SAFEWAY

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

Impact of human-made hazards (D2.2)

Impact evaluation of human-made hazards on diverse infrastructure types

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PUBLIC

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

Grant Agreement No. 769255

Impact of human-made hazards

WP 2 Risk factors and risk analysis

Deliverable ID	**D2.2**
Deliverable name	**Impact evaluation of human-made hazards on diverse infrastructure types**
Lead partner	**UMINHO**
Contributors	NGI, IMC

PUBLIC

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. SAFEWAY has as main expected impacts:

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

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Executive Summary

This deliverable provides an overview on human-made hazards contribution to the malfunctioning of terrestrial transportation systems. A framework to evaluate the impacts of such event is proposed. The contribution of human-made hazard in the malfunctioning of the network is difficult to quantify but a rough estimation can be obtained from a bridge failure database, under construction by IABSE with more than 600 failure cases, where the causes of failure are clustered into natural hazards, human-made-hazards and human errors, each one representing respectively, 21%, 27% and 53% of the failures roots. For vulnerability assessment of the assets according to the uncertainties that encompass the problem, fragility curves are proposed due to its beneficial features and adequate use for the assessment of structures subject to extreme loading conditions. Insights for the characterization of structural resistance and loading conditions are provided, being the last one addressed with more detail by means of impact force, since the ship, vehicle and train collisions represent more than 50% of the failures triggered by human-made hazards. The impacts evaluation is gathered in four major groups, specifically: human, economic, environmental and political/social impacts. The available possibilities for the monetization of the impacts were considered, in order to explore the possibility of using a unique unit of measurement for quantification of the impacts. An organized framework, with some level of detail, for further characterization or forecast of human-made hazards impact in real case scenarios, is the main outcome of this deliverable.

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Glossary of Terms

Human-made hazards	disastrous or disorder events caused by man or women activity, as a user of terrestrial transportation network leading in many cases to terrible outcomes.
Human Error	errors leading to disastrous events perpetrated by engineers or construction workers during conceptual, design, construction and operational activities.
Structural Vulnerability	Attitude of an element to be damaged by an exposure (probability of damage conditional to exposure). On other words, vulnerability stands for the degree to which an asset exposed to a hazard can be damaged (Argyroudis *et al.*, 2019).
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 (Birkmann *et al.*, 2013). Dimensions of vulnerability: 1. Physical dimension refers to conditions of physical assets - including built-up areas, infrastructure, and open spaces that can be affected by natural hazards. 2. Social dimension refers to human welfare including social integration, mental and physical health, both at an individual and collective level. 3. Economic dimension refers to the productive capacity, unemployment and low-income conditions. 4. Accordingly: Physical vulnerability indicators refers to properties or characteristics of the infrastructure affecting the probability of malfunctioning (here: due to occurrence of a natural event). 5. Socio-economic vulnerability indicators refer to factors for human welfare and productive capacity of the society in relation to the malfunctioning of the infrastructure.
Robustness	it addresses the system dependency on a certain type of asset or link failure. On other words, the robustness of a system, depends on how the malfunctioning of an asset will reduce or nullify the operating condition of the networking system due to lack of redundancy or triggering of progressive failure of the network. It is basically the dimension of the system that gives rise or aggravates the costs of malfunctioning of a link in the network system to a disproportionate magnitude if the network is extremely dependent on the asset. One way of measuring it is the ratio between the cost of indirect consequence and overall cost of consequences (direct + indirect).
Exposure	Exposure is used to refer to extreme values of normal design actions, accidental and deterioration process (physical exposure), but it could also include human error in the design,

