pivotal role is determining which climate variables should be considered as risks.
- Existing climate change projections data and evidence to determine future conditions. Climate change data, scenarios and the timescales associated with them are important considerations when determining which climatic variable and impacts to include within an assessment. In order to deliver an effective climate change adaptation assessment strategy for road infrastructure it is essential that the data used is from a reliable and robust source, as it will form the basis for any risk assessment process going forward.
- Developing climate change scenarios and projections where this information does not already exist. It is noted that many vulnerability factors can be mapped using existing GIS data sets. For example, CEDR identifies a method for data collection in their ROADAPT Guidelines. This method uses GIS data sets created from local knowledge, field inventories

and map studies. This method consists of two main sub-steps, GIS data inventory and collection, and completing missing GIS data sets [4].

Once the hazards have been selected, it is suggested, that a climate projection exercise be carried out. It is also necessary to check which data is available to characterize these hazards. If information is available, then the first step would be a climate projection exercise, before performing an assessment of exposure. Knowledge on climate change can be developed by referencing the International Panel on Climate Change (IPCC) [16]. However, the climate data must be specified comprehensively to enable assessment of the potential impacts at a network or object level. In general, case studies summarize the climate change trends at the national level, before characterizing the frequency, duration and/or intensity of past events and future events at a regional or more precise level.

Climate projections are based on the outputs of mathematical models (general circulation models) describing interactions between the earth, the atmosphere, the ocean, etc., and the inputs of the models such as socio-economic scenarios linked with greenhouse gases emissions. Climate projections are thus dependent on the model and the scenario of socio-economic conditions and of greenhouse gases emissions. These climate scenarios are entitled “Representative Concentration Pathways” (RCP). This is why, when leading an exposure assessment, the transport agency will have to choose which climate model and which scenario of socio-economic conditions and greenhouse gases emissions will be used.

The IPCC have compared a large number of climate models and some of these provide national-scaled projections which can be used for the assessment. In order to reduce the uncertainties inherent to climate modelling, some case studies use meta-models, models ensembles or comparison between the outputs of different models. Downscaling is a technique in which GCM data can be used to produce higher resolution data for a certain region, which is also commonly used. Over the last decade the resolution of climate data has increased significantly and climate scientists are working on increasing the resolution even further. The quality of the climate data available will differ by country. The PIARC Framework provides further details on the use of downscaled data projections. For example, the CEDR Climate Projection Database for Roads (ClipDaR) project is a good example of guidelines which aims to assist users in deciding which methods and scenarios to apply for estimating future climate change and impacts on road maintenance using ensemble approaches and downscaling methods.

If no specific models are available for the area of study, then it might be possible to use data from local studies, or to ask experts to define the potential evolution of the climate hazards. This may notably concern hazards such as landslides, sea level at a local scale, flooding, etc. For example, in Quebec, Canada, the Ministry of Transport modelled the risk of permafrost melting using data on the characteristics of permafrost of different region, drainage and snowfall patterns [17; 18; 19].

The choice of the model influences the choice of the climate scenario for data availability reasons. In general, case studies compare different scenarios [6; 20]. A pessimistic approach, e.g. RCP8.5, represents a possible future climate if the increase in the rate of greenhouse emissions is not changed. Alternatively, an optimistic approach, e.g. RCP2.6, corresponds to the implementation of a strong mitigation policy, and an intermediate approach, e.g. RCP4.5, that is relatively close to a possible future if a few mitigation measures are implemeted. When these scenarios are not available, other ones may also be used.

Box 4: CORDEX

CORDEX (Coordinated Regional Climate Downscaling Experiment) is an international initiative to evaluate climate model performance and produce high resolution climate projections for use in impact and adaptation studies for the entire globe. It is sponsored by the World Climate Research Programme and has been running since 2009. The aim of CORDEX is to help bridge the gap between climate scientists and users of projection data. Simulations of multiple models run with four RCPs (RCP2.9. RCP4.5, RCP8.5 and RCP11.2) are being carried out for five domains (Africa, Australasia, South America, North America and Europe up to 2100.

CORDEX is on-going at the time of writing (2018) and this process is not yet complete. There is currently no central archive, but some data can be downloaded from regional portals. The Euro-CORDEX simulations will produce data at 12 km resolution.

Source: CORDEX and EURO-CORDEX website - http://www.cordex.org/about/ and https://www.euro-cordex.net/index.php.en

Finally, the transport agency should choose the period for which the climate data will be extracted from the models. Climate sciences commonly use a thirty-year period to provide relevant statistical data analysis; therefore it is preferable to use a thirty-year period of extraction. Most of the case studies compare a reference period (a past period of 30 years, often 1961-1990), with different futures. This provides a good communication basis with the transport authorities while providing values of climate variables, and shows how much climate change could evolve. Considering a road is composed of assets designed for different lifespans (e.g. a road surface versus a bridge), it may be difficult to project the uncertainties in the long term. It may therefore be relevant to extract projections of climate hazards for a short-term period, e.g. the next 30 years. As many assets are built to last a long time, and in order to be able to better anticipate the climate tendencies, it is also important to extract a long-term period, e.g. 2071-2100. However, it is noted that some projections may not be available for these periods, which can make the comparison more challenging.

Box 5: French national tools to share climate change data

To assess the evolution of the hazards on the DIR Méditerranée's area of study, the working group a range of online free tools, amongst which the most important are:

- Climat HD (<http://www.meteofrance.fr/climat-passe-et-futur/climathd>): Provides simplified information on the climate changes at the scale of France and of French regions. This is interesting to initiate discussions with the transport authorities without starting to develop maps showing the evolution of each selected climate hazard
- DRIAS (<http://www.drias-climat.fr/>): A web portal that provides access to climate projections of the mean and extreme values in intensity, frequency and duration of rain, temperatures, droughts, forest fires, etc., for different scenarios: RCP2.6, RCP4.5, RCP8.5 at the French scale with a precision of 8km^2. The climate data come from models that were assessed by the IPCC (Arpège Climat, WRF, Eurocordex).

Source: Cerema. Analyse de risque DIR Méditerranée, 2017. [6]

Box 6: The Austrian example for climate change adaptation

In Austria, regional evaluations of global climate models (GCMs) may be useful for larger areas such as e.g. the Alpine Space. There are 15 different results from the last generation of GCM available. By considering this ensemble of model results, statements about the safety of the results can be made in addition to the average trend. In order to be able to derive the effects of climate change for subregions of the Alpine region, so-called "implementation approaches" (consideration of regional conditions in a spatial resolution of 10 x 10 km) should be followed by the global climate models. However, regional changes are much more difficult to simulate than changes in global averages, therefore statements, with respect to individual regions, are subject to greater uncertainties.

Source: adapt2to4 research programm, University Graz, 2014. [21]

7.4. Exposure scoring

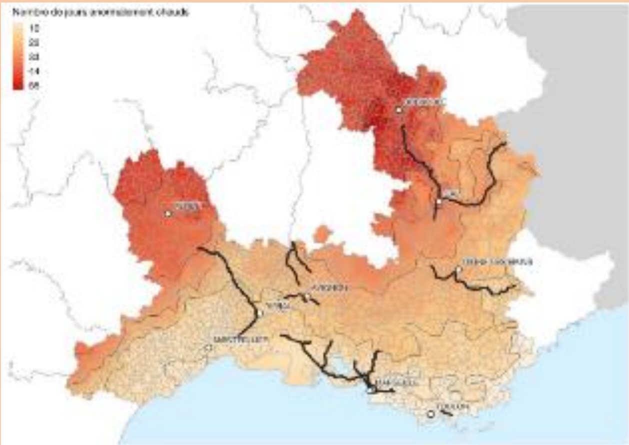
Once the values that characterize the hazards have been identified, it is possible to assess the exposure. It is also important to analyse exposure qualitatively, qualitative (PIARC Framework), semi-quantitative (for example, RIVA (see Section 9)) and on a fully quantitative basis (for example, Infrarisk) (see Section 9). One method of doing this is to define a scoring scale that reflects the evolution of each climate hazard. This enables the transport agency to understand which hazards its network is currently exposed, and how the exposure may evolve.

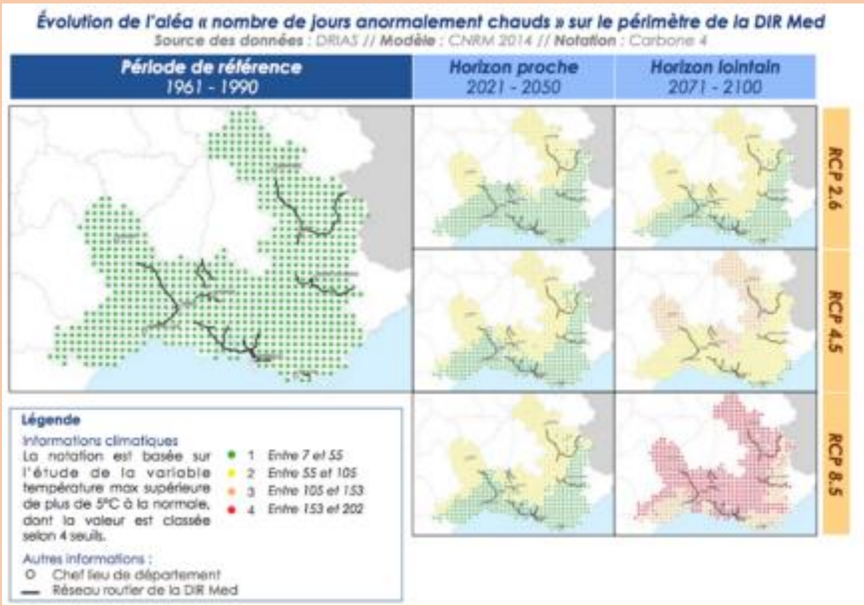
This scoring scale may be initially used to assess the overall score for vulnerability, because it allows for detailed consideration of the hazards and their evolution in the context of climate change, without taking into account the extent of potential damages or disturbance of the network (as a full risk assessment would). A vulnerability assessment is often combined with a criticality assessment to identify assets that are both critical and highly vulnerable to a climate hazard.

Using the same scoring scale for different assessments will enable comparison of the results of each assessment. An example of exposure scoring is identified in Box 7 from France.

Box 7: From exposure characterization to exposure scoring

An example of exposure scoring is provided by the risk assessment lead on the DIR Méditerranée network. The first map shows an extraction of climate data for a reference period of thirty years, and the second map shows the scoring of these data for three different periods: the period of reference, 2021-2050 and 2071-2100.





Source: Cerema. Analyse de risque DIR Méditerranée, 2017. [6]

8. TECHNIQUES AND TOOLS REQUIRED FOR ASSESSING SENSITIVITY, OVERALL VULNERABILITY AND CRITICALITY

This section outlines the case study approaches to support the vulnerability and criticality of road infrastructure assessment stage of the PIARC Framework. It includes state-of-the-art approaches being conducted world-wide on:

- Assessing vulnerability, such as the identification of these data needs, availability and accessibility and scoring of sensitivity.
- Assessing criticality, such as the definition, choice of assessment methodology, and scoring criticality. The notion of criticality does not appear in the PIARC Framework, however many case studies refer to this approach. WG2 has addressed this issue in its report, as a new concept to be addressed in risk assessments, hence in order to complement the WG2 report, criticality has been included.
- Identifying the reasons why a holistic risk assessment is applied using state-of-the-art examples of top-down, indicator-based and quantitative risk and probabilistic risk analysis approaches.

This section focuses on methods for assessing sensitivity, overall vulnerability, and criticality.

8.1. ASSESSING SENSITIVITY

8.1.1. Defining the sensitivity of infrastructure

As noted in Section 6.4, vulnerability includes consideration of exposure and sensitivity. According to the IPCC [1], vulnerability 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. In the PIARC Framework, sensitivity is defined as the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. This means that a category of road asset is more or less sensitive to a category of climate hazard. The sensitivity is assessed by asset category and by climate hazard category. For example, drainage systems are in general sensitive to the precipitation patterns, but relatively insensitive to wind conditions.

The sensitivity of two assets of the same type can differ according to their condition, their building material, their level of maintenance, etc. This is why case studies generally include the notion of aggravating and adaptive factors [6; 14]. Drainage systems are generally sensitive to precipitation patterns, and a drainage system with a poor maintenance may be more sensitive: here, maintenance is an aggravating factor.

When assessing vulnerability, first the sensitivity of each category of asset facing each category of climate hazards is determined in a general manner, and then more precisely by introducing the aggravating and adaptive factors. One method of assessing vulnerability is to identify factors relating to sensitivity and exposure (see Section 8) and score these, based on either data or expert judgement. According to the PIARC Framework, through combining the exposure and sensitivity ratings, it is possible to identify whether an asset is vulnerable, to what degree, and climate variables are affected. A combination of sensitivity and exposure therefore provides an overall score for vulnerability.

8.1.2. Approaches for data collection

A large number of the case studies identified by the internal PIARC TC E.1 Task Force deal with sensitivity as a part of a vulnerability assessment. Many case studies commence with a description of the general impacts due to current and potential future climate hazards on different types of road assets or on specific assets. Using this information, it is therefore possible to conduct a literature review for a proposed project. The case studies provide a good basis for informing the literature review [22; 23; 24; 25…].

It is also possible to assess qualitatively the sensitivity of a network by holding a brainstorming meeting with transport authorities, while asking them, for example, to list on a map of their network the main climate impacts that occurred in the past years (FHWA 2017), or by holding a field visit with experts to identify the most sensitive assets.

The qualitative data collected may provide some key insights into further detail within the sensitivity assessment and define semi-quantitative sensitivity indicators, including aggravating or adaptive factors. However, this approach should only be used in the absence of data. Semi-quantitative indicators are most often used to assess the sensitivity of different assets categories or of specific assets by climate hazards. They may be used to identify for example which section of a road is the most sensitive to high temperatures, depending on the type of asphalt, the traffic level, etc., or to which level of wind speed is a specific type of equipment sensitive. Additionally, it is important to consider that in some countries advanced data collection systems and information may not be available (e.g. GIS formats); hence engagement with local representatives is highly important to obtain the required data.

Therefore, a first necessary step is to break down the network into categories of assets, such as road surface, road structure, bridges, walls, small drainage systems and equipment.

Once this has been undertaken, alternative data collection approaches are available to define the indicators. A literature review of past damages, including details of the hazard that occurred [23] is undertaken, as well as, a collection of expert judgement (interview, questionnaire, visit) to define aggravating or adaptive factors.

Box 8: Assessment of the impacts of water run-off on assets in Sweden

Flooding is an issue for Sweden, which has lead numerous studies to better understand the potential impacts of this hazard on roads and roads assets. For example, an assessment of the evolution of the impact of run-off water on assets of the road drainage system has been conducted in the South of Sweden. The study is based on a model able to take into account run-off water in a specific catchment, indicators related to the vegetation cover which influences the water run-off, and the system of drainage. The climate change scenarios, that describe the evolution of the precipitation pattern and the temperature, and the scenarios of land use change (change in vegetation cover) are based on scientific studies (no RCP scenarios).

Source: Michaelsen, A. Modelling flood risk of transport infrastructure based on watershed characteristics. [11]

8.1.3. Scoring sensitivity

An overall assessment of the case studies identified that it is necessary to define a sensitivity scale and then score the sensitivity according to semi-quantitative indicators or with the results of models. Additionally, the scoring of the sensitivity of each asset is a modulation from the overall scoring of the sensitivity of the asset category by hazard with the aggravating or adaptive factors. This scoring has then been combined with the current and future exposure to assess the evolution of the vulnerability, and a criticality assessment has then been conducted (see Box 9).

The scales developed in the case studies often respond to practical needs of the transport authorities, thus they are often based on the level of the road degradation. It is important to set a single scale for all vulnerability assessments that have to be compared.

This approach is one of the main outcome of the methodology defined in the framework of French National Climate Change Adaptation Plan (PNACC, [14]). One of the studies using this methodology is highlighted in Box 9.

Box 9: Vulnerability assessment of a large road network: DIR Méditerrannée (France)

The case study "DIR Méditerranée" focuses on a 700 km long network of state-owned roads in the Southeast of France.

To score the sensitivity of each network asset, the working group in charge of the case study first disaggregate the networks into general case studies categories, such as for road:

- pavement;
- engineering works;
- small drainage systems;
- equipment; and
- others assets.

Then the asset category "pavement" has once again been disaggregated into:

- road surface;
- road structure;

and the asset category "engineering works" into:

- bridges;
- retaining walls.

This same approach is then applied to the other assets listed above. The main sensitivities of each asset category has been assessed using a literature review, and exchanges with the transport authorities have assisted the working group in defining general sensitivity indicators and to develop a scoring scale. The overall sensitivity of each asset category has thus been scored. More detailed exchanges with experts and with the transport agency are undertaken by the working group to define the aggravating and adaptive factors to differentiate the sensitivity of different assets from the same category. These include the traffic level (with a heavy traffic, the road may suffer from accelerated damages during heat waves), the porosity of the road (the more porous it is, the more it may be damaged by heavy rains), etc.

To score the exact sensitivity, a national database (entitled Isidor) has been used. This database provides information for the state-owned roads on the traffic level, on the materials used to build bridges, it describes the road crackings, etc. The scoring of the sensitivity of each asset is a modulation from the overall scoring of the sensitivity of the asset category by hazard with the aggravating or adaptive factors. This scoring has then been combined with the current and future exposure to assess the evolution of the vulnerability, and a criticality assessment has then been conducted.

Source: Cerema. Analyse de risque DIR Méditerranée, 2017. [6]

Box 10: Overview of the EWENT project in Finland

One of the deliverables published in the framework of the research project EWENT has focused on the impacts of hazards on different types of transport modes, including roads. This research project is based on a large literature review including more than 150 scientific papers or studies, and a media review led on 190 hazards that have occurred in different European countries. Thus, the research study has identified different potential impacts of climate hazards on assets and on the functionalities of road networks and has proposed a classification of the level of impacts according to different values of hazards, at a European scale.

Source: Leviakangas, P., Tuominen, A., Molarius, R., Kojo, H. Extreme weather impacts on transport systems, 2011. [23]

8.1.4. Assessing overall vulnerability

The overall vulnerability of an asset or a section of network is defined in the PIARC Framework as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. In more technical words, vulnerability is a combination of sensitivity and exposure, and 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.

