GIS-Based Infrastructure Management System for Optimized Response to Extreme Events of Terrestrial Transport Networks

Vulnerability and Resilience Factors
D2.3

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PUBLIC

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SAFEWAY

GIS-BASED INFRASTRUCTURE MANAGEMENT SYSTEM FOR OPTIMIZED RESPONSE TO EXTREME EVENTS OF TERRESTRIAL TRANSPORT NETWORKS

Grant Agreement No. 769255

Vulnerability and Resilience Factors

WP 2 Risk factors and risk analysis

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Deliverable name	**Vulnerability and resilience factors**
Lead partner	**NGI**
Contributors	IMC, UMINHO

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SAFEWAY Project Synopsis

According to European TEN-T guidelines, due consideration must be given to the risk assessments and adaptation measures during infrastructure planning in order to improve resilience to disasters. SAFEWAY's aim is to design, validate and implement holistic methods, strategies, tools and technical interventions to significantly increase the resilience of inland transport infrastructure. SAFEWAY leads to significantly improved resilience of transport infrastructures, developing a holistic toolset with transversal application to anticipate and mitigate the effects extreme events at all modes of disaster cycle:

1. **"Preparation":** substantial improvement of risk prediction, monitoring and decision tools contributing to anticipate, prevent and prepare critical assets for the damage impacts;
2. **"Response and Recovery":** the incorporation of SAFEWAY IT solutions into emergency plans, and real-time optimal communication with operators and end users (via crowdsourcing and social media);
3. **"Mitigation":** improving precision in the adoption of mitigation actions (by impact analysis of different scenarios) together with new construction systems and materials, contributing to the resistance & absorption of the damage impact.

SAFEWAY consortium has 15 partners that cover multidisciplinary and multi-sectorial business fields associated with resilience of transport infrastructure in Europe: national transport infrastructure managers & operators, a main global infrastructure operator, partners able to provide various data sources with large coverage in real time, comprehensive ITC solutions, and leading experts in resilience, risk databases, remote sensing-based inspection, and decision systems based on predictive modelling.

SAFEWAY will carry out 4 real case studies distributed through 4 countries, linked to 5 corridors of the TEN-T Core Network. The main aim of SAFEWAY is to contribute to the following impacts:

1. at least 20% improvement in mobility; and
2. at least 20% lower cost of infrastructure maintenance.

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Lead Author	Unni Eidsvig (NGI),	
Other Authors	Christina Ekeheien (NGI),	Nikola Tanasic (IMC), Rade Hajdin (IMC)
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Executive Summary

The scope of this deliverable is to analyse vulnerability and resilience factors affecting a loss of mobility in terrestrial transportation network caused by natural events. The focus is on assessment of the probability and severity of loss of mobility due to natural hazards that are considered as the most critical in the pilot countries. The assessment was done using structural and functional vulnerability functions, which are associated with failure modes of an infrastructure asset and a specific hazard type. The occurrence of a mobility loss is analysed at the level of an asset. Consequences of the mobility loss are analysed considering a transportation network and the functions it serves. The background is given on the key factors for resilience: robustness, resourcefulness, rapid recovery and redundancy.

The review of existing structural and functional vulnerability functions that was performed showed that vulnerability functions are lacking for many types of hazards and assets. Therefore, recommendations for developing vulnerability functions have been made. Each vulnerability function is governed by properties of an asset and/or location for which it was developed. It is suggested to consider intensity parameters for different types of hazards, methods for developing the functions and the assessment of the relationship between structural vulnerability of an asset and functional vulnerability.

The deliverable also reviews the factors affecting the consequences of a mobility loss. These factors are related to the redundancy of the network and the time for recovery after the occurrence of a natural event.

Table of Contents

Glossary of Terms

Adverse event An event that may result in loss of life, health or stability, monetary losses or damage to the environment, DSB (2014). In this work the focus is on adverse events in terms of malfunctioning of infrastructure (caused by natural events).

Consequence The outcomes or potential outcomes arising from the occurrence of an adverse event, expressed qualitatively or quantitatively in terms of monetary loss, disadvantage or gain; damage, injury or loss of life. Consequences could be characterised as direct and indirect. Direct consequences refer to a physical destruction of exposed elements, and indirect consequences stem from related impacts that this destruction has on the functionality of elements.

Exposed elements Population, buildings and engineering works, infrastructure, environmental features and economic activities in the area affected by the adverse event (ISSMGE, 2004).

Failure mode General term to refer to a different type of failures such as structural failure or functional failure (unavailability). Due to slow (deterioration) and sudden (e.g. natural hazard) processes, damages may occur that result in additional failure modes. These are quasi-permanent or transient situations that violate code specifications or owner's/ operator's provisions. Here included are situations that might compromise public perception of safety.

Fragility curve Fragility curves are functions that describe the probability of failure, conditioned on the load, over the full range of loads to which a system might be exposed.

Fragility table Discrete points on a fragility curve, given as a table

Resilience

- The ability to prepare and plan for, absorb, recover from or more successfully adapt to actual or potential adverse events.
- The capacity of systems to cope with adverse conditions to maintain their essential function, identity, and structure, while also maintaining and making use of their capacity for adaptation, learning, and transformation.
- The ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters.

Risk Measure of the probability and severity of an adverse effect to life, health, property, economic activities or the environment. Quantitatively, Risk = Hazard · Potential Worth of Loss. This can be also expressed as "Probability of an adverse event times the consequences if the event occurs" (ISSMGE, 2004).

Vulnerability	Vulnerability refers to the propensity of exposed elements such as physical or capital assets, as well as human beings and their livelihoods, to experience harm and suffer damage and loss when impacted by single or compound hazard events. Dimensions of vulnerability: Physical dimension refers to conditions of physical assets - including built-up areas, infrastructure, and open spaces that can be affected by natural hazards. Social dimension refers to human welfare including social integration, mental and physical health, both at an individual and collective level. Economic dimension refers to the productive capacity, unemployment and low income conditions. In this work, the terms structural and functional vulnerability are used in the quantitative assessment of vulnerability, representing the degree of loss as a dimensionless number between 0 and 1, where 0 means no loss and 1 means total loss. It could also be expressed in terms of a probability of a failure mode as described below:
Structural vulnerability	Structural vulnerability expresses physical damage and is quantified by the probability that the asset exceeds some undesirable limit state, e.g. serviceability for a given level of environmental excitation, such as force, deformation, or other forms of loading to which the asset is subjected. If formulated deterministically, the structural vulnerability could be expressed as an average damage degree.
Functional vulnerability	The degree of capacity loss, described on a scale 0 to 1. It could also represent the probability of exceeding a predefined damage state, e.g. the probability of a total disruption of the transportation service

1. Introduction

Natural events may cause damage to transportation assets, which could immediately or over time result in physical and/or functional loss of a transportation line. Loss of mobility severely affects social and economic activities and the society on the whole. In many areas of Europe, the frequency of extreme weather (EW), floods and landslides are expected to increase with climate change. Maintaining the operational state of roads and railways during extreme weather events or other natural events is an important and demanding task. In addition, great resources are spent on related repairs and upgrades. To reduce risks posed by natural hazards to transportation networks, it is essential to assess the vulnerability of these networks to such events. This deliverable defines and assesses factors contributing to vulnerability and resilience of terrestrial transportation networks.

1.1 The scope

Figure 1 presents the scope of this deliverable as a bow-tie diagram, with the top event defined as "loss of mobility". More specifically, the mobility loss is supposed to be caused by a natural event. The occurrence of the mobility loss is analysed specifically at an asset level, while the consequences are analysed considering the transportation network and the functions it serves.

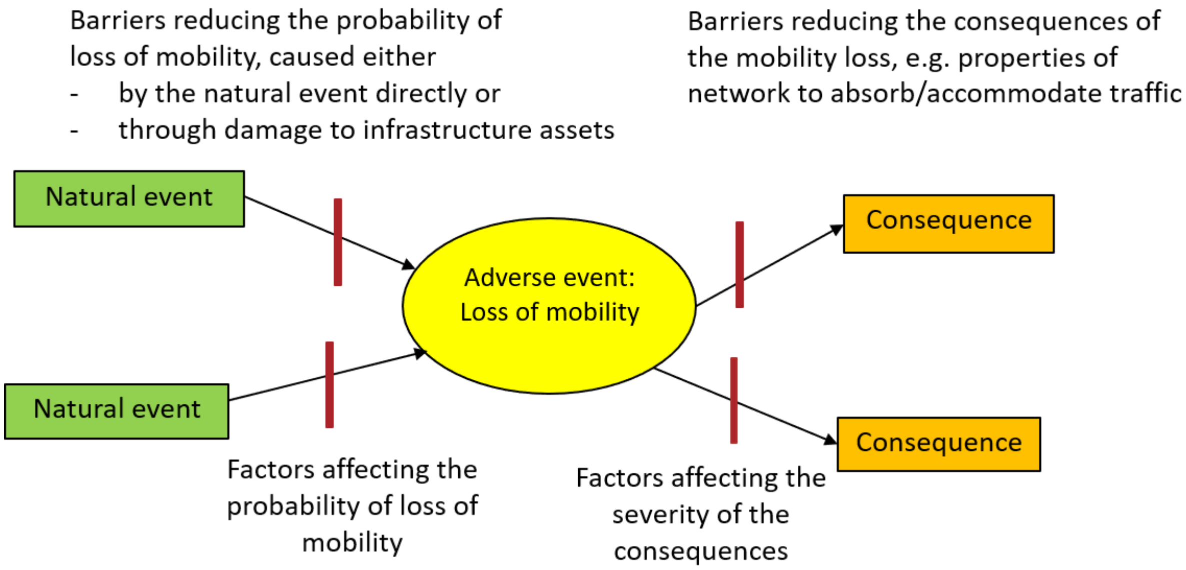


Figure 1: Schematic bow-tie representation of the scope of the work

The scope is divided into three areas, namely:

1. Damage to infrastructure assets which can immediately or over time result in functional loss of a transportation line, i.e. loss of mobility. The tool for an assessment: structural vulnerability functions.

2. Natural events leading to direct loss of mobility by blocking or delaying the traffic, but with no physical damage to an exposed asset. The tool for an assessment: functional vulnerability functions.
3. Indirect consequences of a mobility loss. The assessment encompasses identification of governing factors and a methodology for quantification of consequences.

1.2 Terrestrial transportation infrastructure assets

Transportation infrastructure assets are physical elements that comprise the terrestrial transportation system, such as pavements, tracks, bridges, culverts, signs, pavement markings, and other physical elements. Assets can be exposed to different stresses and loads, originating from natural extreme events, environmental chemical agents, human-made hazards, human errors and normal operation. Some assets are physically and/or functionally more vulnerable to a given type of hazardous event than others and some are more critical for the operation of a network than others with respect to the importance of the service they provide.

SAFEWAY deliverable D3.1 (Amodio et al. 2019) provides an overview of assets within the demonstration sites in Portugal (Santarém and Leiría), Spain (Málaga and Murcia) and UK (Stoke-on-Trent). The main groups of assets considered within SAFEWAY are listed in Table 1.

Table 1: General groups of assets (Amodio et al. 2019)

Asset	Short definition
Bridge	Infrastructure built over a water course so that road or rail traffic can cross from one side of it to the other. This comprises all types of bridges available in the transport network of study (e.g. overline, underline, masonry arch, girder, etc.).
Culvert	Draining element under a roadway, railway or similar.
Embankment	Wall of soil used to raise a terrain level facilitating the pass of a road or to contain a flooding area.
Pavement	Asphalted path for road traffic.
Retaining wall	Rigid walls used for the soil's lateral support.
Track	Group of two parallel rails passed by the train.
Tunnel	Underground passageway built for road or rail traffic.
Viaduct	Infrastructure built over a valley so that road or rail traffic can cross from one side of it to the other.

In this deliverable, the main focus will be on pavements, tracks and bridges. In addition, there are some examples given for embankments.

1.3 Outline of the deliverable

This deliverable is organised as follows:

- Chapters 2 and 3 outline the background for assessment of vulnerability and resilience.
- Chapters 4 and 5 review relevant models for assessment of vulnerability and consequences, both with regard to loss of functioning and damage to assets.
- Chapter 6 provides recommendations on the assessment of impacts, regarding framework, aggregation of results from different failure modes and choice of methods for vulnerability assessment and modelling variables.
- Chapter 7 summarises and concludes the work.

The work within this deliverable is also linked to other SAFEWAY tasks and deliverables:

- Task 2.1:
  - D2.1: Framework for risk assessment; failure modes involving natural events, hazard maps for natural events in Europe.
  - D2.2: Identification of and statistics on human-made hazards. Fragility curves for man-made hazards. Categorisation and assessment of consequences.
- Task 5.2: Application of fragility curves and vulnerability relations in assessment of the consequences.

2. Background

2.1 Vulnerability and resilience of transportation network

The aim of this section is to present state-of-the-art framework for vulnerability and resilience assessment. A high-level conceptual risk model for assessment of impacts to asset systems triggered by natural events is shown in Figure 2. The figure outlines bridge failure from scour in which the processes that create the flood hazard are described in terms of the probability distribution of a relevant load variable, and the response of a bridge is described by a fragility function, representing the conditional probability of a failure occurring for an assumed load level (Lamb et al.; 2017). Figure 2 applies also to risk assessment of other weather-induced events leading to failure of infrastructure assets and loss of mobility. The concept given in Figure 2 is in accordance with well established, generic risk modelling frameworks, including the source–pathway–receptor concept widely used in environmental risk assessment (Defra, 2011), the loading and fragility concepts of reliability analysis (Ellingwood, 2008; USACE, 2010) and the hazard–vulnerability–loss concepts often applied in natural hazard risk assessments (Fell et al.; 2005; IPCC; 2012).

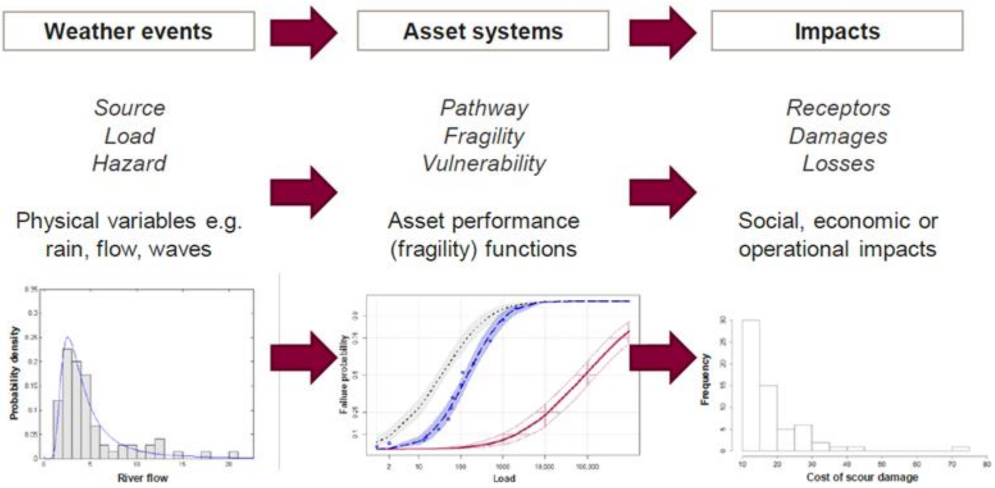


Figure 2: Conceptual risk model (Lamb et al.; 2017). The lower figure row applies to bridge failure from scour

2.1.1 The key factors for resilience

Terrestrial transportation infrastructures such as roads and railways are important in contributing to the resilience of the community to natural hazards. Critical assets, such as bridges or other assets comprising the road and railway network, are particularly essential for the functionality of transportation networks.

Resilience can vary in time due to external events, which can reduce it, or actions focused on improving performance, which can increase it. This introduces a new variable, (T_{RE}) (Porter et al., 2001; Brunei and Reinhorn, 2007; Cimellaro et al., 2009, 2010):

The recovery time (T_{RE}) is the period needed to restore the functionality of a structure, and infrastructure system to a desired level that can operate or function the same, close to, or better than the original one.

