



**Conférence Européenne
des Directeurs des Routes**

**Conference of European
Directors of Roads**



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

Final Programme Report: CEDR Call 2021 Climate Change Resilience



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CEDR Call 2021 Climate Change Resilience Final Programme Report

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By

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EXECUTIVE SUMMARY

This final report provides the results of the ICARUS project, (Improving the uptake of Climate change Adaptation in the decision making processes of Road Authorities), that was selected by CEDR, to conduct research in the domain of implementation of climate change adaptation. The research ensures that existing research and lessons learned from various case studies can be successfully implemented into the processes of National Road Authorities (NRAs). This was formulated in the following key objective of ICARUS:

“To provide guidance and guidelines on how to build and implement the decision case for resilience via adaptation, by balancing the service levels that the road network needs to achieve with the costs and benefits for enhancing resilience”

Road infrastructure is crucial for society, but climate change, as highlighted in the IPCC's Sixth Assessment Report (AR6), poses significant threats through increased likelihood and intensity of extreme weather. While the occurrence of severe weather is better understood, its operational impacts on road assets as well as the services that roads provide to society remain less known. CEDR aims to address these issues to build and maintain reliable, resilient, and sustainable networks across Europe.

NRAs are responsible for constructing and maintaining reliable, resilient and sustainable networks across Europe and therefore need to integrate climate change adaptation strategies into their decision-making processes. In the past decade, significant research has been undertaken, leading to the development of guidelines, methods and tools that provide an understanding of the effects of climate change for roads.

This research led to a big step in understanding resilience. Conducting a resilience assessment has become relatively common practice and the forthcoming development of adaptation strategies has also been undertaken in many cases. Yet, the step to real implementation in practice poses a significant challenge as wide application of the results of previous research projects in NRAs processes had not yet taken place. The step to implementation is the focus of the ICARUS project.

The ICARUS project produced results that can be of immediate benefit to NRAs. The consortium is confident that NRAs will be able to use the following key results of the ICARUS project in their asset management processes for enhancing resilience via adaptation:

- An overview of the baseline for climate change resilience assessments, resilience evaluation and the use of cost benefit assessments for climate change adaptation (D1.1, D2.1 and D3.1);
- A report on the use of impact chains for understanding of direct and indirect impacts (D1.2);
- Guidelines on how to define and use minimum viable service levels for evaluating resilience and adaptation options based on quantification and valuation of associated costs and wider co-benefits and considering a whole life perspective (D2.2);

- Guidelines providing an overview and characterisation of adaptation measures, aimed towards implementation in the various NRAs processes (D2.3);
- Demonstration report showing how adaptation measures can be evaluated (D3.2);
- Report with success factors on implementing Nature-based Solutions (D4.2);
- Resource training pack for different target audiences to ensure implementation of output (D4.3).

Five key recommendations have resulted from the research:

- **Choose the right resilience frameworks for practical use**
Despite the availability of resilience assessment frameworks and tools for climate adaptation, their integration into road authorities' decision-making is limited. The key issue is that resilience assessments are often not linked to decision-making criteria. Economic appraisals for adaptation are rare and often overlook broader benefits like carbon and biodiversity. ICARUS provides outputs to enhance resilience and adaptation assessments, including guidelines on impact chains, an adaptation options database, and cost-benefit analysis guidelines.
- **Connect resilience assessment and appraisal of adaptation options to the decision-context**
Climate change adaptation is one of many factors in road authority decision-making. Key Performance Indicators (KPIs), such as availability and safety, should be linked to resilience and adaptation assessments. Secondary policies, such as sustainability and carbon reduction, should also be considered. Decision-making mechanisms vary, including service, budget, optimum, and policy-driven approaches. Tailoring assessments to the specific context of each road authority is crucial, using existing frameworks as a starting point but customizing them as needed.
- **Make sure to engage strategic, tactical and operational management levels**
Road authorities involve many decision-makers across various managerial levels. ICARUS developed a climate change adaptation process linking steps to strategic, tactical, and operational levels. Engagement across all levels is crucial, with one person managing the process, ideally from the tactical level.
- **Make the case for adaptation through three basic approaches**
Climate change adaptation can be approached in three ways. Monitoring KPIs linked to climate events clarifies their impact on network performance. Incorporating climate adaptation into asset management ensures structural implementation and performance optimization through cost-benefit analyses. Implementing adaptation on a project-specific basis allows tailored investments. Lessons from specific projects can furthermore inform the asset management guidelines.
- **Consider nature-based solutions**
Nature-based solutions (NbS) offer multiple co-benefits, including increased resilience, cost-effectiveness, reduced environmental impact, enhanced social equity, community engagement, and improved reputation. They can address greenhouse gas mitigation, carbon storage, and biodiversity challenges. However, implementation is hindered by resource constraints, knowledge gaps, integration difficulties, and lack of organizational engagement.

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1 POSITIONING THE ICARUS PROJECT WITHIN THE CEDR CLIMATE CHANGE RESILIENCE RESEARCH PROGRAM

1.1 Context

Road infrastructure is the backbone of our society, and a high level of service is expected by citizens, organisations, and governments. At the same time, it is fully acknowledged that the world's climate is changing, which was again highlighted in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6)¹. Extreme weather events are expected to increase in both frequency and severity and will have a significant impact on roads.

Whilst there is a better understanding of the likelihood of more severe weather, there is less knowledge of the operational impacts of climate change on road assets such as structures, pavements, drainage and earthworks. The response can be limited by constraints such as cost and environmental impact, and by a lack of knowledge about the scale of the threat. CEDR has recognised the need to address this theme as part of the other challenges to build and maintain reliable, resilient and sustainable networks across Europe.

Every year, climate change and its impact on roads becomes more apparent. Recent examples are the flooding in Germany, Belgium and the Netherlands in July 2021², the big flood events in Czechia, Slovakia, Poland and Austria³, as well as in Valencia⁴ in Spain in September and October 2024 respectively. In some locations it took several months for the highway network to recover. This caused physical damage as well as socio-economic losses and safety risks for the users of the road network. Besides flooding, extreme events such as landslides, wildfires, and extreme heat significantly affect the road transport network.

1.2 CEDR call on climate change resilience in 2021

National Road Authorities (NRAs) are responsible for constructing and maintaining reliable, resilient and sustainable networks across Europe and therefore need to integrate climate change adaptation strategies into their decision-making processes. In the past decade, significant research has been undertaken, leading to the development of guidelines, methods and tools that provide an understanding of the effects of climate change for roads. Three

¹ IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.

² Koks, E.E., Van Ginkel, K.C.H., Van Marle, M.J.E., Lemnitzer, A., 2022. Brief communication: Critical Infrastructure impacts of the 2021 mid-July western European flood event, NHESS, <https://doi.org/10.5194/nhess-22-3831-2022>.

³ <https://www.ecmwf.int/en/about/media-centre/focus/2024/storm-boris-and-european-flooding-september-2024>

⁴ <https://wmo.int/media/news/devastating-rainfall-hits-spain-yet-another-flood-related-disaster>

previous CEDR calls in 2008, 2012 and 2015 have addressed the topic and much research has been performed within EU FP7, H2020 and Horizon Europe projects.

This research led to a big step in understanding resilience. Conducting a resilience assessment has become relatively common practice and the forthcoming development of adaptation strategies has also been undertaken in many cases. Yet, the step to real implementation in practice poses a significant challenge as wide application of the results of previous research projects in NRAs processes had not yet taken place. Therefore, the CEDR 2021 'Description of Research Needs' related to climate change resilience mentioned: "The aim of this programme is to undertake research on integrating Climate Change into decision-making processes and implementing existing research into practice".

1.3 ICARUS objectives

The ICARUS project was selected by CEDR, to conduct research in the above context. It should ensure that the previous research and lessons learned from various case studies can be successfully implemented into the NRA's processes. This was formulated in the following key objective of ICARUS:

"To provide guidance and guidelines on how to build and implement the decision case for resilience via adaptation, by balancing the service levels that the road network needs to achieve with the costs and benefits for enhancing resilience"

The name ICARUS is a metaphor for the key challenges that NRAs face during the integration of climate change into their decision-making processes. By working towards a too high service level (i.e. flying too high), adaptation will probably prove to be too costly compared to the benefits and will not be implemented. By focusing mostly on the cost of measures (i.e. flying too low), the measures won't be very effective in increasing the resilience of the road network and reaching the required service level. This demonstrates the complexity and the relevance of the objectives of this research. All ICARUS deliverables provide guidance towards a better understanding and assessment of this balance between service levels, cost and benefits of measures, as this is seen as the key for implementation of climate change resilience.

2 OUTPUTS OF THE ICARUS PROJECT

The ICARUS project produced results that can be of immediate benefit to NRAs. The consortium is confident that NRAs will be able to use the following key results of the ICARUS project in their asset management processes for enhancing resilience via adaptation:

- An overview of the baseline for climate change resilience assessments, resilience evaluation and the use of cost benefit assessments for climate change adaptation (D1.1, D2.1 and D3.1)
- A report on the use of impact chains for understanding of direct and indirect impacts (D1.2)
- Guidelines on how to define and use minimum viable service levels for evaluating resilience and adaptation options based on quantification and valuation of associated costs and co-benefits and considering a whole life perspective (D2.2)
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- Demonstration report showing how adaptation measures can be evaluated (D3.2)
- Report with success factors on implementing Nature-based Solutions (D4.2)
- Resource training pack for different target audiences to ensure implementation of output (D4.3).

This chapter places these deliverables in the context of the ICARUS framework in Chapter 2.1. Forthcoming, the key results per deliverable are described in Chapter 2.2.