	execution and use of structures (logical exposure) (Canisius *et al.*, 2011) It is also defined as an event during which the state of the component/system deviates significantly from the 'normal' state (average state in probabilistic terms) in a direction such that it gets closer to the failure surface(Faber and Narasimhan, no date). Hazards or exposures acting on the constituents of a system are also defined in (Faber, 2008) as all possible endogenous and exogenous effects with the potential to cause consequences.
Direct consequences	within this deliverable is set as being fatalities, injuries and cost of restoration of the network for its normal operating condition. Being direct or indirect consequence is extremely dependent on the level of assessment being performed, therefore it is not at all a fixed dimension, thus it should be set according to the elaboration of the problem under risk analysis. It's correlated with the vulnerability of the asset.
Indirect consequences	within this deliverable is set as being the cost of immediate or long-term emergency, cost of disruption of economic activity, environmental impacts, political and social impacts. It's partially correlated with the lack of robustness of the system by means the cost of disruption of economic activities.
Risk	it's a function of, probability of occurrence of a hazard, probability of failure of the asset exposed to the hazard, and direct and indirect consequences triggered by the malfunctioning of the asset and disruption of the network system.
Failure modes	It's a general term to refer to a different type of failures such as structural failure or functional failure (unavailability). Inside each of these main groups, different type o sub failure modes can be identified, for instance, the failure of a service limit state (deflection, crack width) or an ultimate limit state (buckling, flexural or shear failure, etc). The examples given here, are just a small scope of possibilities since several other types and sub-types of failure can be identified for different human-made hazards.
Failure	Is the exceedance of a certain limit state, which depends very much on the failure mode under consideration and, of course, on the loading condition.

1. Introduction

1.1 Scope and objectives

This research is developed within the SAFEWAY project whose main goal is to design and implement holistic methods, strategies, tools and technical interventions to significantly increase the resilience of inland transport infrastructure by reducing its vulnerability and strengthening network systems to extreme events (natural and human-made). For the achievement of SAFEWAY project goals, one of its working package aims is the identification of risk factors (natural and human-made) and vulnerabilities in order to provide an updated inventory of hazards and their impacts. Within this context, this deliverable provides a synopsis on human-made hazards outcomes on the safety and malfunctioning of the infrastructure terrestrial network systems targeting the following goals:

- Identification of human provoked disasters or accidents that could lead to disruption of the terrestrial transportation networks (railway and roadway);

- Proposal of a framework, for vulnerability assessment by means of fragility curves, that will be later tested on chosen case studies;

- Identification of the available tools/formulation for the quantification of impacts, namely, human, economic, environmental and political/social impacts, being the last briefly addressed.

1.2 Overview of links to other deliverables

The SAFEWAY project is divided into ten interconnected working packages. The work developed within the WP2 is mostly connected with WP5, WP7 and WP8. The identification and mapping of threats and impact leading to malfunctioning of the terrestrial transportation system will be used as inputs in the following WP's tasks:

- **WP 5:** Task 5.2 - Infrastructure risk-based models;
- **WP 7:** Task 7.1 – Data acquisition & Ingestion;
  Task 7.3 – Spatial database set-up;
- **WP 8:** Long-term interventions to build resilient European infrastructure.

1.3 Background

The risk assessment in engineering is a procedure used to aid in decision making. The impact evaluation of a hazard in a system is under the scope of risk analysis within risk assessment in engineering. The first necessary step for a risk assessment is the definition of the system and the contextualization of the assessment (Figure 1). Following this line of thought, it is important to state that the assessment is performed to the infrastructure network system damaged by human-made hazards. For an adequate risk assessment, it is imperative the definition of exposure, vulnerability and the robustness of the system, being the last two, a feature of the system responsible for a major or minor direct and indirect consequence, respectively, for the same hazard magnitude. With this, is meant, that the higher the vulnerability of the system more likely is to have higher fatalities and injuries occurrence and increased costs of restoration of the system. For the lack of robustness of the system is attributed to the increase of indirect consequences such as the cost of disruption of the economy and immediate and long-term emergency measures.

After the contextualization and definition of the system the risk assessment is usually followed by four main steps that govern the risk quantification:

1. Hazard identification;
2. Probability of occurrence of the hazard;
3. Vulnerability of the exposed assets;
4. Consequence quantification.

