- FORESEE -

Future proofing strategies FOr RESilient transport networks against Extreme Events

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Guideline to measure Levels of Service and resilience in infrastructures

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EXECUTIVE SUMMARY

The functioning of society depends on the functioning of multi-modal transport infrastructure networks. These networks are designed and managed to be used to transport persons and goods in specific ways, e.g. within specific amounts of time, and with the probabilities of being hurt or injured being below specified thresholds. When extreme events occur, their ability to provide this service can be diminished. In order for managers to determine how to optimally allocate resources to help ensure that these networks continue to provide acceptable levels of service following the occurrence of extreme events, or provide acceptable levels of service as fast as possible following the occurrence of extreme events, it is useful to be able to measure the service provided by, and the resilience of, these networks.

The guideline that you are now reading has been written to allow managers to do this, taking into consideration the fact that there are many different specific multi-modal transport infrastructure networks, embedded in many different physical and organisational environments, being managed by many different organisations. It sets out the principles and basic steps to be used. The guideline emphasizes that measurement of the service provided by, and the resilience of, multi-modal transport infrastructure requires a clear definition of the transport system to be considered, including the infrastructure, the environment in which it is embedded and the organisation that is responsible for it.

Once the transport system is defined, the service to be provided by the transport system, as well as the measure of service to be used is to be defined. Although impossible to do this specifically for all possible transport systems, a list of possible generic service measures to be used are given in the appendices of this guideline as a starting point for the development of detailed service measures for specific situations involving road and rail transport infrastructure.

Once the service is defined at an acceptable level of detail, how resilience is to be measured is to be determined, i.e. through simulations, using resilience indicators with differentiated weights, or using resilience indicators with equal weights. The choice of measurement method depends on, among other things, the specific problem to be addressed, the time frame at disposition and the expertise available to conduct the analysis. If simulations are to be used the user of the guide is directed to two publications that have been written prior to the start of the FORESEE project [Adey et al., 2016; Hackl et al., 2018b]. If it is decided to use indicators of resilience, guidance is given within the document as to how the resilience indicators are to be developed for the transport system to be analysed. As with service measures, although impossible to do determine the resilience indicators specifically for all possible transport systems, a list of possible generic resilience indicators is given as a starting point for the development of detailed resilience indicators for specific situations involving road and rail infrastructure.

If it is not desired to measure service and resilience, the percentage of fulfilment of the resilience indicators, can still be used to give indications of resilience. The percentage of fulfilment should be weighted using the differentiated or equal resilience weights, if these weights are calculated.

All steps proposed in the guideline, as well as the possible ways to measure service and resilience, are explained using a simple and understandable example. The guideline has been used to develop the initial measures of service and extensive list of resilience indicators for the six case studies in FORESEE. These documents are, however, currently confidential. The final measures of service and resilience indicators for each case study will be made public by the end of the project.

For clarity, it is noted that the guideline does not provide, a) extensive lists of possible service or resilience indicators, b) an all-inclusive risk assessment framework, or c) a methodology to evaluate the interventions to be executed to improve resilience. If the reader is interested in these, they are encouraged, after identifying their specific situation of interest, to consult the large and growing body of appropriate literature in these respective areas, including future FORESEE deliverables.

"The authors of the report in particular and the members of the FORESEE project in general, would like to express our special gratitude to the members of the Stakeholder Reference Group (Appendix F) for their helpful contributions and suggestions on the contents of this document."

1 INTRODUCTION

1.1 GENERAL

The functioning of society depends on the transportation of goods and persons. The infrastructure required to enable transportation is built to ensure that this can happen in specified ways, i.e. built to provide specified levels of service. As reductions in service due to extreme events, e.g. floods, earthquakes, heavy snow falls, fog, high winds, whose frequency of occurrence and severity may change due to climate change, can have significant societal consequences, managers of transportation infrastructure manage[1] their infrastructure to minimise this risk, i.e. the probability of having consequences if a natural event occurs multiplied by the consequences if it occurs. In order to do so, however, it is necessary for transportation infrastructure managers to have a clear idea of the service the infrastructure is providing and an understanding of its resilience[2], if affected by extreme events. Recent work on service and resilience related to transportation infrastructure is summarized in the next sections. For recent work pertaining specifically to risk assessment frameworks, the reader is encouraged to consult the large and growing body of literature in this field.

1.2 SERVICE

As efforts increase to improve decision making with respect to the management of infrastructure, researchers and developers of management systems have been working towards quantifying the service provided by infrastructure so that they can determine the optimal time to execute interventions, making trade-offs between the impacts of executing interventions[3] and the impacts of not executing interventions. Some examples of these works for road and rail are shown in Table 1, and Table 2. These examples are, of course, by no means exhaustive. They, and others, can be used as a basis for the description of the service being provided by transportation infrastructure that will facilitate both the quantification of service it provides and the assessment of its resilience.

[1] The word *manage* is used in this document to cover all activities of infrastructure managers in their effort to ensure that infrastructure provides the expected levels of service, including the planning of maintenance activities and the planning of adaptation activities.

[2] The word *resilience* is used in this document encompasses all aspects of how the services provides by the infrastructure may be negatively affected by the occurrence of natural hazards, including the probability that it will be affected by specific hazard events, its vulnerability to the hazard events, and how quickly and easily it can be restored following the occurrence of the hazard events.

[3] The word *intervention* is used in this document to cover all actions taken to ensure the infrastructure provides the service expected of it, including the execution of physical interventions that may be classified as either maintenance or adaptation, the stoppage of traffic, and the increasing of monitoring.

Table 1. Examples of work on the measurement of road service

Citation	Focus of work
Achtnicht, M., 2012	The quantification of the value of CO_2
Adey et al., 2010	An illustration of how the service provided by roads changes as a function of the physical state of the roads
Adey et al., 2012	A complete description of the service provided by roads
Asam, S., et al., 2015	An adaptation guide for roads due to climate change
Caliendo, C., et al., 2012	The quantification of the social cost of accidents
de Blaeij, A., 2003	The quantification of the value of a statistical life
Dykes, A. L., 2018	The quantification of noise levels within cars
ECOPLAN, 2010	A set of indicators to measure the impacts of road infrastructure projects
Elvik, R., 2000	The cost of road accidents
FHWA, 2002	Quantifying service to enable the management of bridges
IHS, A., 2004	The relationship between comfort and road condition
Kasnatscheew, A. et al., 2016	Overview of accident cost calculation methods
Korzhenevych, A., et al., 2014	The quantification of the external costs of road transport
Kumares, C.S., et al., 2007	Principles of evaluating road projects
NZTA, 2010	A guideline to enable the evaluation of road infrastructure projects
OECD, 2001	Strategies and performance indicators to be used in the road section
VSS 2009a	The quantification of the value of travel time
VSS 2009b	The quantification of the external costs of road transport
VSS 2013	The quantification of accident costs
Wütrich, P et al., 2017	The quantification of the costs of air pollution

Table 2. Examples of work on the measurement of rail service

Citation	Focus of work
Aydin, N., 2017	Service quality evaluation of rail transit systems
Bickel, P., 2005	Quantification of energy costs
Caetano, L.F., 2013	Using availability to plan railway interventions
Cascetta, E., 2011	Impacts of high speed rail
Cavana, R.Y., et al, 2007	Measuring the quality of passenger service
Chou, J.-S., et al., 2014	Effects of service quality and customer satisfaction on customer loyalty in high-speed rail services
de Oña, J. et al. (2015)	Perceptions of rail service quality
Eboli, L., et al., 2012	Perceptions of railway service
ISO 37120 (2018)	Proposals of indicators and associated test methods in this document have been developed in order to help cities: a) measure performance management of city services and quality of life over time; b) learn from one another by allowing comparison across a wide range of performance measures; and, c) support policy development and priority setting.
Jou, R.-C., et al., 2013	Willingness to pay for comfort on high-speed rail lines
Maibach, M., et al., 2008	External costs of the transport sector
Milligan, C., 2014	Value of a statistical life
Nathanail, E. (2008)	Measuring the quality of service for passengers
OECD 2018	Indicators of the quality of passenger service
Stenström, C., et al., 2016	Availability of rail infrastructure
Thomas, L.J., et al., 2006	Perceptions of risk and safety
van Oort, N. and van Nes, R. (2010)	Impact of rail terminal design on transit service reliability

1.3 RESILIENCE

As there are an increasing number of efforts to measure service, there are also an increasing number of efforts to measure the reductions in service due to the occurrence of extreme events such as earthquakes. This information is being used to better design and manage infrastructure to help ensure that there are the least negative impacts on society due to reduced service. Examples of recent work are given in Table 3-Table 6.

Table 3. Examples of work on the resilience of infrastructure (1/2)

Citation	Focus of work - Summary
Adey, B.T., et al, 2016	**Ensuring acceptable levels of infrastructure related risks due to natural hazards with emphasis on stress tests** – This work gives a guideline of how to establish simulations frameworks for the evaluation of resilience.
Brown, R., et al., 2014	**Review of resilience of transport networks** - This work summarizes the problems that transport networks in the UK are having due to natural hazards and makes recommendations of how to deal with them.
Figueiredo, L., et al., 2018	**An approach to strengthen and monitor urban resilience** - This work proposes indicators to be used to monitor progress of urban areas in becoming more resilient. It provides recommendations on how local authorities can choose indicators tailored to their policy priorities and develops guidelines for the effective use of indicators in a broader governance framework. The two types of indicators proposed are, Baseline indicators, which provide information on the existing conditions that policy makers have to take into account when formulating policies. They may measure dimensions that are not under the control of local policy makers or dimensions that fall into policy domains not related to resilience. Policy indicators measure the performance of policies along different dimensions. They can be used to assess the effort, efficiency and effectiveness with which a policy is pursued as well as the process through which it is pursued. The four subcategories of policy indicators are input indicators, output indicators, outcome/ result indicators and process indicators. Many of the indicators are at a very high level, e.g. average duration of unemployment during an economic crisis, average annual property damage due to natural disasters over last ten years, level of trust in government, average response time of emergency services.
Hackl, J., et al., 2018a	**Determination of near-optimal restoration programs for transportation networks following natural hazard events** – This work focuses on explicitly modelling the reconstruction of transportation networks following the occurrence of natural hazards, something that is particularly relevant when estimating resilience.
Hackl, J., et al., 2018b	**Estimating network related risks: a methodology and an application for roads** – This work includes a detailed simulation based risk assessment for a road network in the region of Chur, Switzerland, from the simulation of rainfall patterns to the quantification of lost service through the entire restoration period.
Hughes, J.F., et al., 2014	**Measuring the resilience of transport infrastructure** – A resilience measurement framework has been proposed that broadly covers both technical and organisational dimensions of resilience and breaks these down into specific principles and measures which can be utilised to qualitatively assess resilience. Measurement categories include, 1) technical categories, i.e. robustness, redundancy, safe-to-fail, and 2) organization categories, i.e. change readiness, networks, leadership and culture.
ISO/TC 292	**Security and resilience** – This ISO committee has published four standards on the topic of security and resilience, including the - ISO ISO 22300:2018 Security and resilience - Vocabulary - ISO/TS 22375:2018 Security and resilience - Guidelines for complexity assessment process - ISO 22397:2014 Societal security – Guidelines for establishing partnering arrangements - ISO 22398:2014 Societal security – Guidelines for exercises
Jha, A.K., et al., 2013	**Principles, Tools and Practice** – This work summarizes guiding principles, tools, and practices in key economic sectors that can facilitate incorporation of resilience concepts into the decisions about infrastructure investments and general urban management that are integral to reducing disaster and climate risks. It provides practical rules of thumb that can guide stakeholders' decisions to incorporate the management of disasters and climate risks into urban investments.
Lam. J., et al., 2018	**Stress tests for a road network using fragility functions and functional capacity loss functions** – This work focuses on establishing steps to be used when running simulations to verify the resilience of transport infrastructure networks.
Neetesh S., et al., 2018	**A mathematical approach to the measurement of resilience** – This work proposes resilience metrics to describe the recovery curve. A reliability-based definition of damage levels, and a stochastic formulation of recovery is proposed that models the impact of recovery activities and potential disrupting shocks, which could happen during the recovery, on the system state.

Table 4. Examples of work on the resilience of infrastructure (2/2)

Citation	Focus of work - Summary
Prior, T., 2015	**Indicators of resilience for critical infrastructure** – This work includes suggestions as to possible indicators of the resilience of critical infrastructures. They are grouped as 1) A priori critical infrastructure resilience indicators, i.e. probability of failure, quality of infrastructure, pre-event functionality of the infrastructure, substitutability, interdependence, quality and extent of mitigating features, quality of disturbance planning/response, quality of crisis communications/information sharing, security of infrastructure, 2) post-hoc critical infrastructure resilience indicators, i.e. systems failure, severity of failure, post-event functionality, post-event damage assessment, cost of reinstating functionality post-event, recovery time post-event, and recovery/loss ratio.
Rome, E., et al., 2018a	**Impact and Vulnerability Analysis of Vital Infrastructures and Built-Up Areas** – This work contains a practical guideline for conducting a risk-based assessments of the impacts and vulnerabilities of urban areas and their infrastructure related to consequences of climate change. It provides a base for the collaborative execution of a vulnerability assessment, and helps facilitate the understanding of cause-effect relationships of climate change, identify geographical hotspots of vulnerability and risk, and assess what impact on people, economy and built-up area under study can be expected now and for the future due to the changing climate.
Theocharidou, M. et al., 2015	**Critical infrastructure protection** – This work describes a risk assessment methodology for critical infrastructures. There is an overview of risks where the risk of loss of critical infrastructure has been identified as a man-made risk.
USDOT, 2015	**Vulnerability assessment** – This work describes the functioning of an Excel tool developed to assess infrastructure vulnerability. It consists of various types of indicators, grouped as exposure indicators, sensitivity and adaptive capacity indicators. The users are encouraged to assign weights to different ranges of values of the indicators.

Table 5. Examples of work on the resilience of infrastructure in EU research projects (1/2)

Citation	Focus of work - Summary
Colciago, R., et al., 2017	**RAGTIME** - The main objective of this was to define the existing framework in the risk analysis in transport infrastructure projects by investigating best practices, regulations & standards, main studies and researchers in this field.
Hackl, J., et al., 2016	**INFRARISK** – This work focused on the development of a framework to be used to evaluate the risk and resilience of transportation networks. The methodology was developed to enable qualitative and quantitative analysis, and is part of the foundation for the current document.
Herrera I.A et al., 2018	**Resilience Management Guidelines for Critical Infrastructures** – This white paper outlines a pathway towards the integration of the European Resilience Management Guidelines developed as part of the work performed by five Horizon 2020 DRS-07-2014 Projects (i.e. 1) DARWIN: https://h2020darwin.eu/, 2) IMPROVER: http://improverproject.eu/, 3) RESILENS: http://resilens.eu/, 4) RESOLUTE: http://www.resolute-eu.org/ and SMR: http://smr-project.eu/home/). Resilience management addresses essential capabilities for Critical Infrastructure to adapt to an uncertain future and changing environment. Targeted at policy makers, it provides an overview of essential resilience concepts, methods and techniques to attain results from these Projects and to work towards an integrated guideline which could be implemented EU wide.
Lückeratch, D., et al., 2018; Rome E., et al., 2018b	**RESIN -** The project "Climate Resilient Cities and Infrastructures – RESIN" was focused on providing methods and tools to capture and represent cause-effect relationships underlying risks and vulnerabilities in urban population centers, enabling a systematic analysis and evaluation. Highlighting on a number of concepts, such as hazard, exposure, stressors, coping capacity, and vulnerability, these impact chains constitute the base for further quantitative modeling steps.
Oien, K., et al, 2017	**Smart Resilience Indicators for Smart Critical Infrastructure** – This work describes candidate resilience issues and indicators to be used when assessing, predicting and monitoring resilience of Smart Critical Infrastructures (SCIs). A total of 233 candidate issues and 1'264 indicators are provided for various threats, SCIs and the five phases of the resilience cycle used in the SmartResilience project. Structured candidate issues and indicators are mainly provided by collecting existing issues/indicators from the risk, safety, security, crisis management, business continuity and similar domains, considering resilience as an "umbrella".

Table 6. Examples of work on the resilience of infrastructure in EU research projects (2/2)

Citation	Focus of work - Summary
Papathanasiou, N., et al., 2016	**DESTINATION RAIL** – This work focused on the development of a framework that enabled the assessment of risk for all assets in a railway network, in a way that enables systematic comparisons between all assets, taking into consideration their effects on service.
Pathirage, C. et al., 2017	**EU-Circle** – A pan-European framework for strengthening Critical infrastructure resilience to climate change – This work proposed an analytical framework and a conceptual model for critical infrastructure resilience to disaster impacts, in the short run, and climate change, in the long run. The framework addressed the following key questions: 1) How short term (or long term) choices in resilience capacities makes an asset or network more resilient; 2) How these choices can minimize system performance loss when shocks occur; 3) How operational (short term) and strategic (long term) choices can minimize the time taken for an asset (or network) to recover and minimize the total loss of system performance. The framework uses a system dynamics simulation modelling approach to better understand the behaviour of complex infrastructure systems to natural hazards in the short run and climate change impacts over the long run.
Rome, E., et al., 2019	**Climate Resilient Cities and Infrastructures** – This work describes an approach for risk-based analysis of the vulnerability or urban infrastructure to a changing climate. The approach was used to assess case studies within four European cities (Bilbao, Spain; Bratislava, Slovakia; Greater Manchester, United Kingdom; Paris, France).
Thayaparan, M., et al., 2016	**EU-Circle** – This work included a comparison of resilience frameworks against some main features including time horizon, level of applicability (local, regional, national etc.), the main components, and the context for which the frameworks were designed. They looked at different resilience frameworks, such as the NISMOD – long term performance model (UK Infrastructure Transitions Research Consortium, 2015), which looked at 1) Balancing infrastructure capacity and demand in an uncertain future, 2) Risks of infrastructure failure and how to adapt national infrastructure to make it more resilient, 3) How do infrastructure system evolve and interact with society and the economy , and 4) What should the UK strategy be for integrated provision of national infrastructure in the long term, and the UNISDR Disaster Resilient Scorecard (UN Office for Disaster Risk Reduction, 2014) which was focused on the assessment of the level of cities' resilience to natural disasters and used 85 disaster resilience evaluation criteria.
Vollmer, M., et al., 2016	**Smart Resilience Indicators for Smart Critical Infrastructure** – This work tackled the assessment of resilience of modern critical infrastructures which are becoming increasingly smarter (e.g. the smart cities). They identified existing indicators suitable for assessing resilience of SCIs, identified new smart resilience indicators including those from Big Data, they developed a new advanced resilience assessment methodology based on smart RIs and the "resilience in cube (the innovative project tool providing the possibility to define one compound resilience indicator), including the resilience matrix, developed an interactive SCI Dashboard tool, and applied the methodology/tools in 8 case studies, integrated under one virtual, smart-city-like, European case study. The SCIs considered deal with energy, transportation, health, and water.

