CEDR

Conférence Européenne des Directeurs des Routes

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ICARUS

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

Baseline report on minimum service levels, decision-frameworks, and resilience evaluation

Deliverable 2.1 Final version

30-11-2022

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CEDR call 2022: Climate Change

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Baseline report on minimum service levels, decision frameworks and resilience evaluation

30-11-2022

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Summary

This report identifies development and implementation gaps regarding the use and uptake of resilience evaluation methods and the use of service levels to do so.

The main implementation gaps we found are:

- Full application of resilience assessment frameworks including measure evaluation and deciding on minimum service levels and measures.
- Line of sight for resilience assessment across object, connection and network levels. The assessments and ambition setting on these three different levels seems not connected now.
- How to apply existing service level metrics to climate adaptation

The main development gaps we found are:

- Guidelines on how to decide which existing service level metrics should be used, especially in relation to climate change adaptation.
- Consideration of uncertainty in resilience approaches, both in climate change scenarios and return periods of hazards, as well as in predicted costs and benefits
- Building social vulnerability into resilience assessments

These gaps will be addressed in the future work packages of the ICARUS project. This gap analysis was performed by analysing the State of the Art and State of the Practice around three themes: decision frameworks for climate adaptation, resilience thinking and exploration on the use of minimum service levels. It should be noted that understanding of the State of the Practice is a key topic for the success of ICARUS and will be an ongoing process during the remainder of the research.

The research is based on literature, case studies and three workshops that were held with NRA's. The results of this baseline study are used as a foundation for Work Package 2 within the ICARUS project, which focusses on the decision-making process for adaptation and resilience measures to achieve minimum required service levels of the road network.

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1 Introduction

This report aims to set the baseline for research in Work Package 2 of the ICARUS project. Work Package 2 focusses on the decision-making process for adaptation and resilience measures to achieve minimum required service levels of the road network. For this purpose, an overview has been made of the State of the Art (SoA) and State of the Practice (SoP) regarding decision frameworks on improving resilience, resilience assessments and minimum service levels. For each of these issues, literature analysis, stakeholder engagement and knowledge of the ICARUS consortium was used to determine the SoA and SoP. A gap analysis is then performed to delineate future actions for the ICARUS consortium to address these gaps and streamline the uptake of resilience assessment in climate change adaptation for CEDR NRAs.

1.1 Outline of this report

This baseline report answers three research questions:

1. How are climate adaptation strategies established and how to determine where and when measures need to be taken?
2. How are resilience assessments currently performed?
3. How are minimum viable service levels determined?

The first research question will be answered in chapter 2: Decision frameworks for climate adaptation. Research question two is linked to chapter 3: Resilience thinking - definition, quantification, assessment methods. The last research question will be answered in chapter 4. Minimum service levels.

Both the second, third and fourth chapter start with presenting the State of the Art answering corresponding research questions and includes two official guidelines. The second part of each chapter 3, 4 and 5 finishes with the State of the Practice. The State of the Practice includes the workshop results, as well as practical examples.

The report concludes with a gap analysis (chapter five), which is the synthesis of this whole report and aims to identify the gap between the state of the art and the state of the practice in decision making for climate adaptation, resilience thinking and minimum viable service levels. This chapter also includes a roadmap for future studies within the ICARUS project.

The following sections describe the methodologies used while developing the State of the Art (Section 1.2) and State of the Practice (Section 1.3).

1.2 Development of State of the Art

1.2.1 Overview of methods and approaches in literature

The main purpose of the literature review is to consolidate how resilience assessments are performed, how climate adaptation strategies are established and how is determined where and when measures need to be taken.

Literature was selected by making use of different keywords either separately or in combination with each other. To this extent we relied on existing guidelines, research outputs, and academic publications (google scholar). Snowballing (e.g. using references in the found literature as new reference) has been used to find more papers related to a certain topic.

The following keywords and categories were used:

Table 1: Selected keywords for the literature review. The key words are grouped in overarching terms.

Resilience	Climate Adaptation	Service levels	Acceptable risk	Infrastructure	Other critical infrastructure
Resilience Assessment	Adaptation Measures	Minimum Service Levels	Safety	Highway	Rail
Resilience Evaluation	Identification of adaptation measures	Service Level Agreements (SLA)	Evaluation of Risk	Roads	Electricity
Risk			Tolerance levels		Gas
Robustness			Safety thresholds		CI
			Performance indicators		

1.2.2 Providing an overview of guidelines

We selected relevant guidelines and frameworks based on the literature research, the list of guidelines and literature provided in the DoRN complemented with the knowledge of the ICARUS team members. An overview of the used guidelines is available in Annex 1: Overview of existing methods and is referred to in relevant sections. The table in the Annex gives a complete overview of how the guidelines or frameworks score on certain topics relevant to this report.
Because there are not a lot of applications of the guidelines and frameworks, we describe these guidelines and frameworks in the State of the Art. However, the few applications which are there, are presented in the State of the Practice of each chapter.

The two most formal guidelines, the ISO 14091:2021 and the CEN CWA 17819:2021 are described in both chapter 2, 3 and 4 in the State of the Art section, to highlight to what extend these two guidelines add to the topic of each chapter.

1.3 Development of State of the Practice

The State of the Practice in this baseline reports reflects our current understanding of how the State of the Art is implemented. This is based on a combination of literature review and results of 3 online workshops, an initial inventory of cases and the experiences of the ICARUS consortium. It should be noted that understanding of the State of the Practice is a key topic for the success of ICARUS and will be an ongoing process during the remainder of the research. Especially the development of the case study portal and the workshops that will be organized in the remainder of the project will improve our understanding of the State of the Practice.

1.3.1 Workshops

To get an understanding of the current State of the Practice in the use of service levels for climate adaptation and resilience, the ICARUS consortium decided to undertake three workshops with the key stakeholders in the area. The workshops were organized very shortly after project conception, with attendees being invited from various stakeholder groups, as per the list in Table 2 below.

Table 2: List of stakeholder groups present at first ICARUS Stakeholder Workshop

National Infrastructure Authority	National Road and Coastal Administration
Department of Transport	Investment Banking
Local Council	Infrastructure Authority
National Road Authority	Construction Cluster
Infrastructure Owner	Regional Authority
Infrastructure Company	Institution (CEDR PEB member)
National Infrastructure Authority	Policy Advisors

In order to ensure maximum workshop attendance, three identical workshops were conducted on separate dates, with a total of 25 attendees from 9 different countries. The countries represented were Austria, England, Finland, Iceland, Ireland, Italy, the Netherlands, Spain and Wales. The organisation of three separate workshops not only lead to a higher stakeholder input, but also enhanced the field of knowledge and wealth of opinions garnered.

The workshop format was produced through internal meetings of the ICARUS consortium. The workshop was held over approximately 50 minutes and consisted of a combination of concept presentations and stakeholder feedback through Mentimeter and discussion. Initially, a presentation of the ICARUS project motivation and goals was given. The workshop was then split into three sessions, with the various aims in understanding the current SoP as listed below:

1. What is the State of the Practice (SOP) in resilience assessment to Climate Change for road infrastructure?
2. (How) is the concept of service levels used to enhance resilience in practice?
    a. What service level metrics should be used
    b. Are any of these used (and what are the barriers)
3. How are minimum service levels determined?

The workshops were held on the 1st, 5th and 13th September 2022. The workshop results are discussed in the State of the Practice subheadings within this chapter. The State of the Practice as a whole was determined through a combination of these results as well as literature searches and the expertise of the ICARUS consortium in this field.

1.4 Context

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

D1.1: Concise baseline report on determining impacts and risk due to climate change

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

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

In this report often a reference is made to different levels of analysis: asset, connection or network level. Figure 1 presents our understanding of these three levels. The asset level includes individual objects like culverts, small road segments or bridges. The connection level is a road segment between two intersections. The network level assessment includes the whole road network with multiple nodes and links.

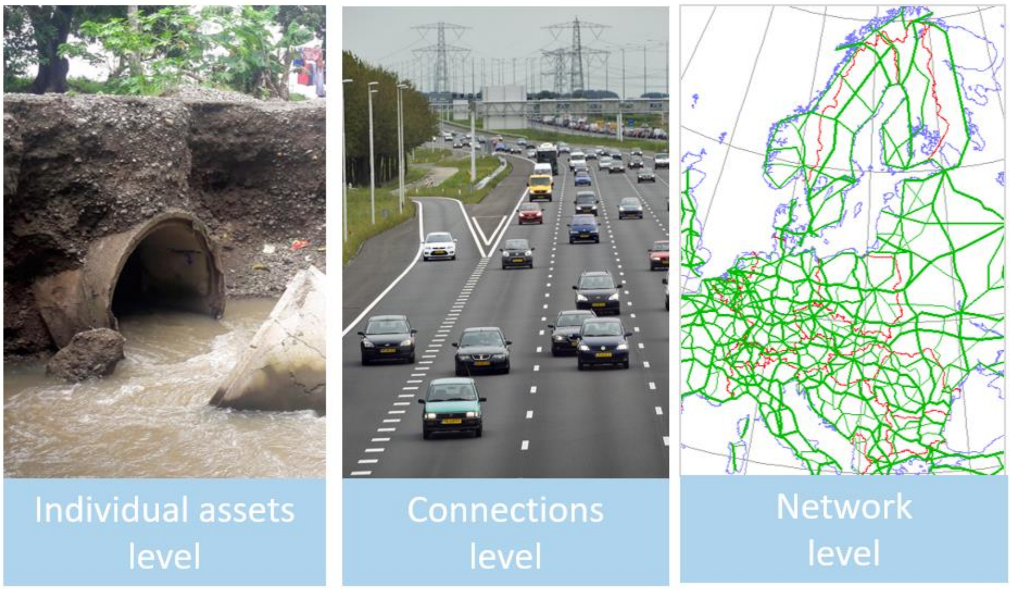


Figure 1.1 Our understanding of different level of assessment: asset - connection and network level

2 DECISION FRAMEWORKS FOR CLIMATE ADAPTATION

Once the risks of potential hazards to roads have been identified (Baseline report 1.1) decisions how to deal with them cannot be made right away. You need to determine how safe or robust the infrastructure should be, what service levels should be used and what measures there are. Those are complex questions. For example: How much water is allowed to remain on the road? And for how much time can the road be out of function? For highway infrastructure, there are no such standards at asset level (yet), and every National Road Authority has to determine the level of ambition themselves.

2.1 State of the Art

Over time several climate change adaptation frameworks have been developed, specifically for (road) infrastructure. In this section we present a brief overview of the important methodologies over the past years. Annex 1: Overview of existing methods summarizes these frameworks and guidelines in the form of a table.

2.1.1 ISO 14091: 2021

ISO 14091 - Adaptation to climate change — Guidelines on vulnerability, impacts and risk assessment is an international standard which introduces the concepts of resilience thinking in climate adaptation. While the document is an international standard, it has not yet been largely implemented in practice particularly for transport infrastructure. The procedure is broadly split up as follows:

1. Preparing a climate change risk assessment
    - Establishing the context
    - Identifying objectives and expected outcomes
    - Establishing a project team
    - Determining the scope and methodology
    - Setting the time horizon
    - Gathering relevant information
    - Preparing an implementation plan
    - Ensuring transparency
    - Facilitating a participatory approach
2. Implementing a climate change risk assessment
    - Screening impacts and developing impact chains
    - Identifying indicators
    - Acquiring and managing data
    - Aggregating indicators and risk components
    - Assessing adaptive capacity

    - Interpreting and evaluating the findings
    - Analysing cross-sectoral interdependencies
    - Independent review
3. Reporting and communicating climate change risk assessment results
    - Climate change risk assessment report
    - Communicating climate change risk assessment results
    - Reporting findings as a basis for appropriate adaptation planning

While this document may appear to be the initial basis for a decision framework for climate adaptation, the practicalities of implementing this are not dealt with. Rather, it can be seen as an overarching approach that more focused guidelines can follow when structuring climate adaptation procedures. It is noted that ISO 14091 proposes the use of risk assessment rather than resilienceand no formal consideration of resilience is provided for in the document.

2.1.2 CEN CWA 17819:2021

As Resilience is still an emerging field in climate change adaptation for road transport, very few code of practice exist. However, the recent Horizon 2020 funded research project, FORESEE has made progress in this regard. The FORESEE project aimed to develop a toolkit to provide short- and long-term resilience schemes for rail and road corridors and logistics terminals that can reduce the magnitude and/or duration of disruptive events produced by humans and nature. Deliverable 1.1 and 1.2 of the FORESEE project provided guidelines on measuring levels of service and resilience in infrastructures, as well as setting target levels. These deliverables were developed into the CEN publication CWA 17819:2021: "Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events". This document may form the initial basis for a European Standard on resilience assessment for transport infrastructure.

The CEN CWA 17819 resilience methodology is grounded on the principle of service levels, with resilience being principally measured in terms of how service is affected , and the cost of the interventions required to ensure that the infrastructure once again provides an adequate service. This is explained more thoroughly in section 4. From a decision framework perspective, CEN CWA 17819: 2021 proposes the use of Cost-Benefit-Analysis (CBA) in conjunction with resilience indicators in order to delineate resilience enhancements which allow adaptation to various hazards. While this framework does not specifically consider climate change and uncertain futures, the procedures application to transport infrastructure exposed to natural hazards makes it particularly applicable to the ICARUS requirements. Decisions are made based on the setting of targets for resilience indicators based on cost benefit analysis. In this case, the process is as follows:

1. Select the indicators for which targets are to be set, e.g. emergency plan indicator.
2. Set each target to the lowest value possible
3. Estimate the additional costs of each unit increase in the value of each indicator from the lowest legally allowed value
4. Estimate the additional benefits of each unit increase in the value of each indicator from the lowest legally allowed value.
5. Estimate the benefit/cost ratio for each unit increase for each indicator to determine if each increase is worthwhile.

6. Set targets for all indicators based on the estimated benefit/cost ratios, the available resources and the opinions of the stakeholders, which should be able to broadly support the targets.

This CBA methodology as it pertains to indicators is expected to form the initial thinking for future standardization in resilience of transport infrastructure and hence, these CBA methodologies will be dealt with more thoroughly in ICARUS D3.1.

2.1.3 TRB: Investing in Transportation Resilience: A Framework for Informed Choices

The Transportation Research Board is one of the programs of the National Academies of Sciences, Engineering, and Medicine of the United States to .o provide leadership in transportation improvements and innovation. . TRB (2021) provided a review of current practice by United States transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience, as well as contemporary research. The report is particularly interesting as it deals with climate change and transport infrastructure. One of the key recommendations of the TRB document is the use of their proposed decision support framework for measuring resilience benefits (or the societal costs avoided from adding resilience). The components of the framework are illustrated in Figure 2.1.

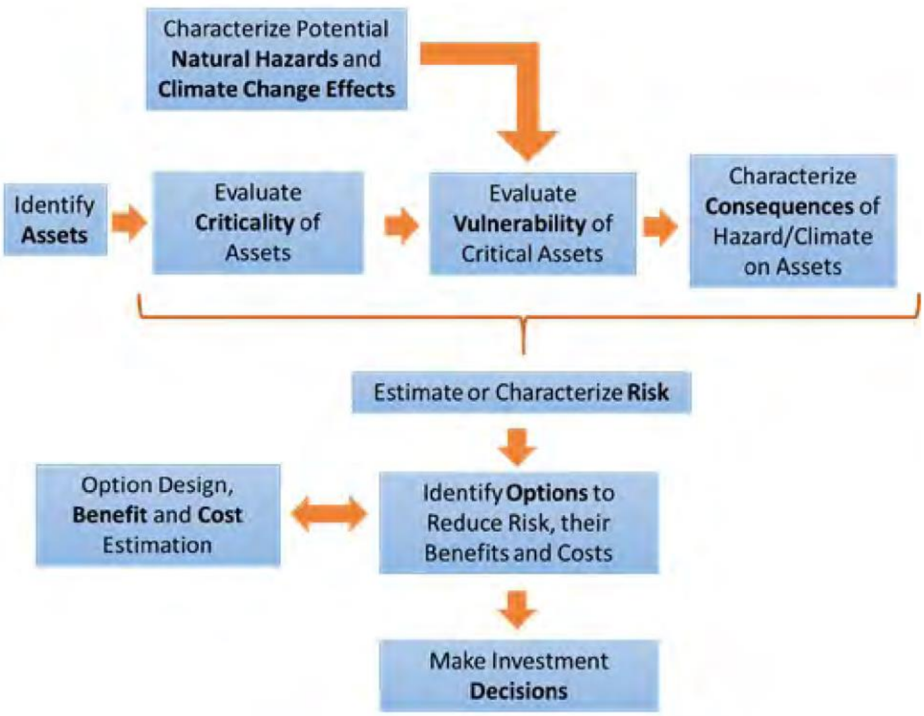


Figure 2.1 Components of the proposed decision support framework from TRB (2021)

The TRB framework begins with a characterization of natural hazards and climate change effects, followed by an evaluation of asset criticality, vulnerability and consequences of hazard impacts. This is used in a formal risk assessment which can be used in conjunction with cost benefit analysis of variations risk reduction options. While this document is focused on transportation resilience, the procedure above is clearly grounded on the principles of risk assessment. The argument here is that when criticality metrics are combined with metrics for vulnerability or risk, they can also give an indication of overall resilience at the system or agency level. The TRB argues that the adoption of direct quantification of resilience is very uneven across agencies. However, the above procedures of analysing hazard likelihood and characterization to assess the vulnerability of assets, networks, and service are more common, as are the use of vulnerability and criticality assessments to prioritize subsequent studies of mitigation actions. Moreover, assessments of consequences are also commonly used to gain an understanding of the impacts of failing to act in the face of climate change. This is the basis for the indirect enhancement of resilience through more traditional risk based approaches.

2.1.4 CCRI: Physical Climate Risk Assessment Methodology (PCRAM)

The Coalition for Climate Resilient Investment (CCRI) is a private sector-led initiative dedicated to supporting investors and governments to better understand and manage physical climate risks (PCRs). The CCRI developed the Guidelines for Integrating Physical Climate Risks in Infrastructure Investment Appraisal. The approach advances a dynamic impact assessment of PCRs that can be incorporated in investment decision making. The Methodology is developed in four steps: Scoping and Data Gathering, Materiality Assessment, Resilience Building and finally, Economic and Financial Analysis. The Materiality Assessment covers aspects similar to a hazard assessment, and outlines financial and/or commercial impacts in general or specific impacts on performance KPIs, like damage costs, downtime, loss of service or socio-economic losses. It essentially consists of a risk assessment approach investigating the impacts of hazards. The resilience building step then focuses on interventions which may be structural or non-structural. In terms of decisions, the CCRI methodology has three decision gates at each of the first three steps: Is data robust, complete and sufficient? Are PCRs material to the asset (i.e. do they impact on the materiality of the asset)? Do suitable resilience options exist? Should the user get to the final stage, the benefits of interventions are compared with the cost of implementing the various options and the disbenefit of doing nothing to determine whether there is a case for investing in resilience. A comparison with risk transfer through insurance should also be considered.

2.1.5 ROADAPT

The ROADAPT (Roads for today adapted for tomorrow, CEDR 2015) project delivered a set of guidelines for the preparation of adaptation strategies by road network administrations. The guidelines cover the basic steps, from climate change projections, to vulnerability and socio-economic assessments.