2.1 Introducing the ICARUS framework and how deliverables fit in the framework

2.1.1 The ICARUS framework: climate adaptation decision making

Road authorities play a crucial role in ensuring the resilience of transportation networks. Decision making at road authorities is closely linked to resilience assessments, which involve evaluating the road system's ability to withstand and recover from disruptive events or changes. By conducting resilience assessments, NRAs can identify the most vulnerable locations of the road network and the risks involved in these as a consequence of natural hazard events. These outcomes can be used in decisions regarding the prioritisation of locations and investments to the infrastructure asset, connection or network. It allows road authorities to prioritise investments, allocate budgets, and allocate resources more efficiently and effectively, ultimately leading to a more resilient transportation system.

However, effective decision-making at NRAs is more complex than just performing the resilience assessment and involves more steps than understanding the current and future performance of the road. For example, the appraisal of adaptation options is often overlooked. The ICARUS framework provides guidance to NRAs which steps they need to take for implementing climate change adaptation in their processes, which will lead to effective decision making. This chapter introduces the ICARUS framework and how the underlying guidelines fit within the framework.

2.1.2 The ICARUS framework with its deliverables

Within ICARUS we adopt 6 main steps for incorporation of climate change adaptation in the processes of the NRAs, based on extensive research into the State of the Art (highest level of development in research) and State of Practice (what is commonly done) in the ICARUS baseline reports (deliverable D1.1, D2.1 and D3.1).

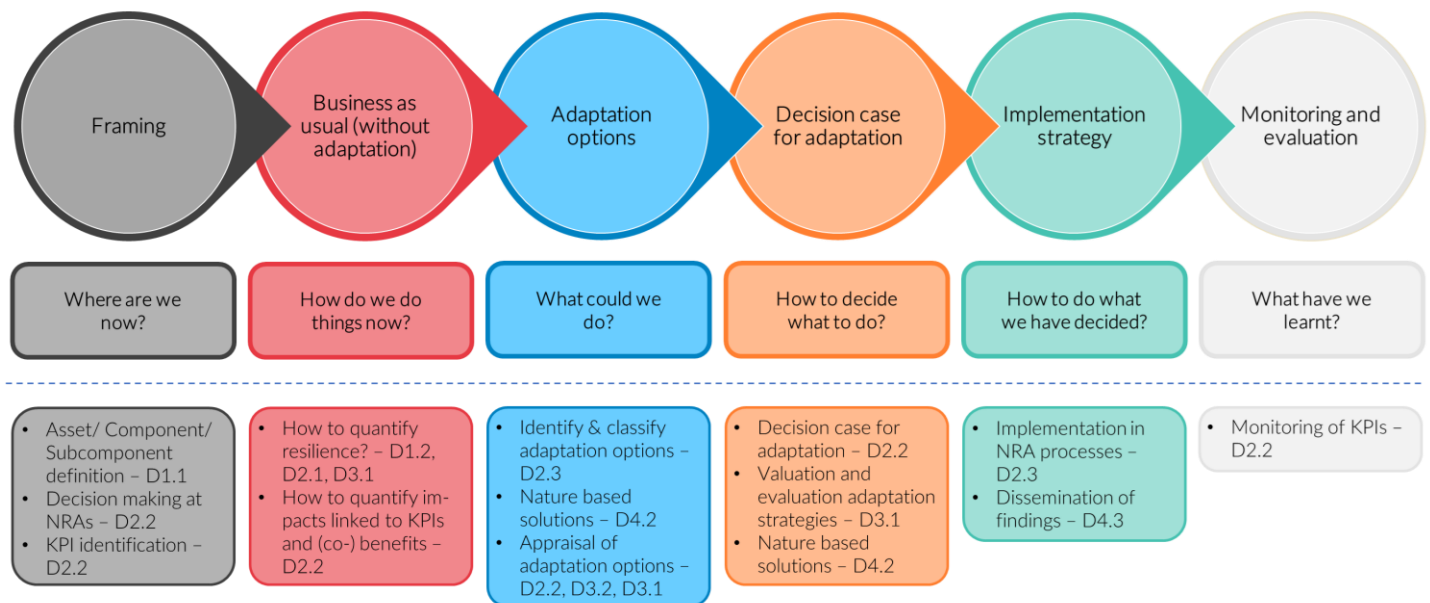


Figure 1 Overview of the steps in the ICARUS framework regarding decision-making and implementation of climate adaptation at NRAs, as well as how these steps are addressed in the underlying guidelines and other ICARUS deliverables.

Figure 1 presents the six steps of the ICARUS framework. The first step is called framing and consists of understanding the decision-making process at NRAs. This comprises a full understanding of the decision-making criteria and policies in that regard. The use of Key Performance Indicators (KPIs) and co-benefits (e.g. reduced carbon emissions, or meeting biodiversity targets, sometimes referred to as ‘wider social and environmental benefits’) should be known to ensure a proper connection to these indicators in the resilience assessment. Furthermore, other boundary conditions for decision making should be clear such as the temporal and spatial scope of the project, capacity, resources and data examination. And finally, a clear overview of all involved stakeholders should be present. By comprehensively understanding these aspects, road authorities can enhance their decision-making processes and effectively work towards implementation of adaptation options for enhancing the resilience of the road network.

In the second step, business as usual is being assessed to understand how resilient the road network is for natural hazards, both for the current and the future situation. Adaptation is not yet considered. Insight into the resilience without adaptation will form the base case and is key to understanding the (co-)benefits of adaptation options.

In the third step, adaptation options are considered. Adaptation options, as well as their benefits and co-benefits, are identified. Adaptation options are being combined and placed on a timeline, to build adaptation strategies. The future resilience with use of these adaptation strategies is being assessed, and (co-)benefits are being valued in such a way that this aligns with the decision-making process of the NRAs.

The fourth step builds the decision case for adaptation. By comparing the resilience for the business-as-usual case with the resilience inclusive of adaptation, one acquires knowledge of the benefits and co-benefits of adaptation strategies that can be evaluated with relevant evaluation methodologies. This step is key in providing the necessary information to decision makers while using the appropriate methods and metrics, allowing them to consider the decision case integrally with other decisions that need to be made.

In the fifth step, the practical implementation of the decided strategies occurs. By following the previous steps, all relevant pre-processing has been done. However, now it needs to be ensured that all the valuable work will be implemented in practice.

The last step consists of monitoring the results of adaptation. How is the performance of the road network developing towards the future? And does this link to the performance that was expected during the resilience assessments and appraisal of adaptation strategies? Effective monitoring enables evaluation of the performance and may lead to further steering of plans towards the future. Also, it further eases the decision case for adaptation, as it provides the metrics for the evaluation of adaptation strategies. This entails a feedback loop from this last step to the very beginning of the framework and all intermediate steps.

2.2 Results per deliverable

This section describes the main learning outcomes per deliverable and presents the most important figures developed within the project. For clarity, deliverable D4.1 (dissemination Strategy and Audience Identification) is not listed because it is an internal document regarding processes and management of the ICARUS project and does not contain information with regards to the ICARUS subjects.

2.2.1 Deliverable D1.1 Baseline Report on determining impacts and risks due to climate change

D1.1 introduces the principles of climate risk in the road sector and provides the foundational knowledge to understand the impacts and risk of climate change on roads according to the Climatic Impact-Driver (CID) concept developed and mapped in the IPCC's AR6. It introduces the elements used to structure impact chains (hazard, vulnerability and exposure; a concept which was developed in D1.2) and provides a literature review of the state of the art and the state of practice. Furthermore it provides better insight into future behaviour of each of the identified CID related to European road transport, based on European Climate Databases. Lastly, it provides the most relevant climate risk indexes for the road sector. D1.1 is a report

that serves as a basis for the development of D1.2. The conclusions drawn from D1.1 are summarised below.

Climate change knowledge for roads

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

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

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

To predict these variables, it's helpful to combine climate model results with other models that simulate various natural processes in the specific area. The Copernicus Climate Change Service provides some of these variables, but usually, they should be evaluated and/or corrected considering local data. Creating these variables uses different scenarios and models, which leads to a range of results that reflect their uncertainty. This uncertainty is a natural part of predicting variables for road design and management. Since the techniques to handle this are often complex, it's usually best to make decisions by considering a wide range of possible future outcomes.

Risk management principles, frameworks, and approaches

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

The characterisation of the risk components differs slightly in both perspectives, mainly regarding the definition of hazard. Generally, in the road sector, hazards are referred to those that are usually assessed in the Disaster Risk Reduction field. Thus, they normally include certain anthropogenic hazards (such as, terrorism, war, vandalism, accidents) that are not

usually considered in the climate change adaptation perspective. However, other types of climate hazards related to slow-onset processes and trends due to climate change (e.g. increasing temperatures, increasing/decreasing precipitation, among others) are neglected. In this sense, their consideration is recommended in road risk assessment guidelines as they are hazards in themselves and lead to changes in the magnitude, duration and frequency of extreme events.

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

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

Climate Impact Drivers and use in the context of roads

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

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

The proposed CID framework applicable to the transport sector is currently in line with climatic data sources available at the European level, which provides insight into its behaviour in the coming decades. The available datasets in the Climate Data Store of the Copernicus Climate Change Service offers reanalysis and projection data for each climatic index and provides additional climatic variables for the calculation of those that are not available. Similarly, the European Environment Agency's interactive climate hazards offers a big picture

and detailed information on the evolution of these indices, which is necessary for smarter decision-making to prevent the worst impacts of climate change across Europe's road sector.

Mapping exposure over the road project cycle

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

Mapping exposure of CID on road networks provides essential information that at-risk communities need to make informed planning decisions throughout the entire life cycle of an asset, connection, or network. Using these maps, governments can better understand and communicate climate change risk to local communities and put/remove or refine adaptation plans in place.