These four steps will be explored throughout this deliverable.

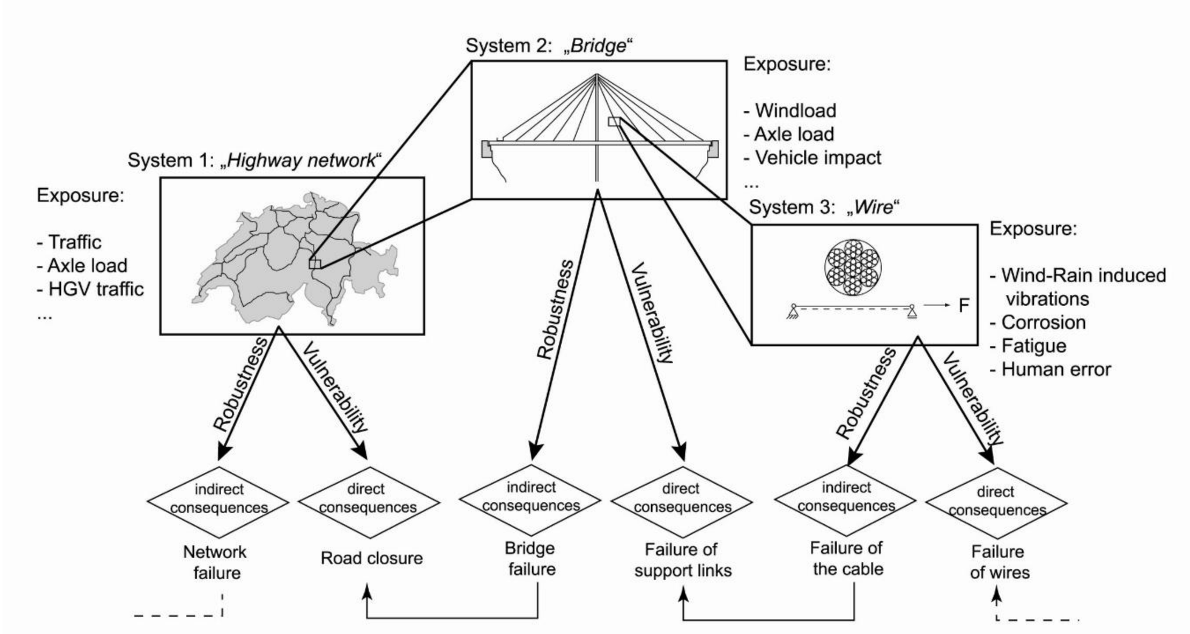


Figure 1: Generic system characterizations for a roadway/railways network and infrastructure object at different scales in terms of exposure, vulnerability and robustness. (Source: (Faber, 2008))

In literature sometimes the definitions used for exposure, vulnerability and robustness are not very clear, sometimes confusing and even contradictory. Thus, for clarification purposes, they are carefully defined in the glossary of terms section, of this deliverable.

1.4 Organization of the deliverable

According to the relevant background information introduced in the previous section the deliverable is organized into the following three main chapters:

I. Human-made Hazard: This chapter is dedicated to the identification of the main human-made hazard affecting the infrastructure network system and selection of the most relevant/frequent ones;
II. Vulnerability Assessment: Description of a framework for the quantification or estimation of the asset's vulnerability given a certain hazard by means of stochastic fragility curves (probability of failure given a certain hazard);
III. The last chapter is dedicated to the description of metrics for the quantification of human, economic, environmental and political/social impacts. Although the impact on those fields will be generally presented, it can be divided into two groups:

- Direct consequences:
  - Fatalities,
  - Injuries,
  - Costs of restoration of infrastructure.
- Indirect consequences:
  - Costs of immediate or long-term emergency,
  - Costs of disruption of economic activities,
  - Environmental impacts,
  - Political and social impacts.

