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Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events

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European foreword

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Introduction

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 potentially disruptive events, e.g. floods, earthquakes, heavy snow falls, fog, high winds, cyberattacks whose frequency of occurrence and severity may change over time, can have significant societal consequences, managers of transport infrastructure manage their infrastructure to minimise this risk, i.e. the probability of having consequences if a disruptive event occurs multiplied by the consequences if it occurs.

In order to do so, however, it is necessary for transport infrastructure managers to have a clear idea of the service the infrastructure is providing and an understanding of its resilience, if affected by disruptive events. In order for managers to be able to optimally reduce risk, they need to be able to measure the service provided by, and the resilience of, their transport infrastructure to these disruptive events. They also have to do this at many different scales, e.g. a bridge, a 100 km road section, an entire transport network, taking into consideration many different types of events and in situations with a wide range of available data, a wide range of available time frames for the estimation, and a wide range of expertise available.

This CWA provides managers with guidance to help ensure complete and systematic definition of service and measurement of resilience, in all situations with which the manager is confronted, and to help identify the suitable resilience enhancing interventions. The three possible ways to measure resilience are proposed 1) using simulations, 2) using indicators with differentiated weights and 3) using indicators with equal weights. Simulations have the highest level of precision but are difficult to use in a way that provides an overview of an entire situation. The accuracy of their results is, of course also dependent on the quality of data and models used. Using indicators is significantly less precise, but provides a better overview of entire situations. Using indicators with differentiated weights provides more accurate overview than using indicators with equal weights. The former requires, however, more time and modelling expertise. The choice as to which of the three way should be used depends greatly on the purpose of measuring resilience to potentially disruptive events, the time to be invested in the assessment and the expertise available. If it is not possible to measure resilience, it is proposed to use the percentage of fulfilment of indicators to obtain an indication of resilience.

In using the guidelines to measure resilience is particularly important to keep in mind the purpose of measuring resilience. For example, exactly how resilience is measure might be different if the purpose of the resilience assessment is to determine how to increase resilience for a single transport system and if the purpose is to compare the resilience of multiple similar but slightly different transport systems.

NOTE 1 In this document the word “intervention” is used to mean anything done by humans, e.g. strengthening a bridge, diverting traffic during an event, and rehearsing activities to be carried out in the case of a disruptive event.

NOTE 2 This document is based on deliverables D1.1 [1] and D1.2 [2] of the FORESEE project which received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 769373.

1 Scope

This document is focused on the resilience of transport systems to specified events. It can be used by any organization that is interested in measuring resilience regardless of size or extent of infrastructure. As transport can occur on infrastructure of multiple types, the measures of service and resilience are also suitable for infrastructure enabling multi-modal transport.

Considering the context of potentially disruptive events, this document is to be used to determine:

— how to measure the service provided by, and the resilience of, transport infrastructure;

— how to set service and resilience targets of transport infrastructure.

This document includes:

— the concepts of how service and resilience can be measured;

— the concepts of how service and resilience targets can be set;

— the steps to determine how to measure service and resilience;

— the steps to set service and resilience targets.

Even if the probability of occurrence of the event is required in the estimation of the system resilience to a specific event, this document provides no guidance as to how to estimate the probability of occurrence of these events. In such situations, this document is to be used to measure the resilience to discrete events whose probabilities of occurrence change over time. Along the same lines, this document is not a complete guideline as to how to conduct a risk assessment of a transport system, of which the resilience to specified events is a part. Instead, it can be used to assess the resilience with respect to the events that are defined in the risk assessment.

This document points out that the assessment of resilience requires, either explicitly or implicitly the modelling of the transport system in space and time, which include the consideration of the interconnections between infrastructure components or between events, including cascading events. It does not, however, provide guidance as how to specifically model these, as the modelling required depends greatly on the specific situation being investigated.

This document also points out that it is essential to define the service being provided by a transport system as a precursor to the assessment of resilience. It does not, however, impose requirements on the services to be considered nor the levels of precision required, as the services considered and the precision required depend greatly on the specific situation being investigated.

For the same reasons, this document does not provide specific information on the organisational requirements to assess resilience, e.g. in terms of human resources, financial skills, partners, schedules or data sources. These requirements depend greatly on purpose of the resilience assessment and the amount of effort the organisation would like to invest, the detail of the resilience estimates they would like to have, and the type of the infrastructure and events to be investigated.

Finally, although the use of expert opinion is recommended in this document in numerous places, no specific guidance is given to which of the plethora of tools and methods that exist should be used. The tools and methods that should be used must be determined on a case-by-case basis and special care is required to ensure their independence.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
absorb phase
the time extending from the start to the end of the disruptive event

The exact definitions of the start and the end of the event is situation dependent.

3.2
intervention costs
all costs incurred by the infrastructure manager

3.3
manage
all activities of infrastructure managers in their effort to ensure that infrastructure provides the expected levels of service, including the planning of maintenance and adaptation interventions

3.4
measure
assess the importance, effect or value of (something)

3.5
measure of service
a quantifiable unit that gives an indication of the level of service being provided

For example, the amount of time required to travel from A to B is a measure of the service provided by a transport system.

3.6
recovery phase
the time extending from the end of the disruptive event to the moment in time where the transport system is once again providing service as expected

The exact definitions of the end of the event and the moment in time where the transport system is once again providing service as expected is situation dependant.

3.7
resilience
ability to continue to provide service if a disruptive event occurs

Note 1 to entry: This definition is tailored to the assessment of resilience of transport systems to potentially disruptive events. It builds on the many different definitions of resilience used by different bodies for different contextual situations. Example definitions includes:

— the IPCC, the Intergovernmental Panel on Climate Change [3]: The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation;

— the NIAC, the National Infrastructure Advisory Council [4]: The ability to function, survive, and thrive no matter what stresses happen and to skilfully prepare for, respond to, and manage a crisis. Finally, it should include the ability to return to normal operations as quickly as possible after a disruption;

— the UNIDSR, the United Nations Office for Disaster Risk Reduction [5]: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.

3.8
service
ability to perform an activity in a certain way

3.9
target
level of service or level of resilience that stakeholders would like to have

4 Concepts

4.1 How service is measured

The service to be provided by transport infrastructure is the safe and sustainable mobility of persons and goods. This service can be operationalized, 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 the construction of the infrastructure and the execution of interventions to counteract gradual deterioration, to restore deteriorated infrastructure so that it provides the required service following the occurrence of disruptive 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 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 transport infrastructure to provide service changes over time due to changing infrastructure. For example, if the infrastructure connecting A and B is in poor, 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, how to measure service can be determined exactly. 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.

4.2 How resilience is measured

Vulnerability is the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt [3]. Resilience encompasses all aspects of how the services provided by infrastructure may be negatively affected by the occurrence of natural or man-made hazards, including the probability that it will be affected by specific hazard events, its vulnerability to the disruptive events, and how quickly and easily it can be restored following the occurrence of the disruptive events.

The definition of resilience in Clause 3.7 makes it explicit as to how resilience is to be measured and removes emphasis on how the system works. With this definition, resilience is to be measured using how service is being affected using each measure of service, and the cost of the interventions required to ensure that the infrastructure once again provides an adequate service.

When considering extreme events, resilience is therefore measured as the cumulative difference throughout the duration of the absorb and recovery phases between

— the service provided by the infrastructure if no event occurs, i.e. before an event occurs and after the infrastructure has been restored, and the service provided by the infrastructure if an event occurs (illustrated in Figures 1 and 2), i.e. during the **absorb** and the **recovery** phase, and

— the costs of intervention if no event occurs and the costs of interventions if an event occurs (illustrated in Figure 3).

This cumulative difference is represented with two areas: red (absorb phase) and blue (recovery phase).

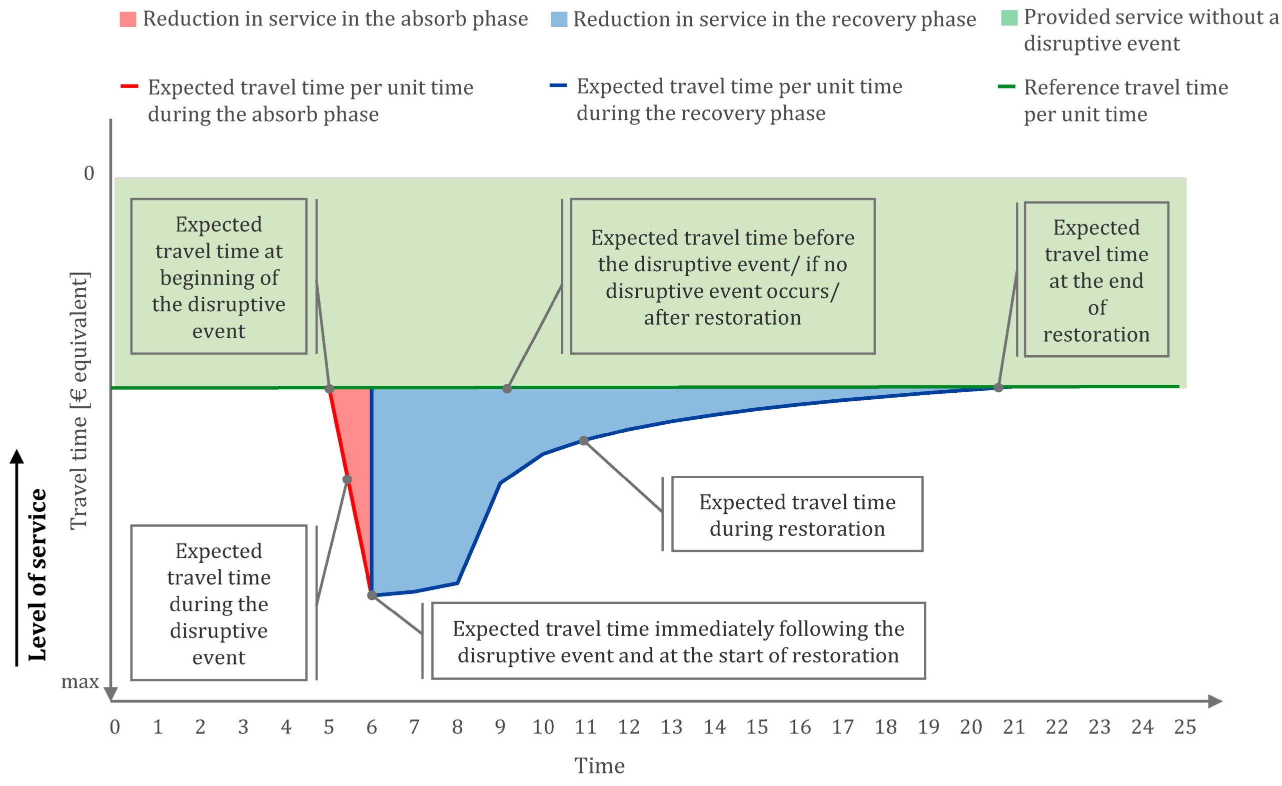


Figure 1 — Illustration of transport infrastructure resilience using the “travel time”measure of service

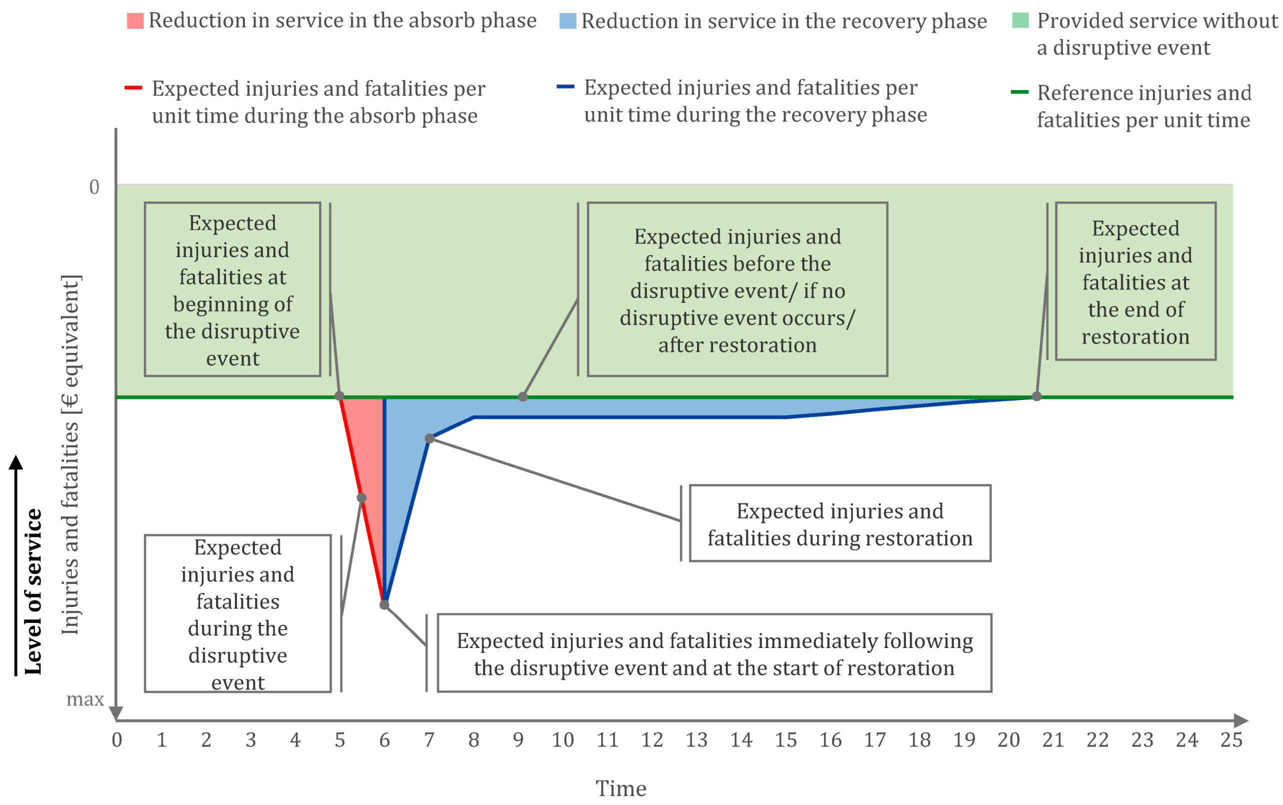


Figure 2 — Illustration of transport infrastructure resilience using the "injuries and fatalities" measure of service

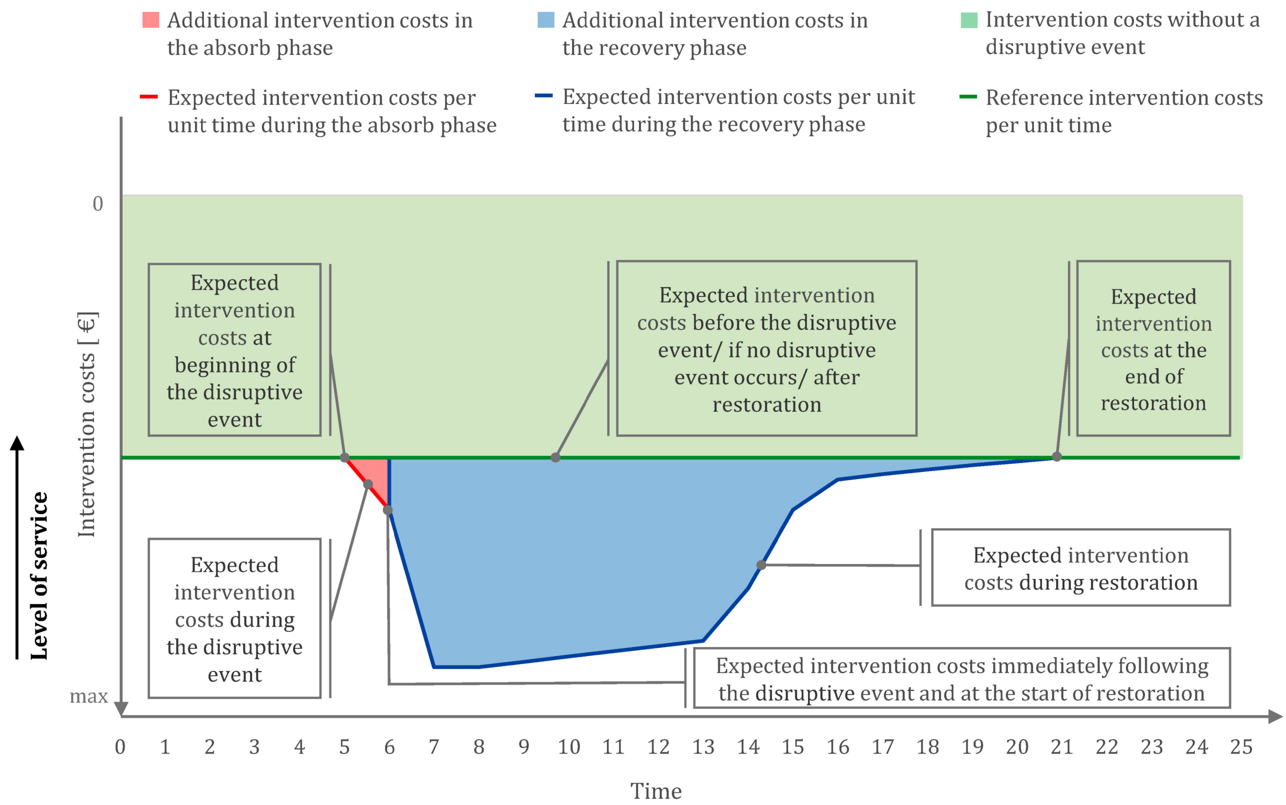


Figure 3 — Illustration of transport infrastructure resilience using intervention costs

Figures 1, 2 and 3 illustrate the resilience of infrastructure enabling the transport of goods and persons from A to B for a scenario where a single disruptive event occurs and the infrastructure is restored so that it provides the same level of service as it did before the disruptive event, using the measures of service expected yearly travel time costs, injuries and fatalities costs, and intervention costs. The green lines indicate the expected costs if there is no disruptive event. The red lines indicate how the expected costs increase from the moment a specific disruptive event begins to the moment that it ends. The blue lines indicate how the expected costs from the moment the disruptive event ends until the moment that the costs are as would be expected without the occurrence of the disruptive event, i.e. service is restored. In Figures 1, 2 and 3, the area between the red-blue and green lines is used as an inverse representation of resilience, i.e. the larger the area, the less resilient the infrastructure, and the smaller the area, the more resilient the infrastructure.