1.4 CONCLUSION

There has been considerable work done in the areas of the measurement of service and resilience of transportation infrastructure. This work has been, and is, highly useful in improving managers understanding of how their transportation infrastructure performs both on a regular basis and following the occurrence of extreme events. Something that has been missing until now, however, has been an explicit quantitative connection between the service provided by infrastructure and the resilience of infrastructure. FORESEE provides this connection.

The remainder of this document contains a guideline of how to quantitatively[4] measure service and resilience for multi-modal transportation infrastructure. The guideline has been built taking into consideration the results of the extensive work listed in this section. **The guideline is to be used by managers to establish how to quantify both the service provided by, and the resilience of, multi-modal transportation infrastructure**, especially when the desire is to

[4] as opposed to qualitatively

have estimates that can be used in the determination of the optimal resilience enhancing interventions to be executed. The guideline can be used to ensure that there is complete and systematic measurement of service and resilience in any infrastructure management decision-making situation throughout the life-cycle of the infrastructure, e.g. while deciding which highway route should be selected to minimise landslide risks over the next 10 years, or deciding when to close down bridges to traffic due to high winds.

The guideline, in some cases, can be used to address the recommendations of others, e.g. Figueiredo, L., et al., 2018. In other cases, it can be used to link the many different possible proposed indicators, e.g. Oien, K., et al, 2017, in ways that make it clearer as to how transportation infrastructure should be improved. As the indicators developed using this guide are compatible with those used to measure the service being provided by transport systems during normal use, FORESEE is contributing to the harmonised assessment of multi modal transport system performance, which is a goal of both the conference of European directors of roads (https://www.cedr.eu/) and the Platform of Rail Infrastructure Managers in Europe (Quinet et al., 2018).

2 THE GUIDELINE

2.1 GENERAL

This guideline is to be used to determine how to measure[5], the service provided by, and the resilience of, transport infrastructure[6]. It includes,

1) the definitions of service and resilience used in this document,
2) the concepts of how service and resilience can be measured, and
3) the steps to determine how to measure service and resilience.

The appendices contain information that can be used to help, in specific situations,

1) define road service, with proposals of possible indicators,
2) define rail service, with proposals of possible indicators, and
3) select road and rail resilience indicators.

2.2 DEFINITION OF SERVICE

Service is defined in the Oxford dictionary as

"*The action of helping or doing work for someone*".

In this guideline, **service** is defined as

the ability to perform an activity in a certain way.

With this definition in mind, the service to be provided by transportation infrastructure, is the safe and sustainable mobility of persons and goods. This service can be operationalised, for example, as the ability to transport from A to B,

- goods and persons within a specific amount of time, and
- goods without being damaged and persons without being hurt or losing their lives.

The provision of this service requires, 1) the construction of the infrastructure, and 2) the execution of interventions to counteract gradual deterioration, to restore the infrastructure so that it provides the required service following the occurrence of extreme events, and to accommodate changing needs.

Transport infrastructure is expected to provide service for long periods of time, spanning several generations, during which society will experience changes in terms of available technology, as well as changes in individual and collective aspirations with regard to life quality. The service to be provided by infrastructure, will therefore, change over time due to changing needs. This may mean, for example, that,

- goods and persons are to be transported from A to B within a smaller amount of time in the future than now, and

[5] To measure - To assess the importance, effect or value of (something)
[6] Transport infrastructure is considered to be all infrastructure to enable travel, e.g. road infrastructure and rail infrastructure or combinations of both. As travel can occur on infrastructure of multiple types, the measures of service and resilience are suitable for infrastructure enabling **multi-modal transport**.

- the probabilities of goods being damaged and persons being hurt or losing their lives while being transported from A to B are to be lower in the future than now.

The ability of transportation infrastructure to provide service changes over time due to changing infrastructure. For example, if the infrastructure connecting A and B is in poor condition, rather than good condition,
- it may take more time to transport goods and persons, and
- the probabilities of goods being damaged and persons being hurt or losing their lives while being transported from A to B may be higher.

With exact definitions of the service being provided, one can determine exactly how to measure service. For example, if the service provided is the ability to transport from A to B,
- goods and persons within a specific amount of time, and
- goods without being damaged and persons without being hurt or losing their lives, then

estimates of
- the time required to transport goods and persons, and
- the extent of damaged goods and number of persons who are hurt or injured

can be used to measure service.

Once it is determined how service is to be measured, the reductions in service due to the occurrence of extreme events, and therefore resilience, can be measured.

2.3 DEFINITION OF RESILIENCE

Resilience is defined in the Oxford dictionary as,

"the capacity to recover quickly from difficulties; toughness."

In the context of critical infrastructure, it has been defined as,

"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents" [7].

The Cabinet Office of the United Kingdom defines it as,

"the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event"[8]

The United Nations Office for Disaster Risk Reduction defines it as,

[7] "Presidential Policy Directive – Critical Infrastructure Security and Resilience, PPD-21, The White House, Office of the Press Secretary, U.S.A." The White House, Office of the Press Secretary, February 2013.
[8] United Kingdom, Cabinet Office (2011)

"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management."[9]

In this guideline, **resilience** is defined as,

the ability to continue to provide service if a hazard event occurs.

This definition encapsulates the essence of the others listed above, but makes it explicit as to how resilience is to be measured, and removes emphasis on how the system works, which must, nevertheless, be considered to measure resilience.

Resilience, with this definition, is to be measured, using,
- each measure of service deemed relevant, in order to assess how service is being affected, and
- the cost of the interventions required to ensure that the infrastructure once again provides and adequate service.

When considering extreme events, resilience is therefore measured as the difference between
- the service provided by the infrastructure if no hazard event occurs and the service provided by the infrastructure if a hazard event occurs (illustrated in Figure 2 and Figure 2).
- the costs of intervention if no hazard event occurs and the costs of interventions if a hazard event occurs (illustrated in Figure 3).

In Figure 1, Figure 2, and Figure 3, resilience is shown as the area between the red-blue and green lines. The larger the area the less resilient the infrastructure. The smaller the area the more resilient the infrastructure.

In Figure 1, resilience is shown using the measure of service expected cumulative yearly travel time of goods and persons being transported from A to B. The green line indicates the amount of travel time expected if there is no hazard event. The red line indicates how the travel time is expected to increase from the moment a specific hazard event begins to the moment that hazard event ends. The blue line indicates how travel time is expected to decrease from the moment the hazard event ends, until the moment that the cumulative yearly travel time of goods and persons travelling from A to B is as would be expected without the occurrence of the hazard event, i.e. service is restored.

[9] https://www.unisdr.org/we/inform/terminology

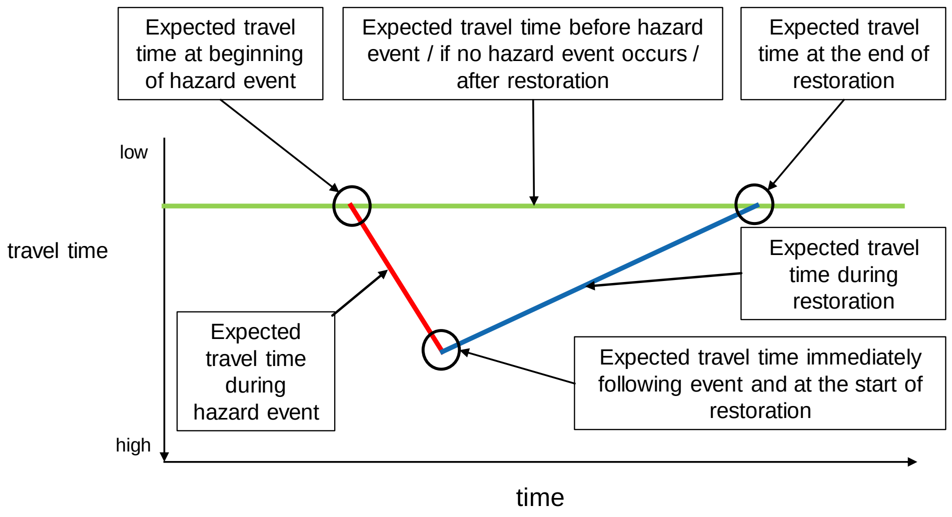

Figure 1. Illustration of resilience, using the measure of service expected cumulative yearly travel time, of infrastructure enabling the transport of goods and persons from A to B for a scenario, where a single hazard event occurs and the infrastructure is restored so that it provides that same level of service as it did before the hazard event

In Figure 2, resilience is shown using the measure of service expected cumulative yearly injuries and fatalities that occur due to goods and persons being transported from A to B. The green line indicates the injuries and fatalities that are expected to occur if there is no hazard event. The red line indicates how the injuries and fatalities are expected to increase from the moment a specific hazard event begins to the moment that hazard event ends. The blue line indicates how the injuries and fatalities are expected to decrease from the moment the hazard event ends, until the moment that the cumulative yearly injuries and fatalities of goods and persons travelling from A to B is as would be expected without the occurrence of the hazard event, i.e. service is restored.

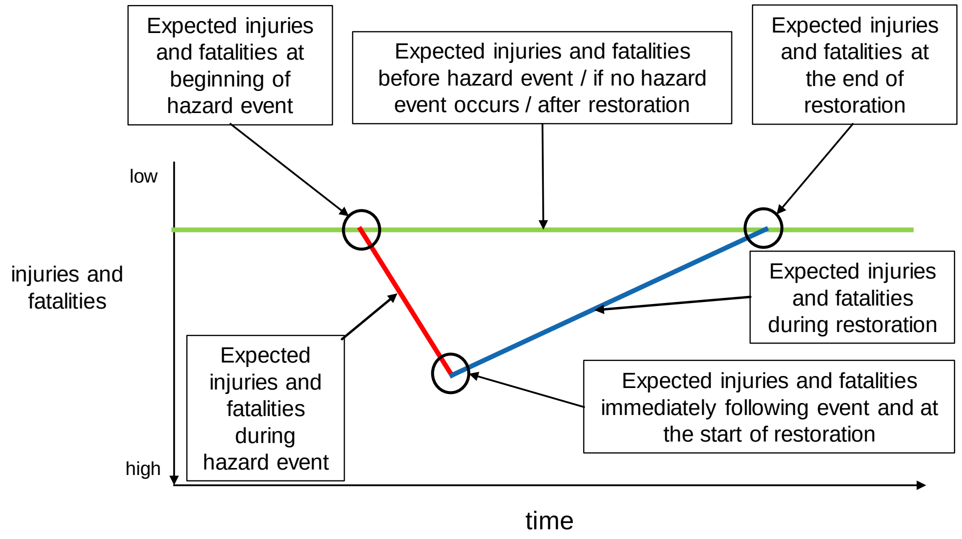

Figure 2. Illustration of resilience, using the measure of service expected cumulative injuries and fatalities, of infrastructure enabling the transport of goods and persons from A to B for a scenario, where a single hazard event occurs and the infrastructure is restored so that it provides that same level of service as it did before the hazard event

In Figure 3, resilience is shown using the expected intervention costs that are required to enable that goods and persons are transported from A to B. The green line indicates the intervention costs[10] that are expected if there is no hazard event. The red line indicates how the intervention costs are expected to increase from the moment a specific hazard event begins to the moment that hazard event ends. The blue line indicates how the intervention costs are expected to decrease from the moment the hazard event ends, until the moment that the cumulative yearly intervention costs would be expected without the occurrence of the hazard event.

[10] Intervention costs are used here to mean all costs incurred by the manager of the infrastructure

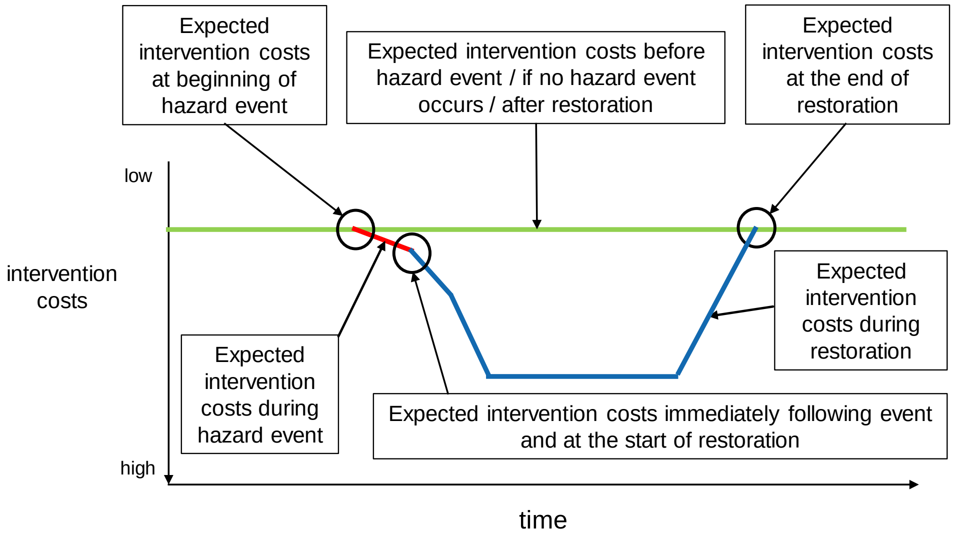

Figure 3. Illustration of resilience, using intervention costs, of infrastructure enabling the transport of goods and persons from A to B for a scenario, where a single hazard event occurs and the infrastructure is restored so that it provides that same level of service as it did before the event

For clarity, it is noted that

- *the values indicates by the green lines in Figure 1 to Figure 3 do not have to be constant over time. For example, the amount of travel time per year while travelling between A to B could increase over a period of ten years due to increasing traffic, or the number of injuries and fatalities per year due to travelling between A and B could be expected to decrease over a period of ten years.*
- *the deterministic scenarios depicted Figure 1 to Figure 3 do not imply that resilience assessment is deterministic. In order to account for the large future uncertainties in how transport systems are likely to evolve over time, it is necessary, at least conceptually, to take into consideration the entire range of possible futures.*
- *if one considers fundamental changes to the transport system following the occurrence of extreme events, one often speaks of adaptation. This has not explicitly been shown to ease understanding of the document.*
- *resilience is in this guideline considered to be measured as the difference between a) the service provided by the infrastructure if no hazard event occurs and the service provided by the infrastructure if a hazard event occurs and b) the costs of intervention if no hazard event occurs and the costs of interventions if a hazard event occurs. It is not measured using partial factors such as the ability of transport infrastructure to resist a hazard or the speed with which the service can be restored following a hazard, although these partial factors are of utmost importance in measuring resilience.*

2.4 MEASURING SERVICE

Measuring the service provided by transport infrastructure over time requires modelling,

1) how the service required from the infrastructure is expected to change in the future, and
2) how the infrastructure is likely to change in the future.

This modelling requires taking into consideration many characteristics of the transport system, including characteristics

1) of the infrastructure, e.g. the number and width of the lanes of a highway, the gradient and degree of curvature of a railway line.
2) of the environment, e.g. the number and type of vehicles that are to use a highway, the number and type of trains to use the a railway line.
3) of the organisation, e.g. how often routine maintenance interventions are executed and what precautions are made to limit the disruptions to vehicles on roads or trains on railways.

The exact characteristics to be taken into consideration depend on the specific transport system to be analysed.[11]
Assuming the required service of the infrastructure remains constant, this involves estimating how the infrastructure is likely to change in the future, taking into consideration all events that might result in a change in the infrastructure. The range of sophistication of the models used depends on, among other things, the problem being investigated, the available data, the expertise of the people involved in the investigation and the time available for the investigation.

The results of the models, regardless of sophistication, are quantified measures of the service provided by the infrastructure. For example, if 10 persons are transported from A to B in 1 hour every day for 365 days and only travel time is used as the measure of service, then the measure of service is 3’650 hours (10x1x365). If a value of 10€ is placed on travel time, then the service provided by the road can be measured as 36’500€. In other words, the service provided by the infrastructure is measured as 3’650 hours or 36’500 €. Other units could be used.

Attention: This does not mean that the infrastructure has a value of 36’500 € in one year, or that it would provide better service if transportation took more time. The 3’650 hours, or 36’500€, is a reference value, from which deviations are to be measured in estimation of resilience. For example, an infrastructure manager might be expected to manage the infrastructure in a way to ensure that persons can be transported from A to B in 3’650 hours, where, if persons were transported from A to B in 3’640 hours, i.e. spent only 36’400€ in travel time, this would be improved service.