2. Human-made Hazard

2.1 Identification

Within the scope of this deliverable and the SAFEWAY project, human-made hazard is defined as disastrous or disorder event caused by men or women activity, as users of terrestrial transportation network leading in many cases to catastrophic consequences. It is important to highlight, for clarification purposes, that this human-made hazard definition does not cover human activities as an engineer/designer. With this is meant that disastrous consequences caused by conceptual, design, construction and operational engineering activity, when addressed in this deliverable will be referred to as human errors (Starossek and Haberland, 2010). Human errors in the design/construction phase will be considered as an uncertainty to be implemented within the resistance models of the structure/infrastructure which will be addressed in Chapter 3.2.

For a better understanding of the above mentioned definition, to refer to potential causes of malfunctions of the terrestrial transportation system caused by human activity, the following examples are here divided in two groups (Ortiz D.S., Weatherford B.A., Greenberg M.D., 2008)(N. Holthausen, C. Zulauf, D. Ruf, I. Kaundinya, K.Thoni, 2011), taking into account the intentionality of producing physical and functional failure (e.g. damage, disruption of services) to an asset:

1. Unintentional:
   - Highway-rail grade-crossing accidents/incidents,
     - Train collisions,
     - Derailments,
     - Suicides (rail tracks),
     - Vehicle obstruction;
   - Ship collision against Bridges;
   - Vehicle and Train Collision against bridges;
   - Bridges overloading by live load (Infrastructure user's error);
   - Fire in tunnels or fire vehicle under and over the bridges;
   - Fire with source in man's action, evolving to large wildfires;
   - Explosion (i.e. gas explosion)
   - Suicides.
2. Intentional (Sabotage):
   - Strikes/occupancy of lines for manifestations;
   - Bombing/Explosion (terrorism purposes);
   - Fire with source in man's action, evolving to large wildfires;
   - Track hazards (Removing of rail track tie bars).

In risk assessment of structures (especially in buildings), it is not uncommon to refer to fire as an abnormal event that could threat structures because of human-made activities. However, in the context of SAFEWAY project, which main concern is the network, it important to refer that usually when a fire evolves to a wildfire (a magnitude that can have a huge impact on the network), it is more often, the consequence of the weather conditions than the human-made activities itself, although it was initiated or triggered by a human-made event. To this reason, wildfires will be dealt within the scope of natural hazards. However, within the framework of this deliverable the following information may be found for fire events in the European Forest Fire Information System (EFFIS) platform (http://effis.jrc.ec.europa.eu)

- Active fires;
- Fire forecast and regions in risk;
- Burnt areas;
- Source of event.

Associated to this data, it is possible to define critical areas where a relevant infrastructure, either railway or roadway, is located and what may be impact to that asset.

2.2 Recorded occurrences

For gathering purposes of statistical information and for a better understanding of human-made hazards significance in the malfunctioning of terrestrial transportation system, a database of recorded occurrences is required. The database itself should contain information on the: i) source event; ii) asset to be analysed, and iii) consequences to the asset.

A selection of databases is provided in Annex 2 (Table 5) for different events affecting the terrestrial transportation system, both roadways and railways. The databases were selected taking into account:

- their geographical application (coincident with the European region and of the case studies of SAFEWAY);
- period of database and updated information;
- division of source/triggering event;
- presentation of consequences.

The analysis of these databases will lead to the achievement of thresholds values for likelihood of events and its consequences required for the models to be defined in WP5 of the SAFEWAY project.

To address the methodology within the SAFEWAY framework, an example of a database related to bridges affected by different events is reported hereafter. One of the initiatives led to a bridge collapse database that is still under development by (Syrkov and Høj, 2019)(Syrkov, 2017). The database has so far reached a remarkable recorded number of 686 bridge failures occurrences dated between 1966 and 2019. Through a detailed analysis over the information available on the database the bridge failures were clustered according to four main groups, for an overall view of the main causes that has been triggering bridge failures all-over the world (Figure 2).

Using the definition presented above, it can be states that human-made hazard is responsible for 27% of the bridge failures recorded at this point.