Although only illustrative, the curves in Figures 1, 2 and 3, could be interpreted as showing the following:

— In Figure 1, additional travel time costs are incurred as vehicles begin to slow down and take detours as heavy rains start. As the heavy rains continue some roads are damaged and some closed for safety reasons, causing increasing numbers of vehicles to take detours. The largest increases in travel time occur at the very end of the storm. Once the storm has passed roads begin to be opened and the infrastructure restored so that travel can return to normal.

— In Figure 2, there is a sharp increase in the number of injuries and fatalities during the absorb phase which happens due to a dam breaking and flood waters coming into contact with bridges and roads resulting in injuries and fatalities. The numbers of new injuries and fatalities drop quickly once roads are closed. During the recovery phase, the number of fatalities and injuries are higher than normal due to the deviations of vehicles around damaged infrastructure or due to the inability of persons injured for other reasons being able to reach a hospital, but return to normal once the infrastructure has been restored and the roads reopened.

— Figure 3, the intervention costs rise due to the placing of sandbags and the evacuation of people during the flood event, and then continue to increase due to the cleaning up immediately following the event and the reconstruction of damaged infrastructure until a maximum yearly expenditure is reached. This maximum yearly expenditure then continues until the infrastructure is almost restored and then tapers off as the last work is completed.

4.3 How service and resilience targets are set

Figure 4 shows the types of service and resilience targets that can be set. They are listed in Table 1. The maximum decrease in service from the beginning to the end of the disruptive event is indicated with the red line, and the gradual restoration of the service to the expected level is indicated with the blue line. Targets can be set for:

1) either intervention costs or a measure of service. For example, a target can be set for the maximum increase in travel time costs per unit time following the beginning of the disruptive event and the time until vehicles can once again travel as they could before the event;

2) combinations of intervention costs and measures of service. For example, a target can be set for the total intervention and travel time costs following the beginning of the disruptive event; and

3) multiple disruptive events. For example, the maximum additional travel time costs per unit time following the beginning of either a 500-year earthquake or a 500-year flood.

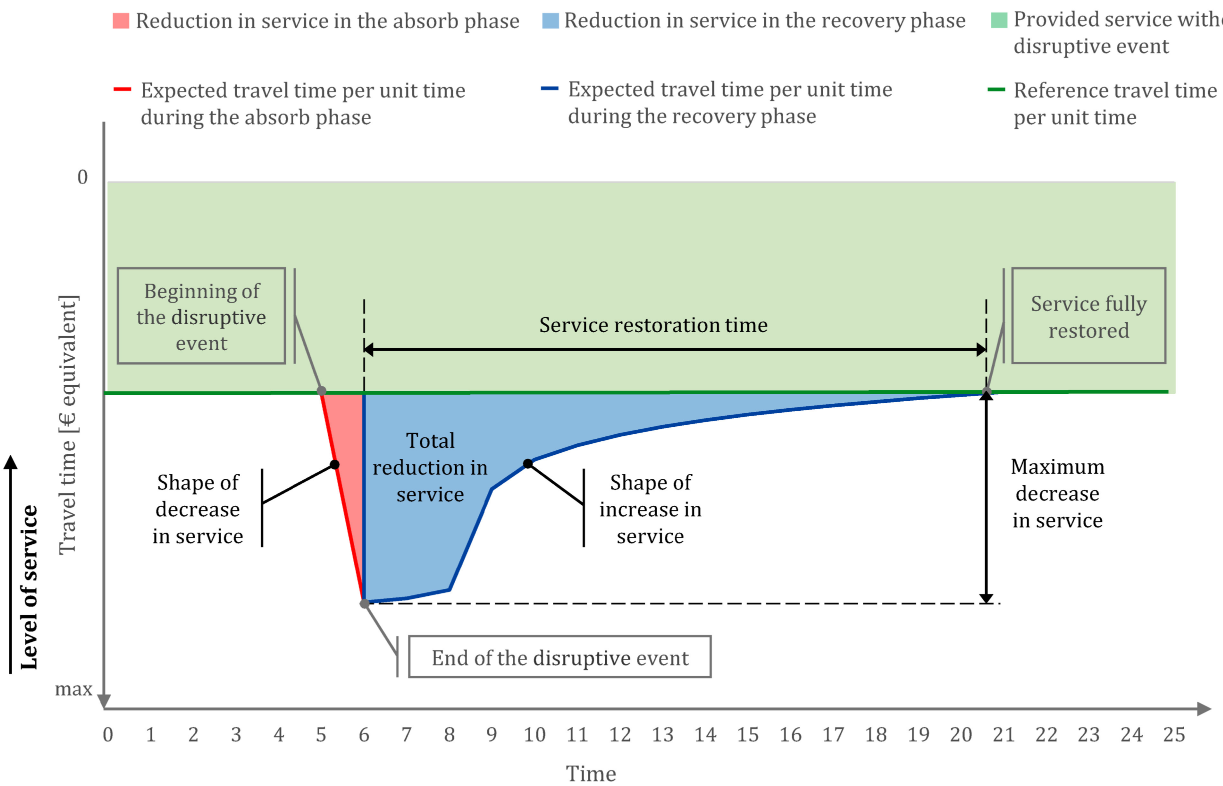


Figure 4 — Illustration of the types of service and resilience targets, using the measure of service travel time as in Figure 1

NOTE The “shape” of the curves is referred to and not the “slope” on purpose, as “shape” encompasses “slope” and not vice versa. The word “slope” would be appropriate if the lines were straight, but they are normally not.

Table 1 — Types of service and resilience targets

Type of target	Description	Example
Maximum increase in intervention costs or decrease in service	Maximal allowed increase in intervention costs or reduction in service after a disruptive event	No more than X additional hours of travel time
Shape of increase in intervention costs or decrease in service	Shape of the intervention costs increase or service decrease curve	Within the first Y minutes of the disruptive event, the travel time is only allowed to increase by X hours, but if the event duration is longer, further increases in travel time are permissible
Shape of intervention costs or reductions of service curve during restoration	Shape of the service restoration	The service should be restored to 80 % of full service within X days, but it is permissible to restore the remaining 20 % in Y weeks
Maximum allowed restoration time	A target can be set on the service restoration time	The service has to be restored fully within X weeks from the beginning of the disruptive event
Maximum total intervention costs or reductions in service	A target can be set on the area between the curves representing the costs of intervention without and with the disruptive event occurring, or the curves representing the service provided if no disruptive event occurred and the service reduction and restoration curves	The area should be no more than X €

5 Define transport system

Before the service provided by, and the resilience of, transport infrastructure is measured, it is necessary to define the parts of the transport system to be considered (Table 2). 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 2 — Parts of the transport system

Part	Description	Examples	Control
Infrastructure	The physical assets that are required to provide service and are considered in the assessment	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

Part	Description	Examples	Control
	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 events	Within the control of the responsible organisation

6 Measure service

6.1 General

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

— define the service the transport system provides;

— determine how the service is to be measured;

— measure and value service.

6.2 Task 1: Define service

In defining service, it is helpful to first think of

— 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;

— the impact of the infrastructure on the stakeholders, i.e. how they are affected.

EXAMPLE If transport infrastructure exists to enable the transport of persons from A to B in 1 hour every day for 365 days in a year, the service provided by the infrastructure can be defined in terms of travel time, or travel time costs. If a disruptive event 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 restaurant 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. Examples of stakeholder groups for public road infrastructure are in Annex A.1 and for rail infrastructure are in Clause B.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 the annexes.

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

6.3 Task 2: 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, and 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

— through running simulations of the transport of persons over the infrastructure over the course of a year and summing the total amount of travel time; or

— by measuring the travel time on specific parts of the infrastructure at specific times (e.g. 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:

— 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

— using the expected ability to transport persons, i.e. ability to satisfy demand if it exists, 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.

NOTE 1 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. In the cases, where expert opinion is used appropriate effort is required to ensure their objectivity, with consideration given to using counter-expertise.

NOTE 2 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.

NOTE 3 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.

6.4 Task 3: Measure and value 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 × 1 × 365). To facilitate comparisons between intervention costs and measures of service it is suggested that the units used to measure service are given monetary values. For example, if travel time has a value of 10€, the service provided, in the previous example, is measured as 36 500 €. Valuing service is an agreement between the stakeholders involved in the assessment. There is no explicitly right or wrong answer. The estimation of the values should as far as possible, however, be related to published values, which may be often found in codes, or collected using one or more valuation techniques, such as hedonic pricing.

NOTE The values associated with 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 [6], and a detailed approach for a specific case can be found in [7].

7 Measure resilience

7.1 General

The tasks involved to measure resilience assuming that the transport system to be considered has been defined and the service is measured are:

1) identify resilience relevant parts of the transport system;

2) determine how resilience is to be measured;

3) measure resilience directly using simulations;

4) measure resilience using indicators with differentiated or equal weights; and

5) estimate percentage of fulfilment of indicators and indicator categories.

Tasks 1 and 2, and Task 3 or 4 are required. Task 5 is optional.

7.2 Task 1: Identify resilience relevant parts of transport system

Task 1 is to determine the resilience relevant parts of the transport system and the relevant factors related to these parts. For example, the resilience relevant parts of infrastructure ensuring transport between A to B may be

— the infrastructure, where two relevant factors might be how a bridge is designed to resist earthquakes and the condition of the bridge;

— the environment, where two 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

— the organisation, where two relevant factors might be the existence of regular monitoring plans and the existence of plans to restore the infrastructure following an earthquake.

7.3 Task 2: Determine how resilience is to be measured

Task 2 is to decide if resilience is to be measured, directly using the reductions in service and additional intervention costs if a disruptive event occurs or indirectly using weighted indicators, or if only an indication of the resilience through the percentage of fulfilment of indicators is to be obtained.

If resilience is to be measured directly using reductions in service, the service provided needs to be simulated first without the disruptive event and then with all disruptive 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. If it is not desired to measure resilience using indicators, which requires estimating the possible reductions in service and intervention costs when disruptive events occur, then the percentage of fulfilment of indicators can be used.

NOTE 1 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.

NOTE 2 The estimates of the future service to be provided with and without disruptive events 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.

NOTE 3 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 disruptive event occurs, which is the most accurate way to do so, but requires by far the most effort.

NOTE 4 Regardless of how the resilience is measured, it is important to realise that poor input will result in poor estimates.

7.4 Task 3: Measure resilience directly using simulations

Task 3 is to measure 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 disruptive events occur and measuring the difference between the service provided when no disruptive event occurred and when the disruptive events occurred. For example, if the total additional intervention costs due to a disruptive event are 1 000 000 € and the total additional travel time costs due to a disruptive event are 1 500 000 €, resilience is measured as 2 500 000 €. The activities included in this task are:

a) estimate the service if no disruptive event occurs and if a disruptive event occurs;

b) estimate the intervention costs if no disruptive event occurs and if a disruptive event occurs;

c) calculate the difference between the service if a disruptive event occurs and the service if no disruptive event occurs;

d) calculate the difference between the intervention costs if a disruptive event occurs and the intervention costs if no disruptive event occurs; and

e) aggregate the differences, if desired.

It is challenging to build simulation tools that are capable of adequately capturing all 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 [5] [6]. 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.

7.5 Task 4: Measure resilience using indicators with differentiated or equal weights

7.5.1 Overview

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

— from the start to the end of a disruptive event, i.e. during **the absorb phase**, including the reductions in service and additional intervention costs during the disruptive event; and

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

The activities included in this task are:

a) identify indicators;

b) check relevancy of indicators;

c) estimate values of the indicators; and

d) measure resilience, either using differentiated weights, or equal weights.

7.5.2 Activity 4a: Identify indicators

Indicators should be identified by,

— selecting each part of the transport system, i.e. the infrastructure, the environment, or the organisation, and then for that part;

— developing categories of indicators[1] at successive levels, until quantifiable indicators are identified that yield indications of the reductions in service and additional intervention costs if the disruptive event occurs; and then

— 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 3 using the small transport system example given in Clause 7.2, i.e. the resilience of the infrastructure connecting A to B may be affected by:

— the infrastructure, where two relevant factors are how a bridge is designed to resist earthquakes and the condition of the bridge;

— the environment, where two relevant factors are the likelihood of having a specific magnitude of earthquake, and the suitability of the regulatory framework enabling how restoration interventions are executed; and

— the organisation, where two relevant factors are the existence of regular monitoring plans and the existence of plans to restore the infrastructure following an earthquake.

NOTE When dealing with indicators it is impossible to have them completely orthogonal. They should be developed to be as orthogonal as possible and acknowledge this shortcoming when interpreting the results.

[1]) A useful first level of indicators consists of the indicators that will provide 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 4) what might happen following the hazard event. These are used in Appendix C.

Table 3 — Example of indicators

Part	Indicator	Relation to phase	Values[a]	Meaning
Infrastructure	Design resistance	Absorb phase - How an asset will react during a disruptive 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 disruptive 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 disruptive event	5	Very low seismic zone
			4	Low seismic zone
			3	Average seismic zone
			2	Moderate seismic zone
			1	Severe seismic zone
	Regulatory framework	Recovery phase – Consequences after a disruptive event	3	Very few administrative hurdles to be crossed after the disruptive event occurs
			2	Some administrative hurdles to be crossed after the disruptive event occurs
			1	Significant administrative hurdles after the disruptive event occurs
Organisation	Frequency of monitoring	Recovery – Consequences during a disruptive event	4	Regular frequent monitoring
			3	Regular but infrequent monitoring
			2	Irregular monitoring
			1	No monitoring
	Quality of emergency plan	Recovery phase – Consequences during a disruptive event	3	Bridge specific plan
			2	Generic plan
			1	No plan

[a] from best to worst – 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.

A more extensive list of possible indicators for transport systems are given in Annex C, 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 can be used in the development of the initial measures of service and an extensive list of indicators.

NOTE 1 In order to obtain wide acceptance of the results, all relevant stakeholders and experts should be involved in the identification of the indicators.

NOTE 2 Indicators 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 disruptive event, e.g. the design resistance to a disruptive event. They are not measures of how a transport system is likely to function over specified periods of time due to disruptive events, e.g. availability. The latter is an intermediary measure, which is in many cases of interest to decision makers and should be reported to help understand the transport system behaviour.

NOTE 3 The difference between the expected intervention costs with and without the occurrence of a hazard event is considered to be a measure of resilience, alongside the differences in the measures of service, and is not itself an indicator.

NOTE 4 If comparisons are to be made between multiple transport systems, the measures of service and the indicators must be the same for all transport systems.

NOTE 5 The values of indicators are interconnected, for example, infrastructure in a high seismic zone, is likely to have a high design resistance.

7.5.3 Activity 4b: Check relevancy of indicators

To ensure that all indicators are relevant, and that there are indicators for all relevant aspects of the service provided by the infrastructure and intervention costs, a change in the value of the indicator has to affect the expected value of the measure of service or intervention costs if a disruptive event occurs, and therefore the resilience of the infrastructure.

The connection between the indicator and resilience should be stated. For example, the higher the value of the seismic zone indicator, the less severe the seismic zone in which a bridge is located. The less severe the seismic zone in which a bridge is located, the lower is the probability of the bridge being affected by an earthquake, and therefore the lower the expected restoration intervention costs and additional travel time costs within a specific period of time. Assuming that everything else is constant[2)], this means that the higher the value of the seismic zone, the higher the resilience of the transport infrastructure. The connections for this example are shown in shortened form in Table 4. Annex C contains example explanations of the connections of a more extensive set of indicators in this shortened form.

NOTE 1 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.

NOTE 2 Table 6 is an example. The selection of the indicators to be used depends on the transport system under assessment, the stakeholders assessing the transport system, and the amount of time and effort to be invested in the assessment of the system. The development of a steering committee with representatives from each stakeholder group would help ensure that no important indicators are missed.

[2)] 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 4 — 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 indicator has the following impact in the resilience [b]
		An increase in the value of the indicator		
		is likely to produce the following impact in the additional costs associated to intervention [a]	is likely to produce the following impact in the additional costs associated to travel time [a]	
Design resistance	The higher the value of the design resistance indicator, the higher the expected design resistance of the bridge	a decrease	a decrease	an increase
Condition state	The higher the value of the condition state indicator, the better the condition state of the bridge	a decrease	a decrease	an increase
Seismic zone	The higher the value of the seismic zone indicator, the less likely it is to have an earthquake of magnitude x	a decrease	a decrease	an increase
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	an increase	a decrease
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	a decrease	an increase
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	a decrease	an increase

[a] With respect to the figures in Clause 4, 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.