This is a random variable, with high uncertainties, dependent on local socio-economic conditions. The calculated resilience can be expressed by use of the resilience triangle (Tierny and Bryneau, 2007), which is commonly referred to in the literature (Caverzan and Solomos, 2014).

Resilient systems reduce the probabilities of failure, as well as the consequences of failure such as deaths and injuries, physical damage, and negative economic and social effects; and the time for recovery. Resilience can be measured by the functionality of an infrastructure system after a disaster and by the time it takes for a system to return to the pre-disaster level of performance. The "resilience triangle" in Figure 3 represents the loss of functionality from damage and disruption, as well as the pattern of restoration and recovery over time. The term quality of infrastructure refers both to quality in function and structure.

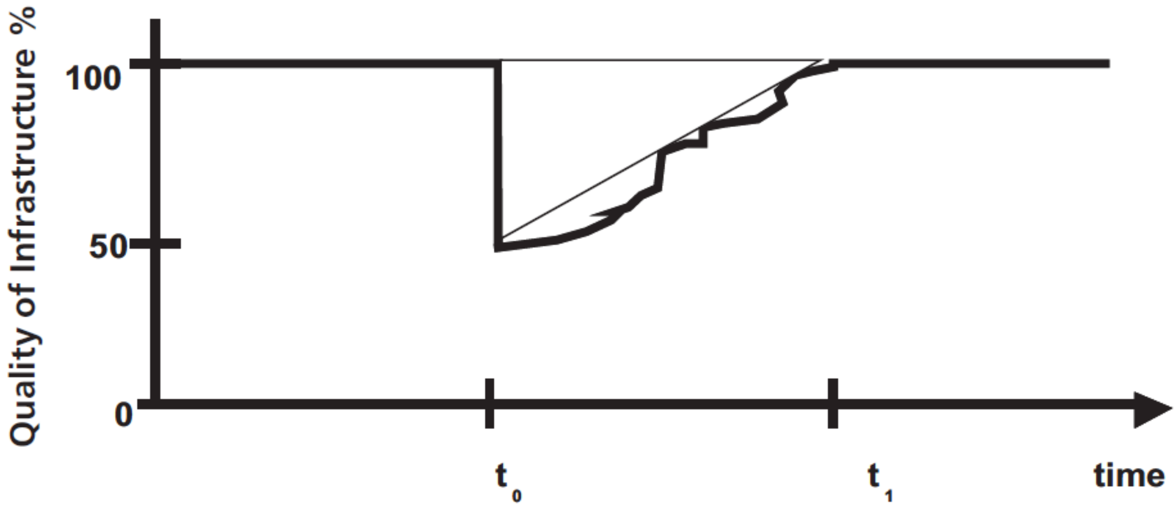


Figure 3: The resilience triangle (Tierny and Bruneau; 2007)

Resilience-enhancing measures aim at reducing the size of the resilience triangle through strategies that improve the infrastructure's functionality and performance (i.e. the quality of service, shown the vertical axis in the figure) and that decrease the time to full recovery (i.e. t_1-t_0, shown on the horizontal axis), see Figure 4. For example, mitigation measures can improve infrastructure performance. The time to recovery can be shortened by improving measures to restore and replace damaged infrastructure.

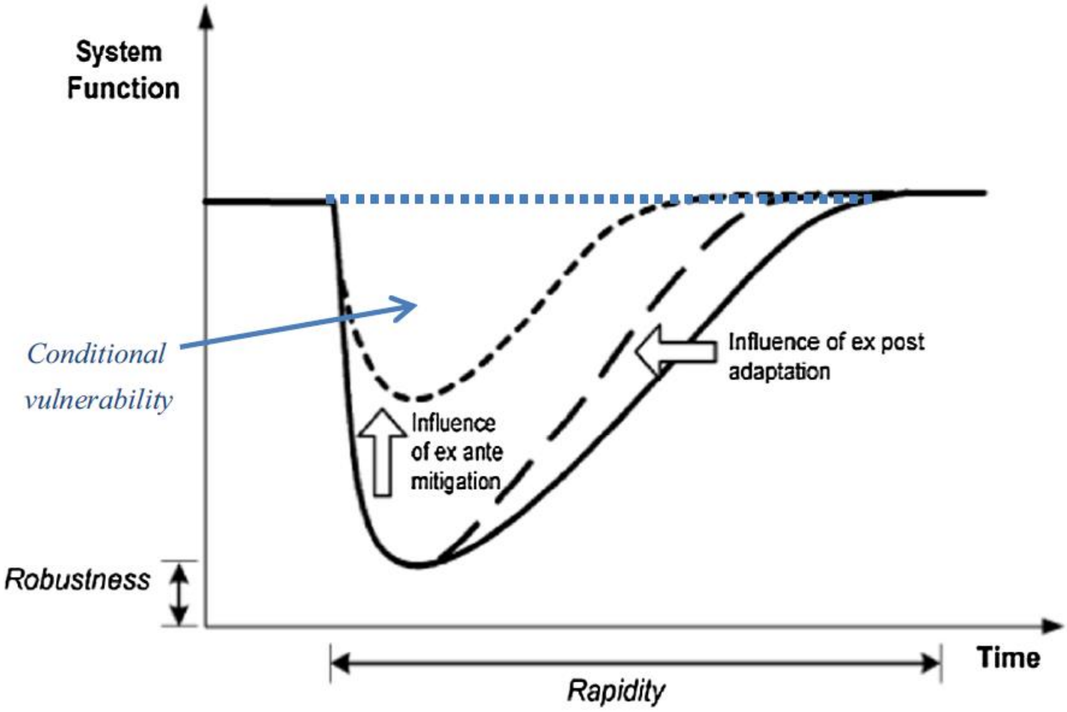


Figure 4: Effects of decision-making on resilience (Mattson and Jenelius; 2015, adapted from McDaniels at al. (2008)

This framework relies on the complementary measures of resilience: ‘‘Reduced failure probabilities,’’ ‘‘Reduced consequences from failures,’’ and ‘‘Reduced time to recovery.’’ This could be expressed as 3 key factors for resilience:

- **Robustness**—the ability of systems, system elements, and other units of analysis to withstand disaster forces without degradation or loss of performance;
- **Redundancy**—the extent to which systems, system elements, or other units are substitutable; that is, capable of satisfying functional requirements if significant degradation or loss of functionality occurs;
- **Rapidity**—the capacity to restore functionality in a timely way, containing losses and avoiding disruptions.

Bruneau et al. (2003) also included resourcefulness as one of the key factors for resilience. Resourcefulness is the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources. This is also in accordance with the four criteria for a resilient infrastructure as referred to at SAFEWAY's webpages: robustness, resourcefulness, rapid recovery and redundancy.

In transportation systems, robustness reflects the ability of the entire system—including the most critical elements—to withstand disaster-induced damage and disruption.

Redundancy can be measured by the extent that alternative routes and modes of transportation can be employed if some elements lose function. After the 1989 Loma Prieta earthquake, for example, expanded use of the Bay Area Rapid Transit system and the trans-Bay ferries overcame to some extent the loss of the San

Francisco Bay Bridge. Resourcefulness reflects the availability of materials, supplies, repair crews, and other resources to restore functionality. The hurricane Katrina in the U.S. in August 2005 was a catastrophe because of the extent and severity of the physical damage and the inability to move critical resources into the disaster-stricken region.

Rapidity is a consequence or outcome of improvements in robustness, redundancy, and resourcefulness. The slow pace of restoration and recovery in the Gulf of Mexico region after Hurricane Katrina indicates low levels of resilience throughout the area. At the same time, some states, communities, and infrastructure systems have been proved more resilient than others.

2.2 Factors affecting the probabilities for a functional loss

This section gives the overview of the terms used in the literature related to the assessment of the probability of material damage and loss of mobility due to natural events. These terms encompass the robustness and redundancy factors of resilience:

- Physical robustness: the physical robustness of risk elements (in particular facilities, equipment, buildings) is an important factor determining damage levels caused by an extreme event (Federal Ministry of the Interior, 2008; Lenz, 2009).
- Buffer capacity: buffer capacity means that the systems impacted by an event have redundancy or auxiliary capacity to sustain service to a certain degree and for a certain time (Federal Ministry of the Interior, 2008; Lenz, 2009).
- Level of protection: robustness/strength of barriers protecting an exposed element (e.g. a structure or a lifeline) from a threat (Federal Ministry of the Interior, 2008; Lenz, 2009).
- Quality level/level of maintenance and renewal: to ensure appropriate quality of the infrastructure, it needs to be maintained and renewed systematically (Lenz, 2009; Vatn et al., 2009).
- Dependencies: dependencies of other infrastructures, specific personnel and specific environmental conditions make the infrastructure more vulnerable (Federal Ministry of the Interior, 2008; Vatn et al., 2009; Lenz, 2009; Kröger, 2008).
- Transparency/complexity/degree of coupling: the complexity of the infrastructure and its dependency on single components to work, contributes to a higher vulnerability (Perrow, 1984; Federal Ministry of the Interior, 2008; Vatn et al., 2009; Kröger, 2008).

2.3 Factors affecting the consequences of loss of mobility

The key factors redundancy (of the network) and rapidity in restoration are central for estimation of the indirect consequences of transportation malfunctioning.

- Rapidity of restoration could also be denoted time to recovery or duration of down time. This duration is affected by the severity of the damage, and the resourcefulness of the operator/maintainer of the infrastructure. The severity of damage depends on the severity of the natural event, but also on the robustness of the infrastructure assets. Resourcefulness refers to material, monetary, informational, technological and human resources.

- Redundancy/substitutes: if there is an outage or reduced capacity in the transportation infrastructure, the consequences of this outage will be less severe if alternative routes or alternative modes of transportation exist.

These key factors encompass properties and factors that could be influenced by the infrastructure operators or maintainers, i.e. where decision-making could have an effect on infrastructure resilience:

- Quality in operation: the resilience of the infrastructure depends on how well it is operated and the ability to adapt to changing framework conditions (Vatn et al., 2009; Kröger, 2008).
- Preparedness: an outage of an infrastructure is easier and more-quickly restored or better handled if the situation has been prepared for (Lenz, 2009; Vatn et al., 2009; Merz et al., 2010). This could be planning for the operations on the surviving parts of the network in case of a recovery period, i.e. lane reversal or shoulder use for roads (Kepaptsoglou et al., 2014). For a railway system this could be elements considering rescheduling of timetables, the rolling stock and crews (Cacchiani et al., 2014; Andersson et al., 2013; Nielsen et al., 2012; Chen and Miller-Hooks, 2012). Preparedness could also relate to prepare for changes in travel demand and behaviour in the response phase of a disaster, when emergency trips have to be prioritized and many roads are impassable (Khademi et al., 2015).
- Early warning, emergency response and measures: if the warning time is sufficiently long, an early warning system combined with emergency response and measures may reduce the consequences of an infrastructure outage (Merz et al., 2010).
- Cascading effects and dependencies: the definition and content of the term cascading effects are discussed by Pescaroli and Alexander (2015) and, in short, referred to as a "chain sequence of interconnected failures" or as second-order/higher-order effects (Rinaldi et al., 2001). Cascading effects and dependencies of other societal functions on the infrastructure increase the societal consequences of the infrastructure loss (Vatn et al., 2009 Federal Ministry of the Interior, 2008; Lenz, 2009). A quantitative framework for assessing cascading effects was proposed by Liu et al. (2015).

There are also fixed factors affecting the severity of the consequences, that could not be influenced by the infrastructure operators or maintainers:

- Number of infrastructure users (typical annual daily traffic, which is the daily traffic amount averaged over a year)
- Societal functions and economic activity served by the transportation infrastructure e.g. transportation of goods and services, access to social security services.
- Costs of delays: traffic delay costs vary with the kind of transport (i.e. passenger transport or freight transport) as well as purpose of passenger transport (i.e. business, commuting or leisure)

3. Assessment of vulnerability and consequences

3.1 Classification of consequences

Extreme weather-related events and natural hazards affecting terrestrial transportation systems may have a variety of consequences. The main consequence types are:

- Life and health
- Economic consequences
- Environmental consequences
- Political/social consequences
- Loss of reputation

SAFEWAY (2019b) provides a description of assessment of these different consequence types. Consequences of natural events may also be classified as direct (as caused directly by the natural event) and indirect (resulting from the physical damages caused by the natural event). The consequences could also be subdivided according to if the consequence is associated with a market value or not, examples are given in Table 2**¡Error! No se encuentra el origen de la referencia.**.

Table 2: Classification of consequences, adapted from Meyer (2013)

	Market values	Non-market values
Direct	Physical damage to assets caused by the natural event; costs associated with rescue, clean up, rebuilding or repairing	- Human casualties and injuries* - Undesirable visual changes in the landscape** - Ecologic damages** - Damage to cultural icons**
Indirect	- Delays/loss of mobility (additional travel time, additional travel distance) - Economic consequences of delays/loss of mobility, e.g. reduced access to/from markets or reduction of value of transported perishables during delayed transportation.	- Depressions, Psychological problems - Increased social vulnerability, e.g. due to reduced access to social security services like hospitals etc.
**Meyer et al. (2013) recommend referring to human casualties as a non-market value. However, other studies (e.g. Lange, Sjöström and Honfi; 2015) suggest monetising also human casualties, through estimation of the value of a statistical life.*		

*** Even if these are non-market values, there are methods to monetise them, e.g. through a "willingness to pay"-estimation[1].*

Consequences could also be categorised according to the level at which they are assessed:

- At an asset level: Analysis of the resistance of the assets and their performance under stressors. These consequences can usually be related to the sustained damage due to a stressor.
- At independent network level:
  - Analysis of the effects of an asset failure on a network; e.g. failure of a bridge foundation would lead to closed transportation line, while damages to the pavement would not.
  - Analysis of events that could lead to malfunctioning of the network directly, e.g. debris on transportation line blocking the traffic.
  - Consequences of the failure of the network on society. The failure of the network is more severe if there are no other means of transportation.
- At interdependent network level: Effect of failure of one transport network on another network: interdependencies between networks.

3.2 Methods and tools for vulnerability assessment

Vulnerability could both be assessed at an asset level or at a network level. At an asset level, functions could be used to express the damage degree to an asset as a function of the intensity of a hazard. The most commonly used functions at asset level are fragility functions describing the probability of failure and/or degree-of loss functions (also referred to as vulnerability functions; Argyroudis et al., 2019). At network level, functions describing the functionality loss (e.g. reduction of a traffic capacity) due to a given hazard intensity could be used.

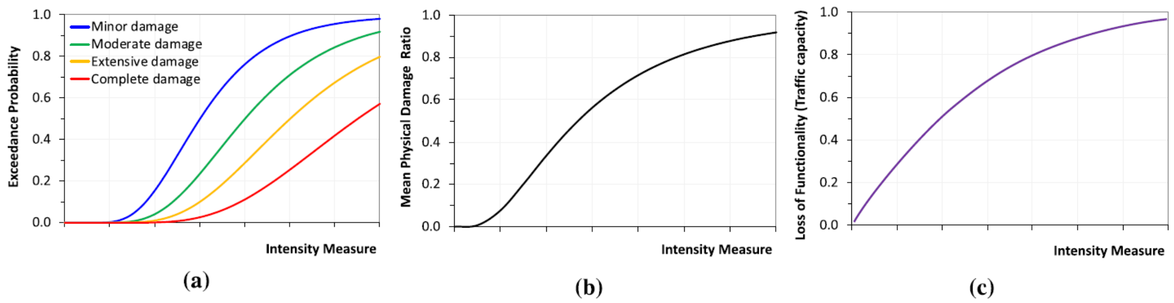


Figure 5: Example of fragility functions (a), degree-of-loss functions (b) and functionality loss functions (c), as the function of a hazard intensity

In Figure 5, the examples a) and b) are related to a physical damage. In example a) there is a probabilistic formulation of the exceedance probability of different damage states, while example b) describes the mean physical damage ratio, which could be applied in a deterministic analysis. The example graph in c) is related to deterministic relationship (i.e. without accounting for uncertainties) between the hazard intensity and the functionality of a network. The mean physical damage

[1] *Willingness to pay, or WTP, is the most a consumer will spend on one unit of a good or service.*

ratio in example b) could be expressed in terms of damage repair costs, usually normalised by asset replacement cost. Also, the example in b) could also represent casualties, commonly given as a fraction of the occupants or travellers, or down-time in terms of days or fractions of a year, during which the asset or system is not operating.