If it is not possible or feasible to measure service thoroughly throughout entire time periods, service indicators, e.g. average annual daily traffic, can be used. For example, in order to

[11] The combination of multiple characteristics are sometimes used to define a “level of service” that is provided by infrastructure. For example, the Highway Capacity Manual of the United States of America (Transportation Research Board, 2000), defines level of service as the operational conditions within a traffic stream without consideration of safety. It uses categories from A, which denotes free flow operation, to F, which denotes a breakdown in flow. The categories are related to other often used concepts in transportation engineering, such as transport density and average annual daily traffic. These definitions of level of service, obviously, can only be calculated by taking into consideration the characteristics of the transport system, e.g. the number and type of vehicles that are to use the highway and the number and width of the lanes of the highway. Once such a level of service is known, it is possible to use this information to measure the service as described in this document, e.g. to estimate the total amount of travel time required to transport persons from A to B, in different situations.

measure the service provided by infrastructure where persons are transported from A to B every day for 365 days, one needs to know the number of persons to be transported from A to B each day and the amount of time required to transport each. Measuring the number of persons to be transported every day may be too costly to do. Instead, it might be decided that one day of measurements on March 31 and one day of measurements in September 30 are sufficient. The estimates of the number of persons to be transported and the speed at which, and the distance over which, they are transported on those days would then be indicators of the service provided by the road throughout the year.

2.5 MEASURING RESILIENCE

Measuring the resilience of infrastructure requires measuring the difference between the service provided over time, when no hazard event occurs, and when a hazard event occurs. Using the example in the previous section, if a hazard event resulted in persons being transported from A to B requiring 50% more travel time for a year, the resilience of the infrastructure with respect to this specific hazard in terms of travel time would be measured as 1'825 hours (5'475 – 3'650) or 18'250€ (54'750-36'500).

Obviously, these numbers don't mean anything alone. They are only meaningful when two situations are compared. For example, if the infrastructure could be modified so that the same hazard event would only result in 10% more travel time when transporting persons from A to B for a year, the resilience of the infrastructure would be measured as 365 hours (4'015 – 3'650) or 3'650€ (40'150 – 36'500). In this case, the infrastructure modification would have led to an increase in resilience of 1'460 hours (1'825-365) or 14'600€ (18'250-3'650). If monetary units are used, the measure of resilience also gives an idea of how much one should be willing to pay for the modification.

Measuring resilience is more difficult than measuring service as it requires estimating what will happen from the point of time that a hazard occurs to the point in time that the required service is once again provided. This depends, on a first level, on many different factors, including,

1) the probabilities of hazard events occurring,
2) how the infrastructure withstands hazard events,
3) how service is provided when the infrastructure does not work,
4) how the infrastructure is restored following the hazard event, and
5) how much it costs to restore the infrastructure.

These first level factors, in turn, depend on many other factors, such as how well an infrastructure manager,

1) is prepared for hazard events,
2) reacts during hazard event, and
3) responds following the hazard event.

And these factors, in turn, depend on more in depth factors, such as how an infrastructure manager,

1) deals with information, e.g. a central database versus many different databases,
2) is structured, e.g. by region or by specialization, and

3) makes decisions, e.g. centralized versus decentralized decision-making.

Due to this complexity, measuring the resilience of transport infrastructure in detail might not be worthwhile, i.e. the gain in information may not be worth the effort. Instead, it might be worthwhile to use resilience indicators, i.e. indicators of how service will be affected due to a hazard event. The indicator set used will need to adequately capture the performance of all relevant aspects of the transport system. For example, if the organisation responsible for the infrastructure has no restoration plans for the infrastructure if the hazard occurs, it is likely that the restoration time will be longer than if it has restoration plans. All other things being equal, a longer restoration time means a higher impact on service and, therefore, less resilient infrastructure. In this case, the presence of restoration plans is an indicator of the resilience.

3 DEFINE TRANSPORT SYSTEM

Before the service provided by, and the resilience of, transport infrastructure are measured, it is necessary to define the parts of the transport system to be considered (Table 7). It is noted that the classification of items within a transport system is situation dependent, i.e. something that is considered to be in one category for one transport system may be in another category in another transport system. For example, if a bridge is controlled by the responsible organisation it may be considered to belong to the infrastructure part of the transport system. If a bridge is not controlled by the responsible organisation it may be considered to belong to the environment.

Table 7. Parts of the transport system

Part	Description	Examples	Control
infrastructure	the physical assets that are required to provide service and are considered	the bridges, tunnels, road sections and rails sections that comprise the infrastructure required for usual and alternative transport routes	within the control of the responsible organisation
environment	the physical environment in which the infrastructure is embedded that might affect the provision of service	the occurrence of earthquakes and floods, proximity of infrastructure to areas where landslides or avalanches can occur	outside the control of the responsible organisation
	the organisational environment in which the infrastructure management organisation is embedded that might affect the provision of service	the regulatory framework, budget allocated to an infrastructure management organisation	outside the control of the responsible organisation
organisation	the organisation(s) responsible for ensuring that the infrastructure provides service	the organisation(s) or part(s) of the organisation(s) that monitors the service being provided from the infrastructure and restores the infrastructure damaged during extreme event events	within the control of the responsible organisation

For clarity, it is noted that

- *the definition of the environment should cover all aspects relevant to the assessment. For example, if cascading events such as an earthquake that triggers a landslide are of concern these need to be considered.*
- *the transport system is to be defined to include all infrastructure of interest, from a single object to an entire multi-modal transport network across Europe. The scale of the transport system to be analysed greatly affects which measures of service and which resilience indicators are to be used.*

4 MEASURE SERVICE

4.1 GENERAL

Once the transport system is defined, service can be measured. The steps to measure service are:

1) Define the service the transport system provides,
2) Determine how the service is to be measured, and
3) Measure the service.

4.2 DEFINE SERVICE

In defining service, it is helpful to first think of,

1) the relevant stakeholders, i.e. the persons and organisations who are affected by the infrastructure that are to be included in the investigation, and then in terms of
2) the impact of the infrastructure on the stakeholders, i.e. how they are affected.

If, for example, transport infrastructure exists to enable that persons can be transported from A to B in 1 hour every day for 365 days, one can define the service provided by the infrastructure in terms of travel time, or travel time costs. If a hazard results in increased travel time, the persons being transported are negatively affected because they must spend more time travelling. To be clear, being a stakeholder is time dependent. Someone who travels from A to B to get to work is a user of the infrastructure from A to B, but if they are later at a bistro next to the road, they are part of group of people that might be affected by the road but are not at that moment in time using it. Example stakeholders groups for public road infrastructure and rail are included in sections 8.1 and 9.1.

The impacts on stakeholders should be grouped by type, and these types should be subdivided at increasingly fine levels until the impact of each type can be reasonably and objectively quantified and modelled. This enables service to be measured at different levels if desired. To help ensure orthogonality, each impact type, on the lowest defined level, should be explained and classified as contributing to one of the pillars of sustainability (economic, societal, environmental). An example should be given for each to help clarify its meaning. Examples of how the service provided by public roads and rails can be defined are given in Appendix A and Appendix B.

It is noted that in order to obtain wide acceptance of the results, it is important to involve all relevant stakeholders and experts in the definition of service.

4.3 DETERMINE HOW TO MEASURE SERVICE

How the service is to be measured should be stated, including the measures to be used, whether their values will be determined through simulations or the use of indicators, if indicators are to be used the indicators to be used and the frequency with which the values of the indicators will be collected. For example, if the measure of service is to be travel time, then the amount of travel time incurred over the course of a year, could be estimated

1) through running simulations of the transportation of persons over the infrastructure over the course of a year and summing the total amount of travel time, or

2) by measuring the travel time on specific parts of the infrastructure on specific on March 31, June 30, September 30 and December 31 and extrapolating this information to cover all parts of the infrastructure and all periods of time in the year.

Measures of service should be evaluated either
1) using the expected use of the infrastructure, e.g. it is expected that 10 persons are to be transported from A to B in the course of a year and that it will take on average 1 hour to transport each of them, yielding a measure of service of 10 hours, or
2) using the expected ability to transport persons, e.g. if 10 persons wanted to travel from A to B in the course of the year, it would take on average 1 hour to transport each of them, yield a measure of service of 10 hours.

The first way takes into consideration the expected demand, the second doesn't.

For clarity, it is noted that
- *how the values of the indicators are obtained is situation dependent. For example, in cases where infrastructure managers have little time and resources and only approximate estimates are required, expert opinion may be used. In cases where, infrastructure managers have considerable time and resources and accurate estimates are required, networks of sensors may be used to collect information in real time.*
- *the accuracy required in the estimation of the values depends on the life-cycle phase of the infrastructure. For example, relatively approximate information about expected travel time might be required during the planning of a new highway, whereas relatively accurate information about expected travel time may be required when assessing how to deviate traffic during a flood event.*
- *the relationship between the increasing effort required to make increasingly accurate estimates and the benefit of having increased accuracy should be taken into consideration when determining how to measure service.*

4.4 MEASURE SERVICE

Once it is determined how to measure service, it needs to be done, either using the results of simulations or using indicators. The result in both cases, however, is the measure of service. For example, if it is expected that 10 persons are to be transported from A to B every day over the course of a year, the service provided by the infrastructure is measured as 3'650 hours (10 x 1 x 365). If travel time has a value of 10€, the service provided is measured as 36'500€.

Attention: These measures of service are solely to be used as reference values in measuring resilience. They are not measurements of the value of the service provided by the transport system, which would require a consideration of how an area would function with and without the transport system.

The models required to measure service depend greatly on the level of detail desired. A general approach that can be used is given in Adey et al., (2016), and a detailed approach for a specific case can be found in Hackl et al., (2018b).

5 MEASURE RESILIENCE

5.1 GENERAL

The steps to determine how to measure the resilience of transport infrastructure, assuming that the transport system to be considered has been defined (section 3), and the service is measured (section 4) are:

1) Identify the parts of the transport system that are likely to have an effect on resilience,
2) Determine if the resilience is to be measured directly using reductions in service and additional intervention costs or if indicators are to be used,
3) If resilience is to be measured directly using reductions in service and additional intervention costs,
    a. estimate the service if no hazard occurs and if a hazard occurs,
    b. estimate the intervention costs if no hazard occurs and if a hazard occurs,
    c. calculate the difference between the service if a hazard occurs and the service if no hazard occurs, and
    d. calculate the difference between the intervention costs if a hazard occurs and the intervention costs if no hazard occurs, and
    e. aggregate the differences if desired.
4) If resilience is to be measured using indicators,
    a. Identify resilience indicators,
    b. Check relevancy of indicators
    c. Estimate values of the indicators,
    d. Measure resilience, either using differentiated resilience weights, or equal resilience weights.
5) If it is desired to have an overview of the percentage of fulfilment of indicators and indicator categories in order to have an idea of where to concentrate efforts to improve resilience, estimate the percentage of fulfilment of the resilience indicators using either differentiated weights, equal weights or no weights.

5.2 IDENTIFY RESILIENCE RELEVANT PARTS OF TRANSPORT SYSTEM

The first step, is to determine the parts of the transport system that are relevant to resilience of the infrastructure and the relevant factors. For example, the resilience of infrastructure connecting A to B may be affected by,

1) the infrastructure, where two of the relevant factors might be how a bridge is designed to resist earthquakes and the condition of the bridge,
2) the environment, where two of the relevant factors might be the likelihood of having a specific magnitude of earthquake, and the suitability of the regulatory framework enabling the expedition of restoration interventions to be executed, and
3) the organisation, where two of the relevant factors might be the existence of regular monitoring plans and the existence of plans to restore the infrastructure following an earthquake.

5.3 DETERMINE HOW RESILIENCE IS TO BE MEASURED

The second step is to decide if resilience is to be measured,

1) **directly** using the reductions in service and additional intervention costs if a hazard occurs or
2) **indirectly** using weighted indicators,
3) **indirecty** using unweighted indicators.

If resilience is to be measured directly using reductions in service, the service provided needs to be simulated first without the hazard event and then with all hazard events to be used to measure resilience. If it is not desired to measure resilience directly using the reductions in service, for example due to lack of time, lack of money, or lack of modelling expertise, indicators can be used.

For clarity, it is noted that

- *the relationship between the increasing effort required to make increasingly accurate estimates and the benefit of having increased accuracy should be taken into consideration when determining how to measure resilience.*
- *the estimates of the future service to be provided with and without hazards have to be made taking into consideration possible changes in the transport system, e.g. there will be 20% more traffic travelling from A to B 10 years from now. The consideration of how to change infrastructure following an extreme event so that it can provide different services than it originally provided is sometimes referred to in resilience literature as adaptation.*
- *in case of doubt as to how resilience is to be measured, it is suggested to first do so indirectly using unweighted indicators, which is the least accurate way to do so but also requires the least effort, then if necessary, to do so indirectly using weighted indicators, and finally to do so directly using the reductions in service and additional interventions costs if a hazard occurs, which is the most accurate way to do so, but requires by far the most effort.*
- *regardless of how the resilience is measured, it is important to realise that poor input will result in poor estimates.*

5.4 MEASURE RESILIENCE DIRECTLY USING SIMULATIONS

Measuring resilience **directly** using reductions in service requires constructing a detailed representation of the transport system in appropriate software, simulating how the future might unfold when different hazard events occur and measuring the difference between the service provided when no hazard event occurred and when the hazard events occurred. For example, if the total additional intervention costs due to a hazard event are 1’000’000€ and the total additional travel time costs due to a hazard event are 1’500’000€, the resilience measure is 2’500’000€.

It is challenging to build simulation tools that are capable of adequately capturing all of the elements of the transportation system relevant to measure resilience. An example of a process to be used to develop simulation tools to measure resilience, and a simulation tool used to measure resilience, can be found in Adey et al., 2016 and Hackl et al, 2018. The inputs and models to be used in running simulations is highly case dependent. It is recommended to use the software tools currently accepted by stakeholders as far as possible. This decreases analysis effort and increases acceptance of the results.

5.5 MEASURE RESILIENCE USING INDICATORS

5.5.1 Overview

Measuring resilience using indicators requires the selection of the relevant indicators. They should be selected to give an adequate indication of how difference between the service provided, and the intervention costs, with and without the occurrence of the hazard event:

1) from the start of a hazard event to the end of a hazard event, i.e. during **the absorb phase**, including the expected reductions in service and additional intervention costs during the hazard event, and

2) from the end of the hazard event to the time when service is again provided at the level it was before the event, i.e. during **the recover phase**, including the expected reductions in service and additional intervention costs during the restoration period.

5.5.2 Identify resilience indicators

Resilience indicators should be identified by,

1) selecting each part of the transport system, i.e. the infrastructure, the environment, or the organisation, and then for that part,
2) developing categories of indicators[12] at successive levels, until
3) quantifiable indicators are identified that yield indications of the reductions in service and additional intervention costs if the hazard occurs, and then
4) determining the possible values of the indicators.

This hierarchical approach helps to ensure that the indicators are as orthogonal as possible. An example is given in Table 8 using only the parts of the transportation system and the indicators, and the small transport system example given in section 5.2 and repeated here for convenience. The resilience of the infrastructure connecting A to B may be affected by,

1) the infrastructure, where two of the relevant factors might be how a bridge is designed to resist earthquakes and the condition of the bridge,
2) the environment, where two of the relevant factors might be the likelihood of having a specific magnitude of earthquake, and the suitability of the regulatory framework enabling how restoration interventions are executed, and
3) the organisation, where two of the relevant factors might be the existence of regular monitoring plans and the existence of plans to restore the infrastructure following an earthquake.

[12] A useful first level of indicators is to think of the indicators that will provide insight into what might happen during the absorb phase of the resilience curve, perhaps divided into indicators that give insight into 1) how an asset is affected during the hazard event, 2) how an asset will react during the hazard event, and 3) what might happen during the hazard event, and insight into what might happen in the recover phase of the resilience curve, i.e. 4) what might happen following the hazard event. These are used in appendix C.

Table 8. Example resilience indicators

Part	Indicator	Relation to phase	Values from best to worst[1]	Meaning
Infrastructure	Design resistance to hazard	Absorb phase - How an asset will react during a hazard event	5	Design code level 5
			4	Design code level 4
			3	Design code level 3
			2	Design code level 2
			1	Design code level 1
	Condition state of bridge	Absorb phase - How an asset will react during a hazard event	5	Like new
			4	Slightly deteriorated
			3	Average
			2	Poor
			1	Alarming
Environment	Seismic zone	Absorb phase – How an asset will be affected during a hazard event	5	Very low seismic zone
			4	Low seismic zone
			3	Average seismic zone
			2	Moderate seismic zone
			1	Severe seismic zone
	Regulatory framework	Recover phase – Consequences after a hazard event	3	Very few administrative hurdles to be crossed after the hazard occurs
			2	Some administrative hurdles to be crossed after the hazard occurs
			1	Significant administrative hurdles to be crossed after the hazard occurs
Organisation	Frequency of monitoring	Recover – Consequences during a hazard event	4	Regular frequent monitoring
			3	Regular but infrequent monitoring
			2	Irregular monitoring
			1	No monitoring
	Quality of emergency plan	Recover phase – Consequences during a hazard event	3	Bridge specific plan
			2	Generic plan
			1	No plan

[1] The best value is the one considered to be linked to the highest resilience, and the worst value is the one considered to be linked to the lowest resilience. There is, on purpose, no connection to the minimum or maximum value of the indicator. The absence of this connections facilitates the use of normally used indicators in different countries. For example, in some countries the best value of the condition state of an infrastructure is 1 and the worst value of the condition state is 5, whereas in other countries it is reversed.

A more extensive list of possible resilience indicators for transport infrastructure are given in section 8, along with how they are related to three commonly used measures of service (i.e. travel time, injuries and fatalities, and socio-economic impact) and intervention costs. These were used in the development of the initial measures of service and extensive list of resilience indicators for the six case studies to be conducted in FORESEE. These documents are, however, currently confidential. The final measures of service and resilience indicators for each case study will be made public by the end of the project.