Most often, the case studies combine the sensitivity with the current or the future exposure using a scale based on the scales of exposure and sensitivity. It is useful to design the scale with the transport authority to define level of scales adapted to practical issues of the authority.

If risk assessments are to be undertaken for different networks, it is important to anticipate that the comparison between the assessment will be possible only if the scale of vulnerability is the same for each study.

Box 11: Improvement of Pasakha Access Road - SASEC Road Connectivity Project

The area of Pasakha Access Road project lies at the bottom of a high steep region in the South-West of Bhutan, partly composed by an unconsolidated formation. The soil water interaction, completed by abrupt slopes, leads to frequent landslides that can severely damage road infrastructures and the agricultural and forest land.

On steep slopes, high stream velocity can occur inducing the erosion of cobbles and boulders. Flash floods in these highly erodible valley slopes sweep earth, mud and solid debris through the rivers and undermine the infrastructure. A non-suitable road design can result in serious road and environment damages due to high concentration of runoff and low quality soils in this region. The environmental impact must be monitored at each step of the design and construction.

Due to climate change, Bhutan's annual air temperature is forecasted to increase by 1°C in the next 25 years and by 2°C in 55 years with higher frequency of heat waves in summer time and greater variation in seasonal temperature. This climate evolution can lead to rutting, stripping and segregation of pavements, creating or accelerating the road failure. Moreover, the variation of temperature will affect thermal expansion and contraction of bridge structures. Premature damage to the ends of deck slabs and road hazard could occur on bridges.

In South-West of Bhutan, precipitations are expected to increase both in intensity and in duration, by 10 to 18% between 1999 and 2050 (according to the Capacity Building of National Environment Commission in Climate Change report). In addition to this, the disparity of rain frequencies between the different seasons will grow, with ever more rain in wetter period and winter even drier. The extreme downpour coupled with clogged drainage system will scour and weaken the pavement surfaces resulting in pot holes and possible removal of bituminous layer.

The increase in rainfall intensity, duration and frequency will result in higher peak flow levels and higher risks of flooding and landslide. These will directly impact stream velocity at bridge locations and then runoff or flood discharging capacity of the drainage system and the extent of flood protection of works and scouring. The bridge and drainage infrastructures can suffer severe damages due to these floods and their solid debris.

Source: Egis, Improvement of Pasakha Access Road – SASEC Road Connectivity Project – Bhutan, 2016. [26]

8.2. Assessing criticality

Criticality is defined by the All-Hazard Guide for Transport Infrastructure (2015, see [27]) as the relevance of an infrastructure element or section to the availability of a road infrastructure system. Additionally, a critical asset is defined in the NCHRP Project 20-05, Synthesis Topic 48-13: *Resilience in transport planning, engineering, management, policy and administration,* as assets, that if lost or damaged, would severely degrade or curtail an owner's ability to perform core functions or its mission.

HB 167 also states that the criticality assessment (in some sources known as the 'asset assessment'), involves the identification of the critical assets (people, property, information and the processes that support them) that may be exposed to, or harmed by, the threat. The criticality assessment is a vital step in the identification of risk as it provides the starting point for a consideration of the pertinent threats, and the organisation's, community's or individual's vulnerability to those threats. In many circumstances it is difficult and costly to conduct a thorough risk assessment for all assets, locations and people. The criticality assessment allows the analysis to focus on those assets that are of most importance to the organisation, community or individual. The choice of assets to be assessed will be guided to a large extent by the context developed for the risk management activity.

Critical infrastructure is also defined in Australia [57] as, "those physical facilities, supply chains, information technologies and communication networks which, if destroyed, degraded or rendered unavailable for an extended period would significantly impact the social or economic wellbeing of the nation or affect Australia's ability to conduct national defence and ensure national security".

In this context, 'significantly' means an event or incident that puts at risk public safety and confidence, threatens our economic security, harms Australia's international competitiveness, or impedes the continuity of government and its services [57].

As outlined in Box 1, the aim of the Australian Government's Critical Infrastructure Resilience Strategy is the continued operation of critical infrastructure in the face of all hazards. The Australian Government's policy approach to critical infrastructure recognises that [57]:

- critical infrastructure is essential to Australia's economic and social prosperity;
- resilient critical infrastructure plays an essential role in supporting broader community and disaster resilience;
- businesses and governments have a shared responsibility for the resilience of our critical infrastructure, requiring strong partnerships; and
- all States and Territories have their own critical infrastructure programs that best fit the operating environments and arrangements in each jurisdiction.

8.2.1. Functional and Project Level Definitions

The PIARC Framework does not define "criticality", but many case studies collected by TC E.1 use this notion to assess the impact of climate change on the functionalities of the networks. In other words, the purpose of criticality assessment is to identify the impact of (local or regional) failures on the performance of the network. This provides a basis to establish the priorities of the adaptation measures to be deployed. According to the French risk assessment methodology, the performance of a network depends on the following factors:

- Connectivity: Does the network allow for travel from one place to another? For example, from a house to an hospital or a school? Or from a fire department to an area impacted by a fire?
- Quality of service: Under which conditions of speed, comfort, safety, reliability, etc. does the network allow users to travel?
- Capacity: How many users can the network convey simultaneously? The notions of quality of service and capacity are closely linked: the more people or goods have to be transported at the same time to the same place, the more inferior the transport quality will be, with wasted time, inferior reliability, congestion, queues, etc.

- Costs: A transport network incurs construction, maintenance and operating costs that are reflected in the prices paid by the users, or in the contribution made by taxpayers.
- Other parameters might be taken into account, such as the symbolic value of a network.

Climate hazards may cause failures which can occur in isolation (e.g. where a road is washed away by a landslide; however, the remainder of the network is unaffected) or at the same time (e.g. flooding or extreme winds and their consequences such as fallen trees may block several roads in the same sector). In both cases, such hazards may only have a minor effect in terms of the performance of the network (the affected roads are not very busy and alternative roads are available; users are still able to travel under conditions that are almost normal) or they may have a very serious impact (travelling becomes much more difficult, or even impossible).

These impacts are measured with the performance factors previously mentioned. As there are many ways to combine and measure these variables, it is necessary to identify which functionality the critical assessment will include. This depends on the aim of the risk assessment (see Section 6.1 on the objectives and scope of the risk assessment). For example, does the road authority want to assess the impact of a failure on the economy of its territory, and thus more particularly on the regular travels? Does it want to identify the networks that have to be protected for the emergency services during a crisis?

The criticality assessment therefore necessitates, first, the identification of the functionalities of the network that have to be assessed. The French risk assessment framework lists the following functions of a network:

- Essential transport functions: this category includes movements that must be possible at all times and at all cost, especially if a hazard occurs. This includes access for rescue services, medical services, firefighters, the police, the evacuation of persons, military transport, etc. This is essentially an issue linked with connectivity. It must be possible to reach anywhere from anywhere, given that the solutions providing this connectivity may include barring access to the transport networks to other users, the design and use of special vehicles, the use of other modes of transport, etc.
- Service or accessibility functions: this category includes movements involving essential services, such as access to food, health services, etc. Substitutes are available for these movements. For example, if one food store becomes inaccessible for people living somewhere, but another food store is available, then there is no particular problem. On the other hand, if all the stores become inaccessible, then the consequences can quickly become very serious.
- Regular travel functions: this category includes all the movements of persons and goods that contribute to the workings of society and, in particular, of the economy. The function of a transport network is to allow these movements to be made under good conditions and, in particular, ensure safety. From the users' perspective (passengers and goods carriers), a loss of performance of the transport network results in travel time delays, the need to postpone or reorganize travel, or to defer activities and to transfer these activities to a site other than the preferred site, or even to cancel them. In a supply chain, this can result in breakdowns in supplies, with economic consequences that go as far as bankruptcy, and, therefore, job losses. Some of these issues are explored further in Section 11.2.2.

8.2.2. Choice of assessment methodologies for criticality

There are three main parameters, which influence the choice of the assessment methodology:

1. Type of function to be considered.
2. Extent of the network and/or the territory in the area of study
3. Data availability at this scale.

The French Framework, including risk assessment methodology, provides guidance on how to choose the most suitable criticality assessment methodology depending on these two parameters. The methodologies are described in Table 2.

	Functionality to be assessed		
	Essential transport function	Service or accessibility function	Regular travel function
Main performance criteria	Connectivity	Connectivity	Quality of service, capacity, costs
Type of methodology to use	- Assessment of inaccessibility based on indicators of connectivity - Identification of the networks that must be protected	- Assessment of inaccessibility based on indicators of connectivity - Identification of the networks that must be protected	- Assessment of performance losses by a multi-criteria method - Assessment of performance losses with a traffic model
Case study examples	RESEAU² [28-31]	RESEAU²	Criticality assessment of Dir Méditerranée in France[6; 20], of multi-criteria methodology used in France

Table 2: Transition from network functionalities to a criticality assessment

The European Project SERON (http://www.seron-project.eu/) uses a similar approach for assessing the criticality (network importance). This is detailed as follows:

Step 1: Road corridor selection and identification of potentially critical infrastructure objects

The aim of Step 1 is to identify the potentially critical infrastructure objects and rank them according to their degree of criticality.

The road operators or owners select a road corridor they want to investigate. This could be any road corridor for which they are responsible, e.g. a TEN-T corridor which has a vital function in the overall road network of a country or within the EU.

Following this step, the relevant technical data of the infrastructure objects along the selected corridor and the traffic data of the corridor have to be collected. This includes general technical data of bridges and tunnels such as the length, type of construction or material used. The road network data used is Average Daily Traffic (ADT) and Heavy Goods Vehicle (HGV) percentage. All infrastructure objects on the selected road corridor are investigated according to their potential criticality.

Step 2: Calculation of network importance

In Step 2, the objects selected in Step 1 are ranked according to their network importance. For this step, detailed road network data is required and a specific traffic and transport model should be applied.

The network importance is defined as the benefit which arises from the prevented non-availability of a certain infrastructure objects. The network importance of a road infrastructure object is not only reflected by the consequences of its non-availability for road transport, but by any kind of socio-economic effects. Therefore, the developed assessment procedure takes into account that road users, traffic flow, the infrastructure object itself as well as the surrounding regional economy may also be affected by the non-availability of infrastructure objects. Resulting consequences are quantified, monetised and summed up to a final importance value. This importance value describes the benefit resulting from the prevented non-availability.

Box 12: A methodology to identify the networks that must be protected: RESAU²

RESEAU² is an approach to identify the most important networks in order to define those one that must be open for rescue services transport or to provide an access to inhabitants to essential services such as hospital or supply centres (e.g. for food) is the RESAU² approach, its process is explained below:

- the first step is to identify the critical centres (hospitals, fire stations, etc., i.e., centres that must remain operational in order to limit and quickly resolve a crisis);
- this is needed to deduce which networks, and transport networks in particular, are essential for these critical centres to function; and
- and the last step is to identify the measures that will enable these networks to remain in operation under any circumstances.

This approach is particularly interesting for a large number of hazards, or hazards disrupting a large part of the network are expected, and for hazards where the occurrence and consequences are difficult to predict. This approach can be based on expert judgements, or better, if feedback from past events is available, data such as the disruption duration of a network or the number of vehicles that have been rerouted may be useful to identity the critical networks and/or the adaptation measures.

Source: Cerema. Stratégie d'exploitation - Vallée du Rhône en Drôme-Ardèche, 2009. [29-31]

Box 13 discusses criticality in the context of redundancy. This topic is to be considered as part of the next cycle in the ongoing refinement of the PIARC Framework.

Box 13: Assessing regular travel criticality: an example of multi-criteria methodology

The criticality assessment may also focus on the performance of the network for regular travels of persons and goods. As models may not be available for each networks, and as it is time-consuming and costly to design models, a multi-criteria method may be used.

A multi-criteria method has already been applied to assess the criticality of a network in a French conurbation. Therefore, the network has been divided into road sections. For each section, the following indicators of criticality have been assessed: the traffic, its structure (internal, junction, transit, or a combination of the three), the alternative roads and their capacity to absorb the traffic that may have been be rerouted from the section that is assessed (if this section would have been cut). The sections were categorized into four groups:

- "low importance": At least one of the alternative roads has a high available capacity;
- "moderate importance": the alternative roads only have a moderate available capacity;
- "high importance": An alternative road with a low capacity is available, and one or two alternative road have a moderate available capacity; and
- "very high importance": The alternative roads have very low available capacity, or there are no alternative roads.

Source: Cerema. Analyse de risque "Nancy-Brabois", 2016. [5]

In this study, the transport network is assessed as critical if it is heavily used and if there are no "good" second choices for the users. Multi-criteria analysis is further discussed in Section 9.

8.2.3. Scoring criticality

As for the sensitivity and vulnerability ratings, it is possible to score the criticality (which can be assessed on a semi-quantitative and fully quantitative basis) by developing a specific scale describing the potential extent of the impact of each climate hazards for the road agency. Close attention is required as to the levels of the scale if it is expected that the results of the criticality assessment will be compared between different risk assessment studies.

In Germany a quantitative approach for assessing criticality has been applied. Further information is provided within: http://www.seron-project.eu/download/SeRoN_D400_ImportanceStructuresTrafficNetwork_summary_1.1.pdf

9. HOW IS A RISK ASSESSMENT APPLIED?

As outlined in Figure 3 in Section 6.2 a holistic risk assessment involves the analyse and prioritisation different risks relevant to an infrastructure/project, and the ranking of assets, locations, and operations according to the level of risk probability (likelihood of future impacts on the asset) and severity (consequence of the impacts on the asset). The assessment and prioritisation of risks within Stage 2 of the PIARC Framework outlines that risk is a function of probability and severity. The risk assessment also aims to provide a list of prioritised risks, whereby high extreme risks would be the focus of an adaptation response [55].

This step therefore involves prioritising risks by raking the severity of each risk as well as identifying the risks that require further attention (AGO in [54]). This section covers the following:

- identify the type of risk assessment chronology and scenarios
- assessing impact probability (likelihood)
- assessing impact severity (consequences)
- establish risk scores and a risk register
- compare risks to other types of risks
- determine which risks area acceptable and which require further attention.

It is important to note that often the words ‘threat’ and ‘risk’ are often used interchangeably across literature. However, risk is not a synonym of threat, although closely related, the two are significantly different. In many circumstances a ‘threat’, or threats will provide a source for one or more risks. It is the interaction between the threat and someone or something, at a particular instance or over a period of time that will create the risk. Threats may exist, but not pose a risk.

In general, three types of risk assessment methodologies are used:

- Case studies such as strategies or policy guidance, assessments developed for broad geographical areas including not only road networks but also, railways, waterways, etc., or assessment for which a few databases on asset specifications are available use a qualitative or semi-quantitative approach.
- Vulnerability and risk assessment for smaller geographical areas (e.g. a city) or focused on a single type of network on a large geographical area (e.g. a road network of hundreds of kilometres) are also based on qualitative and semi-quantitative assessments.
- Vulnerability and risk assessments led for very specific assets (such as bridges or a small section of road) can be based on semi-quantitative or quantitative assessment.

An example of the types of risk assessments which could be undertaken is set out in Table 3. This highlights consideration of qualitative, semi-qualitative and quantitative assessments.

Qualitative	Semi-quantitative	Quantitative
- Strategies or policy guidance - Risk assessment with various networks on broad geographical areas - Risk assessment with a few data/human/economical resources available - First step of a semi-quantitative or quantitative risk assessment	- Risk assessment on mid-geographical areas - Risk assessment focused on one specific network even if the geographical area of study is broad	- Risk assessment of specific assets for which models are available

Table 3: Types of risk assessments

The qualitative, semi-quantitative and quantitative approaches can be combined in an iterative manner. In the case of a vulnerability assessment, if this is led on a very broad network, it shows that some specific assets are more vulnerable, it might be relevant to conduct a quantitative assessment for these specific assets.

In the case studies identified, there are a number of approaches which apply a risk assessment. These comprise:

1. Top down approaches e.g. taking an existing method/framework and implementing these concepts.
2. Indicator based approaches.
3. Quantitative risk analysis and probabilistic risk analysis.

It is noted that a range of case studies have been developed demonstrating various Frameworks and methodologies. Some of these include:

- Intergovernmental Panel on Climate Change. Climate Change. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Suisse
- Banco Interamericano de Desarrollo (BID). (2013). Integración de la Gestión de Riesgo de Desastres y la Adaptación al Cambio Climático en la Inversión Pública (Integration of Disaster Risk Management and Adaptation to Climate Change in Public Investment). Washington, DC
- Inter-American Development Bank (IDB). (2015). Climate Change Risk Management Options for the Transportation Sector. Fact sheets. Washington, DC, USA

- Conference of European Directors of Roads (CEDR). (2010). Risk management for roads in a changing climate. A Guidebook to the RIMAROCC Method. ERA-NET ROAD.

This section provides a summary of some approaches which have been identified as examples of these abovementioned approaches.

9.1. TOP-DOWN APPROACHES

An example of the application of a top-down approach is provided for Mexico.

In the last few years, Mexico has faced an increasing number of challenges due to extreme hydrometeorological events such as tropical cyclones, floods, and droughts. In order to manage climate change, a disaster risk Venn diagram was developed which looked at the climate event (danger), the exposure and the vulnerability. The vulnerability analysis considers a Health Vulnerability Index, Social Vulnerability Index, and agricultural vulnerability indexes (Agricultural Temperature Vulnerability Index, Rainfall Vulnerability Index, and Livestock Vulnerability Index). Danger is defined as a function of the event occurrence frequency, measured by its return period that affects specific sector.

Strategic social and economic infrastructure is also exposed to catastrophic events. Strategic social and economic infrastructure refers to the urban environment, health, education, energy, communications, tourism and commerce. If early assessment is undertaken, this allows substantial time and resources to assess strategic assets which are located in high danger zones.

Natural disasters have historically had a large and widespread impacts on infrastructure. Therefore, Mexico use the DESINVENTAR [3] database, which has helped identify these effects and impacts and their geographical location. There are many natural events that can affect the road infrastructure and this section outlines each of these in detail. Storms have increased in both frequency and intensity causing extreme rainfall, treefalls, inadequate visibility, and strong winds. This has led to a high presence of water and its accumulation, causing flooding, erosion of riverbeds, increased presence of water on the road surface and high penetration of water into natural slopes. Insufficient drainage of storm water can lead to instability of structures, a loss of infrastructure, changes in peak and return periods, and rapid accidents. On the other hand, drought or a water deficit also has severe consequences including: overuse of compaction and dry materials in road construction, insufficient moisture to maintain vegetation cover leading to increase erosion, forest and bush fires, loss of cohesion between different layers of pavement, and settlement of pavement structures. Furthermore, road infrastructure can be affected by changing temperatures, namely temperature rise. This can lead to pavement deformations, road accidents, increased energy consumption due to vehicle air conditioning, damage to vehicles and damage to the good being transported.