3.2.1 Fragility functions

Fragility functions describe the probability of a failure mode, conditioned on a measure of load intensity, over the full range of the load intensities to which a system might be exposed. Broadly speaking, the failure mode can be considered to be any state of the system which is related to physical and/or functional damage. Compared to nominal failure probabilities estimated from reliability indices, fragility functions provide more comprehensive perspective on system reliability, being functions rather than points and being interpreted in terms of absolute probabilities rather than nominal probabilities, implying knowledge of the underlying probability distributions (USACE, 2010).

Fragility curves are essential components for quantitative risk assessment under the following conditions:

- The loads placed on a system are variable and/or uncertain
- The capacity of a system to withstand the loads is uncertain because there is spatial or temporal variability in material strengths, the system is inherently ductile, or the system is poorly understood.
- The system is brittle and poorly understood.

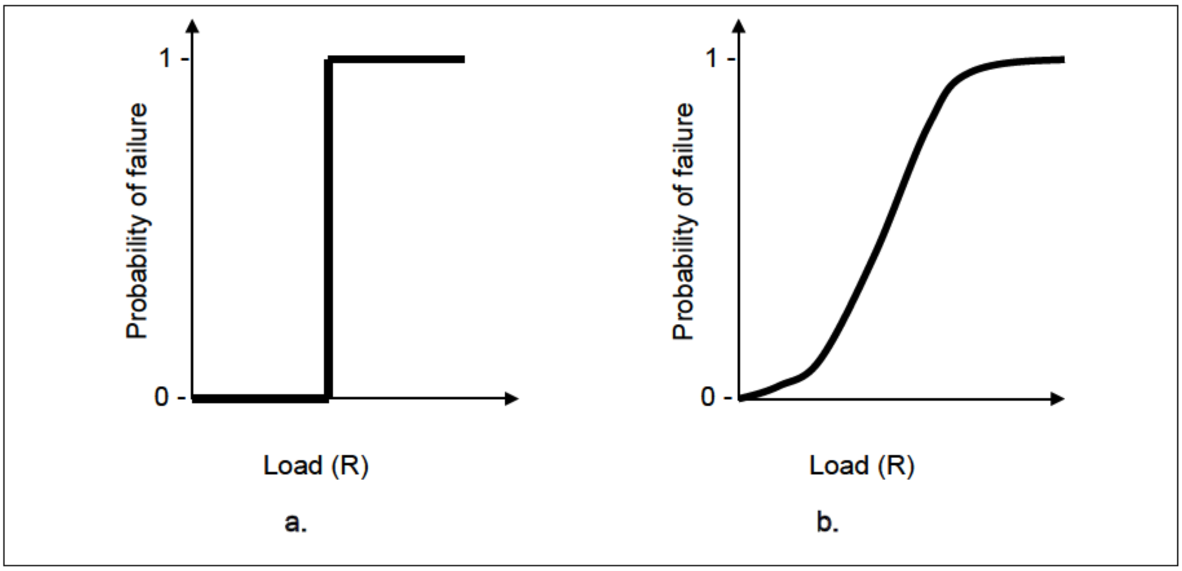


Figure 6: A conceptual fragility curve: (a) step function for very well understood or brittle systems; (b) an S-shaped function for poorly understood or elastic systems (USACE, 2010)

The shape of a fragility curve describes uncertainty in the capacity of the system to withstand a load or, alternatively, uncertainty in what load will cause the system to fail. If there is little uncertainty in capacity or demand, the fragility curve will take the form of a step function, illustrated in Figure 6a. A step function for the probability of failure(p_f) has p_f = 0 below the critical load and p_f = 1 above the critical load. The step function communicates absolute certainty that the system will fail at a critical load and is appropriate for brittle and well-understood systems. For ductile, poorly understood or complex systems, there is uncertainty in the capacity of the system to withstand a load. In these cases, the fragility curve takes the form of an S-shaped function, as shown in Figure 6b. The S-shaped function implies that, over a certain range of demand, the state of the system can only be evaluated with some probability.

The fragility functions express the vulnerability of assets in quantitative terms and can be directly integrated into the quantitative risk assessment. Fragility functions are used to evaluate the reliability of an asset (its probability of damage or failure under the applied load effects) based on a probabilistic approach.

The probability of damage or thresholds in intensity parameters for different damage levels could also be described in terms of tables, i.e. specifying the failure probability for different load conditions. Such tables represent discrete points on a fragility curve and are therefore in this deliverable referred to as fragility tables. Table 3 is an example of a fragility table, expressing the probability of "harmful impacts" in terms of three thresholds. The "harmful impacts" are related to e.g. increased accident frequency for road users, or delays, cancellations and closed transportation lines for road and rail traffic.

Table 3: Threshold values for harmful impact of extreme weather phenomenon (EWENT; 2011)

Phenomenon	1st threshold Harmful impacts are possible, 0.33	2nd threshold Harmful impacts are likely, 0.66	3rd threshold Harmful impacts are certain, 0.99
Wind (gust speed)	≥17m/s	≥25m/s	≥32m/s
Snowfall	≥1 cm/day	≥10cm/day	≥20cm/day
Rain	≥30 mm/day	≥100 mm/day	≥150 mm/day
Cold (mean temperature of the day)	<0°C	<-7°C	<-20°C
Heat (mean temperature of the day)	≥25°C	≥32°C	≥43°C

3.2.2 Degree-of-loss functions

General functions describing degree of loss could be formulated as structural vulnerability functions, expressing the degree of physical loss/material damage to an asset or as functional vulnerability functions expressing the degree of functionality loss. The scale of the degree of loss spans from 0 (no loss) to 1 (total damage or complete functionality loss). In order to express the degree of loss on a scale of 0 to 1, a normalisation of the loss is necessary, e.g.:

- Degree of loss at asset level: Repair cost could be normalised by the cost of a full reconstruction of the asset
- Degree of functionality loss (transport line level): The capacity loss due to the natural event should be normalised by the full capacity of the transport line.

The degree of loss would increase with increasing hazard intensity. For a more vulnerable object, the degree of loss would generally be higher for the same level of hazard intensity than for a less vulnerable object (Figure 7).

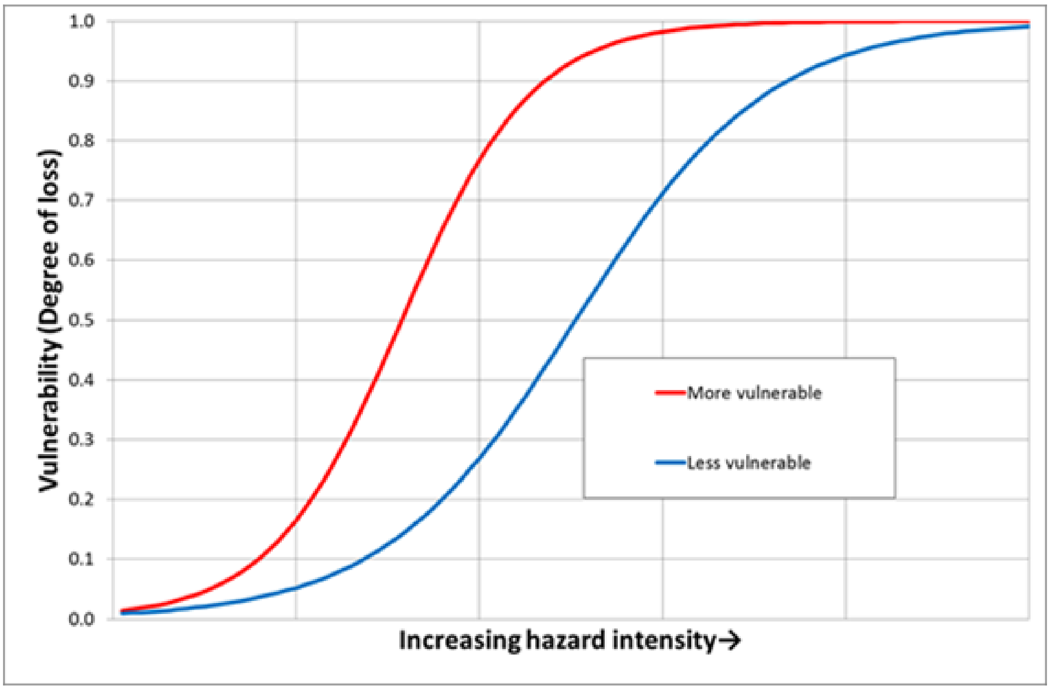


Figure 7: General function expressing the degree of loss as a function of hazard intensity

3.3 Development of fragility functions and degree of loss functions

There are four main approaches to develop fragility curves and functions describing the degree of loss:

- Judgemental: based on expert opinion or engineering judgement.
- Empirical: based on observations.
- Analytical: based on analytical or numerical solution methods.
- Hybrid approach: combining one or more of above approaches.

For fragility curves for assets; analytical approaches validated by experimental data and observations from recent events have become more popular, in particular for earthquake hazard (Argyroudis et al.; 2019). USACE (2010) states that the analytical approach is the most commonly encountered in the peer-reviewed literature. This approach could be applied to different structure types and geographical regions, where damage records are insufficient. Functions describing degree of loss are mainly based on empirical data collected in the field in the aftermath of an event and are consequently specific to the exposed elements in the area where the data has been collected (Schneiderbauer et al., 2017).

3.3.1 Example 1: Judgemental approach

Winter et al. (2014) developed fragility curves for the effects of debris flow on road infrastructure. It was decided that expert engineering judgement should be used due to a lack of a comprehensive empirical dataset as well as the complex nature of the problem. A survey to establish fragility curves for roads hit by debris flows was conducted amongst 176 debris flow experts, with responses from 17 countries. The damage states and fragility curves are shown in Section 4.2.

Lamb et al. (2017) proposed fragility curves for scour of bridges based on results from an international expert elicitation workshop.

3.3.2 Example 2: General empirical approach

This section outlines a general approach for development of degree of loss functions from data. The loss in this model is caused by extreme weather events (EWE) or related hazards. INTACT (2015) and Uzielli et al. (2016) proposed a general model for description of degree of loss with the following functional form:

$$V = V_{ub} \cdot \left\{ 1 - \exp\left[-\left(\frac{I}{A} \right)^{B} \right] \right\} \qquad \text{Eq. (1)}$$

in which:

- V_{ub} is the inherent upper-bound vulnerability, i.e., the maximum value which vulnerability/degree of loss can take as a consequence of its definition. For example, when considering direct physical damage to terrestrial transportation infrastructure and loss is measured as repair cost, vulnerability can be given by the ratio of repair cost to replacement cost. In such cases, the upper-bound vulnerability equals 1, V_{ub}=1;

- I is the intensity of the (extreme weather-related) event, parameterized in terms of a physical attribute describing the damaging potential (e.g. wind speed, rainfall intensity, etc.) or of the event's presumed return period T_R:

$$I = \log_{10}(T_R) \qquad \text{Eq. (2)}$$

The parameters A and B are estimated such that the curve fits best to the empirical data. This calibration of the model can be achieved by generalized least squares (GLS) regression. The regression coefficients are estimates of central tendency, i.e., of a "mean" curve. Probabilistic approaches could also be applied to calibrate the model. The result would then be more like fragility curves, as described in the next subsection.

Figure 8 shows an example of development of a structural vulnerability function for buildings from empirical data. The empirical data were collected during fieldwork after a debris flow event in South Tyrol in August 1987. The validation data (shown as red points in Figure 8) were provided from the insurance companies responsible for the corresponding compensation payments.

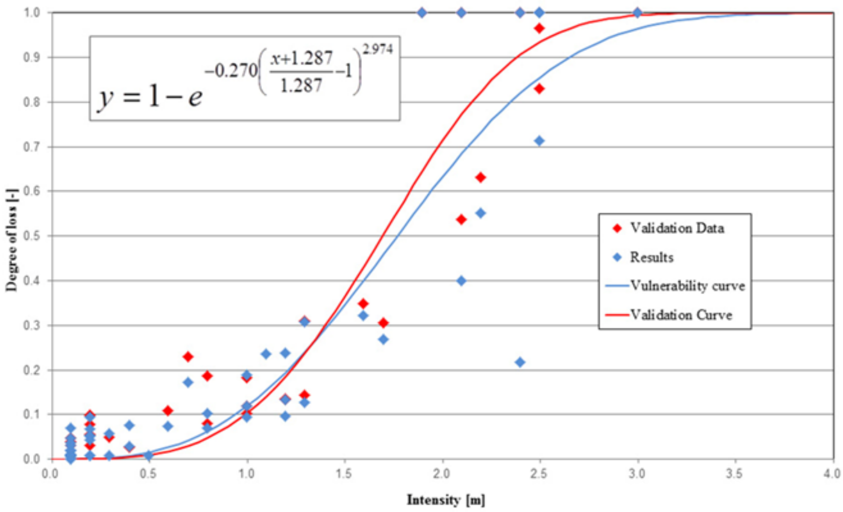


Figure 8: Development of a structural vulnerability function from empirical data for buildings hit by debris flow. The function expresses the degree of loss as a function of debris height in m. (Papathoma-Köhle et al. 2012)

3.3.3 Example 3: Analytical approach applying event tree analysis

In this section, degree of loss is estimated from event tree analysis of the plausible failure modes. Birdsall and Hajdin (2008) presented a vulnerability assessment approach employing hazard and component databases to quantitatively assess the vulnerability of a set of components (bridges, roadways, and culverts) to a range of hazards (avalanches, debris flows, floods, landslides, and rockfalls). This approach documents potential component hazard failure scenarios, identifies common component failure modes, and develops a structured methodology for assessing the potential component failure modes.

The methodology is composed of assessment of the vulnerability of an infrastructure component, identification of common failure modes and analysis of the failure modes using event trees/logic trees.

The vulnerability of a transportation infrastructure component includes the probability of inadequate performance and the related consequences due to a defined set of natural hazard events. The consequences of this inadequate performance can take two different forms: (*a*) direct consequences to the exposed component in the form of structural damage and (*b*) indirect consequences to the transportation traffic by restricting or completely denying the free flow of traffic.

The processes of assessing the vulnerability of an infrastructure component is comprised of the following steps:

- Evaluate whether the given component is exposed to the potential hazard(s).
- Collect natural hazard event magnitude, location, and return period data.
- Collect component location and structural resistivity governing parameters.
- Consult (or develop if required) the infrastructure component failure assessment framework for the respective natural hazard and infrastructure component.
- Assess whether the given component has the structural resistance to withstand the potential natural hazard event magnitudes.
- If the structural resistance is exceeded, use the causality chains in the failure assessment framework to determine the specific failure mode.
- Model or estimate the potential failure durations, direct failure costs, and indirect failure costs.
- Calculate the component and associated link annual risk of failure.

The component failure assessment logic is developed by documenting the scenarios through which each hazard (avalanche, debris flows, floods, landslides and rockfalls) can cause a given component (roadway, bridge, or culvert) to fail.

The roadway is exposed to different hazards (i.e. avalanche, debris flows, floods, landslides and rockfalls). For a roadway component to be operational, other supportive components—specifically, culverts and retaining walls—must also be functional. In addition, Thus, for instance, a landslide can cause a roadway to fail

1. Indirectly by damming a culvert passing underneath a roadway, thereby flooding the roadway;
2. Indirectly by compromising a supporting retaining wall;
3. Directly by undermining the roadway foundation; or
4. Directly by burying the roadway with debris.

Roadway Failure Modes

The set of failure modes is developed by identifying the common failure modes for each component. For example, the five different hazards can cause a roadway component to partially or completely fail in 10 different failure scenarios, but when these hazard–component-specific failure scenarios are studied as a group, three common failure modes can be identified.