For clarity, it is noted that

- *in order to obtain wide acceptance of the results, it is important to involve all relevant stakeholders and experts in the identification of the resilience indicators.*
- *the difference between the expected cost of interventions with and without the occurrence of an extreme event is considered to be a measure of resilience, alongside the differences in the measures of service, and is not considered to be a resilience indicator.*
- *if comparisons are to be made between multiple transport systems, the measures of service and the resilience indicators should be the same for all transport systems*

- *resilience indicators, as defined in this guideline, are parts of the transport system that give an indication of the difference between the service provided, and the intervention costs, with and without the occurrence of the hazard event, e.g. the design resistance to a hazard. They are not measures of how a transport system is likely to function over specified periods of time due to hazard events, e.g. availability. The latter is an intermediary measure, which is in many cases of interest to decision makers, and should by all means be reported on to help understand the behaviour of the transport system, if desired.*

5.5.3 Check relevancy of resilience indicators

To ensure that all indicators are relevant, and that there are indications for all relevant aspects of the service provided by the infrastructure, and intervention costs, the following question for each indicator should be asked for each measure of service and intervention costs:

Does the change in the value of the indicator affect the expected value of the measure of service or intervention costs if a hazard event occurs, and therefore the resilience of the infrastructure?

For clarity, the connection between the indicator and resilience should be stated. For example, the higher the value of the seismic zone indicator, the higher the seismic zone in which a bridge is located. The higher the seismic zone in which a bridge is located, the higher the probability of the bridge being affected by an earthquake, and therefore the higher the expected restoration intervention costs and additional travel time costs within a specific period of time. Assuming that everything else is constant[13], this means that the higher the value of the seismic zone, the lower the resilience of the transport infrastructure. The connections for this example are shown in shortened form in Table 9. Appendix C contains example explanations of the connections of a more extensive set of indicators in this shortened form.

Attention: The connections between indicators – measures of service and intervention costs, and resilience are situation dependent, and therefore need to be determined per situation. In checking the relevancy of the indicators it is important to know 1) that there is a connection, and 2) the direction of the relationship between the values of the indicator and resilience.

[13] This means that there is no variation in bridge design from one seismic zone to another. It is acknowledged that often there are important relationships between indicators, e.g. if a bridge is built in a high seismic zone it is built to a higher standard. This means that if a bridge built for a low seismic zone and a bridge built for a high seismic zone were both subjected to the same hazard event the one in the low seismic zone would behave worse than the one in the high seismic zone. Such relationships can only be taken into consideration directly by measuring resilience using simulations.

Table 9. Example connection between indicator – measure of service – resilience

Indicator	Description	Likely effect on measures of service and intervention costs An increase in the value of the resilience indicator is likely to result in … the expected additional … costs[1]		An increase in the value of the resilience indicator, therefore, means there is … resilience.[2]
		intervention	travel time	
Design resistance	The higher the value of the design resistance indicator, the higher the expected design resistance of the bridge.	a decrease in	a decrease in	an increase in
Condition state	The higher the value of the condition state indicator, the better the condition state of the bridge.	a decrease in	a decrease in	an increase in
Seismic zone	The higher the value of the seismic zone indicator, the more likely it is to have an earthquake of magnitude x.	an increase in	an increase in	a decrease in
Regulatory framework	The higher the value of the regulatory framework indicator, the less likely it is that the responsible organisation will have difficulties restoring service following an earthquake of magnitude x.	an increase in	an increase in	a decrease in
Frequency of monitoring	The higher the value of the frequency of monitoring indicator, the more likely it is that the responsible organisation can react quickly to limit transport disruptions following an earthquake	no change in	a decrease in	an increase in
Quality of emergency plan	The higher the value of the quality of the emergency plan indictor, the faster the restoration is likely to take place and, therefore, the lower the additional travel time due to the earthquake.	no change in	a decrease in	an increase in

[1] With respect to the figures in section 2, an increase in the expected additional costs means that the area between the green and red/blue lines is likely to be larger and a decrease means that the area is likely to be smaller.
[2] With respect to the figures in section 2, an increase in the value of a resilience indicator means that the likely area between the green and red/blue lines is likely to be smaller, and a decrease means that the area is likely to be larger.

5.5.4 Estimate values of resilience indicators

Once the resilience indicators have been selected the values of each have to be determined for the time period in question. The values should then be displayed to give,

1) an overview of the values,
2) an indication of the resilience, and, if desired,
3) an indication as to what can be done to improve the resilience.

Examples of each are shown in Table 10.

Table 10. Values of resilience indicators

Part	Indicator	Number of possible values	Value	Meaning of value[1]
Infrastructure	Design resistance to hazard	5	2	Design code level 2
	Condition state	5	4	Slightly deteriorated
Environment	Seismic zone	5	3	Average seismic zone
	Regulatory framework	3	1	Significant administrative hurdles to be crossed after the hazard occurs
Organisation	Frequency of monitoring	4	1	No monitoring
	Quality of emergency plan	3	3	Bridge specific plan

[1] The meanings of each of the possible values for the example are given in Table 8.

5.5.5 Measure resilience

5.5.5.1 General

Measuring resilience using indicators, instead of measuring resilience directly, requires correlating the values of the indicators with resilience as well as possible. This can be done by assuming there is a maximum reduction in service for each measure of service, and a maximum amount of additional intervention costs due to each resilience indicator, and they occur when that indicator alone has its worst value while all others have their best values. As the maximum reduction in service and maximum amount of additional intervention costs can be estimated in two ways, they lead to two types of weights, as follows,

1) differentiated resilience weights – where the maximum reductions in service and the maximum additional intervention costs are different for each resilience indicator.

2) equal resilience weights – where the maximum reductions in service and the maximum additional intervention costs are the same for each resilience indicator

How they are estimated is explained in the upcoming sections.

Attention: The worst value means the value which results in the lowest resilience. The best value means the value which results in the highest resilience. The worst/best value is not necessarily the lowest/highest value of the resilience indicator. The worst and best values have to be determined for each resilience indicator.

5.5.5.2 Using differentiated resilience weights

Measuring resilience using differentiated resilience weights requires making a connection between the values of the indicators and the value of resilience. This can be done as follows,

1) imagine that **all indicators** have their best values and estimate the reduction in service, for each measure of service, and additional intervention costs, if the hazard occurs,
2) imagine that **each indicator** has its worst value and estimate the reduction in service for each measure of service, and the additional intervention costs, if the hazard occurs, and
3) assuming a linear relationship between the worst and best values for each indicator that is considered to be relevant for each measure of service and intervention costs (determined in section 5.5.3) and using the actual values of the indicators, measure the resilience.

Measuring resilience using differentiated resilience weights,

1) gives an **indication of the reductions in service,** for each measure of service, and the additional intervention costs,
2) gives an indication of the possible increase in service, and reduction in additional intervention costs, by improving the value of each resilience indicator,

3) gives an approximate consideration of the interactions between resilience indicators, by looking at higher levels of resilience indicators and resilience indicators categories, and
4) requires less effort than measuring resilience directly (section 5.4), but is less accurate.

Measuring resilience using differentiated resilience weights is illustrated using the example transport infrastructure from A to B as follows:

If all resilience indicators have their best values and the frequency of monitoring indicator has its worst value (1 out of 4),

- the maximum additional travel time that might be incurred due to the disruption to the transport system while it is verified that the infrastructure can be used as intended, could be 10’000 hours, where if travel time is valued at 15€/hour would mean that the maximum additional travel time costs could be 150’000€, and
- the maximum additional intervention costs that might be incurred due to the restoration of the transport infrastructure from A to B could be 0€ because the bridge would not fail and no intervention costs due to restoration would occur.

Together this would mean that the maximum additional costs due to the frequency of monitoring indicator are 150’000€. An extension of this example is given in Table 11. Combining these estimates with the resilience indicator values and estimated reductions in service per measure of service, and additional intervention costs in Table 11 gives the measures of resilience shown in Table 12 - Table 13. The values are shown graphically in Figure 7 - Figure 8 in Appendix E (section 11). Explanations of the aspects to be seen in the tables are included in the table footnotes.

Table 11. Maximum and minimum expected reductions in service due to each resilience indicators for each measure of service using differentiated weights

Part	Indicator	Best or worst value	Value	Maximum expected additional intervention costs [€]	Maximum expected reductions in service		Maximum expected total costs [€]
					Travel time [hrs]	Travel time costs [€]	
Infrastructure	Design resistance to hazard	Best	5	0[1]	0	0	0
		Worst	1	500’000	100’000	1’500’000	2’000’000
	Condition state of bridge	Best	5	0	0	0	0
		Worst	1	100’000	70’000	1’050’000	1’150’000
Environment	Seismic zone	Best	5	0	0	0	0
		Worst	1	1’000’000	100’000	1’500’000	2’500’000
	Regulatory framework	Best	3	0	0	0	0
		Worst	1	0[2]	60’000	900’000	900’000
Organisation	Frequency of monitoring	Best	4	0	0	0	0
		Worst	1	0[2]	10’000	150’000	150’000
	Quality of emergency plan	Best	3	0	0	0	0
		Worst	1	0[2]	50’000	750’000	750’000

[1] Although, in this example the maximum expected additional intervention costs and reductions in service for the best value of the indicator is assumed to be zero, this does not have to be the case. It might be reasonable to believe that if an indicator has its best value that there would still be additional intervention costs if a hazard event occurred. The values of zero are used here for the simplicity of clarification.
[2] When the costs associated with the best and worst values of a resilience indicator are the same, it means the indicator is not relevant for this measure of service or intervention cost.

Table 12. Resilience measures using indicators and differentiated resilience weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs [€]	Maximum expected reductions in service		Maximum expected total costs [€]
					Travel time [hrs]	Travel time costs [€]	
Infrastructure	Design resistance to hazard	5	2	375'000	75'000	1'125'000	1'500'000[1]
	Condition state of bridge	5	4	25'000	17'500	262'500	287'500
Environment	Seismic zone	5	3	500'000	50'000	750'000	1'250'000
	Regulatory framework	3	1	0	60'000	900'000	900'000
Organisation	Frequency of monitoring	4	1	0	10'000	150'000	150'000
	Quality of emergency plan	3	3	0	0	0	0[2]

[1] Using differentiated weights, it is shown the largest contributor to the lack of resilience is the design resistance to hazard resilience indicator (i.e. 1'500'000€).
[2] The quality of the emergency plan resilience indicator is the smallest contributor to the lack of resilience. This is because it is already considered to be as good as possible.

Table 13. Resilience measures using transport system parts, and differentiated resilience weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs [€]	Maximum expected reductions in service		Maximum expected total costs [€]
					Travel time [hrs]	Travel time costs [€]	
Infrastructure	Design resistance to hazard	5	2	400'000	92'500	1'387'500	1'787'500
	Condition state of bridge	5	4				
Environment	Seismic zone	5	3	500'000	110'000	1'650'000	2'150'000[1]
	Regulatory framework	3	1				
Organisation	Frequency of monitoring	4	1	0	10'000	150'000	150'000[2]
	Quality of emergency plan	3	3				

[1] At the part level, one sees a slightly different view than at the lower levels, because there are multiple resilience indicators pro part of the transport system. It is shown that the largest contributor to the lack of resilience is the environment (i.e. 2'150'000€).
[2] The smallest contributor to the lack of resilience is the organisation (150'000€). This is because the frequency of monitoring is considered to have a relatively small effect on resilience, and the quality of the emergency plan resilience indicator has the highest value possible.

5.5.5.3 Using equal resilience weights

Measuring the resilience using equal resilience weights requires making a connection between the values of the indicators and resilience. This can be done as follows,

1) imagine that **all indicators** have their best values and estimate the reductions in service, if the hazard occurs, for each measure of service,
2) imagine that **all indicators** have their worst values and estimate the reductions in service, if the hazard occurs, for each measure of service, and then
3) assuming a linear relationship between the best and the worst values for each indicator that is considered to be relevant for that measure of service (determined in section 5.5.3), and using the actual values of the indicators, measure the resilience.

Measuring resilience using equal resilience weights,

1) gives an **indication of the reduction of service** for each measure of service,
2) gives an indication of the possible increases in service by improving the value of each resilience indicator,
3) gives approximate consideration of the interactions between resilience indicators, by looking at higher levels of indicators and indicators categories, and
4) requires less effort than measuring resilience directly (section 5.4) and less effort than measuring resilience using differentiated weights, but is less accurate.

Measuring resilience using equal resilience weights is illustrated using the example transport infrastructure from A to B as follows:

If all resilience indicators have their worst values,

- the maximum additional intervention costs that might be incurred due to the restoration of the transport infrastructure from A to B might be estimated as 1’000’000€, and
- the maximum additional travel time that might be incurred could be estimated as 100’000 hours, where if travel time is valued at 15€/hour would mean that the maximum additional travel time costs might be estimated as 1’500’000€.

Together this would mean that the maximum additional costs due to the hazard event are 2’500’000€. An extension of this example is given in Table 14. Combining the estimates Table 14 with the resilience indicator values and the estimated reductions in service in Table 14 yield the measures of resilience per indicator and indicator category (Table 15 - Table 16). The values are shown graphically in Figure 9 - Figure 10 in Appendix F (section 12).

Table 14. Maximum and minimum expected reductions in service due to the values of resilience indicators for each measure of service using equal weights

Part	Indicator	Best or worst value	Value	Maximum expected additional intervention costs [€]	Maximum expected reductions in service		Maximum expected total costs [€]
					Travel time [hrs]	Travel time costs [€]	
Infrastructure	Design resistance to hazard	Best	5	0	0	0	0
		Worst	1	1’000’000	100’000	1’500’000	2’500’000
	Condition state of bridge	Best	5	0	0	0	0
		Worst	1	1’000’000	100’000	1’500’000	2’500’000
Environment	Seismic zone	Best	5	0	0	0	0
		Worst	1	1’000’000	100’000	1’500’000	2’500’000
	Regulatory framework	Best	3	0	0	0	0
		Worst	1	0	100’000	1’500’000	1’500’000
Organisation	Frequency of monitoring	Best	4	0[1]	0	0	0
		Worst	1	0	100’000	1’500’000	1’500’000[2]
	Quality of emergency plan	Best	3	0[1]	0	0	0
		Worst	1	0	100’000	1’500’000	1’500’000

[1] When the worst and best values are the same it reflects the fact that the indicator is not relevant for this measure of service or the intervention costs.
[2] The worst and best values of the total costs encompass the fact that not all relevant indicators affect all relevant service types. Because frequency of monitoring and quality of emergency plan do not affect intervention costs, the effect of these indicators on the resilience of the transport system is lower than the other indicators (1’500’000€ is less than 2’500’000€).

Table 15. Resilience measures using indicators and equal resilience weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs [€]	Maximum expected reductions in service		Maximum expected total costs [€]
					Travel time [hrs]	Travel time costs [€]	
Infrastructure	Design resistance to hazard	5	2	750’000	75’000	1’125’000	1’875’000[1]
	Condition state of bridge	5	4	250’000	25’000	375’000	625’000
Environment	Seismic zone	5	3	500’000	50’000	750’000	1’250’000
	Regulatory framework	3	1	0[3]	100’000	1’500’000	1’500’000
Organisation	Frequency of monitoring	4	1	0	100’000	1’500’000	1’500’000
	Quality of emergency plan	3	3	0	0	0	0[2]

[1] Using indicators, it is shown that the largest contributor to the lack of resilience is the design resistance to hazard resilience indicator (1’875’000€). This is because it has the second lowest value possible and affects both measures of service. It is even a larger contributor than the frequency of monitoring resilience indicator (1’500’000€), even though this indicator has the lowest value possible, because it is only relevant for the travel time measure of service.
[2] The least contributor to the lack of resilience is the quality of the emergency plan resilience indicator (0€). This is because it already has the best value possible.
[3] The maximum expected additional intervention costs in this case is 0€ because the regulatory framework is not considered relevant to the cost of the interventions, only the length of time to execute the intervention.

Table 16. Resilience measures using transport system parts and equal resilience weights

Part	Indicator	Number of possible values	Value	Estimated reductions in service and additional intervention costs			
				Intervention costs [€]	Travel time [hrs]	Travel time costs [€]	Total costs [€]
Infrastructure	Design resistance to hazard	5	2	1’000’000	100’000	1’500’000	2’500’000
	Condition state of bridge	5	4				
Environment	Seismic zone	5	3	500’000	150’000	2’250’000	2’750’000[1]
	Regulatory framework	3	1				
Organisation	Frequency of monitoring	4	1	0	100’000	1’500’000	1’500’000[2]
	Quality of emergency plan	3	3				

[1] At the part level, one sees a slightly different view than at the lower levels, because there are multiple indicators pro part of the transport system. In this case, it is shown that the largest contributor to the lack of resilience is environment (2’750’000€), which is the sum of the possible estimated reductions in service and additional intervention costs due to the seismic zone and challenging regulatory framework. Obviously, this overestimates the total reductions in service and additional intervention costs, as the numbers are not strictly additive.
[2] The smallest contributor to the lack of resilience is the organisation (1’500’000€).

5.5.5.4 Discussion

The **most accurate** but most effort intensive way to measure resilience is to **measure resilience directly by modelling the reductions in service and the additional intervention costs** if it is impossible for a hazard to occur and if it is probable that a hazard occurs. This yields clear estimates of how the probability of occurrence of the event, the magnitude of the reductions in service and the additional intervention costs during the event, estimations of the length of time required to restore service following the end of the event and the magnitude of the reductions in service and the additional intervention costs during the restoration period. Such simulations result in clear measures of resilience and give clear views of what can be done to improve resilience.

The **second most accurate** and second most effort intensive way to **measure resilience is using resilience indicators with differentiated resilience weights**, i.e. weights that take into consideration the maximum and minimum possible reductions in service and additional intervention costs due to the values of each indicator. This still, however, requires the estimation of the expected reductions in service for each measure of service and the additional intervention costs due to the values of each resilience indicator.