Figure 2: Source of main realized hazard leading to bridge failure

Human error is defined as being any design, construction and operation errors that does not exceed the currently available engineering knowledge, and which took place due to poor working conditions, lack of training, supervision and check-up procedures (Galvão *et al.*, 2018). These errors were grouped according to the information provided in Figure 3:

- **Design and construction errors** - Construction Negligence, Design defect, construction defect, design and construction defects;
- **Operation errors** – Overloading by live load during inspection and maintenance works, corrosion, deterioration of concrete, fatigue. Basically, this group is considering bridges failures triggered by wrong maintenance, inspection and monitoring procedures;
- **Natural hazards** – Failures triggered by natural events such as floods and earthquakes. Within working package 2, the deliverable 2.1 comprehend a vast range of useful information concerning natural hazards.

Taking a deeper look to the database, a more detailed level of information regarding human-made hazards can be here presented, referring to each of the main hazard linked to the four sources of main hazard. The source and the main hazard are linked through colour match used in Figure 2 and Figure 3. The following and in this order of occurrence are the most recorded human-made hazards according to Figure 3:

1. Overloading by live load – 10%
2. Vehicle collisions – 9.2%
3. Ship collisions – 4.3%
4. Fire vehicle on & under the bridge – 1.4%
5. Explosion – 0.6%
6. Terrorism – 0.6%
7. Train Collisions – 0.3%