The basis is the application of a QuickScan methodology on climate change risks for road infrastructure (Figure 2.2, Bles et al., 2016). The methodology builds on a risk-based approach, where the basis is an overview of climate change related hazards, followed by a geospatial vulnerability analysis demonstrating which locations of the road are affected. The vulnerability is combined with a socio-economic impact analysis to identify the consequences of the hazard. After a risk evaluation ROADAPT also provides an overview of what adaptation measures are selected and how to define a strategy). ROADAPT is integrated with the Risk Management for Roads in a Changing Climate (RIMAROCC) framework which was developed in 2010 with the goal to create a common transnational method for risk analysis and risk management related to climate change effects on road networks in Europe (Bles, 2010).

ROADAPT recommends to use the following criteria for assessing the consequences of events: availability, safety, effects on surrounding road network, direct technical costs, reputation and environment and provides a methodology to assess these consequences with a semi quantitative approach. In the risk evaluation phase it is recommended to set a level of acceptable risk, based on a combination of likelihood of events and the consequences by making use of a risk matrix. Though not mentioned within ROADAPT this clearly links to the target service levels of a road authority: if the target service levels are exceeded, the level of risk will be unacceptable.

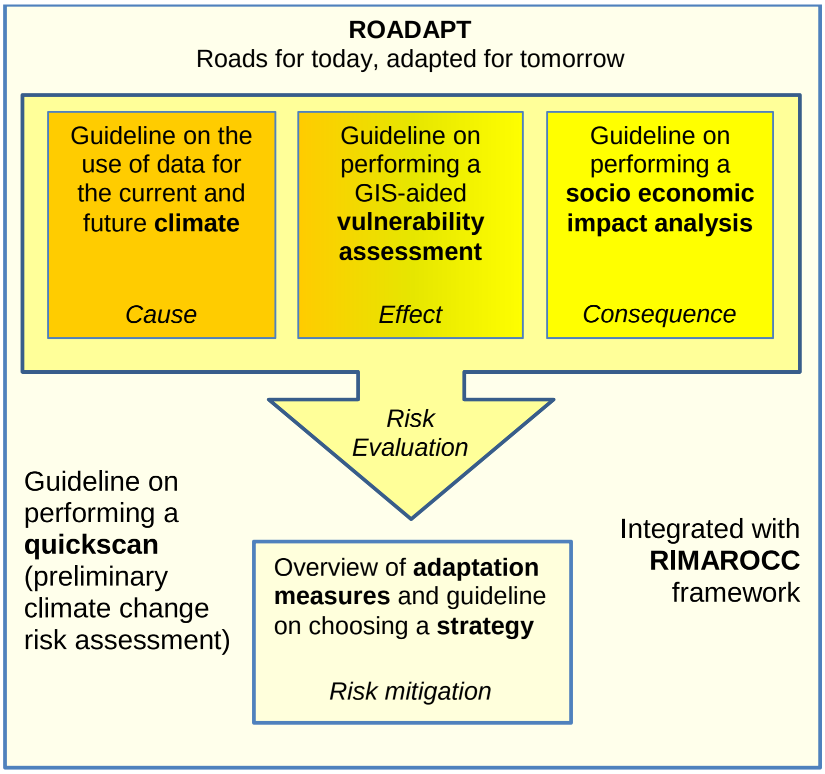


Figure 2.2 ROADAPT QuickScan methodology to assess climate risks for road infrastructure

2.1.6 PIARC: International climate change adaptation framework for road infrastructure

The PIARC climate change adaptation framework (PIARC, 2015) is designed to ensure that any road authority can start taking effective steps to increase the resilience of their roads to climate change. It is said to be designed to account for barriers to taking actions as well as varying levels of preparedness and adaptive capacity. It can be applied at all scales from object to network scale. To ensure applicability in all circumstances it provides a general approach, rather than being prescriptive and very detailed. It uses an approach with 4 stages as is visualized in the figure below. These stages link to the risk assessment processes and approaches that are already in place at road authorities. The framework explicitly mentions the prioritization of risks, the development of an action perspective for climate adaptation and the implementation in the relevant processes of organizations. For this purpose it even highlights the need to build a business case for adaptation.

At the same time, all stages are described in general terms and it is difficult for a user of the framework to directly understand what steps need to be taken. Furthermore, it is to be noted that the framework is a risk based framework (which was the state of the art in 2015). Prioritisation of hotspots is advocated to be done based on combining probability and consequences. Resilience is being mentioned, but not explicitly addressed in the four stages. Also, the process described is mainly semi quantitatively rather than quantitatively.

In the annexes of the framework also a list of barriers for implementation is listed. These seem to still be of relevance for the ICARUS research:

- Lack of resources
- Lack of understanding/education or will to change behaviours
- Lack of knowledge, understanding, guidance and expertise relating to climate change adaptation (including barriers relating to modelling climate change effects and impacts)
- Difficulties in identifying priorities for action
- Financial resources
- Incorporating climate change adaptation into other sectors, plans, programmes, strategies, etc.
- Collaboration with other sectors, stakeholders, etcetera

Currently, PIARC is updating the framework. Main items being addressed are the consideration of criticality assessments, adaptation pathways to address decision making under uncertainty, as well as the evaluation of the overall economic value of adaptation measures. In this sense, the concept of resilience is also being integrated in the framework.

Stage 1: Identifying scope, variables, risks and data
- Establishing assessment scope and aims
- Defining key tasks and delivery plan
- Early stakeholder consultation and establishing roles and responsibilities
- Assessing vulnerability
- Assessing adaptive capacity
- Assessing climate change projections and scenarios

Stage 2: Assessing and prioritising risks
- Assessing impact probability
- Assessing impact severity
- Establishing Risk Scores

Stage 3: Developing and Selecting Adaptation Responses and Strategies
- Identification of adaptation responses and opportunities
- Selection and prioritisation of adaptation responses and opportunities
- Development of an Adaptation Action Plan or Strategy

Stage 4: Integrating findings into decision-making processes
- Incorporating recommendations and requirements into programs, processes and investments
- Education, awareness and training
- Effective communication
- Developing a business case
- Future planning and monitoring

Figure 2.3 PIARC framework

2.1.7 FHWA: Vulnerability Assessment and Adaptation Framework

The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework (the Framework) is a manual developed for State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining, or operating transportation infrastructure in the United States. The Framework provides an in-depth and structured process for conducting a vulnerability assessment (Figure 2.4) based on the selection of key climate variables (temperature, precipitation, riverine hydrology, sea level rise, and storm surges), compilation of data (asset, climate, hydrology) and how the vulnerability is assessed (stakeholder input, indicator-based desk review or engineering informed assessments). This is followed by the steps to take to identify adaptation options and how to evaluate those (using multi-criteria analyses, or other economic analyses) and what kind of costs and benefits are there to be considered. The costs and benefits to consider include direct costs and direct benefits (avoided maintenance and construction costs and time to repair), and indirect effects (environmental impacts, human health and well-being costs and benefits). Finally, the results may be integrated into decision-making processes to assist with project planning and prioritisation, design, environmental review, operations and maintenance, and asset management.

For each step the framework features examples from assessments conducted between 2010 and 2017 and includes links to related resources that practitioners can access for additional information (Federal Highway Administration (2017)).

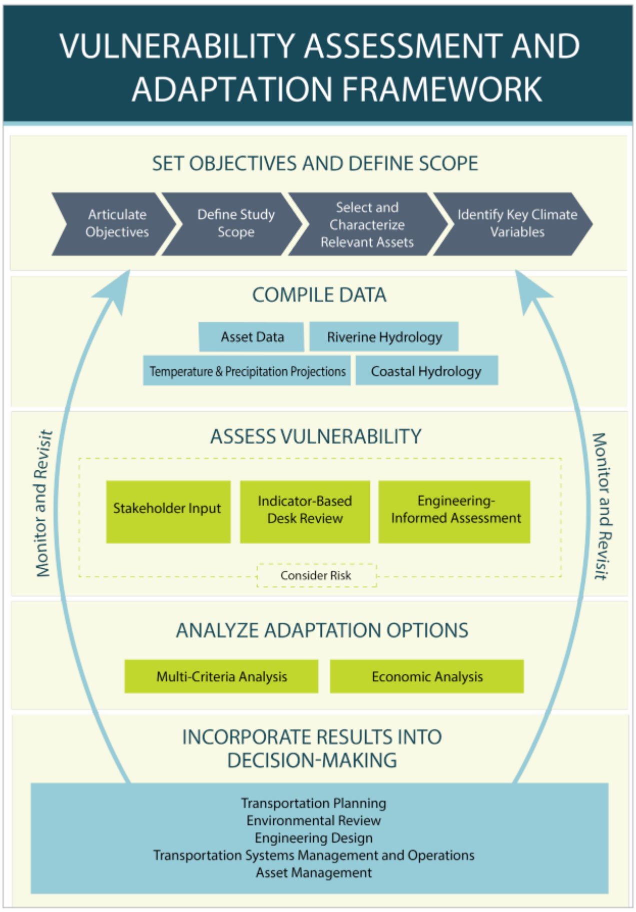


Figure 2.4 FHWA framework (Federal Highway Administration (2017)).

2.1.8 Enhancing Resilience Decision Framework (ERDF)

The Enhancing Resilience Decision Framework (ERDF) has been developed to demonstrate how a decision framework should look and is depicted in Figure 2.5 (De Jonge, 2021). The new aspect of this framework is that it compares the current level of resilience with a certain ambition level: the desired level of resilience. This should be done based on predefined criteria and thus this evaluation creates an understanding what the gap is between the ambition and the current level. The evaluation can be done making use of the green boxes on the right side of the diagram. The report describes the steps to take to come to decision-making.

The current level of resilience could be determined making use of the execution of stress-tests and to identify what the impact is of natural hazard events. In section 3.1.2 of this report methods will be explained on how to quantify resilience, and section 3.1.3 gives an overview of the guidelines.

The desired level of resilience should be determined in close collaboration between the government, road operator (NRA) and the user. How to determine this desired level, is elaborated on in section 4.1.2. The desired level of resilience is best expressed as a minimum or maximum service level. When the desired level of resilience is higher than the current level of resilience, suitable adaptation measures should be selected.

The measures must be evaluated using for example a societal cost benefit analysis (SCBA), which can be performed either quantitatively or qualitatively. Within ICARUS baseline report of WP 3 on Appraisal Methodologies, Benefits and Costs will explain those and work on how to evaluate the measures.

When appropriate measures are taken, this leads to an adaptation plan, which leads to a *new level of resilience*. Sometimes, the *desired level of resilience* can never be reached, because the measures are too costly (see red arrows in Figure 2.5). Then, the *desired level of resilience* has to be lowered, because otherwise it can never meet the *new level of resilience* (after adaptation).

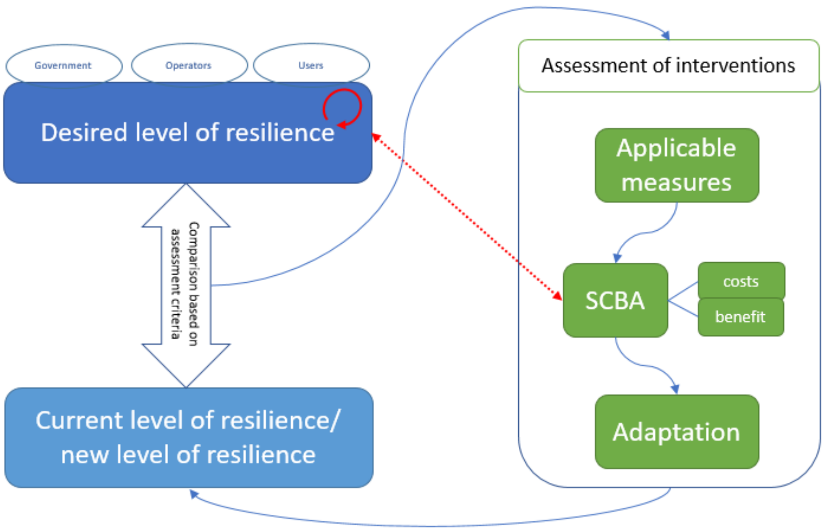


Figure 2.5 Decision framework on how climate adaptation is evaluated and its relation to the service level indicators (Bles et al., 2020, De Jonge, 2021).

2.1.9 Six step approach for climate adaptation of critical infrastructure

Another framework worth mentioning is developed for the Dutch knowledge portal on climate adaptation regarding critical infrastructure protection, see Figure 2.6. It was developed on commission of the Dutch ministry to gain insight in climate adaptation of specifically critical infrastructures. The road network, as part of main transportation infrastructure, is explicitly mentioned and targeted here. The framework is made for infrastructure owners and operators as well as local governments.

The proposed process consists of six steps starting with stress testing the critical infrastructures, calculating impact, including cascading effects, quantifying risk, setting an ambition, and finally proposing appropriate measures. For each step different methodologies and case study examples are given (Kennisportaal Klimaatadaptatie, n.d.).

Figure 2.6 Framework for climate adaptation of CI of the Dutch knowledge portal on climate adaptation.

2.1.10 WATCH manual

For the CEDR call 2015, from desk to road, the WATCH project has developed a manual (Foucher et al, 2018). The manual aims at assessing current and future resilience of NRAs water management facilities, ensuring optimal design, maintenance planning and asset management. The approach considers two levels of analysis (high and detailed level) including risk assessment, socio-economic evaluation protocol and definition of measures and strategies.

On the high level, the analysis is performed for sub-groups of assets in order to identify the best adaptation strategy for those sub-groups (classification based on extrinsic site factors, infrastructure intrinsic factors, consequences and hazard level). The goal of this "screening" level is to prioritize the assets that should be further studied in the detailed level.

On the detailed level, an analysis is carried out for each type of asset following 4 main steps: asset inventory, hydrological calculations, hydraulic analysis of the asset and asset risk evaluation. The adaptation strategy from the high level is translated into design options, up to the individual asset. Design and maintenance choices are compared using a socio-economic evaluation for specific assets. The final socio-economic evaluation, aggregated at the project level, should then be compared to the initial economic evaluation to confirm the validity of the strategy selected at the high level.

The WATCH manual explicitly addresses evaluation of risk to a certain to be established reference risk levels. Since the manual is specifically written in the context of water management for roads that is being undertaken by the NRAs (i.e. culverts and pipes), the decision making linked to this risk evaluation is explicitly written for these types of assets and is rather specific (if compared to the other guidelines described in the SoA). Socio-economic appraisal of the current status, compared with adaptation measures, are at the core of the manual to establish an effective adaptation strategy. Though the manual focusses on risk assessment, the criticality and effects of disruption on road users are incorporated in the steps.

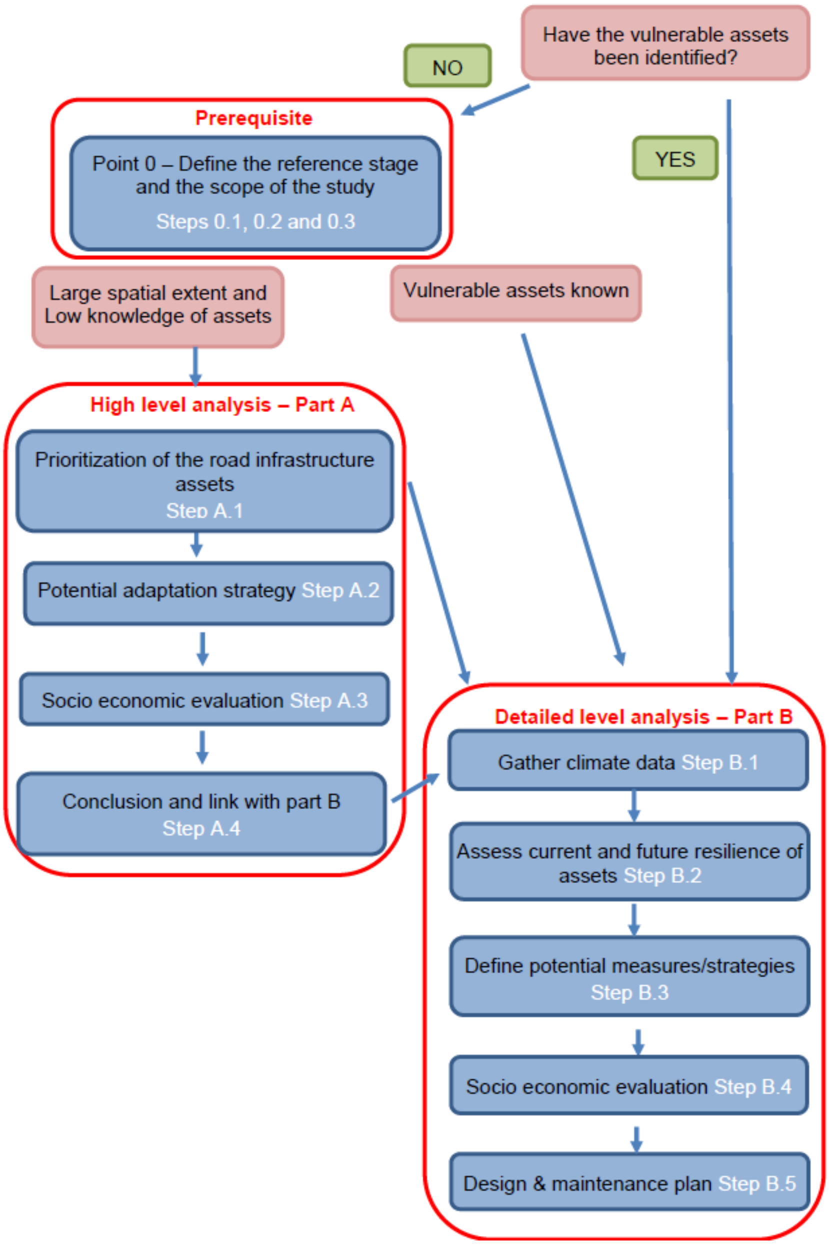


Figure 2.7 The WATCH decision tree

2.1.11 Decision-making under Deep Uncertainty - methods and guidelines

Many investments and policy decisions are based on long-term objectives, which need to be decided on in the near-term. Policy makers often need more than a single prediction or a scenario-based decision where the large uncertainties of for example climate change effects are accounted for. DMDU approaches can be used to identify tipping points. This could also be a viable method to apply to critical infrastructures: to determine tipping points where certain service levels cannot be reached anymore and to identify adaptation planning approaches. One example is provided in Chapter 2.2.5.

Based on Lempert et al., 2004 deep uncertainty arises when decision-makers do not know or cannot agree on the likelihood of alternative futures or how decision or actions are related to consequences. This can happen when they don't agree on (i) the models to describe the system, (ii) the probabilities and interdependencies of the inputs of the model and (iii) how to measure the desirability of the model outcomes (Lempert et al. 2004). This uncertainty makes it hard to make decisions on where to place or prioritize the interventions or could result in making decisions based on cost-benefit approaches with high uncertainty (Fankhauser and Soare, 2013). Recently several methods have been developed to support decision-makers in these circumstances with deep uncertainty (Hallegatte et al., 2012).

DMDU Guidebook for Transportation Planning under a changing climate (IADB)

Specifically, for development in Latin America and the Caribbean (LAC) the Inter-American Development Bank (IADB) has developed a guidebook for transportation planning under a changing climate and is developed to support IADB team members that work on transportation sector funding and planning. It presents the methodological steps that are necessary for the implementation of DMDU methodologies and reviews several such methods, including scenario planning, Adaptive Pathways, and robust decision making (RDM).