[b] With respect to the figures in Clause 4, an increase in the value of an 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.

7.5.4 Activity 4c: Estimate values of indicators

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

— an overview of the values;

— an indication of the resilience, and, if desired;

— an indication as to what can be done to improve the resilience.

The number of possible values used in an assessment and their scales shall be determined for each assessment. They should be determined to represent the ranges of values of interest. The number of values to be used depends on the level at which they can be assessed. Table 5 shows some examples.

NOTE It is useful to use ranges of values that are common in the area being investigated, e.g. if a country normally uses 5 condition states to evaluate the condition of bridges, then it is highly likely that these five condition states should be used in the assessment.

Table 5 — Example values of indicators

Part	Indicator	Number of possible values	Value	Meaning of value[a]
Infrastructure	Design resistance	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 disruptive event occurs
Organisation	Frequency of monitoring	4	1	No monitoring
	Quality of emergency plan	3	3	Bridge specific plan

[a] The meanings of each of the possible values for the example are given in Table 3.

7.5.5 Activity 4d: Measure resilience

7.5.5.1 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 estimated the maximum reduction in service for each measure of service and the maximum additional intervention costs due to each indicator having its worst value while all others have their best values. As the maximum reduction in service and maximum additional intervention costs can be estimated in two ways, they lead to the following two types of weights:

1. Differentiated weights: where the maximum reductions in service and the maximum additional intervention costs are different for each indicator.

2. Equal weights: where the maximum reductions in service and the maximum additional intervention costs are the same for each indicator.

The following subclauses explain how they are estimated.

NOTE The worst value means the value which results in the lowest resilience. The best value means the value which results in the highest resilience.

7.5.5.2 Using differentiated weights

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

— set all indicators to their best values and estimate the reduction in service for each measure of service, and additional intervention costs, if the disruptive event occurs;

— set all indicators to their best values expect one and set that indicator toits worst value, and then estimate the reduction in service for each measure of service, and the additional intervention costs, if the disruptive event occurs; and

— assuming a relationship, e.g. 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 7.5.3) and using the actual values of the indicators, measure the resilience.

NOTE 1 Given the large approximations that are being made when using indicators, it is suggested that a linear relationship be used. An assessor should have very good reasons to use more sophisticated relationships.

NOTE 2 The weight of an indicator is the difference between the value of reduction in service if the indicator has its worst value and the value of the reduction in service if the indicator has its best value. A large difference means that the indicator has a large weight. A small difference means that the indicator has a small weight. The definition of large and small, however, only has meaning for a specific transport system and in comparison with the other indicators being used in the assessment.

NOTE 3 The reduction in service should be agreed upon by all stakeholders involved in the assessment.

Measuring resilience using differentiated weights,

— gives an indication of the reductions in service for each measure of service and the additional intervention costs;

— gives an indication of the possible increase in service and reduction in additional intervention costs by improving the value of each indicator;

— gives an approximate consideration of the interactions between indicators by looking at higher levels of indicators and indicator categories; and

— requires less effort than measuring resilience directly (see 7.4), but is less accurate.

Measuring resilience using differentiated weights is illustrated using the example transport infrastructure from A to B as follows: If all 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 6. Combining these estimates with the indicator values and reductions in service per measure of service and additional intervention costs in Table 6 gives the measures of resilience shown in Table 7 - Table 8. The values shown in Table 8 are the sums of the values given in Table 7 per transport system part, i.e. the measures of resilience per transport system part are the sum of the measures of resilience of its indicators components. The values are shown graphically in Figure D.1 - Figure D.2 in Annex D.3. Explanations of the aspects to be seen in the tables are included in the table footnotes.

NOTE 1 Table 9 contains examples. The maximum expected additional intervention costs and maximum reductions in service are estimated for each transport system. They can be assessed using everything from sophisticated models to expert opinion. The assessors should, however, keep the method of approximation in mind when reporting the results, in terms of accuracy and precision. Assessors should strive to have estimates made at a consistent level of accuracy and precision as they attempt to obtain a complete picture of their resilience.

NOTE 2 The numbers in Table 10 are the relevant sums of those in Table 9. For example, the maximum expected additional intervention costs related to infrastructure indicators is 400 000 €, which is the sum of the maximum expected additional intervention costs related to the design resistance indicator and the condition state of the bridge indicator, which are 375 000 € and the 25 000 € in Table 9. Although these numbers are perhaps not strictly additive, the use of indicators prohibits more sophisticated considerations. The additive assumption still provides a measure of the resilience related to the different groups of indicators. If this approximation is deemed not acceptable, an assessor should progress to the use of simulations, as described in Clause 7.4.

Table 6 — Example maximum and minimum reductions in service due to each indicator for each measure of service using differentiated weights

Part	Indicator	Best or worst value	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service		Maximum expected total costs (€)
					Travel time (h)	Travel time costs (€)	
Infrastructure	Design resistance	Best	5	0[a]	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[b]	60 000	900 000	900 000
Organisation	Frequency of monitoring	Best	4	0	0	0	0
		Worst	1	0[b]	10 000	150 000	150 000
	Quality of emergency plan	Best	3	0	0	0	0
		Worst	1	0[b]	50 000	750 000	750 000

[a] Although, in this example the maximum reductions in service and additional intervention costs 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 disruptive event occurred. The values of zero are used here for the simplicity of clarification.

[b] When the costs associated with the best and worst values of an indicator are the same, it means the indicator is not relevant for this measure of service or intervention cost.

Table 7 — Example resilience measures using indicators and differentiated weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service		Maximum expected total costs (€)
					Travel time (h)	Travel time costs (€)	
Infrastructure	Design resistance	5	2	375 000	75 000	1 125 000	1 500 000[a]
	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[b]

[a] Using differentiated weights, it is shown the largest contributor to the lack of resilience is the design resistance indicator (i.e. 1 500 000 €).

[b] The quality of the emergency plan indicator is the smallest contributor to the lack of resilience. This is because it is already considered to be as good as possible.

Table 8 — Example resilience measures using transport system parts, and differentiated weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service		Maximum expected total costs (€)
					Travel time (h)	Travel time costs (€)	
Infrastructure	Design resistance	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[a]
	Regulatory framework	3	1				
Organisation	Frequency of monitoring	4	1	0	10 000	150 000	150 000[b]
	Quality of emergency plan	3	3				

[a] At the part level, there is a slightly different view than at the lower levels because there are multiple indicators per part of the transport system. The largest contributor to the lack of resilience is the environment (i.e. 2 150 000 €).

[b] The smallest contributor to the lack of resilience is the organisation (150 000 €). This is because the frequency of monitoring has a relatively small effect on resilience, and the quality of the emergency plan indicator has the highest value possible.

7.5.5.3 Using equal weights

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

— imagine that all indicators have their best values and estimate the reductions in service, if the disruptive event occurs, for each measure of service;

— imagine that all indicators have their worst values and estimate the reductions in service, if the disruptive event occurs, for each measure of service; and then

— 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 7.5.3), and using the actual values of the indicators, measure the resilience.

Measuring resilience using equal weights,

— gives an indication of the reduction of service for each measure of service;

— gives an indication of the possible increases in service by improving the value of each indicator;

— gives approximate consideration of the interactions between indicators, by looking at higher levels of indicators and indicators categories; and

— requires less effort than measuring resilience directly (see 7.4) and less effort than measuring resilience using differentiated weights, but is less accurate.

Measuring resilience using equal weights is illustrated using the example transport infrastructure from A to B as follows: If all 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 disruptive event are 2 500 000 €. An extension of this example is given in Table 9. Combining the estimates Table 9 with the indicator values and the reductions in service in Table 9 yield the measures of resilience per indicator and indicator category (Table 10 - Table 11). The values are shown graphically in Figure E.1 - Figure E.2 in Annex E.

NOTE Table 11 contains examples. The maximum reductions in service and the maximum expected additional intervention costs is estimated for each transport system under assessment. They can be assessed using everything from sophisticated models to expert opinion. The assessors should, however, keep the method of approximation in mind when reporting the results, in terms of accuracy and precision. Assessors should strive to have estimates made at a consistent level of accuracy and precision, as they attempt to obtain a complete picture of their resilience.

Table 9 — Example maximum and minimum reductions in service due to the values of indicators for each measure of service using equal weights

Part	Indicator	Best or worst value	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service: Travel time (h)	Maximum reductions in service: Travel time costs (€)	Maximum expected total costs (€)
Infrastructure	Design resistance	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[a]	0	0	0
		Worst	1	0	100 000	1 500 000	1 500 000[b]
	Quality of emergency plan	Best	3	0[a]	0	0	0
		Worst	1	0	100 000	1 500 000	1 500 000

[a] 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.

[b] The worst and best values of the total costs encompass the fact that not all relevant indicators affect all relevant service types or intervention costs. 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 10 — Example resilience measures using indicators and equal weights

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service: Travel time (h)	Maximum reductions in service: Travel time costs (€)	Maximum expected total costs (€)
Infrastructure	Design resistance	5	2	750 000	75 000	1 125 000	1 875 000[a]
	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[c]	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[b]

Part	Indicator	Number of possible values	Value	Maximum expected additional intervention costs (€)	Maximum reductions in service		Maximum expected total costs (€)
					Travel time (h)	Travel time costs (€)	

[a] Using indicators, it is shown that the largest contributor to the lack of resilience is the design resistance 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 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.

[b] The smallest contributor to the lack of resilience is the quality of the emergency plan indicator (0 €). This is because it already has the best value possible.

[c] 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 11 — Example resilience measures using transport system parts and equal weights

Part	Indicator	Number of possible values	Value	Reductions in service and additional intervention costs			
				Intervention costs (€)	Travel time (h)	Travel time costs (€)	Total costs (€)
Infrastructure	Design resistance	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[a]
	Regulatory framework	3	1				
Organisation	Frequency of monitoring	4	1	0	100 000	1 500 000	1 500 000[b]
	Quality of emergency plan	3	3				

[a] 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 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.

[b] The smallest contributor to the lack of resilience is the organisation (1 500 000 €).

7.5.6 Summary

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 no disruptive event occurs and if disruptive event 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 indicators with differentiated 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 reductions in service for each measure of service and the additional intervention costs due to the values of each indicator.

The third most accurate and third most effort intensive way to measure resilience is using 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 disruptive event, and not due to the values of each indicator. This only requires the estimation of the 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[3)].

7.6 Task 5: Estimate percentage of fulfilment of indicators and indicator categories

7.6.1 General

Once a measure of resilience exists, it is often useful 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. This can be done using:

— differentiated weights, i.e. the worst value of each indicators represents the maximum reductions in service, for each measure of service, and the maximum additional intervention costs for each relevant indicator;

— equal 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

— no weights.

These are explained in the following three subclauses, using the possible values shown in Table 5.

7.6.2 Using differentiated weights

The reductions in service and additional intervention costs per indicator, upon which the percentages of fulfilment using differentiated weights are calculated, are shown in (Table 12). The percentages of fulfilment of indicators and indicator categories are shown in (Table 13 and Figure 5).

The percentages of fulfilment of an indicator using differentiated weights, Pf_{i_dw} are given by:

$$Pf_{i\_dw} = \left(1 - \frac{Rs_{av\_dw} + Ic_{av\_dw}}{Rs_{wv\_dw} + Ic_{wv\_dw}}\right) \cdot 100\ \%$$

where

RS_{av_dw} = reductions in service with the actual indicator value using differentiated weights;

3) 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.

IC_{av_dw} = additional intervention costs with the actual indicator value using differentiated weights;

RS_{wv_dw} = reductions in service with the worst indicator value using differentiated weights;

$IC_{worst.value\_dw}$ = additional intervention costs with the worst indicator value using differentiated weights.

EXAMPLE The reductions in service and additional intervention costs attributed to the frequency of monitoring 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. This is the same as the reduction in service because the indicator has its worst value;

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

The percentages of fulfilment of the indicator categories using differentiated weights $\left(Pf_{ic\_dw}\right)$ are calculated as follows:

$$Pf_{iC\_dw} = \left(1 - \frac{\sum_{n=1}^{N} RS_{av\_n\_dw} + \sum_{n=1}^{N} IC_{av\_n\_dw}}{\sum_{n=1}^{N} RS_{wv\_n\_dw} + \sum_{n=1}^{N} IC_{wv\_n\_dw}}\right) \cdot 100\ \%$$

where

$\sum_{n=1}^{N} RS_{av\_i\_dw}$ = reductions in service with the actual values of all indicators in the indicator category n using differentiated weights;

$\sum_{n=1}^{N} IC_{av\_n\_dw}$ = additional intervention costs with the actual values of all indicators in the indicator category n using differentiated weights;

$\sum_{n=1}^{N} RS_{wv\_n\_dw}$ = reductions in service with the worst values of all indicators in the indicator category n using differentiated weights;

$\sum_{n=1}^{N} IC_{wv\_i\_dw}$ = additional intervention costs with the worst values of all indicators in the indicator category n using differentiated weights.

EXAMPLE The reductions in service and additional intervention costs attributed to the actual value of 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 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 reductions in service and additional intervention costs due to the worst 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 12 — Example reductions in service and additional intervention costs per indicator using differentiated weights

Part	Indicator	Number of possible values	Value	Reductions in service and additional intervention costs				
				Min./ Actual/ Max.	Intervention costs (€)	Travel time (h)	Travel time costs (€)	Total costs (€)
Infrastructure	Design resistance	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 13 — Example percentages of fulfilment using differentiated weights

Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using differentiated weights	
				of indicators	of parts
Infrastructure	Design resistance	5	2	25 %	43.3 %
	Condition state of bridge	5	4	75 %	
Environment	Seismic zone	5	3	50 %	36.8 %[c]
	Regulatory framework	3	1	0 %	
Organisation	Frequency of monitoring	4	1	0 %[a]	83.3 %
	Quality of emergency plan	3	3	100 %[b]	

[a] The indicator with the lowest of the possible values is the frequency of monitoring indicator, which is 0 % fulfilled, i.e. a value 1 of 4.

[b] The indicator with the highest of the possible values is the quality of emergency plan indicator, which is 100 % fulfilled, i.e. a value of 3 of 3.

[c] Using differentiated weights, the precentages of fulfilment of the parts of the transport system categories show that the environment indicators are only 36.8 % fufilled. This is more than the 25 % that the user of this document might expect because the seismic zone indicator has a greater weight, i.e. it has more effect on resilience than the regulatory framework 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))*100 % = 36.8 %*

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.

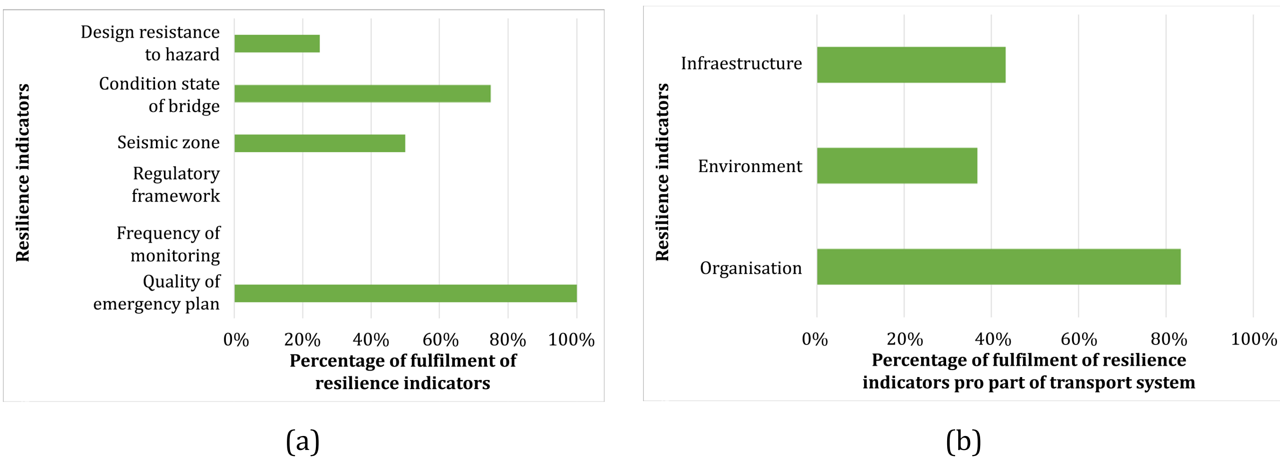


Figure 5 — Example percentages of fulfilment using differentiated weights, a) indicators, and b) indicators grouped by part of transport system

7.6.3 Using equal weights

The reductions in service and additional intervention costs per indicator, upon which the percentages of fulfilment using equal weights are calculated, are shown in (Table 14). The percentages of fulfilment of indicators and indicator categories using equal weights are shown in (Table 15 and Figure 7). The percentages of fulfilment of an indicator using equal weights $\left(Pf_{i\_ew}\right)$ are given by:

$$Pf_{i\_ew} = \left(1 - \frac{RS_{av\_ew} + IC_{av\_ew}}{RS_{wv\_ew} + IC_{wv\_ew}}\right) \cdot 100\%$$

where

RS_{av_ew}	=	reductions in service with the actual value of the indicator using equal weights;
IC_{av_ew}	=	additional intervention costs with the actual value of the indicator using equal weights;
RS_{wv_ew}	=	reductions in service with the worst value of the indicator using equal weights;
IC_{wv_ew}	=	additional intervention costs with the worst value of the indicator using equal weights.