1. A roadway can fail due to the failure of supporting components (culverts and
1. retaining walls).
2. A roadway foundation can be eroded or undermined.
3. A roadway can be buried in debris and/or water.

These failure modes can be confirmed and organized in a causality chain by observing that the first failure mode (a roadway can fail due to the failure of supporting components) can be the result of a flood discharge exceeding culvert capacity, a flood compromising the foundation of a retaining wall, a landslide compromising the foundation of a retaining wall or an avalanche, debris flow, landslide, or rockfall burying the culvert. If the supporting components are not affected by the hazard, a hazard can undermine the roadway foundation (failure mode 2) or bury the roadway in debris or liquid (failure mode 3).

This failure assessment process is presented in Figure 9 and determines the controlling failure mode by contrasting hazard and component data. Each failure scenario has different direct consequences, but all induce the same marginal indirect result: the closure of the infrastructure link.

Culvert Failure Modes

Turning to the culvert component, there are five hazard–component failure scenarios that can be simplified into two common failure modes:

1. A culvert can be clogged with debris.
2. A culvert discharge capacity can be exceeded.

The first culvert failure mode, a culvert becoming clogged with debris (i.e., avalanche, debris flow, landslide, or rockfall debris) it is assumed that the culvert has no independent resistance against these four hazards. The various hazards and hazard magnitudes can cause different direct failure costs and durations, but the final result is the same: the partial or complete failure of the culvert.

In the second failure mode, the vulnerability of a culvert is dependent on its design discharge capacity, which could be expressed in terms of the return period of the discharge.

Bridge Failure Modes

For bridges, six common failure modes can be identified:

1. A bridge pier foundation can be compromised.
2. A bridge superstructure can fail vertically in shear or flexure.
3. A bridge superstructure can fail horizontally in shear or flexure.
4. A bridge superstructure–substructure connection resistance can be horizontally or vertically exceeded.
5. A bridge pier can transversely fail in shear or flexure.
6. A bridge roadway surface can be submerged in water or debris.

This relatively large number of failure modes is the result of two key factors: a bridge is, by definition, an elevated structure (a bridge's primary form of structural resistance) and the superstructure, superstructure–substructure connection, and the substructure all have their own structural capacities (multiple additional forms of resistance). Thus, when a hazard does exceed this primary form of resistance, the hazard can cause failure not only by burying the roadway surface in debris, but also by exceeding the superstructure's structural resistance vertically, the superstructure's structural resistance horizontally, the superstructure–substructure connection resistance, or the substructure resistance.

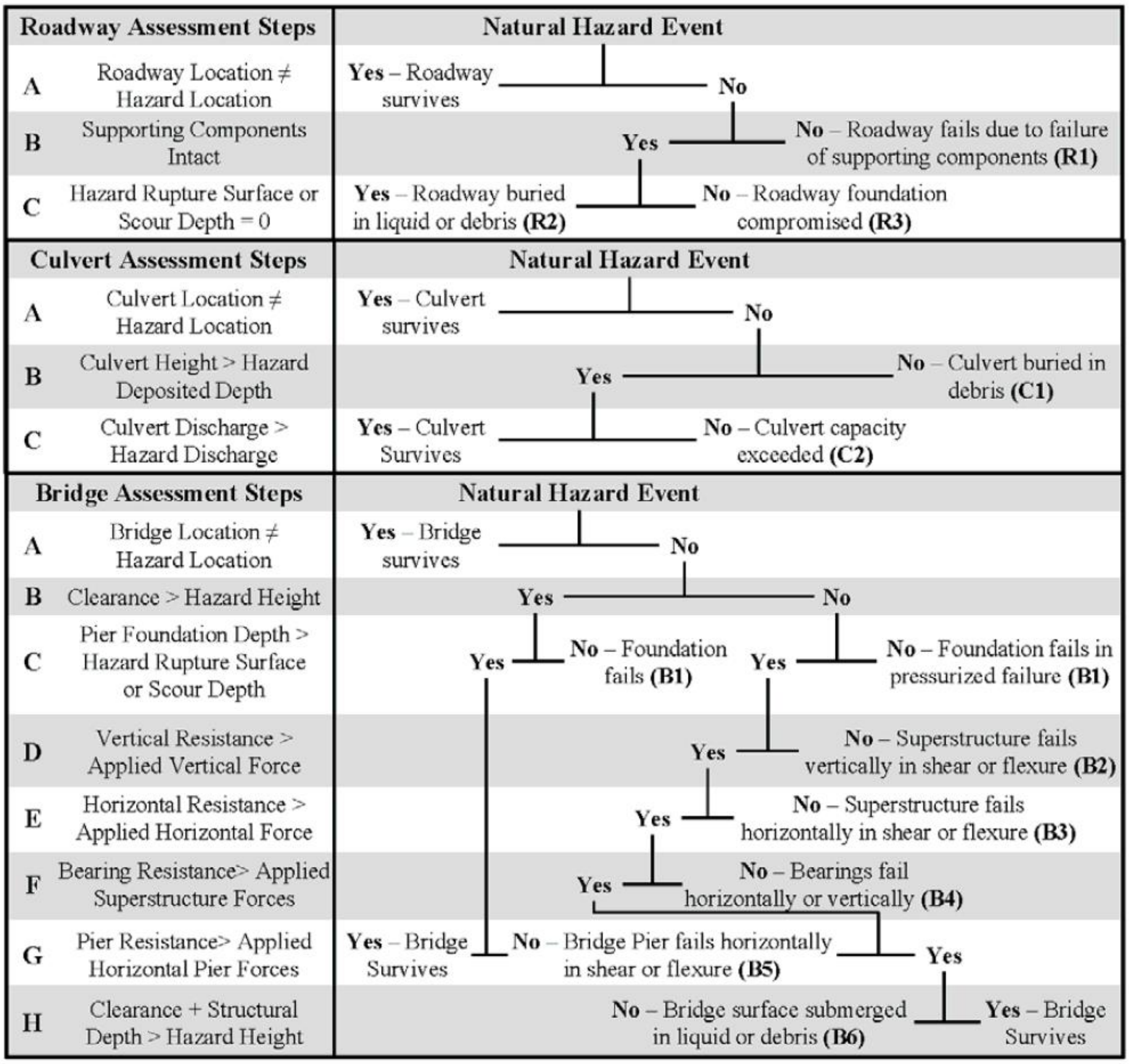


Figure 9: Structured component failure mode assessment approach

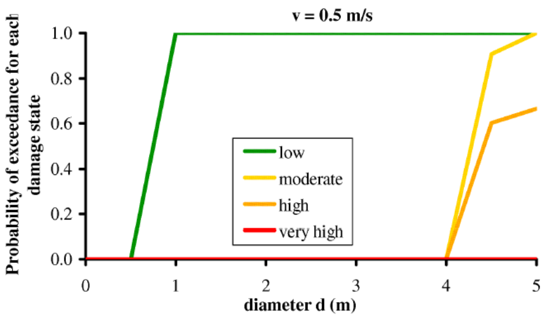
3.3.4 Example 4: Analytical approach applying numerical modelling and reliability analysis

This section outlines the development of fragility curves from numerical modelling and reliability analysis. The performance levels of an asset are defined through damage threshold called limit states, which define the boundaries between different damage conditions or damage states. Fragility curve is dependent on the relationship between the capacity (resistance) and the demand (loads), and these, on the other hand, are dependent on the failure mode that can be triggered by a hazard. Fragility curves could be developed from the definitions of the limit states. For example: complete failure is defined by the limit state function: load > resistance. Limit state functions may be either explicit, written as a function of basic random variables or implicit, implied through a numerical model. Probability of failure is calculated from the uncertainty in the load and in the resistance by using methods for reliability assessment, e.g. the first-order reliability method (FORM) or Monte Carlo Simulation. SAFEWAY (2019b) gives further description of reliability analysis and the calculation of probability of failure.

USACE (2010) demonstrated that there is a direct linkage between the three concepts of reliability: partial safety factors, reliability index, and fragility curves. The fragility curve is a more valuable characterization of system reliability than either the factor of safety or the reliability index. The factor of safety is often used deterministically to evaluate the adequacy of system under a design load, but assumes that capacity is known. The reliability index introduces the concepts of uncertainty in capacity and demand, but only provides information about reliability relative to a single design point. The fragility curve provides a characterization of system reliability over the full range of loads to which a system might be exposed. Thus, it provides more information than the reliability index.

Apel et al. (2004) used a Monte Carlo simulation approach to develop fragility curves for levees. The fragility curve estimated the probability of a levee breach conditional on two independent load variables: overtopping height and overtopping duration. The authors obtained 104 realizations of the limit state condition for selected combinations of independent load variables and then constructed a three-dimensional failure surface.

Mavrouli and Corominas (2010) proposed fragility functions for reinforced concrete buildings exposed to rock fall, based on analytical evaluation. A variety of scenarios of rock fall hitting reinforced concrete buildings analysis were modelled numerically. The examples of resulting fragility curves are shown in Figure 10.



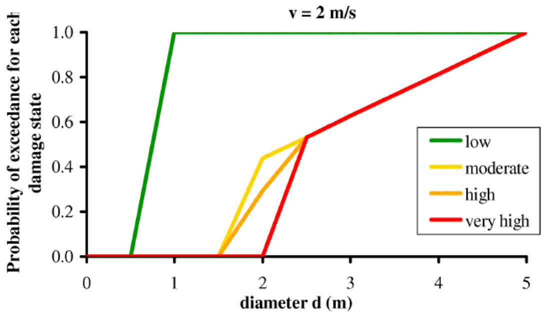


Figure 10: Fragility functions, expressing probability of exceeding damage states as a function of rock diameter for different rock velocities (Mavrouli and Corominas; 2010)

3.3.5 Example 5: Hybrid approach

A hybrid approach to developing fragility curves uses a combination of two or more of the three approaches discussed above in an attempt to overcome their various limitations. Empirical approaches tend to be limited by the availability of observational data; judgmental approaches tend to be limited by subjectivity of expert assessments; and analytical approaches tend to be limited by modelling deficiencies, restrictive assumptions, or computational burdens. There are many ways of implementing a hybrid approach. One approach is to construct a fragility curve using one approach over one segment of the load and a different approach over a remaining segment of the load.

Another possibility is to combine fragility curves developed using judgemental or analytical approaches with observational data through Bayesian updating. For example, Singhal and Kiremidjian (1998) used observed building damage data to update analytical fragility curves for reinforced concrete frames. The Bayesian updating procedure was used to improve the robustness of the fragility curve and produced confidence bounds on estimates of the probability of failure.

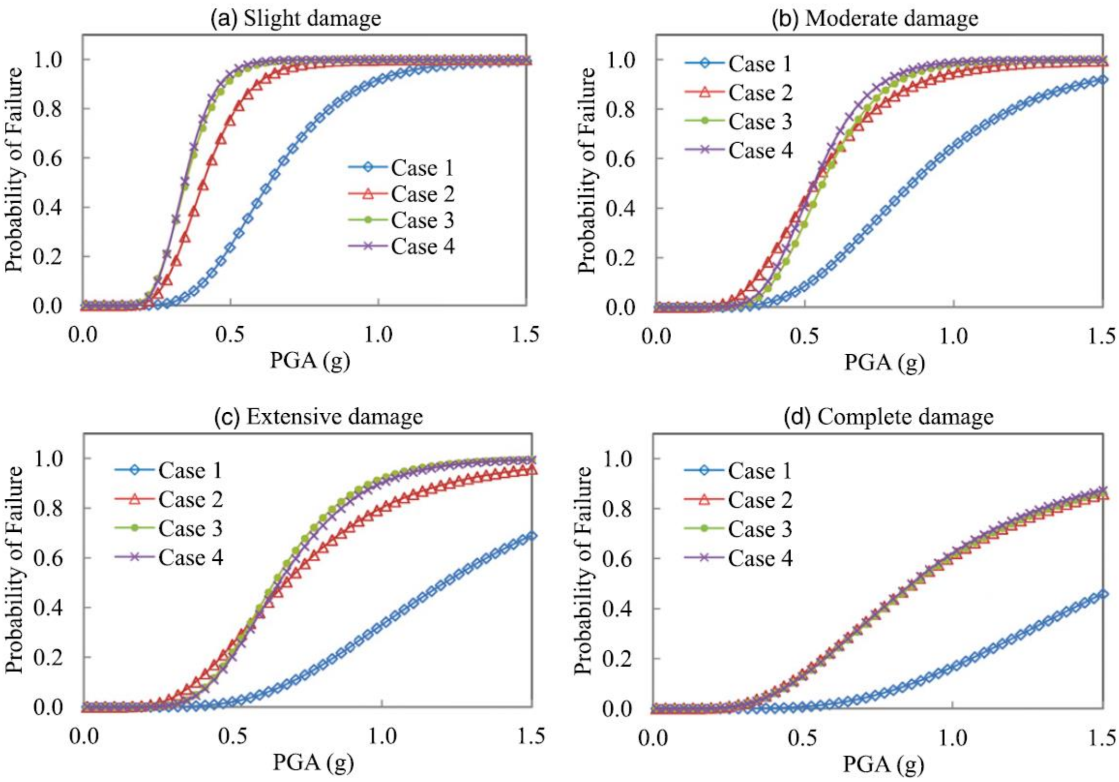


Figure 11: Comparison between the analytical and Bayesian updated fragility functions: (a) slight damage; (b) moderate damage; (c) extensive damage; (d) complete damage. Case 3: Bayesian updated curves of Case1 using hybrid simulation data; and Case 4: Bayesian updated curves of Case 2 using hybrid simulation data. (Singhal and Kiremidjian; 1998)

Jeong and Elnashai (2007) suggest calibrating analytical fragility curves to observational data as another hybrid approach.

3.4 Methods for estimation of indirect consequences

This section gives a short and broad overview of methods for estimation of the indirect consequences of the malfunctioning of a terrestrial transportation line. A malfunctioning transportation line would leave the travellers with several options: postpone or cancel the trip, change mode of transport or travel destination, or take a detour (Erath et al., 2009). The indirect consequences of malfunctioning terrestrial transportation lines are influenced by factors such as duration of the malfunctioning, alternative transportation routes or alternative modes of transportation, additional travel time and additional travel costs. Other indirect consequences encompass costs related to work time lost, and loss of income due to perishable goods spoiling. Long term indirect effects of a repeatedly malfunctioning infrastructure could also encompass change in travel patterns affection e.g. tourism and businesses depending on the transportation line.

3.4.1 Network analysis

Network analysis could be used to determine the flow of vehicles through a transport network. Network analysis could be based on:

- graph theory and topological properties of the transport network. This approach requires network typology data and considers the importance of different edges, cascading failures and interdependencies between different networks
- understanding of the dynamic behaviour exhibited on networks (e.g. traffic flow) through the use of transportation system models; modelling demand and supply side of the transport system and travellers' responses to disturbances and disruptions

Graph theory

In graph theory, the transportation network is a directed graph where each edge has a capacity and each edge receives a flow. The amount of flow on an edge cannot exceed the capacity of the edge.

In its most general notions and based on graph theory, networks are a collection of vertices (or nodes) that are connected by arcs (or links). Graph-theoretical concepts are useful for the description of transport network characteristics and its connectivity. Graph theory and strategy-specific approaches usually focus on the networks ability to resist a series of failures without being torn apart and still providing a defined level of connectivity. However, they usually lack the ability to consider an inherent characteristic of transport networks i.e. the interaction between network demand and supply (Erath; 2011).

Dynamic modelling:

In Dynamic modelling, the traffic flow could be modelled e.g. considering the traffic as a fluid and using models based on fluid dynamics equations. The modelling could also encompass behavioural responses of the travellers to network disruptions or other changes in the supply side of the transport system. The travellers' behaviour would affect the demand side of the transport system.