Based on the guidelines developed by the IADB specifically for the Latin America and the Caribbean (LAC) region every DMDU analysis should start with the Decision Framing, which is used to understand a problem and to create a shared understanding. This can be done with a so-called XLRM (x=uncertainty factors, l=policy levers, r=relationships, m=performance metrics) framework (Lempert et al.,2003). Figure 2.8 demonstrates how such a completed XLRM matrix could look like. I Once the XLRM matrix exists DMDU approaches can be applied. The guidebook describes how the scenario planning, adaptive pathways and robust decision making (RDM) methods can be applied.

Uncertainty Factors (x)	Policy Levers (L)
» Temperature and rain variability » Number of intensity of storms » Economic growth and traffic demand » Environmental regulation » Construction and maintenance costs » Funding (local, state, private, economic conditions) » Political climate (provincial disputes) » Policy environment (provincial, national)	» Bridge design » Redundancy (increasing road network to reduce detour in eventual flooding)

Relationships (R)	Performance Metrics (M)
» Change in logistic costs -> change in traffic and in socio-economic variables (GCD, labor, poverty, inequality) » Change in the reliability of the network -> change in socio-economic variables (GCD, labor, poverty, inequality) » Change in highway supply -> change in the highway demand	» Average operational costs (logistics) » Operational cost (logistics) » Average speed » Number of days without traffic interruption » Provincial and Mercosur connection » Jobs created for the public work » Long-term jobs created » Reduction of regional inequality » International competitivity of the provinces » GDP growth

Figure 2.8 Example of what a completed XLRM framework could look like

Scenario Planning

DMDU can be applied in several ways. For example, making use of scenario planning processes, during which stakeholders and planners follow steps to identify what would happen in certain scenarios to be able to be prepared for future conditions (Lyons et al., 2014). This process starts with identifying the current conditions and the planning horizon (e.g. 2050,2100), identifying the driving forces and structure them in most critical. In a narrative-approach, future scenarios will be developed and for each narrative the implications identified. Based on this it is possible to identify what actions should be taken and prioritise on the best actions to take under what circumstances and what an adaptive plan should look like.

Dynamic Adaptive Policy Pathways (DAPP)

When decision makers and analysts face a deeply uncertain future (e.g. due to climate change), they need more than traditional prediction or scenario-based decision methods to help them to evaluate alternatives and make decisions. The Dynamic Adaptive Policy Pathways (DAPP) approach aims to support the development of an adaptive plan that is able to deal with conditions of deep uncertainties.

DAPP has demonstrated to be valuable for identifying the points in time when policy-makers can make decisions for investments in adaptation measures to improve the resilience of their road network (example in Figure 2.9).

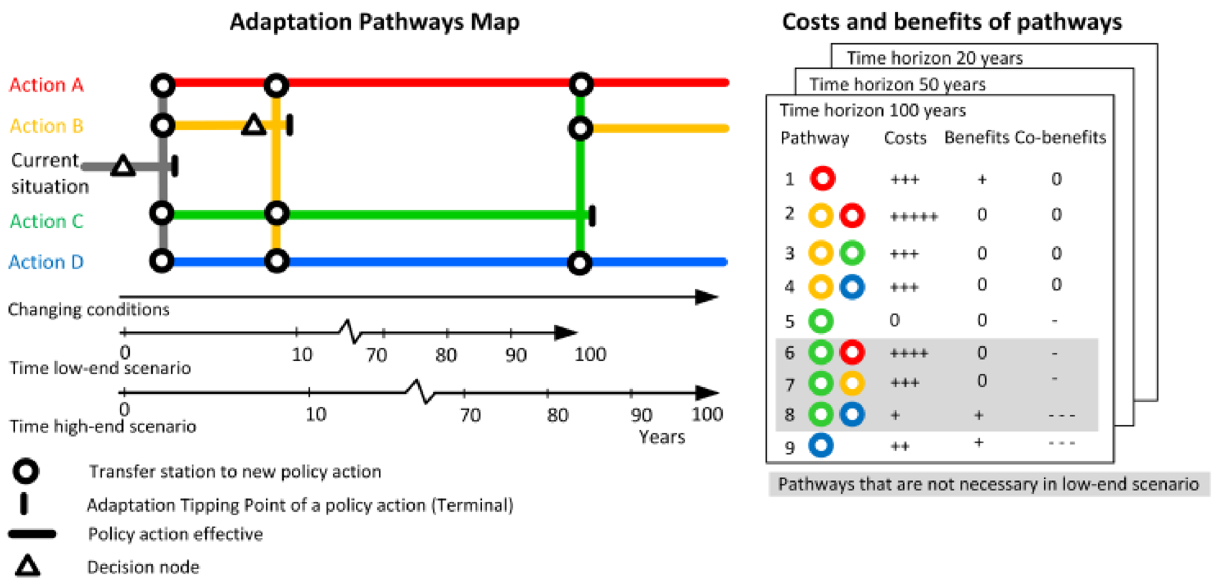


Figure 2.9: An example of adaptation pathway which is a result of the dynamic adaptive policy pathways (DAPP) approach (Haasnoot et al., 2013).

Robust Decision Making (RDM)

Robust Decision Making (RDM) is an analysis where models and human input iteratively test identified strategies for future conditions (Lempert et al. 2003). This is done on a large dataset of future scenarios where proposed policies are stress-tested. The goal is to find strategies that perform well in many potential future scenarios, ultimately leading to an increased robustness. Understanding the conditions of each strategy illustrates the vulnerabilities of each proposed strategy and trade-offs among the strategies. When new information is available the approach can be used to update the designed strategy and include monitoring and corresponding response measures. RDM can be used in group processes, where the basis can be a design framing session, during which stakeholders define the key factors in the analysis, the objectives and criteria, and the actions they can take to achieve these objectives (XLRM framework as described in Section 2.1.11).

2.1.12 State of the Art summary

Many guidelines and approaches exist with appraisal methods to identify effective measures and design an adaptation strategy towards an uncertain future when addressing climate change. We found ten specific frameworks/standards addressing these points and summarised them in Annex 1. Of these two, the ISO 14091: 2021 and the CEN CWA 17819:2021 are most formalized. Most of the guidelines take uncertainty towards the future due to climate change into account, at least to some extent. We found only a few guidelines or frameworks which use service levels.

2.2 State of the Practice

This section starts with the perspectives and use of climate adaptation frameworks in Ireland, Spain and The Netherlands. This information came from experts from the ICARUS consortium. Furthermore, a literature review was completed in order to find examples of decision frameworks which have been put into practice. As seen in Section 2.1 there are many examples, but only few have been put into practice. Still we try to present some of them here.

2.2.1 Transport Infrastructure Ireland's (TII) Climate Change Adaptation Strategy

In 2017, Ireland's national road authority, TII, published a "Strategy for Adapting to Climate Change on Ireland's Light Rail and National Road Network" (Transport Infrastructure Ireland, 2017). Due to the expected increase in winter rainfall and heavy precipitation events in Ireland, TII's strategy for adapting to climate change focuses on minimising disruption due to flooding events through Management, Improvement, Prevention and Cooperation.

The **Management** phase is required when a motorway has to be closed due to flooding. TII will cooperate with emergency services to inform users, co-ordinate clean-up and prioritise strategic sections of the motorway of greatest economic importance.

Following a flooding event, the section of road which had to be closed is investigated and mitigation measures to prevent future flooding events are explored in the **Improvement** phase.

Measures which TII plan to take to minimise and **prevent** future flooding events include identification of hot spots and preparation of action plans, enhancement of the maintenance and rehabilitation programme, ensuring climate change is accounted for in planning and construction of future schemes, participation in research projects, and participation of knowledge sharing with European partners through the CEDR technical group on climate change.

In the **Co-ordination** phase, co-ordination with local authorities, road operators, emergency services and the Office of Public Works (OPW) is maintained.

2.2.2 Climate Adaptation in Spain

In September 2012, the Fomento Group and the Ministry of Agriculture, Food and Environment carried out a preliminary analysis of the possible needs for adaptation to climate change of the backbone network of transport infrastructures in Spain; the intention is that these results feed into the reflection promoted by the EEA (European Environment Agency) and, at the same time, contribute to the Spanish administration having a better understanding of the issue and being able to promote initiatives and take the appropriate decisions when the time comes (GRUPO DE TRABAJO, 2013).

Following review of weather and climate data and the associated risks to the transport infrastructure in Spain, it is recommended that when infrastructure design criteria are reviewed and updated, different alternatives should be considered for different levels of risk, since the adoption of design criteria whose primary objective is to avoid risk often increases the cost of infrastructure construction and costs more money than the implementation of measures aimed primarily at improving risk management.

With regard to roads, it is recommended in the short term to review the regulations and design recommendations for earthworks in order to reduce the vulnerability of cut and fill slopes to combined drought and more intense rainfall events and more severe extraordinary floods.

In the medium term, it is recommended that road managers should consider in detail the opportunity to revise standards 6.1-IC and 6.3-IC of the Instrucción de Carreteras, in order to adapt the design of sections and rehabilitation of bituminous pavements to the expected increase in maximum temperatures and decrease in average rainfall. The increase in maximum temperatures can lead to an increase in the risk of rutting and non-structural cracking due to premature oxidation of the binder, making it advisable to revise the map with the summer thermal zone included in standards 6.1 IC and 6.3 IC, on the basis of which the type of bituminous binder is chosen, as well as the ratio between its dosage by mass and that of the mineral dust.

2.2.3 Implementation in the United States

As described in Section 2.1.7, The Federal Highway Administration (FHWA) published the "Vulnerability Assessment and Adaptation Framework" in 2017 which offers guidance to transportation agencies on how to assess the vulnerability of transportation infrastructure and systems to extreme weather and climate effects (Federal Highway Administration, 2017). The framework offers three methods to assess vulnerability which include Stakeholder Input, Desk-Based Review, and Engineering-Informed Assessments.

Minnesota Department of Transportation (MnDOT) developed a set of vulnerability indicators in an Indicator-Based Desk Review to understand their assets' vulnerability to floods. They weighted the indicators to produce scores for sensitivity, exposure and adaptive capacity, enabling them to identify the most vulnerable elements of their networks. The results of their Indicator-Based Desk Review is shown in Figure 2.10.

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

Figure 2.10 Example of Indicator-Based Desk Review: MnDOT scaled and weighted indicators of sensitivity, exposure, and adaptive capacity of assets under study to create vulnerability scores. This allowed MNDOT to group assets into vulnerability tiers (Federal Highway Administration, 2017).

The FHWA also ran a climate resilience pilot program in which a number of transportation agencies in the US participated with the aim of developing resilience and vulnerability assessments which may then be integrated into decision making frameworks, A couple of examples are presented here:

- The North Jersey Transportation Planning Authority (NJTPA) assessed the vulnerability of the State’s aging transportation systems. The NJTPA wanted to understand how to make more strategic capital investments in light of the changing climate. They identified the climate events which would pose risks to their infrastructure, such as extreme heat and flooding, and then developed adaptation strategies which could be implemented during the decision-making process at the design stage.
- The Metropolitan Transportation Commission (MTC) in San Francisco revised their vulnerability assessment with future climate predictions, allowing the development of adaptation strategies which can then be used when making investment decisions.
- The Tennessee Department of Transportation (TDOT) conducted a comprehensive vulnerability assessment of their infrastructure assets throughout the state. They used past and future weather and climate data to assess their infrastructure assets and prioritise the most vulnerable assets. More detailed analysis may be performed on the most vulnerable assets, with the data also being incorporated in a risk-based transportation asset management plan (Federal Highway Administration, 2017).

2.2.4 Enhancing climate resilience of the Dutch main road network

Rijkswaterstaat, the Dutch road authority, has formulated the objective to achieve a climate resilience road network in 2050, by starting to act in a climate resilience manner from 2020 onwards. To reach this objective several studies have been conducted:

- A resilience assessment, which is called a *stresstest*. This stresstest consisted of assessment of the hazard, exposure, vulnerability and impacts of several climate events. Impacts have been quantitatively assessed in terms of damages (i.e. the costs for Rijkswaterstaat to repair/reconstruct the road after the climate event) as well as in terms of losses for road users (i.e. vehicle loss hours due to traffic jams and detours). Uncertainty has been addressed by using upper and lower bandwidths for the duration and economic valuation of the different events. Climate change is considered with the assumption that the impact will remain similar, but the likelihood of occurrence will change.
- Providing action perspectives for developing an adaptation strategy in an implementation agenda. For all climate events, a list of measures has been gathered. Lists of measures have been compiled by making use of available State of Art procedures (eg. ROADAPT – Section Error! Reference source not found.), completed with expert input from the road authority. The effects of measures have been scored in a multi criteria assessment to two types of criteria. First, criteria that are used in the asset management system (PRA) being the effects of measures on availability, safety, environment and image. Secondly, criteria that link to decision making being robustness and flexibility of the measures, co-benefits and organizational feasibility. By comparing the effects with costs, a first indication of the cost effectiveness of measures could be provided. For the most promising measures, cost benefit assessments have been performed to identify on a national basis on which locations, the benefits of measures outweigh the costs of measure implementation.

It was perceived though, that only considering economic impacts (damages and losses) did not reflect the entire need for evaluation of the resilience. Therefore, the resilience has also been evaluated using the asset management framework of Rijkswaterstaat (van Maaren, 2018). This framework makes use of a risk matrix in which likelihood and impact are on both axes and provides a structured approach to derive the level of acceptable risk. The impact is classified using various criteria while using the acronym RAMSSHEEP: Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Euro (monetary), and Politics. None of the hazards impacted security or health. Therefore, these were left out of the further assessment. This approach was received well by the regional offices, since it links to daily practices and provides a clear way of evaluating all information.

Still, in practice it appears difficult to fully implement all outcomes of the stresstest and action perspective. A difficult question to answer is what the desired level of resilience of the road network should be. The policy goal for climate resilience that was set at the strategic level was “the service of the road network should at a minimum be kept the same in 2050, compared to the current service level”. To establish this acceptable level, several dialogues have been held with the policy makers and lead to the choice to use the RAMSSHEEP asset management framework (ref: PRA). Though, it proves to be complicated to balance the ambition for a level of resilience with the cost of adaptation, when incorporating all possible impact criteria together with economic output of damages and losses. As a part of the implementation agenda, effort was made to integrate adaptation into the asset management process of Rijkswaterstaat and make a clear ‘line of sight’ for adaptation choices. To construct a line of sight, goals must be set at policy level, that can be expressed in functional goals for the network. Asset managers should be able to make defendable choices between these goals and other goals in case of a deficit of money.

In practice, this proves to be challenging. Service requirements are being present for at the network level (e.g. availability or safety related) as well as for the object level (e.g. via design guidelines and requested capability for specific return periods). It is qualitatively understood that an increase of requirements at the object level will lead to a better performance at the network level, but a clear quantitative substantiation is not available. It appears that within a certain level (strategic/tactical/operational) and related scope (network, connection/object), analyses are being performed, but that the interaction between the levels is unclear.

The following conclusions can be drawn. In general, on a project basis (for design, replacement, renovation or maintenance) it is possible to identify how resilience can be improved by making use of existing frameworks (ref: PRA) and cost benefit assessments. However, for real implementation it would be necessary to be able to identify hotspots and to address resilience in design and maintenance guidelines. For that purpose, it is necessary to have a full understanding of the Line of Sight. How do service requirements on a network level decompose to requirements on a connection and object level, as well as vice versa to have an understanding how changes in design and maintenance guidelines at the object level will

2.2.5 DMDU applications in the Netherlands and Philippines

Applications of the use of DMDU to enhance resilience are not widely available. However, the Dynamic Adaptation Policy Pathways (DAPP) methods has been applied in the Netherlands to enhance road resilience via climate adaptation. Here, the approach has been used to develop an adaptation strategy for the A58 road (Leijstra et al., 2018) and describes different investment options (listed on the left) to increase the resilience of the road for pluvial flooding. These investment options can be implemented at different stages in time (Figure 2.11).

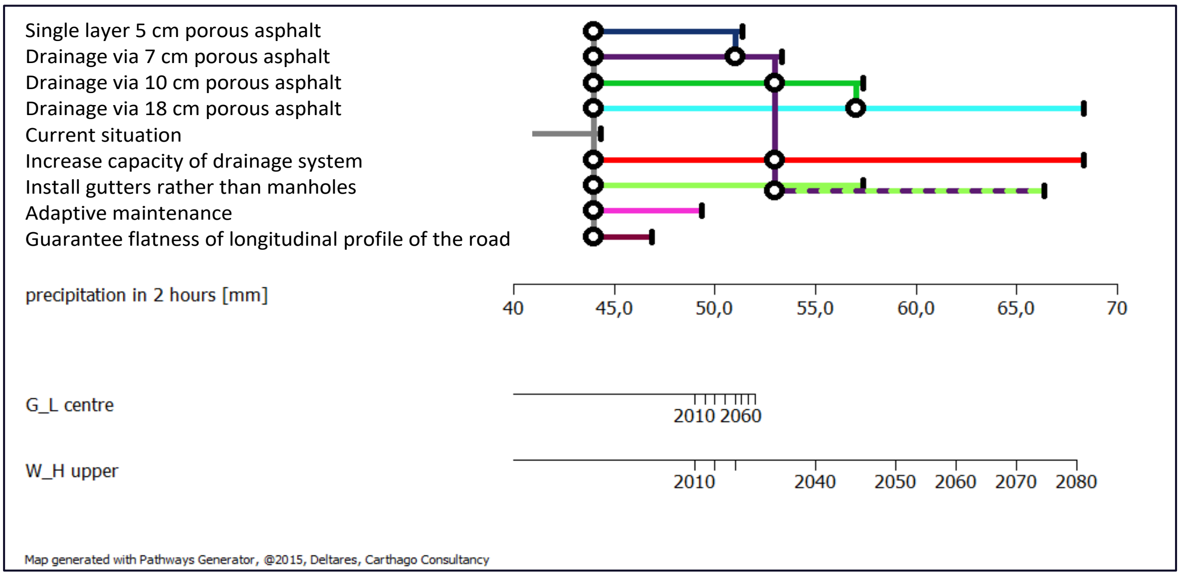


Figure 2.11: An example of adaptation pathways, associated with pluvial flooding (Leijstra et al, 2018).

In another example in the Philippines (Warren et al. 2019), the approach has been broken down to the key principles of DMDU, allowing local governments to use the method in practice to prioritize investments on the road network. This includes an assessment of prioritized road sections from a resilience assessment, identification of possible measures, analysis of effectiveness of the measures, assessment of the future performance of measures including an analysis of robustness under various possible future conditions, prioritisation of the measures and building of adaptation pathways.

2.2.6 State of the Practice Summary

Various climate adaptation strategy practices across Europe and internationally were reviewed in this section. Many guidelines and approaches exist with appraisal methods to identify effective measures and design adaptation strategies towards an uncertain future. Their absorption in practice varies greatly between the European countries and internationally.

It may be concluded that in most cases, decision making for climate adaptation is based upon the minimisation of risk at minimum cost. This is evidenced through the risk procedures of Spain and the US (FHWA, 2017). Only in the Netherlands has evidence been found of the direct use of resilience thinking in performance of climate adaptation plans.

Adaptation strategies are widely based upon the minimisation of risk at minimum cost. The risk incorporates impact or consequence analysis which may consider service measures, but not explicitly investigate the evolution of service measure losses over time.

Reference is also made to Deliverable 3.1 of the ICARUS project in which the appraisal of measures is being discussed, as well as the consideration of co-benefits.

3 RESILIENCE THINKING - DEFINITION, QUANTIFICATION, ASSESSMENT METHODS

3.1 State of the Art

Risk assessments are, nowadays, common practice for understanding the impacts of extreme events on critical infrastructure and transportation networks in particular. For the most part, such assessments include an identification and characterization of the hazards, an identification and characterization of the infrastructure exposed to such hazards and its vulnerabilities (see also the report of task 1.1 of the ICARUS project D1.1 Baseline report on determining impacts and risks due to climate change). However, resilience assessments go beyond the risk assessments, because this also includes the system's ability to plan for, recover from and adapt to external events over time (Figure 3.1, Linkov, 2014).