EXAMPLE The 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 indicator categories using equal weights, Pf_{iC_ew} , are given by:

$$Pf_{ic\_ew} = \left(1 - \frac{\sum_{n=1}^{N} RS_{value\_n\_ew} + \sum_{n=1}^{N} IC_{value\_n\_ew}}{\sum_{n=1}^{N} RS_{worst.value\_n\_ew} + \sum_{n=1}^{N} IC_{worst.value\_n\_ew}}\right) \cdot 100\ \%$$

where

$\sum_{n=1}^{N} RS_{av\_n\_ew}$	=	reductions in service with the actual values all indicators in the indicator category n using equal weights;
$\sum_{n=1}^{IN} IC_{av\_n\_ew}$	=	additional intervention costs with the actual values all indicators in the indicator category n using equal weights;
$\sum_{n=1}^{IN} RS_{wv\_n\_ew}$	=	maximum reductions in service with the worst values of all indicators using equal weights;
$\sum_{n=1}^{N} IC_{wv\_n\_ew}$	=	maximum additional intervention costs with the worst values of all indicators using equal weights.

EXAMPLE The reductions in service and additional intervention costs attributed to the 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 14 — Example reductions in service and additional intervention costs per indicator using equal weights

Part	Indicator	Number of possible values	Value	Reductions in service and additional intervention costs				
				Min./ Actual/ Max.	Intervention costs (€)	Travel time (hr)	Travel time costs (€)	Total costs (€)
Infrastructure	Design resistance	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 15 — Percentages of fulfilment with equal weights

Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using equal weights	
				of indicators	of parts
Infrastructure	Design resistance	5	2	25 %	50 %
	Condition state of bridge	5	4	75 %	
Environment	Seismic zone	5	3	50 %	31.25 %[c]
	Regulatory framework	3	1	0 %	
Organisation	Frequency of monitoring	4	1	0 %[a]	50 %
	Quality of emergency plan	3	3	100 %[b]	

[a] The indicator with the lowest of the possible values is the frequency of monitoring indicator, which is 0 % fulfilled, i.e. a value 1 of 4.

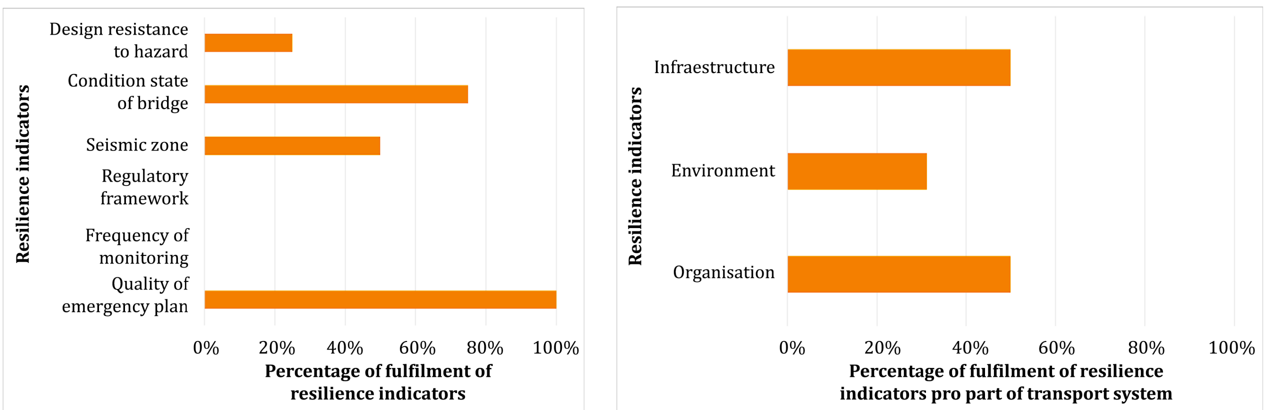
[b] The indicator with the highest of the possible values is the quality of emergency plan indicator, which is 100 % fulfilled, i.e. a value of 3 of 3.

[c] Using equal weights, the precentages of fulfilment of the parts of the transport system categories, show the environment indicators are 31.25 % fulfilled. This is because there is no difference between the contribution of a unit change in the value of the seismic zone indicator and a unit change in the value of the regulatory framework indicator, 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

$$(1 - (500\,000+750\,000+1\,500\,000) / (1\,000\,000+1\,500\,000+1\,500\,000))*100\ \% = 31.25\ \%$$

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



(a) (b)

Figure 6 — Percentages of fulfilment using equal weights, a) indicators, and b) indicators grouped by part of transport system

7.6.4 Using no weights

The percentages of fulfilment using no weights, Pf_{nw} are shown in Table 16 and Figure 7. The percentages of fulfilment of an indicator using no weights are calculated as follows:

$$Pf_{i\_nw} = \frac{I_{av} - 1}{I_{worst.v} - 1} \cdot 100\ \%$$

where

I_{av} = the actual value of the indicator;

I_{wv} = the worst value of the indicator.

EXAMPLE For the frequency of monitoring indicator which has a value of 1, the percentage of fulfilment is (1-1)/(4-1)*100 % = 0 %.

The percentages of fulfilment of the indicator categories using no weights $\left(Pf_{ic\_nw}\right)$ are calculated as follows:

$$Pf_{ic\_nw} = \frac{\sum_{n=1}^{N} Pf_{nw\_n}}{n_i}$$

where

Pf_{nw_i} = the percentage of fulfilment of the indicators, or indicator subcategories, within the indicator category;

n_i = the number of indicators, or indicator subcategories, within the indicator category.

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

Table 16 — Percentages of fulfilment with no weights

Part	Indicator	Number of possible values	Value	Percentage of fulfilment of indicators and indicator categories using no weights	
				of indicators	of parts
Infrastructure	Design resistance	5	2	25 %	50 %
	Condition state of bridge	5	4	75 %	
Environment	Seismic zone	5	3	50 %	25 %[c]
	Regulatory framework	3	1	0 %	
Organisation	Frequency of monitoring	4	1	0 %[a]	50 %
	Quality of emergency plan	3	3	10 0%[b]	

[a] The indicator with the lowest of the possible values is the frequency of monitoring indicator, which is 0 % fulfilled, i.e. a value 1 of 4.

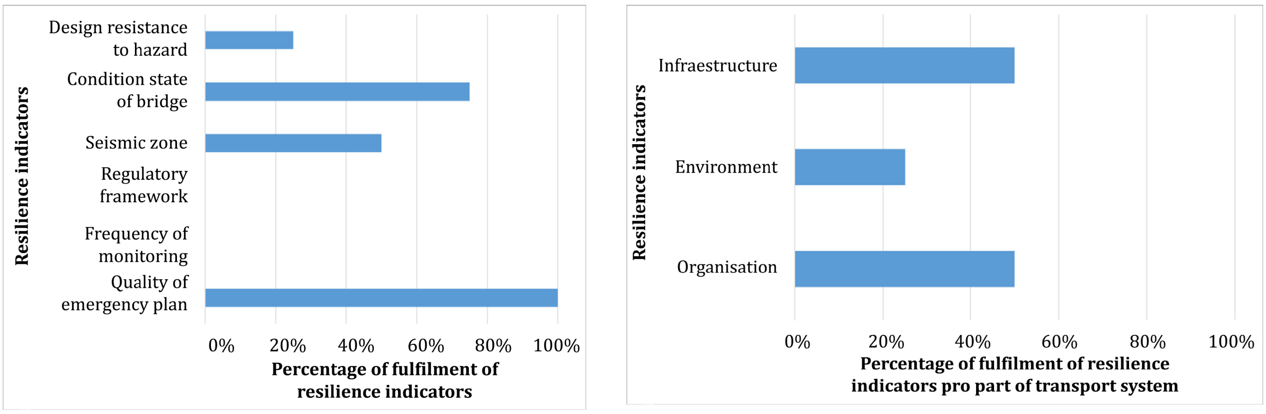
[b] The indicator with the highest of the possible values is the quality of emergency plan indicator, which is 100 % fulfilled, i.e. a value of 3 of 3.

[c] Using no weights, the precentages of fulfilment of the parts of the transport system categories, show the environment indicators are 25 % fulfilled.

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

(50 % + 0 %) / 2 = 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.



(a) (b)

Figure 7 — Percentages of fulfilment using no weights, a) indicators, and b) indicators grouped by part of transport system

8 Set targets

8.1 Overview

The setting of targets for resilience is an activity that helps convert the wishes of stakeholders into something that infrastructure managers can use in deciding which resilience enhancing interventions are to be executed. As with measuring levels of service and resilience, exactly how targets are set depend on the transport system being investigated and the exact purpose of setting targets.

In general, the process to set service and resilience targets comprises the following tasks:

— gather all relevant stakeholders;

— determine legal requirements;

— determine stakeholder requirements; and

— set targets.

The specific method to be used to set targets, i.e. task 4, depends on:

— how resilience is measured, i.e. using simulations or indicators; and

— whether or not cost-benefit analysis is to be used.

If service and resilience are measured using simulations, targets are set for the target types described in Table 1. If service and resilience is measured using indicators, targets are set on the values of the indicators. Targets are set either with or without cost-benefit analysis. The choice of whether to use cost-benefit analysis depends on how service and resilience are to be measured, the information available, and the time and expertise available. If the information, time, and expertise are available cost-benefit analysis should be used. If they are not available, targets are to be set using expert opinion.

The setting targets is explained in this clause without providing details as to how to estimate the costs and benefits used. How these are estimated is to be determined on a case-by-case basis and must fit with the estimation of the possible reductions in service as estimated in the previous clause. They can be estimated using a large number of possible methods ranging from sophisticated estimation techniques and the use of extensive data to expert opinion and no data. The former requiring considerable time and effort, but providing relatively accurate results. The latter required little time and effort, but providing only approximate results. An assessor has to be aware of the level accuracy used in the assessment when reporting on and interpreting the results. Documentation as to how the costs and benefits have been estimated should be kept to ensure that the assessment can be reproduced, and easily updated if required. The costs and benefits must be estimated considering acceptable time horizons. The time horizon used should be clearly stated in documentation.

8.2 Task 1: Gather all relevant stakeholders

In this task, all relevant stakeholders are gathered, whose opinion on setting the service and resilience targets, or the indicator targets, should be considered. This is greatly dependent on the transport system itself, and the potential scope of the service and resilience targets, or the indicator targets. For example, if service and resilience targets are only to be set based on intervention costs, the relevant stakeholders will only encompass those managing the infrastructure and those providing financial contributions. If, however, service and resilience targets are to be set based on intervention costs and travel time, the group of relevant stakeholders will be larger, and will include, for example, the users of the network. As transport is an integral part of society, the stakeholders will probably also include political representatives.

8.3 Task 2: Determine legal requirements

In this task, the legal requirements for service and resilience targets, or indicator targets, are determined. Examples of legal requirements from laws or contractual agreements that prescribe service or resilience targets are:

— levels of redundancy in transport networks;

— limits on the maximum number of expected accidents; and

— speed limits to control the amount of NOx gases that are emitted.

Examples of legal requirements for indicator targets are:

— the condition of a bridge has to be 4 or better;

— the design resistance has to be at least that specified in a specific national code; and

— the frequency of monitoring has to be every 2 years or less.

As these originate from various sources, e.g. general laws and concessionaire contracts, and obtaining a complete list often requires a considerable effort, legal specialists should be tasked with identifying these requirements. All service and resilience targets, or indicator targets, have to at least fulfil all legal requirements. Example legal requirements for the example indicators are shown in Table 17.

Table 17 — Example legal requirements for indicators (indicators without legal requirements are omitted)

Part	Indicator	Values from best to worst	Meaning	Target
Infrastructure	Design resistance	5	Design code level 5	Legal requirement: Value 2 Concessionaire's contract: Value 3
		4	Design code level 4	
		3	Design code level 3	
		2	Design code level 2	
		1	Design code level 1	
	Condition state of bridge	5	Like new	Legal requirement: Value 2
		4	Slightly deteriorated	
		3	Average	
		2	Poor	
		1	Alarming	
Organisation	Quality of emergency plan	3	Bridge specific plan	Legal requirement: Value 2
		2	Generic plan	
		1	No plan	

8.4 Task 3: Determine stakeholder requirements

In this task, the requirements of the stakeholders in addition to legal requirements are determined. Examples influencing the service and resilience targets are:

— restrictions on the types of restoration interventions that can be executed due to the design of the transport network;

— restrictions on the type of equipment that can be used in restoration activities because of accessibility;

— specifications on the type of monitoring activities required following the occurrence of a disruptive event;

— specifications on the number of staff required per restoration activity;

— specifications as to the number of emergency response teams available in extreme situations; and

— expectations that connectivity is to be restored as fast as possible following a disruptive event.

Examples for indicators targets are:

— the condition state of a bridge must be above 3;

— the design resistance of all bridges must be better than that prescribed by the most recent code.

There are indicators for which it is meaningless to set a target. For example, the seismic zone in which a bridge is located is an indicator of the level of service that it will provide following a disruptive event, and of its resilience, but as it cannot be changed, it makes little sense to set a target seismic zone for the bridge.

It is helpful to think along the lines of the stakeholders defined in task 1, e.g. first think about the additional (i.e. not already legally determined) requirements of the infrastructure managers, the users, the directly affected public and the indirectly affected public.

8.5 Task 4: Set targets

8.5.1 General

In this task, the targets are set. The next four subclauses show the different methods, depending on whether service and resilience is measured directly or with indicators, and whether or not cost-benefit analysis should be used.

8.5.2 Task 4a: Service and resilience targets without cost-benefit analysis

With this method, the service and resilience targets are set taking into consideration the requirements defined in the previous two tasks, and by using direct measures of service and resilience without cost-benefit analysis. The previously defined requirements set limits on possible targets. Setting targets requires the opinion of domain experts and the involved stakeholders. As this is often a highly iterative task, sufficient time should be planned to reach a widely supported agreement.

The targets should be set, or consciously not set, for:

— each type of target (Table 1);

— each type of intervention costs and measures of service;

— each combination of intervention costs and measures of service; and

— each combination of type and intensity of the disruptive events considered.

In setting the targets, the interdependencies between the measures of service and intervention costs should be considered, e.g. it may not be wise to target very low amounts of additional travel time and very low intervention costs following a disruptive event.

Once the targets are set, it should be determined how they are measured. An example of targets and methods of measurements are shown in Table 18 for the earthquake event from Deliverable D1.1. This task should conclude with a set of targets that are broadly accepted by the stakeholders.

Table 18 — Example service and resilience targets for an earthquake event

Intervention costs / Service measures	Target type	Description	Target	Measurement
Intervention costs	Maximum increase in intervention costs or decrease in service	The costs of the emergency measures	Maximum emergency budget: 2 000 000 € per event	via the bookkeeping system of the infrastructure owner
	Maximum total intervention costs or reductions in service	The total costs incurred until the travel time service is returned to normal	Maximum total costs: 4 500 000 € per event	
Travel time	Maximum increase in intervention costs or decrease in service	The increase of travel time after an earthquake event	Below 45 min. per trip	via automated traffic flow monitoring system
	Shape of intervention costs or losses of service curve during restoration	The way in which travel time returns to normal after an earthquake event	Within 1 week after the earthquake: Max. delay of 30 min. per trip; Within 3 weeks after the earthquake: Max. delay of 15 min. per trip	
	Maximum allowed restoration time	The total time from onset of the earthquake event until normal travel time	Within 12 Weeks after the earthquake: no traffic delays	

In summary, setting service and resilience targets without cost-benefit analysis can be summarised as collecting all necessary expert opinion to formulate a broadly accepted set of service and resilience targets that take into consideration all aspects of the transport system that are deemed important, including the interdependencies between intervention costs and levels of service. The targets are formulated so that it is clear how they are to be measured.

8.5.3 Task 4b: Indicator targets without cost-benefit analysis

With this method, the indicator targets are set, taking into consideration the requirements defined in the previous two tasks and by using indicators without cost-benefit analysis. The previously defined requirements set limits on possible targets, i.e. due to some of the requirements some targets may not be possible. Setting targets requires the opinion of domain experts and the involved stakeholders. As this is often a highly iterative task, sufficient time should be planned to reach a widely supported agreement.

The targets should be set, or consciously not set, for

— each indicator; and

— each combination of indicators.

For example, Table 19 shows a list of consciously included and excluded indicators, together with a reason for inclusion or exclusion.

Table 19 — Example included and excluded target indicators

Part	Indicator	Decision	Reason
Infrastructure	Design resistance	Include	Legal requirement present
	Condition state of bridge	Include	Legal requirement present
Environment	Seismic zone	Exclude	Outside the sphere of influence of the infrastructure operator
	Regulatory framework	Exclude	
Organisation	Frequency of monitoring	Include	Increases awareness of problems
	Quality of emergency plan	Include	Legal requirement present

In setting the targets, the interdependencies between the indicators should be considered, e.g. having bridges in a moderate condition state if they have a high design resistance might provide the same resilience as having bridges in a good condition state if they have a moderate design resistance.

Once the targets are set, it should be determined how they are to be measured. An example of targets and methods of measurements are shown in Table 20, for one earthquake event within 3 years, i.e. the targets should be met for one single earthquake and another happening 4 years later, but need not be met if the second earthquake happens 2 years after the first. This task should conclude with a set of targets that are broadly accepted by the stakeholders.