In the implementation of the Framework in Mexico, the risk assessment was carried out through the methodologies and maps developed by the National Center for Disaster Prevention, for the

[3] Sistema de inventario de efectos de desastres, http://www.desinventar.org/es/

different types of climatic hazards, such as floods, heat waves, hydrometeorological phenomena, etc. [4]

- Centro Nacional de Prevención de Desastres. (2012). Mapas de índices de riesgo a escala municipal por fenómenos hidrometeorológicos (Maps of risk indexes at municipal level due to hydrometeorological phenomena). México, DF
- www.anr.gob.mx/Descargas/Metodologias/Hidrometeorologico.pdf
- Centro Nacional de Prevención de Desastres. (2016). Metodología para elaborar mapas de riesgo por Temperaturas máximas (1ª etapa ondas de calor) (Methodology to prepare risk maps for maximum temperaturas). México, DF
- http://www1.cenapred.unam.mx/COORDINACION_ADMINISTRATIVA/SRM/FRACCION_XLI_A/33.pdf

9.2. INDICATOR BASED APPROACHES

9.2.1. Resilience and Assessment of Climate Risk: Experiences from Road Infrastructure in Germany

There are three main groups where road infrastructure performance is affected. These are the user, the owner, and the operator. For the user, owner and operator resilience refers to reliability of the road, safety on the road, and availability of roads for travel. For the user these are largely influenced by mobility demand quality of life and competitiveness. For the owner and operator these are influenced by mobility supply, climate change and ageing infrastructure. Mobility supply, although increasingly complex, can be managed by innovation and smart management solutions that are interdisciplinary and multi-modal.

Climate change, natural hazards and extreme weather can affect the road infrastructure in many ways; therefore, the road infrastructure needs to be resilient. This can be achieved through adaptability, robustness, durability, and recovery of infrastructure. When assessing these impacts, Climate and Natural Hazard Impact Classification or Assessment Frameworks can provide an integrated perspective on the complex transport interdependencies, and connectivity redundancies. A large component of this process is a risk analysis to assess the exposure, vulnerability and criticality from the network level right through to the object level.

Due to the requirement for risk analysis, a R&D project model “RIVA” was developed which provides an assessment of key transit areas of the federal main road network in the context of climate change. This asks the following questions:

- Which road elements and assets are prone to specific climate hazards?
- How can we assess the level of hazard and risk in systematic ways?
- To what extent is a systematic risk analysis at the network level possible?

The methodology of the RIVA model follows a process of identification, analysis, and evaluation of elements at risk, consequences and cause-effects. Test corridors were selected for the application of the RIVA model with different climate and geography, traffic volume (low, medium, high),

[4] http://www.atlasnacionalderiesgos.gob.mx/archivo/visor-capas.html

construction type, age, condition, TEN-T and international connectivity. There were nine sections identified between 60 to 130 km in length and 1200 km of the federal road network. The model identifies climate risk, the elements at risk, and estimates the criticality/risk potential via a risk index.

Another example of the vulnerability indicator-based approach on exposure and related characteristics is provided in Table 4. It sets out the vulnerability component, indicator, particular asset type, range of stressors and the location of the project).

Vulnerability component	Indicator	Asset Type	Stressors	Location of pilot study
Exposure	Elevation relative to the nearest flood zone	Road, Bridge, Culvert, etc.	Coastal flooding Heavy precipitation	South Florida

Table 4: Example vulnerability indicators based on FHWA pilot studies[5]. Source: FHWA (2016)

9.2.2. Assessing the risks incurred by future extreme climate events on infrastructures and networks: a risk assessment framework in France

In the framework of the French National Climate Change Adaptation Plan (PNACC), Cerema and partners have defined a harmonised methodology to assess the vulnerabilities, criticality and risk of transport infrastructure and services for land, sea and airport networks. The aim of the PNACC is to establish a statement of vulnerability and criticality for land, sea and air transport networks in continental France and in French overseas territories and to prepare appropriate and phased response strategies to local and global climate change issues.

The methodology of assessment has been implemented for example on a large state-owned road network in the South-East of France (DIR Méditerranée) [6; 20]. The first step of the study was to define the objectives and scope of the study, and to create an appropriate working group with various specialists and with the road agency (see Section 6.2). The working group had undertaken an extreme events assessment by listing and selecting relevant climate extreme events (see Section 7.2) by using several databases of past, present and future events, amongst which were DRIAS and Climat HD (see Section 7.3). The current and projected characteristics of events have then been analysed for frequency, spatial occurrence and temporal occurrence. This allows a score to be assigned to each extreme event according to its projected evolution of intensity or occurrence (see Section 7.4).

Criteria are then used to generate vulnerability indicators, which are based on how specific climate events will physically affect the different components of road infrastructure on the network (see

[5] Between 2013-2015 FHWA (2016) conducted a Climate Resilient Pilot program to assess options to improving resilience, and to synthesise the lessons learned in assessing transport vulnerability and assessment of options for improving resilience. As part of this project, a consolidated list was developed of vulnerability indicators used across a range of pilot projects and these indicators are broken into the vulnerability components of exposure, sensitivity and adaptive capacity.

Section 8.1.4). The evolution of the vulnerabilities has been assessed by combining the vulnerability scoring and the extreme events scoring.

In parallel, the criticality of the network has been assessed mainly for the regular travel function of this network; for example, based on criteria linked with the traffic load and the economy of the territory. It has therefore been necessary to identify the possibility of road disruption even without infrastructure damages, which are associated with climate events.

Once an assessment of criticality is obtained, this can also be evaluated with the criticality scoring which has been combined with the risk assessment. This will influence the development of adaptation measures and strategies. In the framework of the PNACC, Cerema with its partners have also analysed which standards currently used for the design, maintenance and operation of transport infrastructure should be adapted to climate change. The adaptation of standards is currently being undertaken. This is an example for transport adaptation (see Section 10.1.1).

Other work towards implementing the framework is ongoing. For example, the frameworks application to a large city centre with many transport networks, national and local roads, as well as public transport, and on a large harbour.

9.3. Quantitative risk analysis, assessment and probabilistic risk analysis approach

9.3.1. U.S. FHWA Climate Resilience Pilots: Highlights, Outcomes, and Next Steps

In 2012, the Federal Highway Administration (FHWA) developed a climate change and extreme weather vulnerability assessment framework (semi-quantitative example). This framework defines the project scope, assesses vulnerabilities and integrates vulnerability into decision-making. This framework was developed after funding five pilot vulnerability assessment studies at transportation agencies around the country. It mostly focuses on conducting a vulnerability assessment by determining vulnerability as a function of exposure, sensitivity, and adaptive capacity. It also touches briefly on integrating results into decision-making. Although, when this framework was developed in 2012 it was noticed that there were some gaps that needed filling, namely; examples were required for non-coastal states, climate impacts due to changing temperatures were not included, how to incorporate the effects of changing precipitation patterns was not included, and building these vulnerability assessments into decision-making was not covered. Therefore, a second round of nineteen pilot studies was undertaken in order to ensure that transport agencies across the country would be able to use the framework, and to fill the gaps.

An example of one of these studies is the three-tiered approach undertaken in Maryland, which assessed the vulnerability of assets in two different counties. Tier I mapped projected sea level rise, storm surge, and riverine flooding and screened for assets exposed to climate stressors. Tier II used an indicator-based approach to assess the vulnerability of bridges and roads. Tier III was informed by the results of the first two tiers and specifies adaptation measures on a site-specific basis, this was although outside the scope of the pilot study. Maryland is also using the maps they developed as part of this pilot program in order to consider sea level rise impacts in environmental review. For example, all minor federally funded roadwork projects in the coastal counties need to fill out a form to receive environmental clearance. The form asks whether the work will take place in an area potentially impacted by sea level change based on the maps. If yes, it notes that the project must consider sea level change.

Another example is from Massachusetts. Massachusetts DOT used a hydrodynamic model to develop a series of maps showing the likelihood of inundation from sea level rise and storm surge at any location over the Boston area today, in 2030, in 2070, and in 2100. They used these maps to predict vulnerabilities to transportation infrastructure. For example, looking at a tunnel portal, what they found in a particular place, was that temporary barriers would be enough to protect from a 1,000 year storm in the near term (which is what the tunnel was designed for), but due to sea level rise, more comprehensive protection such as watertight floodgates would be necessary by 2030.

The following paragraph is a short summary of outcomes from some of the other pilot projects. Results from the Caltrans District 1 pilot are informing studies on US 101 and are helping a local transportation agency assess routing options over a river. Caltrans replicated their District 1 study for the remaining the Districts in the State. Connecticut DOT plans to update their Drainage Manual because of their pilot study. Capital Area MPO and Hillsborough MPO have incorporated vulnerability assessment into their 2040 Long Range Transportation Plans. Michigan DOT is adding new fields to their asset management systems to display the vulnerability assessment results. Iowa DOT is adding data generated during the pilot project into their Bridge Watch program to help decision-makers take a proactive approach to public safety during potential overtopping events. The Maryland State Highway Administration is using the results of the pilot program to delineate coastal locations vulnerable to flooding to help screen new project plans and design for future climate impacts.

The recommendations from the pilot program for the FHWA included: further refine the Framework to reflect lessons learned from pilot projects, provide resources to help evaluate the costs and benefits of adaptation strategies, facilitate coordination with U.S. Army Corps of Engineers and other federal agencies and help secure additional funding for analysis and implementation of adaptation strategies. It was identified that more information was needed regarding comprehensive and accessible data on assets, historical data on impacts and cost, and information on values for costs and benefits. It was also identified that guidance tools were required to assist with utilizing climate information, cost-benefit assessments and integration of vulnerability assessment results and adaptation into transportation planning. FHWA released an updated version of their Framework in December 2017.

9.3.2. INFRARISK

In INFRARISK, stress tests approaches and methodologies are applied using integrated modelling tools for decision-support. This is to establish the resilience of critical infrastructure to rare low frequency extreme events, and to aid decision-making regarding robust infrastructure development and protection of existing infrastructure. This has been achieved through developing an operational analysis framework that considers the impact of individual hazards on specific infrastructure systems, and the coupled interdependencies of critical infrastructure, addressing the complexity of “Known Unknowns” and “Unknown Unknowns” scenarios through robust risk and uncertainty modelling.

A general framework for the assessment of different hazard types is available. This framework is based on the harmonization of probabilistic models, which estimate a set of intensity measures at the vulnerable sites based on the occurrence of source events, accounting for various uncertainties. The parameters that are specific to each hazard types are summarised in a Hazard Distribution Matrix. Based on the hazard models a framework for harmonized fragility models has been derived. Sources of uncertainty that are involved in the risk assessment process for different hazard types are identified.

Practical software tools and guidelines are available that support infrastructure owners and operators in assessing the probability of occurrence of extreme rare events and assessing the vulnerability of critical infrastructure.

10. SELECTING AND MONITORING ADAPTATION MEASURES AND RESPONSES

A wide range of adaptation measures have been considered internationally, and these have been identified and implemented on the basis of purpose, location, cost or implementation timeframes. The matrix developed for this report (as outlined in Section 5.4), indicates that there is considerable information available on types of adaptation measures and responses, including structural, operational, organisational and planning measures. Fewer case studies are available on the monitoring of the efficiency of adaptation measures, however some specific examples are identified in Queensland, Australia with the real-world testing of foam-bitumen stabilisation resulting from recent cyclone events.

This section outlines the types of adaptation measures and responses being applied internationally, and discusses the application of these in terms of adaptation needs and monitoring of these measures.

10.1. IDENTIFYING TYPES OF ADAPTATION MEASURES

As transport infrastructure involves long-term investments with design lives of 20 to 40 years, and bridges over 100 years, an understanding is required of the expected impacts of future climate change over the asset lifetime. This could enable considerable cost savings in the long-term. If practitioners and decision-makers are forewarned of any costly future effects on existing infrastructure, it is possible to better prepare for these events [32]. A way of preparing for future climatic impacts is through the identification, prioritisation, implementation and monitoring of adaptation measures to increase the resilience of networks and ensure the levels of risk are acceptable, and current levels of service are maintained. These responses act as a guide for practitioners and can vary widely in terms of ease of implementation (cost, resources and technical feasibility). Some can be delivered through existing maintenance programs, whilst others require stand-alone capital investments [4]. As such, there is a direct link between adaptation strategies and decreasing the likelihood and consequences of climate change impacts. This linkage is outlined in a Climate Change Risk Assessment [58] developed by VicRoads, shown in Figure 4, which shows the types of climate change events, impacts and consequences on roads, and adaptation strategies to decrease the likelihood and consequence of impacts.

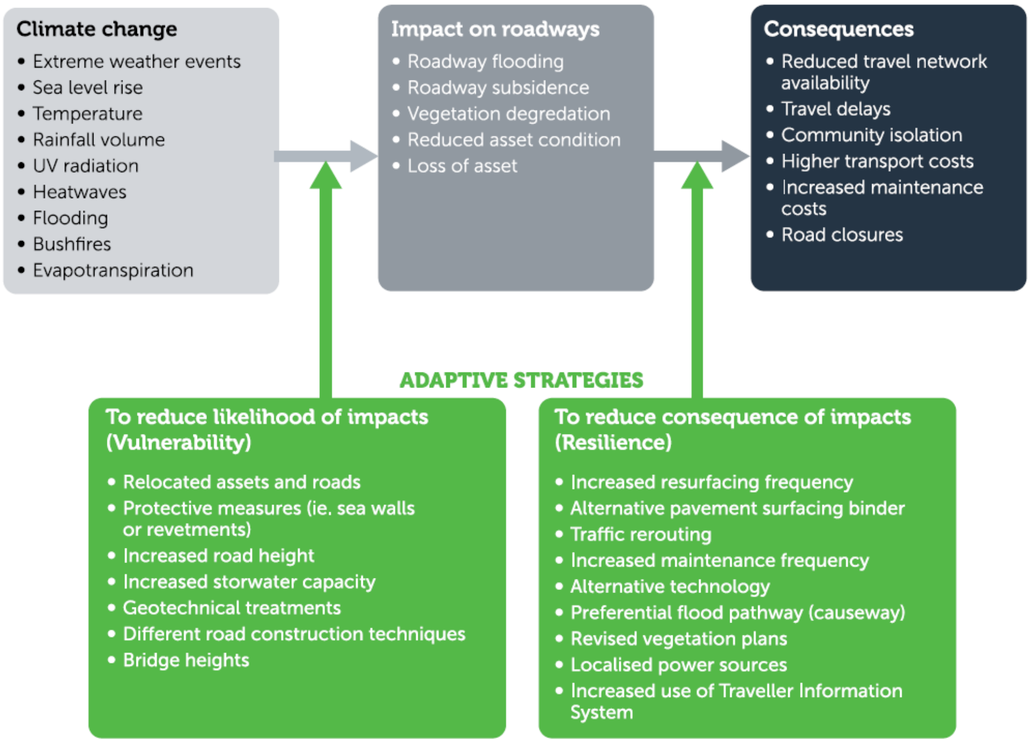


Figure 4: Adaptation strategies to decrease the likelihood and consiquences of climate change impacts. Source: Adapted from Melillo, Richmond, & Yohe (2014), cited in VicRoads (2015)

According to FHWA [33], adaptation solutions can be natural, structural, or policy-based and can range from site-specific to regional. Adaptation measures can include:

- New assets to withstand environmental conditions anticipated in the future
- Retrofitting existing infrastructure to a standard that includes resilience to anticipated effects of climate change and future-proofing designs
- Increased redundancy of the system to ensure that other infrastructure alternatives exist for transport services (e.g. building alternative access routes and contingency plans)
- Reallocate assets to avoid damage
- Institute intensive or targeted maintenance schedules (e.g. maintenance and monitoring of drainage systems)
- Integrate findings into system planning
- Improve operations plans for weather emergencies, including early warning systems, reactive measures and procedures (e.g. improving communication to society prior, during and after events, or resilience of supply chains, such as reliance on one maintenance contractor can lead to difficulties if the location is inaccessibility following an event) [33; 34].

For the purpose of this report, the abovementioned measures have been documented according to the TC Internal Task Force Matrix categorisations. These are outlined in Table 5, and have been expanded in sub-sections below.

Adaptation measures (Infrastructure related)	Adaptation measures (Traffic hazard management)	Adaptation measures (Maintenance measures)	Adaptation measures (Planning)
• Road adaptation measures • Bridge retrofit, … • Tunnel (protection for flooding, …..) • Retaining structures • Evacuation route • Others	• Intelligent Transport Systems (ITS) • Early warning systems • Re-routing (short term and planned)	• Periodic • Routine • Service restoration	• Integration of climate change in the design phase • Technical regulations • Adaptation of current regulations to climate change • Legal frameworks • Others

Table 5: Adaptation measures for infrastructure, traffic hazarad management, maintenance and planning

Adaptation measures can be defined as hard measures [6] (e.g. barrier walls for protection from erosion, levees, alternative surfacing), and also involve the use of soft measures (e.g. creation of wetlands, barrier islands, green infrastructure to cope with high precipitation events, establishing well-prepared command and management structures, providing appropriate information systems or training personnel for managing catastrophes), or the implementation of strategies and planning measures (e.g. amendments to regulations or standards). Additionally, according to Petkovic et al. (2008), adaptation measures can be categorised as:

- Measures for new roads: climate adapted design and construction
- Measures for existing road networks: climate-adapted operation and maintenance
- Preparedness measures adapted to a more demanding climate
- Developing a knowledge base for climate adaptation.

[6] According to the ACRP adapt2to4 project, Austria, this is defined as “grey adaptation” whereby reactive investments are usually high and can have high impacts on ecosystems. Additionally, the report defines “green adaptation” as low-cost and low-regret adaptation since it supports, maintains or extends existing ecosystem services. It often involves foresight and proactive action and should be implemented before excessive damages have occurred (e.g. afforestation or reforestation of forests to retain mass movements in avalanches). “Soft adaptation” can also offer a non-invasive, low-cost and can be implemented without implications for ecosystems (e.g. flood zoning, alternatives to allow modal switches for all arterial connections).