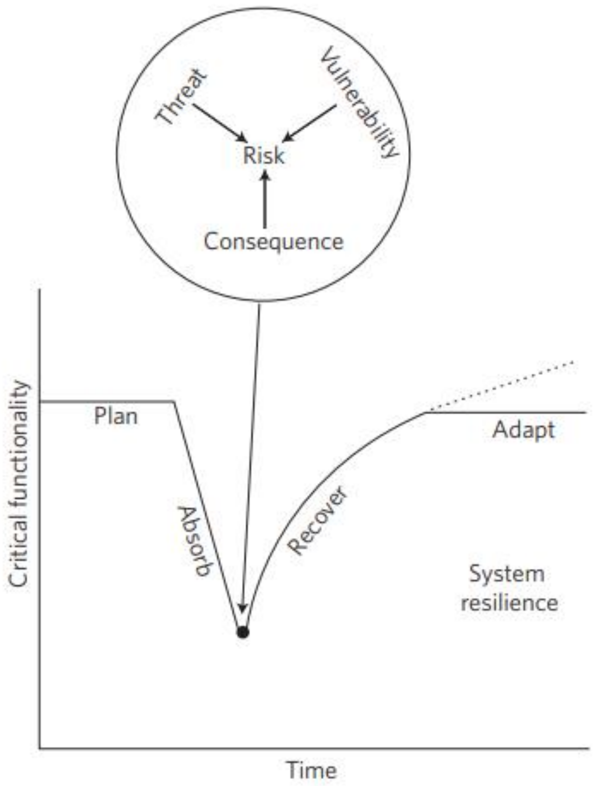


Figure 3.1 Resilience management framework as described by Linkov et al. (2014)

In the resilience management framework as described by Linkov et al. (2014), risk can be described as the total reduction in functionality, whereas the resilience also includes the slopes of absorption and the shape of the recovery curve, thus including time component. The dashed line suggests that resilient systems potentially adapt as such that the functionality may improve ('building back better').

This change towards resilience thinking results in several changes. As one example the focus is shifting from 'the asset level' towards a service level. In other words, the change from risk to resilience, will result in a change from protecting the assets from any type of hazard, towards ensuring a continuous (minimum) level of essential services or functionality to society (Petersen et al. 2020). From this point of view, it makes sense to start addressing how this 'minimum level of essential services' should be established. This will be discussed later in Chapter 4 Minimum service levels.

3.1.1 Definition of resilience

Resilience has been defined in many ways across a variety of disciplines, including infrastructure resilience. Over the past twenty years the number of publications on *resilience* expanded rapidly. However, there is still no universally accepted definition, and because the concept exists in many domains the question arises if this is even desirable. At the same time, it is important to be able to communicate between the different fields what is meant by the concept. Koslowski & Longstaff (2015) proposed a multidisciplinary framework to classify the different definitions and provide a holistic understanding. The framework distinguishes four categories with a high or low degree of normativity and complexity. The four categories are I: The capacity to rebound and recover, II: The capacity to maintain a desirable state, III: The Capacity of a system to withstand stress, and IV: The capacity to adapt and thrive. In many definitions related to (critical) infrastructure resilience, these four components are included as well.

There are many sources summarizing the definitions of resilience, even within the field of infrastructure resilience. For example, the Critical Infrastructure Preparedness and Resilience Research Network (CIPRNet), published an extensive list of definitions used in different domains and across different countries (CIPRNet). Also, the IMPROVER project, a European Union funded project has made an overview of definitions (Theocharidou et al. (2016)). Furthermore, Ayyub, (2014) presents an overview of most commonly used definitions with high impact, and in PIARC an extensive literature review is presented on definitions of resilience in the context of infrastructure and specifically roads (PIARC). To give an impression of the variety in definitions, but also similarities, some important definitions are presented below:

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

- In the urban context: Definition of the 100 Resilient Cities Network: "The capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience." (Resilient Cities Network, n.d.)From the ISO 37123:2019 norm on sustainable cities and communities – indicators for resilient cities: "adaptive capacity of an organization in a complex and changing environment" (Sustainable cities and communities — Indicators for resilient cities | ISO 37123, 2019).

- In the context of disaster risk reduction: Definition of the United Nations International Strategy for Disaster Reduction (2009): "The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions." (UNISDR, 2009) Definition of the National Academy which is widely used: "The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse event." (National Research Council, 2012, p.1)

- In the context of critical infrastructure: In the European project FORESEE resilience is defined as the ability to continue to provide service if a hazard occurs. In another European project IMPROVER resilience is defined as: 'The ability of a critical infrastructure system exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, for the preservation and restoration of essential societal services (L. Petersen, Lange, and Theocharidou 2020.).

Concluding, there are many different definitions of resilience. Later on, the ICARUS consortium will formulate its own definition, or choose the on that fits best with the purpose of the users of the research outcomes.

3.1.2 Which methods are used to quantify resilience?

In general resilience can be visualized in two ways, by either looking at the response of a system over time during the disaster, or by looking at the systems response for increasing severity of events. These two types will be elaborated in more detail this chapter.

Table 3. Overview of methods on how quantify resilience

	Short description	Who is the end user	Requirements for usage
Robustness or network criticality	Method by which you map the indirect consequences if a component of a network fails partially or completely.	Public governments or private sector that would aim to analyse the network	You need input data on usage and the network characteristics and/or expert knowledge to perform the analysis.
Resilience Triangle	A resilience triangle is based on the definition of resilience where a graph is made based on the temporal stages of the different phases in resilience and how this impact the functionality of infrastructure	Risk analysts, Public Governments	You will need information on the duration of the event and the impact on the functionality of the system.
Response Curve	A response curve is a graph showing the effect on society for low and higher probability events. For example, what effect will it have on the people or economy in an area if certain infrastructure fails?	Risk analysts, Public Governments	You will need the following information: - consequences of hazardous events on critical infrastructure - the number of people affected - the duration of outages Or experts are involved who can estimate this information.

Robustness of the network or criticality of the network

A last example to quantify resilience when taking into account the recurrence time of an event is presented by Pregnolato et al., (2017). The impact of floods on the road network is quantified as a percentage of linkages disrupted, and by using network analysis transformed into additional journey time and length. This is then monetarized to enable comparison with measures to prevent flooding. Though this is a very elaborate method, it only includes the *robustness* component of a network and disregards the recovery rate of a system. It can hence only be used to assess measures which reduce the total impact, rather than including measures which speed up the recovery process. Robustness is also used as metric for interruptions of the road network for flooding events all over Europe to determine so-called tipping points for functioning of the system (van Ginkel, 2022).

Resilience triangles

Four temporal dimensions of resilience, as deducted from the definitions of resilience *plan*, *absorb*, *recover* and *adapt* (for example the commonly used definition from the National Research Council, (2012)) are demonstrated. The temporal dimensions from the definition of critical infrastructure chosen in this research are *resist*, *absorb*, *accommodate to* and *recover from*. Resist would here be situated right at the point in time where the shock starts (between *plan* and *absorb)*, and *accommodate to* between *absorb* and *recover*. Critical functionality (K) here has a value between 0 and 1 (see Figure 3.2) but can have other metrics as well (percentage in the following example). The National Infrastructure Commission of the United Kingdom (2020) acknowledges the temporal view in resilience thinking and uses *anticipate*, *resist*, *absorb*, *recover*, *adapt and transform*.

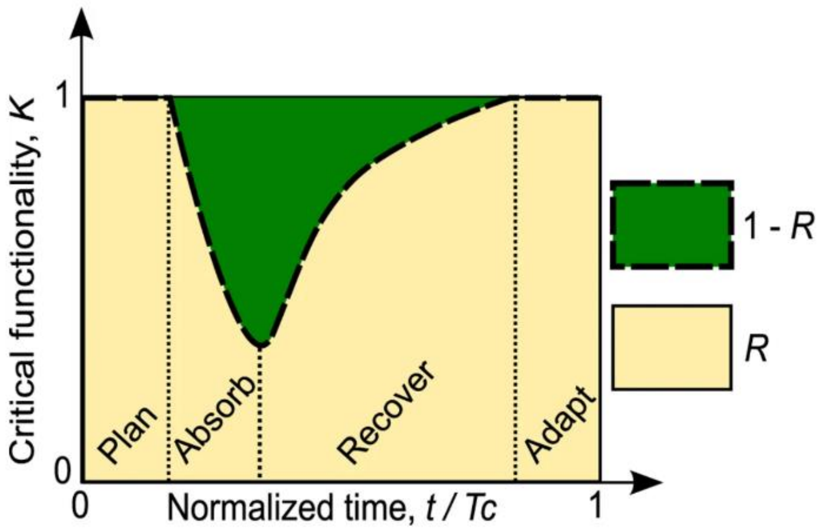


Figure 3.2: Critical functionality of a system over time when exposed to a certain shock and its resilience, including the concepts plan, absorb, recover and adapt (Ganin et al., 2016)

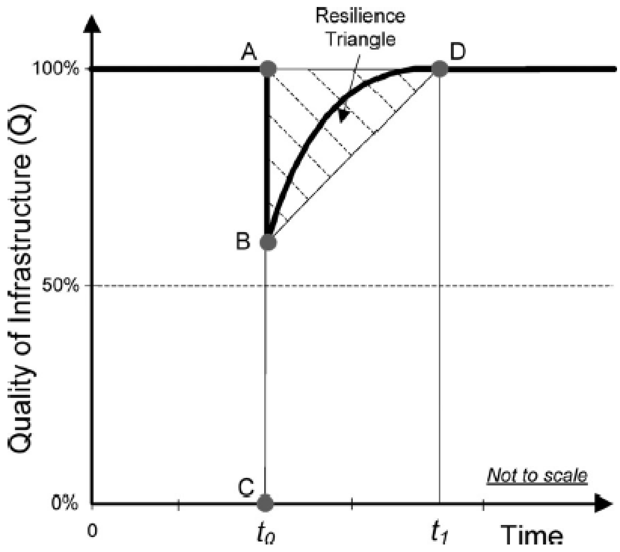


Figure 3.3 The resilience triangle, adopted from Tierney & Bruneau (2007).

Resilience triangles can also be used to quantify resilience, as shown in Figure 3.3. Here is clear that at point A the hazardous event starts, leading to a reduced functioning of the infrastructure (in Figure 3.3 stated as 'Q – quality of infrastructure). It drops down to a certain point B, after which the infrastructure will start to recover between t0 and t1. At point D the infrastructure functions as before. When depicting this cycle in a graph, it is called the resilience triangle (Tierney & Bruneau, 2007). This implies that a reduced probability of failure and fast recovery times after an external shock increases resilience of infrastructure systems. It allows to calculate the amount of resilience, as proposed by (Attoh-Okine et al., 2009) in the following formula:

$$Resilience = \frac{\int_{t0}^{t1} Q(t)dt}{100(t0 - t1)}$$

Q = Infrastructure quality/ performance of a system in percentages

t 0 = time of incident

t 1 = time of full recovery

According to this model, the unit of measurement of resilience are performance per unit time, where performance is measured in percentages, thus percentage over time. Lastly, (Shinozuka et al., 2003) add that in this triangle the properties of *Robustness* and *Rapidity* can be added and quantified by using the following formula:

$$Robustness = B - C$$

$$Rapidity = \frac{A - B}{t1 - t0}$$

Robustness is measured in percentages of quality of infrastructure, and rapidity in average recovery rate in percentage over unit of time. The robustness is also sometimes referred to as the maximum damage or impact of a hazard, and the rapidity as the recovery rate (Murdock et al., 2018).

The second way to quantify resilience is by including the expected recurrence time of an event in combination with the damage to or disruption of a system. Events with a high predicted likelyhood of occurrence have low severity, while events with a low predicted likelyhood have a high severity. This likelihood of occurance can be quantified in annual exceedance probablity or the inverse of this the recurrence time of an event. When drawing the curve between the expected damage of different hazards with increasing severity it is called a system response curve. The response curve is drawn per type of hazard with an increasing severity and includes only one infrastructure system.

Response curve

The second way to quantify resilience is by including the expected recurrence time of an event in combination with the damage to or disruption of a system in a so-called response curve. With the Response Curve, you can show how a system, responds to a specific hazard. What is the effect (response) of a flood on an area? How many people are affected, what is the economic damage? A flood that occurs annually will have little or no effect, whereas an exceptionally large flood will have a large effect and society may be disrupted largely where infrastructure systems are down for an extended period of time. When drawing the curve between the expected damage of different hazards with increasing severity it is called a system response curve. The response curve is drawn per type of hazard with an increasing severity and includes only one infrastructure system. A scematic representation is presented by Murdock et al. (2018), and is presented in Figure 3.4. The *resistance threshold* is a certain point of hazard severity after which the infrastructure system starts functioning less. For example: during a flash flood a road network can function up to 100% untill a certain amount of mm of rain. When the road network's function starts deteriorating, the resistance threshold is breached. The *recovery threshold* is a point after which there is so much damage, that the system is beyond recovery. For example when damages to a bridge are so severe that the bridge will be removed instead of repaired.

To subsequently quantify resilience using a systems response curve is by calculating the area under the curve. Depending on the metric on the y-axis, this can be either the expected annual damage (damage on the y-axis) or the expected annual losses. Damage is often quantified in monetary terms. To calculate the annual expected losses often the metric *people x disruption* time is used. *Time* can be either minutes (for example travel time loss), hours or even days. *People* is the number of people affected by the disruption. Research by Murdock et al., (2018) shows an example how this methodology is implemented in a case study in Toronto, Canada, for the road and electricity network.

The Response Curve can also be used to determine the acceptable level of risk in close collaboration with the relevant stakeholders. When the curve in the graph is higher than the acceptable level, measures can be proposed. Measures that increase the robustness of the system lead to a shift of the curve to the right . Consider, for example, the embankment or elevation of important objects when high water is imminent. Measures that increase flexibility or redundancy will lower the curve. For instance, you can greatly reduce the impact of failure of the network by increasing the number of connections in the network at critical locations. The curve helps to make failure of vital functions negotiable. Because the curve provides insight into possible effects, you can have better discussions about the 'acceptable' level of a response and which measures you can best deploy.

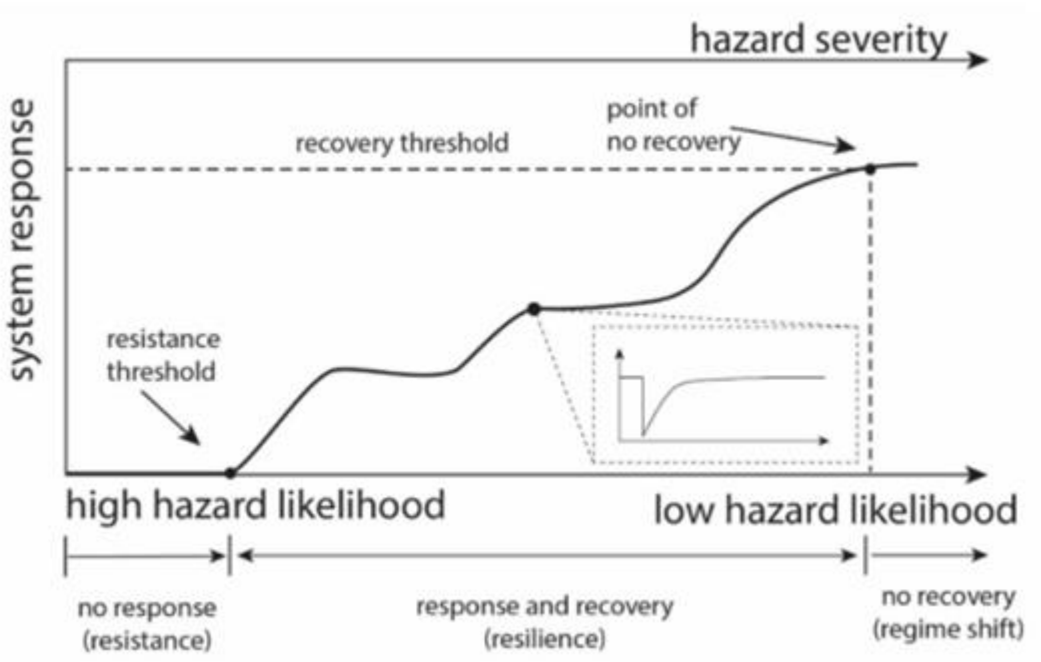


Figure 3.4: Relationship between likelihood of occurrence of a hazard and the amount of disruption or damage to a system (Murdock et al., 2018).

Uncertainties in quantifying resilience

Quantifying natural hazard impacts on critical infrastructure networks inherently involves uncertainties which makes decision-making complex. These uncertainties stem from the hazard modelling, climate change projections (which is more elaborated on in Baseline 1.1), exposure, vulnerability, and end-user data, as well as economic valuation (which will be elaborated on in Baseline 3.1).

Uncertainty in vulnerability can be accounted for in the construction of the damage functions. This is mostly used in scientific applications, and only a few examples exist in practice (e.g. the Dutch example as described in Section 2.2.4. Based on scientific literature, Huizinga is a well-known source for maximum damage to road infrastructure (Huizinga, 2017). More recently, van Ginkel (2021) updated these damage curves with an overview of road constructions costs and maximum damage per road type have been identified for the event of flooding. This includes differences in damage between low-flow velocities and high-flow velocities (van Ginkel, 2021). Based on uncertainty in vulnerability functions, for a global study on multi-hazard risk analysis of road and railway infrastructure uncertainty is included and shows that the global expected annual damage for these infrastructures could vary between approximately 7 and 17 billion USD (25-75% of the bandwidth, Koks et al, 2019). Attempts have been made for a fully quantitative approach while including the uncertainties of hazard, vulnerability, exposure and the socio-economic valuation of measures for highway measures to pluvial floods (van Marle et al., 2022).

Guidelines accounting for uncertainty do not always include explanations and steps on how to include uncertainty. Some of them mention that it should be taken into account and others recommend to use lower and upper limits for analyses.

3.1.3 ISO 14091: 2021

ISO 14091 is the most standardised formal guidance for adaptation to climate change. However, as mentioned previously, the approach does not relate specifically to road infrastructure or even infrastructure in general. Moreover, the approach to adaptation is focused on risk assessment as shown in section 2.1.1. The word resilience is not mentioned in the body of the text although the principles of risk assessment may tend to enhance resilience indirectly as noted in other sources (TRB, 2021).

3.1.4 CEN CWA 17819:2021

CEN CWA 17819 has made significant advances in resilience thinking and standardisation. The CEN CWA 17819 resilience methodology is grounded on the principle of service levels, with resilience being principally measured in terms of how service is affected using each measure of service, and the cost of the interventions required to ensure that the infrastructure once again provides an adequate service. Resilience is therefore measured as the cumulative difference throughout the duration of the absorb and recovery phases between:

- the service provided by the infrastructure if no event occurs, i.e., before an event occurs and after the infrastructure has been restored, and the service provided by the infrastructure if an event occurs (illustrated in Figure for the “travel time” measure of service), i.e., during the absorb and the recovery phase, and
- the costs of intervention if no event occurs and the costs of interventions if an event occurs (illustrated in Figure .