The **third most accurate** and third most effort intensive way to **measure resilience is using resilience indicators with equal weights**, i.e. weights that only take into consideration the maximum and minimum possible reductions of service and the additional intervention costs due to the hazard event, and not due to the values of each indicator. This only requires the estimation the expected reductions in service for each measure of service and the additional intervention costs, and assuming that variations in each indicator affect each measure of service and intervention costs equally.[14]

5.6 ESTIMATE PERCENTAGE OF FULFILMENT OF RESILIENCE INDICATORS AND RESILIENCE INDICATOR CATEGORIES

5.6.1 General

Once a measure of resilience exists, it is often useful to have an overview of the percentage of fulfilment of resilience indicators and resilience indicator categories, in order to have an idea of where to concentrate efforts to improve resilience. This can be done,

1) using differentiated resilience weights, i.e. the worst value of each indicators represent the maximum reductions in service, for each measure of service, and the maximum additional intervention costs for each relevant indicator,
2) using equal resilience weights, i.e. the worst value of each indicator represents the maximum reductions in service, for each measure of service, and the maximum additional intervention costs for all relevant indicators, and
3) using no weights.

These are explained in the following three sections, using the possible values shown in Table 10.

5.6.2 Using differentiated weights

The estimated reductions in service and additional intervention costs per resilience indicator, upon which the percentages of fulfilment using differentiated weights are calculated, are shown in (Table 17). The percentages of fulfilment of resilience indicators and indicator categories are shown in (Table 18 and Figure 4).

The percentages of fulfilment of a resilience indicator using differentiated resilience weights are calculated as follows:

1 minus the expected reductions in service and the additional intervention costs due to the value of the indicator divided by the maximum reductions in service and additional intervention costs if the indicator has its worst value.

For example,

- the expected reductions in service and additional intervention costs attributed to the frequency of monitoring resilience indicator are 150’000€, which is composed of 150’000€ of travel time costs and 0€ intervention costs, and
- the maximum reductions in service and additional intervention costs due to the value of the indicator is 150’000€, which is composed of 150’000€ travel time costs and 0€ intervention costs.

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[14] Although not dealt with in this document, an additional and less accurate way to have an idea of the resilience of a transport system is to conduct qualitative assessments. As the goal of this document is the measurement, only quantitative assessment methods are discussed.

- the percentage of fulfilment is, therefore, 1-150’000€/150’000€ = 0%, i.e. the value of the frequency of monitoring resilience indicator cannot be worse.

The percentages of fulfilment of the resilience indicator categories are calculated as follows:

1 minus the expected reductions in service and additional intervention costs due to the values of all indicators in the indicator category divided by the maximum expected reductions in service and additional intervention costs if all indicators in the indicator category have their worst values.

For example,
- the expected reductions in service and additional intervention costs attributed to the indicators representing the organisation part of the transport system are 150’000€, which is composed of 150’000€ of travel time costs and 0€ intervention costs and due to the frequency of monitoring indicator and 0€ of travel time costs and 0€ intervention costs due to the quality of the emergency plan indicator, and
- the maximum expected reductions in service and additional intervention costs due to the value of the indicators is 900’000€, which is composed of 150’000€ travel time costs and 0€ intervention costs due to the frequency of monitoring indicator and 750’000€ of travel time costs and 150’000€ intervention costs due to the quality of emergency plan indicator.
- the percentage of fulfilment is, therefore, 1-150’000€/900’000€ = 83.33%.

Table 17. Estimated reductions in service and additional intervention costs per resilience indicator using differentiated weights

Part	Indicator	Number of possible values	Value	Estimated additional costs and reductions in service				
				Min./ Actual/ Max.	Inter-vention costs (€)	Travel time (hr)	Travel time costs (€)	Total costs (€)
Infrastructure	Design resistance to hazard	5	2	Min	0	0	0	0
				Actual	375’000	75’000	1’125’000	1’500’000
				Max	500’000	100’000	1’500’000	2’000’000
	Condition state of bridge	5	4	Min	0	0	0	0
				Actual	25’000	17’500	262’500	287’500
				Max	100’000	70’000	1’050’000	1’150’000
Environment	Seismic zone	5	3	Min	0	0	0	0
				Actual	500’000	50’000	750’000	1’250’000
				Max	1’000’000	100’000	1’500’000	2’500’000
	Regulatory framework	3	1	Min	0	0	0	0
				Actual	0	60’000	900’000	900’000
				Max	0	60’000	900’000	900’000
Organisation	Frequency of monitoring	4	1	Min	0	0	0	0
				Actual	0	10’000	150’000	150’000
				Max	0	10’000	150’000	150’000
	Quality of emergency plan	3	3	Min	0	0	0	0
				Actual	0	0	0	0
				Max	0	50’000	750’000	750’000

Table 18. Percentages of fulfilment using differentiated resilience weights

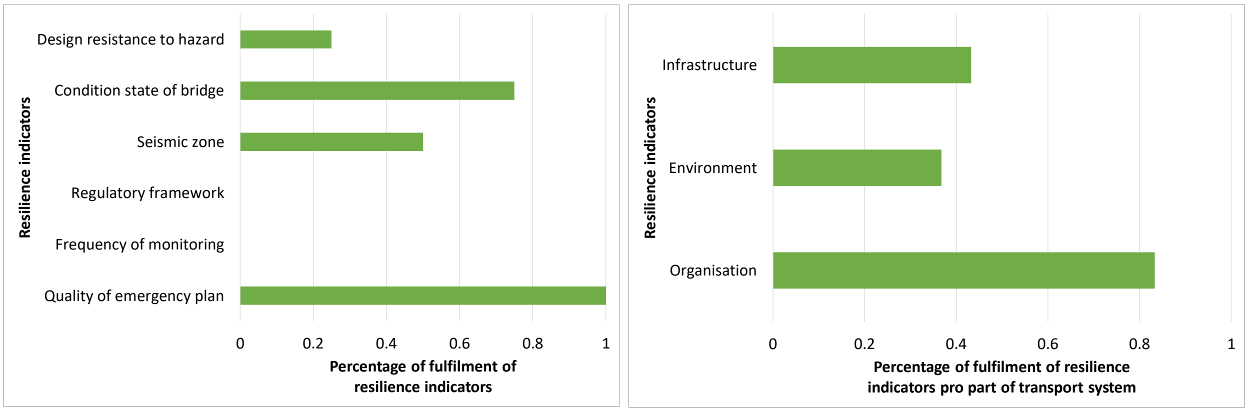
Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using differentiated weights	
				of resilience indicators	parts
Infrastructure	Design resistance to hazard	5	2	0.25	0.433
	Condition state of bridge	5	4	0.75	
Environment	Seismic zone	5	3	0.5	0.368[3]
	Regulatory framework	3	1	0	
Organisation	Frequency of monitoring	4	1	0[1]	0.833
	Quality of emergency plan	3	3	1[2]	

[1] The resilience indicator with the worst value is the frequency of monitoring resilience indicator, which is 0% fulfilled, i.e. a value 1 of 4.
[2] The resilience indicator with the best value is the quality of emergency plan resilience indicator, which is 100% fulfilled, i.e. a value of 3 of 3.
[3] Using differentiated resilience weights, the precentages of fulfilment of the parts of the transport system categories, show the environment resilience indicators are only 36.8% fuflilled. This is less than 25% that one might expect because the seismic zone resilience indicator has a greater weight, i.e. it has more effect on resilience, than the regulatory framework resilience indicator.

The calculation is: *1 minus the sum of the reductions in service and additional intervention costs due to each indicator, or indicator category, taking into consideration their current value divided by the sum of the total reductions in service and additional intervention costs due to each indicator, or indicator category.* For the infrastructure part of the transport system for example,

1 – (500'000+750'000+900'000) / (1'000'000+1'500'000+900'000) = 0.368

This is more informative than giving the indicators, or indicator categories equal weights and saying that there is 25% fulfillment, as it takes into consideration the seismic zone has a bigger contribution to the lack of resilience than the regulatory framework.



(a) (b)

Figure 4. Percentages of fulfilment using differentiated resilience weights, a) indicators, and b) indicators grouped by part of transport system.

5.6.3 Using equal resilience weights

The estimated reductions in service and additional intervention costs per resilience indicator, upon which the percentages of fulfilment using equal weights are calculated, are shown in (Table 19). The percentages of fulfilment of resilience indicators and indicator categories using equal weights are shown in (Table 20 and Figure 6). The percentages of fulfilment of a resilience indicator using equal resilience weights are calculated as follows:

1 minus the expected reductions in service and additional intervention costs due to the value of the indicator divided by the maximum reductions of service and additional intervention costs if the indicator has its worst value.

For example,
- the expected reductions in service and additional intervention costs attributed to the frequency of monitoring indicator is 1’500’000€, which is composed of 1’500’000€ of travel time costs and 0€ intervention costs, and
- the maximum reductions in service and additional intervention costs due to the value of the indicator is 1’500’000€, which is composed of 1’500’000€ travel time costs and 0€ intervention costs. The percentage of fulfilment is, therefore, 1-1’500’000€/1’500’000€ = 0%.

The percentages of fulfilment of the resilience indicator categories are calculated as follows:

1 minus the expected reductions in service and additional intervention costs attributed to all indicators, or indicator categories, in the category divided by the maximum reductions in service and additional intervention costs if all indicators in the indicator category have their worst values.

For example,
- the expected reductions in service and additional intervention costs attributed to the resilience indicators representing the organisation part of the transport system are 1’500’000€, which is composed of 1’500’000€ of travel time costs and 0€ intervention costs due to frequency of monitoring and 0€ of travel time costs and 0€ intervention costs due to the quality of the emergency plan, and
- the maximum reductions in service and additional intervention costs due to the value of the indicators is 3’000’000€, which is composed of 1’500’000€ travel time costs and 0€ intervention costs due to frequency of monitoring and 1’500’000€ of travel time costs and 0€ intervention costs due to the quality of the emergency plan. The percentage of fulfilment is, therefore, 1-1’500’000€/3’000’000€ = 50%.

Table 19. Estimated reductions in service and additional intervention costs per resilience indicator using equal weights

Part	Indicator	Number of possible values	Value	Estimated additional intervention costs and reductions in service				
				Min./ Actual/ Max.	Inter-vention costs (€)	Travel time (hr)	Travel time costs (€)	Total costs (€)
Infrastructure	Design resistance to hazard	5	2	Min	0	0	0	0
				Actual	750’000	75’000	1’125’000	1’875’000
				Max	1’000’000	100’000	1’500’000	2’500’000
	Condition state of bridge	5	4	Min	0	0	0	0
				Actual	250’000	25’000	375’000	625’000
				Max	1’000’000	100’000	1’500’000	2’500’000
Environment	Seismic zone	5	3	Min	0	0	0	0
				Actual	500’000	50’000	750’000	1’250’000
				Max	1’000’000	100’000	1’500’000	2’500’000
	Regulatory framework	3	1	Min	0	0	0	0
				Actual	0	100’000	1’500’000	2’500’000
				Max	0	100’000	1’500’000	2’500’000
Organisation	Frequency of monitoring	4	1	Min	0	0	0	0
				Actual	0	100’000	1’500’000	1’500’000
				Max	0	100’000	1’500’000	1’500’000
	Quality of emergency plan	3	3	Min	0	0	0	0
				Actual	0	0	0	0
				Max	0	100’000	1’500’000	1’500’000

Table 20. Percentages of fulfilment with equal resilience weights

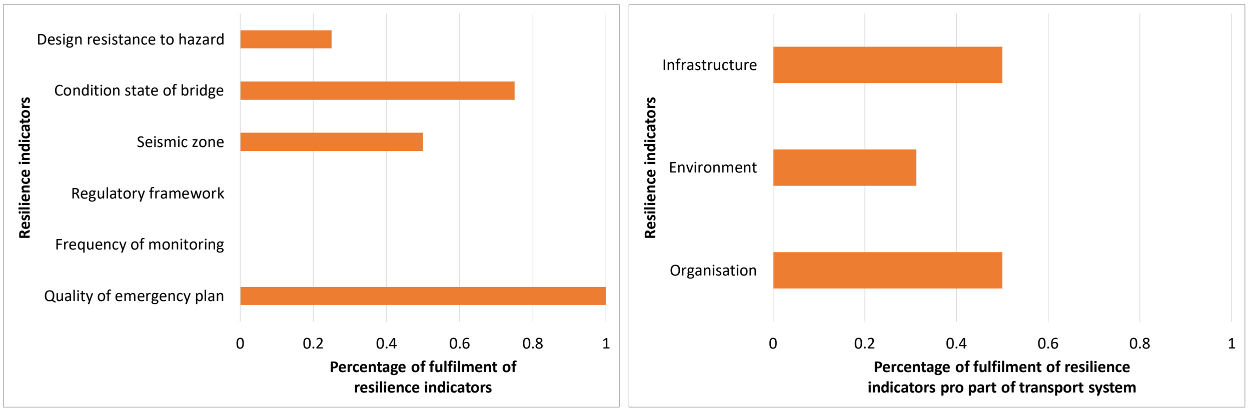
Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using equal weights	
				of resilience indicators	of parts
Infrastructure	Design resistance to hazard	5	2	0.25	0.5
	Condition state of bridge	5	4	0.75	
Environment	Seismic zone	5	3	0.5	0.3125[3]
	Regulatory framework	3	1	0	
Organisation	Frequency of monitoring	4	1	0[1]	0.5
	Quality of emergency plan	3	3	1[2]	

[1] The resilience indicator with the worst value is the frequency of monitoring resilience indicator, which is 0% fulfilled, i.e. a value 1 of 4.
[2] The resilience indicator with the best value is the quality of emergency plan resilience indicator, which is 100% fulfilled, i.e. a value of 3 of 3.
[3] Using equal resilience weights, the precentages of fulfilment of the parts of the transport system categories, show the environment resilience indicators are 31.25% fulfilled. This is because there is no difference between the contribution of a unit change in the value of the design resistance to hazard resilience indicator and a unit change in the value of the condition state of bridge hazard, which is considered using differentiated weights. The calculation is:

1 minus the sum of the reductions in service and the additional intervention costs due to each indicator, or indicator category, taking into consideration their current value divided by the total reductions in service and additional intervention costs due to each indicator or indicator category

1 – (500'000+750'000+1'500'000) / (1'000'000+1'500'000+1'500'000) = 0.3125

This is less informative than the result using differentiated weights, as there is no difference between maximum expected reductions in service and additional intervention costs between indicators. The use of the equal resilience weights here under weights the effect of the seismic zone on resilience, compared to the use of the differentiated weights.



(a) (b)

Figure 5. Percentages of fulfilment using equal resilience weights, a) indicators, and b) indicators grouped by part of transport system.

5.6.4 Using no resilience weights

The percentages of fulfilment using no resilience weights are shown in Table 21 and Figure 6. The percentages of fulfilment of a resilience indicator using no weights are calculated as follows:

(the value of the indicator minus 1) divided by (the worst value of the indicator minus 1)

For example, for the frequency of monitoring indicator which has a value of 1, the percentage of fulfilment is (1-1)/(4-1) = 0%.

The percentages of fulfilment of the resilience indicator categories are calculated as follows:

the average of percentage of fulfilment of the indicators, or indicator categories, within the indicator category.

For example, for the indicators representing the organisation part of the transport system have the two resilience indicators, i.e. the frequency of monitoring resilience indicator and the quality of the emergency plan resilience indicator, which are 0% and 100% fulfilled. The indicators representing the organisation part of the transport system can, therefore, be considered to be (0+1)/2 = 50% fulfilled.

Table 21. Percentages of fulfilment with no resilience weights

Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using no weights	
				of resilience indicators	of parts
Infrastructure	Design resistance to hazard	5	2	0.25	0.5
	Condition state of bridge	5	4	0.75	
Environment	Seismic zone	5	3	0.5	0.25[3]
	Regulatory framework	3	1	0	
Organisation	Frequency of monitoring	4	1	0[1]	0.5
	Quality of emergency plan	3	3	1[2]	

[1] The resilience indicator with the worst value is the frequency of monitoring resilience indicator, which is 0% fulfilled, i.e. a value 1 of 4.
[2] The resilience indicator with the best value is the quality of emergency plan resilience indicator, which is 100% fulfilled, i.e. a value of 3 of 3.
[3] Using no resilience weights, the precentages of fulfilment of the parts of the transport system categories, show the environment resilience indicators are 25% fulfilled.

The calculation is: *the average of the fulfilment of each indicator*

$$(0.5 + 0) / 2 = 0.25$$

This is less informative than the result using differentiated or equal weights, as there is no consideration of the relationship between the indicators and resilience, beyond the fact that there is one.

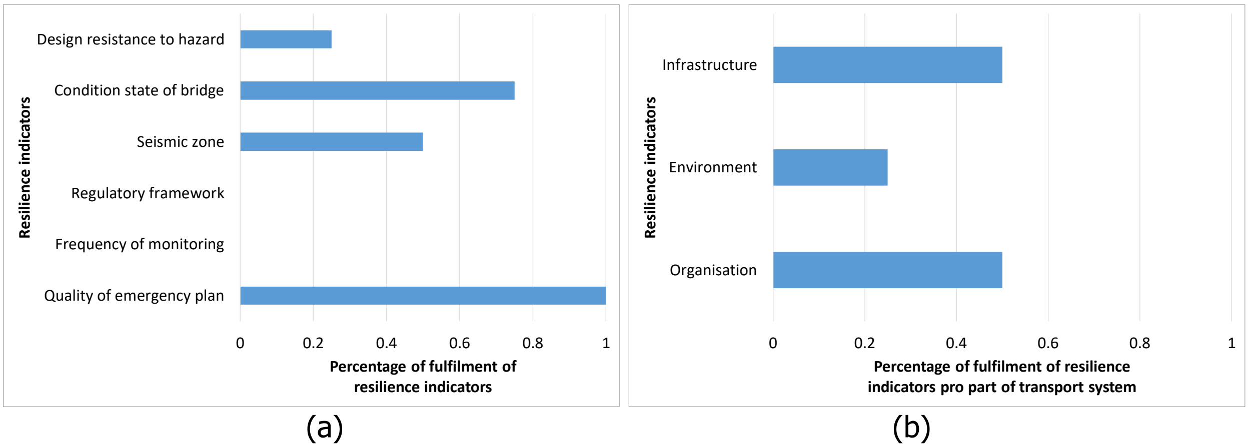


Figure 6. Percentages of fulfilment using no resilience weights, a) indicators, and b) indicators grouped by part of transport system.