Vulnerability of the assets

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

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

One way to decrease an asset's vulnerability, would be to adopt a Nature-based solution (NbS) to help prevent damage to infrastructure during climate events. NbS may be implemented to improve local areas for communities, as well as providing benefits during extreme events, however, they need to be carefully implemented and managed. More information on NbS is found in D4.2.

2.2.2 Deliverable D1.2 Report on impact chains, vulnerability and hazard classification

In the face of increasing climate-related challenges, NRAs must adopt effective strategies for assessing risk, vulnerability, and resilience of road infrastructure. This deliverable, D1.2, is a guideline that aims to bridge the gap between high-level climate projections and practical decision-making for road asset management. It provides a methodology for classifying and prioritising hazards based on their impact on resilience, tailored to the specific needs and management levels within NRAs.

Mapping risk pathways for road assets involves several key factors, for example climate projections (in terms of both magnitude and geography) and the criticality of infrastructure within the transport network... Traditionally, hazards have been classified based solely on their characteristics. However, the ICARUS approach proposes a more actionable framework, linking scientific climate projections to real-world consequences faced by NRAs.

The guideline supports decision-making across three management levels:

1. **Strategic Level (Top-down approach):** At this level, NRAs rely on long-term climate projections from authoritative bodies such as the IPCC and guidance from the European Commission, which promotes climate resilience and neutrality in infrastructure planning for the 2021–2027 programming period. However, balancing long-term planning with short-term prioritisation is critical. The ICARUS framework facilitates this offering a structure to classify and prioritize hazards. This helps to integrate adaptation strategies into overarching infrastructure policies.
2. **Tactical Level:** ICARUS offers a methodology to connect large-scale climate projections to their direct and indirect impacts on road infrastructure. It introduces two key tools: **Impact Chains** and the **Resilience Score**. Together, these tools form a **two-step methodology** which forms the core output of D1.2.
3. **Operational Level (Bottom-up approach):** On the ground, understanding and documenting specific impacts, (whether damages or opportunities,) is key. This level involves integrating lessons from real events and using relevant KPIs to refine resilience strategies. It feeds back into the broader system, ensuring continuous improvement and adaptation.

The main objective of this ICARUS guideline is to provide clear recommendations on building an impact chain framework for risk and hazard assessment based on NRA-specific conditions. It highlights the crucial relationship between assets (component/subcomponent level), CIDs, and their changing influence under various climate scenarios. Additional goals include promoting systematic CID prioritisation and strengthening the link between impact chains and resilience planning.

By aligning scientific insights with governance structures and operational realities, ICARUS helps embed climate adaptation within sustainable transport infrastructure development, enabling NRAs to take informed and effective action in the face of climate change.

Although in ICARUS only the conceptual part is developed, the impact chains (of which a visualization is showed in figure 2) are the basis for the development of more sophisticated quantitative studies (e.g. Bayesian networks).

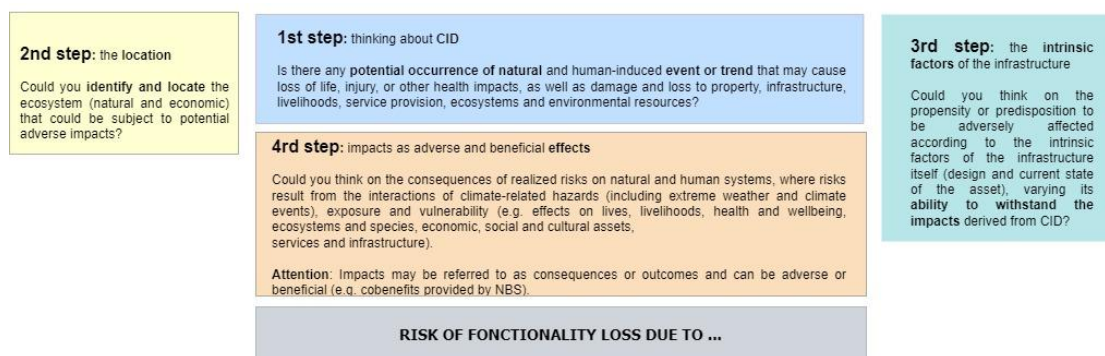


Figure 2 Impact chain graph for hazards and transportation infrastructure. This image is just for reference, we refer to the deliverable for further exploration of this concept.

The last part of the deliverable introduces a new method to classify the effect of hazards according to their effect on road resilience considering their impact before (e.g., forecast and preparation time), during (e.g. hazard duration, intensity, scale and physical impact) and after (e.g. recovery time) an event using multicriteria analysis. It uses the developed impact-chains, and builds upon it.

2.2.3 Deliverable D2.1 Baseline report on minimum service levels, decision frameworks and resilience evaluation

In this deliverable, a literature review is performed on the state of the art and state of the practice of three themes: decision frameworks for climate adaptation, resilience thinking and minimum service levels. The gap analysis resulted in implementation gaps and development gaps, which we list below.

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 of 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 (for instance as 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 (CBA's) or Decision Making under Deep Uncertainty-techniques (DMDU-techniques, of which examples are presented in D2.1). 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 there is a lack of understanding of how these metrics link to each other. 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 (RCM) strategies which exist on the object level. No examples were seen which make the link between optimisation on the object and increasing resilience on the network level. Error! Reference source not found. illustrates the current understanding on this topic.

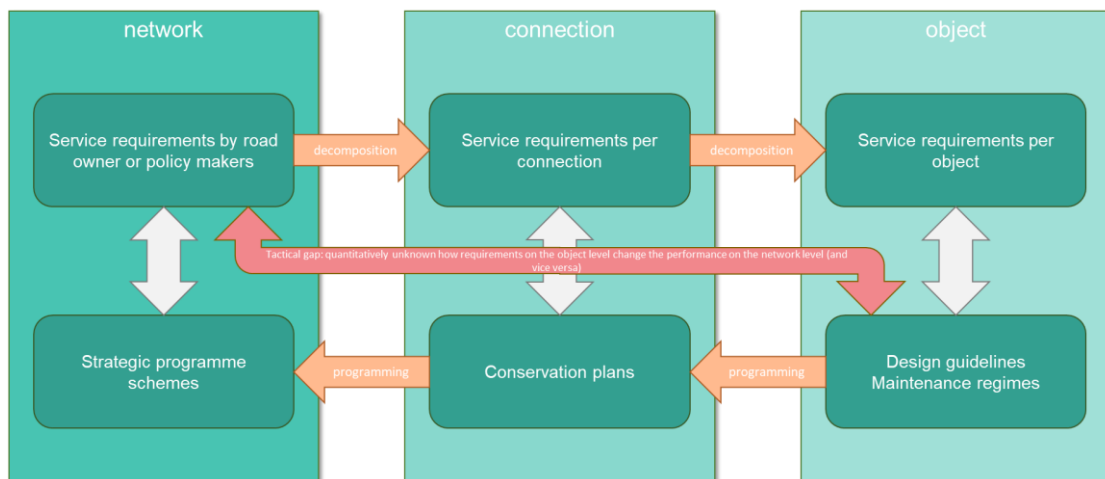


Figure 3 Line of sight for resilience assessment across different levels, introducing the tactical gap.

Development gaps

There are many 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 a need to understand which service level metrics can be applied. The formal guideline CEN CWA 17819:2021 ("Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events") 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 to advance resilience thinking in the face of climate change. Current guidelines also seem to provide limited information on reducing social vulnerability in line with resilience thinking. This also leads to a further gap associated with combined consideration of various service level metrics across different return periods of hazards and 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.

2.2.4 Deliverable D2.2 Guidelines on using performance metrics to make the case for adaptation

While the significance of resilience and climate change adaptation is well understood, practical implementation remains a challenge. Integrating climate change adaptation into decision-making processes can be complex, often resulting in a gap between knowledge and action. To bridge this gap, it is essential to determine how resilience and adaptation options can be effectively expressed to facilitate decision-making.

Deliverable D2.2 serves as a guideline for NRAs on using performance metrics to make the case for adaptation. Within the deliverable the link between KPIs, benefits, and co-benefits of adaptation is explored, ultimately describing how to operationalise these within a decision-making context. By effectively expressing and evaluating adaptation strategies based on the existing decision-making context at NRA's, the decision-makers at those NRAs can optimise their efforts to build resilience and foster a more sustainable and resilient future.

The decision-making process at NRAs is multidimensional and is done via different steering mechanisms; sometimes decisions are made via guidelines and design standards (often at asset scale), whereas other decisions are made via KPIs (which are described mostly at a network scale). The challenge of implementing climate change adaptation options within these decision-making processes of NRAs is complex due to the existence of a tactical gap:

- It is not well understood how changes in guidelines and standards lead to different performance in terms of KPIs.
- The effect of climate hazards and climate change on KPIs is not well understood, further complicated by external factors like societal changes.
- There is limited understanding of how the effectiveness of adaptation options can be measured in terms of performance and changes in KPIs.

This is further complicated by boundary conditions which need to be clarified and specified before decisions can be made. These boundary conditions include:

- Temporal and spatial scope: e.g. what is the time horizon the NRA aims to make the decision on and what is the spatial extent?
- Data examination: e.g. the quality and accuracy of the data should be validated to determine which approaches can be used to perform resilience assessments and approach for the appraisal of adaptation options.

- Capacity and resources within and outside the NRA e.g. what is the proposed budget, and are all human resources available and is all expertise in-house?

The guidelines developed provides recommendations to overcome this tactical gap. The central theme in these recommendations is the differentiation between benefits and co-benefits that link to the decision-making context of NRAs and KPIs in particular. The metrics used for KPIs, policies and other indicators are often not suitable for assessments of adaptation options, and thus need to be converted to a more applicable metric to be used in the evaluation of adaptation options. As a result, the guideline recommends the use of benefits and co-benefits rather than KPIs.