3.4.2 Assessment of costs

- Meyer et al. (2013) gave a broad review of assessment of indirect costs of natural hazards affecting infrastructure. The review encompasses methods like event analysis, econometric approaches, input-output analysis, computable general equilibrium analysis, intermediate models, public finance analysis and idealized models.
- SAFEWAY (2019b) provides a description of assessment of economic consequences.
- Winter et al. (2018) outlined possible approaches to estimating the economic impacts of landslides on a road network. Economic impacts of a number of debris flow events in Scotland were included as application examples.

4. Functional vulnerability models

This section focuses on review of models expressing malfunctioning of terrestrial transportation lines at network level. A summary of the reviewed models is given in Table 4. Models found especially relevant for use in analysis of the demonstration sites in SAFEWAY are described more in detail in the following subchapters.

Table 4: Models expressing capacity loss of roads and railway for different natural event triggers, extended from Snelder and Calvert (2016)

Trigger	Type of model	Source(s) of model	Short description of model
Rain	Functional capacity loss functions and tables	Agarwal et al (2006), Brilon and Ponzlet (1996), Chung et al. (2005), Calvert and Snelder (2013), Federal highway administration (2006), Hogema (1996), Hranac et al. (2006), Ibrahim and Hall (1994), Martin et al (2000), Maze et al. (2006), Smith et al. (2004), Van Stralen et al. (2014), Vukovic et al. (2013)	Vehicle speed reductions and road capacity reductions due to rain
Rain	Fragility table	Vajda et al. (2014)	Probability of adverse impacts as function of precipitation
Snow	Fragility table	Agarwal et al. (2006), Hranac et al. (2006), Martin et al. (2000), Maze et al. (2006)	Vehicle speed reductions and capacity reductions due to snow precipitation or snow on road
Snow	Fragility tables	Vajda et al. (2014)	Probability of adverse impacts as function of precipitation
Flooding	Function expressing reduction of vehicle speed (i.e. could be transferred to a functionality loss function)	Pregnolato et al. (2017)	Vehicle speed as function of floodwater depth
Flooding	Functional capacity loss functions	Lam et al. (2018), Hackl et al. (2018)	Functional capacity loss functions for road section inundation expressed as a function of inundation depth. Functional capacity loss expressed as a function of bridge scour damage state, which is related to discharge.

Trigger	Type of model	Source(s) of model	Short description of model
Temperature extremes – heat waves	Fragility table	Network Rail (2014b), Network Rail (2015) Dobney at al. (2010), Chapman et al. (2008)	Temperature thresholds for different undesirable events related to buckling of railway tracks Speed reductions as function of temperature to avoid rail buckling
Temperature extremes – heat waves	Fragility table	Vajda et al. (2014)	Probability of adverse events for different threshold values of temperature
Wind	Fragility table	Vajda et al. (2014)	Probability of adverse events for different threshold values of temperature
Reduced visibility	Verbal description	Maze et al. (2006),	Free speed reduction due to reduced visibility
Landslides	Fragility curve	Winter et al. (2014).	Fragility curves for roads subjected to debris flows expressed as a function of landslide volume. Damage states expressed in terms of blockage of road or damage to surfacing, i.e. related to mobility.
Landslides	Fragility function and functional capacity loss function	Lam et al. (2018)	Damage state exceedance probability for mudflow-blocking as a function of volume. The functional capacity loss is further expressed as a function of the damage state

4.1 Functional capacity loss due to flooding of roads

The simplest models for assessment of mobility on roads would be to assume that a road is fully operational or fully blocked and to define a threshold for water depth on the road to distinguish between these two. More sophisticated approaches describe the reduction of mobility (e.g. in terms of capacity reduction or in terms of reduction in travel speed as a continuous function of water depth).

Pregnolato et al. (2017) developed a relationship between depth of standing water and vehicle speed. The function that describes this relationship (Figure 12) was constructed by fitting a curve to video analysis supplemented by a range of quantitative data that was extracted from existing literature. The proposed relationship was a good fit to the observed data, with an R-squared of 0.95. The study also identified the maximum threshold for safe driving, stopping, and steering (without loss of control) to be 30 cm, on the basis of observations and driving tests. A road is therefore assumed to be impassable when the threshold limit of 30 cm is reached.

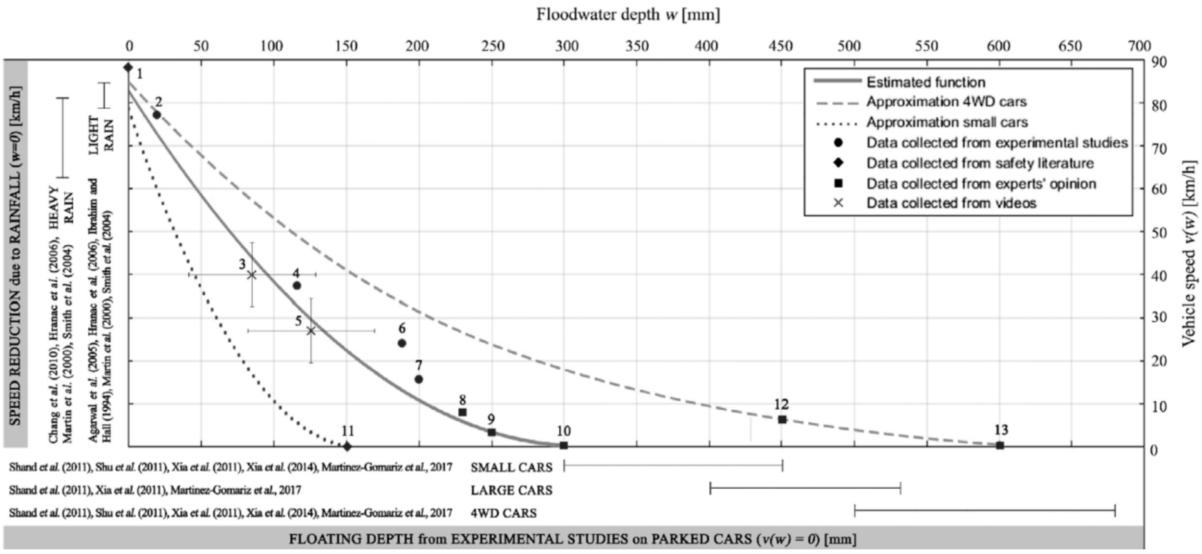


Figure 12: Depth-disruption function relating flood depth on a road with vehicle speed (Pregnolato et al. 2017)

Hackl et al. (2018) introduced a methodology to support network managers in the quantification of the risk related to their networks. The risk of a complete chain of events, from a source event to its societal events is quantified over space and time. In the assessment, four damage states were defined, expressing increasing severity of damage: 0: operational, 1: monitored, 2: capacity-reduced, 3: closed. The content of each damage state for the failure modes: bridge local scour, road section inundation and road section mud-blocking is described in Table 5.

Table 5: Damage states for bridge local scour, road section inundation and road section mud-blocking (Hackl et al.; 2018)

State	Label	Bridge local scour	Road section inundation	Road section mud-blocking
s_0	*operational*	no changes in bridge response	no observed damages, negligible sign of sediments	no observed damages
s_1	*monitored*	first noticeable changes in bridge response	presence of sediments and debris	encroachment limited to verge/hard strip
s_2	*capacity-reduced*	significant changes in the bridge response	elements of the road section slightly damaged	blockage of hard strip and one running lane
s_3	*closed*	lack of pier stability to support the bridge	loss of subgrade layer	complete blockage of carriage-way and/or repairable damage to surfacing

The applied fragility curves are interesting, because Hackl et al. (2018) demonstrated that these are applicable and fit into a holistic risk assessment. The formulations of damage states and intensity parameters could be applied when developing fragility curves considering the same failure modes. However, a verification or adaptation to local condition would be necessary before applying the fragility functions in Figure 13. The main focus of Hackl et al. (2018) is not on development of fragility curves and little information is found about how these curves were derived.

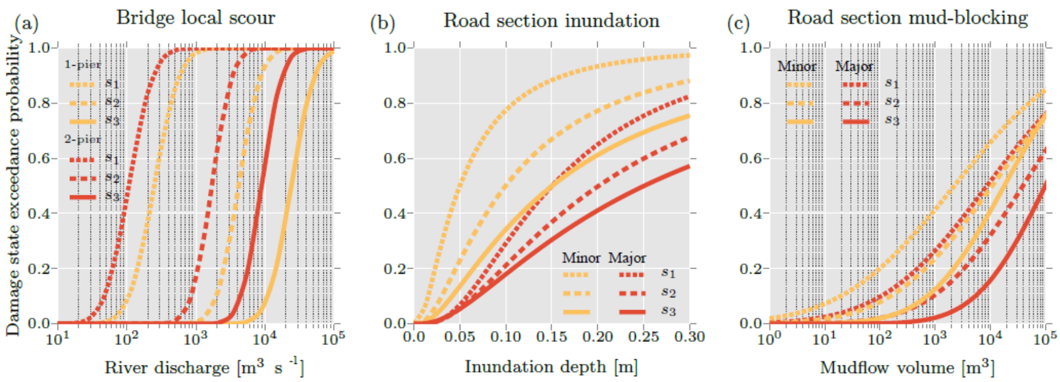


Figure 13: Functional loss functions for (a) bridge local scour, (b) road section inundation, and (c) road section mud-blocking. The horizontal axis represents the intensity measure 4 of the corresponding hazard. For (a) bridge local scour and (c) road section mud blocking the axes are displayed in log-scale. The vertical axis represents the expected functional loss (Hackl et al.;2018)

4.2 Functional capacity loss due to landslides/mass movements

Winter (2019b) expressed the structural and functional vulnerability of roads to debris flow through fragility functions that relate flow volume to probabilities of failure for different failure modes. Fragility curves have been produced that indicate the probability of a debris flow of a given volume exceeding each of three damage states (Table 6). Typically, damage to roads resulting from debris flow may include one or more of the following:

- Debris covering the carriageway, preventing vehicle movements.
- Damage to the carriageway surfacing materials.
- Blockages and other types of damage to the drainage system.
- Damage to vehicle restraint systems.
- Damage to support structures including slopes and retaining walls downhill from the road.

Representative damage states associated with the consequences of a debris flow of a given volume intersecting a road were defined in Table 6. The damage states range from 'limited damage' which, for high speed roads, is unlikely to significantly affect the passage of vehicles, through 'serious damage', to 'destroyed' involving complete blockage and damage to the road itself that for, high-speed roads at least, will almost certainly need to be repaired prior to reopening to traffic without restrictions on speed. The fragility curves are illustrated in Figure 14.

Table 6: Damage states definitions applied by Winter (2019b)

Damage state	High-speed roads	Local (low-speed) roads
P1 (Limited damage)	Encroachment limited to verge/hard strip	Partial blockage of carriageway
P2 (Serious damage)	Blockage of hard strip and one running lane	Complete blockage of carriageway and/or damage to ancillaries
P3 (Destroyed)	Complete blockage of carriageway and/or repairable damage to surfacing	Complete blockage of carriageway and/or damage to surfacing. For unpaved roads the surfacing may remain damaged but passable at reduced speeds post clean-up

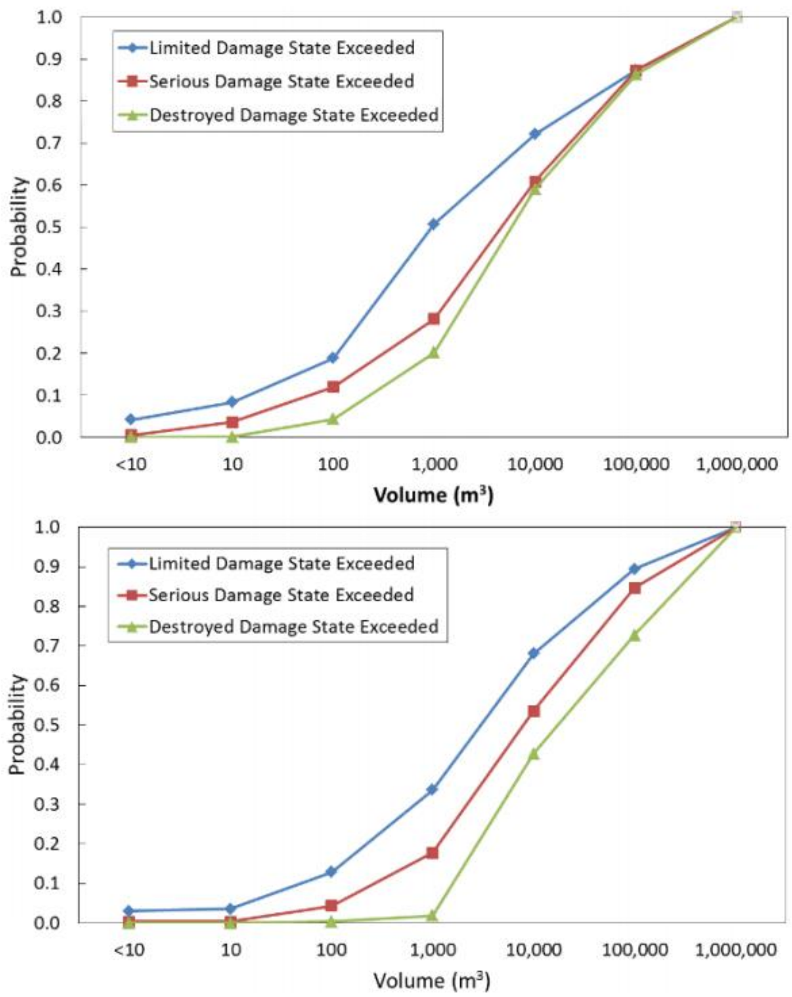


Figure 14: Fragility curves for roads hit by debris flow. Top: Local (low-speed) roads. Bottom: High speed roads. The volume on the horizontal scale refer to the volume of debris intersecting the road

4.3 Threshold models for extreme weather events

EWENT (2011) examined failure modes for terrestrial transportation initiated by snowfall, wind gusts, low temperature and blizzards. Three threshold values were chosen for each weather parameter representing failure modes leading to different severity of consequences.

Table 7: Description of failure modes and consequences for transportation infrastructure and users, with related thresholds of the triggering extreme weather event (adapted from EWENT; 2011)

High temperature – daily maximum temperature		
Threshold	**Failure mode**	**Consequences**
≥25°C	Fatigue among drivers.	Possible increased crash rate in road transportation.
≥32°C	Damage to pavement	Increased accident rate, delays, diversion.
≥43°C	Rail equipment failure, rail track buckling, heat exhaustion.	Increased accident rate, delays, diversion.
Heavy precipitation		
Threshold	**Failure mode**	**Consequences**
≥50 mm/24 h	Flooded roads, reduced pavement friction.	Damage to secondary (sand-covered) roads, increased collision risk on roads.
≥100 mm/24 h	The sewer system fills up; water rises to street level from drains. Rainwater fills underpasses and lower lying streets. Drain well covers may become detached and cause danger to street traffic. Reduced visibility, flooded underpasses.	Increased rate of road accidents, delays, damaged roads.
≥150 mm/24 h	Road structures may collapse and gravel roads are badly damaged. Bridges may be flooded. The metro system might be flooded, damaging track switch motors, the signalling system, power distribution system If a car is driven into deep enough water, the motor stops and may be flooded. Rainfall may induce landslides causing wash-out of roads or rail tracks. Roads and rails might be covered by water or by transported debris and mud	Disrupted traffic, increased rate of road accidents, delays in road and rail traffic, damaged or closed roads and rail tracks.

4.3.1 Threshold models for wind speed

Too high wind speed on bridges creates dangerous conditions for the travellers on the bridge. As part of the preparedness several warning levels and warning levels might be defined, as shown in Table 8.

Table 8: Wind speed thresholds for London North West Route (NetworkRail; 2014a)

Wind Speed	Action	Element
Forecast of gusts up to 59mph	No action	**Wind 1**
Forecast of gusts from 60mph to 69mph (not sustained)	Be aware of the possibility of 'Wind 3' being reached	**Wind 2**
Forecast of frequent gusts from 60 to 69mph (sustained over 4 hours+)	50 mph speed restriction for all trains in the affected Weather Forecast Area	**Wind 3**
Forecast gusts 70mph or over	50 mph speed restriction for all trains in the affected Weather Forecast Area	**Wind 3**
Forecast gusts 90mph or over	All services suspended in the affected Weather Forecast Area	**Wind 3**

The thresholds used for determination of the warning levels and for precautionary closure of the bridge are based on both the velocity and the direction of the wind. The strongest restriction is usually for winds perpendicular to the transportation line. Further it is usually distinguished between wind gusts and mean wind, with stronger requirements to mean wind. Table 9 shows an example of such formulation for a Norwegian bridge.