Three possible ways to measure resilience are proposed 1) using simulations, 2) using indicators with differentiated weights and 3) using indicators with equal weights. Simulations have the highest level of precision but are difficult to use in a way that provides an overview of an entire situation. The accuracy of their results is, of course also dependent on the quality of data and models used. Using indicators is less precise but provides a better overview of complex network situations. From the perspective of the current State of the Practice, simulation-based methods may be considered a step beyond the current State of the Practice, bordering on state of the art.

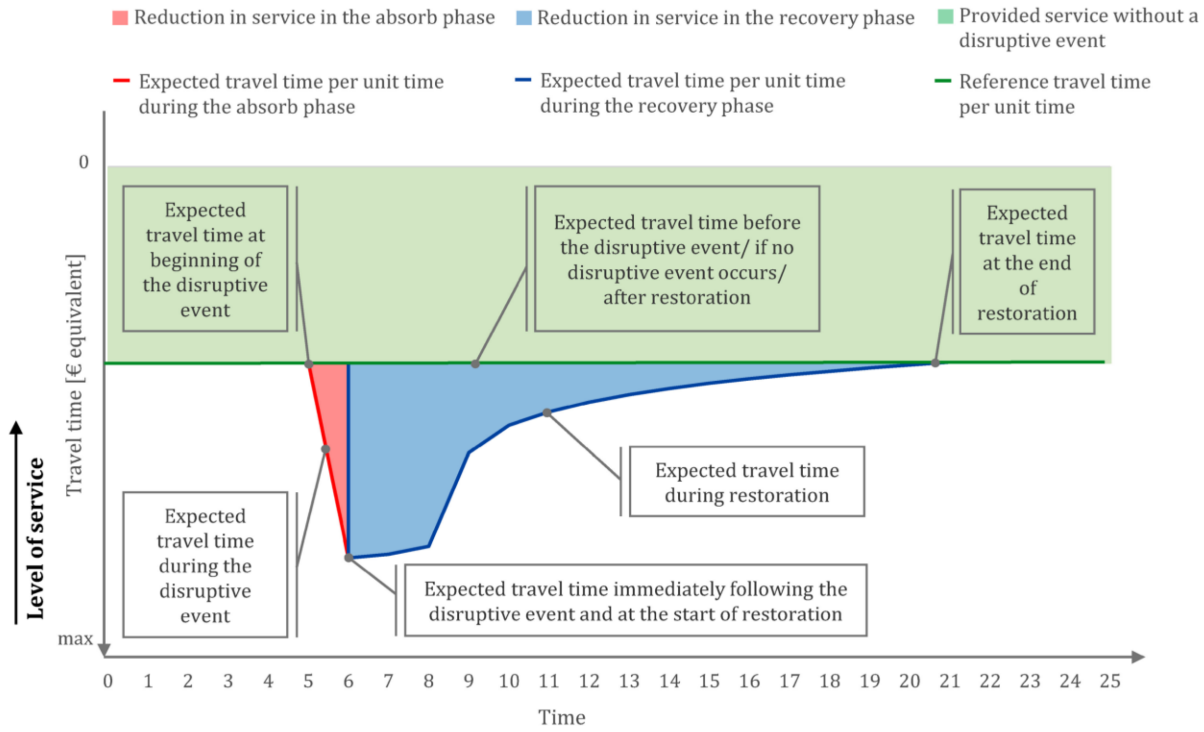


Figure 3.5: Illustration of transport infrastructure resilience using the "travel time" measure of service (CEN CWA 17819:2021)

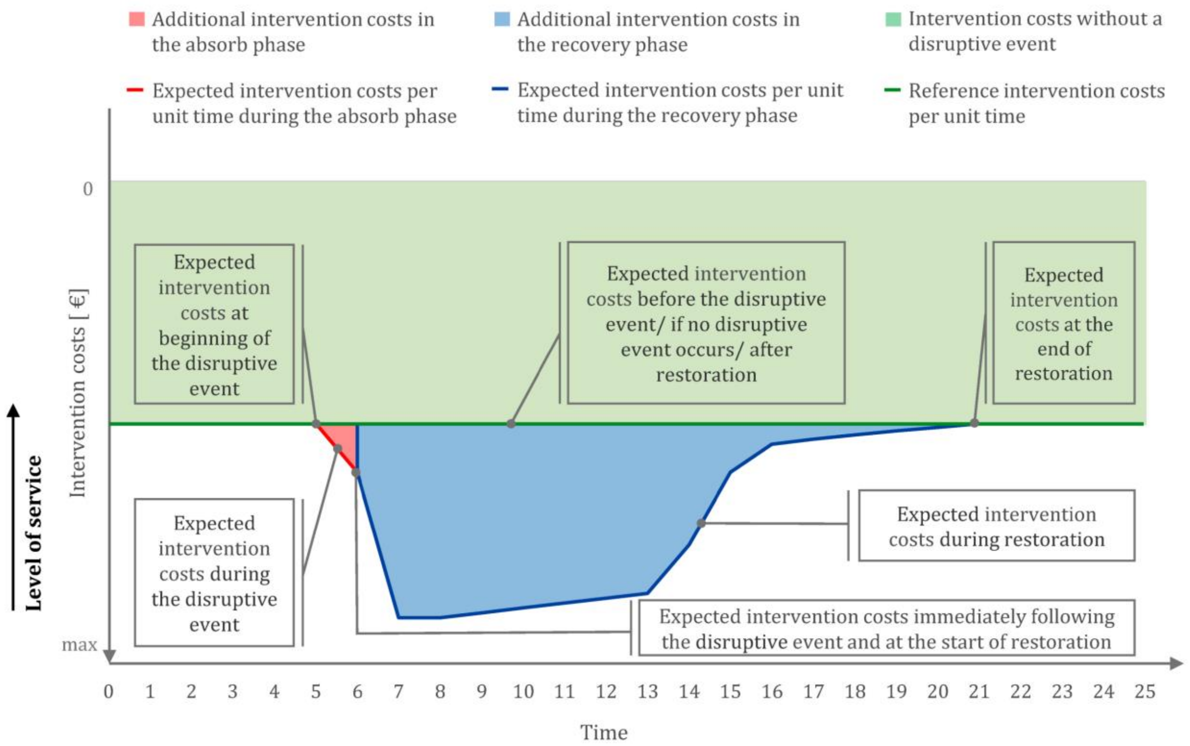


Figure 3.6: Illustration of transport infrastructure resilience using intervention costs (CEN CWA 17819:2021)

The steps involved in evaluation resilience consist of definition of the transport system, measurement of the service provided, followed finally by the overall measurement of resilience. Using simulations to calculate service requires constructing a detailed representation of the transport system in appropriate software, simulating how the future might unfold when different disruptive events occur and measuring the difference between the service provided when no disruptive event occurred and when the disruptive events occurred. This requires expert knowledge and is not covered within the CEN CWA 17819 standard. The approach for measuring resilience using indicators is explained in detail in CEN CWA 17819. The activities involved are as follows:

1. Identify indicators
2. Check relevancy of indicators
3. Estimate values of indicators
4. Measure resilience

This procedure allows users to consider the temporal aspects of resilience and also delineate enhancement at the infrastructure, organisational and environmental levels. The approach is therefore a very good application of a standardised procedure which is close to the state of the art and should be considered in future frameworks for road resilience.

3.1.5 State of the Art summary

This section presents a clear picture of the current advances in resilience assessment and decision making in transport infrastructure. While the overall process varies internationally, there is a general consensus that quantitative resilience assessment requires consideration of breakdown in service measures and the temporal aspects of service breakdown. There are many examples of indicator-based approaches to delineating resilience enhancements (e.g. in CEN CWA 17819) by reducing service breakdown over time. Indicators may relate to infrastructure, environment or organisational aspects, and should include socio-economic aspects of infrastructure users where possible.

3.2 State of the Practice

3.2.1 Literature Review

The Transportation Research Board (TRB) Report from 2021 (TRB, 2021), describes current practice in measuring and managing transportation system resilience. They have found that more and more transportation agencies are adopting resilience assessments to review their infrastructure and inform decision making, however, that there is no common set of resilience metrics.

This is a similar result to that seen from our workshops where participants were aware of resilience assessments, but there seemed to be confusion about how the assessments were performed.

Colorado Department of Transportation (DOT) and Utah DOT have both used the comprehensive Risk Analysis and Management for Critical Asset Protection (RAMCAP) framework developed by the American Society of Mechanical Engineers (ASME) in pilot studies to assess the risk and resilience of their networks.

Colorado DOT's "Risk and Resilience Analysis Procedure", based on RAMCAP considers natural hazards in its risk-based asset management program. It covers rockfalls, floods, and debris flows after fire for roadways, bridges, and culverts. Both risk and resilience are assessed for each asset, where risk is measured as the cost to both users and asset owners, and resilience builds on this incorporating risk but also the value of the asset to its users and wider society. Colorado DOT calculate the risk based on intermediary calculations for vulnerability, hazard likelihood and consequences. An additional intermediary calculation for criticality is used to calculate the resilience.

Annual risk, resilience and criticality are calculated for each mile of the highway system, which can then be ranked from highest to lowest risk, enabling the most critical sections of the highway network to be identified.

Similarly, Utah DOT uses RAMCAP, however, with a more extensive range of hazards, including avalanches and earthquakes (for bridges only) in addition to rockfalls, floods, and debris flows. A slightly different calculation is also used, whereby vulnerability is not considered in the risk calculation. The change in sensitivity is included however, and this considers how risk may be reduced by decreasing sensitivity of an asset to a hazard. Consequences are also measured using costs, while criticality is measured in terms of redundancy, annual average daily traffic (AADT), and truck traffic, with a double weighting on redundancy. Risk is then calculated, and used with criticality to calculate resilience.

The US Federal Highway Administration "Vulnerability Assessment and Adaptation Framework" (FHWA, 2017) presents a number of examples of resilience being incorporated into Transportation Planning:

- Maryland State Highway Administration (SHA) is using results from its vulnerability assessment to identify locations which are vulnerable to flooding. This information is then used to inform future planning and resilience design.
- The Hillsborough Transportation Planning Organization (TPO) are incorporating results from their vulnerability assessment into a long term plan to increase the security and resilience of their multimodal network. The vulnerability assessment identified areas of the network which are prone to flooding, Three investment scenarios were generated, low, medium and high, and the benefits of each were calculated for the vulnerable areas. These were weighed against losses felt by the residents and business communities when their areas were subjected to flooding, and the most beneficial investment scenarios were then chosen.
- Finally, Capital Area Metropolitan Planning Organisation (CAMPO) in Texas integrated results from their vulnerability assessment into its 2040 Regional Transportation Plan. Climate-related risks to the area were identified, along with measures to increase the transportation system's resilience. Mitigation measures to increase resilience to weather events include identifying alternate wildfire and flood evacuation routes, and addressing drought-related impacts on the transportation system.

3.2.2 Workshop Results

The workshop attendees were asked questions in relation to their understanding of the concept of resilience, resilience assessment, and how service levels are set and measured in their organisations.

Their responses in relation to understanding of resilience and resilience assessment are given in this section.

The participants were first asked to classify their understanding of the concept of resilience and responses are shown in Figure 3.7. Over half of all participants responded that they are completely comfortable with the vocabulary.

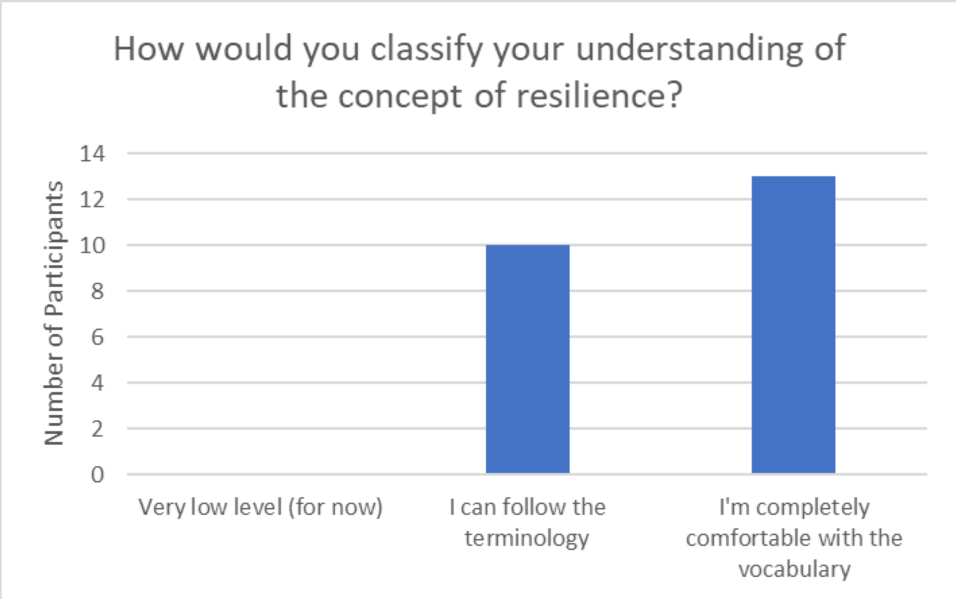


Figure 3.7 Participants' Understanding of Resilience

They were then asked "At which level of assessment does your focus/expertise lie?". Note that it was possible to respond to all three levels, asset, connection and network as shown in Figure 3.8. The responses for this question were varied, with some respondents who demonstrated expertise at all levels, and others focusing on one level only. Most responded that they had focus/expertise at the network level.

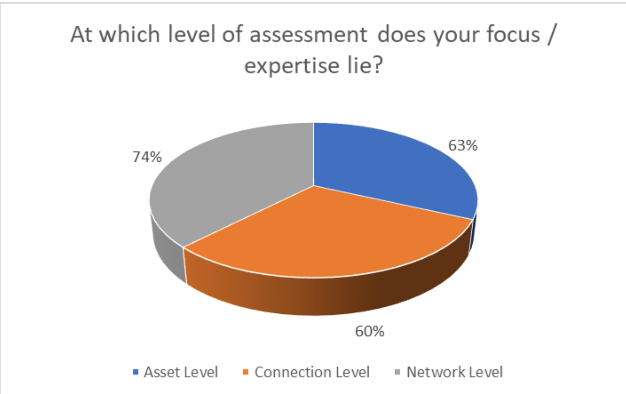


Figure 3.8 Level of Assessment of Participants' Expertise

The final question in this session was to determine at what level resilience is assessed within the participants' organisations – see results in Figure 3.9. In contrast with the expertise of the participants in the previous question, the majority responded that resilience was assessed at asset level in their organisations, with some assessment also at network and connection levels. It was unclear why this is the case, however a possibility is the difficulty in obtaining sufficient information to perform an assessment at wider connection or network.

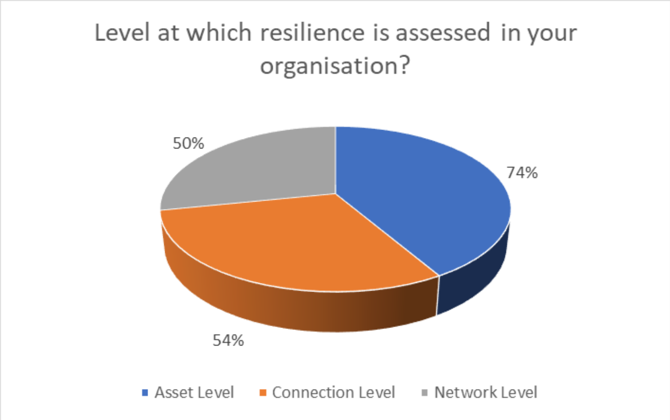


Figure 3.9 Assessment of Resilience Within Organisations

3.2.3 State of the Practice Summary

Review of the literature presented a few examples of implementation of resilience assessments and how they are incorporated with wider network assessments, However, there appears to be multiple approaches, even when using the same tool, and there is no consistent method.

Analysis of the workshop results showed no significant correlations between country and responses when assessing understanding of the concept of resilience, and resilience assessment within the organisation. This is deemed to be due to the small sample number of participants per country and high variability of implementation of resilience assessment within each organisation.

There seemed to be a higher level of understanding from participants from countries which would be deemed to have a more advanced stage of maturity in infrastructure management, where 4 out of 5 participants from the Netherlands and Finland stated that they were completely comfortable with the concept of resilience, compared to none of the three participants from Italy. However, once more detail was requested in the workshop, there were various levels of personal and organisational understanding of the concept of resilience and implementation of service levels across all participants, regardless of country or organisation type.

Overall, the uptake of formal quantification of resilience in industry appears to be significantly slower than the methodologies developed in the literature. This is due to various barriers to implementation stemming from a lack of funding and data, difficulties with modelling an uncertain future, as well as the many stakeholders within and outside the NRA's that need to be involved. The workshop results have indicated that it proves to be difficult to open up a dialogue between the strategical, tactical and operational levels within the NRAs.

4 MINIMUM SERVICE LEVELS

Service levels are used to measure how the road is functioning. As with the resilience assessment, this can be done at different levels (asset, connection or network level). Often the resilience assessment describes the *functioning of the system* as a service level of the infrastructure network. This chapter explores how minimum service levels are used in the State of the Art and State of the Practice, and how or if they relate to the resilience assessment.

4.1 State of the Art

4.1.1 Service level metrics vs resilience indicators

Service level metrics are useful when we want to know if the road, be it on asset or network level, is functioning as it should. Examples of service levels can broadly be categorized in:

- Availability (travel time, vehicle loss hours, accessibility of a place), safety of road users, maintainability (e.g. repair cost)
- Environmental effects (pollution, CO2 emissions, circularity)
- Politics or image
- Design criteria (return period, design life, Load and Resistance Factor Design)

On asset level, service level metrics are often documented in design guide manuals. This is already state of the practice, though, how to deal with a changing climate is not in there, and also not to be found in literature.

In literature we find a variety of indicators for the connection or network level, which are also sometimes called *functionality metrics* or *resilience metrics*. Sun et al. (2018) present in a literature review the most used metrics. In their vision the functionality metrics exist of both *topological metrics* (e.g. connectivity or centrality) and *traffic related functionality metrics* (e.g. travel time, throughput, congestion index). Resilience metrics could be also functionality based (e.g. using the resilience triangle method, or using socio-economic metrices. Another review is given by the National Academy of Sciences (2021). They present the most common functionality metrics as "Weighted sum of Assets in service" (can also be referred as criticality), total travel time and connectivity. For resilience metrics they add either the mean value of the resilience curve (*resilience index*), or the surface under the curve (*resilience triangle*), or time to complete recovery/target level functionality.

4.1.2 How are decisions made on minimum functioning or acceptable risk?

The widely used principle to describe how safe something should be in safety decision making is called the ALARP technique, an abbreviation of 'As Low As Reasonably Practicable' (Jones-Lee & Aven, 2011), or sometimes ALARA meaning 'As Low As Reasonably Attainable/Achievable' (Melchers, 2001). This approach acknowledges that there are economical and practical limits to prevent unsafe situations and proposes some sort of goal or standard regarding safety. It has been used in many domains for a long time, for example in nuclear safety, water safety or off shore constructions. The method is recognized as the main approach to setting tolerance levels for acceptable risk (Health and Safety Executive (HSE), 1992; Kam et al., 1993). The ALARP principle assumes that there is an upper and lower bound between a risk which is acceptable. The upper bound is the unacceptable risk, and the lower bound is the acceptable risk but beyond the possibility to achieve. Because the lower the risk of failure, the more expensive or complex it becomes to ensure this. Hence the 'as low as possible' approach is taken, for which 'reason' and 'practicality' are leading in decision making. Melchers, (2001) states the main shortcomings of this approach, but acknowledges that proposing a better technique is difficult.