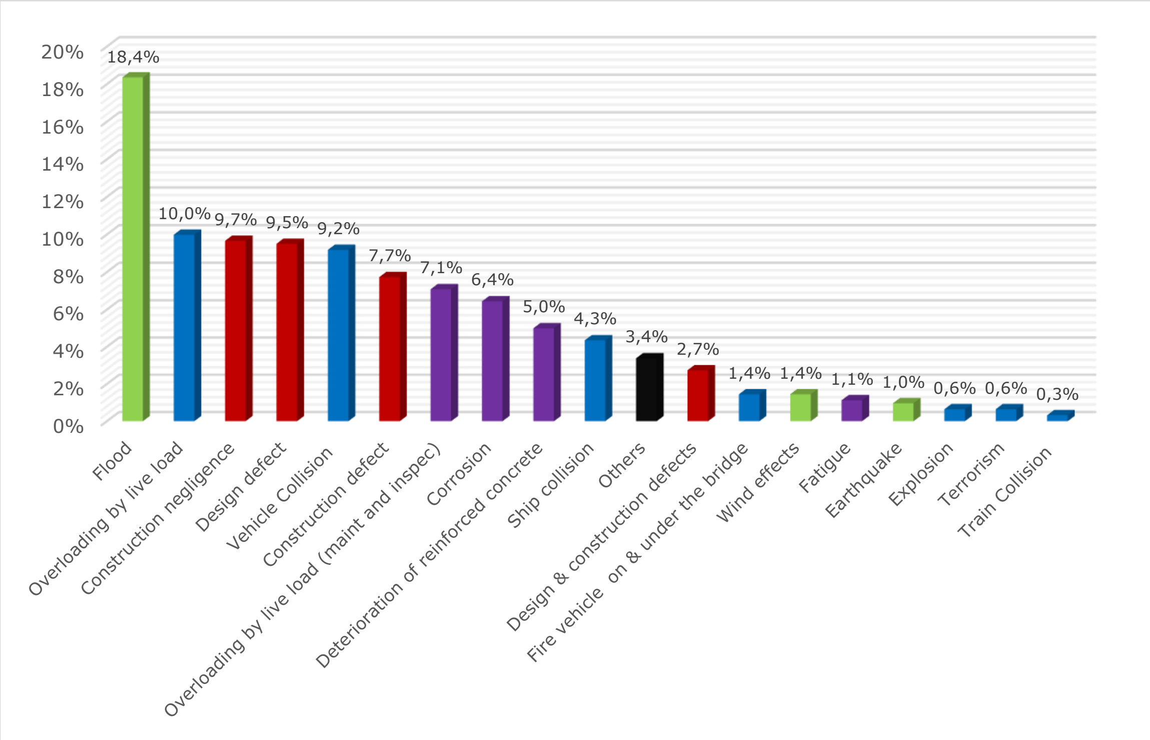


Figure 3: Main realized hazard leading to the bridge failure

Another useful information recorded in the database is the number of fatalities and injuries per each bridge failure, which is an indicator of the consequences related to a human-made hazard. Linking this information to the source and the main realized hazards presented, a human impact chart of the hazardous events is displayed in Figure 4. According to the information provided by the chart it is possible to identify three human-made related events with high human impact per event occurrence, namely, train collision, terrorist attack and explosion, although they were the least recorded ones. In terms of impact, these events are followed by errors of operation, design and construction errors and natural hazards.

Other databases about bridge failures and their causes can be found in the literature, some with more detailed information than others. The following are advised for further investigation (Imhof, 2004; Scheer, 2010) and https://www.iii.org. The latest presents consequences related to human-made disasters for different years and provides number of incidents, deaths and estimated insured loss impact for rail disasters and also collapse of buildings/bridges.

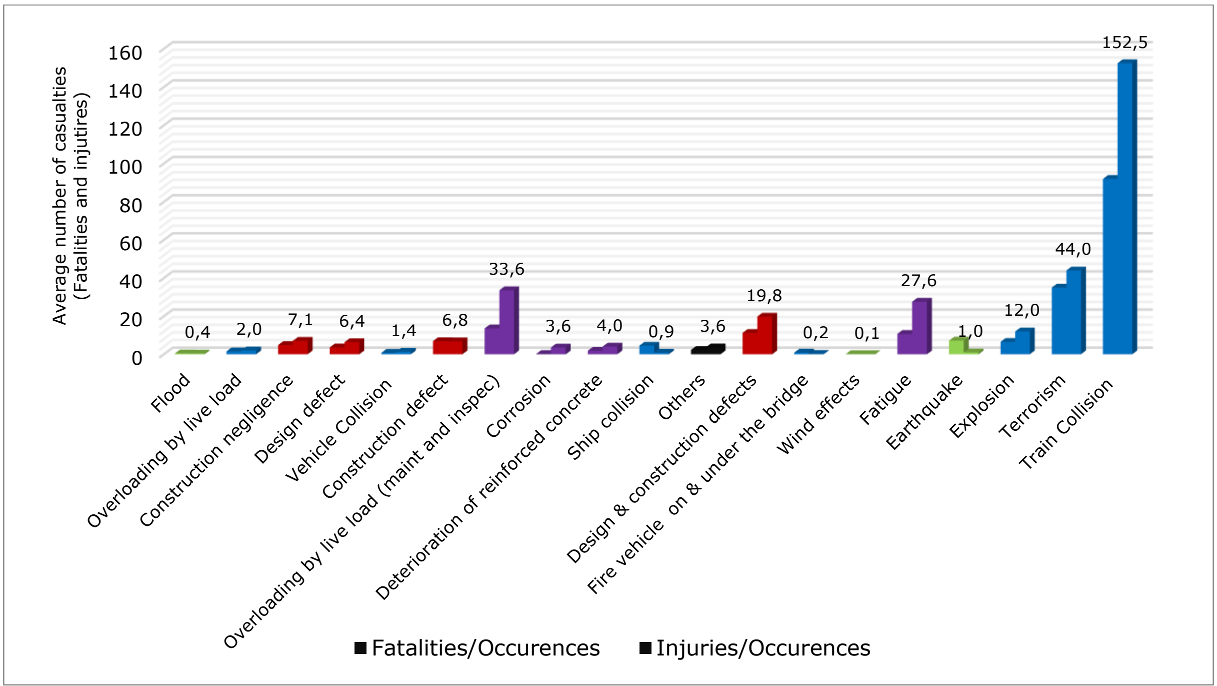


Figure 4: Average number of fatalities and injuries per number of occurrences of the source event