Table 9: Threshold for wind speed at the Hardanger bridge in Norway

Thresholds based on wind	
Wind gust perpendicular to road	**Mean wind 1 min**
Warning high: 24 m/s Close: 30 m/s	Warning: 17 m/s Warning high: 20 m/s Close: 25 m/s

4.3.2 Threshold models for temperature

Although railway tracks are designed to withstand a reasonable range of temperatures, once a critical rail temperature is reached, problems may occur. Railway buckling could be avoided by lowering of the speeds of the trains if the temperature in the tracks are too high. Table 10 presents imposed speed restrictions on temperature differences from the Stress-Free Temperature (SFT) for railways in UK, representing Critical Rail Temperature (CRT) values for standard track in good and poor states of repair. These represent the extremes of the spectrum and a continuum exists between depending on the actual track condition. There are many exceptions to the rule, for example at areas prone to subsidence, level crossings and bridges.

Table 10: Speed restrictions for different temperatures and track conditions; Chapman et al. (2008)

Track condition	On standby	Impose 30/60 mph speed restriction	Impose 20 mph speed restriction
Good condition	SFT + 32 °C	SFT + 37 °C	SFT + 42 °C
Inadequate ballast	SFT + 10 °C	SFT + 13 °C	SFT + 15 °C

SFT Stress free temperature (normally 27 °C in UK)

5. Structural vulnerability functions

Review has been conducted on available structural vulnerability functions for different hazard types and assets. An overview is given in Table 11. Selected functions are described more in detail in the next subchapters.

Table 11: Fragility models at asset level (extended from Argyroudis et al. 2019)

Trigger	Failure mode	Short description of model	Source(s) of model
Flood	Different failure modes of bridges with shallow foundations due to local scour	Probability of a bridge failure, which accounts for soil-structure resistance to local scour	Tanasic (2015)
Flood	Different failure modes of bridges due to scour and corrosion effects	Fragility estimates, intensity parameter: water velocity	Kim et al. (2017)
Flood	Bridge scour leading to bridge failure	Probability of a bridge failure, for different return periods of flood	Lamb et al. 2017
Flood	Bridge scour leading to bridge failure	Damage states exceedance probability as function of discharge	Lam et al. (2018)
Flood	Railway embankment fill and track ballast scour	Fragility curves for ballast scour as function of overtopping water depth and ballast failure as function of overtopping flow rate per unit length.	Tsubaki et al. (2016)
Flood	Dike failure*	Fragility curves for dike failure as function of water level for different failure mechanisms (overtopping, piping, macro-stability, combined effects)	Wojciechowska et al. (2015)
Flood	Failure of levees due to overtopping or piping	Fragility surface as function of overtopping water depth (overtopping failure) and height difference between river water level and water level behind the levee (piping failure)	Lozano-Valcárcel and Obregón(2017).
Flood	Material damage to road (four-lane road)	Material damage to road caused by flooding for 3 levels of intensity	Bundesamt für Strassen ASTRA (2012)

Trigger	Failure mode	Short description of model	Source(s) of model
Extreme precipitation	Levee failure *	Fragility functions for levee failure as a function of rain intensity for various rain durations and return periods	Jasim and Vahedifard (2017).
Extreme temperature	Rail buckling	Thresholds for rail buckling	Dobney et al. 2009
Landslide	Material damage to road (four-lane road)	Material damage to road for different landslide types for 3 intensity levels for each landslide type	Bundesamt für Strassen ASTRA (2012)
* Authors believe that this model is transferrable to embankment failure			

5.1 Material damage to road due to flooding

The Swiss road authorities provide guidelines for assessment of material damage of roadways caused by flooding; The guidelines suggest the degree of loss values of road segment as shown in Table 12.

Table 12: Vulnerability of roadway segments (Bundesamt für Strassen ASTRA, 2012)

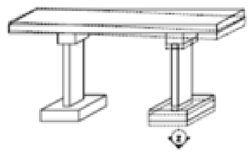
Process	Intensity	Vulnerability (Degree of loss of road segment)	Comment
Flooding (dynamic; v> 1m/s)	**Low (h < 0.5 m or v · h < 0.5 m²/s)**	**0.05**	**h: flow depth** **v: flow velocity**
	Medium (0.5 < h < 2 m or 0.5 < v · h < 2m²/s)	**0.05**	**h: flow depth** **v: flow velocity**
	High (h > 2 m or v · h > 2 m²/s)	**0.35**	**h: flow depth** **v: flow velocity**
Flooding (static; v < 1m/s)	**Low (h < 0.5 m)**	**0**	**h: flow depth**
	Medium (0.5 < h < 2 m)	**0.01**	**h: flow depth**
	High (h > 2 m)	**0.1**	**h: flow depth**

5.2 Local scour at bridge foundations due to flooding

The flooding is the most frequent and the most widespread cause of inadequate bridge performance in the world, as discussed in (Faber, 2007), (Imhof, 2004) and (Sullivan, 2005). In an extreme flooding event, the two most common types of bridge failure are related to washing away of approach/es (the stretch of the road leading directly to a bridge) and a damage (including collapse) due to local scour at foundation/s. The first failure mode can be in most cases analysed without knowledge on bridge type/geometry, but for the consideration of the second mode, a more detailed analysis is required i.e. the one which account for bridge resistance to undermining of its foundations. In addition, the superstructures of steel and timber bridges may be swept away by the flooding waters, so for these would be reasonable to analyse a scenario of overtopping as well. Generally speaking, during a flooding event all mentioned failure modes can occur simultaneously. In any case, the special attention should be paid to the conditions which can exacerbate the water flow action at bridge foundations, such is debris/ice blockage.

Local scour is regarded as observable, non-interceptable process which does not leave ample time for an adequate mitigation action. The issue with local scour assessment lies with the uncertainties of scour development at a bridge site, which are dependent on hydraulic and soil parameters and bridge properties. The magnitude of scour at bridge foundation that can cause failure is dependent on the specific bridge system to which it pertains. For example, a 1.0m deep scour cavity at a central pier of a multi-span concrete bridge may not be particularly detrimental. However, the same for a masonry arch structure could mean collapse.

It is common approach in many countries to act reactively, i.e. the failure mode is acknowledged only when there is damage observed (e.g. a differential settlement, extent/evidence of scour). Then, a qualitative or a semi-quantitative assessment is performed, e.g. as presented in Figure 15, to prioritize bridges for maintenance. These approaches can aid in definition of thresholds for a degree of loss functions but still, the effects of scour on different bridge types need to be considered in order to apply the functions on a portfolio level.

Damages of the substructures			
S3	**Differential settlement**		
Definition: vertical differential settlement between the two foundational systems supporting the same deck. Relative displacement measurement. **How to detect**: visual inspection and manual measurement. Since the damage sometimes is difficult to be detected, it is also possible to check soil conditions close to foundations, and the joints of the related substructures in the deck.			
Description: differential settlement between elements supporting the same deck. For each column, it is necessary to refer to both the adjacent columns for assessing the largest value.			
B	**3**	**How to quantify**: it has to be detected by measuring and checking relative displacements. A photo of the damage has to be taken.	
K_2	Intensity criterion: Measurement of the differential settlement	$K_2 = 0.5$	< 2 cm
		$K_2 = 1.0$	from 2 to 5 cm
		$K_2 = 1.5$	from 5 to 10 cm
		$K_2 = 2.0$	> 10 cm
K_3	Extension: Location of the damage	$K_3 = 1.0$	It is not necessary to assess the extension of the defect. $K_3 = 1$ if the damage is present.

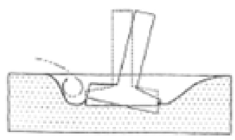
Damages of the substructures			
S5	**Foundation scour**		
Definition: foundation scour **How to detect**: visual inspection of the soil close to foundations.			
Description: soil settlement of the soil at the foundation. The substructures are an obstacle to flowing water and the damage occurs due to the related soil erosion in a flooding event.			
B	**4**	**How to quantify**: the evaluation of the scour area can be performed with a visual inspection but it is necessary to have information of foundation geometry. The damage is not to be reported when foundational systems are by design uncovered by soil (see original projects). The extension of this damage can be measured with a meter.	
K_2	Intensity criterion: Ratio between the area of the foundation element and the eroded area	$K_2 = 0.6$	< 10%
		$K_2 = 1.0$	from 10 to 25%
		$K_2 = 1.6$	from 25 to 50%
		$K_2 = 2.0$	> 50%
K_3	Extension: Location of the damage	$K_3 = 1.0$	It is not necessary to assess the extension of the damage. $K_3 = 1$ if the damage is present.

Figure 15: An example of assessment of defects/damages of a foundation system - differential settlements and erosion, adapted from (Rete Ferroviaria Italiana S.p.A. , 2014)

The effects of local scour on bridge stability in flooding events and related failure modes are rarely investigated. In bridge management practice, the flooding is tackled with risk-based approaches, e.g. (FEMA, 2007), (Pearson, et al., 2002) and (ASTRA, 2014). Here, the magnitude of a hazard and the related structure exposure are accounted for, but the resistance of a structure to a failure in the event is not adequately considered. In most cases, the direct costs of a failure, e.g. loss of life and limb and repair & reconstructions, are assessed; while an adequate evaluation of the indirect consequences of bridge failures, e.g. travel time loss, is rarely performed.

The main parameter that is used in the evaluation of probability of a bridge failure due to scour is a local scour depth (e.g. Johnson & Dock, 1998). The rule of thumb criterion for bridge failure is when the calculated scour depth reaches the bottom of the substructure's foundation. However, this latter criterion is clearly too conservative to be used for every bridge type in a network. The importance of evaluation of bridge resistance to scour at foundations is reviewed in (Hajdin et.al, 2018), where the related differences between girder, frame and arch bridges are discussed. The given approach considers vulnerable zones of a bridge, which comprise those bridge elements or their segments with a crucial role in resistance to a failure due to local scour at substructure foundation(s). Any type and severity of damage at these zones are of interest (e.g. Figure 16), as they may decrease the overall bridge resistance to an oncoming flooding event and increase the probability of failure.

In the case of the shallow foundations, several factors need to be accounted in the failure mode analysis. An example for the multiple span RC girder bridge is given in Figure 16. For the girder and frame bridges with shallow foundations, the ultimate extent of scour cavity beneath the foundation level govern the probability of failure (Tanasic, 2015). When exposed to a same scour scenario, i.e. foundation undermining, the least resistance to local scour is displayed by the bridges where there is no restraint to the horizontal displacement of the top of the affected substructure. But if there is restraint to horizontal movement, the role of the main girder and adjacent substructures should be considered in resistance. By design, the bridges with deep foundations seem more resistant to scour, but this should be confirmed by analysing the failure modes which involve pile buckling, pile cap failure and loss of friction force for various local scour depths (Ramey & Brown, 2004).

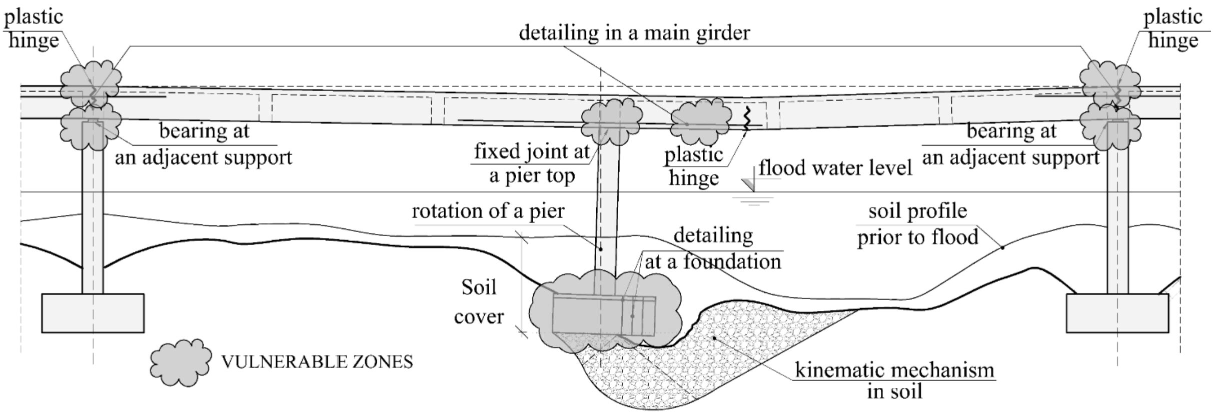


Figure 16: An example of a failure mode due to local scour at a pier - multiple-span RC girder bridge and its vulnerable zones - adapted from Tanasic & Hajdin, 2017

In addition to the uncertainties related to empirical evaluation of local scour, one must account for the variability of the soil cover at the substructures as well. The latter is especially important for the masonry bridges. Their main weakness to scour is the lack of resistance in tension of used construction materials, which causes fragmentation of the structure in subparts and differential settlements for a scour cavity beyond the foundation depth.

For the purpose of modelling the structural vulnerability functions, the failure modes per bridge type must be clearly defined with respect to the ultimate local scour depth at the affected substructure. This ultimate scour depth includes height of soil above and below foundation level which need to be eroded to trigger a failure mode (e.g. a kinematic mechanism). The ultimate scour depth is to be compared to the potential scour depth calculated by empirical formulas, to evaluate the related probability of failure. The empirical formulas (e.g. Arneson et al. 2013) contain the hazard parameter i.e. water velocity/discharge, thus hazard magnitude in an exposure scenario can be directly related to a failure mode.

6. Recommendations for impact assessment

6.1 Proposed framework for assessment of impact

Figure 17 shows an overview of the steps necessary for assessment of impact of natural events on transportation systems. The content of each of the steps is elaborated in the next subsections.

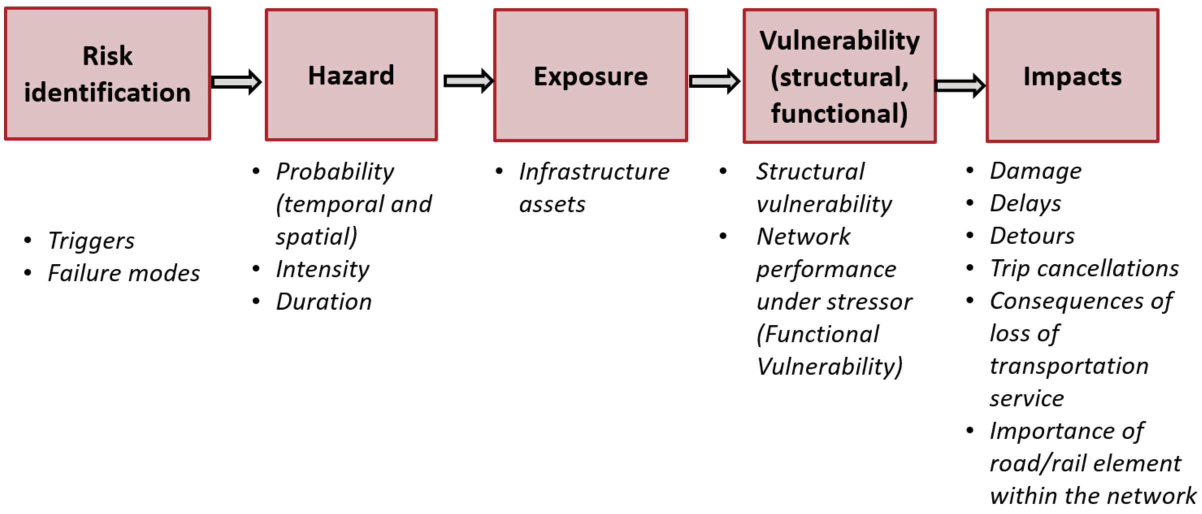


Figure 17: Framework for assessment of impact of natural events on transportation systems

6.2 Risk identification

The risk identification consists of answering the question: What could go wrong? Possible undesirable scenarios i.e. events or sequence of events with their causes are identified. Within the scope of this deliverable, this would entail identification of failure modes per asset and natural hazard triggering them. This has been already performed in SAFEWAY (2019a) for road and rail assets.