The PIARC International Climate Change Adaptation Framework for Roads provides a list of adaptation responses according to climate change impacts, and also lists some adaptation case studies. Some specific case studies of adaptation measures and responses collected by the E.1 Case Study Taskforce are identified in Boxes 14 to 26.

10.1.1. Infrastructure related adaptation measures

This section details infrastructure solutions for both hard and soft adaptation measures. In terms of hard solutions, adaptation measures applicable to alternative pavements are being considered internationally. Examples include treatments such as foamed bitumen stabilisation have been used to return assets to the equivalent (pre-damage) standard and improve the resilience of the pavement. Foamed bitumen is formed by injecting a small quantity of cold water into hot bitumen to produce an instantaneous expansion. In this foamed state, bitumen is highly efficient at wetting and coating the finer particles of the pavement material, forming a mortar, and binding the mixture together. In Queensland, Australia, much of the road network is built on expansive soils creating shrink / swell effects that damage the roads. The significant flooding experienced during extreme weather events also highlights resilience issues with some traditional pavement types, hence when used in suitable environments with appropriate stabilisation, foamed bitumen offers much greater resilience, as well as better fatigue performance and improved performance compared to traditional pavements[7]. See Section 10.2 for an example of the effectiveness of this adaptation measure. It is noted that this is an example only and other measures may be considered depending on climatic circumstances in countries.

[7] TMR, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

Box 14: Analysis of the standards for road design, maintenance and operations requiring adaptation (France)

In the framework of the French National Climate Change Adaptation Plan, Cerema published in 2015 a report on the adaptation of standards to design, maintain and operate all type of networks including roads, to climate change. Therefore, a working group was established that was composed of specialists of types of infrastructures: roads, waterways, ports, airports, railways, cableways, etc. from various partner institutes.

The report first describes the climate change trends at the French scale, and the potential evolution of hazards or climate-related variables of importance for transport networks: high and low temperatures, precipitations (including freeze-thaw cycles, snow and ground movements), wind, sea elevation and swell, biodiversity. Then, the report provides an overall description of potential impacts of current and future hazards on networks, and notably on specific road assets and on the functionalities of the road, mainly traffic support.

This helped the working group to understand the effect of climate change on the transport networks and to move to the second step of this report: the analysis of climate-sensitive standards. The working group has listed each document usually used by transport authorities to design, maintain and operate each type of infrastructure: standards, technical guidelines and regulation, and analysed the circumstances in which one climate-related variables are used. The group also took into consideration documents without climate-related variables, which might be impacted by climate change. This work has been done thanks to databases or expert judgements

The documents were then finally listed and classified into three categories of priority of adaptation, and a list of the climate projections required to adapt these reference documents was compiled.

This subsequent adaptation allows future changes in the climate to be taken into consideration more effectively.

Source: Cerema. Potential impacts of climate change on transportation infrastructures and systems, on their design, maintenance and operation standards, and the need for detailed climate projections for their adaptation, 2015. [22]

When adapting to increased temperatures, it is noted some inorganic materials, such as asphalt, steel, concrete and aggregate (sand) are not as exposed to risks associated with rising temperatures as much as previously thought. In a Mitchell Freeway Extension Project [35], Main Roads Western Australia assessed bridges and spray seal and noted that there is sufficient resilience built into traditional structural design solutions that an increase in temperatures (by up to 7°C by the year 2100) is unlikely to have a significantly detrimental effect on their structural sufficiency, associated expansion plates, bearing or guardrails. However, increased temperatures may affect the operation of finger plates due to increased expansion. These issues are intended to be periodically reviewed as more information becomes available, to increase resilience in the future.

Road drainage is identified across many case studies as a possible adaptation measure. Drainage structures can be transverse structures such as culverts or floodways, and can also include longitudinal structures such as table drains. Risk is decreased if these drains are kept in good condition and free of debris or other material, so that they operate efficiently and move water away from the road as quickly as possible without scour [36]. However, an area of deficiency is where intakes are blocked or loaded beyond capacity. The Norwegian Public Roads Administration [37] identifies that to ensure robust infrastructure, culvert and pipe designs should be based on detailed hydrological analysis. In order to improve the robustness of drains, the following adaptation measures are proposed:

- Hydrological analysis should include analysis of natural and manmade spillways, and planning of the drainage system should include measure to collect and control water in these spillways
- Drainage systems should be designed for volume/time, erosion and abrasion, and sediment blockage, and these designs should enable runoff throughout its lifetime with minimum necessary maintenance
- Overflow pipes can be used to increase robustness
- Measures for erosion and material transport control can be built in the catchments upstream from vulnerable parts of the drainage system [37].

An example, where drainage systems have been blocked by sediments leading to extensive damage and minor landslides is shown in shown in Norway (see Box 15). Similarly, Box 16 shows adaptation measures that are applied in Denmark to adapt road drainage to rain events.

Box 15: Drainage system impacts and adaptation measures in Norway

In Odenrun, Norway the drainage system was blocked by sediments and diverted water onto a private property, which had not developed a natural erosion protection. This led to extensive damage and landslides. Sediments from the slides and water transport hit the railroad downstream, plugging drainage and causing a collapse of the railroad embankment. This illustrates the importance of analysing spillways the water can follow if upstream drainage is blocked, and the importance of increasing dimensions and the use of control measures in areas with erosion and sedimentation (The Norwegian Public Roads Administration 2013).

Source: The Norwegian Public Roads Administration, 2013. [37]

Box 16: The Lyngby road, Denmark

The Lungby road was closed on three occasions between 2010-2011. The Helsingør motorway at Ryparken Station was sunk into the surrounding land to reduce noise levels and create space for crossroads. Whilst the road's drainage can cope with water run-off from the road, the conduits throughout which the water is pumped also function as an overflow channel for northern Copenhagen. Problems arise when the conduits are overburdened, hence a number of measures have been implemented by Greater Copenhagen Utility to increase the capacity of these conduits. The risk of flooding has been reduced, however this road still remains vulnerable. The Danish Road Directorate protects road surfaces and signage equipment against increased temperatures and stronger winds e.g. road surfaces, signage, signage structures, barriers and noise reduction screens. By way of adaptation measures worn road surfaces are replaced, and diminishing road-sign structures in relation to relevant climatic models are evaluated.

Source: Danish Road Directorate, 2013. [38]

In relation to drainage, soft adaptation measures such as land-use changes have been considered. In Sweden a study by Kalantari (2011) was undertaken on adapting road drainage structures to climate. It was found that a number of drainage adaptation measures can be implemented to address more frequent floods. These include:

- Increasing areas with high infiltration capacity e.g. reforestation – this can reduce peak runoff and volumes. Increasing the hydraulic friction of a watershed by reforestation can decrease the flow velocity upstream and minimise the peak runoff flow downstream. Higher interception, evaporation and infiltration rates due to the impact of reforestation can also reduce runoff volume [39, cited in 13].
- Reducing the agricultural intensity around streams with vegetation buffers – these include strips of grass or other vegetation between a cropped area and a stream or a drainage ditch. These strips are designed to intercept stormwater, reduce runoff flow and stabilise the stream bank against landslides (Minnesota Department of Natural Resources 2011, in [13]). This measure can slow down stormwater and reduce peak runoff flow in the downstream part of the watershed, and can be used as a method to trap sediments, and other pollutants.
- Implementation of grassed waterways – to prevent or control gully erosion along drains and surface runoff to drains. These are more efficient in small basins.

Other adaptation measures are also being considered, such as improved scour protection, increased stability of precast end walls, providing pipe/culvert resilience, hydraulic assessments. An example of reconstruction of foreshores and rock walls built to protect highways from future events is provided in Box 17, for the Cardwell Foreshore, Queensland which was extensively damaged during Cyclone Yasi in 2011.

Box 17: Reconstruction of the Cardwell Foreshore, Queensland

In Queensland, Australia the Cardwell foreshore was extensively damaged during Cyclone Yasi in February 2011. There was severe damage to the Bruce Highway (link between Cairns and Townsville) and the Cardwell Esplanade. The reconstruction of the foreshore involved the redevelopment of a rock wall to protect the highway from future events, and also provided tourism benefits. The project involved the reconstruction of a 1.4 kilometre two-lane section of the Bruce Highway. The Cardwell Foreshore reconstruction was officially opened in 2013 and was delivered under the National Disaster Recovery and Relief Arrangements (NDRRA), Department of Transport and Main Roads, and the Cassowary Coast Regional Council.

Damage to the Bruce Highway

Before reconstruction

After reconstruction

Source: Department of Transport and Main Roads, Queensland, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

Adaptation measures can also be applied to the design of new roads. The example of a new road in La Réunion island (France) illustrates the solutions used to take in consideration see level changes (Box 18).

Box 18: New road design in La Réunion island (France):

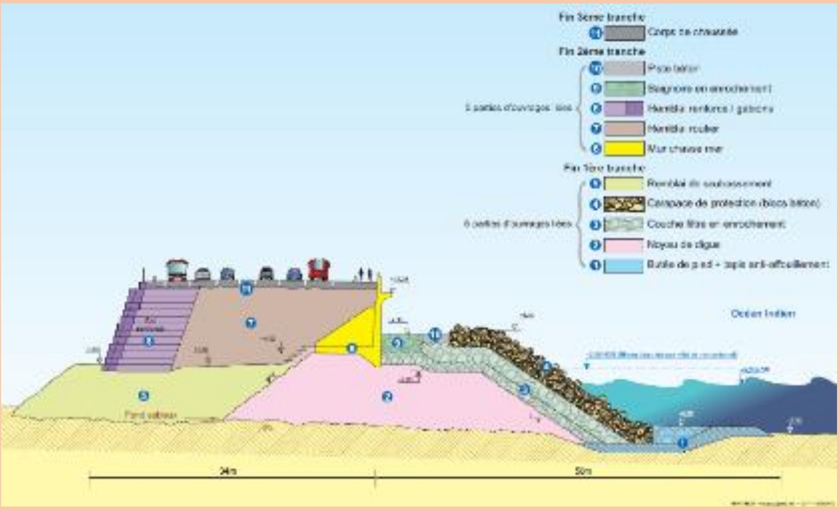
The current coastal road is constantly threatened by two hazards: the falling rocks of the cliff due to heavy rains and the seasonal wave surges. The chosen option for the new shore road is to abandon the current route for a new secure road made up of viaducts and dikes.

This new road is exposed to climate change impacts such as see level rise (increase of 1m in 100 years) and increased wave surge.

Moreover, the increase in rainfall intensity, duration and frequency on the road will also result in higher peak flow levels and higher risks of flooding.

The measures taken to cope with climate change (sea level and surge) are the following:

- Geometry and material of the dike chosen to ensure the dike stability.
- Retaining wall (sea wall) to prevent from flooding by the waves.
- Tetrahedral concrete structure used in breakwaters.
- Checking of culverts functioning according to sea level rising, erosion protection with tetrahedral concrete structures.
- Checking of bridges functioning according to sea level rising, erosion protection with concrete rock lined and adaptation of head walls.



cross section of the dike. ©Egis

The dike, its materials, sizes and scour protections as well as the sea wall are designed to cope with wave surges taking into account climate change:

- Evaluate the stability of the dike at the singular points of the road.
- Measure water crossings above the retaining wall.
- Measure the levels reached by the wave peaks to calibrate the altimetry of the viaducts.
- Evaluate erosion protection with tetrahedral concrete structure at culvert outlet.

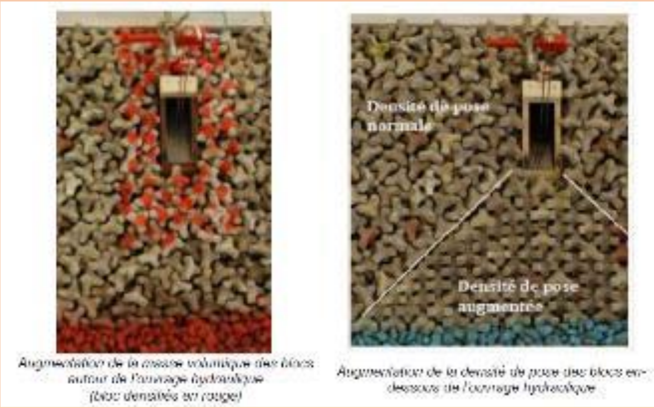
3D model representing wave surges (dike on the left, wave-making machine on the right) - ©Egis

A global modelling of the dike is also undertaken in order to evaluate the general behaviour of the dike under extreme stress measured and interpreted during 3D tests. The mechanical behaviour of the seawall and dike has been numerically modelled using the FLAC 3D software.

Efficiency of the sea wall for waves protection using a 3D model - ©Egis

The erosion protection for culverts outlets are made of tetrahedral concrete structure.

The retained erosion protection were evaluated using a 3D model (increase of density of blocks around the culvert and rise of blocks density below the culvert).



Nouvelle route du littoral – erosion protection at culvert outlets - ©Egis

Source: Egis, Nouvelle route du littoral, 2016. [40]

10.1.2. Traffic and hazard management adaptation measures

The objective of robust and reliable infrastructure is that the infrastructure should be able to cope with both expected and unexpected events. Effective adaptation strategies aim to ensure that there are few stoppages and disruptions due to accidents, congestion, or damaged infrastructure [41].

Adaptation measures such as the use of Intelligent Transport Systems (ITS), early warning systems and re-routing are applied to reduce the impacts of climate change events on the community. From a social perspective, the communication of weather events is of critical importance for preparing and recovery before, during and after events, and is connected to accessibility of emergency services. This also involves also the reduction in failure probabilities in a system, such as enabling the redundancy of a system to prioritise alternative options, choices and substitutions under stress e.g. alternative routes. This sub-section therefore covers:

- Intelligent Transport Systems
- Early warning systems
- Re-routing (short term and planned).

Effective communication via ITS solutions can aid in ensuring the preparedness of infrastructure. Big data for smart roads, smart systems and smart data is increasingly being used in some countries such as South Korea, United Kingdom and Norway. This is where data, information is transferred in real time directly to drivers on accidents, weather (information is transferred directly to drivers) to prevent accidents or delays before they occur. Smart Bridges and Highways bring together real time sensory data, which provides increased resilience of infrastructure. Data is transferred using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies, and there is common use of sensors within the infrastructure [3].

Data can also be used to reduce traffic disruption, and enhancing traffic safety and flow providing resilience at the network level. Therefore, information can be transferred faster to road asset users in the event of natural and man-made e.g. security events. A wide range of case study examples on the use of big data and communication to road users were identified throughout a Forum of European National Highly Research Laboratories (FEHRL) Scanning Tour across South Korea and Japan [3] highlighting the need to ensure that infrastructure is resilient in terms of preparedness, robustness, recovery and adaptation. Such examples include, the Korea Expressway Corporation Traffic Information Centre and Broadcasting studio. Data is collected in real time, processed (via the ICT Centre in KECRI) and disseminated to the public in the form of call centres, broadcasting room, and directly to vehicles and drivers (via mobile phones or on-board smart devices in less than two minutes) to prevent accidents or delays before they occur immediately and provides a direct interface between data and road users [3].

The use of early warning systems, and preventative measures have been highlighted in Norway, with a web portal developed through cooperation between Norwegian Public Roads Administration (NPRA), Norwegian Water Resources and Energy Directorate (NVE), Bane Nor (The Norwegian Rail Administration), and the Norwegian Meteorological Institute (MET). The web portal www.xgeo.no has been developed to enable better road operation tracking from extreme weather events. The tool visualises temporal and spatial climate and climate change data and allows for the preparation, monitoring and forecasting of events by combining data from meteorology departments, road departments and other related agencies. The information provides a good basis for operating the road network, but is dependent on good registration of events e.g. development of electronic reporting and smart phone apps for registration of events [42]. This is further outlined in the PIARC Framework [4 : Box 4c].

The web portal xgeo.no also forms the basis for a common alert system for floods and landslides, www.varsom.no, whereby warnings of flood, snow avalanche, debris landslides are issued to road operators, road users and the general public. The national avalanche warning service was launched in January 2013, by the Norwegian Avalanche Centre, which produced avalanche bulletins (according to European standards as part of the European Avalanche Warning Services (www.avalanches.org)). The main objective of these early warning services is to avoid accidents and reduce problems due to avalanches. The service contains information regarding the forecasting group, a professional observer corps, information and communication systems, snow and weather models and automatic hydro-meteorological stations [37].

Box 19: Avalanche Warning Services, Norway

The Norwegian Avalanche Centre and the portal www.varsom.no, were launched in January 2013. The virtual centre is a collaboration between the Norwegian Water Resources and Energy Directorate (NVE), Bane Nor (The Norwegian Rail Administration), Norwegian Meteorological Institute (MET) and The Norwegian Public Roads Administration (NPRA). The centre delivers continuous updates on the current situation and future development of risk from floods, avalanches and debris flow, to national and regional stakeholders and to the general public. NVE is responsible for the service.

www.varsom.no issues forecasts and warnings for several types of geohazards. Each geohazard has its unique forecasting environment and points of contact. The centre publishes bulletins at the warning portal www.varsom.no, at least twice a day, and for three days ahead. Debris flow alerts are issued all year round, whereas the snow avalanche alerts are issued only in the defined "avalanche season", which is 1st Dec – 31st May. The Centre's avalanche bulletins are produced according to European standards as part of the European Avalanche Warning Services (www.avalanches.org). The flood and debris flow alerts follow a four tier scale, sometimes presented in a popular way, by the help of rubber boots

The main user groups are within recreational winter sports, road and railroad authorities and emergency authorities. The bulletin and forecasts are important tools for evaluating the snow avalanche conditions, but do not provide the correct answer for every snow-covered slope. The bulletin and forecasts are therefore set up to be as educational as possible; with an informative and educational avalanche service, the avalanche awareness will increase, and enable the public to avoid accidents. For example, Avalanche problems are described through typical situations as they occur in avalanche terrain.

Source: Norwegian Public Roads Administration, 2013. [37]

Communication of information to road users is therefore of high importance to ensure that road user costs and socio-economic costs are reduced. When a road is closed due to flooding the Danish Road Directorate in cooperation with the police, call-out services and authorities to manage the situation to optimise goals for road users with regard to the condition of the road.