3. Structural Vulnerability Assessment

The vulnerability assessment of a structure is usually expressed through damage functions that correlate the severity of hazard with the level of expected damage. The most common used damaged functions are fragility and degree of loss functions. The first function express physical damage and gives the probability that the exposed asset exceeds some undesirable limit state. While the second describe the losses to a given asset as function of environmental actions. The losses are commonly expressed in terms of damage repair costs, usually normalised by replacement cost, 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 (Argyroudis *et al.*, 2019). Within this deliverable, the vulnerability is quantified by means of fragility functions expressing the physical damage of the terrestrial network system exposed assets. Thus, the quantification of the structural resistance uncertainties surrounding a certain limit state, that represents the boundaries of physical damage with regard to a specific failure mode, is a requisite to quantify the probability of exceedance of a certain limit state. The vulnerability of an asset can be affected by several factors, such as:

a) Degradation or deterioration of structures;
b) Magnitude and effect of the hazard (axial, bending and/or shear force, temperature);
c) Target element (pier, girder, deck, structure foundation, soil foundation).
d) Triggered failure mode (a structural or functional failure, inside which, we can have several different types of sub-failure modes);
e) Limit state under consideration (SLS, ULS, functionality loss);

These factors, affect essentially, the characterization of two main groups, the resistance condition of the asset and loading conditions imposed by the human-made hazard. The broad scope of assets of a terrestrial networking system and the diversity of human-made hazards that can take place represent a large scope of possibilities for their loading and resistance characterization. Therefore, this chapter will refer to general tools for this end, describing also, the exposed assets, the structural resistance probabilistic characterization and a general description on how to build a fragility curve with some insights on collision load quantification.

3.1 Exposed assets

The terrestrial infrastructure transportation system is composed by different types of assets connected in agreement to complement each other's functionalities and needs. Assets are everyday subjected to different exposure events, namely, natural extreme events, environmental chemical agents, human-made hazards, human errors and normal cyclic loads. Some assets are physically and/or functionally more vulnerable to a given type of exposure than others and some are more critical for the proper operation of the network system then others according to the importance of the service they provide. Looking at the network system, the following crucial assets, within the SAFEWAY working package 2 scope, are highlighted:

- Bridges and viaducts (Roadway, Railway and Footway)
- Tunnels
- Embankments
- Retaining wall
- System operation centres of railways
- Train Stations
- Rail tracks
- Roadway
- Elevated Tracks
- Power infrastructures

Another important step in the vulnerability assessment of an infrastructure is the identification of the asset failure modes that can be triggered on an exposed asset by the exposure or hazardous events under the uncertainties that surrounds the civil engineering structures.

For exemplification purposes and due to the expertise of the authors in bridge engineering the present deliverable offers different examples of the methodology to be implemented in SAFEWAY taking bridges as application object. However, the steps for impact evaluation of human-made hazard on different infrastructure assets may follow the same logical procedure. Moreover, the different events and variables for impact assessment and for monetarization unit are presented in Annexes 1 and 2, regardless of the type of terrestrial infrastructure in consideration.

3.2 Structural resistance - uncertainties

Regardless of the demand or load that a structure is exposed to, the knowledge of its material and mechanical properties, conservation status and overall structural response must be modelled, and the respective uncertainties defined. Following, uncertainty as concept for structural purposes is defined and how to model them is considered.

3.2.1 Types of Uncertainties

Uncertainties are present on every single engineering challenge and it is commonly accepted that uncertainties should be interpreted and differentiated according to their type and origin. According to (Abel and Henriques, 1998), uncertainty sources may be attribute to: i) physical uncertainty; ii) uncertainty during the modelling processes; iii) statistical uncertainty; iv) uncertainty due to human errors. Moreover, according to (Bulleit, 2008), the uncertainties that a structural engineer may run into during a design process comes mainly from: i) time; ii) statistical limits; iii) model limits; iv) randomness; and v) human error.