6.3 Hazard assessment

Hazard is assessed in terms of probability of occurrence (or its frequency) and magnitude (or intensity). The probability should be expressed in terms of temporal probability (e.g. annual probability) and spatial variability (e.g. visualised on maps).

There are two main ways to assess hazards, by:

1. Frequency or annual probability of the hazard event for a selected range of intensities/magnitudes
2. Intensity for hazard events representing a certain frequency or return period.

The first approach is common for representation of meteorological parameters. The second approach is common for natural hazards like floods and landslides etc.

An overview of natural hazard data bases is provided in Appendix 1 in SAFEWAY (2019a). Hazard maps may represent current or future hazard situation, where the latter typically would account for climate changes. For projections of future hazard situations or assessment of changes in the hazard situation, a time span and representative concentration pathway need to be selected.

6.3.1 Hazard representations in terms of temporal probability or frequency

The hazard representation for meteorological parameters is most commonly represented by the return period for intensity parameters exceeding thresholds. Figure 18 is an example of such a presentation, showing the number of days with maximum temperature above 35°C. Other examples of this type of hazard representation are:

- number of days per year with windspeed above 17 m/s
- annual probability of a 3-hr precipitation higher than 50 mm

The values of the thresholds for intensity parameter causing consequences could be chosen from fragility functions or fragility tables.

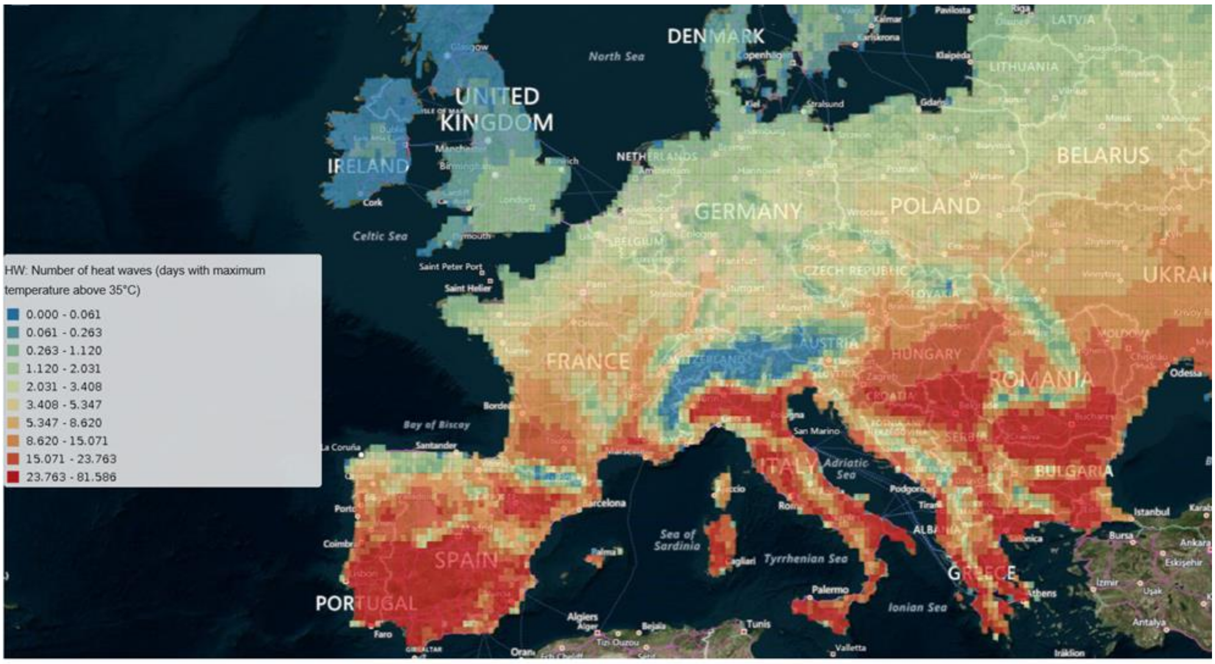


Figure 18: Hazard presented as frequency of an event above a threshold (Here: number of days with maximum temperature above 35°C) (Source: INTACT-Wiki; http://scm.ulster.ac.uk/~scmresearch/intactnew/index.php/Extreme_weather_maps)

6.3.2 Hazard representations in terms of intensity

The hazard could also be expressed as intensities of the hazard for different return periods. In Figure 19, the intensity parameter is the flood depth and the return period of the flood event is 25 years. Other examples of spatially varying hazard parameters:

- Flood depth of the 100-year flood
- Volume of the 100-year landslide
- Maximum temperature in the 100-year heatwave
- Peak ground acceleration of the 100-year earthquake

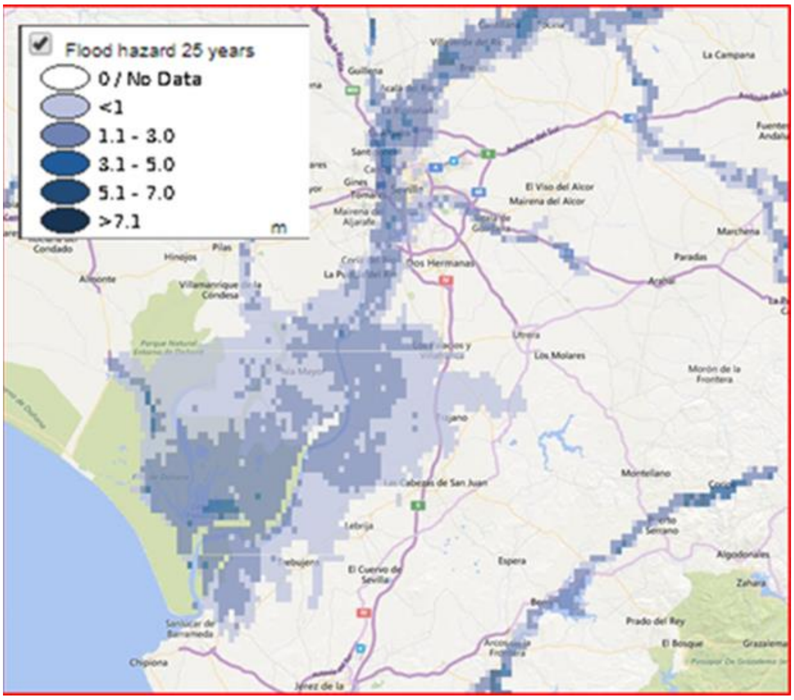


Figure 19: Flood depth for flood with return period 25 years. (Source: Global Assessment Report on Disaster Risk Reduction)

An important input from the hazard assessment to the vulnerability assessment is the intensity of the hazard. This intensity would differ with the return periods of the hazard selected for the analysis. Section 3.3 outlines different methods for development of damage-, loss- and fragility curves. Within all the described methods it is necessary to decide on a parameter to represent hazard. Recommendations for choice of intensity parameters for different hazard types and failure modes are given in Table 13.

6.4 Exposure

The exposed infrastructure assets can be identified by overlapping the hazard maps with road and railway networks (Figure 20). SAFEWAY (2019a) produced hot-spot maps for the pilot areas indicating the most exposed parts of the transportation lines.

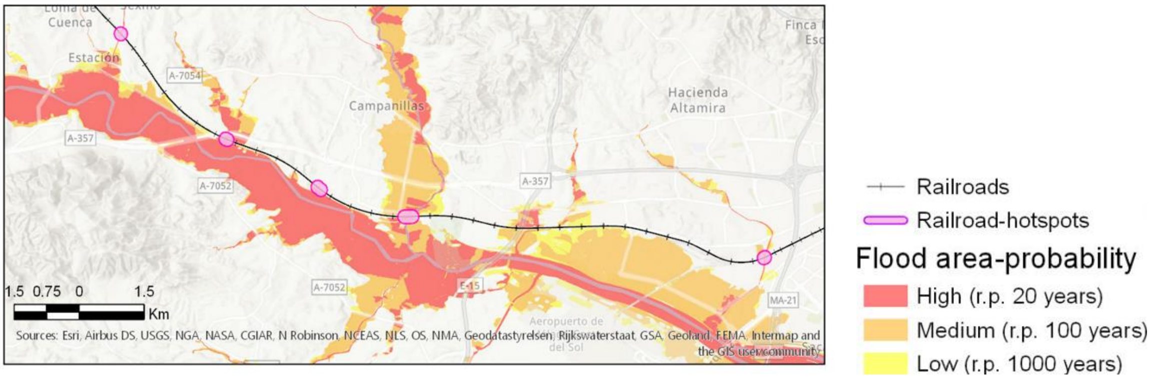


Figure 20: Exposure of railway track to floods for different flood return periods (20-years, 100-years and 1000-years). The exposed parts of the railway are indicated with pink ellipses. (Source: *Ministerio para la Transición Ecológica, https://www.miteco.gob.es/es/agua/temas/gestion-de-los-riesgos-de-inundacion/mapa-peligrosidad-riesgo-inundacion/*)

Users, economic activity and environment can get indirectly exposed to the event due to failures of related infrastructure assets, which is accounted for in the impact assessment (Section 6.6).

6.5 Vulnerability assessment (structural and functional)

A well-established way to analyse vulnerability is to use damage-, loss- or fragility functions. Such functions can express both functional vulnerability, representing the functional loss of the transportation line, and structural vulnerability, representing damage degree or the exceedance probability of damage levels. All these functions can be expressed in terms of hazard intensity, which is a parameter characterizing the damaging potential of the natural event.

6.5.1 Structural vulnerability functions at an asset level

For application of structural vulnerability functions at an asset level, the assessment could be performed at different levels:

- For an individual asset: accounting for properties of each asset and a failure mode
- For a portfolio of assets: categorise the assets into classes and apply a structural vulnerability function describing a representative asset type and its failure mode

The assessment of the individual assets is time consuming and computationally expensive as it requires development of a series of structural vulnerability functions. Thus, for the demonstration sites in SAFEWAY, it is proposed to work on the portfolio level:

- Classification of exposed objects into homogeneous classes (e.g. grouping of different asset types and/or subclasses of assets)
- Estimation of number of objects and within each class in the study area
- Relating the failure mode to an intensity parameter of a hazard process (see Table 13). The related damage could either be represented as an average degree of loss of the asset type or the exceedance probability of a damage levels for the asset type.

Table 13 summarises the recommendations regarding intensity parameters for structural vulnerability functions for flood related failure modes. It was chosen to focus on flooding, as the main SAFEWAY scenario (described in internal deliverable InD 9.1.1) for application and validation of SAFEWAY results is related to flooding.

Table 13: Recommended intensity parameters for flooding induced failure modes

Assets affected	Failure mode(s)	Intensity parameter
Bridges	Damage (incl. collapse) caused by scour at foundations; Washing away of access roads; Bridge deck swept away.	Water velocity/height or flood discharge & duration (i.e. hydrograph data)
Culverts	Overtopping (i.e. capacity exceeded); Washing away of access roads; Clogging by debris.	Flood discharge
Embankments	Damage caused by erosion	Flood discharge
Roadway and rail tracks	Inundation; Washout; Deterioration; Loss of skid resistance due to excess water	Flood discharge

However, even when considering a portfolio of assets, significant variabilities exist across different countries and different classes of assets are encountered depending on the classification of the transport system (Argyroudis et al.; 2019). The review of existing damage-, loss- and fragility functions showed that these are not sufficient for intended analysis and need to be updated to consider various natural events and related failure modes. Prior to the vulnerability assessment, one of the following steps should be accomplished:

1. Verification of existing fragility functions to site-specific conditions.
2. Adaptation of existing fragility functions to site-specific conditions.
3. Development of new fragility functions based on recommended intensity parameters in Table 13 and using approaches in Section 3.3.2 or 3.3.3.

6.5.2 Recommended functional vulnerability models for extreme weather events and related hazards

Functional vulnerability models would have a higher transferability between locations than asset-specific models, because they focus on general conditions affecting the traffic flow, mobility or safety of the travellers. An overview of functional failure modes with recommended modelling variable is given in Table 14.

Table 14: Recommended intensity parameter for functional vulnerability

Trigger/Hazard	Failure mode(s)	Intensity parameter
Rainfall/Urban flooding/Flooding	Vehicle speed reduction and/or traffic capacity reduction due to water on road/tracks	Water depth
Flooding	Blocking of traffic (partial/full)	Volume of debris
Landslide/debris flow	Blocking of traffic (partial/full)	Volume of landslide/debris intersecting road/track
Heatwave	Speed reductions for trains to avoid derailment	Temperature
Wind	Closed bridge due to strong wind gusts	Wind speed and wind direction. (Stricter criteria for wind gusts perpendicular to the traffic)
Forest fire	Precautionary closure of road/rail traffic due to dangerous driving conditions	Suggestion: a binary parameter describing whether there is a fire close enough to stop traffic.

6.6 Impacts

An overview of monetisation of different consequence types was given in SAFEWAY (2019b) and reproduced with slight modifications in Table 15 below. The table applies consequence classes described in Section 3.1. However, the consequence class political/social consequences are omitted here, as the monetisation of this type of consequences is not feasible.

Table 15: Impacts on life and health, economy and environment with respective monetisation variables

Consequences	Main groups	Monetisation variables
Life and health	- Fatalities - Injuries - Displaced people - Changes in accident rates due to use of alternative paths	- Cost per fatalities - Cost per injuries - Cost per displaced people
Economic	- Immediate or long-term emergency measures	- Costs of emergency measures
	- Restoration of infrastructure	- Debris Removal costs - Cost of Inspection - Cost of Demolition, Reconstruction and Repair
	- Disruption of economic activity	- Restoration time - Costs of Additional travel time - Annual average daily traffic
Environmental	- CO_2 Emissions due to repair works - CO_2 Emissions due to traffic congestion - Emissions of pollutants	- Costs of Material production emissions - CO_2 emission costs per Kg - Burned materials emissions - Additional travel distance (detours)

In addition to the factors listed in Table 15, one needs an estimation of factors that are needed to define the following consequences for a more complete risk assessment:

- Severity of a service disruption (e.g. full/partial closure)
- Related duration of the service disruption (e.g. hours, days, months)

The severity and duration of service disruption is governed by the failure mode caused by a hazard (e.g. full/partial closure). In general, the failure modes can be divided into 3 main types, which involve a different course of events from a malfunctioning of infrastructure back to its normal operation (Table 16).

Table 16: Types of failure modes leading to different service interruption and downtime

Failure modes leading to a disruption of transportation service	Preconditions to normal operation
1. Damage of asset(s) (structural and functional failure)	Repair/restoration/replacement of asset(s)
2. Malfunction of service with no damage to asset(s) (e.g. due landslide or debris on road/tracks)	Clearing of the road/track
3. Exceedance of a threshold of a weather parameter creating dangerous conditions for service users. No damage to the asset but there is precautionary closure of the transportation line.	Change in weather conditions

Each of the failure mode types in Table 16 could result in different duration of disruption, but generally the first type of failure mode would be related to longest duration (i.e. months, years). The severity of service disruption caused by the second type of failure mode would depend on volume of material on the roadway/track to be removed. For the third failure mode, no human effort is required to return to normal operation, as this solely depends on natural conditions. The related service disruption would have in general a shorter duration (e.g. hours) compared to the case of first two failure mode types.

In order to calculate the probability of a service disruption, caused by different natural hazards and to analyse the vulnerability and consequences of failure modes it is suggested to use event trees or a Bayesian network. Guidance for such analyses is provided as an example in the next subsection.

6.6.1 Demonstration example using event tree approach

This section demonstrates assessment of the connection of a structural failure mode of an asset with a functional failure mode (encompassing severity of service disruption and related duration of service disruption). The example considers flooding of roadway due to exceeded culvert capacity for a generic location.