This is achieved through:

- call-out services ready to close the road and ensure road-user safety

- informing road users about the flood e.g. traffic information services such as vejdirektoratet.dk, mobile telephone apps, GPS, and radio traffic updates
- clearing-up quickly e.g. emergency pumps
- improving traffic flow on relevant roads using diversion routes (Danish Road Directorate 2013).

Other innovative responses have also been developed to improve signage and communication of flood events, using recycled materials for the signage infrastructure. This is identified in Logan City Council, Queensland Australia.

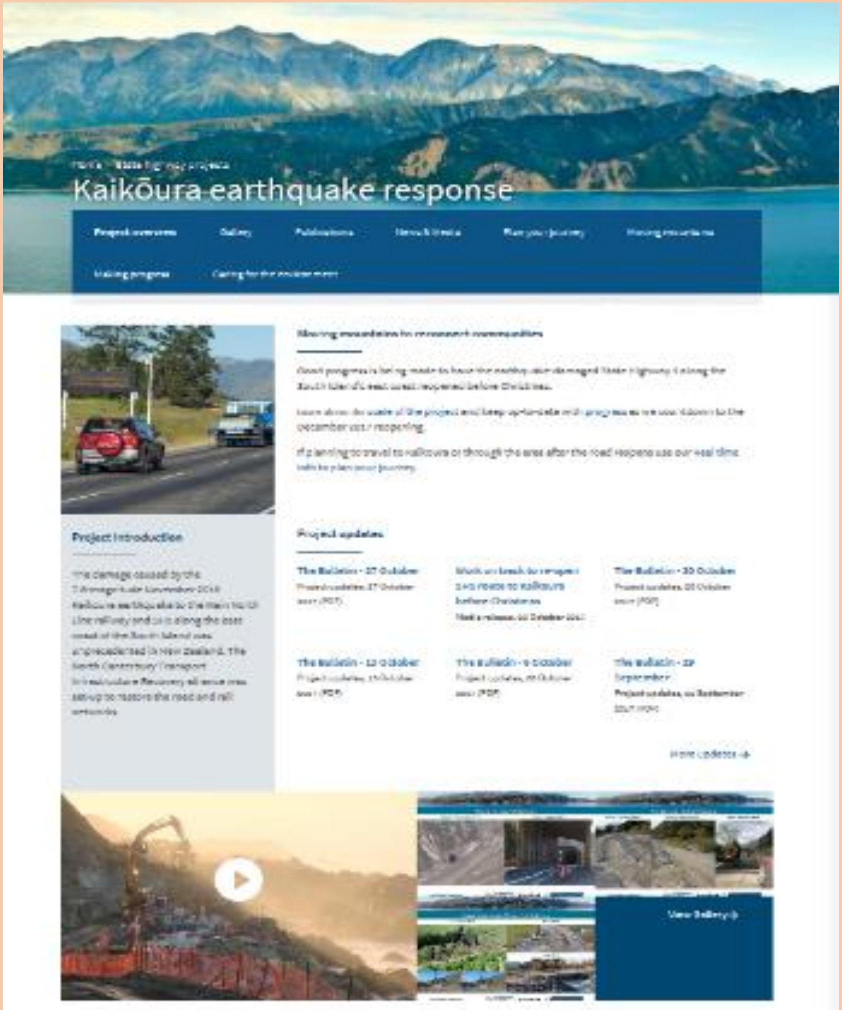
Communication to road users can also be provided to road users using internet updates of road reconstruction following significant climate change events. Whilst coverage of earthquakes is outside the scope of the Strategic Plan for TC E.1, Box 20 provides an example how information can provided to road users following in New Zealand.

Box 20: Kaikoura earthquake response public information website, New Zealand

The damage caused by the 7.8-magnitude November 2016 Kaikoura earthquake to the Main North Line railway and SH1 along the east coast of the South Island was unprecedented in New Zealand. The North Canterbury Transport Infrastructure Recovery alliance was set-up to restore the road and rail networks.

The procurement model is to get things done as quickly as possible. The work by NCTIR includes repairing and rebuilding the transport networks to be more resilient and safer, helping keep everyone better connected in the future. The rebuild is a massive undertaking, and even after access is restored, there will be an ongoing repair programme to improve and help keep the network resilient.

Information is provided to the public regarding reopening updates via the website as illustrated below.



Source: New Zealand Transport Agency (www.nzta.govt.nz)

The road network is a fundamental component to the effective running of the economy and a compromised network has the potential to present a serious loss in the economic wealth of a nation (Highways Agency 2011). This is highlighted in a case study for Highways Agency (now called Highways England) in Box 21.

Box 21: The 2007 flood disruption to the Highways Agency, United Kingdom

Unprecedented downpours across the country caused widespread flooding in July 2007, resulting in travel disruption for many drivers. Closures affected the motorway network (M1, M4, M5, M18, M25, M40, M50, and M54) and many local and trunk roads were also disrupted. The repair costs for all roads (including non-HA roads) were estimated at £40–60 million. Flooding on one day alone – 20 July – caused 2 per cent of the delays for the whole year. The flooding of what was a small part of the road network led to almost 10,000 people being stranded. Particularly hard hit were the M5 and M50, which were closed in both directions. Traffic officers turned drivers around in the opposite direction where possible, and diverted drivers to Strensham Services where they provided emergency food and water. The Highways Agency issued travel advice to drivers via the media and websites in advance of the forecast rainfall and 24/7 throughout the flooding. Highways Agency traffic officers and contractors also provided aid to flood prevention operations beyond the strategic road network. This included transporting emergency services staff, implementing local road closures and diversions, and provision of sandbags.

Traffic officer is seen on TV rescuing people stranded on the M5.

Source: Highways Agency. [43]

The rerouting of freight and passenger networks (short term and planned), and enhancing the resilience of a transport system is outlined as a beneficial adaptation measure.

Whilst the redirection of traffic, has benefits to road users by way of improving travel time, reducing vehicle operating costs and reducing freight delay costs, there can be a wider economic aspect to the rerouting of infrastructure on road maintenance. This is due to the nature of the loading of vehicles to roads. Heavy vehicles cause more stress on roads than light vehicles and, particularly when road pavements are wet, and can cause most of the damage as the pavement is already saturated and weakened. In 2008/2009 many roads in Queensland were limited to 80% carrying capacity in order to prevent long-term damage to the road [36; 44].

It is also recognised that other adaptation measures can include community adaptation. For example, increasing community self-reliance is an adaptive measure whereby some communities have experienced flood or storm related events on a frequent basis. As adaptive measures, people in communities may ensure that they have sufficient food resources, in preparation for inaccessibility to shopping centres. Alternatively, examples have also been shown whereby arrangements are made with other locals to carpool children to nearby locations for schooling.

10.1.3. Maintenance adaptation measures

Threats from the climate are continually identified, analysed and reduced often as an integrated part of maintenance, new construction and rehabilitation of roads [41]. Climate change emphasises the need to perform effective maintenance and to reduce maintenance backlog. It is recommended that all scheduled maintenance and repair should include adaptation measures wherever necessary, to ensure sufficient capacity for the remaining service life of the asset [42]. This includes consideration or cost-effective ways to reduce the life-cycle costs of assets throughout their design life.

Adaptation options can also be identified for different levels of options (full robustness/full protection or preventative maintenance options). For example, where a road is engineered to be significantly immune to the effects of major weather events, this may involve raising the pavement height in vulnerable areas, increased sub-surface drainage, widening shoulders, importing high-quality granular materials (bitumen or cement modified), or rehabilitating and re-sealing the road at regular intervals. It is acknowledged that these full resilience options can involve extensive rehabilitation work required to make a given link fully resilient, protected, and are often expensive. Additionally, this approach may not be suited to lightly trafficked roads where high agency costs may not be sufficiently offset by reduced road user costs. Conversely, other resilience approaches such as more periodic major work or maintenance on the road targeted at both strategically valuable links and high vulnerability sections, can be considered. This option requires increased spending on programmed rehabilitation, and lower (condition or age-based) trigger points for remedial works. This approach aims to increase immunity of the network to immediate effects e.g. precipitation, such that the repair program after events are a fraction of the current magnitude. This scenario acknowledges that whilst major events may still cause some road closures and delays, the damage will be greatly reduced to allow rapid emergency works to re-open sections [36]. Further analysis of these approaches are provided in Section 11.1.5 as an example of Life-Cycle Costing methodologies used for prioritising adaptation measures.

Additionally, operation contracts (signed on a 5-7-year basis) need to take into consideration the observed trends and the uncertainty of the climate, such as unusual weather combinations, more vegetation along the road, temperatures around freezing point, drifting snow etc. Contracts need to be formulated in a flexible way in order to take into account the unpredictable element [42].

10.1.4. Operational, organisational and planning adaptation measures

Operational, organisational and planning adaptation measures involves integration of climate change in the:

- design phase;
- technical regulations, possible changes to existing regulations and standards to accommodate improved resilience due to climate change events; and
- legal frameworks.

The importance integrating adaptation measures in the planning and design phase of road construction to prevent damages due to climate change is being considered internationally. The aim is to avoid excessive vulnerability by adequate planning and design, whereby climate is considered in all planning processes and as early as possible when developing a project. Such examples include:

- Introduction of climatic conditions among the assumptions for designing roadways.
- Alignment of the road should be chosen in such a way that the risk of flooding, landslides, drifting snow and similar weather impacts is reduced, or is easier to handle.
- The vertical alignment should be chosen with respect to a conservative flood level (e.g. 200-year flood rather than a 100-year return period). This includes bridge design, concerning free height and erosion protection.
- Landslide protection measures should be planned taking into consideration the impacts of climate change e.g. debris flows and slush avalanches.
- Management of run-off water and development of separate plans for storm water management.
- Comprehensive drainage solutions should be planned over a large area, extending from the road e.g. increasing the use of retention basins, terrain ditches. This is being further investigated by the NIFS program, Norway [42].

For example, Egis [26] notes in a study on improving road design and construction of the Pasakha Access Road, Bhutan, that adaptation measures for road pavements, bridges and culverts, slope failures and landslides can be implemented. The design of drainage structures has been based on future predicted design to ensure that the road pavements will not be flooded. It entails larger drainage systems such as drains with increased discharge capacity instead of commonly shaped drains. Other infrastructure adaptation measures can be considered included such as for road pavement, bridge and culverts, and slope failure and landslides. This is detailed further in Box 22.

Box 22: Adaptation measures used in the improvement of Pasakha Access Road - SASEC Road Connectivity Project

- Road Pavement:

The design of drainage structures has been based on future predicted design discharge so that the road pavements will not be flooded and disrupted early by runoff. This approach led to larger drainage systems such as drains with increased discharge capacity instead of common shaped drains. Egis also advised the Bhutanese Department of Road to raise construction quality through quality control during construction and adopt stronger concrete grade. After the construction, the local government will need to provide sufficient resources for maintenance in a way, for example, to ensure well-functioning of subsurface drainage to keep the construction layer dry and guarantee their durability.

- Bridge and culverts:

Considering the future estimated design flow, sufficient river training structures, wing walls, aprons and scour protection structures have been applied for bridges and culverts both upstream and downstream of the constructions. In the same way, drainage capacity of bridges and culverts has been increased, while designing them wider and higher, and a number of relief culverts have been proposed according to the site requirement.

In addition to these measures, Egis informed Bhutan's government about other recommendations for improving the design of infrastructures in that region. Applying enough safety factors in design of bridges and culverts is a good way to secure the construction. Moreover, in this unstable area, avoiding hazardous zones like stretches prone to flooding and landslides wherever possible is vital for the roads durability.

Egis insisted in regularly monitoring and cleaning out drainage system and watercourses to ensure a clear runoff into culverts and under bridges.

- Slope failure and landslides:

In a way to stabilise the steep slope areas, bioengineering techniques have been extended to their maximum. They consist in planting local species of plants and grasses, especially in the stabilising zones to prevent reactivation of the slides.

Other recommendations have been suggested in the design such as reducing slope gradients near the road to get close to their natural stability or constructing check dams or retaining walls to comfort the unstable slopes and protect the road. Moreover, increasing soil and materials investigation will permit to identify unstable areas and mitigation measures before the construction phase.

Source: Egis, Improvement of Pasakha Access Road - SASEC Road Connectivity Project – Bhutan, 2016. [26]

It is however acknowledged that in the development of new assets, most adaptive responses may be part of a current building design phase, however, there is at times scope to develop an adaptation pathway that considers how the asset may be upgraded to deal with climate change risk in the future, and as new data becomes available. Management of an existing asset can also see adaptation responses put into place now, with a sequence of others scheduled into the future as responses to key triggers or thresholds and future decision points [45]. Additionally, it is noted that adapting certain assets may increase or reduce the adaptability of other assets [33].

It is also important to determine when rebuilding of infrastructure is appropriate (and inclusion of climate change adaptation measures into the design phase) and whether to include co-benefits into adaptation measures which also assist in reducing greenhouse gas emissions. In some studies that despite the appealing idea to adapt to change, it may be more likely that the adaptations in the transport sector occur when the infrastructure as reached the end of its lifespan and rebuilding is necessary (Taylor & Philip 2011, cited in [46]). Additionally, redesign for adaptation measures can take place after frequent events and the recognised need to make infrastructure more resilient. One example is the Houghton Highway Bridge in Queensland which is a climate change proof bridge that will withstand waves generated by a severe 1-in-2000 year storm event. The construction of this new bridge took place next to the old bridge and provided additional immediate benefits to the users such as reducing traffic delays, includes pedestrian and cycle paths connecting with existing cycle networks, and seeks to improve safety for mariners in terms of navigation clearance, whilst also maintains the environmental and cultural heritage features of the area [44]. To enable adaptation therefore requires a complex and site-based analysis of the impact patterns and trends in climate.

Embedding adaptation into the organisation is critical to formulating appropriate management and mitigation solutions to remove or reduce climate risks. This is directly influence on the success of the future operation, maintenance and improvement of the strategic road network (SRN) [47]. This includes consideration of existing standards, and modifications to standards is an important organisation adaptation measure. Highways England (previously the Highways Agency) acknowledges that the networks have experienced significant problems due to extremes in rainfall and temperatures and these occurrences are likely to increase in frequency and severity over time as the impacts of climate change increase over time. Major parts of the network are susceptible to weather events, changes in asset integrity, and as such adversely affecting journey reliability and safety. In order to treat these risks, changes to technical standards are being proposed to increase resilience to climate change. These include HD33 drainage standard, and the Enrobé à Module Élevé (EME2) revised pavement specification [47].

Additionally, tools have been developed to incorporate climate change considerations into specific standards. An example is through the design of a Western Australia Infrastructure Sustainability Rating Tool developed by the Department of Main Roads Western Australia (MRWA), which evaluates sustainability initiatives and potential environmental, social and economic impacts of infrastructure projects including climate change (climate change risk assessment, and adaptation measures), and incorporating these considerations into standards. This tool is being developed across the industry. Two elements within the IS tool relate to climate change (climate change risk assessment, and adaptation measures). Also, plans have been developed by MRWA on the development of an appropriate response to adapt to the changing climate and ensure that communities are adaptable. MRWA are incorporating climate change considerations into specific standards e.g. sea level rise is considered for costal projects (Bettini, L. Main Roads Western Australia, PIARC Technical Workshop, May 2017). Other examples of operational and organisational initiatives to improve network management strategies, and improve the resilience of their infrastructure via improvements to standards is outlined in Box 23 and 24, for the Department of Transport and Main Roads (TMR) Queensland, and Logan City Council, Queensland, Australia.

Box 23: Increasing the resilience of infrastructure, Department of Transport and Main Roads, Queensland

The main challenges facing the Department of Transport and Main Roads (TMR), Queensland are extreme weather events, which caused $6 billion of damage to state-owned roads from 2010-2013, allowing for significant opportunities to make the network more resilient. Therefore, TMR have developed numerous operational and organisational initiatives to improve the resilience of their infrastructure including:

- updated design guidelines provided engineering criteria and guidance for planning, designing and delivering work under the Commonwealth's Natural Disaster Recovery and Relief Arrangements (NDRRA)
- infrastructure rebuilt to current engineering standards, including elevating sections of highway to allow for the continuation of traffic flow during a flooding events. This flood resilient design was used on one side of the Bruce Highway, south of Rockhampton. During flooding events both directions of traffic would share the elevated section of the highway
- treatments such as foamed bitumen stabilization to return assets to equivalent standards but more resilient
- complementary funding used to improve resilience, such as widening, sealing road shoulders and geotechnical repairs.

TMR's response to improving resilience involves planning and responding; providing pavement resilience through adopting a whole-of-life approach. It was identified that the Transport Network Reconstruction Program (TNRP) guidelines address the provision of improved road resilience, emphasise the importance of addressing contributory causes and recognise that trade-offs are necessary.

Source: Department of Transport and Main Roads, Queensland, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

Box 24: Asset life cycle strategies for optimal service life and enhanced flood immunity for vulnerable roads in Logan, Queensland

There are two major rivers in the city of Logan, with 54 feeder creeks and 30 rural creeks. There have recently been severe weather events affecting flows along both of these main rivers. In 2017, the Albert River had a 1 in 100-year event. Additionally, in 2017, the Logan River had a 1 in 20-50 year event. These events inundated 185 houses, and caused the need to close 103 roads. Flooding such as this has regularly occurred since 2011 (specifically in 2011, 2012, 2013 and 2015).

Due to this regular flooding, the city of Logan developed two network resilience classifications:

- Roads flooded and immediate damage - where roads need to be closed due to water being present on the surface; this closure period can vary from days to weeks. Flooded Roads Risk Analysis undertaken in 2011.
- Roads affected due to prolonged raining period refers to when the pavement is saturated for an extended period of time, likely caused by blocked or inefficient drainage facilities.

These network management strategies need have been adapted to both the El Nino Cycle and the La Niña Cycle. The Council, aims to balance the deterioration rates by intervening through a flexible and prudent network management for resilience road network. To manage the potential impacts through La Nina Cycles, the Council intervenes and invests in resilience of the network during neutral and El Nino Cycles, and evaluates/reviews the strategy post a La Nina cycle.

A project is now underway to develop maps of the soil characteristics under key infrastructure. This includes the reactivity, corrosivity, volume change, etc. This data is to be gathered from the council's pavement geotechnical data, CSIRO data and Alliance partner data (for Water Asset Management). This project will help to guide future infrastructure decisions in order to minimise the challenges current faced by the Logan City Council.