5.6.5 Discussion

In order to have an idea of where to concentrate efforts to improve resilience,

- the percentage of fulfilment with differentiated resilience weights, provides the most insight. It takes into consideration the maximum reductions in service for each measure of service and additional intervention costs due to each indicator and the current value of the indicator. It has to be coupled with measuring resilience using differentiated weights (section 5.5.5.2).

- the percentage of fulfilment with equal resilience weights, provides the second most insight. It takes into consideration the maximum reductions in service for each measure of service and additional intervention costs and the current value of each indicator. As it is assumed that all indicators contribute equally to resilience, the idea of what should be modified to improve resilience is less accurate. The determination of the weights is, however, easier. It has to be coupled with measuring resilience using equal weights (section 5.5.5.3).

- the percentage of fulfilment with no resilience weights, provides the least insight. It only takes into consideration the current value of each indicator, which means there is no consideration as to the importance of the indicator. No measurement of resilience is required.

If desired, one can also mark the resilience indicators as a function of the ability to change them. For example, the figures in Appendix D (section 11) and Appendix E (section 12), could have the bars where the responsible organisation has control in black and the others another colour. This is particularly useful in explaining to the public what can be done to improve resilience and whether or not it is worthwhile.

6 CONCLUSION

This guideline is to be used to determine how to measure, the service provided by, and the resilience of, transport infrastructure. It includes concepts of service and resilience, and how they are linked, that enables both service and resilience to be measured. These concepts are suitable for a range of investigations from detailed model-based investigations, using simulations with extensive modelling effort to general expert opinion based investigations, using indicators.

Before using this guideline to determine how to measure service and resilience, it is important to have a clear objective to do so, e.g. to determine the areas of a specific transport system or a specific part of a transport system to improve to improve resilience, or to make comparisons between transport systems or parts of transport systems. If comparisons are to be made, special attention is required to ensure that the same measure of service and resilience, and perhaps the same resilience indicators, are used.

Once it is determined how to measure, the service provided by, and the resilience of, transport infrastructure, the next step is to determine the target values for the service and resilience to be provided. Guidance on setting targets will be given in D1.2 "Guideline to set targets for the levels of service provided by, and resilience of, transport infrastructure".

As measures of service and resilience, and target values, are only useful if used in regular infrastructure management decision making, examples of how this can be done will be given in D1.3 "Examples of the use of measures of service and resilience in the governance of transport infrastructure".

A methodology to determine optimal resilience enhancing actions will be given in D4.3 " A methodology for the selection and definition of efficient and optimal actions".

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8 APPENDIX A: EXAMPLE ROAD STAKEHOLDERS, INTERVENTION COSTS AND MEASURES OF SERVICE

8.1 STAKEHOLDERS

When investigating roads, one can think of the stakeholders in the categories shown in Table 22.

Table 22. Road stakeholder groups

Stakeholder group	Definition	Examples
Manager	the entity responsible for decisions with respect to physically modifying the infrastructure	a road authority, a concessionaire
Users	the persons who are using the roads	a person being transported on a road.
Directly affected public	the persons who are in the vicinity of the road but are not using it	a person in a house next to the road that hear vehicles driving on the road, a person working at a gas station near a road
Indirectly affected public	the persons who are not in the vicinity of the road but are affected by its use	a person in a house far away from the road that do not hear vehicles driving on the road, but are affected by a changing climate due to the emissions produced by vehicles using the road.

8.2 INTERVENTION COSTS

8.2.1 Road manager

Road managers execute interventions to ensure that infrastructure continues to provide an adequate level of service. It can be quantified as shown in **Table** 23.

Table 23. Road manager intervention costs

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Intervention[1]	the impact of executing interventions	Labour	the economic impact of people performing tasks	the cost of labour required for the execution of interventions
		Material	the economic impact of people ensuring that materials are available for use	the cost of material required for the execution of interventions
		Equipment	the economic impact of people ensuring that equipment is available for use	the cost of equipment required for the execution of interventions
	Impact of accident during the execution of interventions	Infrastructure property damage	the economic impact of repairing damages caused due to the execution of interventions	the cost of replacing the damaged property or as part of the fatality or injury costs
		Workforce injury	the societal impact due to injury at work place	the willingness of the manager to pay to avoid a workforce injury
		Workforce fatality	the societal impact due to death at work place	the willingness of the manager to pay to avoid a workforce fatality

[1] commonly used

8.3 MEASURES OF SERVICE

Example measures of service related to road users, the directly affected public and the indirectly affected public are given in the following subsections.

8.3.1 Road users

The service provided by road infrastructure can be thought of as the ability for persons to be transported from A to B, i.e. road users,

1) within a specific amount of time,
2) without being hurt or losing his/her life,
3) with only a specific amount of wear and tear on his/her vehicle,
4) without being physically or psycologically negatively affected, and
5) without having excessive noise

The associated measures of service and how they can be quantified are shown in Table 24.

Table 24. Measures of service related to the road user

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Travel time[1]	the impact of travel condition in terms of time lost in travel	work	the economic impact of wasting work time travelling	salaries
		leisure	the economic impact of wasting leisure time travelling	salaries
		commuting	the economic impact of delay during commuting travel	salaries
Accident[1]	the impact on the users due to the users being involved in an accident	property damage	the economic impact of repairing the vehicle	the cost of replacing the damaged property or as part of the fatality or injury costs
		injury	the societal impact due to the injury	the willingness of the passenger to pay to avoid injury
		fatality	the societal impact due to the fatality	the willingness of the passenger to pay to avoid death
Vehicle operation	the impact on the vehicle cost	operation	the economic impact of people ensuring that fuel and oil is available for use	the cost of fuel and oil
		maintenance	the economic impact of people repairing vehicles and ensuring that materials, e.g. tires and brake pads, are available for use	the costs of vehicle maintenance
Comfort	the impact of travelling on the users	physical	the societal impact of obtaining for example, bruises from an extremely bumpy ride	the willingness of the passenger to pay for the reduction of the physical effects of the ride such as noise or vibration
		psycho-logical	the societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, or of seeing things while travelling	the willingness of the passenger to pay for the reduction of the psychological effects of the ride
Noise	the societal impact due to the users coming in contact with sound emissions			the willingness of passengers to pay for the reduction of noise

[1] commonly used

8.3.2 Road directly affected public

The service provided by road infrastructure can be thought of as the ability for persons to be transported from A to B without persons living near the road (i.e. the directly affected public or wayside residents) being,

1) hurt or losing his/her life,
2) physically or psychologically negatively affected,
3) subjected to excessive noise, and
4) subjected to excessive emissions.

These can be quantified as shown in Table 25. The reason they should be handled seperately is that the directly affected public is affected in fundamentally different ways than the users.

Table 25. Measures of service related to the directly affected public

<table>
<tr><th colspan="2">Level 1</th><th colspan="3">Level 2</th></tr>
<tr><th>Label</th><th>Description</th><th>Label</th><th>Description</th><th>It can be estimated…</th></tr>
<tr><td rowspan="3">Accidents</td><td rowspan="3">the impact on the directly affected public due being involved in an accident</td><td>property damage</td><td>the economic impact of repairing property damaged due to a vehicle coming off of the road</td><td>from the cost of replacing the damaged property or as part of the fatality or injury costs</td></tr>
<tr><td>injury</td><td>the societal impact due to the injury</td><td>the willingness of the affected public to pay to avoid injury</td></tr>
<tr><td>fatality</td><td>the societal impact due to fatalities</td><td>the willingness of the affected public to pay to avoid death</td></tr>
<tr><td rowspan="2">Comfort</td><td rowspan="2">the impact of travelling on the directly affected public</td><td>physical</td><td>the societal impact of physical changes due to people travelling on the road, e.g. due to vibrations</td><td>the willingness of the affected public to pay to avoid the physical effects, for example, noise and vibration, of the railway traffic</td></tr>
<tr><td>psychological</td><td>the societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, due to others travelling.</td><td>the willingness of the persons affected to pay to avoid the physical effects</td></tr>
<tr><td>Noise</td><td colspan="3">the societal impact due to the directly affected public coming in contract with sound emissions</td><td>the willingness of the persons affected to reduce noise</td></tr>
<tr><td rowspan="9">Emissions</td><td rowspan="9">the impact on people due to the environment being impacted by particle emissions</td><td>CO_2</td><td>the societal impact due to emissions (human health)</td><td>the willingness of the persons affected to reduce emissions</td></tr>
<tr><td>PM_{10}</td><td colspan="2" rowspan="8">same as for CO_2</td></tr>
<tr><td>Nitrogen</td></tr>
<tr><td>Carbon monoxide</td></tr>
<tr><td>Aldehydes</td></tr>
<tr><td>Nitrogen dioxide</td></tr>
<tr><td>Sulphur dioxide</td></tr>
<tr><td>Polycyclic aromatic hydro-carbons</td></tr>
<tr><td>Dust</td></tr>
</table>

8.3.3 Road indirectly affected public

The service provided by road infrastructure can be thought of as the ability for persons to be transported from A to B without society in general (i.e. the indirectly affected public)

1) being negatively affected by others being hurt or losing their lives due to road transport,
2) having existing roads, negatively affecting socio-economic development,
3) being negatively affected by excessive emissions being emitted from road transport, and
4) being negatively affected by excessive amounts of non-renewable resources being consumed.

These can be quantified as shown in Table 26 - Table 30.

Table 26. Measures of service related to the indirectly affected public (1/3)

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated as…
Accidents	the impact on the indirectly affected public of accidents occurring on roads	injuries	the economic impact due to an injury	the production loss cost, medical cost, administrative cost and other costs for the society due to an injury
		fatalities	the economic impact due to a fatality	the production loss cost, medical cost, administrative cost and other costs for the society due to a fatality

Table 27. Measures of service related to the indirectly affected public (2/3)

Level 1		Level 2		Level 3		
Label	Description	Label	Description	Label	Description	It can be estimated as…
Socio-economic activity	the contribution of the road operation to socio-economic development	Persons	the impact of not being able to transport people	Productive ness	the economic impact due to not being able to travel, e.g. not being able to work	the influence of passenger transport on society for example, labour mobility
				Health	the societal impact due to injuries and fatalities of not being able to get proper medical care	the willingness of the society to pay
		Goods	the impact of not being able to move goods	Productive ness	the economic impact due to not being able to deliver goods, e.g. because of not being able to work as planned	the influence of freight transport service to the economy of the society, for example market accessibility
				Health	the societal impact due to not being able to deliver goods, e.g. due to fatalities because of lack of food or medical supplies	the willingness of the society to pay
		Employ-ment	the impact of interventions in terms of employing people	Economic impact	the economic impact of lack of employment opportunities	the influence of the employment opportunities to the economy of the society
				Social impact	the societal impact of lack of employment opportunities	the willingness of people to pay for providing employment

Table 28. Measures of service related to the indirectly affected public (3/3)

Level 1		Level 2		Level 3		
Label	Description	Label	Description	Label	Description	It can be estimated using…
Emissions	the impact on people due to the environment being impacted by particle emissions	CO_2	the impact due to the emissions	production	the environmental impact of emissions emitted during the production of materials	the willingness to pay to reduce emissions
				material transport	the environmental impact of emissions emitted during the transport of materials	the willingness to pay to reduce emissions
				person transport	the environmental impact of emissions emitted during travel	the willingness to pay to reduce emissions
				health	the societal impact due to emissions (human health)	the willingness to pay to reduce emissions
		PM_{10}	same as for CO_2			
		nitrogen				
		carbon monoxide				
		aldehydes				
		nitrogen dioxide				
		sulphur dioxide				
		polycyclic aromatic hydrocarbons				
		dust				
Environ-ment consumption	depletion of finite amounts of non-renewable resources	energy	the environmental impact due to the consumption of energy not related to emissions, e.g. depletion of finite amounts of non-renewable energy sources			the willingness to pay to reduce emissions
		materials	the environmental impact of consuming materials, not related to emissions			the willingness to pay to reduce emissions
		land	the environmental impact due to the consumption of land not related to emissions			the willingness to pay to reduce emissions
		culture	the societal impact of changing things important to our identity (of which heritage is part)			the willingness to pay to reduce emissions

9 APPENDIX B: EXAMPLE RAIL STAKEHOLDERS, INTERVENTION COSTS AND MEASURES OF SERVICE

9.1 STAKEHOLDERS

When investigating rail, one can think of the stakeholders in the categories shown in Table 29.

Table 29. Rail stakeholders

Stakeholder		Description	Example
Owner		Organisations responsible for decisions on physically modifying the railway infrastructure	A national railway management organisation
User	Passenger	People who intent to use or are using or have just used the passenger trains	A passenger on a train
	Freight customer	Organisations that are users of the freight trains	A company shipping wheat
	Carriers	Organisations that operate passenger and/or freight trains	A company operating trains
Directly affected public		People other than passengers or workforce members who are in the vicinity of the railway but do not intent to travel, or travel on a train, or have just travelled on a train	A car driver driving a car across a level crossing
Indirectly affected public		People who are not in the vicinity of the railway but are affected by it	A person who is affected by climate change

9.2 INTERVENTION COSTS

9.2.1 Rail manager

Rail managers execute interventions to ensure that infrastructure continues to provide an adequate level of service. It can be quantified as shown in Table 30.

Table 30. Rail manager intervention costs

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Intervention[1]	Impact from executing interventions	Labour	the economic impact of infrastructure workers performing tasks	the cost of labour required for the execution of interventions
		Material	the economic impact of ensuring the availability of required material for the intervention	the cost of material required for the execution of interventions
		Equipment	the economic impact of ensuring the availability of required equipment for the intervention	the cost of equipment required for the execution of interventions
	Impact of accident during the execution of interventions	Infrastructure property damage	the economic impact of repairing damages caused due to the execution of interventions	the cost of replacing the damaged property or as part of the fatality or injury costs
		Workforce injury	the societal impact due to injury at work place	the willingness of the owner to pay to avoid workforce injury
		Workforce fatality	the societal impact due to death at work place	the willingness of the owner to pay to avoid workforce death

[1] commonly used

9.3 MEASURES OF SERVICE

Example measures of service related to rail users, the directly affected public and the indirectly affected public are given in the following subsections.

9.3.1 Rail users

Three groups of users can be used to quantify the railway service, the passengers, the freight costumers, and the carriers. The service types of each are explained in succession in the following sections.

9.3.1.1 Passengers

The service provided by rail infrastructure can be thought of as the ability for persons to be transported from A to B, i.e. rail users,

1) within a specific amount of time,
2) without being hurt or losing his/her life, and
3) without being physically or psycologically negatively affected, and
4) without having excessive noise.

These can be quantified as shown in Table 31.

Table 31. Measures of service related to rail passengers

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Accident[1]	Impact on the users due to the users being involved in an accident	Personal property damage	the economic impact of repairing the properties of the passengers that are damaged	the cost of replacing the damaged property or as part of the fatality or injury costs
		Injury	the societal impact due to injury	the willingness of the passenger to pay to avoid injury
		Fatality	the societal impact due to death	the willingness of the passenger to pay to avoid death
Time[1]	Impact of travel condition in terms of time lost in travel	Business travel	the economic impact of delay during business travel	salaries
		Commuting travel	the economic impact of delay during commuting travel	salaries
		Leisure travel	the economic impact of delay during leisure travel	salaries
Comfort	Impact of discomfort	Physical	the societal impact of being physically affected by an uncomfortable ride	the willingness of the passenger to pay for the reduction of the physical effects of the ride such as noise or vibration
		Psychological	the societal impact of being psychologically affected by experiencing an unpleasant event during the trip	the willingness of the passenger to pay for the reduction of the psychological effects of the ride
Noise	The societal impact due to the users coming in contact with sound emissions			the willingness of passengers to pay for noise reduction

[1] commonly used

9.3.1.2 Freight costumers

The service provided by rail infrastructure can be thought of as the ability for persons to have goods transported from A to B, i.e. freight customers,

1) within a specific amount of time, and
2) without being hurt or losing his/her life.

These can be quantified as additional costs as shown in Table 32.

Table 32. Measures of service related to rail freight customers

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Time[1]	Impact of lost time	Stored freight	the economic impact of increasing the waiting time of goods in transport	the value of freight transport time
Accident[1]	Impact of accident involvement	freight property damage	The economic impact of repairing the goods that are damaged due to the use of railway service	the costs of replacing the damaged freight

[1] commonly used

9.3.1.3 Passenger carriers

The service provided by rail infrastructure can be thought of as the ability for persons to have passengers transported from A to B, i.e. passenger carriers,

1) within a specific amount of time,
2) without being hurt or losing his/her life,
3) without excessive spending on the maintenance and operation of the rolling stock, and
4) with the possibility of making profit.

These can be quantified as shown in Table 33.