Climate change adaptation options often yield co-benefits that extend beyond their primary benefits, positively impacting multiple sectors and stakeholders or society and the world in general. Understanding and valuing these co-benefits is essential to maximise the efficiency and effectiveness of climate change adaptation strategies. Since many NRAs are not allowed to invest for objectives beyond their service level agreement, it is key to link all co-benefits to existing policies and KPIs.

The key recommendations of the deliverable are outlined below.

1. Key recommendations for influencing decision-making at NRAs:
 - Have a clear understanding of steering mechanisms which play a role in the NRAs and what are the key decision criteria NRAs use.
 - Develop an approach to link the input-based (often asset-focused) indicators with the output-based (often network-based) KPIs by quantifying these.
 - Identify dose-effect relationships for adaptation options, i.e. the effectiveness of a measure to reduce the impact of extreme weather events.
 - Consider effective communication across the different levels of steering mechanisms and decision-making due to the differences in metrics for estimating performance of the road.
 2. Key recommendations for using performance metrics for making the case for climate adaptation:
 - To make the translation from KPIs to, and use of, benefits and co-benefits:
 - i. Identify the relevant decision criteria for the NRA, based on the list of KPIs, other policies and other indicators.
 - ii. Translate these criteria to benefits and co-benefits.
 - iii. Identify a feasible metric (that is similar to or at least correlated to the metrics used for the KPIs) that can be used to assess and quantify the benefits and co-benefits.
 - To make most use of KPIs in the context of climate adaptation, it is recommended to adjust the KPI thresholds:
 - i. To ensure that unforeseen and/or extreme events such as climate hazards are adequately included in the performance measurement. When climate hazards are not expressed in the KPIs, the rationale for climate change adaptation is difficult to make.
-

- ii. To ensure for an appropriate spatial scale, often at connection level (or even to the asset level for critical assets).
 - iii. To consider KPIs for specific seasons.
3. Key recommendations for gaining insight in the value of adaptation options:
 - The application of valuation methods will always be associated with some uncertainty. The accuracy of applying a measure should be determined based on the level of detail needed to be sufficiently informative in the specific context and the number of available resources. This trade-off between needed level of detail and resources used should always be considered carefully.
 - It is generally recommended to consider the magnitude/importance of the expected benefits. Whether a benefit is considered significant or not should go into the consideration given to the level of detail needed. Benefits that are expected to influence decision-making should in general require more scrutiny than benefits that are expected to influence decision-making to a lesser extent.
 - Carefully consider what the relevant baseline should be, before starting to assess the expected benefits. Choosing the right baseline scenario will be vital in terms of not only the results, but eventually also the context in which these are applied.
4. Key recommendations for making the case for adaptation: three approaches are recommended to facilitate the decision making. These approaches are visualised in the scheme below.
 - Approach 1 involves gaining insight into the effects of climate hazards on road performance by analysing trends in KPIs and their correlation with climate threats. This understanding helps determine the need for adaptation and future performance changes.
 - Approaches 2a and 2b focus on changing guidelines and standards to incorporate climate adaptation. The former aims to maintain current performance, while the latter involves optimising performance by evaluating costs, benefits, and co-benefits associated with guideline changes.
 - Approach 3 addresses the need for adaptation on a project-specific basis, considering factors such as political concerns, past climate events, and stakeholder involvement. Applying approach 3 can also serve as a basis for optimising guidelines through approach 2b.

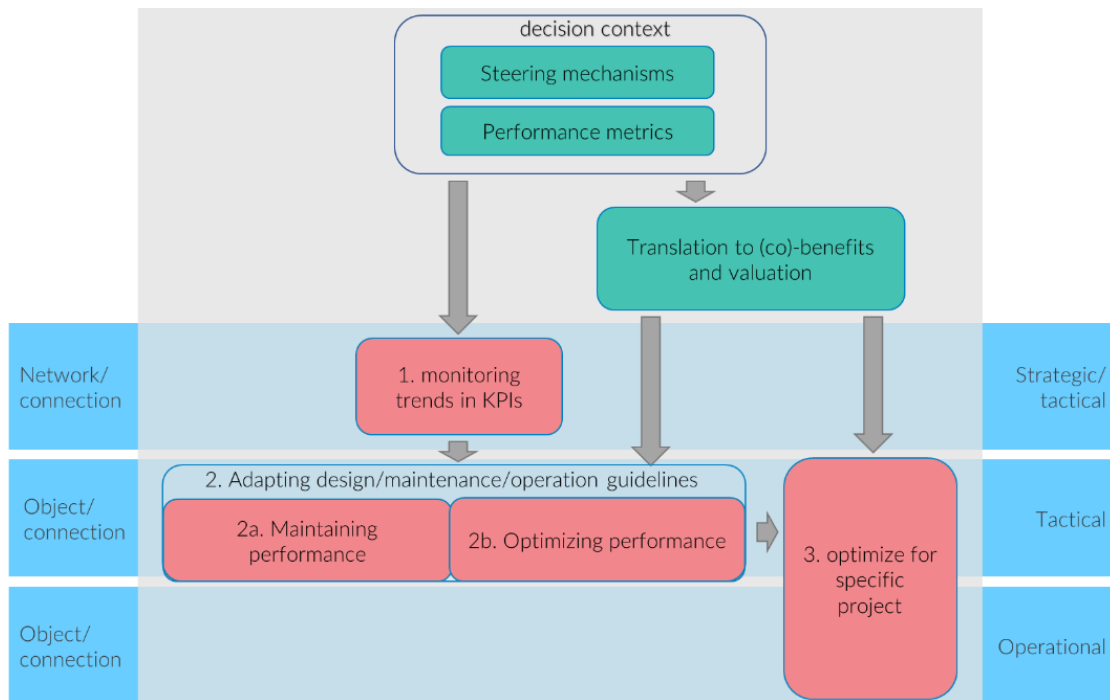


Figure 4 Visualisation of the recommended three approaches to make the case for adaptation and facilitate decision making

2.2.5 Deliverable D2.3 Guidelines providing an overview of and characterisation of adaptation options, with recommendations on implementation

It is widely acknowledged that there is a growing need to adapt infrastructure to the differing and increased threats that climate change brings. Road authorities in Europe face increasing pressures with ageing infrastructure, growing populations, and increased traffic numbers and traffic loading on their networks, with minimal increases to budgets. In addition, climate change brings increased frequencies of extreme weather events, increasing risk to road infrastructure.

Deliverable D2.3 provides guidance to road authorities on how to implement climate change adaptation measures and is accompanied with the [Adaptation Options Database](#). In the spreadsheet a wide variety of adaptation options including NbS is provided, and emerging technology solutions, which can be implemented at all stages of the project life cycle, for any or all asset types, at an object, connection and/or network level, to increase resilience to specific climate impacts. Guidance on how to select the most appropriate climate change adaptation options is provided, along with a review of gaps and barriers to implementation of adaptation. Key challenges for road authorities in implementing climate change adaptation have been identified through workshops and literature review as a lack of information and data, lack of resources, both financial and skills, and provision of incentives for organisations to act. Solutions are proposed to these barriers, using emerging technologies where appropriate. Finally, guidance is provided on how adaptation may be implemented at an organisation level in NRA processes.

An adaptation implementation process (see Figure 5 below) has been developed through which NRAs of different organisational maturity can progress from awareness of the requirement to protect their infrastructure against extreme weather and climate change, to implementing climate change adaptation in practice, either at an asset management level or an individual project level. Some NRAs may have a specific project in mind when starting the framework, whilst others may wish to raise their organisational awareness. The route through the framework will differ if concentrating on a project or the entire network.

The process indicates at which level or combination of levels (strategic, tactical and operational) at the NRA should be involved at each stage. It also details where expert input is required.

There are five building blocks (awareness, decision context, resilience assessment, adaptation plan and implementation in practice) within which there are individual stages. As NRAs progress through the stages, there are a series of 'yes/no' gates, where the NRA either moves along the process or reevaluates requirements. In some cases, resources (internal or external) may not be available to move immediately to the next stage, or the case might not be made to move the next stage. In such cases, there are loops to revisit previous stages, so there may be progression in the future, or if the decision contexts are changed.