Other initiatives the council are undertaking include:

- regular surveys to determine the life length of the road surface and any defects or damage present;
- monitor road network performance to determine the service life of both road surface and pavement;
- the use of automated flood warning systems;
- critical infrastructure analysis for flood plain management; and
- using flood and disaster communication systems.

The Logan City Council employs smart city technologies in order to manage their flood impacts. It is recognised that flexible road management strategies need to be in place in order to manage the risks of a variable climate including identifying flood prone areas, identifying key strategic routes and managing the networks.

Source: Logan City Council, Queensland Australia, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

Other approaches to embed climate change adaptation measures into organisations has been identified in New Zealand through the New Zealand Coastal affects assessment guideline developed by the New Zealand Transport Agency. This guideline is in response to the Agency's focus on long-term climate change impacts, such as sea level rise, increased inundation, and various environmental effects to ensure resilience of the New Zealand highway network (see Box 25 for further detail).

The United States FHWA has developed technical guidelines and methods for incorporating sea level rise and future precipitation for highways in coastal and riverine environments. The guidelines each offer a range of analytical approaches depending on the criticality and expected lifespan of a facility. These Guidelines include:

- Hydraulic Engineering Circular 25 Vol 2, Highways in the Coastal Environment: Assessing Extreme Events

  https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf

- Hydraulic Engineering Circular 17, Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience, 2nd Edition,

  https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

Several transportation agencies in the United States have incorporated adaptation consideration into their own program processes. The Washington State DOT has guidance documents on considering climate change impacts in environmental review and transportation planning. Both of these guidelines direct project planners to refer to results from a climate impacts vulnerability assessment that the agency undertook in 2010. The environmental guidelines further provide an analytical process for evaluating climate change impacts on proposed projects and the surrounding affected environment. The Maryland State Highway Administration screens for sea level rise impacts as part of its project environmental review in coastal counties. For example, the state's environmental clearance form for minor federally funded roadwork projects asks whether the work will take place in an area potentially impacted by sea level change based on maps of mean sea level and mean high higher water in the years 2050 and 2100. If yes, it notes that the project must consider sea level change. New York State DOT includes precipitation and sea level changes in its design guidelines for bridges. The guidelines call for new and replacement bridges to increase current peak flows by 10 or 20 percent, depending on the county, to account for future projected flows. The guidelines also call for new and replacement coastal bridges to consider design criteria that incorporate sea level rise projections. Designers shall consider sea level rise up to and including the state's medium projection. For critical bridges, designers shall consider sea level rise up to and including the state's high sea level rise projection and the current Q500 flows. Caltrans also has guidance on incorporating sea level rise into planning and development of projects [8].

[8] http://www.dot.ca.gov/ser/downloads/sealevel/guide_incorp_slr.pdf

Box 25: The New Zealand Transport Agency, Coastal Affects Assessment Guideline, 2017

The NZ Transport Agency has developed the *Coastal affects assessment guideline* in response to the Agency's focus on long-term climate change impacts, such as sea level rise, increased inundation, and various environmental effects to ensure resilience of the New Zealand highway network.

It sets out a risk management framework that would provide a consistent decision-making process for coastal asset. More recently the whole coastal risk assessment process for the Kaikoura projects used the guide. The Guidelines provide an auditable trail and can demonstrate good risk management and cooperate responsibility (and governmental). It has been used for a range of our other projects, as well as many coastal scientists and engineering practitioners.

The guide was developed for project teams involved in the project approval and consenting stages, as well as in the design, construction and management of coastal assets to:

- Identify environmental effects that may influence the maintenance, renewal, new development or management of assets in the coastal environment over the course of the asset's design life.
- Undertake a qualitative risk assessment of environmental effects identified using this guideline.
- Develop measures to address effects on the Transport Agency's assets and/or the environment posed by the coastal environment.

The risk assessment process outlined in this guide summarises and documents key threats to assets and coastal environments, enabling project teams to develop suitable mitigation and management solutions. It sets out a risk management process to identify management solutions consistently and recording the analysis.

Overall, the guide describes a coastal environment risk assessment approach intended to inform the planning, design and management of state highway assets in coastal environments. It outlines key questions to be considered based around risks to the assets and their effects on changing coastal dynamics, such as sea level rise and increasing tide or storm impacts.

Source: New Zealand Transport Agency, 2017 (www.nzta.govt.nz).

The PIARC Framework (2015) also proposes a range of non-engineering options. These include:

- Alignment of master planning and land use planning e.g. development of roads in areas that are hazard prone, or realignment of roads to protect transport infrastructure. Care must be given to understanding the implications of resettlement of populations and economic activities. This is further discussed in Section 11.
- Environmental management e.g. preserving biodiversity or conserving vegetation to help regulate hydraulic cycles to minimise the impacts of floods.

10.2. EVALUATION OF THE EFFECTIVENESS/MONITORING OF ADAPTATION MEASURES

According to HB 167 and ISO, this step is referred to as “Monitor and review”. As an example of this evaluation, in May 2017 a workshop was held for PIARC Technical E.1 on Adaptation Strategies increasing the resilience of infrastructure, and hosted by the Department of Transport and Main Roads, Queensland and organised by the Australian Road Research Board (ARRB) and Austroads. This Workshop provided an opportunity to disseminate knowledge between PIARC and all spheres of government and universities in Australia. At this Workshop, a range of adaptation options were identified which highlight the application of pavement adaptation measures, and their effectiveness.

As identified in Section 10.1.1, foam bitumen stabilisation used in Queensland, Australia, and is an example of how the effectiveness and future monitoring of this measure is being undertaken. The performance of these pavements was tested through numerous flood events including Cyclone Debbie, 2017 .[9] It was identified that the condition of the pavements when the flood waters resided following this event remained intact, see Box 26 for examples.

[9] Cyclone Debbie was a category 4 cyclone occurred in Queensland in 2017. This was the strongest tropical cyclone in the Australian region since Cyclone Quang in 2015, and the storm caused A$2.4 billion (US$1.85 billion), primarily as a result of extreme flooding (http://www.rpfbuilding.com.au/cyclone-debbie-2017-case-study/).

Box 26: Case study examples of the effectiveness of foam-bitumen stabilisation and monitoring

In Queensland, Australia, a number of case study examples exist on the effectiveness of foam-bitumen stabilisation following cyclone and flood events. These include:

- Camp Cable Road, Bruce Highway near Bowen, Queensland - 3-metre floodwaters inundated Camp Cable Road on the Mt Lindsay Highway. When waters receded, the foamed bitumen pavement was found to be completely intact.

Camp Cable Road, Queensland, Australia.

Source: Department of Transport and Main Roads (TMR), Queensland, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

- Stegemann Road in Logan City Council, Queensland is identified as flood prone area. Foam bitumen stabilisation was selected as the pavement material to balance the construction cost and flood risk, and was found to be still performing after Cyclone Debbie.

Steggeman Road, Logan City Council, Queensland, Australia.

Source: Logan City Council, Queensland Australia, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

- Foam-bitumen applied at the Yeppen, Queensland floodplain kept traffic moving during Rockhampton flooding. Additionally, there was no reported damage to key sites such as Toowoomba Range, Cunningham's Gap, Blackbutt Range and Warrego Highway following the application of foam-bitumen.

Source: Department of Transport and Main Roads (TMR), Queensland, PIARC Technical Workshop: International Adaptation Strategies and Increasing the Resilience of Infrastructure, Brisbane, May 2017.

11. APPROACHES TO INCLUDING ADAPTATION IN APPRAISAL & EVALUATION

Adaptation is increasingly recognized as an important part of many policies, as unavoidable climate change will affect almost every part of our society. The progressive uptake of adaptation strategies and plans has been accompanied by greater consideration of the costs and benefits of alternative courses of action [48].

Following the identification of adaptation measures as outlined in Section 10, it is important to prioritise often a long list of options into a small number of options which face the network, assets, operations and locations. Prioritisation of these measures requires the use of economic techniques to determine which adaptation option are most appropriate for selection. For example, not all adaptation measures are suitable for certain locations, or from an economic, social or environmental perspective. The options selected may only be appropriate for a particular location (urban, regional or rural) or type of road (sealed or unsealed), and their selection may also be determined by the frequency intervals of events, possible accelerated road deterioration of aged seals on roads. This section sets out a range of techniques which have been applied via case study examples. These include Cost-Benefit Analysis (CBA), Life-Cycle Costing (LCC), Multi-Criteria Analysis (MCA) methods and Adaptation Pathways approaches. Other approaches can also involve Real Options Analysis (ROA), Monte Carlo simulations, Cost-Effectiveness Analysis (CEA) and Portfolio Analysis [49], Robust Decision Making (RDM), and Iterative Risk Management (IRM).

The purpose of this section is to provide information defining these techniques, however the steps for application using these methodologies is provided in the PIARC Framework [4]. Additionally, it has been identified that some of these methodologies are not currently covered in the PIARC Framework. Hence, some of these refinements to the Framework were provided to the Technical Committee E.1 Working Group 2 for inclusion in this report.

11.1. ECONOMIC METHODOLOGIES

According to the ECONADAPT project, the economic assessment of adaptation measures is different from a normal economic appraisal, in that the focus of analysis is on managing uncertainties and risks. It must take into account different time-scales, complex systemic relationships and dynamics, multiple sources of uncertainties, etc. The FP7 ECONADAPT project (2013-2016) aimed to provide user-orientated methodologies and evidence relating to economic appraisal criteria to inform the choice of climate change adaptation actions using analysis that incorporates cross-scale governance under conditions of uncertainty. A critical theme was to support the application of adaptation economics in the period following the publication of the EU's 2013 Adaptation Strategy, focusing on key decision areas that need enhanced economic information, and on the key users of such information. This project also acknowledges that it is not a one-size-fits all approach to economic appraisal of climate change adaptation options and that each adaptation situation is unique [48].

ECONADAPT highlights that economic analysis can provide valuable information to decision-makers and stakeholders by:

- Bringing clarity on trade-offs associated with different development paths in the medium to long term, and providing an indication of the net value of different options under different possible futures;
- Highlighting, in a more transparent way, the value of future benefits, including the importance that current generations place on the future. This can ultimately enhance the consideration of sustainability principles in decision-making;
- Strengthening the capacity of society to envisage and plan strategically in face of high uncertainty and supporting the identification of robust solutions capable of high performance against a large number of futures, thereby enhancing the resilience of society against future risks;
- Presenting a structured approach to design, implement and evaluate projects, measures and policy programmes, and enabling the comparison of trade-offs between wait-and-see strategies and immediate action. This can ultimately support the application of the precautionary principle and enhance the capacity of society to adapt to non-linear dynamics in the climate and natural system [48].

This section provides an overview of different economic techniques which can be considered as the appropriate approach for specific adaptation scenarios. A summary of methods in adaptation economics and their potential use is provided in Figure 5.

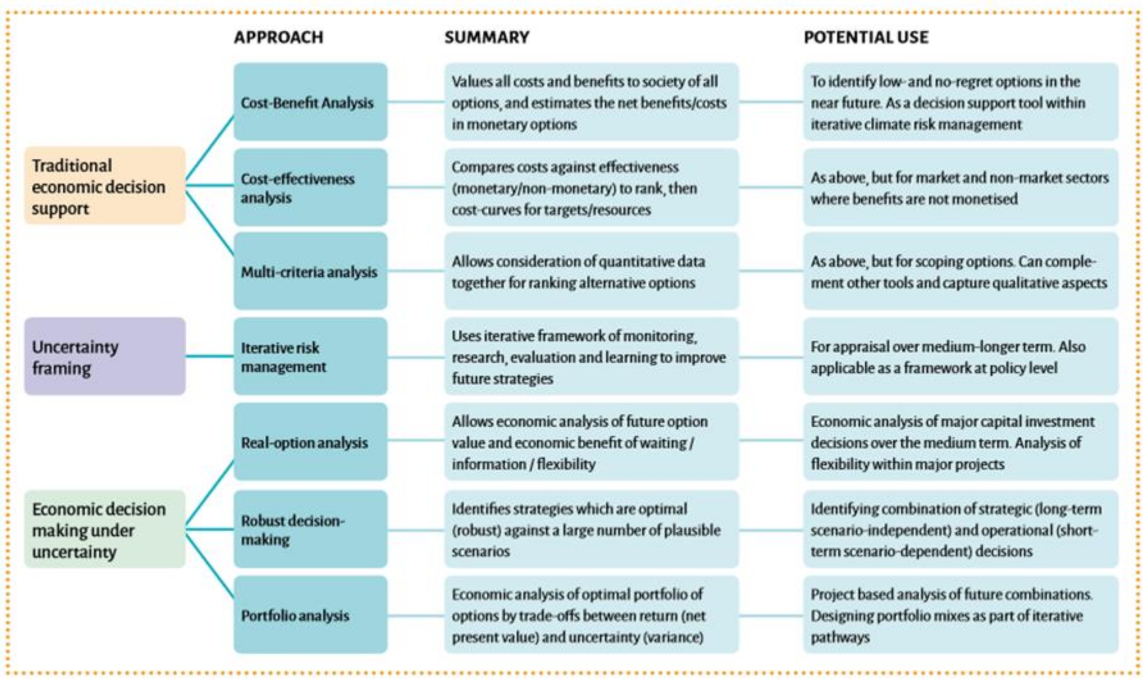


Figure 5: Methods in adaptation economics and their potential use. Source: Tröltzsch, 2016. [48]

Another example is the Arcadis Global, Bankable Resilience Tool (BaRT) which is a cost-benefit and multi-criteria analysis tool that is used to support cities and developers in evaluating their resilience options when planning an urban (re)development project. This was applied for the EU project RESIN in Europe.

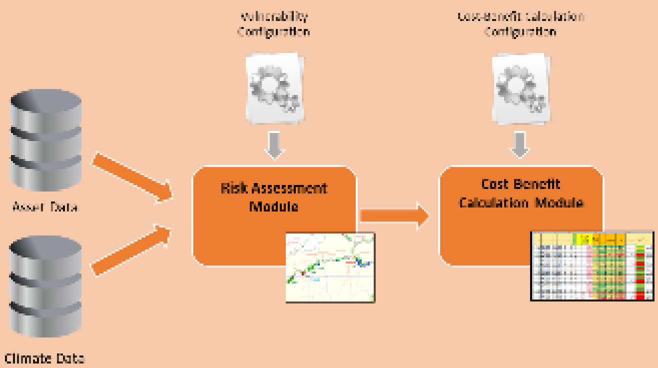
11.1.1. Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) determines the economic efficiency of a project or policy by comparing the net present value of the costs of planning, preparing and implementing the adaptation intervention to its benefits. Benefits are related to the avoided damage costs or the accrued benefits following adoption and implementation [48]. CBA focusses on the associated benefits and costs of adaptation responses and should incorporate indirect impacts in addition to the CBA result. For example, indirect impacts include reduced access to a network link which may limit tourism or freight, while enhanced road access through the provision of more links may enhance tourism [4]. This approach is perhaps appropriate for an analysis that is focused on current climate variability (the adaptation deficit), as well as Cost-Effectiveness Analysis (CEA). The CEA methodology is used to compare different options aiming to achieve similar outcomes. Cost-effectiveness analysis is generally most useful for short-term adaptation assessment, for example when ranking low and no regret options. This is because CEA does not explicitly deal with uncertainty and optimises the selection of adaptation interventions against a single objective usually under one climate scenario [48].

In undertaking a CBA, practitioners are provided with indicative information relating to the expected costs, benefits and responses. Responses can be ranked in terms of their total benefit. The benefit of an adaptation response for infrastructure can be measured by the expected value of the reduction in damage costs between the base-case scenario of no adaptation and the project case scenario in which the adaptation measure has been implemented. CBA provides an estimate of the present value of network benefits from implementing various options analysed, and can be used to appraise and compare different adaptation options or groups of options. Consideration should be given through a CBA of whether responses deliver additional benefits beyond building adaptive capacity, and whether the responses improve the resilience of critical infrastructure at the expense of other sectors of the economy or transport sectors [4]. The PIARC Framework [4] provides further details on determining the expected impacts of events on assets, and how to determine the expected impacts on infrastructure.

Box 27: DeTECToR (Decision-support tools for embedding climate change thinking on roads)

The DeTECToR (Decision-support Tools for Embedding Climate Change Thinking on Roads) project was commissioned through the Conference of European Directors of Roads (CEDR) Transnational Research Programme to help European road authorities include climate change in economic appraisal and procurement processes. The project includes the development of a cost-benefit tool to enable the comparison of the cost-effectiveness of different adaptation strategies. The software tool has two modules; the first enables the user to assess the climate risk to their road network and the second to compare the whole life costs associated with different adaptation options. The user uploads asset and climate data into the tool, and configures the settings to tailor it to their network. The CBA module uses cost data input by the user and the calculated level of climate risk to estimate the overall cost. This includes the initial cost to implement the adaptation strategy, accident, traffic delay and maintenance costs. The user can compare different adaptation options, and a no adaptation option.



High- level structure of the DeTECToR cost benefit tool (Reeves et al, 2018)

Source: DeTECToR website - https://detector.trl.co.uk/

11.1.2. Probabilistic Analysis

As a result of uncertainties in climate change projections and climate change risks, accounting for costs and benefits can sometimes be challenging. Probabilistic analysis involves attaching a probability distribution for the possible value of any given specific cost or benefit component of an adaptation response, rather than a single deterministic value. The outcome is a probability distribution which represents the new present values, which then allows for computation of an expected net present value for the adaptation response option [4]. BITRE [50] indicates that some investment cost estimates can be developed using quantitative (probabilistic) risk analysis approaches. For example, project costs with sufficient contingency can provide a 50% (P50) and 90% (P90) likelihood that costs will not be exceeded. Here with half of the probability distribution on either side, P50 is the median of the probability distribution [50].

The CBA results used for decision-making should be the expected values, using probability distributions for the NPV and BCR. For investment costs, these are outlined by ensuring the P50 value (median) equals the mean or expected value if the probability distribution is symmetrical. If this is the case, the P50 value can be used as an approximation of the mean for the central scenario for a CBA, and the P90 can be used as a sensitivity test to gauge impacts on investment that are higher than expected [50].