Still, this approach only tells us something about a maximum risk, but not about the resilience we actually strive for, or when we do not tolerate disruption of the infrastructure anymore. As Ale (2005) describes, tolerable or acceptable risks is not something fixed. It depends on the historical, legal and political context of a country. The work by Gooijer et al. (2011) gives a striking example: four different consultancy firms from different countries are asked to assess the risk of a new hypnotical LPG storage plant. The results in terms of risk are rather similar, though the policy implications vary because the level of acceptance of this risk is interpreted differently.

Concluding, there is no general accepted minimum resilience or risk, let alone minimum required service levels. If there are norms or standards on functionality, they are dependent on the context of the country and stakeholders of that infrastructure.

4.1.3 Methods to decide on minimum level of service

Given this notion, we still need to make decisions on when to take measures. To be able to make informed and fair decisions, it is necessary to structure the decision-making process. In literature we see some methods, which are presented below.

Table 4. Overview of methods on how to evaluate risks and thus determine where to take measures

	Short description	Who is involved?	Requirements for usage
(Corporate) Risk Matrix	The risk matrix helps you to evaluate risks. With this systematic method, you measure and categorise risks based on knowledge of probability, consequence and relative importance.	Individuals, public governments, private sector	There are few requirements for users
Response Curve	A response curve is a graph showing the effect on society for low and higher probability events. For example, what effect will it have on the people or economy in an area if certain infrastructure fails?	Risk analysts, Public Governments	You will need the following information: - consequences of hazardous events on critical infrastructure - the number of people affected - the duration of outages

			Or experts are involved who can estimate this information.
Multi-criteria analysis	A multi-criteria analysis (MCA) is a decision analysis that assigns a value to multiple criteria in decision making and ranks policy alternatives accordingly.	For public governments as well as private sector	There are few requirements for users
User tolerance levels	Impact analysis which includes user of infrastructure on the individual level.	Users of the infrastructure, individuals/ households	Access to a panel of users to fill out a questionnaire

(Corporate) Risk matrix

Often, mostly in industries, corporate risk matrices exist. This is a table describing on one axis the consequences and on the other axis the probability. A certain combination of probability and consequence makes a risk acceptable, undesirable or unacceptable. When those risk matrices do not exist the risk evaluation has to be performed in close collaboration with the involved stakeholders.

RISK MATRIX		CONSEQUENCE			
		1: NEGLIGIBLE	2: LIMITED	3: MAJOR	4: SEVERE
PROBABILITY	1: NEGLIGIBLE	Acceptable	Acceptable	Acceptable	Acceptable
	2: LOW	Acceptable	Acceptable	Undesirable	Undesirable
	3: MODERATE	Acceptable	Undesirable	Undesirable	Undesirable
	4: HIGH	Acceptable	Undesirable	Undesirable	Unacceptable
	5: CERTAIN	Undesirable	Undesirable	Unacceptable	Unacceptable

Figure 4.1: Example of a corporate risk matrix (Rijkswaterstaat, 2018).

Multi criteria analysis

Multi-criteria analysis is a systematic approach to rank possible policy solutions to a given problem based on different criteria and priorities. For example, suppose you want to solve a dangerous and busy intersection. Then there are several policy alternatives: you build a roundabout, you provide traffic lights, you build a parallel road, and so on. Which alternative is best depends on many different criteria and priorities. Criteria include soil quality, investment costs, air quality, safety, environment, incorporation into the spatial structure. Criteria play a central role in multi-criteria analysis. They express the value created by different alternatives. By linking criteria to policy alternatives, you can compare their effects. In a multi-criteria analysis, you first make an overview of the policy alternatives and the effects per alternative. You then process this information so that you can weigh the criteria against each other. Based on this, you can rank the policy alternatives. This can be done by displaying the quantitative or qualitative effects in an evaluation table

User tolerance levels

Another method to determine when to take measures is to find out what tolerance levels are of disruption for the individual user, including socio-economic variations. We see two types in literature: questionnaire based and using agent-based modelling.

The concept of using tolerance levels is a fairly new method of which the basis lies within the research project IMPROVER where they use the questionnaire-based approach in case studies exploring how to establish tolerance levels of users of critical infrastructure disruption. It is suggested to use the minimum level of service and rapidity of restoration as indicators to measure the public tolerance to disruption. The case studies all use a questionnaire approach, which further developed in three cases to establish so-called tolerance triangles. In the last case study situated in Hungary, the resilience of the system is compared with the tolerance levels of the users. The used metric is 'additional travel time'. A weighted average of the respondents is used to arrive at the average acceptable additional travel time for each specific duration of the disruption. To quantify the resilience of the infrastructure itself the ITRA (Technical Resilience Analysis) methodology is used (Honfi et al., 2018), which led to the resilience triangle in the form as described earlier. Because it is plotted in the same graph as the tolerance triangle, the two can be compared, see Figure . The metric used to indicate performance quality is 'additional travel time' (inverted on the y-axis, zero being the highest value representing full performance). However, the ITRA analysis had not been fully carried out, thus the results of the curve are purely to demonstrate how the comparison can be made. The authors evaluate the methodology as promising and especially valuable for the network operator to give input on the tolerable amount of service reduction during a crisis.

Research by de Jonge (2021) builds on this. Part of the ERDF framework is applied, as described in section 2.1.8. To establish the level of resilience, which can be compared to the *desired level of resilience,* the author carries out a physical resilience assessment with the metric *users not willing to accept posed disruption.* This assessment includes the tolerance levels of the users of the case study area, which are derived with a stated choice experiment which is questionnaire based.

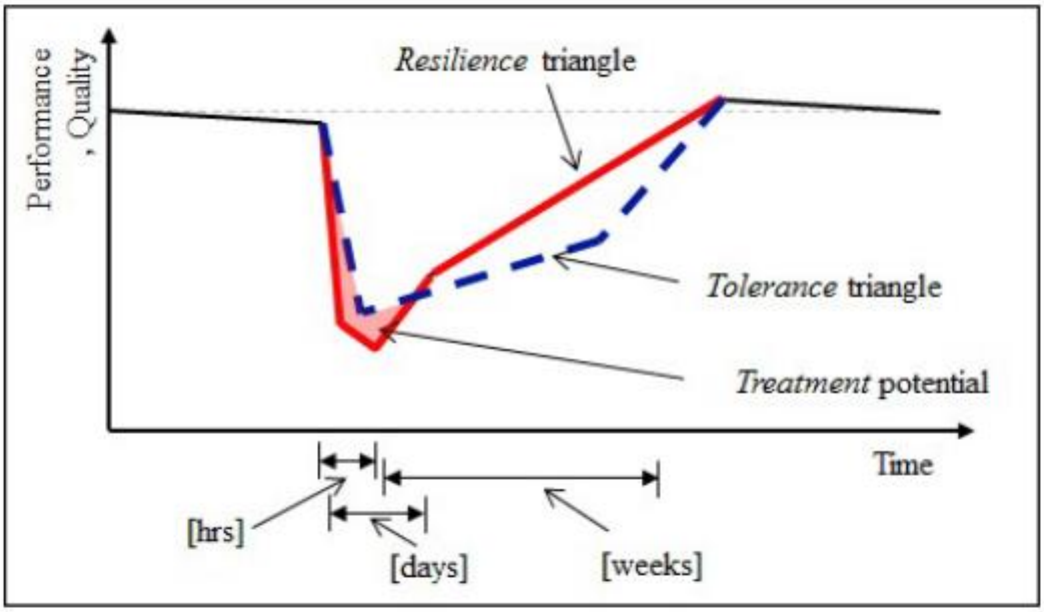


Figure 4.2: Schematic representation of a resilience triangle with acceptable level (Petersen et al. 2019).

Identifying tolerance levels to critical infrastructure disruption using agent based modelling is explored by Esmalian et al. (2019). Also in this method socio-economic characteristics of the households play an important role to determine the tolerance levels. Next to that physical attributes of the infrastructure are used in the model, and various simulations are done with different extreme disruptive events. The *service gap* describes the gap between the physical condition of the infrastructure system and the household tolerance levels towards disruption of these systems. A second research by Esmalian et al. (2021) uses empirical data of Hurricanes to create models which determine household tolerances towards disruption of eight different critical infrastructures. The authors establish *susceptibility curves*, which bridge the gap between the reliability and resilience analysis of the physical infrastructure systems, and the impact these disruptions have on the communities. A third research worth mentioning on tolerance level modelling is the work by Yang et al. (2021). The authors establish a mathematical model to quantify the societal impact considering individuals' choices of water-related activities (critical infrastructure) and negative well-being (tolerance) and apply it in a case study in Osaka. The results are not used yet for decision making, but provide a richer impact assessment then solely looking at infrastructures' physical resilience.

Concluding, using tolerance levels in the resilience assessent enables dicisionmakes to include socio-economic characteristics which leads to different, more equal and possibly more efficient measures to increase resilience.

4.1.4 ISO 14091: 2021

As mentioned previously, ISO 14091 is not founded on general principles of resilience and hence, does not have a focus on service level evolution over time or setting of minimum service levels. Service levels are considered as one of many impacts that can be considered within a climate risk assessment. These are considered purely as consequences within the risk calculation, in monetary terms where possible.

4.1.5 CEN CWA 17819:2021

The principle of service levels is central to the CEN CWA 17819 methodology. As discussed in previous sections, the methodology uses service levels along with intervention costs to quantify resilience. The final action in the methodology is the setting of resilience targets which may be considered in terms of setting minimum service levels. This may be done for service / resilience targets or for indicators, and each can be done with or without cost-benefit analysis. Setting service / resilience targets without cost-benefit analysis can be summarised as collecting all necessary expert opinion to formulate a broadly accepted set of service and resilience targets that take into consideration all aspects of the transport system that are deemed important, including the interdependencies between intervention costs and levels of service. The targets are formulated so that it is clear how they are to be measured. The process for setting targets for indicators is similar, with the targets being set or consciously not set against each indicator considered in the assessment. Examples might include the setting of the condition state indicator for a bridge to 3, or the setting of the frequency of monitoring indicator to 4 based on regular, frequent monitoring. Again, measurement of the targets should be planned in advance. The process for setting targets was summarised in section 2.1.2.

An organisation may obtain the sample three target sets described in Table 5. The organisation must decide how these target sets are to be achieved. Examples for target sets 1-3 may include:

1. To ensure that the users of the infrastructure experience no increase in travel time if the threat occurs, a second bridge to design code level 5 will be built.
2. To ensure that the legal requirements are met, the existing bridge will be strengthened.
3. To ensure that restoration intervention costs remain within a specified budget, the existing bridge will be strengthened in a way that makes it easy to rehabilitate following the occurrence of a disruptive event.

Table 5: Description of Target Sets (reproduced from CEN CWA 17819: 2021)

			Targets per type of target		
Target set	Label	Description	Maximum reduction of the service of travel time	Maximum restoration time	Maximum restoration intervention costs
1	No changes in service	There is no change in travel time given a 100-year flood occurs	None	Not specified	Not specified
2	Legal minimum	All legal requirements for travel time are fulfilled	Largest legally permitted	Largest legally permitted	Not specified
3	Restoration budget	The available budget will be used fully, in order to maximise the service achievable with the money available	Not specified	Not specified	Under the specified restoration budget

Considering the Foresee and CEN CWA 17819 approach in the context of the ICARUS requirements, it is clear that the global quantitative approach will be very useful. The quantitative framework would be beneficial to the ICARUS use case implementation, and will facilitate development of a business case (WP3). The CEN CWA 17819 approach caters for transport networks to natural hazards, which is similar to the ICARUS requirement of climate change impact drivers for road infrastructure.

Annex A of CEN CWA 17819 provides the following lists of information relating to resilience and service measures for road transport:

1. Stakeholders: A list of stakeholder groups, providing a definition of the group as well of examples of stakeholders in each group.
2. Intervention costs: A list and description of various intervention costs (Impact of executing interventions as well as Impact of accidents during the execution of interventions), along with a suggested means to estimate these costs.
3. Measures of Service: Examples are related to road users, the directly affected public and the indirectly affected public. This list is extremely extensive and there is insufficient information available to NRAs on which specific service level metrics should be applied, nor how to quantify them.

The measures of service list in Annex A of CEN CWA 17819 provides an extensive list of the various service measures available which may be considered within the ICARUS project.

4.1.6 Summary State of the Art

Much of the current literature in climate adaptation considers the application of minimum service levels. This has been demonstrated through the application of MCA, CBA, response curves etc. for the setting of service level metrics. These are often delineated as *functionality metrics* or *resilience metrics*. The work of Petersen et al. (2019) highlights some examples of how to apply this process.

There are a number of examples in the literature of how to apply service levels to climate adaption. CEN CWA 17819 is a notable example which may potentially be the industry standard in the coming years.

4.2 State of the Practice

4.2.1 Transport Infrastructure Ireland (TII)

Although service level targets are unclear, Transport Infrastructure Ireland (TII) publish an annual summary of key performance indicators of the national road network in Ireland in their "National Roads Network Indicators" reports (Transport Infrastructure Ireland, 2022). Metrics used to determine service provided include traffic flow rates and level of service (A to F), Annual Average Daily Traffic (AADT) journey time reliability, incident data including collisions, incident duration and average response time are recorded. In addition, metrics on pavement condition and bridge condition are recorded and published. Safety data including numbers of fatalities and injuries incurred on each of the motorway, national primary and secondary roads are also recorded. Finally, data on vehicle emissions on the National Roads Network is also published. An extract from the 2021 annual report is given in Figure 4.3.

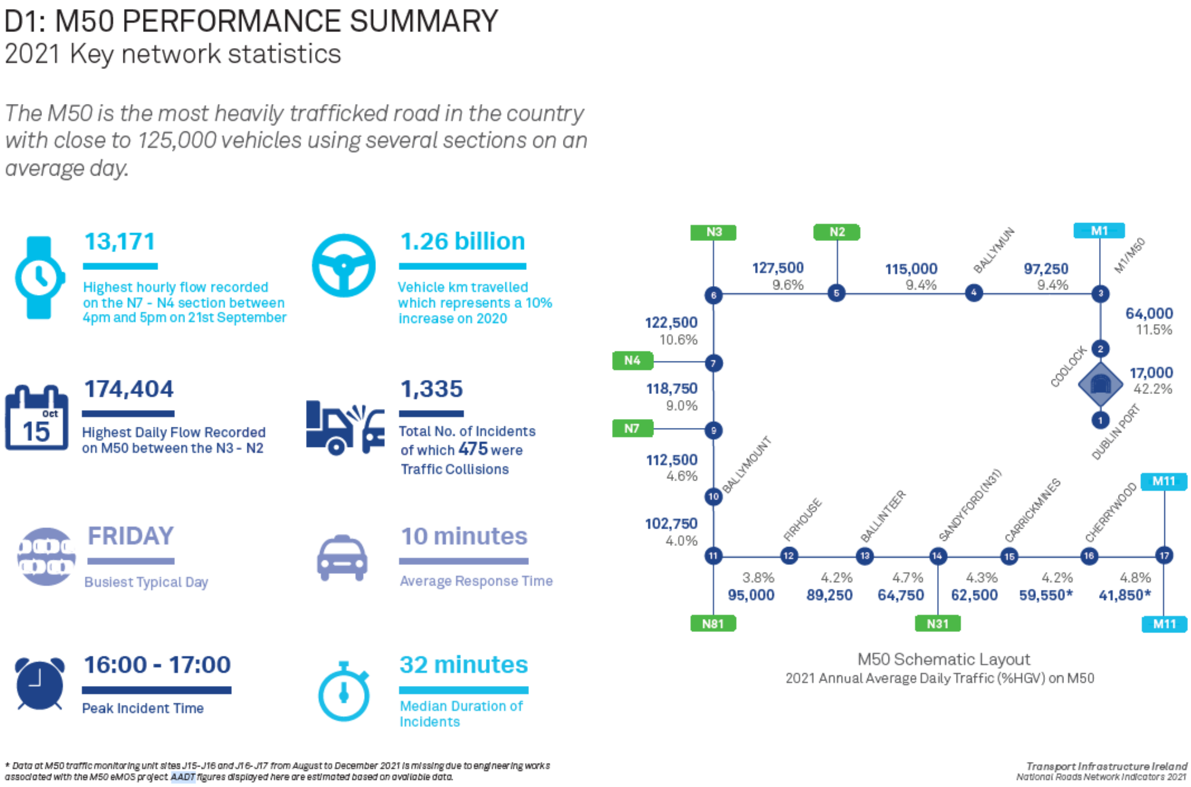


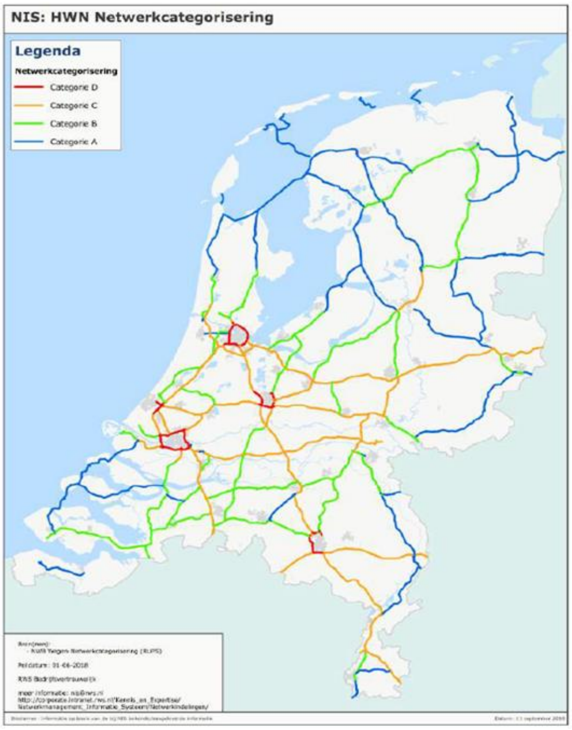
Figure 4.3 Extract from TII's National Roads Network Indicators report showing M50 performance in 2021 (Transport Infrastructure Ireland, 2022)

4.2.2 Example Netherlands

In Chapter 2.2.4 a description has been provided on how resilience is evaluated in the Netherlands. It has been described that a gap exists between enhancing resilience on the object/connection level to achieve service requirements on the network level. In this chapter examples are provided on how service requirements are used in the Netherlands.

A Service Level Agreement exists between Rijkswaterstaat (Dutch road authority) and the Ministry. In this agreement a so called 'Doelenboom' (tree with objectives) is present that includes Performance Indicators (so called PINs). These performance indicators are expressed for the network level and are for instance in terms of Availability of the road and Safety for the road user. Performance of the road network is monitored per region and summarized for the network performance, after which it is being reported. These metrics are not decomposed to a lower spatial scale yet, for determining requirements on lower levels (from network to connection or object scale). This is part of research that is currently being conducted by Rijkswaterstaat. If this becomes standard practice, it is foreseen to be used to evaluate current and future expected levels of resilience on the object/connection scale to identify whether actions could be needed.

Via the performance of criticality assessments, the Dutch road authority has categorized the road network into 4 categories, based on traffic intensity, redundancy and economic importance of the region. The purpose of these categories is to allow for tailoring measures to the specific needs. In practice is proves to be difficult to really being used and in general no variation of requirement is made over the categories. One example though is the maximum allowed unplanned closure of the road. This example is provided in the figure below.



		Unplanned closure of the lanes		
Road category	*norm*	*Acceptable*	*Not desirable*	*Not acceptable*
Blue and Green	8 uur	≤ 4	4 tot 8 uur	≥8 uur
Orange and Red	4 uur	≤ 1	1 tot 4 uur	≥4 uur

Figure 4.4 Allowance of unplanned closure of lanes, linked to the four network categories (Rijkswaterstaat, 2019). 'Uur' means 'hour' in Dutch.