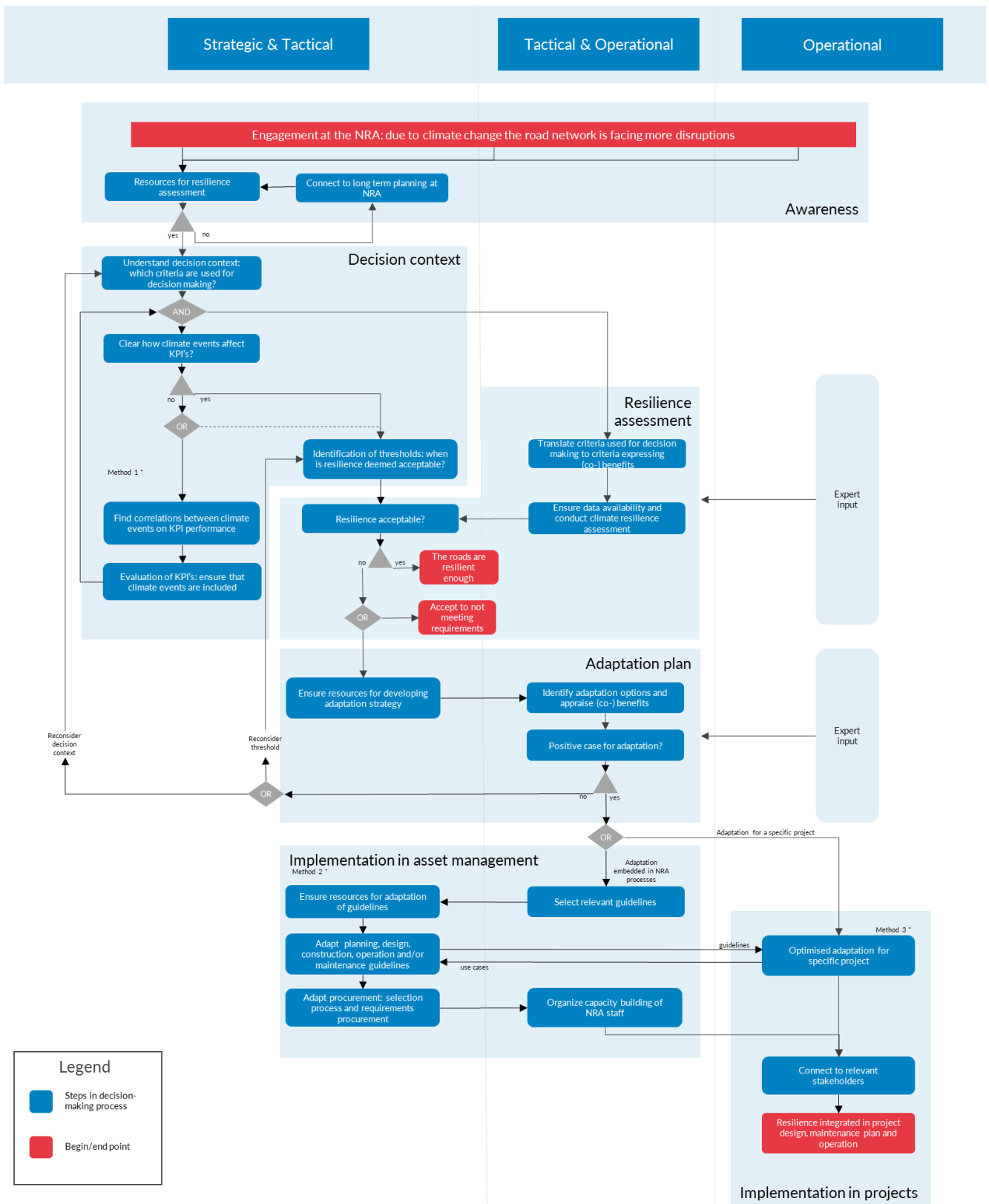


Figure 5 the ICARUS adaptation implementation process framework

The key takeaways for implementing climate change adaptation are outlined below:

1. To ensure that climate change adaptation finds its way in the daily processes of NRAs, many different NRA staff members have an active role and different layers of the organisation need to be involved and should be engaged. This ranges from continuous shifts between high-over strategic decisions at the strategic level, practical assessments at the tactical level and practical key input from the operational level. Engagement at all levels is a prerequisite for successful implementation. It is recommended to have one person in charge of streamlining the entire process between the different levels of the NRA. Depending on the organisation of the NRA, this can be on different levels. In general, we deem it most effective when an NRA staff member, with a task in the field of climate change adaptation at the tactical level, takes the leading role. This person should be able to interact clearly with the other two levels.
2. Linking with the decision context of the NRA and the policy makers is of critical importance. It's a pitfall to start with a resilience and adaptation assessment right away. Ensuring decision making requires that the resilience assessment is designed such that the results make sense to the decision makers. Resilience and adaptation frameworks are abundantly available. It is key that the use of these frameworks is tailored to the typical decision context of the NRA. This decision context includes the steering mechanisms and the criteria that are used for decision making. Customised resilience and adaptation assessments will produce outcomes that will push the right buttons for decision making.
3. Implementation may take place via two routes, which are interlinked. One route is via adapting the asset management which eventually will lead to an uptake of adaptation in all processes of an NRA. The other route is via implementation at an individual project level. Both approaches strengthen each other. Insights gathered at the project level will inform the process of adapting the asset management via changing the planning, design, construction, maintenance and operational guidelines.
4. Research may be necessary to understand how climate change may impact the KPIs that are used for monitoring the performance of the road network. If climate events, let alone climate change, are not reflected in the KPIs, it generally won't be possible to make a case for adaptation, since climate events won't lead to a lower measured performance of the road. When it is not understood how climate change affects the performance of the KPIs, it won't be possible to underline in the resilience assessment how climate change will lead to a lower performance.

2.2.6 Deliverable D3.1 Current evidence-base of using cost-benefit analysis for assessing road infrastructure projects within the climate adaptation regime

The ICARUS project, framed within the CEDR Transnational Road Research Programme, aims at developing knowledge products for the integration of climate resilience into decision-making processes, as well as implementing existing resilience thinking and research into practice within the NRAs. The expected outcomes of the project are linked to the reduction of disruptive impacts of climate hazards on existing (and planned) road infrastructure. It is within this context that this report studies economic appraisal/evaluation methods grouped

under three major streams: traditional economic decision support; uncertainty framing; and economic decision-making under uncertainty. Specifically, the report focused on Cost-Benefit Analysis (CBA) as a dominating tool supporting decision-making in the road infrastructure sector. Other approaches such as Multi-Criteria Analysis (MCA) were also analysed.

The deliverable identified key knowledge and implementation gaps on the links between CBA, climate resilience and road infrastructure, based on a state of the art literature review and a state of practice assessment, including insights collected through participatory workshops with NRAs. The key gaps identified can be summarised as:

- The use of economic appraisal methods dealing with climate uncertainty within NRAs is limited.
- It is uncertain to what extent NRAs are making use of 'hybrid' approaches combining CBA and MCA, and how this enables inclusion of the three key adaptation themes outlined in this report (uncertainty, valuation, and equity), as well as inclusion of co-benefits.
- Life-Cycle Costing (LCC), or variations of LCC, seem to be preferred by NRAs to a certain extent, as it's considered an easy and straightforward method to apply, especially when quantifying costs and linking the results to development of policies. The state of the art and state of the practice, however, do not show this, with CBA and MCA being more predominant.
- It is not clear how NRAs are dealing with co-benefits when developing CBA. The report outlines specific adaptation-related valuation methods which help in capturing those intangible benefits, but it is uncertain to what extent the NRAs are working with this.
- The dynamics of decision-making within the NRAs need to be properly understood, to better tailor the development and outputs of ICARUS. The literature review did not reveal particularly strong decision-making levels within transportation agencies or road organisations. Moreover, the workshops did not give a clear picture either, and the interface between the asset and operational level was not clear.
- Inclusion of and engagement with stakeholders as part of the decision-making process of the NRAs needs to be looked at in more detail.

The main learnings from the State of the Art

From the different socio-economic appraisal methods outlined in the deliverable, what dominates the scientific literature is primarily the development of CBA studies and frameworks, but with different variations/additions to a traditional CBA, incl. a 'hybrid' approach combining MCA and CBA and an increasing trend to account for climate uncertainties and equity considerations. Using MCA and CBA allows inferring high flexibility to the process, which is very positive especially when considering uncertainties and context-led constraints through multiple and different stakeholders.

Even in contexts where CBA is a well-established decision-support tool, investment decisions are often strongly influenced by other political preferences or decision-makers take an

approach whereby criteria is handled through non-monetised ways despite those criteria being included in the CBA. Hence, there's an indication that a 'hybrid' approach combining CBA and MCA can help in making decision-makers' preferences more transparent and streamlined by explicitly including all decision factors and thus establishing a strong link between policy objectives and appraisal results while still providing information for cost-efficient investment decisions.

The use and link of CBA to support decision-making linked to climate change adaptation measures has increased notably in the last 3-4 years. Although the use of CBAs has increased, resulting in benefit-cost ratios for various adaptation measures on the asset level of the entire road network, it has not yet led to strategic decisions on possible changes of design and maintenance guidelines. This exemplifies the importance of considering the level at which decision-making takes place within a NRA, as it affects the practical implementation of business case development and CBA particularly.

The deliverable argues that the discount rate is the important parameter affecting the decision-making when performing a CBA. An overview is presented of discount rates used across geographies. There seems to be no consensus on discount rates in the context of climate resilience. A common recommendation is to perform trial-and-error using sensitivity analysis with different discount rates. Furthermore, the deliverable provides an overview of a few holistic frameworks recently developed to address the business case for resilience, linking CBA and resilience in more depth and addressing key issues like climate risks, uncertainties, data, asset management, KPIs and sensitivity analysis.

Finally, the deliverable presents descriptions of the non-tangible, indirect benefits of adaptation measures, i.e., the co-benefits (also referred to as externalities) that provide an added value beyond the primary value given by an adaptation solution. Co-benefits are important drivers linked to the improvement of resilience but are not always easy or possible to quantify or monetise. These indirect effects can be environmental and social and represent an important category of benefits that result from redesigning or relocating transportation facilities or investing in protective features to improve resilience, for example through implementing NbS.

State of the Practice

The state of the practice presented in this report builds on three pillars:

- i) The key outputs and takeaway messages from three stakeholder workshops with NRA's.
- ii) A collection of industry-led examples on the framing and use of CBA.
- iii) A brief overview of the practice of combining CBA and MCA methods.

The key takeaway messages from the stakeholder workshops with NRAs are:

- LCC, despite not being the most used method by participants, captured many discussions and was highlighted as being easy and straightforward to apply, especially when quantifying costs and linking the results to development of policies.
- Following on the above, LCC showed to be used for Carbon Appraisal assessments at strategic level, expanding the original scope to something more in the direction of Life Cycle

Carbon Analysis throughout the entire supply chain of a railway authority in the UK, effectively linking Resilience and Decarbonization. Issues like whole-life carbon and embodied carbon were mentioned.

- The divisions by level seemed not to be as cemented as expected. Especially the interface between asset and operational level was somewhat blurry.
- One comment during the discussions was that the size of the investment (overall) determines the type of economic evaluation method used, by large.

The various case studies offer examples of how CBA is being used to support decision making within the transport, built environment and water utilities sectors.