Table 33. Measures of service related to rail passenger carriers

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Time	Impact of lost time	Competiveness	the economic impact passenger demand reduction	the willingness of a carrier to pay to decrease delays
		Operation	the economic impact of operating the rolling stock	the cost for providing the fuel and the personnel
Accident	Impact of accident involvement	Vehicle property damage	the economic impact of repairing the rolling stock damaged due to the use of railway service	the cost of replacing the damaged vehicle or vehicle's parts
		Injury	the societal impact due to injury of the carrier's personnel	the willingness of the passenger carrier to pay to avoid injury of the personnel working on a passenger train
		Fatality	the societal impact due to a fatality amongst the carrier's personnel	the willingness of the passenger carrier to pay to avoid a fatality of the personnel working on a passenger train
Vehicle operating costs	Impact on the vehicle cost	Maintenance and operation	the economic impact of maintaining and operating the rolling stock	the cost of maintaining the braking system, wheels, suspension system, and telecommunication system
Profit	Impact of change in the profit	Mode choice impact	the economic impact of reduction of the railways' market share	the willingness of all carriers to pay to increase the demand for railway passenger travel
		Physical	the societal impact of being physically affected by an uncomfortable ride	the willingness of the passenger carrier to pay for the reduction of the physical effects experienced by the personnel during the ride such as noise or vibration
		Psychological	the societal impact of being psychologically affected by experiencing an unpleasant event during the trip, i.e. shock or traumatic stress	the willingness of the passenger carrier to pay for the reduction of the physiological effects experienced by the personnel during the ride

9.3.1.4 Freight carriers

The service provided by rail infrastructure can be thought of as the ability for persons to have freight transported from A to B, i.e. freight carriers,
1) within a specific amount of time,
2) without being hurt or losing his/her life,
3) without excessive spending on the maintenance and operation of the rolling stock, and
4) with the possibility of making profit.

These can be quantified as shown in Table 34.

Table 34. Measures of service related to rail freight carriers

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Travel time	Impact of lost travel time	Competiveness	the economic impact freight's demand reduction	the willingness of a carrier to pay to decrease delays
		Operation	the economic impact of operating the rolling stock	the cost of providing the fuel and the personnel
Accident	Impact of accident involvement	Vehicle property damage	the economic impact of repairing the rolling stock damaged due to the use of railway service	the cost of replacing the damaged vehicle or vehicle's parts
		Injury	the societal impact due to injury	the willingness of the of the freight carrier to pay to avoid injury of the personnel working on a passenger train
		Fatality	the societal impact due to death	the willingness of the freight carrier to pay to avoid death of the personnel working on a passenger train
Vehicle operating costs	Impact on the vehicle cost	Interventions	the economic impact of executing interventions on the rolling stock to be available for use	the cost of maintaining the braking system, wheels, suspension system, and telecommunication system
Profit	Impact of change in the profit	Mode choice impact	the economic impact of reduction of the railways' market share, i.e. the cost from reducing the railway ridership due to uncomfortable ride	the willingness of all carriers to pay to increase the demand for railway freight travel
		Physical	the societal impact of being physically affected by an uncomfortable ride	the willingness of the freight carrier to pay for the reduction of the physical effects experienced by the personnel during the ride such as noise or vibration
		Psychological	the societal impact of being psychologically affected by experiencing an unpleasant event during the trip, i.e. shock or traumatic stress	the willingness of the freight carrier to pay for the reduction of the physiological effects experienced by the personnel during the ride

9.3.2 Rail directly affected public

The service provided by rail infrastructure can be thought of as the ability for persons and goods to be transported from A to B, without persons living near the rail infrastructure (i.e. the directly affected public) being,

1) hurt or losing his/her life,
2) physically or psychologically negatively affected,
3) subjected to excessive noise, and
4) subjected to excessive emissions.

These can be quantified as shown in Table 35.

Table 35. Measures of service related to the rail directly affected public

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Accident	Impact of being involved in accident	Personal property damage	the economic impact of repairing properties of the affected public due to accidents at the railway	the cost of replacing the damaged property or as part of the fatality or injury costs
		Injury	the societal impact due to injury, i.e. human cost due to injury of the affected public due to accidents at the railway	the willingness of the of the affected public to pay to avoid injury
		Fatality	the societal impact due to death, i.e. human cost due to fatality of the affected public due to accidents at the railway	the willingness of the affected public to pay to avoid death
Comfort	Impact of unsatisfactory transport service	Physical	the societal impact of the affected public of being physically affected by the traffic operation of the railway	the willingness of the affected public to pay to avoid the physical effects, for example, noise and vibration, of the railway traffic
		Psychological	the societal impact of the affected public of being psychologically affected by experiencing an unpleasant event, i.e. shock or traumatic stress, due to the traffic operation of the railway	the willingness of the persons affected to pay to avoid the physical effects
Noise	The societal impact due to the non-users coming in contact with sound emissions			the willingness of the persons affected to pay for the reduction of noise
Emissions	Impact on people due to the environment being impacted by particle emissions	CO_2	the societal impact due to emissions (human health)	the quantification of health damage due to the environmental pollution
		PM_{10}		
		Nitrogen		
		Carbon monoxide		
		Aldehydes		
		Nitrogen dioxide		
		Sulphur dioxide		
		Polycyclic aromatic hydro-carbons		
		Dust		

9.3.3 Rail indirectly affected public

The service provided by rail infrastructure can be thought of as the ability for persons and goods to be transported from A to B without society in general (i.e. the indirectly affected public)

5) being negatively affected by others being hurt or losing their lives due to rail transport,
6) having existing rail infrastructure, negatively affect socio-economic development,
7) being negatively affected by excessive emissions being emitted from rail transport, and
8) being negatively affected by excessive amounts of non-renewable resources being consumed.

These can be quantified as shown in Table 36 to Table 38.

Table 36. Measures of service related to the rail indirectly affected public (1/3)

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using…
Accident	Impact of accidents	Injury	the economic impact due to injury	the production loss cost, medical cost, administrative cost and other costs for the society due to an injury
		Fatality	the economic impact due to death	the production loss cost, medical cost, administrative cost and other costs for the society due to a fatality

Table 37. Measures of service related to the rail indirectly affected public (2/3)

Level 1		Level 2		Level 3		
Label	Description	Label	Description	Label	Description	It can be estimated using…
Socio-economic activity	Impact of changes on the socio-economic activity	persons	the impact of not being able to transport people	productive-ness	the economic impact due to not being able to travel, e.g. not being able to work	the influence of passenger transport on society for example, labour mobility
				health	the societal impact due to injuries and fatalities of not being able to get proper medical care	the willingness of the society to pay for the transport service
		goods	the impact of not being able to move goods	productive-ness	the economic impact due to not being able to deliver goods, e.g. because of not being able to work as planned	the influence of freight transport service to the economy of the society, for example market accessibility
				health	the societal impact due to not being able to deliver goods, e.g. due to fatalities because of lack of food or medical supplies	the willingness of the society to pay for the transport service
		Employment	the impact of lack of employment opportunities	Economic impact	the economic impact of lack of employment opportunities	the influence of the employment opportunities in the railway to the economy of the society
				Social impact	the societal impact of lack of employment opportunities	the willingness of people to pay for providing employment

Table 38. **Measures of service related to the rail indirectly affected public (3/3)**

<table>
<tr><th colspan="2">Level 1</th><th colspan="2">Level 2</th><th colspan="3">Level 3</th></tr>
<tr><th>Label</th><th>Description</th><th>Label</th><th>Description</th><th>Label</th><th>Description</th><th>It can be estimated using…</th></tr>
<tr><td rowspan="12">Emissions</td><td rowspan="12">Impact on people due to the environment being impacted by particle emissions</td><td rowspan="4">CO_2</td><td rowspan="4">the impact due to the emissions</td><td>production</td><td>the environmental_impact of emissions emitted during the production of materials</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>material transport</td><td>the environmental impact of emissions emitted during the transport of materials</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>person transport</td><td>the environmental impact of emissions emitted during travel</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>health</td><td>the societal impact due to emissions (human health)</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>PM_{10}</td><td colspan="4" rowspan="8">same as for CO_2</td></tr>
<tr><td>nitrogen</td></tr>
<tr><td>carbon monoxide</td></tr>
<tr><td>aldehydes</td></tr>
<tr><td>nitrogen dioxide</td></tr>
<tr><td>sulphur dioxide</td></tr>
<tr><td>polycyclic aromatic hydrocarbons</td></tr>
<tr><td>dust</td></tr>
<tr><td rowspan="4">Environ-ment consumption</td><td rowspan="4">Depletion of finite amounts of non-renewable resources</td><td>energy</td><td colspan="3">the environmental impact due to the consumption of energy not related to emissions, e.g. depletion of finite amounts of non-renewable energy sources</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>materials</td><td colspan="3">the environmental impact of consuming materials, not related to emissions</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>land</td><td colspan="3">the environmental impact due to the consumption of land not related to emissions</td><td>the willingness to pay to reduce emissions</td></tr>
<tr><td>culture</td><td colspan="3">the societal impact of changing things important to our identity (of which heritage is part)</td><td>the willingness to pay to reduce emissions</td></tr>
</table>

10 APPENDIX C: EXAMPLE GENERIC ROAD AND RAIL RESILIENCE INDICATORS

10.1 OVERVIEW

This appendix contains example generic resilience indicators related to the infrastructure (Table 39), the environment (Table 40), and the organisation (Table 41), developed through discussions within the FORESEE project for the 6 case studies to be conducted within FORESEE. The indicators are grouped with respect to their relationships with the resilience curves shown in section 2, i.e.

- the absorb phase – broken down into
  - How an asset is affected during the hazard event, and
  - How an asset will react during the hazard event

- the recover phase – broken down into
  - What will happen during hazard event, and
  - What will happen after the hazard event.

The association of an indicator to a group means that it has the greatest effect on this part of the resilience curve. It does not mean it does not affect another part.

Initial specific resilience indicators have been developed for each of the FORESEE case studies. They are not presented here due to privacy concerns and taking into consideration the fact that they are likely to change throughout the course of the FORESEE project, as more information becomes available as to, for example,

  - the transport systems to be considered,
  - the aspects of the transport systems on which to focus,
  - the availability of information,
  - the amount of effort available to collect the information,
  - the amount of information required to make a decision.
- the range of possible values, and why they were chosen, e.g.
  - their use by the responsible organisation,
  - their designation in codes, and
  - their fitting with descriptions of physical processes.

Table 39. An overview of the proposed infrastructure resilience indicators, and their relationships to the absorb and recover phases

Phase	Absorb			Recover
Category	How an asset is affected during the hazard event	How an asset will react during the hazard event	What will happen during the hazard event	What will happen after the hazard event
Resilience indicators	Condition state of protective structures/systems	Compliance with the current hazard design code	The presence / age of a warning system	Expected condition state of infrastructure
	The presence and adequacy of hazard effect reduction system	Condition state of infrastructure	The presence / age of a safe shutdown system	The number of possible existing alternative routes
	-	-	The presence of emergency / evacuation paths	The possibility of building a temporary alternative route
	-	-	The presence / condition of systems help evacuate persons	The possibility of using another means to satisfy transport demand

Table 40. An overview of the proposed environment resilience indicators, and their relationships to the absorb and recover phases

Phase	Absorb			Recover
Category	How an asset is affected during the hazard event	How an asset will react during the hazard event	What will happen during the hazard event	What will happen after the hazard event
Resilience indicators related to the physical environment	Hazard zone	Extent of past damages due to hazards	Presence of persons/property	Height
	Frequency of past hazards	Duration of past down time due to hazards	Hazard zone of peripheral infrastructure	Accessibility
	Severity of past hazards	-	Traffic	-
	Frequency of future hazards	-	Hazardous / flammable goods traffic	-
	Severity of future hazards	-	-	-
	Ability of environment to absorb hazard	-	-	-
	Ability to intervene to mitigate effects of hazard	-	-	-
Resilience indicators related to the organizational environment	-	-	-	Budget availability

Table 41. An overview of the proposed organisation resilience indicators, and their relationships to the absorb and recover phases

Phase	Absorb			Recover
Part	How an asset is affected during the hazard event	How an asset will react during the hazard event	What will happen during hazard event	What will happen after hazard event
Resilience indicators	The presence of a routine maintenance strategy	-	The frequency of monitoring	Expected time for tender
	The presence of an maintenance strategy	-	The presence of an emergency plan	Expected time for demolition
	The extent of interventions executed prior to the event	-	The practice of the emergency plan	Expected time for construction
	-	-	-	Availability of appropriate labour
	-	-	-	Flexibility in hiring appropriate work force
	-	-	-	Availability of materials
	-	-	-	Expected time for material delivery
	-	-	-	Availability of construction equipment

10.1 INFRASTRUCTURE

Table 42. Infrastructure: Indicators of how an asset is affected during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Condition state of protective structures/systems	The better the condition state of the protective structures/systems before the event, the more likely they will work as intended.	yes	yes	yes	yes	yes
The presence and adequacy of hazard effect reduction system	The presence and adequacy of hazard effect reduction system makes it more likely some consequences of failure will be avoided.	yes	yes	yes	yes	yes

Table 43. Infrastructure: Indicators of how an asset will react during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Compliance with the current hazard design code	The greater the degree of compliance with the current design code, the more likely the asset will behave as expected.	yes	yes	yes	yes	yes
Condition state of infrastructure	The better the condition state of the infrastructure before the event, the less likely it will fail.	yes	yes	yes	yes	yes

Table 44. Infrastructure: Indicators of what will happen during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
The presence / age of a warning system	The presence of a warning system makes it more likely that some consequences of failure will be avoided, and the younger a warning system the more likely it is that it will work as expected when required.	no	yes	yes	yes	yes
The presence / age of a safe shutdown system	The presence of a safe shut-down system makes it more likely some consequences of failure will be avoided, and the younger a safe shut down system the more likely it is that it will work as expected when required.	no	yes	yes	yes	yes
The presence of emergency / evacuation paths	The presence of emergency / evacuation paths, makes it more likely some consequences of failure will be avoided.	no	yes	yes	yes	yes
The presence / condition of systems help evacuate persons	The presence of systems to help evacuate persons, makes it more likely some consequences of failure will be avoided	no	yes	yes	yes	yes

Table 45. Infrastructure: Indicators of what will happen after the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Expected condition state of infrastructure	The better the condition state of the infrastructure after the event, the easier/faster it is likely to be restored.	yes	yes	yes	yes	yes
The number of possible existing alternative routes	The number of possible existing alternative routes make it easier to provide service following a hazard event before the failed infrastructure is restored.	no	yes	no	yes	yes
The possibility of building a temporary alternative route	The possibility of building an alternative route, makes it easier to provide service following a hazard event before the failed infrastructure is restored.	no	yes	no	yes	yes
The possibility of using another means to satisfy transport demand	The possibility of using another means to satisfy transport demand makes it easier to provide service following a hazard event before the failed infrastructure is restored.	no	yes	no	yes	yes

10.2 ENVIRONMENT – PHYSICAL

Table 46. Environment-Physical: Indicators of how an asset is affected during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Hazard zone	The hazard zone affects the likelihood that an asset will be affected by a hazard of a predefined severity.	yes	yes	yes	yes	yes
Frequency of past hazards	The frequency of past hazards indicates the likelihood of another hazard occurring.	yes	yes	yes	yes	yes
Severity of past hazards	The severity of past hazard indicates the likelihood of hazards of a specific magnitude occurring.	yes	yes	yes	yes	yes
Frequency of future hazards	The prediction of the frequency of future hazards indicates the likelihood of another hazard occurring.	yes	yes	yes	yes	yes
Severity of future hazards	The prediction of the severity of future hazard indicates the likelihood of hazards of a specific magnitude occurring.	yes	yes	yes	yes	yes
Ability of environment to absorb hazard[1,2]	The greater the ability of the environment to absorb a hazard the lower the consequences of the hazard.	yes	yes	yes	yes	yes
Ability to intervene to mitigate effects of hazard[3]	The greater the ability to intervene during a hazard to mitigate effects the lower the consequences of the hazard.	yes	yes	yes	yes	yes

[1] For example, if the hazard event is flooding, the ground permeability would be indicator of the ability of the environment to absorb the hazard event

[2] For example, if the hazard event is a landslide, the land type, the terrain type and the extent of vegetation cover would be indicators of the ability of the environment to absorb a hazard event.

[3] For example, if the hazard event was a fire, the proximity to a fire station would be an indicator of the ability to intervene to mitigate effects of the fire hazard.