Table 20 — Example indicator targets

Part	Indicator	Values from best to worst	Meaning	Target	Measurement
Infrastructure	Design resistance	5	Design code level 5	Legal requirement: 2 Agreed upon target: 3	A one-time inspection by an external expert
		4	Design code level 4		
		3	Design code level 3		
		2	Design code level 2		
		1	Design code level 1		
	Condition state of bridge	5	Like new	Legal requirement: 2 Agreed upon target: 3	Yearly inspection by an external expert
		4	Slightly deteriorated		
		3	Average		
		2	Poor		
		1	Alarming		
Organisation	Frequency of monitoring	4	Regular frequent monitoring	Agreed upon target: 4	An external audit every 5 years
		3	Regular but infrequent monitoring		
		2	Irregular monitoring		
		1	No monitoring		
	Quality of emergency plan	3	Bridge specific plan	Legal requirement: 2 Agreed upon target: 3	An external audit every 5 years
		2	Generic plan		
		1	No plan		

Setting indicator targets without cost-benefit analysis can be summarised as collecting all necessary expert opinion to formulate a broadly accepted set of indicator targets, including the interdependencies between indicators. The targets are formulated so that it is clear how they are to be measured.

8.5.4 Task 4c: Service and resilience targets with cost-benefit analysis

With this method, the service and resilience targets are set, taking into consideration the requirements defined in the previous two tasks, and the benefits and costs of achieving the targets. It is similar to that described in Clause 8.5.2, with the exception that the costs and benefits of achieving the targets are explicitly estimated. The sub-tasks required to do this are:

— select the types of targets to be set for restoration intervention costs and each measure of service;

— develop possible sets of targets, keeping in mind the legal restrictions;

— determine the scenarios of how the targets in each target set are to be reached;

— estimate the costs of achieving the targets sets and the benefits of each scenario in terms of the restoration intervention costs and measures of service; and

— evaluate the ability of each scenario to achieve the target sets taking into account the legal requirements and select the best one with respect to the benefits and costs.

In the first sub-task, possible types of targets to be set are selected, e.g. for a 100-year flood event, targets might be set on the maximum allowed time until the amount of travel time incurred by the users is restored to normal and the maximum increase in restoration intervention costs. The types of targets should be selected for all measures of service that stakeholders consider important and the restoration intervention costs. In selecting the possible types of targets, the effort required to develop, and evaluate, whether the sets of targets have been achieved, should be considered. For example, if specific levels of additional travel time reduction over the restoration period is targeted, which is a specific shape of restoration curve for the travel time measure of service, the effort required to estimate the reduction in additional travel time during the restoration period must be considered. Example types of targets are shown in Table 21.

Table 21 — Example service and resilience target types for a 100-year flood event

Restoration intervention costs or measure of service	Target type	Description
Restoration intervention costs	Maximum increase in restoration intervention costs	The amount of money required to finance the activities of the emergency response team
	Maximum total restoration intervention costs or reductions in service	The total amount of money spent on interventions from the beginning of the disruptive event until the users can once again travel as they could prior to the disruptive event
Travel time	Maximum decrease in service	The maximum increase of travel time per day following a 100-year flood
	Restoration curve shape	The way in which travel time returns to normal following a 100-year flood
	Restoration time	The total amount of time from onset of the 100-year flood until users can once again travel as they could prior to the disruptive event

In the second sub-task, possible sets of targets are determined while taking into account the legal restrictions. These sets of targets consist of a combination of one or more targets for one or more types of targets. An example set of targets is shown in Figure 8 for the travel time measure of service. The green horizontal line represents the expected travel time. The black line represents the additional travel time following the disruptive event. The grey dashed lines below and above the black line represent the uncertainty related to the reduction of service (black line). The red dotted line represents the legal requirements to be fulfilled. The blue dotted lines and the blue letters show the targets included in the example target set, i.e.:

a) the maximum reduction of the travel time measure of service;

b) the maximum allowed time until the travel time measure of service is returned to normal;

c) the maximum allowed reduction in the travel time measure of service per unit time during the absorb phase;

d) the maximum allowed reduction in the travel time measure of service per unit time during the recovery phase; and

e) the total lost travel time from the beginning of the disruptive event until full restoration of service.

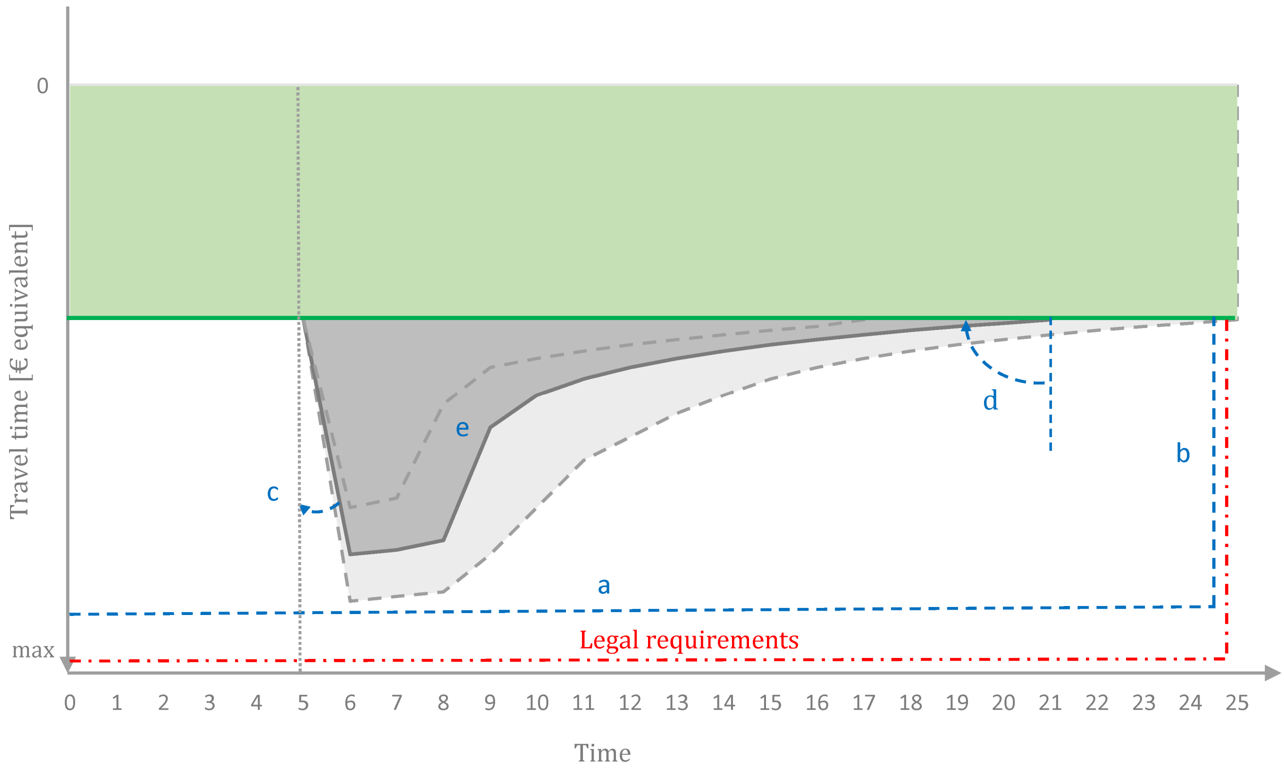


Figure 8 — Example target types for the travel time measure of service

Although Figure 8 shows a target set for only one measure of service, they can include targets on all measures of service and the restoration intervention costs. An example is shown in Figure 9, which includes targets on the “travel time” measure of service and the restoration intervention costs, or more specifically:

a) the maximum reduction of the travel time measure of service;

b) the maximum total time from the beginning of the disruptive event until the transport system again functions as normal;

c) the maximum reduction of the travel time measure of service per unit time during the absorb and recovery phases; and

d) the maximum additional intervention costs from the beginning of the disruptive event until the transport system again functions as normal.

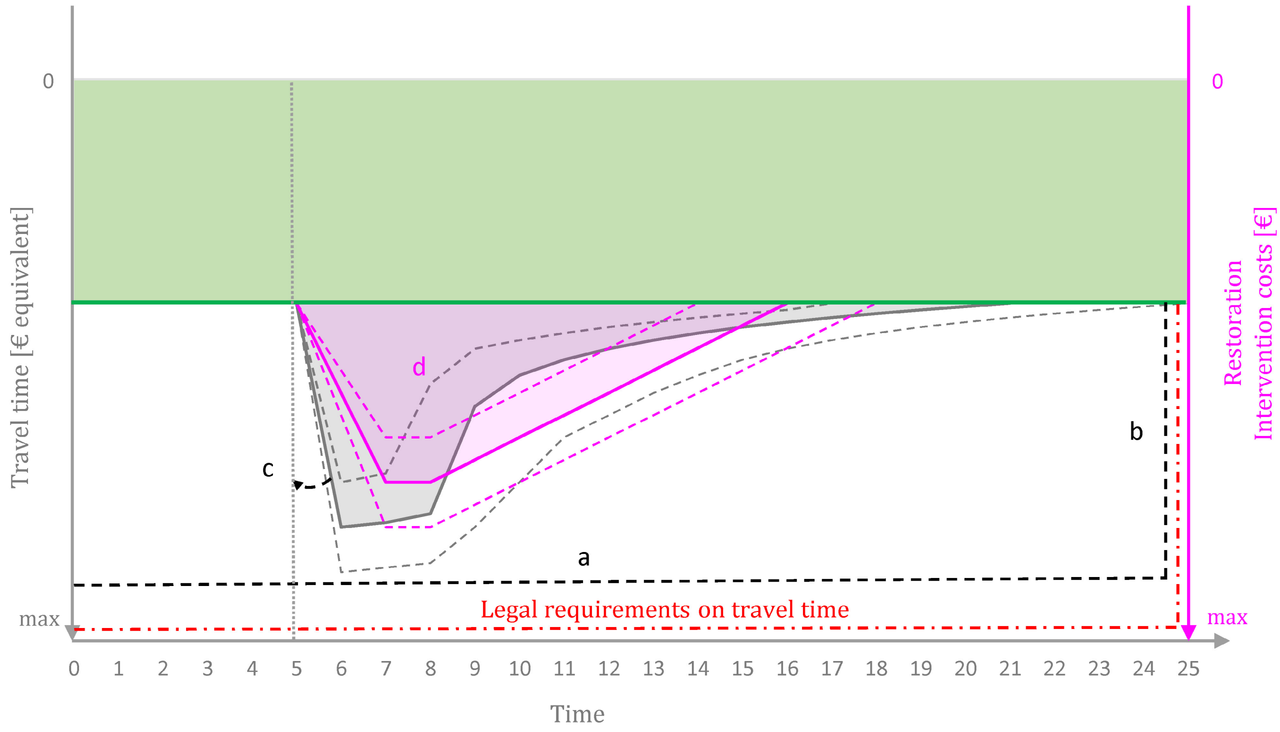


Figure 9 — Example of types of target for the travel time measure of service and the restoration intervention costs

An example of multiple possible target sets is given in Table 22 and Figure 10 to Figure 12. Figure 10 shows that there is to be no additional travel time incurred and no restoration intervention costs following the event. Figure 11 shows that the additional travel time incurred should be kept within legal limits, i.e. the maximum allowed reduction of service. There are no constraints placed on the restoration intervention costs. Figure 12 shows that the restoration intervention costs are to be kept with a specified budget limit. There are no constraints placed on the additional travel time. Although, there is uncertainty in all cases whether targets will be met, the probabilities of them not being met should be negligible. The definition of negligible must be agreed on by stakeholders. The costs associated with each target set are given in Table 23.

Table 22 — Example target sets

Target set	Label	Description	Targets per type of target			Illustration
			maximum reduction of the service of travel time	the maximum restoration time	the maximum restoration intervention costs	
1	No changes in service	There is no change in travel time given a 100-year flood occurs	None	Not specified	Not specified	Figure 10
2	Legal minimum	All legal requirements for travel time are fulfilled	Largest legally permitted	Largest legally permitted	Not specified	Figure 11
3	Restoration budget	The available budget will be used	Not specified	Not specified	Under the specified	Figure 12

Target set	Label	Description	Targets per type of target			Illustration
			maximum reduction of the service of travel time	the maximum restoration time	the maximum restoration intervention costs	
		fully, in order to maximise the service achievable with the money available			restoration budget	