- The DoT Oregon case demonstrates why cost-benefit analyses are better in building the business case for climate adaptation compared to an evaluation of cost-effectiveness
- The use of CBA analysis within the Buzzard Point masterplan highlights the importance of incorporating co-benefits into the CBA
- The example of CBA use within the Danish water utilities sector details the approach by which utility companies ensure only cost-effective projects providing appropriate service levels receive investment.
- The use of both CBA and MCA analysis in the case of investment decision making in a new highway in northern Italy highlights the differences in outcomes with each method and promotes the use of a combined method to ensure robust and rational choices for highway development.
- The overview of the combined CBA and MCA approach outlines the inter-disciplinary expertise required in climate adaptation (and specifically flood risk) CBA analysis. It also highlights best practice in involving the CBA team early on and consistently throughout out the design and evaluation process.

2.2.7 Deliverable D3.2 Demonstration report showing how principal adaptation measures can be evaluated

While the significance of resilience and climate change adaptation is well understood, practical implementation remains a challenge. Integrating climate change adaptation into decision-making processes can be complex, often resulting in a gap between knowledge and action.

This report supports the implementation of climate change adaptation within NRAs processes by **providing practical guidance on what the implementation of adaptation means in practice**. This is done by case studies and practical examples in which we demonstrate how the approaches, as described in earlier deliverables within the ICARUS project, can be executed and used. The practical examples start when the outcomes of the resilience assessment indicate that the performance of the network is not meeting the requirements and what steps need to be taken to demonstrate the adaptation.

This deliverable demonstrates:

The application of 10 key adaptation measures with clear descriptions regarding (i) guidance on their implementation, (ii) how costs, benefits and co-benefits can be valued and (iii) best practices.

A case study on how to define optimum service levels for suitable adaptation options, based on cost-effectiveness analysis. For the selection of cost-effective adaptation options, it is determined how these can be appraised to achieve the requirements for the performance of the network. The example makes use of minimum service levels for evaluating resilience and adaptation options based on quantification and valuation of associated costs and co-benefits. Difficulties for implementation include dealing with uncertainties (e.g. time horizons, different climate scenarios and uncertainties in economic valuation). It is recommended to consider these uncertainties by describing these or combining this with decision-making under (deep) uncertainty approaches.

A demonstration of the use of the implementation process diagram, as developed in Deliverable D2.3. This diagram takes the users through a process of becoming aware of the need to consider climate change adaptation in their processes, how the decision will be made in terms of the criteria being used, undertaking a resilience assessment, and if the roads are assessed to be not resilient enough, to undertake an adaptation plan and implement it in their asset management processes or at a project level.

An overview of barriers and ways to overcome these barriers. Depending on the organisational maturity in regard to climate change resilience assessment and adaptation, there will be various barriers to implementation. These generally fall into four categories:

- Lack of information: this can include a lack of awareness on what impacts climate change and extreme weather events could have on the road network, how this could affect individual assets and network performance in general. Following on from this, there is also a lack of information on how climate events will affect the organisational KPIs (for example, availability or safety).
- Lack of resources: this is a key issue for all NRAs and falls broadly into two key areas, lack of skilled personnel within the organisation and/or a lack of funding. In terms of a lack of funding, this can limit the ability to bring in external experts to support the organisational objectives and increase organisational capability.
- Organisational barriers: particularly where there are lower levels of organisational maturity regarding embedding climate change assessment and adaptation, there can be a lack of engagement and potentially a lack of buy-in at various levels within the organisation. This, in turn, leads to a lack of strategic planning.
- Procurement challenges: NRAs often have procurement processes based on traditional methods of construction, operation and maintenance. These are not always immediately compatible with requirements to undertake climate resilience assessments and adaptation measures. This is particularly the case if, for example, an adaptation measure is best served by an off-highway nature-based solution.

Recognising the challenges outlined above, the ICARUS project proposes measures to address them in Deliverable 3.2. At its core is targeted communication at a level appropriate to both the level of organisational maturity and at different levels within the NRA.

By introducing 3 levels of organisational maturity, the implementation process also recognises that not all NRAs will be at the same stage of thinking in this area:

- Getting started – at this stage, the message will be around awareness raising and seeking a budget to undertake a resilience assessment. This relates to Stage 1 on the Implementation Process.
- Embedding process – here, a resilience assessment will have been undertaken and adaptation options explored. In this Stage 2 of the Implementation, the focus will be on making the case for adaptation.
- Processes embedded – at this point, resilience assessments and adaptation plans will have been undertaken, and the focus will be on knowledge sharing and promoting good practice and making this business as usual.

Effective communication is also addressed. The implementation process identifies that some aspects will be driven by the strategic and tactical areas of the NRA, some by the tactical and operational areas, and at a project level, solely at an operational level. As such, the level, detail and message need to be tailored to the audience. The directors at the strategic level will need to understand how climate change might affect the network and the organisational objectives – effective communication at this level can help set the strategic direction of the organisation and help achieve buy-in at other levels. Those in the tactical level need more detailed information regarding the processes and how to embed resilience into organisational processes, whilst those at the operational level need practical guidance on how to undertake new construction and maintenance processes.

Deliverable 3.2 also suggests potential means of communication, which include heat maps and traffic light coding to demonstrate critical hotspots or critical climate impact drivers. Impact chains could be used to demonstrate the connection between climate change and the impact on road infrastructure. Storytelling and narratives were identified as a potentially useful way of visualising the impacts of climate events and identifying adaptation options.

Furthermore, practical guidance regarding the communication of the results is given. Within the NRA, three different audiences have been identified previously and are included in the implementation plan; these are strategic, tactical and operational. The key objective is to ensure that there is awareness of the ICARUS project, the resources available and links to other resources (e.g. previous CEDR projects, PIARC, national strategies). The different audiences should be involved at the different stages of implementation and by making use of different means (such as narratives/storylines, good visualisation and access to the different data sources regarding the resilience assessment as well as the effect of adaptation options).

2.2.8 Deliverable D4.2 Nature-based Solutions Report

This deliverable introduces the concept of NbS as an adaptation option for road infrastructure to increase resilience to climate change. It provides NRAs a way to assess NbS as an adaptation option, as NbS are gaining recognition in the infrastructure sector and offers an

opportunity to leverage natural systems to provide resilience against climate change impacts, while being cost-effective, enhancing multiple benefits and providing flexibility.

NbS is a relatively new concept in the context of road infrastructure, and several definitions of the concept are introduced in the report. The European Commission defines NbS as *'solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience'*⁵. This definition underscores an integrated approach while emphasising building resilience and providing systemic benefits. NbS can be viewed as an umbrella concept for several other concepts such as Green Infrastructure.

NbS have not been widely adopted in the road sector and in traditional road asset management, environmental aspects such as biodiversity have not been given a high priority. When facing societal challenges, asset owners and managers need to develop new solutions. Understanding the value brought about by implementing NbS is one way to address the challenges.

When considering NbS, the engagement should be more extensive with some stakeholders than when considering grey infrastructure. The stakeholders include, amongst others, NRAs, consultants and contractors, environmental authorities, local authorities and municipalities and landowners. By fostering inclusive decision-making processes and leveraging local knowledge, expertise and resources, collaboration and participatory planning enhance the effectiveness, equity, and sustainability of NbS. Individual stakeholders have different views on implementation of NbS and one significant issue is collaboration with stakeholders that own or use the land adjacent to the roads. NbS may take more space than grey infrastructure, while the NRAs usually manage only the space reserved for the road itself and its immediate surroundings. Therefore, it is important to plan and implement NbS with e.g., landowners. On the other hand, one special aspect of NbS is collaboration with stakeholders and inclusion of local communities, which means that the discussions and negotiations are an essential part of implementing NbS.

Climate change poses several challenges to the design and implementation of NbS. NbS often rely on ecosystem-based approaches, however, ecosystems are complex and dynamic systems that can be affected by climate change-induced stressors, which may undermine the effectiveness of NbS and require adaptive management strategies. Climate change adaptation and mitigation strategies in the road sector should consider cross-sectoral linkages, synergies, and trade-offs to optimise co-benefits and minimise unintended consequences.

Within ICARUS a key focus area is to provide road authorities with a selection of adaptation options, guidance on choosing the most appropriate options for their infrastructure, and guidance on how to implement adaptation. An Excel database of adaptation options has been developed as part of this project, as presented in Deliverable 2.3. The adaptation option

⁵ [Nature-based solutions - European Commission](#), accessed on 1-5-2025.

measures are classified according to the definition of NbS by the European Commission, the classification being 'Yes', 'No' or 'Potential'. As there is some ambiguity to the extent to which a measure is a NbS there is a degree of subjectivity in the characterisation of the measures in the database. This means also that some measures may be considered as NbS if there is sufficient focus on maximizing the green aspects. In the implementation of NbS there must be space for innovation, flexibility and adjusting the measures so that they can be adapted to local conditions and situations. The benefits related to nature and environment are expected to be positive for NbS and in many cases, NbS is required to ensure realisation of co-benefits.

It is recognised in the deliverable that there are both drivers and barriers for the implementation of NbS. The drivers include answers to societal challenges, e.g. providing carbon storage and mitigating greenhouse gas emissions, contribution to biodiversity net gain and providing ecosystem services. Barriers on the other hand include lack of resources, lack of information and uncertainty to climate change, organisational engagement and lack of longer-term planning in climate change adaptation.

The deliverable further presents guidelines for implementation of NbS. The most important elements to consider for implementation of NbS are getting buy in from the organisation, involvement of stakeholders and local communities, including maintenance as an essential part of the planning process, monitoring and detailed design specifications. The guidelines and the NRAs increasing embracement of sustainability along with funding depending on sustainability goals can help lower and overcome the barriers of NbS implementation.