Risk identification:

Analysis object: road link over a culvert

Hazard: flooding event

Failure mode: flooding of roadway due to exceeded culvert capacity

*there are two types – with or without damage to the road, but both may include road capacity reduction

Hazard assessment:

Flood hazard maps of selected return periods, showing water depth and velocity.

Exposure:

Identify flood exposed parts of the transportation line in study area from hazard maps

Vulnerability:

- Functional vulnerability as a function of flood depth of road.
- Material damage to roadway due to flooding.

Impact:

In this example, there are several scenarios that will lead to different consequences. The severity of the consequences is determined in terms of the severity of the service disruption (e.g. if the road is only partly closed or the traffic is possible with reduced speed) and the duration of the service disruption. Suggestions for categorisation of consequences is given in Table 18.

Demand

The demand expresses the. transport needs, usually expressed in AADT (annual average daily traffic). A capacity reduction of the road is only a problem if the capacity is reduced below the demand.

The contents of the assessment steps in the event tree analysis is described in Table 17.

Table 17: Definition of events and considerations for assessment of event probabilities

Assessment steps	Data and models useful for defining events and assessment of event probabilities	Example of assessment
What is the probability of the flooding event in the study?	Flood hazard maps with different return periods of flooding	A 200-year flood is considered
Is the culvert capacity exceeded?	Dimensioning of the culvert Observations from inspections regarding reduction of culvert capacity	The culvert is dimensioned for the 200-year flood, but there is a long time since last inspection and the capacity may have been reduced due to debris deposition. A 50% probability of exceeded culvert capacity is assumed.

Assessment steps	Data and models useful for defining events and assessment of event probabilities	Example of assessment
Is the flood depth at the roadway above a threshold for full service disruption?	Flood depths from flood hazard maps. Threshold values for flood depths leading to service disruptions from functional vulnerability models.	A threshold of 30 cm flood depth for service interruptions (from Figure 12) is chosen. Probability of a flood depth larger than 30 cm could be estimated considering different degree of culvert capacity reduction.
Is the intensity of the flooding high enough to cause material damage?	Flood intensity values Structural vulnerability functions	The intensity of the flooding is compared to thresholds for material damage in Table 12.
Is the capacity reduced below demand?	Data on capacity and demand Functional vulnerability model to estimate capacity reduction	The capacity is reduced below demand if it is reduced with more than 30%.

In the assessment four consequence severity classes are adopted (Table 18).

Table 18: Adopted consequence severity classes

Consequence severity class	Description
Very high	Closed road for long duration (weeks – months)
High	Closed road for days or severe capacity reduction for weeks
Moderate	Moderate capacity reductions with limited durations (hours – days)
Low	Insignificant delays or capacity reduction with duration less than an hour

Figure 21 illustrates the event tree constructed from the assessment steps in Table 17. The upper table within Figure 21 indicates which considerations should be done to assess the probabilities of each of the events in the event tree and Figure 22 examplifies how these considerations could be used for quantification of probabilities.

Figure 21 shows the sequence of events leading to the different severities of consequences explained in Table 17:

Very high consequences:

Flooding occurs – culvert capacity is exceeded – roadway is flooded with a flood depth more than 30 cm – the velocity of the flooding water is high enough to cause material damage to the roadway

High consequences:

Flooding occurs – culvert capacity is exceeded – roadway is flooded with a flood depth more than 30 cm – the velocity of the flooding water not high enough to cause material damage to the roadway

Moderate consequences:

Flooding occurs – culvert capacity is exceeded – roadway is flooded with a flood depth less than 30 cm – the capacity of the roadway is reduced to less than the demand

Low consequences:

Flooding occurs – culvert capacity is exceeded – roadway is flooded with a flood depth less than 30 cm – the capacity of the roadway is still larger than the demand, or

Low consequences or no consequences:

Flooding occurs – culvert capacity is not exceeded

Quantitative assessment of the probability of different consequence classes is shown in Figure 22 for illustration purposes. The reasoning behind estimation of probabilities are given in the top table in Figure 22. The probability of each sequence of events is found by multiplication of all the event probabilities within the sequence.

Discussion of example

The provided example demonstrates analysis of a malfunctioning asset that could lead to a service disruption. It distinguishes between events with and without material damage.

Service disruption could also occur directly (without damaging an asset). On the other hand, it is also possible to have events with damage to assets, that does not affect the transportation service (e.g. minor damage to pavements). For assessment of these failure modes, it is recommended to identify the sequence of events leading to the consequences, in the same way as in this example. In the given example, the duration of the service disruption (i. e. the recovery time) is linked only to the efforts required after an event to return from a malfunctioning infrastructure to normal operation. However, as explained in Section 2.1, the recovery time depends also on the resourcefulness of the operator, affecting how the situation is managed.

Another simplification in the example is that the severity of the consequences is defined from the severity and duration of the service disruption only. This would be a good approach if there is no redundancy in the transportation infrastructure, i.e. if no diversion roads exist, if possible diversion roads are flooded as well or if the diversion roads imply a very long detour. If proper diversion roads exist, the severity of the consequences would be lower than in this example and Table 18 would need to be modified.

Flooding occurs	Culvert capacity exceeded?	Roadway flooded with flood depth above a certain threshold?	Upper branch: Intensity of flood > threshold for causing of material damages to roadway? Lower branch: Capacity of roadway< demand?	Consequences
Specify which scenario to look at: e.g. 100-yr flood occurs; 1000-yr flood occurs - or 100-yr rainfall, 1000-yr rainfall for urban floods	Analysis of failure of culvert in separate event tree if necessary; considering: Time since last inspection of culvert? Debris deposition in culvert? Defective maintenance? Culvert properly sized/discharge properly estimated considering: climate changes; changes in upstream conditions; modeling uncertainties?:	Threshold to be obtained from functional vulnerability models Information from flood hazard maps Hydraulic modeling with reduced culvert capacity for different rainfall scenarios	Upper branch: Depending both on flood depth and flood velocity. Use intensity parameter from Table 12. Lower branch: A capacity reduction of the road is only a problem if the capacity is decreased below the demand	Consequences of the event would vary with the different failure modes. Key issues for determining severity of consequences: -Severity of service disruption -Duration of the service reduction (There are also other factors affecting the severity of the consequences, but these are common for the failure modes)

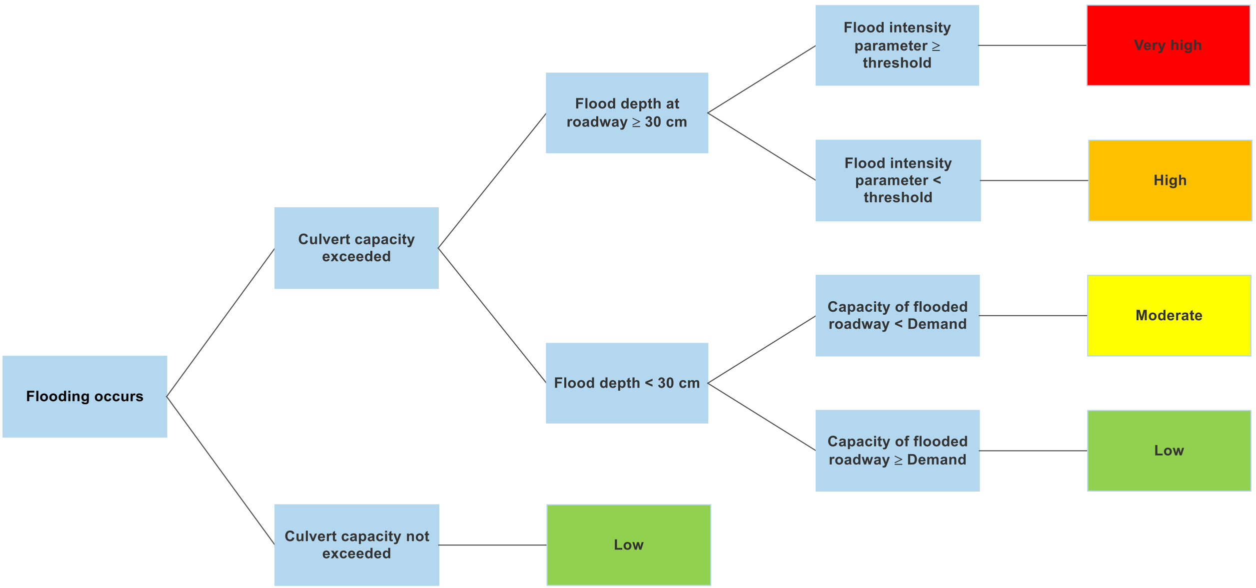


Figure 21: An example of an event tree for assessment of probability of different consequence classes for the flooding hazard

Flooding occurs	Culvert capacity exceeded?	Roadway flooded with flood depth above a certain threshold	Upper branch: Intensity of flood >threshold for causing of material damages to roadway Lower branch: Capacity of roadway< demand?	Consequences
200-years flood	The culvert is dimensioned for 200-year flooding, but there is a long time since the last inspection and the capacity is probably reduced. A probability of 50% for exceeded culvert capacity is assumed.	A threshold of 30 cm is chosen, in accordance with Figure 12, corresponding to full service disruption. Inspection statistics shows that the critical level of clogging for the circumstances considered in this case occurs in 20% of the cases.	**Upper branch:** The intensity of the flooding is assessed to be around the threshold between material damage and no material damage (e.g. from Table 12). Therefore a 50% probability of material damage is applied. **Lower branch:** Assessments applying a functional vulnerability model indicate that the probability of reducing the capacity below demand is 60% for flood depths below 30 cm	Each sequence of events will lead to a different consequence in terms of severity and duration of service disruption. The probability of each consequence class is found by multiplying the probabilities along the branch. The value is shown next to the consequence class.

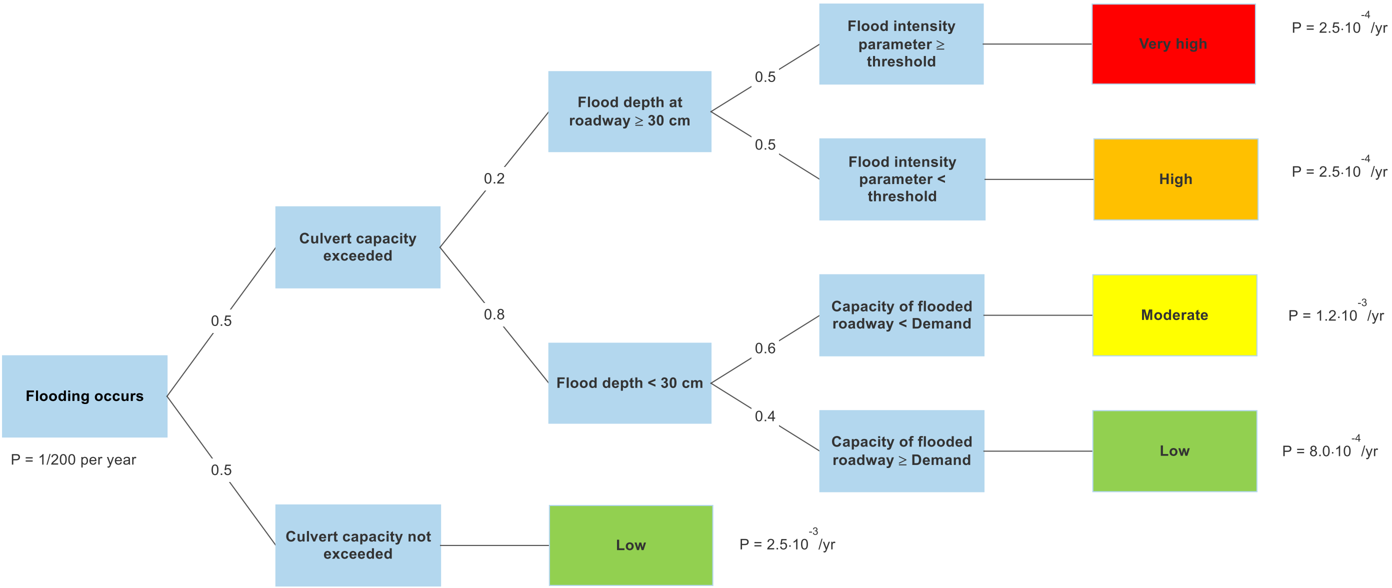


Figure 22: Quantitative assessment of the probability for different consequence classes

6.6.2 Failure modes and consequence types in a risk analysis

¡Error! No se encuentra el origen de la referencia. summarises the failure modes for d ifferent asset types as well as the triggering hazard with suggested main modelling variable for the consequence assessment. For each failure mode, the most significant consequence types are specified. The estimation of the different consequence types is discussed in SAFEWAY(2019b). In addition, the table provides a distinction between structural and functional failure of the services.

The "+" signs in the consequence columns of **¡Error! No se encuentra el origen de la referencia.** indicate a screening of the most significant consequences of the failure mode. Thus, the "-" means there is an insignificant impact on the total consequences. A "+/-" sign means that the failure mode may lead to significant consequences, but not necessarily. For example, landslide masses disrupting the transportation service could lead to excessive material damage of a roadway - or not. Whether a failure mode would result in social/political consequences could be site dependent, e.g. the closure of a road could have social/political consequences if that road represents the only connection to a hospital.

Table 19: Summary of the main parameters for vulnerability and risk analysis adopted in the SAFEWAY

Hazard		**Asset**		**Consequences**				
Type	Modelling variable	Type	Failure mode	Structural	Human	Economic	Environmental	Social /Political
Flooding	Water discharge	Bridge	Damage caused by scour at foundations	+	+	+	-	+/-
Flooding	Water discharge	Culvert	Failure of culvert leading to water overtopping and material damage to road/rail	+	+	+	-	+/-
Flooding	Water discharge	Embankment	Damage caused by erosion	+	+	+	-	+/-
Flooding	Water discharge	Roadway or rail track	Deterioration of roadway/rail track	+	+	+	-	-
Rainfall/urban flooding	Water depth	Roadway	Speed- and capacity reductions due to water on road	-	-	+	-	-
Flooding	Volume of debris	Roadway or track	Service disruption due to debris on road/track after flooding	+/-	-	+	-	+/-
Landslide	Volume of landslides	Roadway or track	Service disruption due to landslide masses on road/track	+/-	-	+	-	+/-
Heatwave	Temperature	Track	Speed reductions of trains to avoid buckling of tracks	+/-	-	+	-	-
Wind	Wind speed	Bridge	Closed bridges due to strong wind gusts	-	-	+	-	-
Forest fire	Binary modelling variable	Roadway or track	Precautionary closure due to dangerous conditions for traffic users	-	+	+	+	+

7. Conclusions

A general work-flow for impact assessments of adverse natural events affecting terrestrial transportation lines has been established. The steps in the work-flow encompass identification of modes of malfunctioning or degradation of the infrastructure caused by different natural events, assessment of their frequency and assessment of the vulnerability of transportation networks to such events.

A well-established way to analyse vulnerability is to use damage-, loss- or fragility functions. Such functions can express both functional vulnerability, representing the functional loss for a transportation line, and structural vulnerability representing damage degree or the exceedance probability of damage levels pertinent to a transportation asset. These functions can all be expressed in terms of an event intensity, which is a parameter characterizing the damaging potential of a natural hazard.

In order to analyse functional vulnerability, various asset types with their interdependencies i.e. network topology and geographical coincidence must be considered. Here, the applied damage and fragility functions for evaluating structural vulnerability must account for location-specific data on assets and asset properties. The review of existing damage-, loss- and fragility functions showed that these are not sufficient for intended analysis and need to be updated to consider various natural events and related failure modes. The recommendations are provided on how to elaborate new damage-, loss- and fragility functions to overcome a large number of uncertainties related to impacts of natural events on infrastructure and account for resistance of infrastructure. These recommendations concern both the choice of intensity parameters for different types of hazards and definition of possible failure modes, the methods for developing the functions and the assessment of the relationship between structural vulnerability of the asset and functional vulnerability.

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