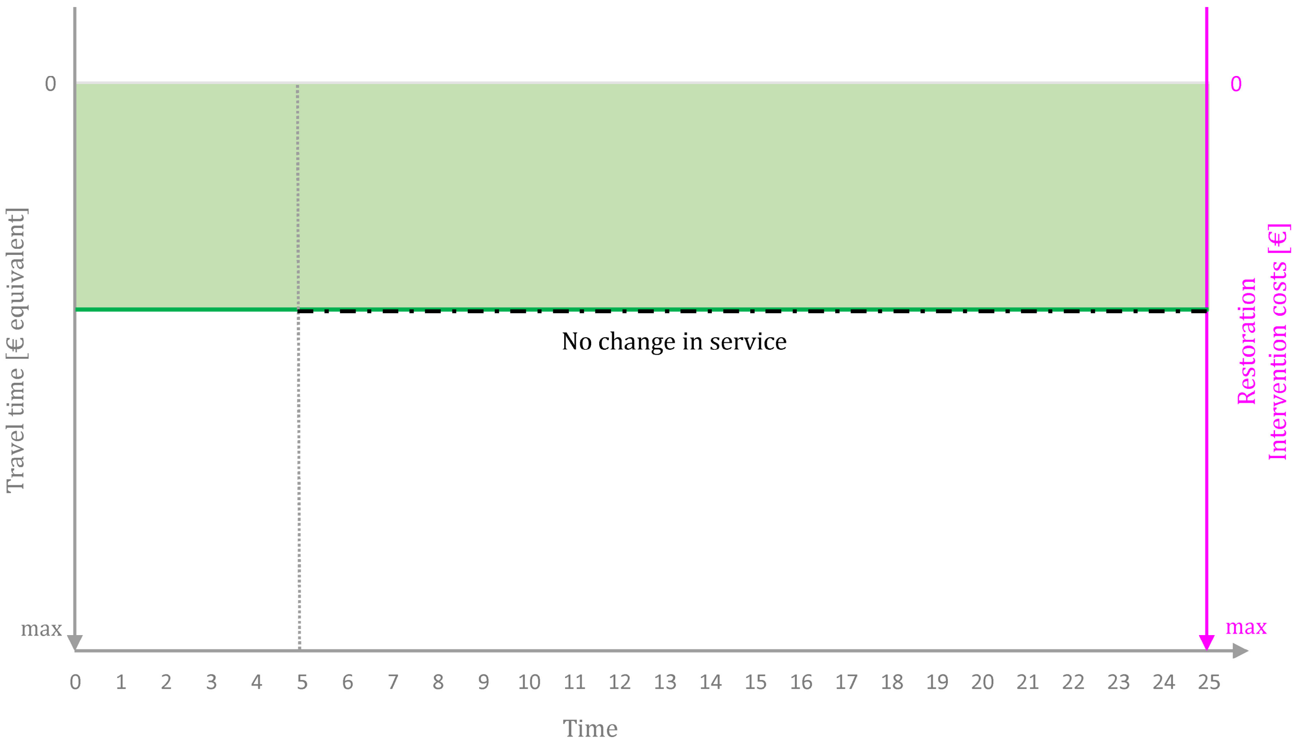


Figure 10 — Graphical representation of target set 1

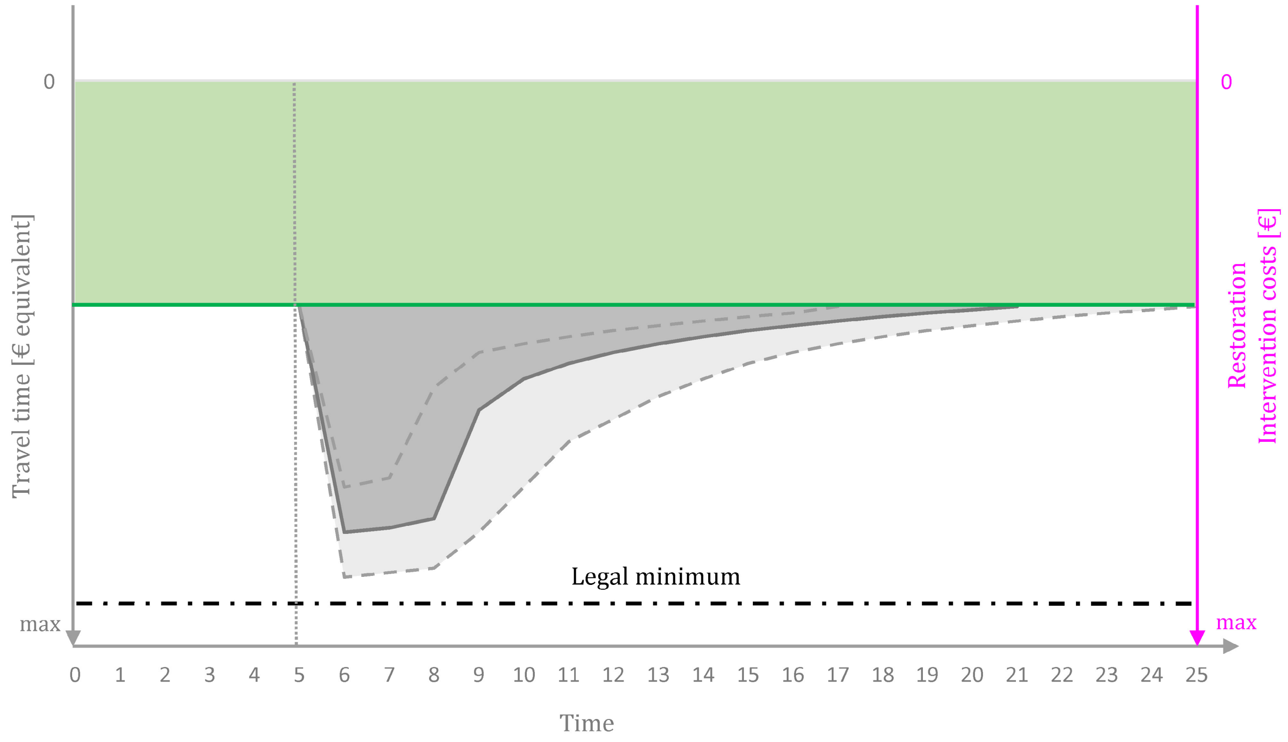


Figure 11 — Graphical representation of target set 2

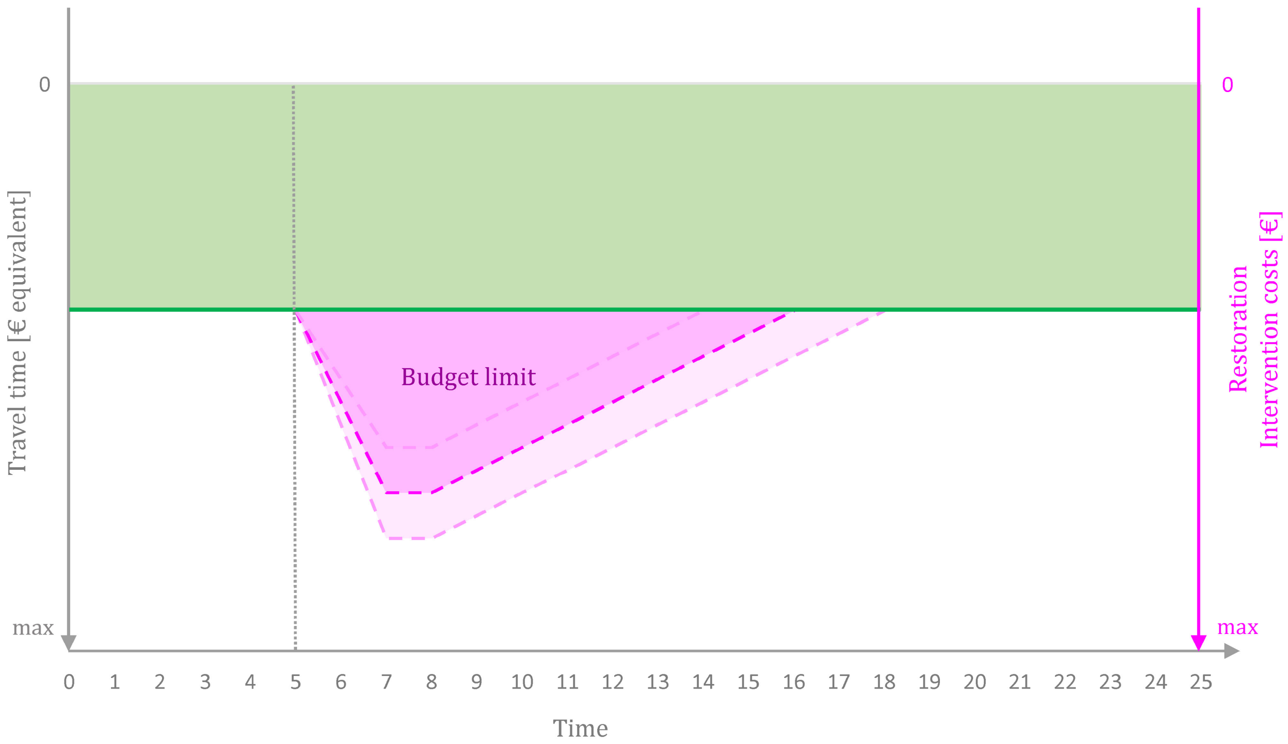


Figure 12 — Graphical representation of target set 3

In the third sub-task, how these target sets are to be achieved is determined. For example,

— To ensure that the users of transport infrastructure experience no increase in travel time if a 100-year flood event occurs, a second bridge to design code level 5 will be built.

— To ensure that the legal requirements are met, the existing bridge will be strengthened.

— To ensure that restoration intervention costs remain within a specified budget, the existing bridge will be strengthened in a way that makes it easy to rehabilitate following the occurrence of a disruptive event.

If it is realised during the determination of how the target sets could be achieved, that achieving a target set is not possible, e.g. there is not enough money for the second bridge, it should be excluded from further consideration.

In the fourth sub-task, the costs of attempting to achieve the targets sets, and the effect of each of the scenarios on the restoration intervention costs and the measures of service are estimated. This requires estimating how the modified transport system will behave following the disruptive event. This is done using a combination of available data, expert opinion, models and simulations. It is advised to use ranges of values for all uncertain variables.

EXAMPLE Constructing a second bridge designed to code level 5, might cost 10 500 000 € (low estimate), 13 000 000 € (medium estimate), or 16 500 000 € (high estimate). It might, however, yield benefits in terms of the reduction in restoration intervention costs and the measure of service travel time, that are needed due to the state of the object after the event. For example, the costs of restoring the bridge could be reduced by 150 000 € (low estimate), 160 000 € (medium estimate), or 170 000 € (high estimate), and the additional travel time incurred during the restoration period could be reduced by 28 000 000 € (low estimate), 31 000 000 € (medium estimate), or 34 000 000 € (high estimate). Table 23 contains, for all three example, target sets, examples of ranges of costs to achieve targets, restoration intervention costs, and effects on the travel time measure of service.

Table 23 — Expected costs of achievement of target set, effects on restoration intervention costs and effect on the travel time measure of service

Costs / Measure of service	Estimate	Costs and benefits of the target sets		
		Target set 1 **“No changes in service”** **(€)**	**Target set 2** **“Legal minimum”** **(€)**	**Target set 3** **“Restoration budget”** **(€)**
Costs of achievement of target set	Low Medium High	10 500 000 13 000 000 16 500 000	9 600 9 600 9 600	20 000 30 000 40 000
Benefit in terms of reduction in restoration intervention costs	Low Medium High	150 000 160 000 170 000	17 000 18 000 19 000	12 000 13 000 14 000
Benefit in terms of reduction in additional travel time costs	Low Medium High	28 000 000 31 000 000 34 000 000	17 550 19 500 21 450	95 400 106 000 116 600
Benefit	Low Medium High	28 150 000 31 160 000 31 417 000	34 550 37 500 40 450	34 550 37 500 40 450
Net benefit	Worst (low benefits – high costs)	11 650 000 18 160 000 23 670 000	30 850 27 900 24 950	67 400 89 000 110 600

Costs / Measure of service	Estimate	Costs and benefits of the target sets		
		Target set 1 "No changes in service" (€)	Target set 2 "Legal minimum" (€)	Target set 3 "Restoration budget" (€)
	Medium (medium benefits – medium costs Best (high benefits – low costs)			

In the fifth sub-task, the ability of each scenario to achieve the sets of possible targets is evaluated and the one with the highest net-benefit is selected, with the selected set of targets having broad support from the stakeholders. To do this, the costs of achieving the target sets are compared with their benefits, in terms of the reduction in restoration intervention costs and the effects on the measures of service for which targets are set. The level of precision of the estimates can vary depending on the sophistication of the analysis.

Three simple examples of how this works are shown in Table 23. The bottom row shows the net-benefit for the three target sets, divided into worst, medium and best case. For target set 1, for example:

— the worst net-benefit is 11'650 000 € = (28 000 000 € + 150 000 €) - 16 500 000 €,

— the medium net-benefit is 18 160 000 € = (31 000 000 € + 160 000 €) - 13 000 000 €

— the best net-benefit is 23 670 000 € = (31 417 000€ + 170 000 €) - 10 500 000 €.

It can be seen from Table 23 that target set 1 gives the highest net-benefits.

If target set 1 is selected, the user of this document should proceed with the construction of the second bridge to withstand a 100-year flood event, i.e. to ensure that there are no restoration intervention costs and no additional travel time costs following a 100-year flood event.

Setting service and resilience targets with cost-benefit analysis can be summarised as collecting all necessary expert opinion to formulate sets of service and resilience targets that take into consideration all aspects of the transport system that are deemed important. This includes the interdependencies between intervention costs and measures of service and selecting the scenario and set of targets that has broad stakeholder support and yields the maximum net-benefit. The targets are formulated so that it is clear how they are to be measured.

8.5.5 Task 4d: Indicator targets with cost-benefit analysis

With this method, the indicator targets are set, taking into consideration the requirements defined in the previous two tasks, and based on the assumption that the net-benefit, i.e. the benefits – the costs should be maximised. It is similar to that described in Clause 8.5.3, with the exception that the costs of achieving the targets is explicitly evaluated regarding the benefits of reaching the targets.

The targets should be set, or consciously not set, for

— each indicator; and

— each combination of indicators.

The method is based on an incremental benefit/cost ratio calculation that investigates the benefit/cost ratio of increasing the indicator target by one level. Choosing the highest indicator target with a positive benefit/cost ratio yields the indicator target with the highest overall net-benefit. The sub-tasks required to set targets when reflecting on the costs and benefits of changing indicator values are:

1) Select the indicators for which targets are to be set, e.g. the emergency plan indicator

2) Each target is set to the lowest value possible, e.g. the emergency plan indicator should have a value of 2 (meaning for example that the emergency plan is practised every 2 years), if regulations require that frequency 2.

3) Estimate the additional costs of each unit increase in the value of each indicator from the lowest legally allowed value, e.g. the additional costs of increasing the emergency plan indicator from

   a) 2 to 3, i.e. practising the emergency plan every year instead of every two years, is € 0.8 million due to the higher number of hours spent on practising; and

   b) 3 to 4, i.e. practising the emergency plan every 6 months instead of every year, is € 2.0 million due to the even higher number of hours spent on practising that requires extra personnel to be hired to coordinate and fill in the missing hours in normal work.

4) Estimate the additional benefits of each unit increase in the value of each indicator from the lowest legally allowed value, e.g. the additional benefits of increasing the emergency plan indicator, due to increases in the probability that all organisations involved in emergency actions will act as expected leading to reduced restoration times, from

   a) 2 to 3, is € 1.9 million due to less travel time costs as the restoration time is shorter;

   b) 3 to 4, is € 1.95 million due to even less travel time costs as the restoration time is now as fast as possible.

5) Estimate the benefit/cost ratio for each unit increase for each indicator to determine if each increase is worthwhile, e.g. the benefit/cost ratio from

   a) 2 to 3 is 1.9 / 0.8 = 2.375 which is greater than 1, meaning that it is worthwhile to increase the value of the emergency plan indicator from 2 to 3;

   b) 3 to 4 is 1.95 / 2.0 = 0.975 which is less than 1, meaning that it is not worthwhile to increase the value of the emergency plan indicator from 3 to 4.

6) Set targets for all indicators based on the estimated benefit/cost ratios, the available resources and the opinions of the stakeholders, which should be able to broadly support the targets, e.g. the target for the emergency plan indicator is 3.

Using the example from Clause 8.5.3, targets for the indicators “condition state of object” and “frequency of monitoring” are shown in Table 24, along with the legal requirement for the indicators (col. “Legal req”.), the possible values of the indicators, and the increment costs (for the condition state indicator due to executing more interventions to keep the condition state better, and for more frequent monitoring due to higher monitoring costs), increment benefits (due to lower restoration intervention costs and less travel time because of the better state of the object following the event due to the initial condition of the object, and faster restoration due to better information because of frequent monitoring), benefit/cost ratio of increasing the value of the indicator by one are shown. The last column shows the total net-benefit, i.e. the sum of the upgrade benefits from indicator level 1 to the respective indicator level minus the sum of the associated upgrade costs. For example, the net-benefit for the condition state of object, level 3 is (12 913 € + 10 505 €)-(8 000 € + 10 000 €) = 5 418 €.

Table 24 — Costs and effects on service of increases in the values of indicators

Indicator	Legal req.	Possible values	Increment costs (€)	Increment benefit (€)	Benefit / cost ratio	Net benefit (€)
Condition state of object	-	1	-	-	-	-
		2	8 000	12 913	1.61	4 913
		3	10 000	10 505	1.05	5 418
		4	11 000	11 121	1.01	5 539
		5	12 000	9 900	0.83	3 439
Frequency of monitoring	2	1	-	-	-	-
		2	10 000	8 800	0.88	-1 200
		3	12 000	12 200	1.02	-1 000
		4	15 000	10 244	0.68	-5 756

To follow the incremental process, and because there is no legal requirement for the condition state of the object, the incremental process starts at level 1, and with a benefit/cost ratio of 1.61, is moved to level 2 as a target. As the benefit/cost ratio for moving from level 2 to level 3 is 1.05, the target is further moved to level 3. Even more, as the benefit/cost ratio to upgrade from level 3 to level 4 is 1.01, and thus larger than 1.0 (but barely), the target is moved to level 4. The move from level 4 to level 5, however, is not done with the benefit/cost ratio being 0.83 and thus smaller than 1. This signifies that for every extra Euro spent, there is only a return of 0.83 Euros. Therefore, the target should stay at level 4. The associated net-benefit, which is the highest, is 5 539 €.

For the indicator "frequency of monitoring" the process starts at level 2, which is the legal requirement. The benefit/cost ratio to upgrade to level 3 is 1.02, and so the target is moved to level 3. As the further upgrade from level 3 to level 4 has a benefit/cost ratio of 0.68, the target stays at level 3. The associated net-benefit, which is the highest but still negative, is -1 000 €.

With this, the target for the indicators should be set to level 4 of 5 for the indicator "condition state of object" and level 3 of 4 for the indicator "frequency of monitoring".

Setting indicator targets with cost-benefit analysis can be summarised as a process that takes the level of an indicator first to the legal minimum, and then incrementally upgrades the level step-by-step upwards to the maximum level, if the benefit/cost ratio of the specific upgrade step is larger than 1.0. This also results in the indicator target with the highest net-benefit.

NOTE 1 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.

NOTE 2 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 indicators are to be used.

Annex A
(informative)

Example road stakeholders, intervention costs and measures of service

A.1 Stakeholders

When investigating roads, the user of this document can think of the stakeholders in the categories shown in Table A.1.

Table A.1 — Road stakeholder groups

Stakeholder group	Definition	Examples
Owner/manager	Entity responsible for decisions with respect to physically modifying the infrastructure	A road authority, a concessionaire
Users	Persons who are using the roads	A person being transported on a road, a person transporting something on a road
Directly affected public	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	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

A.2 Intervention costs

Road managers execute interventions to ensure that infrastructure continues to provide an adequate level of service. It can be quantified as shown in Table A.2.

Table A.2 — Road manager intervention costs

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Intervention	Impact of executing interventions	Labour	Economic impact of people performing tasks	Cost of labour required for the execution of interventions
		Material	Economic impact of people ensuring that materials are available for use	Cost of material required for the execution of interventions
		Equipment	Economic impact of people ensuring that equipment is available for use	Cost of equipment required for the execution of interventions
	Impact of accident during the execution of interventions	Infrastructure property damage	Economic impact of repairing damages caused due to the execution of interventions	Cost of replacing the damaged property or as part of the fatality or injury costs
		Workforce injury	Societal impact due to injury at workplace	Willingness to pay to avoid a workforce injury
		Workforce fatality	Societal impact due to death at workplace	Willingness to pay to avoid a workforce fatality

A.3 Measures of service

A.3.1 General

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

NOTE The tables in the following clauses provide examples of how the value of units service can be determined. No detailed explanation of exactly how they should be estimated is provided. How they are to be estimated depends on the transport system under assessment, the stakeholders involved and the time and effort that should invested in the project.

A.3.2 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,

— within a specific amount of time;

— without being hurt or losing his/her life;

— with only a specific amount of wear and tear on his/her vehicle;

— without being physically or psycologically negatively affected; and

— without having excessive noise.

The associated measures of service and how they can be quantified are shown in Table A.3.

Table A.3 — Measures of service related to the road user

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Travel time	Impact of travel condition in terms of time lost in travel	Work	Economic impact of wasting work time travelling	Salaries of the persons travelling
		Leisure	Economic impact of wasting leisure time travelling	Willingness to pay to reduce travel time
		Commuting	Economic impact of delay during commuting travel	Willingness to pay to reduce travel time
Accident	Impact on the users due to the users being involved in an accident	Property damage	Economic impact of repairing the vehicle	Cost of replacing the damaged property or as part of the fatality or injury costs
		Injury	Societal impact due to the injury	Willingness to pay to avoid injury
		Fatality	Societal impact due to the fatality	Willingness o to pay to avoid fatalities
Vehicle operation	Impact on the vehicle cost	Operation	Economic impact of people ensuring that fuel and oil is available for use	Cost of fuel and oil

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
		Maintenanc e	Economic impact of people repairing vehicles and ensuring that materials, e.g. tires and brake pads, are available for use	Costs of vehicle maintenance
Comfort	Impact of travelling on the users	Physical	Societal impact of obtaining for example, bruises from an extremely bumpy ride	Willingness to pay to reduce the physical effects of the ride, such as noise or vibration
		Psycho-Logical	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	Willingness to pay to reduce the psychological effects of the ride
Noise	Societal impact due to the users coming in contact with sound emissions			Willingness to pay to reduce noise

A.3.3 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:

— hurt or losing his/her life;

— physically or psychologically negatively affected;

— subjected to excessive noise; and

— subjected to excessive emissions.