The deliverable underlines that understanding and assessing the performance of NbS is crucial for mainstreaming NbS into regulations, guidelines, and plans. Key performance indicators are valuable for NRAs to measure progress and steer decisions. KPIs thus play a key role in the decision making of NRAs. This means that, while assessing the NbS adaptation options, it is of high importance to link the assessment criteria to the KPIs as much as possible. In general, it is easier for the NRA to make the case for implementation of adaptation options when more positive effects are linked to KPIs. Depending on the design choices made for adaptation options, co-benefits may be maximised and thus aid in making the case for implementation. Integrating NbS into adaptation strategies can bring about multiple co-benefits beyond the primary benefits. Including co-benefits in a cost-benefit assessment provides a better understanding of the full effects that climate adaptation options introduce, in addition to the expected primary benefits linked to KPIs. A list of benefits likely to be associated with options for climate adaptation and resilience including NbS options is presented in this deliverable.

Valuation of costs and benefits provides a way of evaluating different options in decision making. The comparison of costs and benefits of implementing adaptation options or resilience measures provides a transparent way of considering different alternatives. Benefits of NbS and other adaptation options will often be defined as either tangible or intangible concerning valuation. The benefits linked to NbS adaptation options are often intangible, hence, there is no universally adopted approach to measure and quantify these in valuation. ICARUS suggests a four-step staged method for applying valuation in decision-making

contexts. This approach also covers valuation of NbS adaptation options. While all benefits listed in the deliverable may materialise through the implementation of NbS, some socio-economic and environmental benefits are linked to the effects of nature and will likely only be present if an NbS is chosen as the adaptation measure for implementation. Examples of these benefits are e.g. ecosystem services, water quality, and health effects.

Finally, the deliverable presents a fictitious case study demonstrating the evaluation of an NbS adaptation option. The NbS evaluation option is assessed through the NRA's KPIs and potential benefits and co-benefits are identified. Two different service levels are defined to identify the optimum level. In the case study, costs and benefits for the NbS adaptation option are quantified. The case study shows an example of how the NbS adaptation can be assessed through KPIs and how value can be determined for the benefits and co-benefits.

2.2.9 Deliverable D4.3 Resource Training Package

A key requirement of the ICARUS project was that the results needed to be implemented in practice and not exist merely as research papers. Experience within the project consortium with similar projects, recognised that there were several levels with NRAs that needed to be targeted to ensure implementation. The different NRA levels, as introduced in D1.2, involve different stakeholders:

- The Strategic Level – the directors who set the strategy and direction of the NRA
- The Tactical Level – the technical staff within the NRA who implement the strategy in practice
- The Operational Level – the ‘boots on the ground’ who design, manage and maintain schemes at an asset level.

It was also recognised that the level of information required, and the level of engagement would differ, and the message has to be shaped accordingly. Those at a strategic level need to understand the key issues and how climate change risk and adaptation relate to the organisational objectives. Those at the tactical level need more detailed information on the technical aspects and how to translate these into the day-to-day management of the network.

These were addressed in the delivery of a training package on the ICARUS website that provides videos of presentations given online, supporting .pdf slides and Frequently Asked Questions as well as Quiz questions to test knowledge. For all but the introduction to the project and the understanding of climate change and roads (1.1), two sets of presentations and supporting slides are available: a detailed one for practitioners and a summarised version for decision-makers. The specific items covered are:

- Introduction to the ICARUS project;
- 1.1 Climate change and roads
- 1.2 Introduction to resilience concepts
- 2.1 Impact chains, vulnerability and hazard classification
- 2.2 Understanding the NRA decision context

- 2.3 Making the case for climate adaptation
- 2.4 Process on implementing climate change adaptation
- 3.1 Climate change adaptation options
- 3.2 Nature-based Solutions

More detailed information on all the aspects covered in the videos and slides can be found presented in the reports also available on the ICARUS site, and these are signposted for those who wish to gain a more detailed understanding of specific aspects of the project.

3 FINAL ICARUS EVENT

On Monday 16 September and Tuesday 17 September 2024, the final event of the ICARUS project was held in Delft, the Netherlands, at the main office of Deltares. During these two days, a wide group of NRA stakeholders was present to learn from the project's findings and reflect on the content.

The final event aimed at both presenting the key outcomes of the project, as well as providing a training to the participants. The first day started with a long presentation about the entire project results. This was organized as a hybrid session with both live and online participants. This presentation was followed with in depth more detailed introductions to key outcomes, each combined with a training linked to a case study and discussion between participants and the ICARUS consortium. The list of participants and the agenda of the event are listed in Annex A and B. The main discussion points and reflections are summarised below.

3.1 Adaptation implementation process

The adaptation implementation process was presented, after which a discussion was held linked to quiz-questions to test and explain how the different steps in the process should be used to ensure implementation of adaptation. Participants found this part of the event challenging but understood the importance of tailoring resilience and adaptation to the decision context. Key Performance Indicators that are used for decision making were understood to be very important in that respect. The main takeaways from the discussion around KPI's are that the requirements for a resilience and adaptation assessment should align with the KPI's. If KPI's were not achieved, their relevance could need reassessment. An element that could be added to the implementation process is an explicit go- no go moment referring to the decision to accept to do nothing if requirements were not reached.

3.2 Impact chains

After a short introduction to impact chains, the participants were challenged to create their own impact chains. While doing so many interesting discussions were being held. In addressing impact chains, it's crucial to distinguish between hazards and impacts to identify appropriate adaptation options. The process to these options involves many steps and stakeholders that are often overlooked. Societal impacts in the impact chains are also road user experience, sustainability, health, and safety. Also the positive influence on accessibility should be considered. As a visual and analytical tool to identify critical links in the system it helps organisations to permeate the concept of resilience and therefore needs everyone's participation. It can be used for inspiration, to better understand how the road system functions and to focus more detailed assessments when necessary. Discussions arose on the definitions used for exposure and vulnerability. It became clear that in the end these discussions should not be in the way of having the right analysis; it is probably better to just choose one definition, rather than to get stuck in a definition-discussion.

3.3 Adaptation options database and evaluation of adaptation options

The database was very well received by the participants. A good aspect of the database is that it allows for flexible use and can be adapted to specific needs of the user. For instance, if threats are lacking, these can be easily added. It was noted that the adaptation options database is not exhaustive and may be customised for each jurisdiction. A recommendation for extending the database is to differentiate between the short-term (disaster) versus long-term (climate) adaptation options.

To choose the best options the organisational priorities and process considerations are important. Evaluation of the methods can be done using a cost benefit assessment. Participants reflected that the training was very useful in addressing the need to go through all steps for climate adaptation and to base decisions on benefits and co-benefits that are linked to the decision context.

3.4 Nature-based Solutions

This part of the programme was introduced with a presentation after which a case study was followed to have specific discussion on NbS implementation. The ICARUS recommendations were thought to be very helpful to consider NbS besides other options. At the same time the discussions made very clear that when considering co-benefits of NbS, these oftentimes fall outside the jurisdiction or prime objectives of the NRA. This then often means that NbS are even not allowed to be considered. Another important remark made was that not only asset managers should be involved, but a larger set of stakeholders who might benefit from NbS such as landowners, other road owners, citizens or road user/industry groups.

In general, NbS are easier to implement in specific projects rather than to embed them in guidelines. However, if it is implemented in specific projects and well evaluated, it can end up in guidelines. Linking the NbS to the KPI's can improve the uptake of NbS.

3.5 General comments

The ICARUS project was very well received by the stakeholder group and discussions with the NRAs were enjoyable and practical. There clearly was one key learning point for all participants, which was the importance of understanding the decision context and how KPIs steer decision making. Only when that is clearly understood, adaptation can be implemented in the daily processes of the NRA's. Another evident insight for many participants was the presence of the tactical gap and the need to close it.

The participants stated the following key lessons and insights from the ICARUS project:

- Establishing the link between the existing decision context with the resilience and adaptation assessment is key for implementation. Or in other words: the bottleneck in climate change adaptation is organisational rather than technical.
- Expressing resilience criteria (benefits and co-benefits) needs to be done in relation to the KPI's that are used as well as other decision-making criteria. Using co-benefits in the cost benefit assessment can greatly facilitate the case for adaptation.

- It is important to understand how climate change impacts the KPI's that the NRA is using. Without this basic insight, it will be difficult to ensure engagement of all managerial levels.
- Cost benefit assessments are key to show the effectiveness of adaptation measures.
- The tactical gap, showing that it is not well understood how changes at the asset/object level will change the performance at the network level, is a key challenge that needs to be solved. This will also enhance other decision making at the NRA's.
- It is important to be pragmatic, rather than to try to solve all theoretical issues first.

The following feedback about the program of the final event was provided:

- The presentations and training made clear what needs to be done and who needs to be informed. However, time is needed to digest all materials that have been introduced and discussed before one is able to really execute the steps.
- The programme and structure of the final event was well received. Especially the short theoretical introductions, followed by practical case studies, lively discussions and quizzes made it a very well thought out programme with lots of insights that could be absorbed
- The training provided clear explanations. Now the next steps need to be identified. The resource training package was deemed to be interesting in that respect.
- The first day of the programme was a bit overwhelming, but the second day revealed that it was really nice to see how all pieces of the puzzle came together.

The following lessons learned about the ICARUS project were discussed:

- It is apparent that there is a good scientific base, while the outcomes are not too theoretical but seem implementable. The key message could however be explained in a more easy way to really make sure that it comes across at the strategic level of NRA's.
- Climate mitigation should not be overlooked. In one of the examples carbon capture was identified as a co-benefit of adaptation. This could just as well be the other way around, where climate adaptation can be seen as a co-benefit of some mitigation measures.
- A lot of lessons are also interesting to other transport sectors, for example for railways.
- Although the NRA attendees present were engaged in climate adaptation, they sometimes struggled to get organizational buy-in. However, it became easier if adaptation and/or more resilient infrastructure were key strategies for the organization. This is a barrier that is not easily overcome.
- There seems to be a general lack of practical ready-to-use guidelines on assessment of climate adaptation measures, which makes it difficult for NRA staff to argue for implementation. The general agreement was that the ICARUS project addresses this gap and will be very helpful.