11.1.3. Real Options Approach and Adaptation Pathways

When investments are nearer term (especially high upfront capital irreversible investments), there is potential for learning as new climate risk information available becomes available, and where there is an existing adaptation deficit, Real Options Analysis (ROA) is a potentially useful tool [48].

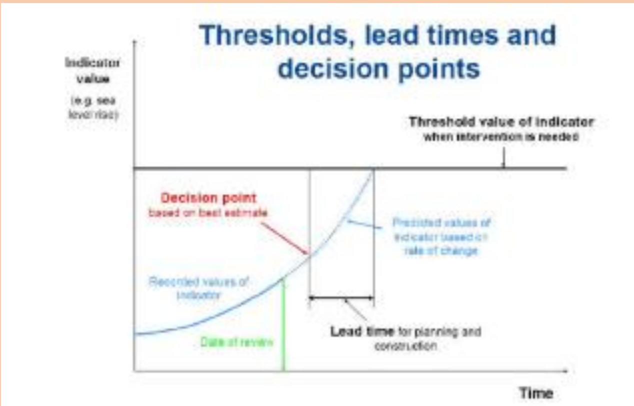
Real Options Analysis quantifies the investment risk associated with uncertain future outcomes and is used when considering the value and flexibility of investments. It can be used to inform how a project can adapt, expand or scale back in response to unfolding events (Watkiss et al. 2013 cited in [51]). Identifying and assessing options over time can be a powerful way to deal with downside risk (the risk of a bad outcome). A real option is a decision taken today that makes it possible for policy makers to take a particular action in the future. Options are explored that involve adopting a 'wait and see' approach until a major uncertainty is resolved or lessened and the project is more clearly going to be successful [50].

Adaptation pathways is a similar approach, whereby once risk treatments have been determined they are often arranged into a sequence in order to be responsive and flexible to changing circumstances. This sequence of risk treatments can be termed as an adaptation pathway. Each adaptation pathway that is formed, can be considered to be an adaptation option [45].

Adaptation pathways can be short and once-off, or more commonly can be more complex, particularly for larger assets where managing the risk is a process of adaptive decision-making over time. Adaptation pathways generally establish a structured, continuous process of assessing and implementing risk treatments in response to new information and changing circumstances [45]. An example of adaptation pathways is demonstrated in Box 28 for the Thames river. Further information can be found relating to the costs of adaptation in Dore and Burton, 2011 [52].

Box 28: Adaptation pathways applied in the Thames Estuary 2100, England

The Thames Estuary 2100 (TE2100) is a plan developed by the (English) Environment Agency for the management of the tidal flood risk to London from the River Thames. The plan, published in 2012, applies an adaptation pathway approach, taking into account existing climate projections, but also being designed to adapt to future projections. TE2100 evaluated the Thames estuary flood defences include the Thames Barrier and 350km of flood walls, embankments, pumping stations and flood gates in the light of projected sea level rises and makes recommendations on how to continue the protection of the 1.3 million people and £275 billion worth of property served by these defences. The strategy employed included developing worst case climate scenarios to estimate potential sea level rise, designing high level adaptation options and evaluating these to ascertain the magnitude of sea level rise they were likely to protect against, and the carrying out CBA of these for different climate scenarios. The lead times for each adaptation option were estimated and decision points identified at which responses would need to be approved in order for the action to be implemented before the threshold. The strategy is reviewed every 5 to 10 years, and if the rate of climate change has changed the implications for the decision points are reviewed. This strategy enables optimisation of the cost-benefit ratio in the face of uncertainty, and for all options to be kept open, for example ensuring land that could be needed in the future is retained. Action is going ahead on the recommendations based on current projections, but a switch to more extensive interventions could be carried out in the future if necessary.



Thresholds, lead times and decision points (HM Treasury, 2009)

Source: Accounting for the effects of climate change, supplementary green book guidance (HM Treasury, 2009)

11.1.4. Multi-Criteria Analysis

PIARC [4] identifies that Multi-Criteria Analysis (MCA) is a comparative assessment of options that accounts for several criteria simultaneously. In comparison to CBA, whilst many costs and benefits can be valued in monetary terms, many environmental and social impacts are more qualitative in nature. Hence, MCA offers a methodology for the assessment of climate change impacts that are not able to be valued in monetary terms e.g. political sensitivity, public acceptance and some environmental impacts [4].

As adaptation interventions are often in areas that are difficult for valuation, and usually involve a lack of quantitative information, Multi-Criteria Analysis (MCA) is often used [48]. MCA provides a comparative assessment of options and ranks these according to criteria simultaneously. The advantages and disadvantages of this methodology, and steps for application are provided in the PIARC Framework [4].

11.1.5. Life-Cycle Costing

A widely used measure of the economic impacts of climate change is the application of Life-Cycle Costing (LCC) assessments, which estimate road agency costs and road user costs based on the prediction of, and changes in, road condition and traffic use. In undertaking these assessments, agency costs represent the savings made resulting from the adoption of more effective pavement maintenance, repair, rehabilitation and resealing practices. Under the projected climate change impacts, agency costs are expected to increase unless more resilient measures are considered. Other costs include accident costs, vehicle operating costs, travel time delay costs, and the costs associated with delays in the delivery of freight [7].

LCC analysis allows for a flexible range of inputs and variables, in order to best-model the life-cycle effects of climate change on assets. This method applies a number of alternative options and involves testing the sensitivity of the model to changes in key inputs e.g. the frequency of events. LCC analysis considers the damage itself, its immediate recovery time and cost, its eventual reconstruction and the cost of repairs, community and industry delays, and other road user costs, as an overall change in net present value (NPV) for all options. It includes the life-cycle costs of 'what actually happened' (base case) and two possible alternatives, a preventative maintenance approach, and a full resilience approach. These can be used and compared for an analysis of the costs and benefits of adaptation initiatives for improved resilience. This also assists with the identification of optimal solutions applicable under different operating circumstances, with current traffic levels being the main driver of the solutions, having accounted for disruption impacts [7]. This methodology has proven to be very effective in the prioritisation of adaptation measures and maximising the return from investment for road agencies.

11.1.6. Other approaches

Other approaches used in the application of risk management and adaptation include [48]:

- For long-term applications in conditions of a low current adaptation deficit, Iterative Risk Management (IRM) may be more applicable.
- For the analysis of adaptation in the face of uncertainty, when risk of maladaptation is high, Robust Decision Making (RDM) can be employed. RDM has broad application for current and future time periods and focuses on robustness rather than optimality as a decision criterion;
- For the analysis under high uncertainty of combinations of adaptation projects which are potentially complementary, Portfolio Analysis (PA) can be a useful approach.

11.2. PRIORITISATION OF RESILIENCE OPTIONS ANALYSIS

It is recognised that historically, works programs have been focussed on achieving the highest priority treatments which in some cases have resulted in an overall deterioration in network condition over time e.g. as measured by condition indicators such as roughness and seal age. There has been a shift towards achieving more strategic, timely maintenance and rehabilitation programs compared to one-off major reconstruction programs, in the face of climate change impacts [36].

It is also acknowledged that the funding available for maintenance, rehabilitation and pavement resealing works is limited, and that there are challenges associated with addressing the management of the network in terms of the impact of climate change (other issues such as increasing axle load, also have to be managed, whether or not they are associated with climate change). As a result, there is a recognised need to review pavement management, maintenance and rehabilitation practices to decrease exposure to damage in a cost-effective manner [36].

11.2.1. Economic approaches to selecting and prioritising adaptation measures and responses

This section demonstrates the main outcomes of a project under the National Assets Centre of Excellence (NACoE) program that analysed the life-cycle costing implications of rain and flood events in Queensland, Australia [36]. This has been undertaken through a series of case studies under three different strategies; a base case mirroring actual experience with a limited rehabilitation and maintenance budget, a preventative maintenance ‘stitch-in-time’ approach with reduced intervention thresholds and reduced event impacts, and a ‘full resilience’ (full-robustness) approach incorporating extensive reconstruction and a vision of full flood immunity. Through life-cycle costing, the agency cost savings, accident cost savings, and other costs (costs incurred during flood and rain events, elevated road user costs due to prematurely rough pavements, time costs due to temporary speed limits, freight costs due to extended/delayed trips during events and the value of cancelled trips due to closed roads), have been determined and used to estimate total transport costs and potential economic savings. This also assists in the identification of optimal solutions applicable under different operating circumstances, with current traffic levels being the main driver of the solutions, having accounted for disruption impacts [36].

“Stitch-in-time” versus full resilience (robustness) implies risk treatment options. With “full resilience” risk is fully mitigated (no consequences) while for stitch in time risk is not fully mitigated but reduced (less severe consequences) [36].

The Net Present Value (NPV) and Marginal Benefit Cost Ratio (MBCR) under each of the scenarios identified above were calculated according to the methodology outlined in the National Guidelines for Transport System Management in Australia (Australian Transport Assessment and Planning Guidelines) (Australian Transport Council 2006 in [36]), and the results are outlined in Box 30. Additionally, a sensitivity analysis was also conducted for accelerated road deterioration on aged seals, or to address the uncertainty surrounding future climate effects on the road network. Three recurrence intervals of flood events were considered, namely longer, normal and shorter [36] (see Box 30 for further information).

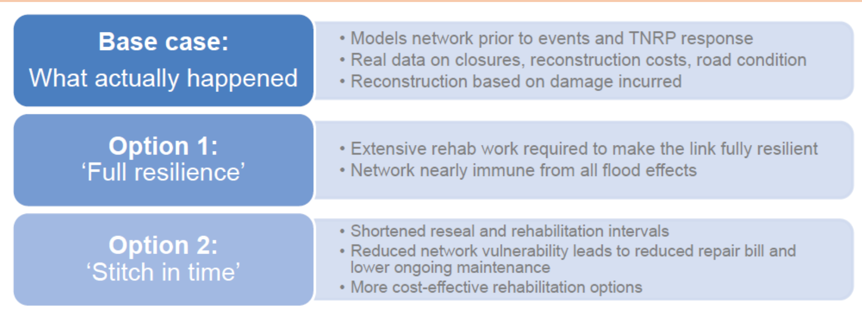
The findings were aggregated to enable determination of which resilience option e.g. full resilience or preventative maintenance, would be more appropriate for a particular location or type of road according to increases or decreases in the frequency of events [36]. The results are identified in Box 29.

Box 29: A4: Accounting for Life-Cycle Costing Implications and Network Performance Risks of Rain and Flood Events, Queensland, Australia

Between 2009 and 2013, Queensland experienced road closures of 23-62% of their roads due to an increase in frequency and severity of storms. Approximately 26%, or 8,741 km of the state-controlled network required full or partial reconstruction.

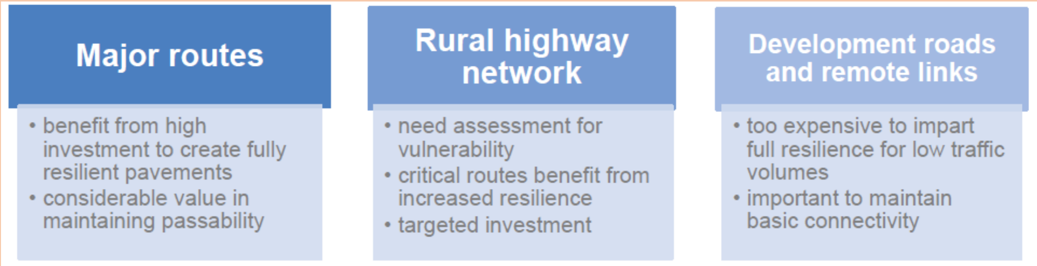
The project aimed to provide clarity to Department of Transport and Main Roads (TMR), Queensland and government funding bodies on the life-cycle cost implications of rain and flood and extreme weather events, and the funding levels required to enable the desired level of service to be achieved e.g. "What are the economic benefits of improving the ability of the road network to better withstand the effects of flooding events, and how might it be done?". Seven case studies across four representative regions across Queensland were selected, according to traffic volume, function and flood event frequency, and to enable some conclusions to be drawn regarding the whole network. The risk factors chosen included the damage itself, its immediate recovery time and cost, its eventual reconstruction and the cost of repairs, community and industry delays and associated costs.

The model was run over a 30-year analysis period, so that a period of several years before the major event could be incorporated, as well as a significant length of time afterwards to allow for reasonable assumptions to be made regarding future event reoccurrence intervals. Additionally, the analysis considered the condition e.g. based on the measured pre-event level of rutting and roughness, and vulnerability based on a combination of seal width, seal age pavement age and soil properties for 1km sections of road. Three case studies were identified, and the outputs were compared across each case studies as follows:



The base case uses actual data from the road closure database, reconstruction completion reports, and TMR-sourced data to quantify the life-cycle cost impact of rain and flood events on the network. Funding in this scenario is often limited, and major works occur after event-incurred damage. The Full resilience option represents a scenario where the road has been engineered to be sufficiently immune to events, and no reconstruction works would be required after a major event, and delays due to road closures would be reduced. The 'stitch-in-time" option advocates periodic major work targeted at vulnerable sections with more aggressive trigger points for remedial works. The network is more immune to immediate effects and repair programs post-events are a fraction of the current magnitude. Delays may still occur here, however the damage will be greatly reduced and allow for more rapid emergent works to reopen sections.

When considered at a network level, including accounting for traffic levels on specific routes, it was found that different combinations of Option 1 or 2 could be more suitable for particular roads as shown below.



Using these options, it can be determined that Option 1 represents a fully resilient road which was modelled to increase the life-cycle costs over the seven case, with very high agency costs not sufficiently offset by reduced road user costs. This approach was found to be best suited to heavily trafficked routes, where any closures and repair works come at a high cost and should be avoided if possible. Option 2 is where more proactive, targeted progressive rehabilitation programs in a preventative maintenance (stitch-in-time) approach is estimated to deliver a net life-cycle cost savings much higher than Option 1. This involved a small increase in agency costs being more than compensated for in reduced road user costs due to a more resilient network. When comparing the base case and two alternative options, it was found that this equates to a Marginal Benefit Cost Ratio (MBCR) of 6.9 for the stitch-in-time model, whereby an extra dollar of agency spending on the selection of roads returns $6.90 in road user cost savings.

Source: Beecroft, Peters and Toole: ARRB Conference 2016; Beecroft & Peters, National Asset Centre of Excellence Project A4, 2017. [7, 36]

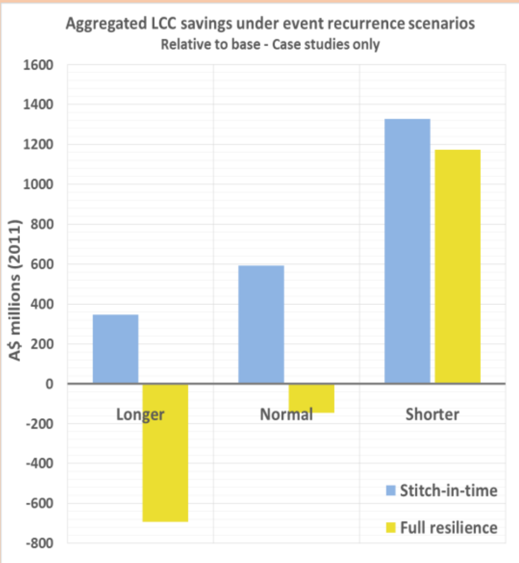
Box 30: Reoccurrence intervals of major future events: sensitivity analysis using LCC, Queensland, Australia

The results identified in Box 30 above for the TMR LCC analysis presents a picture of the shifts towards one of the option cases, however it was noted that the analysis relied on a series of critical assumptions. There remains a large degree of uncertainty in climate change impacts, hence two critical factors were selected for further scenario analysis to evaluate the impact that these uncertainties have on final results. These included the impact of varying the recurrence interval of major weather events, and also by implementing accelerated deterioration on aged seals to simulate the 'performance drop-off' that regions have experienced after the target seal age has been exceeded.

Three recurrence intervals were evaluated and compared to the results generated from the life-cycle costing model as follows:

- Longer recurrence interval – where events are considered to be 'once-in-a-lifetime' events
- Normal recurrence interval – which anticipates an additional major event in the 30-year analysis period
- Shorter recurrence interval – with multiple severe rain and flood events (per those experienced during 2010-2013 in Queensland.

Each of the seven case studies were analysed under each interval and revealed the following results:



Under a stitch-in-time option, the impact of shorter intervals is greatly lessened. Building a fully resilient network was also found to insulate the network against the risk of increased events. It was identified that overall there are still benefits in shifting towards a stitch-in-time model owing largely to the benefit of spacing out rehabilitation across many years rather than focussing major works to a narrow post-event period.

Source: Beecroft, Peters and Toole: ARRB Conference 2016; Beecroft & Peters, National Asset Centre of Excellence Project A4, 2017. [7, 36]

Box 31: An example of semi-quantitative approach to assess risks and prioritise adaptation options

The Highways Agency, Great-Britain, has published in 2009 a framework that provides a systematic process to identify activities that will be affected by climate change, determinate associated risks, and identify preferred options to address and manage them.

The process is divided into seven steps:

- define objectives and decision-making criteria;
- identify climate trends that affect the Highway Agency;
- identify Highway Agency vulnerabilities;
- risk appraisal;
- option analysis to address vulnerabilities; and
- develop and implement adaptation action plans.

The identification of the main vulnerabilities and the risk appraisal is based on semi-quantitative criteria such as: the extension and the severity (duration) of the disruption, the uncertainty of the climate change, etc.

This is a basis to lead an adaptation options analysis, for which the Highway Agency proposes:

- to first identify feasible adaptation option;
- to then determine expected outcomes of these options;
- to estimate financial costs and benefits; and
- to determine the preferred option by comparing various adaptation scenarios: a "do minimum" scenario, a "future-proof designs", etc.

Sources: Highways Agency. [34; 47]

11.2.2. Wider Economic Issues

It has been identified through past events that wider economic implications can result from climate change. An example of this complex issue was highlighted in 2006 when Cyclone Larry in Northern Queensland caused severe damage to road infrastructure and crops e.g. banana plantations. This had flow-on effects to the economy, where government expenditure was required to rehabilitate communities and re-introduce accessibility to these communities affected by flood. Other impacts included increases in the price of bananas for consumers, and implications for the freight industry in terms of reduced freight demand due to lost production [36; 44]. There were also impacts on the community, such as job loss, loss of income and depression, which are not often incorporated into an assessment, however they play a significant role in post-event recovery.