These can be quantified as shown in Table A.4. The reason they should be handled seperately is that the directly affected public is affected in fundamentally different ways than the users.

Table A.4 — Measures of service related to the directly affected public

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Accidents	Impact on the directly affected public due being involved in an accident	Property damage	Economic impact of repairing property damaged due to a vehicle coming off of the road	Cost of replacing the damaged property
		Injury	Societal impact due to the injury	Willingness to pay to avoid injury
		Fatality	Societal impact due to fatalities	Willingness to pay to avoid death

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Comfort	Impact of travelling on the directly affected public	Physical	Societal impact of physical changes due to people travelling on the road, e.g. due to vibrations	Willingness to pay to avoid the physical effects, for example, noise and vibration, of the railway traffic
		Psychological	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	Willingness to pay to avoid the physical effects
Noise	Societal impact due to the directly affected public coming in contract with sound emissions			Willingness to pay to reduce noise
Emissions	Impact on people due to the environment being impacted by particle emissions	CO_2	Societal impact due to emissions (human health)	Willingness to pay to reduce emissions
		$PM_{2,5}$ and PM10	Same as for CO_2	
		Nitrogen		
		Carbon monoxide		
		Aldehydes		
		NOx		
		Sulphur dioxide		
		Polycyclic aromatic hydro-carbons		
		Ozone		
		Dust		

A.3.4 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)

— being negatively affected by others being hurt or losing their lives due to road transport;

— having existing roads, negatively affecting socio-economic development;

— being negatively affected by excessive emissions being emitted from road transport; and

— being negatively affected by excessive amounts of non-renewable resources being consumed.

These can be quantified as shown in Table A.5 to Table A.7.

Table A.5 — Measures of service related to the indirectly affected public (1/3)

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Accidents	Impact on the indirectly affected	Injuries	Economic impact due to an injury	Production loss cost, medical cost, administrative cost and other costs for the society due to an injury

Level 1		Level 2		
Label	Description	Label	Description	It can be estimated using, for example
	public of accidents occurring on roads	Fatalities	Economic impact due to a fatality	Production loss cost, medical cost, administrative cost and other costs for the society due to a fatality

Table A.6 — 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 using, for example
Socio-economic activity	Contribution of the road operation to socio-economic development	Persons	Impact of not being able to transport people	Productiveness	Economic impact due to not being able to travel, e.g. not being able to work	Influence of passenger transport on society for example, labour mobility
				Health	Societal impact due to injuries and fatalities of not being able to get proper medical care	Willingness to pay to reduce societal impact
		Goods	Impact of not being able to move goods	Productiveness	Economic impact due to not being able to deliver goods, e.g. because of not being able to work as planned	Influence of freight transport service to the economy of the society, for example market accessibility
				Health	Societal impact due to not being able to deliver goods, e.g. due to fatalities because of lack of food or medical supplies	Willingness to pay to reduce societal impact
		Employ-ment	Impact of interventions in terms of employing people	Economic impact	Economic impact of lack of employment opportunities	Influence of the employment opportunities to the economy of the society
				Social impact	Societal impact of lack of employment opportunities	Willingness to pay to provide employment

Table A.7 — 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, for example**
Emissions	Impact on people due to the environment being impacted by particle emissions	CO_2	Impact due to the emissions	Production	Environmental impact of emissions emitted during the production of materials	Willingness to pay to reduce emissions
				Material transport	Environmental impact of emissions emitted during the transport of materials	Willingness to pay to reduce emissions
				Person transport	Environmental impact of emissions emitted during travel	Willingness to pay to reduce emissions
				Health	Societal impact due to emissions (human health)	Willingness to pay to reduce emissions
		$PM_{2,5}$ and PM_{10}	same as for CO_2			
		Nitrogen				
		Carbon Monoxide				
		Aldehydes				
		NOx				
		Sulphur dioxide				
		Polycyclic Aromatic Hydrocarbons				
		Ozone				
		Dust				
Resource consumption	Depletion of finite amounts of non-renewable resources	energy	Environmental impact due to the consumption of energy not related to emissions, e.g. depletion of finite amounts of non-renewable energy sources			Willingness to pay to reduce emissions
		materials	Environmental impact of consuming materials, not related to emissions			Willingness to pay to reduce emissions
		land	Environmental impact due to the consumption of land not related to emissions			Willingness to pay to reduce emissions
Social aspects	Culture	Cultural heritage	Societal impact of changing things important to our identity (of which heritage is part)			Willingness to pay to reduce emissions

Annex B
(informative)

Example rail stakeholders, intervention costs and measures of service

B.1 Stakeholders

The following table provides an example of categories for stakeholders to be considered in the assessment of rails.

Table B.1 — Rail stakeholders

Stakeholder		Description	Example
Owner/manager		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

B.2 Intervention costs

Rail managers execute interventions to ensure that infrastructure continues to provide an adequate level of service. The following table provides an example of quantification.

Table B.2 — Rail manager intervention costs

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Intervention	Impact from executing interventions	Labour	Economic impact of infrastructure workers performing tasks	Cost of labour required for the execution of interventions
		Material	Economic impact of ensuring the availability of required material for the intervention	Cost of material required for the execution of interventions
		Equipment	Economic impact of ensuring the availability of required equipment for the intervention	Cost of equipment required for the execution of interventions
	Impact of accident during the execution of interventions	Infrastructure property damage	Economic impact of repairing damages caused due to the execution of interventions	Cost of replacing the damaged property or as part of the fatality or injury costs
		Workforce injury	Societal impact due to injury at work place	Willingness o to pay to avoid workforce injury
		Workforce fatality	Societal impact due to death at work place	Willingness o to pay to avoid workforce fatality

B.3 Measures of service

B.3.1 General

The following subclauses provides examples of measures of service related to rail users, the directly affected public and the indirectly affected public.

NOTE The tables in the following clauses provide examples of how the value of units service can be determined. No detailed explanation of exactly how they should be estimated is provided. How they are to be estimated depends on the transport system under assessment, the stakeholders involved and the time and effort that should invested in the project.

B.3.2 Rail users

B.3.2.1 Groups of 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 clauses.

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 the following table.

Table B.3 — Measures of service related to rail passengers

Level 1		**Level 2**		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Accident	Impact on the users due to the users being involved in an accident	Personal property damage	Economic impact of repairing the properties of the passengers that are damaged	Cost of replacing the damaged property or as part of the fatality or injury costs
		Injury	Societal impact due to injury	Willingness of the passenger to pay to avoid injury
		Fatality	Societal impact due to death	Willingness of the passenger to pay to avoid death
Time	Impact of travel condition in terms of time lost in travel	Business travel	Economic impact of delay during business travel	Salaries of the persons travelling
		Commuting travel	Economic impact of delay during commuting travel	Willingness to pay to avoid a delay
		Leisure travel	Economic impact of delay during leisure travel	Willingness to pay to avoid a delay
Comfort	Impact of discomfort	Physical	Societal impact of being physically affected by an uncomfortable ride	Willingness of the passenger to pay for the reduction of the physical effects of the ride such as noise or vibration
		Psychological	Societal impact of being psychologically affected by experiencing an unpleasant event during the trip	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			Willingness of passengers to pay for noise reduction

B.3.2.2 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 having the goods damaged.

These can be quantified, as additional costs, as shown in the following table.

Table B.4 — Measures of service related to rail freight customers

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Time	Impact of lost time	Stored freight	Economic impact of increasing the waiting time of goods in transport	Value of freight transport time[a]
Accident	Impact of accident involvement	freight property damage	Economic impact of repairing the goods that are damaged due to the use of railway service	Costs of replacing the damaged freight
[a] Which will depend on the type of goods being transported, e.g. perishable or not.				

B.3.2.3 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 the passengers 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 the following table.

Table B.5 — Measures of service related to rail passenger carriers

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Time	Impact of lost time	Competiveness	Economic impact passenger demand reduction	Willingness to pay to decrease delays
		Operation	Economic impact of operating the rolling stock	Cost for providing the fuel and the personnel
Accident	Impact of accident involvement	Vehicle property damage	Economic impact of repairing the rolling stock damaged due to the use of railway service	Cost of replacing the damaged vehicle or vehicle's parts

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
		Injury	Societal impact due to injury of the carrier's personnel	Willingness to pay to avoid injury of the personnel working on a passenger train
		Fatality	Societal impact due to a fatality amongst the carrier's personnel	Willingness 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	Economic impact of maintaining and operating the rolling stock	Cost of maintaining the braking system, wheels, suspension system, and telecommunication system
Profit	Impact of change in the profit	Mode choice impact	Economic impact of reduction of the railways' market share	Willingness to pay to increase the demand for railway passenger travel
		Physical	Societal impact of being physically affected by an uncomfortable ride	Willingness to pay for the reduction of the physical effects experienced by the personnel during the ride such as noise or vibration
		Psychological	Societal impact of being psychologically affected by experiencing an unpleasant event during the trip, i.e. shock or traumatic stress	Willingness o to pay for the reduction of the physiological effects experienced by the personnel during the ride

B.3.2.4 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 the following table.

Table B.6 — Measures of service related to rail freight carriers

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Travel time	Impact of lost travel time	Competiveness	Economic impact freight's demand reduction	Willingness to pay to decrease delays
		Operation	Economic impact of operating the rolling stock	Cost of providing the fuel and the personnel
Accident	Impact of accident involvement	Vehicle property damage	Economic impact of repairing the rolling stock damaged due to the use of railway service	Cost of replacing the damaged vehicle or vehicle's parts

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
		Injury	Societal impact due to injury	Willingness to pay to avoid injury of the personnel working on a freight train
		Fatality	Societal impact due to death	Willingness to pay to avoid death of the personnel working on a freight train
Vehicle operating costs	Impact on the vehicle cost	Interventions	Economic impact of executing interventions on the rolling stock to be available for use	Cost of maintaining the braking system, wheels, suspension system, and telecommunication system
Profit	Impact of change in the profit	Mode choice impact	Economic impact of reduction of the railways' market share, i.e. the cost from reducing the railway ridership due to uncomfortable ride	Willingness to pay to increase the demand for railway freight travel
		Physical	Societal impact of being physically affected by an uncomfortable ride	Willingness to pay to reduce the physical effects experienced by the personnel during the ride such as noise or vibration
		Psychological	Societal impact of being psychologically affected by experiencing an unpleasant event during the trip, i.e. shock or traumatic stress	Willingness to pay for the reduction of the physiological effects experienced by the personnel during the ride

B.3.3 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 the following table.

Table B.7 — Measures of service related to the rail directly affected public

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Accident	Impact of being involved in accident	Personal property damage	Economic impact of repairing properties of the affected public due to accidents at the railway	Cost of replacing the damaged property
		Injury	Societal impact due to injury, i.e. human cost due to injury of the affected public due to accidents at the railway	Willingness to pay to avoid injury

Level 1		Level 2		
Label	**Description**	**Label**	**Description**	**It can be estimated using, for example**
		Fatality	Societal impact due to death, i.e. human cost due to fatality of the affected public due to accidents at the railway	Willingness to pay to avoid fatalities
Comfort	Impact of unsatisfactory transport service	Physical	Societal impact of the affected public of being physically affected by the traffic operation of the railway	Willingness to pay to avoid the physical effects, for example, noise and vibration, of the railway traffic
		Psychological	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	Willingness to pay to avoid the physical effects
Noise	The societal impact due to the non-users affected by sound emissions			Willingness to pay for the reduction of noise
Emissions	Impact on people due to the environment being impacted by particle emissions	CO_2	Societal impact due to emissions (human health)	Willingness to pay to reduce detrimental effects on health due to the environmental pollution
		$PM_{2,5}$ and $PM_{2,5}$ and PM_{10}		
		Nitrogen		
		Carbon monoxide		
		Aldehydes		
		NOx		
		Sulphur dioxide		
		Polycyclic aromatic hydro-carbons		
		Ozone		
		Dust		

B.3.4 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)

— being negatively affected by others being hurt or losing their lives due to rail transport;

— having existing rail infrastructure, negatively affect socio-economic development;

— being negatively affected by excessive emissions being emitted from rail transport; and

— being negatively affected by excessive amounts of non-renewable resources being consumed.

These can be quantified as shown in the following tables.

Table B.8 — 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, for example**
Accident	Impact of accidents	Injury	Economic impact due to injury	Production loss cost, medical cost, administrative cost and other costs for the society due to an injury
		Fatality	Economic impact due to death	Production loss cost, medical cost, administrative cost and other costs for the society due to a fatality

Table B.9 — 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, for example**
Socio-economic activity	Impact of changes on the socio-economic activity	Persons	Impact of not being able to transport people	Productive-ness	Economic impact due to not being able to travel, e.g. not being able to work	Influence of passenger transport on society for example, labour mobility
				Health	Societal impact due to injuries and fatalities of not being able to get proper medical care	Willingness o to pay for the transport service
		Goods	Impact of not being able to move goods	Productive-ness	Economic impact due to not being able to deliver goods, e.g. because of not being able to work as planned	Influence of freight transport service to the economy of the society, for example market accessibility
				Health	Societal impact due to not being able to deliver goods, e.g. due to fatalities because of lack of food or medical supplies	Willingness to pay for the transport service
		Employment	Impact of lack of employment opportunities	Economic impact	Economic impact of lack of employment opportunities	Influence of the employment opportunities in the railway to the economy of the society
				Social impact	Societal impact of lack of employment opportunities	Willingness to pay to provide employment opportunities

Table B.10 — Measures of service related to the rail indirectly affected public (3/3)

Level 1		Level 2		Level 3		
Label	**Description**	**Label**	**Description**	**Label**	**Description**	**It can be estimated using, for example**
Emissions	Impact on people due to the environment	CO_2	Impact due to the emissions	Production	Environmental impact of emissions emitted during	Willingness to pay to reduce emissions

Level 1		Level 2		Level 3		
Label	**Description**	**Label**	**Description**	**Label**	**Description**	**It can be estimated using, for example**
	being impacted by particle emissions				the production of materials	
				Material transport	Environmental impact of emissions emitted during the transport of materials	Willingness to pay to reduce emissions
				Person transport	Environmental impact of emissions emitted during travel	Willingness to pay to reduce emissions
				Health	Societal impact due to emissions (human health)	Willingness to pay to reduce emissions
		$PM_{2,5}$ and PM_{10}	Same as for CO_2			
		Nitrogen				
		Carbon Monoxide				
		Aldehydes				
		NOx				
		Sulphur dioxide				
		Polycyclic Aromatic Hydro-carbons				
		Ozone				
		Dust				
Resources consumption	Depletion of finite amounts of non-renewable resources	Energy	Environmental impact due to the consumption of energy not related to emissions, e.g. depletion of finite amounts of non-renewable energy sources			Willingness to pay to reduce emissions
		Materials	Environmental impact of consuming materials, not related to emissions			Willingness to pay to reduce emissions
		Land	Environmental impact due to the consumption of land not related to emissions			Willingness to pay to reduce emissions
Social aspects	Culture	Cultural heritage	Societal impact of changing things important to our identity (of which heritage is part)			Willingness to pay to reduce emissions

Annex C
(informative)

Example generic road and rail indicators

C.1 Overview

This appendix contains example generic indicators related to the infrastructure (Table C.1), the environment (Table C.2) and the organisation (Table C.3) The indicators are grouped with respect to their relationships with the resilience curves shown in Clause 4.2, i.e.

— the absorb phase, divided by:

- how an asset is affected during the disruptive event;
- how an asset will react during the disruptive event; and
- what will happen during disruptive event; and

— the recovery phase, explained as:

- what will happen after the disruptive 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.

Table C.1 — An overview of the proposed infrastructure indicators, and their relationships to the absorb and recovery phases

Phase	Absorb			Recovery
Category	**How an asset is affected during the disruptive event**	**How an asset will react during the disruptive event**	**What will happen during the disruptive event**	**What will happen after the disruptive event**
Indicators	Condition state of protective structures/systems	Compliance with the current 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 C.2 — An overview of the proposed environment indicators, and their relationships to the absorb and recovery phases

Phase	Absorb			Recovery
Category	How an asset is affected during the disruptive event	How an asset will react during the disruptive event	What will happen during the disruptive event	What will happen after the disruptive event
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	-	-	-
Indicators related to the organizational environment	-	-	-	Budget availability

Table C.3 — An overview of the proposed organisation indicators, and their relationships to the absorb and recovery phases

Phase	Absorb			Recovery
Category	How an asset is affected during the disruptive event	How an asset will react during the disruptive event	What will happen during disruptive event	What will happen after disruptive event
Indicators	The presence of a routine maintenance strategy	-	The frequency of monitoring	Expected time for tender
	The presence of a 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

Phase	Absorb			Recovery
Category	How an asset is affected during the disruptive event	How an asset will react during the disruptive event	What will happen during disruptive event	What will happen after disruptive event
	-	-	-	Flexibility in hiring appropriate work force
	-	-	-	Availability of materials
	-	-	-	Expected time for material delivery
	-	-	-	Availability of construction equipment

C.2 Infrastructure

Table C.4 — Infrastructure: Indicators of how an asset is affected during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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
[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.						