Table 47. Environment-Physical: Indicators of how an asset will react during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Extent of past damages due to hazards	The extent of past damages indicates the extent of future damages if a hazard event occurs.	yes	no	no	no	yes
Duration of past down time due to hazards	The extent of past down time indicates the extent of future damages if a hazard event occurs.	no	yes	yes	yes	yes

Table 48. Environment-Physical: Indicators of what will happen during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Presence of persons/property	The presence of persons in the vicinity of an asset affects the consequences of a failure.	no	no	yes	no	yes
Hazard zone of peripheral infrastructure	The hazard zone affects the likelihood that peripheral infrastructure will be affected by a hazard of a predefined severity.	no	yes	yes	yes	yes
Traffic	The more the infrastructure is being used the higher the consequences of failed infrastructure	no	no	yes	yes	yes
Hazardous / flammable goods traffic	The more the infrastructure is being used to transport hazardous / flammable goods the higher the consequences of failed infrastructure	no	no	yes	yes	yes
Height	The height of an asset affects the consequences of a failure.	no	no	no	no	yes

Table 49. Environment-Physical: Indicators of what will happen after the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Height	The height of an asset affects the ease with which it can be restored.	yes	yes	no	no	yes
Accessibility	The accessibility of an asset affects the ease with which it can be restored.	yes	yes	no	no	yes

10.3 ENVIRONMENT – ORGANISATIONAL

Table 50. Environment-Organisational: Indicators of what will happen after the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Budget availability	The available budget affects how quickly restoration interventions can be executed	no	yes	yes	yes	yes

10.4 ORGANISATION

Table 51. Organisation: Indicators of how an asset is affected during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
The presence of a routine maintenance strategy	The presence of a routine maintenance strategy indicates that an asset will react as expected during a hazard event	yes	yes	yes	yes	yes
The presence of an maintenance strategy	The presence of a routine maintenance strategy indicates that an asset will react as expected during a hazard event	yes	yes	yes	yes	yes
The extent of interventions executed prior to the event	The greater the extent of interventions executed prior to an even the greater the likelihood that an asset will react as expected during a hazard event	yes	yes	yes	yes	yes
The extent of recent maintenance of surrounding area	The greater the extent of recent maintenance of the surrounding area, the greater the likelihood that an asset will react as expected during a hazard event	yes	yes	yes	yes	yes

Table 52. Organisation: Indicators of what will happen during the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
The frequency of monitoring	The greater the frequency of monitoring the greater the readiness of an organisation to react during a hazard event.	yes	yes	yes	yes	yes
The presence of an emergency plan	The presence of a current emergency plan indicates that the organisation will act quickly and appropriately during the hazard event.	no	yes	yes	yes	yes
The practice of the emergency plan	An increase in the frequency of practicing of an emergency plan indicates that the organisation will act quickly and appropriately during the hazard event.	no	yes	yes	yes	yes

Table 53. Organisation: Indicators of what will happen after the hazard event

Indicators	Description	A change in the value of the resilience indicator is likely to result in a change in the expected additional … costs				A change in the value of the resilience indicator, therefore, means there is a change in resilience.
		inter-vention	travel time	accident	socio-econ.	
Expected time for tender	An increase in the expected time for tender slows down the restoration process	yes	yes	no	yes	yes
Expected time for demolition	An increase in the expected time for demolition slows down the restoration process	yes	yes	no	yes	yes
Expected time for construction	An increase in the expected time for construction slows down the restoration process	yes	yes	no	yes	yes
Availability of appropriate labour	An increase in the number of appropriate workers available speeds up the restoration process.	yes	yes	no	yes	yes
Flexibility in hiring appropriate work force	An increase in hiring flexibility speeds up the restoration process.	yes	yes	no	yes	yes
Availability of materials	An increase in the availability of materials speeds up the restoration process.	yes	yes	no	no	yes
Expected time for material delivery	An increase in the expected time for material delivery slows down the restoration process.	yes	yes	no	no	yes
Availability of construction equipment	An increase in the availability of construction equipment slows down the restoration process.	yes	yes	no	no	yes
Expected time for construction equipment delivery	An increase in the expected time for equipment delivery slows down the restoration process.	yes	yes	no	no	yes

11 APPENDIX D: RESILIENCE MEASURES USING INDICATORS AND DIFFERENTIATED WEIGHTS

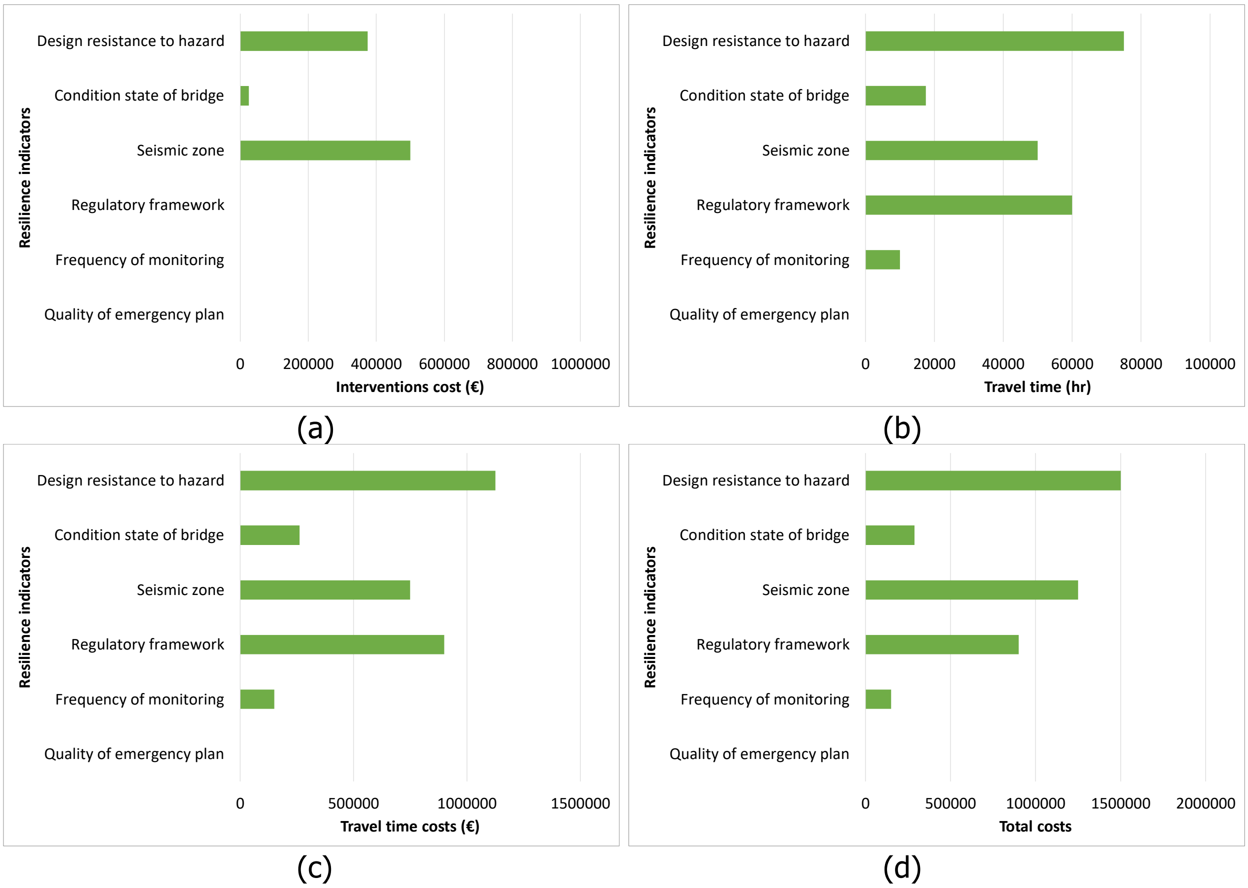
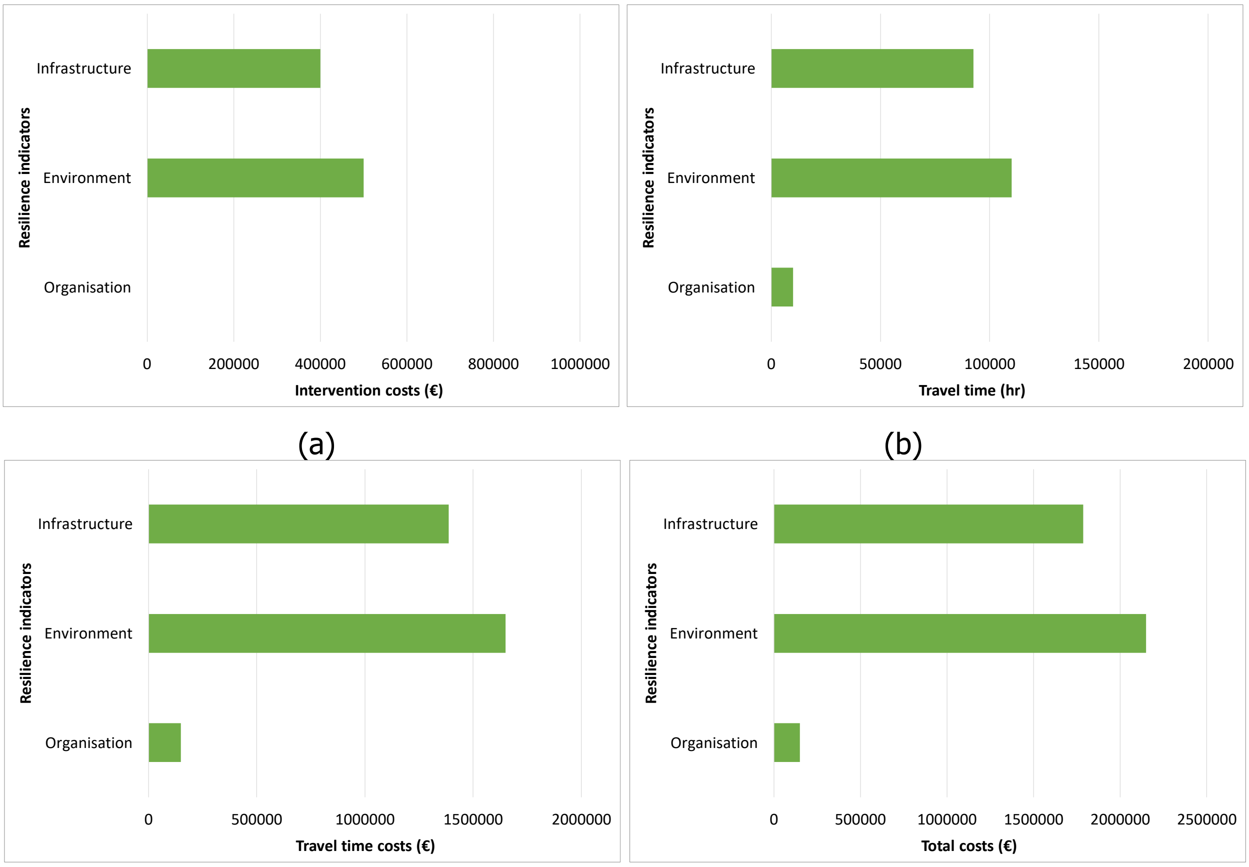


Figure 7. Resilience measures using indicators and using differentiated weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs.



(a) (b) (c) (d)

Figure 8. Resilience measures using transport systems parts and differentiated weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs.

12 APPENDIX E: RESILIENCE MEASURE USING EQUAL RESILIENCE WEIGHTS

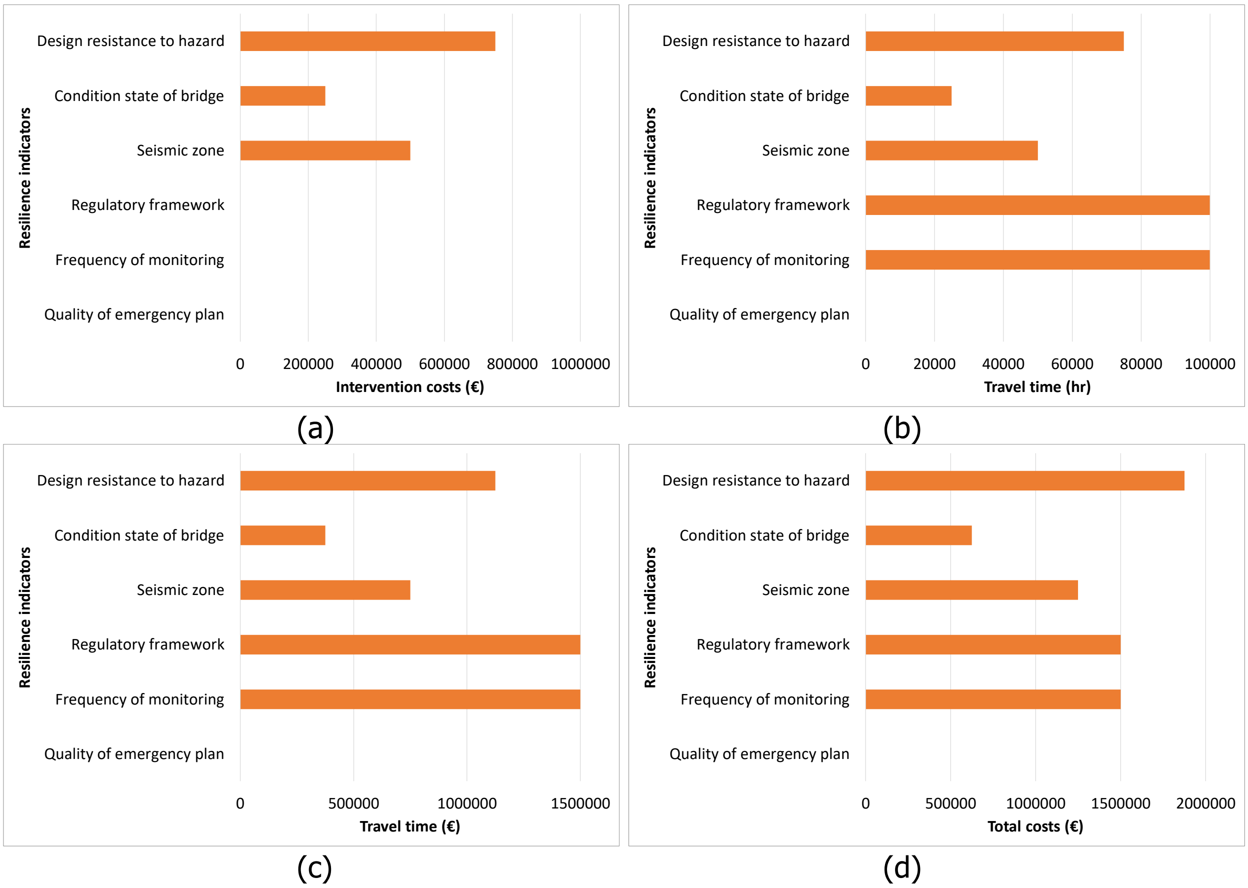
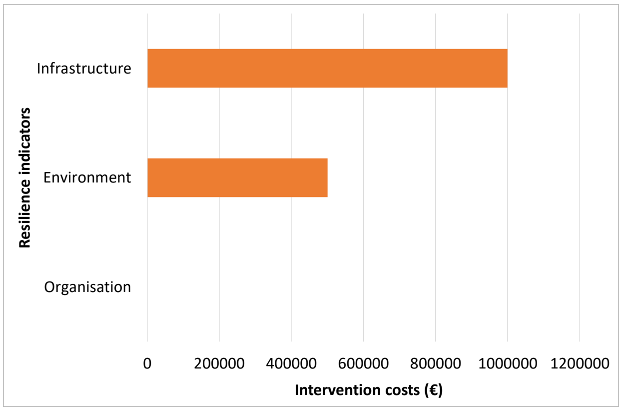
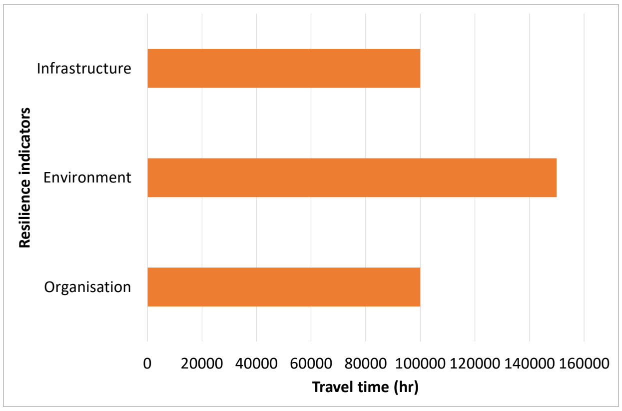


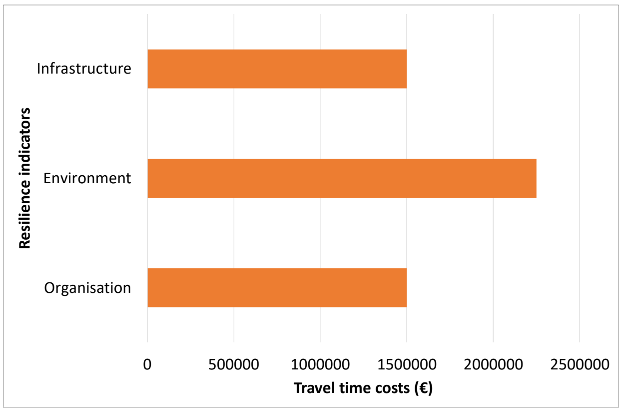
Figure 9. Resilience measures using resilience indicators and equal resilience weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs.



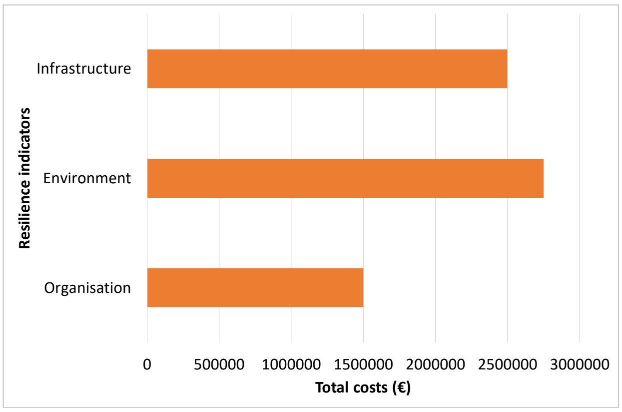
(a)



(b)



(c)



(d)

Figure 10. Resilience measures using equal weights, a) indicators, b) indicators grouped by part of transport system.

13 APPENDIX F: MEMBERS OF THE STAKEHOLDER REFERENCE GROUP

Table 54. Members of the stakeholder reference group

Organization	Contact person	Country
SRG chairman	**Jesús Rodríguez**	**Spain**
ADIF (Railways)	José Conrado Martínez	Spain
ALICE (ETP on logistic)	Fernando Liesa	----
Arup	Savina Carluccio	UK
ASFINAG	Karl Engelke	Austria
CEDR (Conference of European Directors of Roads)	Steve Phillips	----
Deutsche Bahn (DB Umwelt)	Michael Below	Germany
Federal Railway Authority EBA	Maike Norpoth	Germany
Federal Railways SBB	Thierry Pulver	Switzerland
Harris County Toll Road Authority HCTRA	John Tyler	USA
Highways England	James Codd; Angus Wheeler	UK
National Infrastructure Commission NIC	Matt Crossman	UK
NCSR Demokritos	Thanasis Sfetsos	Greece
PIARC (World Road Association)	Miguel Caso	----
Rijkswaterstaat	Willem Otto Hazelhorst	The Netherlands
Road Directorate (M. Fomento)	Oscar Gutiérrez-Bolivar	Spain
Sevilla University	Francisco García Benítez	Spain
Trafikverket	Johan Jonsson	Sweden
Transport for London	Fiona Thompson	UK
Transport Infrastructure Ireland	Billy O'Keeffe	Ireland
Univ. Chalmers	Björn Paulsson	Sweden
Univ. Lulea	Björn Täljsten	Sweden