4.2.3 AustRoads

Austroads is the collective of the Australian and New Zealand transport agencies, representing all levels of government. In 2015, Austroads published a report on the findings of a project to develop "a level of service (LoS) framework for network operations from the perspective of all road users" (Austroads, 2015). This framework, which was developed for the connection level, can then be used by road agencies in the planning and decision-making processes for their networks.

Detailed Level of Service (LoS) requirements for each category of road user were developed through literature review, consultation with experts and stakeholders, and refinement following implementation in case studies. Transport needs such as mobility, safety, access, information and amenity needs for motorists, transit users, fright, pedestrians and cyclists were assessed. An overview of the framework that was developed is shown in Figure 4.5 and Figure 4.6.

Road user	LOS needs	LOS measure
Private motorist	Mobility	Congestion, travel time reliability, travel speed
	Safety	Crash risk
	Access	Ability to park close to destination; ability to access roadside land or ability to depart an intersection
	Information	Traveller information available
	Amenity	Aesthetics, driving stress, pavement ride quality
Transit user	Mobility	Service schedule reliability, operating speed
	Safety	Crash risk of transit vehicle, crash risk of transit users while accessing/egressing transit vehicle
	Access	Service availability (urban services only), level of disability access, access to transit user stops/stations from key origins and destinations
	Information	Traveller information available
	Amenity	Pedestrian environment, on-board congestion, seat availability, security, comfort and convenience features, aesthetics, ride quality
Pedestrian	Mobility	Footpath congestion, grade of path, crossing delay or detour
	Safety	Exposure to vehicles at mid-blocks; Exposure to vehicles at crossings; trip hazards
	Access	Crossing opportunities, level of disability access
	Information	Traveller information available including signposting
	Amenity	Footpath pavement conditions, comfort and convenience features, security, aesthetics

Figure 4.5 Overview of LoS Proposed Framework developed by AustRoads (Austroads, 2015).

Road user	LOS needs	LOS measure
Cyclist	Mobility	Travel speed, congestion, grades
	Safety	Risk of cycle-to-cycle/pedestrian crash Risk of crash caused by surface unevenness or slippage Risk of crash with stationary hazards Risk of cycle-to-motor vehicle crash at mid-blocks Risk of cycle-to-motor vehicle crash at intersections and/or driveways
	Access	Access to and ability to park close to destination, cycle restrictions
	Information	Traveller information available, including signposting
	Amenity	Aesthetics, comfort and convenience, security, pavement ride quality
Freight	Mobility	Congestion, travel time reliability, travel speed
	Safety	Crash risk
	Access	Level of freight vehicle type access
	Information	Traveller information
	Amenity	Pavement ride quality, driving stress

Figure 4.6 Overview of LoS Proposed Framework developed by AustRoads (Austroads, 2015).

AustRoads then went a step further and applied the framework to three case studies prioritising a sustainable mode of transport in each:

1. Kew Triangle Project, a principal tram route
2. Footscray Rd/Napier St Bicycle Treatment, supporting the principal bicycle network
3. Box Hill Activity Centre, a principal transport to promote walking, cycling and transit use.

They found that the framework was useful in identifying gaps in LoS but also in assessing impacts of developments in one mode of transport on other road users. This can assist in decision-making in whether a project should go ahead based on the road user hierarchy in the network plan.

4.2.4 Workshop Results

The workshop attendees were asked questions in relation to their understanding of the concept of resilience, resilience assessment, and how service levels are set and measured in their organisations. Their responses in relation to service levels are given in this section.

20 attendees (80%) responded either "Yes, we use them", or "a little" to the question "Are you familiar with service levels within your organisation?" Of these 20, 13 (65%) stated that they were familiar with service levels at Asset level, with less awareness of the existence of service levels for Connection and Network levels respectively. See Figure 4.7Figure for full details.

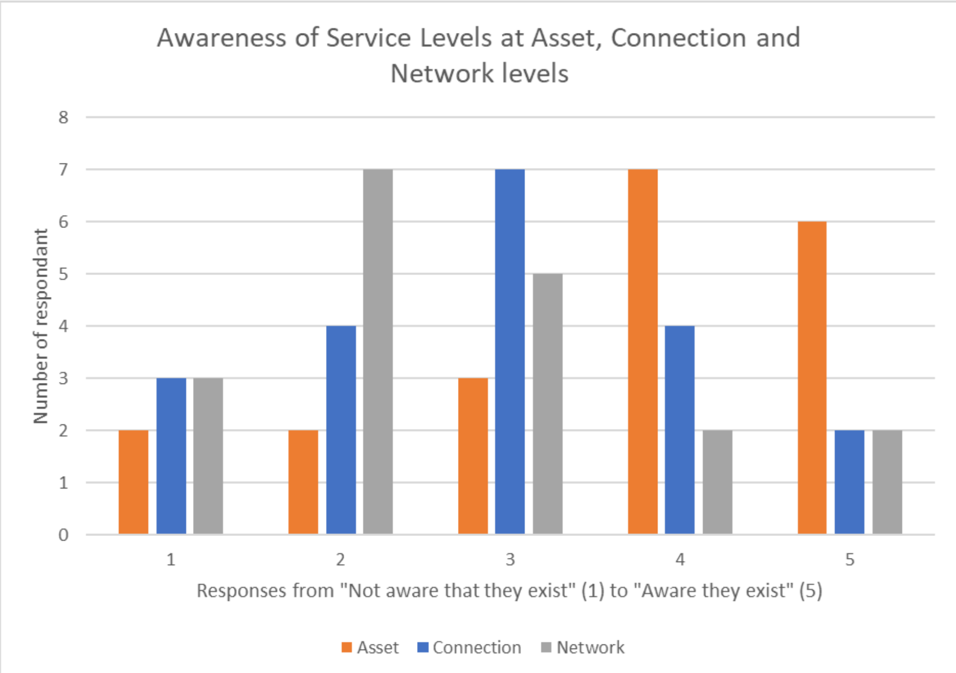


Figure 4.7 Participants' Awareness of Service Levels within their Organisation

The most common criterion used to measure the service level at all levels (asset, connection and network), was shown to be Safety, followed by costs at asset level, Availability at Connection Level, and Politics/Image at Network level as shown in Figure 4.8.

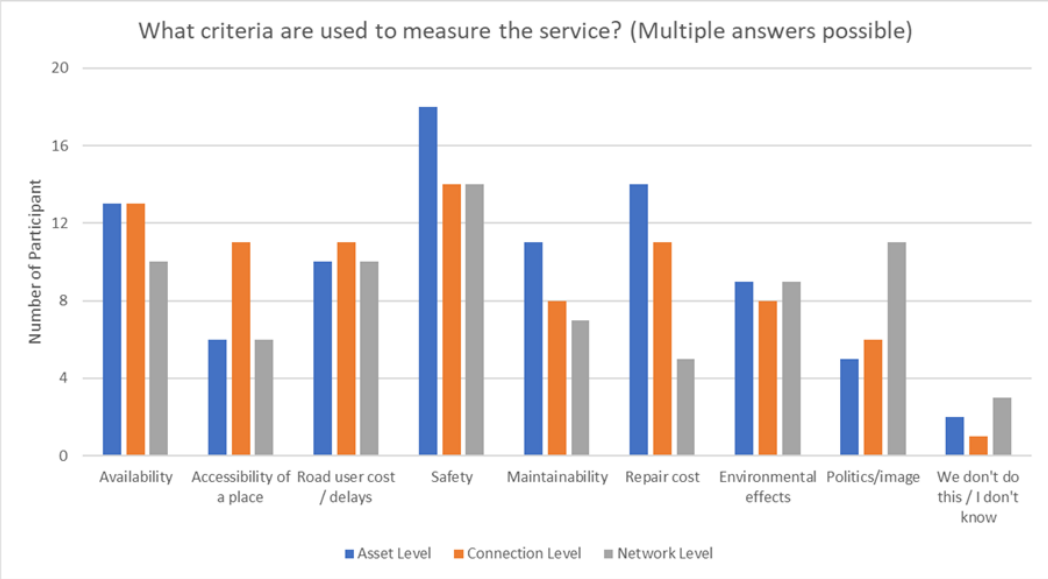


Figure 4.8 Criteria used to measure the service

Of the 20 respondents that were familiar with service levels within their organisations, participants responded that an indicator for climate hazard either exists currently or is in the development process in 17 organisations when asked if "specific Service Level indicators exist for climate hazards". The most common service level indicators related to climate hazards were found to be flooding, rainfall and high wind speed as shown in Figure 4.9Figure where the most frequent responses are shown in larger font.

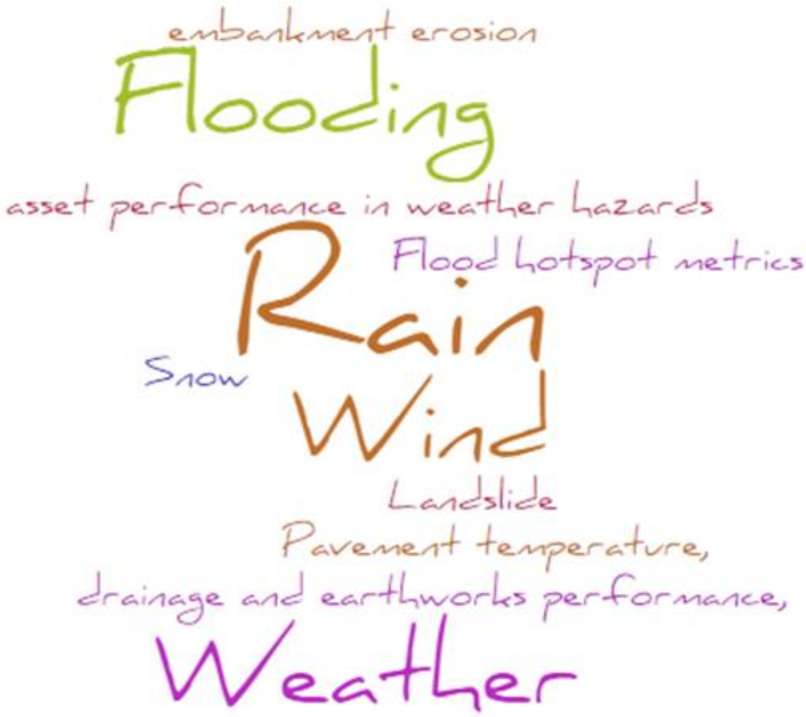


Figure 4.9 Service level indicators related to climate hazards

There were a number of barriers shown to impede the use of Service Levels. The majority of these pertained to a lack of information, lack of funding and uncertainty related to changing climate conditions, however, participants also cited complexity of assessment, difficulty in balancing risk, ageing assets and low probability of impact as less common barriers. These are shown in a word cloud Figure 4.10 with the most frequent responses in larger font.

These barriers seen by the participants in our workshops are similar to those mentioned in the literature (National Academies of Science, 2021) where data availability, limited modelling capability and absent tools and incentives were noted as barriers to agencies performing resilience assessments in the US.

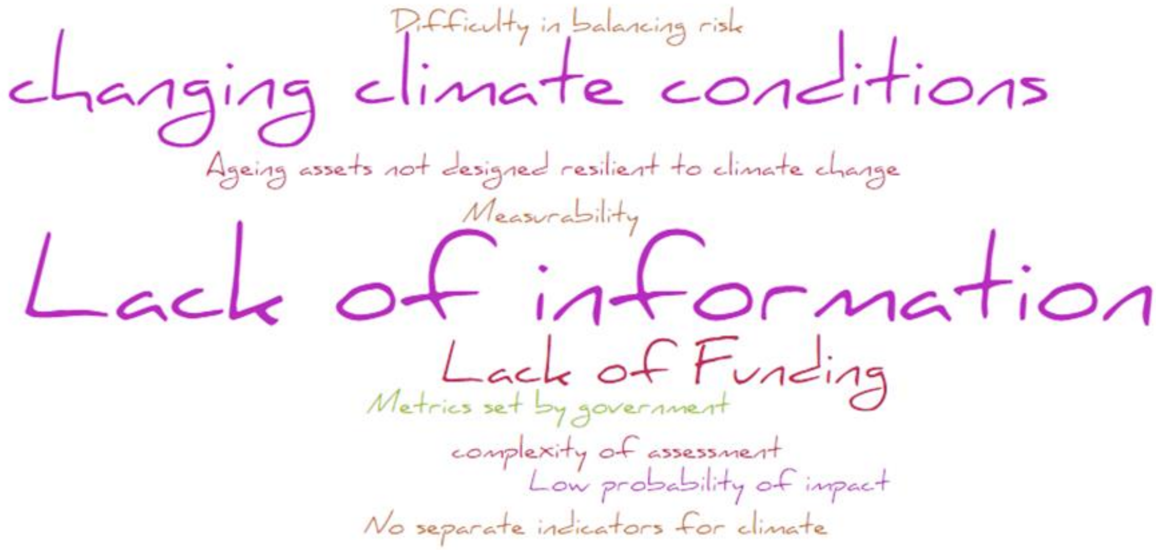


Figure 4.10 Barriers to Implementation of Service Levels

Minimum service levels are typically defined by organisations as the minimum acceptable levels of service to be provided by the infrastructure operator. There was some awareness of these minimum values as the majority of respondents (60%) answered that they were aware of the approximate values, or at least knew where to find the values. 5 (25%) of the respondents stated that there were no minimum service levels defined in their organisation, whilst only 3 (15%) responded that they were aware of minimum values of service levels. Results are shown in Figure 4.11Figure .

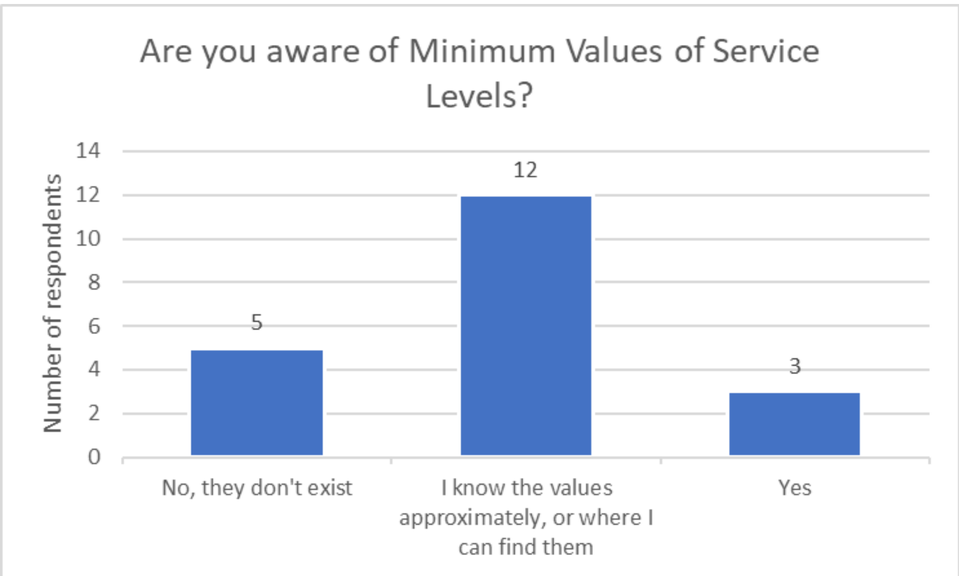


Figure 4.11 Awareness of Minimum Service Levels

Participants were then asked if they knew who set the target values for the minimum service levels. Just over half (11) of participants responded with some knowledge of who is responsible for setting them with no responses recorded for the remainder of participants as shown in Figure 4.12. Participants were asked to differentiate between asset, connection and network levels, however, respondents were generally unclear and didn't differentiate between the levels.

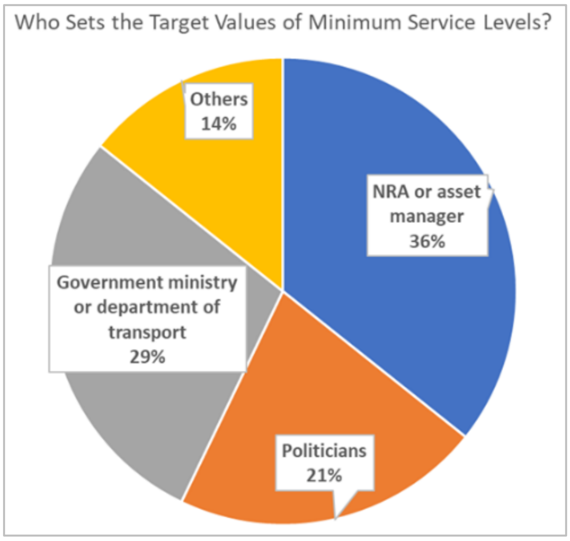


Figure 4.12 Minimum Service Values Target Levels

In the first workshop, the participants were asked if "minimum service levels vary for different categories/criticalities of roads in the network?". Although it was a small sample number of just the first workshop, the majority of participants were aware of variations in minimum service levels for different categories or criticalities of roads in the network as shown in Figure 4.13.

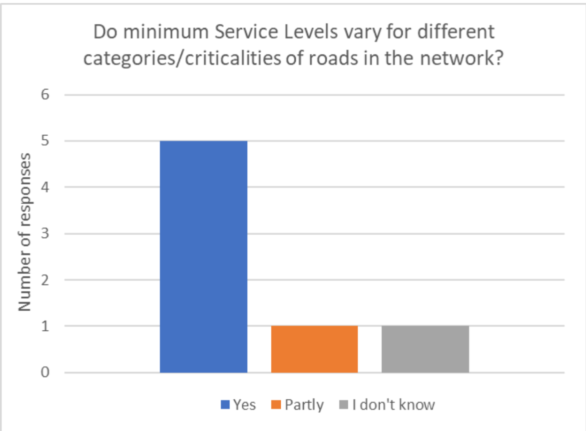


Figure 4.13 Participants' Awareness of Varying Service Levels for Roads in the Network

The method used to set the target levels was clearer to respondents with almost all respondents selecting responses in relation to how the service levels are selected (see Figure 4.14). It is clear that Cost Benefit and other Socio-Economic Evaluation Methods are a popular choice when it comes to setting Target Values, particularly at the asset level. At the same time though, this result from the workshop has not been verified with cases in the State of the Practice. The authors of this baseline report have not seen an example in which CBA actually has been used to set target values for service requirements of a road network.