Figure 6 impression of final event

4 CONCLUSIONS AND RECOMMENDATIONS

Based on the research conducted in the ICARUS project, as outlined in the various deliverables, the following main conclusions/recommendations can be made related to the prime ICARUS objective, which is about ensuring the implementation of climate change adaptation in the daily processes of road authorities.

4.1 Good resilience frameworks exist, but need practical use

Based on the three baseline reports, the following conclusions can be made:

1. Plenty of well documented resilience assessment frameworks exist, as well as guidelines and approaches for appraisal of adaptation measures for climate adaptation. Also, tools are available that can be used to assess resilience and adaptation.
2. However, integrated use of the frameworks in decision making processes of road authorities is limited. Oftentimes, the evolution of service measure loss over time is not considered. Also, the outcomes of the resilience assessments are not linked to the key decision-making criteria (KPIs) of the NRA. This makes integrated decision making on climate change adaptation complicated.
3. Within NRAs, the use of economic appraisal methods for assessing effectiveness of adaptation options is uncommon.
4. When economic appraisal for adaptation options is being used, benefits are usually expressed in damages and losses, but co-benefits including carbon, biodiversity effects and equity are often not considered. This is a missed opportunity as it may enhance the decision case of adaptation.

Within ICARUS we have provided several outputs that elaborate on these existing frameworks and can be used as key input for resilience and adaptation assessments. Most important outputs are the guidelines on developing impact chains, the adaptation options database, and guidelines on conducting cost-benefit analyses to determine optimum service levels.

4.2 Connect resilience assessment and appraisal of adaptation options to the decision-context

Climate change adaptation is just one factor influencing decision making at road authorities, besides many others. To influence decision making, it is key to connect to the specific decision context of the road authority. This decision context has various dimensions:

- Most road authorities will have Key Performance Indicators, oftentimes expressing the services that the road network needs to provide for society, on the network scale. These are criteria like availability and safety for instance. The resilience and adaptation assessment should provide results that are linked to these KPIs. Within ICARUS we talk about the benefits of adaptation, when adaptation affects these KPIs.

- Most authorities also will have secondary policies in place. These may link to other objectives that are not the prime objectives of the authority. For instance, these are linked to sustainability or carbon reduction. It makes sense to ensure that also these secondary objectives are being considered in the assessment. Within ICARUS we talk about co-benefits, when adaptation affects these secondary objectives.
- Road authorities will have different steering mechanisms for decision making. In general, 4 steering mechanisms can be identified being service driven, budget driven, optimum driven and/or policy driven. It is key to understand these steering mechanisms and to make sure that the appraisal of adaptation options links to these mechanisms.

This makes very clear that there is no one size fits all approach for resilience and adaptation assessments. These assessments need to be tailored to the specific decision context of the road authority that is undertaking the assessment. Existing frameworks can be used as a starting point in that regard, but will always need to be customised.

4.3 Make sure to engage strategic, tactical and operational level

The organisation of road authorities is complex with involvement of many decision makers, specialists and staff on various managerial levels. Within ICARUS we have developed a climate change adaptation implementation process. This process provides the steps that need to be taken, and links these steps to the different managerial levels that are existing at the NRAs. In this regard, we distinguish between the strategic, tactical and operational levels. The process is complex and 'flows' back and forth between these levels. This makes very clear that all levels always need to be engaged. It is recommended to have one person in charge of the process, who will manage the involvement of all managerial levels. It makes sense if this responsibility is linked to someone at the tactical level.

4.4 Three basic approaches for making the case for adaptation

When implementing climate change adaptation, this can be done via different approaches, which are linked to different scales and levels of the organisation:

1. The case for adaptation can be made by monitoring trends in KPIs linked to climate events. This makes the relationship between climate events and network performance clear. However, this can only be done for frequent events and requires monitoring. More infrequent events have too little data to allow validation.
 2. Climate change adaptation can be implemented by changing the asset management to incorporate climate adaptation. This is done at object or connection level and ensures structural implementation of adaptation in practice. When making the case for adaptation, this can be done to maintain existing performance or performance can be optimised following cost-benefit analyses.
 3. Climate change adaptation can be executed on a project-specific basis at an object or connection level. This results in more efficient use of public money for specific situations.
-

Number two and three link and strengthen each other, where lessons learnt in specific project can serve as a basis for implementation in guidelines.

4.5 Consider nature-based solutions

NbS should be considered when choosing adaptation options. NbS often pose multiple co-benefits for example: increase of natural resilience, often pose multiple benefits, create potential for higher cost-effectiveness, reduced environmental impact, enhancing social equity, community engagement or positive impact on reputation.

While it answers large societal challenge regarding greenhouse gas mitigation, carbon storage and biodiversity, NbS are not automatically implemented due to lack of resources, lack of knowledge, difficulties in integration in guidelines and/or lack of organisational engagement.

5 RECOMMENDATIONS FOR IMPLEMENTATION OF THE ICARUS OUTPUTS

The aim of the ICARUS project was to ensure that climate change adaptation can be implemented in the daily processes of NRAs. Chapter 4 provides the content related key conclusions and recommendations for making the step to implementation. This chapter provides recommendations on how the ICARUS materials can be best used to make sure that awareness around, as well as a proper understanding of, these conclusions and recommendations are best obtained.

To get the key messages of ICARUS across, the following elements have been addressed within the project:

- A project website (<https://icarus.project.cedr.eu/>) has been designed, which allows an easy entrance into the project. The website provides an explanation about the project background and objectives. The website furthermore allows for downloading all deliverables of the ICARUS project.
- The website also provides the resource training package that is described in Chapter 2.2.9 of this final report. This is an easy access to all output of the project. It is recommended to first watch a video that is made for the relevant audience and then read the further details in the relevant deliverables. The resource training package provides videos, slides, as well as a quiz to test the obtained knowledge. The combination of video and slides can be used to familiarize an NRA staff member with the topic, allowing this NRA staff member to consequently use the slides to train other NRA personnel.
- Furthermore, on the website a case study portal can be found. This portal provides access to descriptions of case studies with various backgrounds, that can be used to learn from good practices elsewhere.

During the final event, the following recommendations were identified to make the step to implementation of the ICARUS results:

- Start developing demonstrator projects, in which the ICARUS outcomes are being piloted in practice, in a collaboration between the NRA's and the ICARUS consortium.
 - Tailored in-house trainings, making the ICARUS recommendations specific for the NRA at which the training is provided.
 - To see this stakeholder gathering at the final event as a Community of Practice, that will share experiences at a regular basis.
 - Use LinkedIn to share the results of the project. Especially the resource training pack is worth being communicated widely via social media.
-

ANNEX A PARTICIPANTS OF FINAL EVENT

At the event, participants could either be live in Delft for the entire event, or join online to participate in the afternoon of the first day.

Participants at the event:

Organisation

Vejdirektoratet

Deltares

Rijkswaterstaat

Research Driven Solutions

Rijkswaterstaat

Ramboll

Tecnia

Provincie Zuid-Holland

Federal Highway Research Institute Germany

Maple Consulting Ltd

National Highways

CEDR

Sanral

Statens Vegvesen

Bundesanstalt für Straßenwesen

Transport Infrastructure Ireland

Deltares

Federal Highway Research Institute

Deltares

Rijkswaterstaat

Rijkswaterstaat

Rijkswaterstaat

Online participants

Organisation

Anas spa

National Highways

Rijkswaterstaat

ANAS S.p.A.

Transport for London

Transport for London

Ministerio de Transportes y Movilidad Sostenible

National Highways

National Highways

Rijkswaterstaat

Federal Ministry for Climate Action

Ineco

Ministry for Climate Action, Environment, Energy, Mob., Inn. and Tech.

National Highways

Rijkswaterstaat

National Highways

National Highways

National Highways

U.S. Federal Highway Administration

GDDKIA

Dept. for Transport (DfT)

National Highways

University of Cambridge

INES

Federal Highway Administration

Transport for London

Belgian Road Research Centre (BRRC)

National Highways

National Highways

National Highways

Ineco

Department for Transport

Slovenian infrastructure agency

INES Ingenieros Consultores SL

TII

Transport for London

National Highways

University of Groningen

BMK

Väylävirasto

National Roads and Motorways Warsaw

IMT

University of Cambridge

ANNEX B AGENDA OF FINAL EVENT

Location: Deltares office in Delft, the Netherlands

Day 1 – Monday, 16 September 2024

13:00	Registration & lunch
14:00	Welcome and introduction
14:15	Hybrid session - presentation of ICARUS project results with Q&A session: ICARUS - Improve the uptake of Climate change Adaptation in the decision making processes of NRAs
15:45	Break
16:00	Demonstration and training on the ICARUS climate change adaptation implementation process (<i>in-person only</i>)
18:00	End of Day 1
19:00	Dinner

Day 2 – Tuesday, 17 September 2024

09:00	Demonstration and training on the use of impact chains to understand climate resilience
10.15	Break
10:30	Demonstration and training on the use of the adaptation options database and evaluation approaches of adaptation options
12:30	Lunch
13:30	Demonstration and training on specific recommendations to include Nature-based Solutions in climate change adaptation solutions
14.30	Break
14.45	Demonstration and training on overcoming implementation barriers
16:00	Summary of obtained feedback, open questions, implementation issues and Closing remarks
17:00	End of Conference

CEDR Contractor Report 2025-03

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