Table C.5 — Infrastructure: Indicators of how an asset will react during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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	Yes	Yes	Yes	Yes	Yes

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	Travel time	Accident	Socio-econ.	
	the event, the less likely it will fail					

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.6 — Infrastructure: Indicators of what will happen during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.7 — Infrastructure: Indicators of what will happen after the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	Travel time	Accident	Socio-econ.	
The number of possible existing alternative routes	The number of possible existing alternative routes make it easier to provide service following a disruptive 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 disruptive 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 disruptive event before the failed infrastructure is restored	No	Yes	No	Yes	Yes
a If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.						

C.3 Environment – Physical

Table C.8 — Environment-Physical: Indicators of how an asset is affected during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[d]
		Intervention	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

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[d]
		Intervention	Travel time	Accident	Socio-econ.	
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[a,b]	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[c]	The greater the ability to intervene during a hazard to mitigate effects the lower the consequences of the hazard	Yes	Yes	Yes	Yes	Yes

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

[b] For example, if the disruptive 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 disruptive event.

[c] For example, if the disruptive 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.

[d] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.9 — Environment-Physical: Indicators of how an asset will react during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.10 — Environment-Physical: Indicators of what will happen during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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	Yes	No	No	No	Yes

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.11 — Environment-Physical: Indicators of what will happen after the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

C.4 Environment – Organisational

Table C.12 — Environment-Organisational: Indicators of what will happen after the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	Travel time	Accident	Socio-econ.	
Budget availability	The available budget affects how quickly restoration interventions can be executed	No	Yes	Yes	Yes	Yes

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

C.5 Organisation

Table C.13 — Organisation: Indicators of how an asset is affected during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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 a 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 event 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

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.14 — Organisation: Indicators of what will happen during the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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 disruptive 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 disruptive 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 disruptive event	No	Yes	Yes	Yes	Yes

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Table C.15 — Organisation: Indicators of what will happen after the disruptive event

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	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	Yes	Yes	No	No	Yes

Indicators	Description	A change in the value of the indicator is likely to result in a change in the expected additional costs associated to				A change in the value of the indicator means there is a change in resilience[a]
		Intervention	Travel time	Accident	Socio-econ.	
	slows down the restoration process					
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

[a] If a change in the value of the indicator affects either the expected additional intervention costs, travel time costs, accident costs or socio-economic costs, then it affects the resilience.

Annex D
(informative)

Example: Resilience measures using indicators and differentiated weights

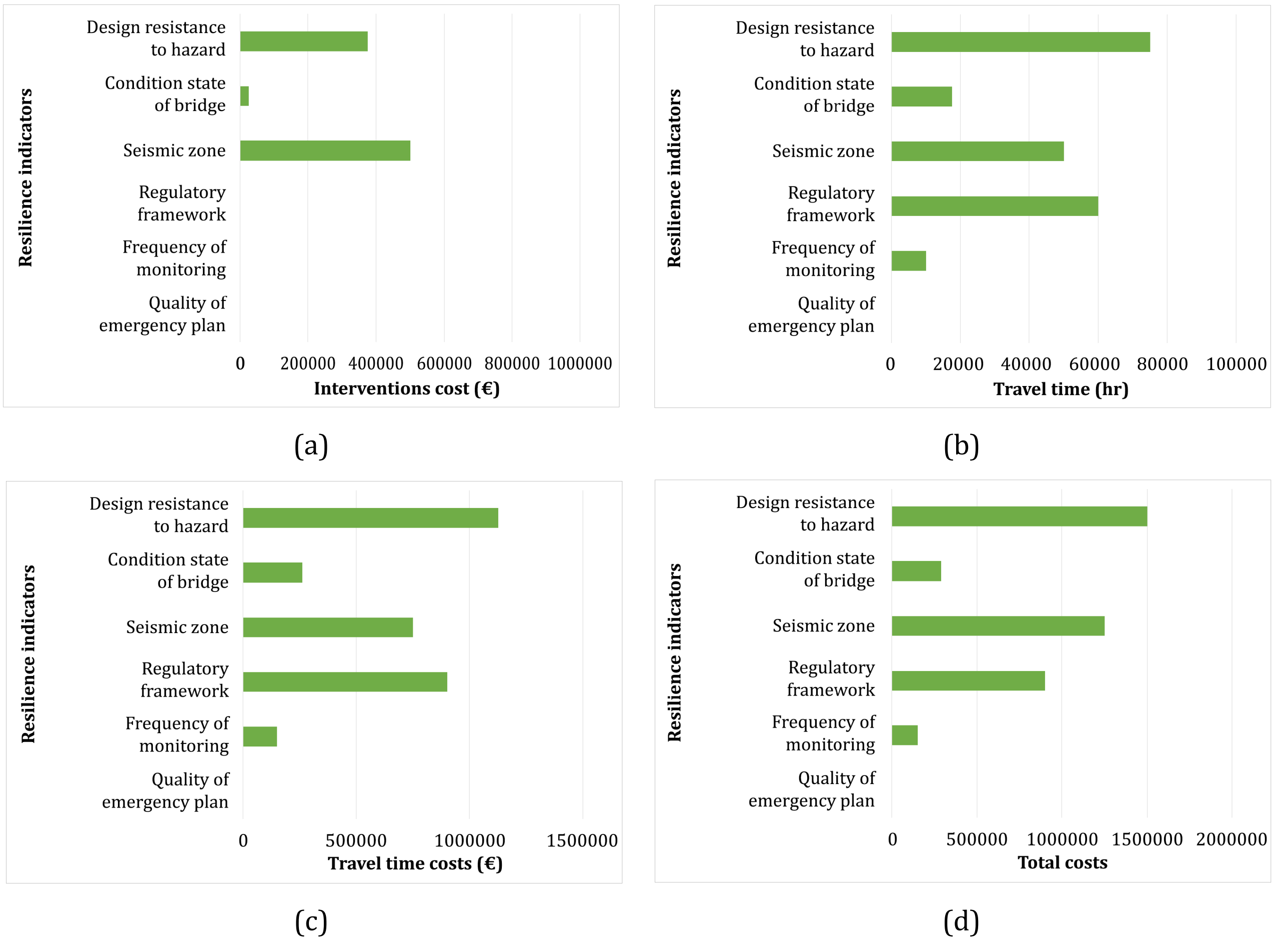
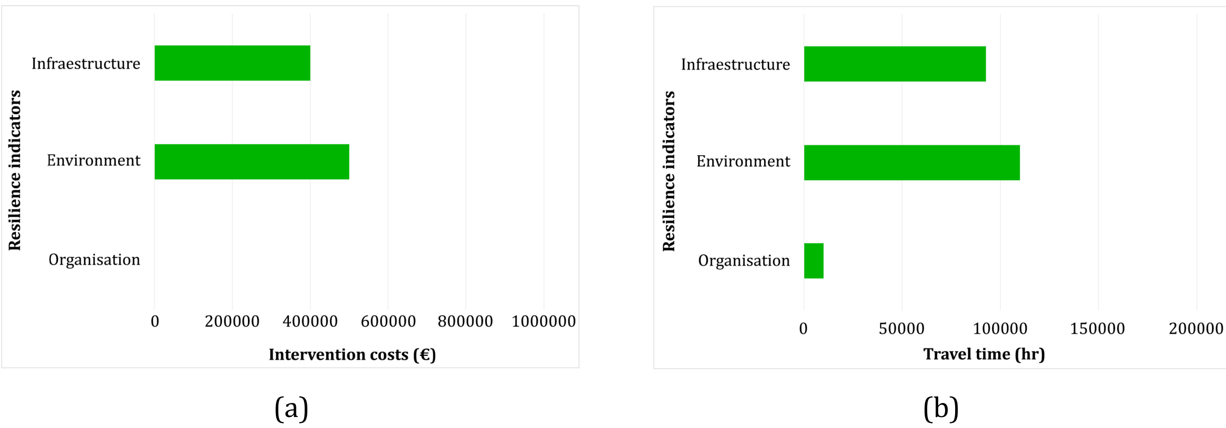
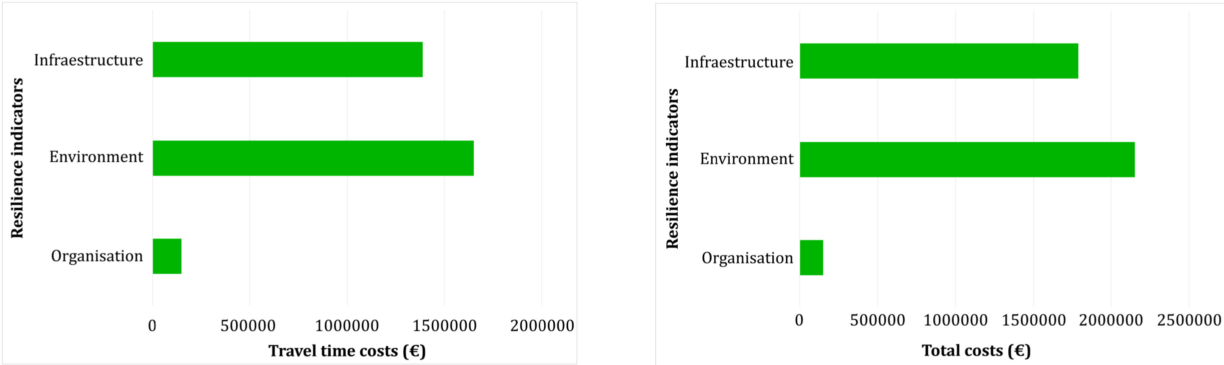


Figure D.1 — Example resilience measures using indicators and using differentiated weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs



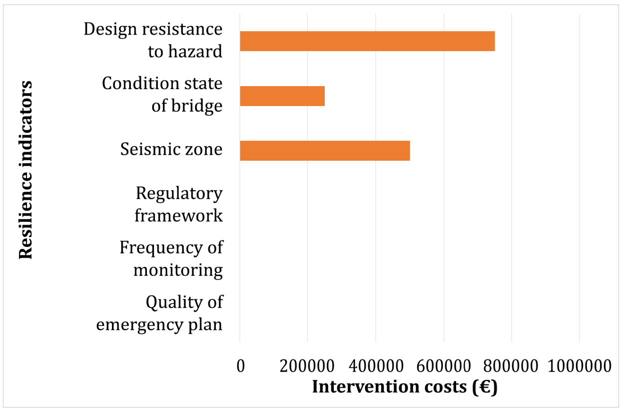


(c) (d)

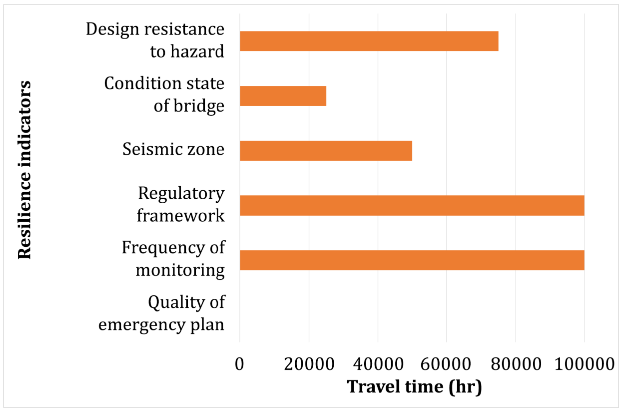
Figure D.2 — Example resilience measures using transport systems parts and differentiated weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs

Annex E
(informative)

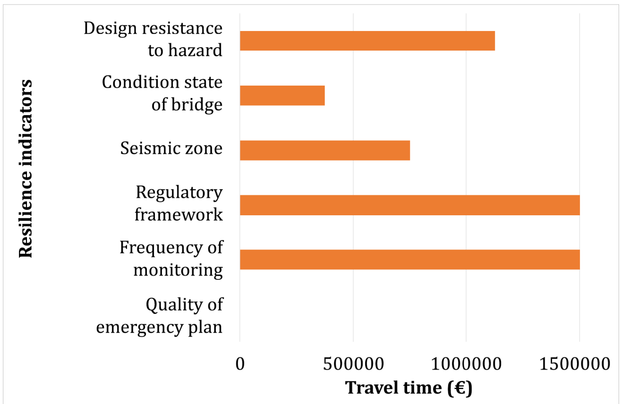
Example: Resilience measure using equal weights



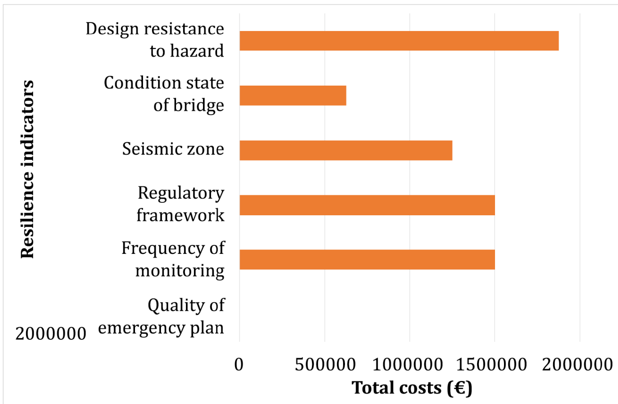
(a)



(b)



(c)



(d)

Figure E.1 — Example resilience measures using indicators and equal weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs

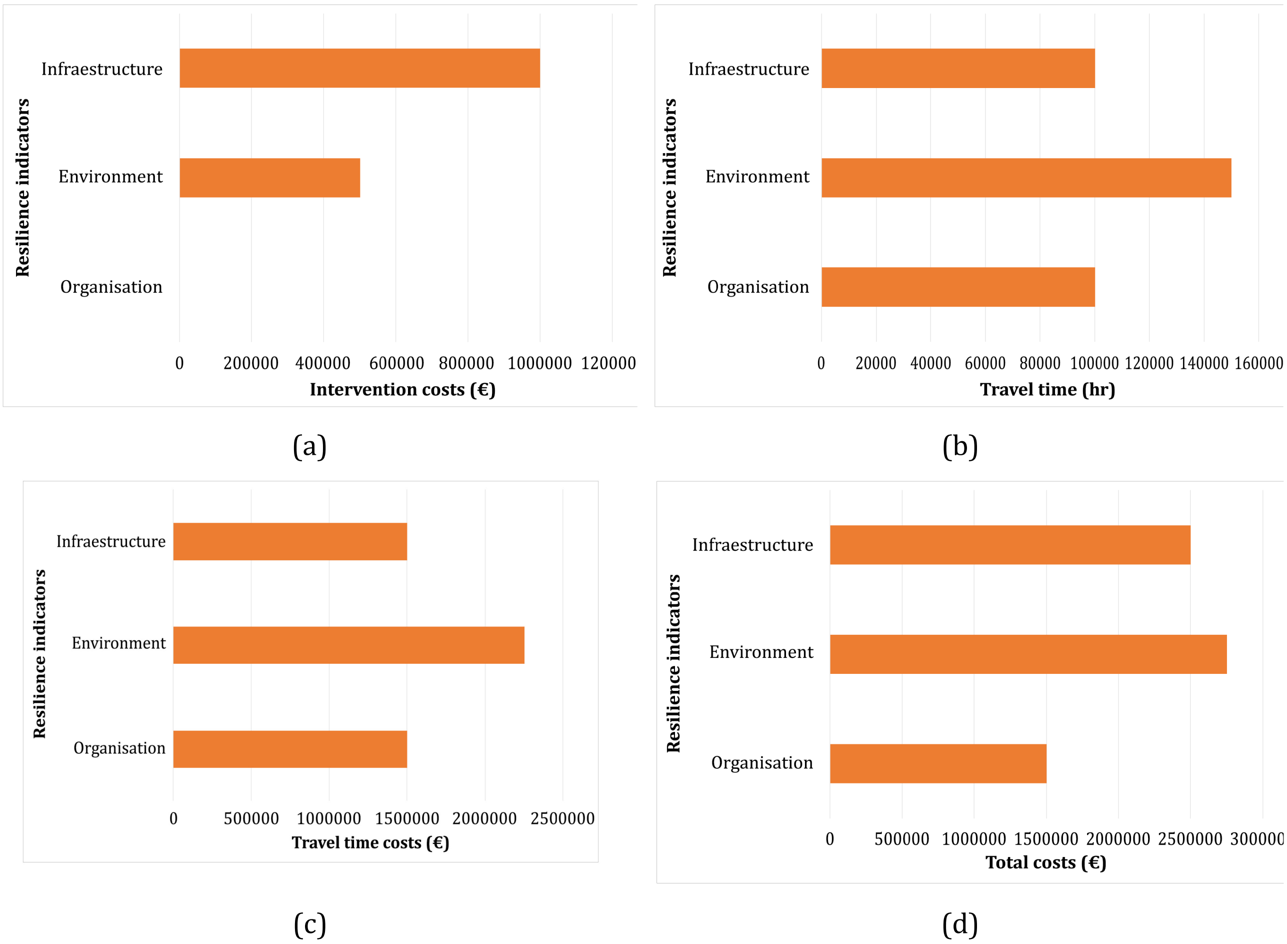


Figure E.2 — Example resilience measures using indicators grouped by part of transport system and equal weights, a) intervention costs, b) travel time, c) travel time costs, and d) total costs

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