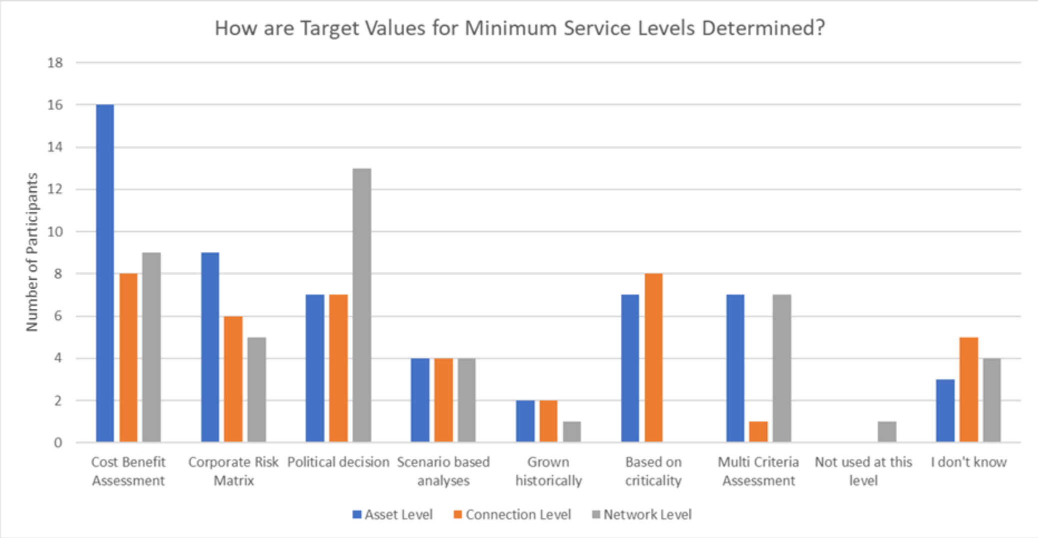


Figure 4.14 How Minimum Service Level Target Values are determined

4.2.5 State of the Practice Summary

It was seen that most workshop participants are aware that some service levels exist within their organisation, with the majority of these pertaining to assets rather than connections or networks. This may be due to the relative ease of obtaining data and performing assessments at asset level rather than at connection or network level.

However, there seems to be a lack of clarity on how the service levels are defined and there also seem to be many barriers to their implementation in practice, such as lack of information, lack of funding and uncertainty on how to measure service levels with changing climate conditions. These barriers were common across representatives from all organisations, even those which would be considered at an advanced stage of maturity such as the Netherlands and Finland. This result aligns with that seen in the literature where similar barriers to the implementation of resilience assessments were noted (National Academies of Science, 2021).

Representatives from Highways England, who responded that they currently use service level metrics set by the government at both asset level and network level. These metrics relate to safety, flood resilience and environmental metrics, and refer also to design metrics. However, the National Highways representatives noted that one of the barriers was "trying to understand how much the existing weather-related service level metrics relate to climate / environmental metrics". Similarly, a Dutch representative stated that they don't want new service metrics, however, would like "to know what actions they need to take and would like to stick with the metrics they have and understand how they can be adopted for Climate Change".

The findings from the workshops aligns with the literature, in that there appears to be much confusion regarding how service levels are to be assessed in reality. AustRoads appear to be ahead of the curve on this front with a detailed project considering transport needs of all road users and formulating corresponding service levels across multiple areas. However, this was performed only at a connection level.

Overall, it appears that some consistency is required in addition to more guidance on how to measure service levels, and perform resilience assessments of asset, connections and networks. While service level metrics exist, they are applied more for investigating the past or present performance of the infrastructure and are not used to evaluate and project the resilience of infrastructure.

5 GAP-ANALYSIS

This section aims to identify the gap between the state of the art and the state of the practice in decision making for climate adaptation, resilience thinking and minimum viable service levels. Conclusions from each of the primary chapters above are summarized from the perspective of the State of the Art and the State of the Practice. This summary allows clear identification of the gaps at each of these levels.

The gap analysis was performed through qualitative analysis of the data reviewed in this deliverable, the literature sources, stakeholder engagement and knowledge of the ICARUS consortium. An effort is made here to suggest how these gaps can be eliminated in order to bring the SoA and SoP closer together and implement effective climate change adaptation in road infrastructure through resilience thinking. The gap analysis is therefore crucial to this baseline report as it will set the route map to achieving the objectives of ICARUS. The end of this section summarises the gaps identified and proposes methods to close these gaps, both within and beyond the ICARUS scope.

5.1 Conclusions State of the Art

For the sake of readability of this final chapter, we summarize the main conclusions per chapter again below, on which we base the gap analysis.

5.1.1 Decision framework for climate adaptation

Many guidelines and approaches exist with appraisal methods to identify effective measures and design an adaptation strategy towards an uncertain future. Some examples also exist on the identification of service optimums. These decision frameworks adequately address the uncertainty associated with adaptation to an uncertain future associated with climate change, particularly through the use of risk-based approaches.

5.1.2 Resilience thinking

The results of this report present a clear picture of the current advances in resilience assessment and decision making in transport infrastructure. Many definitions of resilience exist and there are also different ways to quantify resilience. Resilience is formally quantified through frameworks like that of CEN CWA 17819:2021 and advanced approaches defined in sections 2.1 and 3.1. Resilience is quantified considering breakdown in service measures and temporal aspects of service breakdown are considered. There are many examples of indicator-based approaches to delineating resilience enhancements by reducing service breakdown over time. Indicators may relate to infrastructure, environment or organisational aspects, and may include socio-economic aspects of infrastructure users as well.

5.1.3 Minimum service levels

Much of the current literature in climate adaptation considers the application of minimum service levels, these are often delineated as *functionality metrics* or *resilience metrics*. Different methodologies exist on how decisions can be made what a minimum service level could be, though, often the 'As Low As Possible' principle is still used. Methods like a risk matrix, multi-criteria analysis, or user tolerance levels can help with this.

There are a number of examples in the literature of how to apply service levels to climate adaption. CEN CWA 17819 is a notable example, although this guideline may be considered to be slightly beyond the current state of the art, bordering on practice.

5.2 Conclusions State of the Practice

5.2.1 Decision framework for climate adaptation

The primary conclusion of current SoP in decision making for climate adaptation is that adaptation strategies are widely based upon the minimisation of risk at minimum cost. The risk incorporates impact or consequence analysis which may consider service measures, but not explicitly investigate the evolution of service measure losses over time.

5.2.2 Resilience thinking

The State of the Practice demonstrates little or no formal quantification of resilience. The process of risk assessment is much more commonly used to indirectly enhance resilience but often adaptation is applied to the infrastructure only, and organisation / environmental indicators are sometimes ignored. Literature sources have suggested that the apparent lack of uptake in resilience quantification is uneven knowledge in this area, and the familiarity of risk assessment methodologies. Inconsistency was the primary theme resulting from both literature review and workshops, with mixed levels of personal as well as organisational understanding of the concept of resilience and implementation of service levels demonstrated across all participants, regardless of country or organisation.

Further barriers to implementing resilience in practice, according to stakeholders, stem from a lack of funding and data, difficulties with modelling an uncertain future, as well as the many stakeholders within and outside the NRA's that need to be involved. It proves to be difficult to open up a dialogue between the strategical, tactical and operational levels within the NRAs.

5.2.3 Minimum service levels

Through investigation of literature and stakeholder engagement it has been determined that while service level metrics exist, they are applied more for investigating the past or present performance of the infrastructure and are not used to evaluate and project the resilience of infrastructure against an uncertain future of climatic disruption. Wider knowledge or awareness of service levels at the asset level were noted through the workshops which may be due to the relative ease of obtaining data and performing assessments at asset level rather than at connection or network level.

Engagement with the NRAs for this report has indicated that there is a need to understand which existing indicators can currently be used to address climate change, and how they should be applied. Workshop participants across all organisations cited multiple barriers to their implementation in practice such as such as lack of information, lack of funding and uncertainty on how to measure service levels with changing climate conditions. This is consistent with the conclusions of TRB (2021): "There is no single metric or value that can perfectly reflect all aspects of resilience in all elements of a given system. Instead, decision makers must look at a variety of metrics to assess and understand the impacts of the investments they make … to improve the resilience of the assets in the transportation system."

5.3 Implementation Gaps

Decision frameworks for climate change adaptation exist within the state of the art and are beginning to become commonplace in standardisation and guidelines. However, examples how these frameworks are applied in practice are rare and could assist in closing the gap on resilience understanding across NRAs. The determination of minimum service levels (as for instance is being described in the CEN CWA 17819:2021) to achieve certain required levels of resilience is also not implemented in practice, let alone quantitative approaches using Cost Benefit Assessments or Decision Making under Deep Uncertainty. Such methods are only used on a case by case project basis and not related to determining minimum service levels.

In terms of application of service levels, it has been found that metrics exist across different levels of assessment (network/connection/object), but we may not be as close to implementation regarding applying metrics for climate adaptation. It also appears that a clear understanding of how these metrics link to each other is not understood. In many cases, service requirements are present at the network level (e.g. availability or safety related) as well as for the object level (e.g. via design guidelines and requested capability for specific return periods). It may be qualitatively understood that an increase of requirements at the object level will lead to a better performance at the network level, but a clear quantitative substantiation has not been found. Though present at a project or case by case basis, no examples have been found where an analysis of risk, cost and performance has been made to identify the optimum requirements for design and maintenance, as well as required service levels on the network scale. Here it appears that within a certain level (strategic/tactical/operational) and related scope (network, connection/object), analyses are being performed, but the interaction between the levels is unclear. It is therefore recommended that development of a resilience framework for CEDR NRAs should duly consider the communication across the different levels of assessment. For example, there needs to be a clear understanding / mapping of how object level achievements lead to resilience enhancements at the network level. This also links to Reliability Centered Maintenance (RCB) strategies which exist on the object level. We however did not see any examples which make the link between optimization on the object and increasing resilience on the network level. Figure 5.1 illustrates the current understanding on this topic.

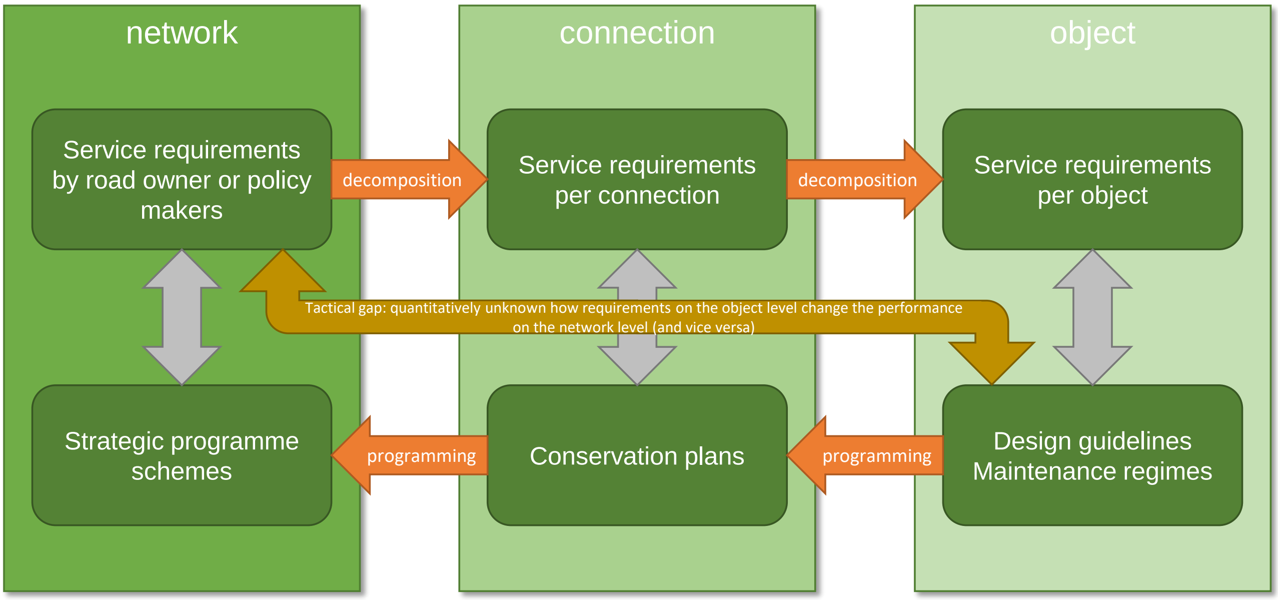


Figure 5.1 Line of sight for resilience assessment across different levels

5.4 Development Gaps

There are a number of gaps in current resilience practice which must be addressed prior to uptake by NRAs. Firstly, NRAs have been found to have various examples of service level metrics in place which are tracked over time. However, these have not been mapped to resilience frameworks. Stakeholders have informed the ICARUS consortium that there is little need or appetite for new service level metrics across the asset, connection or network levels, but rather there is a need to understand **how existing service level metrics can be applied for climate adaptation in resilience analysis**. Secondly, and relatedly, there is need to understand which service level metrics can be applied. CEN CWA 17819:2021 provides an extensive list of measures of service which can be applied in a formalised resilience assessment but **does not suggest how to select service level metrics which should be applied, nor any details on how to quantify them.**

Further development is also required in the **consideration of uncertainty** in resilience approaches. Even the current state of the art seems to address uncertainty only in risk-based approaches and by using an upper and lower bandwidth only, except for Decision Making under Deep Uncertainty approaches. Consideration of uncertainty is required in order to advance resilience thinking in the face of climate change. Current guidelines also seem to provide **limited information on building social vulnerability** in line with resilience thinking. This also leads to a further gap associated with combined consideration of various service level metrics across various different return periods of hazards as well as multi-hazard approaches. While multi-hazard approaches are common in traditional risk-based approaches, this is not the case for the most advanced resilience-based approaches to decision making.

5.5 Actions to address the gaps and recommendations

A qualitative assessment of the current gaps between SoA and SoP was performed based on the results of this study. The most significant gaps which act as barriers to NRA adaptation to climate change are listed in Table 6 below. A key action is proposed to address these gaps, as well as an indication of the ICARUS output which aims to address this action. This table will serve as a reference point for future work in the ICARUS project to ensure the project objectives are achieved in a manner which will streamline the adoption of resilience analysis in climate adaptation for CEDR NRAs.

Table 6: Overview of Gaps, Proposed Actions and ICARUS Scope

Type	Gap	Action	ICARUS Scope
Implementation Gap	Sample applications of resilience frameworks	Future guidelines should be developed alongside advanced demonstrators implemented by CEDR NRAs and need to clearly understand and address barriers for implementation	ICARUS Deliverable 2.2, 2.3, 3.2 & 5,1; Milestone 4.2
	Line of sight for resilience assessment across object, connection & network levels	Investigation to application of service measures for adaptation at network, connection/object level and mapping this back to benefits and co-benefits at the strategic/tactical/operational levels of organisation.	ICARUS Deliverable 2.3 & 3.2
	Application of service level metrics to climate adaptation	Development of future guidelines which concisely investigate the service level metrics available to NRAs in order to make clear recommendations on how they should be applied for resilience calculation	ICARUS Deliverable 2.2
Development Gap	Which existing service level metrics should be applied to climate adaptation		
	Consideration of uncertainty in resilience approaches	Climate adaptation plans to address uncertainty in hazard impact chains as well as socio economic pathways.	ICARUS Deliverable 1.2 & 3.2
	Building social vulnerability into resilience assessment	Application of frameworks and demonstrators considering NBS with wider social co-benefits	ICARUS Milestones 1.1, 2.1, 3.2 & Deliverable 4.2

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Annex 1: Overview of Existing Methods

Method/guidelines	Short description	Specific attention to road	Considers uncertainty	Climate Change hazards?	Developing adaptation strategy	Conducting resilience assessment	Minimum service levels
ISO 14091 : 2021 Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment	Guidelines for assessing the risks related to the potential impacts of climate change risks. It does not relate specifically to infrastructure, and is more a general overview of how a strategy might be defined.	No – not even specifically infrastructure	Yes	Yes	No – it is specified but not described	No – more related to risk	No – only a high level description of "Impacts"
CEN CWA 17819: 2021 - Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events	Pre-standardisation guidelines on quantification of resilience from service measures using an indicator-based approach.	Transport Infrastructure in General, with specific examples for roads	No	Not directly	Yes – CBA performed to enhance resilience	Yes	Yes – method to set "targets" or "minimums"

Method/guidelines	Short description	Specific attention to road	Considers uncertainty	Climate Change hazards?	Developing adaptation strategy	Conducting resilience assessment	Minimum service levels
TRB: Investing in Transportation Resilience: A Framework for Informed Choices	Review of current practice by transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience, as well as contemporary research.	Transport Infrastructure in General	Yes	Yes	Yes	Yes, although the approach is more related to risk	No – service levels considered as consequences
CCRI: Physical Climate Risk Assessment Methodogy (PCRAM)	Advances a dynamic impact assessment of physical climate risks (PCRs) that can be incorporated in investment decision making. Methodology based on data gathering, materiality assessment, Resilience building and economic / financial analysis	No	Yes	Yes	Yes – "Resilience Building"	Yes, although the approach is more related to risk	No – service levels not considered, just "Impacts" / "Severity"
ROADAPT - Guidelines for adaptation of road infrastructure to climate change	The ROADAPT (Roads for today adapted for tomorrow) project provided in 2015 a set of guidelines for the preparation of adaptation strategies by road network administrations. The guidelines cover the basic steps, from climate change projections, to vulnerability and socio-economic assessments.	ROADAPT focuses on highways and roads	Yes, making use of a lower and upper limit	Yes	Yes – on the selection of adaptation measures and strategies for mitigation	Yes – guidelines on socio-economic impact and vulnerability	No

Method/guidelines	Short description	Specific attention to road	Considers uncertainty	Climate Change hazards?	Developing adaptation strategy	Conducting resilience assessment	Minimum service levels
PIARC: International climate change adaptation framework for road infrastructure	International framework for climate change adaptation, developed by the World Road Association.	Yes, specifically written for roads	Yes, but no practical recommendati ons	yes	yes	no	no
Vulnerability Assessment and Adaptation Framework (FHWA)	The Federal Highway Administration's (FHWA's) Vulnerability Assessment and Adaptation Framework (the Framework), is a manual geared toward State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, maintaining, or operating transportation infrastructure. The Framework describes the primary steps involved in conducting a vulnerability assessment with examples from assessments conducted nationwide between 2010 and 2017.	Yes, US applied	Yes, Uncertainty in climate change projections , uncertainty in risk evaluation and in prioritisation of adaptation options	Yes	Yes, Vulnerability assessment and how to integrate in decision-making	Yes, Involves prioritisation of adaptation options and economic analyses how to prioritise	No

Method/guidelines	Short description	Specific attention to road	Considers uncertainty	Climate Change hazards?	Developing adaptation strategy	Conducting resilience assessment	Minimum service levels
ERDF framework (de Jonge (2021))	This framework demonstrates how a certain *current level of resilience* should be compared with a certain *desired level of resilience*, based on the same indicators, to be able to make an adaptation strategy.	No	No	Yes	Included but not applied	Yes	Yes
Six step approach for climate adaptation of critical infrastructure (Dutch framework)	General framework from vulnerability assessment towards proposing measures to increase resilience. Focusses on critical infrastructures in general and offers various methods within each of the six steps.	no	Could be	Yes	Yes	Yes	Not specifically
WATCH manual	The manual aims at assessing current and future resilience of NRAs water management facilities, ensuring optimal design, maintenance planning and asset management.	Yes, more specifically to the water management assets	Upper and lower limit approach	Yes, flood and rainfall related	Yes - a practical manual has been developed	Yes - specifically for water management assets	No

Method/guidelines	Short description	Specific attention to road	Considers uncertainty	Climate Change hazards?	Developing adaptation strategy	Conducting resilience assessment	Minimum service levels
A DMDU Guidebook for Transportation Planning under a changing climate (IADB)	This guidebook introduces and provides guidance on applying methods for DMDU to transportation planning and is developed to support IADB team members that work on transportation sector funding and planning. It presents the methodological steps that are necessary for the implementation of DMDU methodologies and reviews several such methods, including scenario planning, Adaptive Pathways, and robust decision making (RDM).	Yes, focused in Latin America and the Caribbean	Yes, focuses on DMDU approaches	Explains how climate change will impact transportatio n and provides an overview of the sources of information	This is described in more detail in other guidebooks by the IADB, but a general Risk Management and Transportation Risk Analysis section is included.	Involves the decision-making side and decision-making under deep uncertainty (DMDU) approaches	A brief overview is included in the explanation of the DMDU approaches