Other economic impacts should be considered in both the short and longer term. For example, direct impacts or short-term impacts include road/rail closures, and cracking, potholing or bleeding of pavement surfacings due to increases in the frequency and severity of heatwaves and rainfall/flood events. Therefore, these events need to be considered in the design, location and maintenance of new and existing transport networks. Indirect, or longer-term impacts, can include the effects on the location of populations and human activity altering the demand for transportation [32]. Furthermore, short and long-term impacts can result in increased maintenance costs. For example, increased temperature will accelerate the rate of deterioration of seal binders and require earlier surface dressings/reseals. An associated problem is the new-generation, multiple-axle heavy vehicles applying higher loads to the pavement. These events necessitate the need to implement more climate adaptive responses.

Additionally, there are many flow-on effects on the transport network and community arising from the deterioration of transport infrastructure due to climate change. The flow-on effects of an extreme heat event, as one example, are outlined in Figure 6.

Figure 6: Flow-on effects of climate change impacts on transport [Adapted from 59]

An example of a project quantifying the costs and benefits for assessing climate change impacts, and the impacts across other sectors is demonstrated in the Include Cost of Inaction – Assessing Costs of Climate Change for Austria (COIN) project. This is outlined further in Box 32.

Box 32: Cost of Inaction – Assessing Costs of Climate Change for Austria (COIN)

"What are the costs arising from climate change in Austria, if we fail to adapt?" This is the key question raised by the COIN (COst of INaction) project which is supported by the Austrian Federal Government's Climate and Energy Fund in the context of the Austrian Climate Research Program (ACRP). The answer to this question is of importance to policy makers as well as to businesses and private households, because what ultimately matters is that we carefully consider the measures which need to be taken to keep climate change costs as low as possible. For this purpose, a consortium of twelve Austrian research institutions investigates the range of additional costs and benefits that will arise from climate change (without plans for adaptation) over the next decades, up until the year 2100. With regard to potential impacts of climate change, the project focuses on 13 areas and fields of activity throughout Austrian society and economy. These included agriculture, forestry, human health, ecosystems and biodiversity, water supply, electricity, building and living, heating and cooling, transport and mobility, manufacturing and trade, natural disaster management, urban spaces, tourism.

To quantify the costs and benefits, the COIN project has, on the one hand, developed economic methods for assessing climate change impact and, on the other hand, it has identified the climate conditions which cause costs to arise in the individual areas and fields of activity. Thus, an increase in heat waves such as that of 2003 and its implications for human health can lead to increasing costs for the health care and disaster management system, especially for elderly and sick people. To provide a comprehensive overview of the potential costs, the twelve areas are not only considered individually. Road damage caused, e.g., by mud slides does not only cause direct repair costs. It also leads to interruptions of passenger and freight transport, which, in turn, can lead to loss of industrial production. Correspondingly, loss of production in agriculture or forestry also leads to losses in further processing sectors. COIN outlines these interdependencies and consequential effects so as to permit an estimation of all costs – direct and indirect.

Source: Climate Change in Austria: The Costs of Inaction, 2015. [53]

11.3. Developing an Adaptation Action Plan and Verifying the Cost Effectiveness of Measures Ex-Post, Benefit Realisation

Once the most appropriate adaptation measures have been prioritised, and a list of options has been prioritised and ranked as outlined above, it is necessary to implement these adaptation responses. This requires determination of a number of actions, priorities, timescales and responsibilities [4].

The PIARC Framework highlights that an Adaptation Plan provides a means of achieving this by detailing the timescales under which the adaptation measures are to be implemented, and presentation of funding required. This approach is outlined in detail in the PIARC Framework [4].

Ongoing monitoring and review of climate change risks, vulnerabilities and the effectiveness of adaptation initiatives is essential. This involves the review of findings, strategies and plans as more information becomes available and as new risks become apparent. The steps for conducting this part of the assessment is provided in the PIARC Framework [4].

12. CONCLUSIONS

As outlined, the purpose of this report is to articulate the task of Working Group 1 and highlight a state-of-the-art case study analysis of adaptation strategies to increase the resilience of road infrastructure at the policy, strategic, system level and project-specific level. It has been developed in parallel with the task of the Working Group 2, which is to refine the PIARC Framework and build from this work developed in the previous cycle. It outlines the methodological detail supporting each stage of the PIARC Framework, hence both reports are highly inter-related.

This report for Working Group 1 includes coverage of state-of-the-art case study examples of four main areas. In accordance with the PIARC Strategic Plan, these comprise, data requirements for exposure assessment, vulnerability and criticality assessments for roads, adaptation measures and economic approaches of assessing which adaptation measures provide the most cost-effective responses. These have been presented in this report by way of state-of-the-art case studies on adaptation strategies and resilience.

It is envisaged that the results of this Working Group report will assist in implementation of the PIARC Framework and opportunities exist to extend this work into further cycles. This may include consideration of the inclusion of worked examples of the methodological approaches identified in this WG1 report. This would involve integration of best-practice case studies and data requirements and converting these into worked examples for each phase of the updated Framework). This will be further considered in the next Strategic Plan for the 2020-2023 cycle.

13. BIBLIOGRAPHY / REFERENCES

[1] Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver. A.J. and Wehner, M. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities, Earthquake Spectra 19(4), p737-738.

[3] Evans, C., Goger, T., Kovarik, J., Sensvold, B., Krieger, J., Palhol, F., van den Hark, M. (2016). FEHRL Scanning Tour: Infrastructure Resilience in South Korea and Japan, Australian Road Research Board and Forum of European National Highway Research Laboratories.

[4] PIARC (2015). International Climate Change Adaptation Framework for Road infrastructure, Reference 2015R03EN, PIARC, Paris.

[5] CEREMA (2016). Analyse de risque Nancy-Brabois - Plan National d'Adaptation au Changement Climatique, volet infrastructures et systèmes de transport, action 4. Cerema, France.

[6] CEREMA (2017). Analyse de risque DIR Méditerranée. Cerema, France.

[7] Beecroft, A., Peters, E., Toole, T. (2016). Life-cycle costing of rain and flood events in Queensland – Case studies and network-wide implications, 27th ARRB Conference, Melbourne.

[8] Drejza, S., Friesinger, S., Bernatchez, P. (2015). Vulnérabilité des infrastructures routières de l'Est du Québec à l'érosion et à la submersion côtière dans un contexte de changements climatiques – Volume 3, Laboratoire de dynamique et de gestion intégrée des zones côtières, UQAR, Québec.

[9] Kalantari, Z. (2014). Road structure under climate and land use change, KTH royal institute of technology, PhD Thesis, TRITA LWR PhD 2014:01, Stockholm.

[10] Nickman, A. (2016). Road Disasters? Modeling and assessment of Swedish roads within crucial climate conditions, KTH royal institute of technology, PhD Thesis, TRITA LWR PhD 2016:06, Stockholm.

[11] Michaelsen, A. (2015). Modelling flood risk of transport infrastructure based on watershed characteristics, KTH royal institute of technology, Master Thesis, TRITA-IM-EX 2015:06, Stockholm.

[12] Briel, A. (2013). Hydrological modelling at road structures in a changing climate and landuse, KTH royal institute of technology, TRITA-LWR-EX-13-35, Stockholm.

[13] Kalantari, Z. (2011). Adaptation of road drainage structures to climate change. KTH royal institute of technology, TRITA-LWR-LIC 2061, Stockholm.

[14] CEREMA (2015). Analysis of the risk incurred by extreme climate events on infrastructures, systems and transport services - National climate change adaptation plan: transportation infrastructures and systems, action 3, Cerema, France.

[15] Miralles-Wihelm, F., Munoz Castillo, R. (2014). Climate services: A tool for adaptation to climate change in Latin America and the Caribbean: Action plan and case study applications, Inter-American Development Bank, IDB-TN-531.

[16] IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[17] L'herault, E., Allard, M., Barrette, C., Dore, G. Sarrazin, D. (2012). Investigations géotechniques, caractérisation du pergélisol et stratégie d'adaptation dans un context de changements climatiques pour les aéroports d'Umiujaq, Inukjuak, Puvirnituq, Akulivik, Salluit, Quaqtaq, Kangirsuk et Tasiujaq, Nunavik, Université Laval.

[18] Gravel Gaumond, F., Dore, G. (2013). Suivi des comportements thermique et mécanique du remblai de la piste de Puvirnituq, Rapport GCT-2013-03, Ministère des Transports du Québec.

[19] L'herault, E., Allard, M., Lemay, M., Barrette, C., Carbonneau, A.-S., Duchar, M.-A. (2015). Route d'accès à l'aéroport de Tasiujaq : développement des connaissances sur les propriétés du pergélisol et identification de solutions d'adaptation dans un contexte de changements climatiques, Université Laval.

[20] CEREMA, CARBONE 4 (2018). Rapport sur la réalisation d'une analyse de risque selon une méthodologie imposée et évaluation de cette méthodologie, Cerema, France.

[21] Bednar-Friedl, B. (2014). Adaptation costs – an economic assessment for prioritizing adaptation measures and policies in a +2°C to +4°C world, Wegener Center for Climate and Global Change, University Graz.

[22] CEREMA (2015). Potential impacts of climate change on transportation infrastructures and systems, on their design, maintenance and operation standards, and the need for detailed climate projections for their adaptation - National climate change adaptation plan: transportation infrastructures and systems, action 1, Cerema, France, 2015.

[23] Leviakangas, P., Tuominen, A., Molarius, R., Kojo, H. (2011). Extreme weather impacts on transport systems, EWENT project D1, VTT Technical Research Centre of Finland, 2011.

[24] Leviakangas, P., Saarikivi, P. European Extreme Weather Risk Management – Needs, Opportunities, Costs and Recommendations, EWENT project D6, VTT Technical Research Centre of Finland.

[25] World Bank, Direction Des Routes Du Maroc, Ingerop (2015). Adaptation des routes au risque et au changement climatique au Maroc - Guide simplifié.

[26] Locquet E., Aldebert, P. (2016). Improvement of Pasakha Access Road - SASEC Road Connectivity Project – Bhutan, Case Study Abstract, Egis.

[27] Kaundinya, I, Nisancioglu, S., Kammerer, H., Oliva, R. (2016). All-hazard for transport infrastructure, Transportation Research Procedia, vol. 14, p1325-1334.

[28] CEREMA (2011). Démarche RESAU² : Résilience des Acteurs de l'Urgence et des Réseaux, Cerema, France.

[29] CEREMA (2009). Stratégie d'exploitation - Vallée du Rhône en Drôme-Ardèche, phase 1 : diagnostic circulation, Cerema, France.

[30] CEREMA (2009). Stratégie d'exploitation - Vallée du Rhône en Drôme-Ardèche, phase 2 : Scénarios et réponses Sécurité Civile : Réseaux stratégiques pour la gestion de crise, Cerema, France.

[31] CEREMA (2009). Stratégie d'exploitation – Vallée du Rhône en Drôme-Ardèche, phase 3 : propositions d'orientations stratégiques, Cerema, France.

[32] AUSTROADS (2004), Impacts of Climate Change on Road Infrastructure, AP-R243/04, Sydney, NSW.

[33] Federal Highway Administration (2017). Vulnerability Assessment and Adaptation Framework: 3rd Edition, Office of Planning, Environment, & Reality, FHWA-HEP-18-020.

[34] Highways Agency (2009). Climate Change Adaptation Strategy and Framework, United Kingdom.

[35] Williamson, T., Mclean D. (2016). Climate Change Risk Assessment Mitchell Freeway Extension Project. Position paper, CPD Contractors, W01000-EN-PP-9002, Australia.

[36] Beecroft, A., Peters, E. (2017). A4: Accounting for Life-Cycle Costing Implications and Network Performance Risks of Rain and Flood Events (2013/14‑2015/16). National Asset Centre of Excellence (NACOE) A4, Project No. 010561, Australia.

[37] Engeset, R. (2013). National Avalanche Warning Service for Norway: Established 2013, Norwegian Water Resources and Energy Directorate, International Snow Science Workshop Grenoble, Chamonix Mont-Blanc, Norway.

[38] Danish Road Directorate. (2013). Strategy for Adapting to Climate Change, Vejdirektoratet, Denmark.

[39] Hundecha, Y. and Bardossy, A (2004). Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model, J. Hydrol., 292, 281–295.

[40] Locquet E., Aldebert, P. (2016). Prise en compte de la hausse du niveau de la mer dans la conception de la NRL – Ile de la Réunion, Case Study Abstract, Egis.

[41] The Swedish Transport Administration (2014). The Swedish Transport Administration's Strategy for Climate Change Adaptation, Sweden.

[42] Petkovic, G., Humstad T., Dolva, BK. (2008). Analysis at the Nation level of Vulnerability and Adaptation Measures in Norway, Norwegian Public Roads Administration, Norway, n.d.

[43] Highways Agency (2008). Annual Report 2007-2008. United Kingdom, 2008.

[44] Evans, V., Tsolakis, D., Naudé, C. (2009). Framework to Address the Climate Change Impacts on Road Infrastructure Assets and Operations, Australian Transport Research Forum.

[45] Commonwealth Scientific And Industrial Research Organisation (2017). Climate Compass: A proposed climate risk management process for Commonwealth agencies, CSIRO, Australia.

[46] Nyman, M (2016). Managing knowledge sharing of extreme weather induced impacts on land transport infrastructure: Case study of the Swedish Transport Road Administration, Karlstad University Studies, Sweden.

[47] Highways Agency (2011). Climate Change Risk Assessment, United Kingdom.

[48] Tröltzsch, J., Rouillard, J., Tarpey, J., Lago, M., Watkiss, P., Hunt, A. (2016). The economics of climate change adaptation: Insights into economic assessment methods, ECONADAPT Deliverable 10.2.

[49] OECD (2016). Adapting Transport to Climate Change and Extreme Weather: Implications for Infrastructure Owners and Network Managers, International Transport Forum Research Reports, OECD Publishing, Paris.

[50] Bureau of Infrastructure, Transport and Regional Economics (2014). Overview of Project Appraisal for Land Transport, BITRE, Department of Infrastructure and Regional Development, Canberra, Australia.

[51] Lazarow, N. (2016). Real options for coastal adaptation: CoastAdapt, National Climate Change Research Facility, Gold Coast, Australia.

[52] Dore, M., Burton, I. (2011). The Costs of Adaptation to Climate Change in Canada: A stratified estimate by sectors and regions. On-line publication.

[53] Steininger, K., König, M., Bednar-Friedl, B., Kranzl, L., Loibl, W., Prettenthaler, F. (eds.) (2015). Climate Change in Austria: The Costs of Inaction, Springer, Berlin.

[54] Institute of Public Works Engineering Australia (IPWEA) 2017, Climate Change Risk Assessment for Roads and Transport Infrastructure, IPWEA (NSW) Roads and Transport Directorate, Prepared by Jennifer Yap.

[55] AECOM (2012). Climate Change Vulnerability Assessment Framework for Infrastructure, Policy and Cabinet Division, Chief Minster and Cabinet Director, Canberra, ACT.

[56] Federal Highway Administration (2016). 2013-2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned and Recommendations, US Department of Transportation, FHWA, July, Document FHWA-HEP-16-079.

[57] Commonwealth Of Australia (2015). Critical Infrastructure Resilience Strategy Policy Statement, https://www.tisn.gov.au/Pages/default.aspx

[58] VicRoads (2015). Climate Change Risk Assessment, State Government of Victoria, file:///C:/Users/ceaz4618/AppData/Local/Microsoft/Windows/INetCache/IE/YGUOIY35/Climate%20Change%20Adaptation%20Strategy.pdf

[59] The Climate Institute 2013 Infrastructure Interdependencies and Business-Level Impacts A new approach to climate risk assessment, Australia <http://www.climateinstitute.org.au/verve/_resources/TCI_InfrastructureInterdependenciesReport_April2013.pdf>

14. GLOSSARY

GLOSSARY	
Term	Definition
Adaptation	Adaptation is adjustment within natural or human systems in response to actual or projected climatic stimuli or their effects, which aims to moderate harm or exploit beneficial opportunities (PIARC Framework, 2015).
Adaptive Capacity	The ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies (PIARC Framework, 2015).
Consequence	Outcome of an event affecting objectives. An event can lead to a range of consequences. A consequence can be certain or uncertain and can have positive or negative effects on objectives (ISO, 2009).
Critical Assets	Critical assets are those that are essential for supporting the social and business needs of both the local and national economy (PIARC, Asset Management Manual, 2017).
Criticality	The relevance of an infrastructure element or section to the availability of a road infrastructure system. Note: Based on All-Hazard Guide for Transport Infrastructure, 2015.
Exposure	The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected (Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, IPCC, 2012).
Frequency	Measure of the likelihood of an event expressed as a number of events or outcomes per defined unit of time (ISO, 2009).
Likelihood	Chance of something happening (ISO, 2009).

	ISO uses the word "likelihood" is used to refer to the chance of something happening, whether defined, measured or determined objectively, subjectively, qualitatively or quantitatively, and described using general terms or mathematically (such as probability or a frequency).
Probability	Impact probability relates to the likelihood of an impact occurring within a given timeframe (PIARC Framework, 2015). Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty (ISO, 2009).
Resilience	The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events. Note: Definition developed by the study committee based on the extant literature and is consistent with the international disaster policy community (UNISDR, 2011), U.S. governmental agency definitions (SDR, 2005; DHS Risk Steering Committee, 2008; PPD-8, 2011), and NRC (2011).
Risk	Effect of uncertainty on objectives. Risk is often characterized by reference to potential events, consequences, or a combination of these and how they can affect the achievement of objectives. Risk is often expressed in terms of a combination of the consequences of an event or a change in circumstances, and the associated likelihood of occurrence (ISO, 2009).
Risk Analysis	Process to comprehend the nature of risk and to determine the level of risk. Risk analysis provides the basis for risk evaluation and decisions about risk treatment (ISO, 2009).
Risk Evaluation	Process of comparing the results of risk analysis against risk criteria to determine whether the level of risk is acceptable or tolerable (ISO, 2009).
Risk Management	Coordinated activities to direct and control an organization with regard to risk (ISO, 2009).
Risk Treatment	Process of developing, selecting and implementing controls (ISO, 2009).
Sensitivity	Is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli (PIARC Framework, 2015).

Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (PIARC Framework, 2015).

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