The last type results from the human contribution during the structure/infrastructure lifecycle. This uncertainty concerns not only the natural variation during the implementation of each task, but also the interventions and errors made during the processes of documentation, design, construction and structure/infrastructure use. Modelling of this type of uncertainty is still limited and often only of qualitative character. Nevertheless, one way to decrease it is by using well known quality control methods, such as peer reviews and third parties' inspection, which are scope of WP3 of SAFEWAY project.

A division with a broader acceptance is that uncertainty is categorized by either aleatory or epistemic. Aleatory, by definition, means reliant on luck or chance, thus, aleatory uncertainty comes from natural variability over space and time or to inherent randomness. On the other hand, epistemic means dependent on human knowledge. Therefore, epistemic uncertainty is uncertainty that could, in theory, be reduced by increasing the field of knowledge about it. In that framework, according to (Der Kiureghian and Ditlevsen, 2008), uncertainties are characterized as epistemic, if the modeler sees a possibility to reduce them by gathering more data or by refining models, whereas are categorized as aleatory if the modeler does not foresee the possibility of reducing them. A common attribution of uncertainty in an engineering problem is presented in Figure 5.

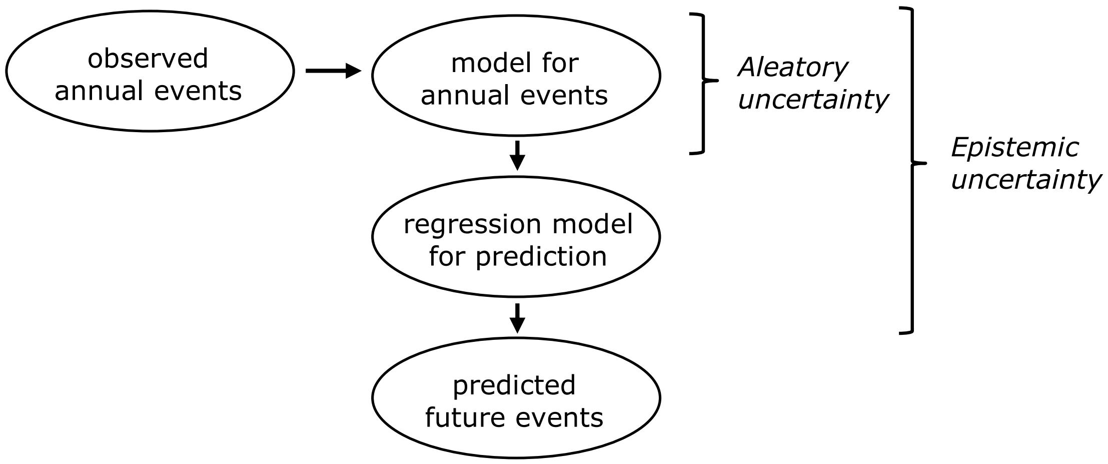


Figure 5: Example of uncertainty attribution in a typical engineering problem. (Source: adapted from (Faber, 2012))

The motivation for having this differentiation within an engineering modelling process is that the unknown quantity of uncertainty may be represented in that model by considering additional non-physical variables. These variables allow to consider information obtained through compilation of more data, of different sources, or use of more advanced scientific methodologies. A crucial point is that these auxiliary variables also define statistical dependencies (correlations) in a clear and transparent way. Most problems of engineering interest involve both types of uncertainties, and actually uncertainty by itself is often a mixture of aleatory and epistemic uncertainty.

Within the SAFEWAY project, human error will be modelled through the use of random variables with different levels of uncertainty based on the existence of prior information obtained through monitoring systems (connection with WP3).

3.2.2 Random variables

Any type of event is associated with a certain level of uncertainty, which can be analysed through a given probabilistic method. Consistently, it may be argued that the more robust the uncertainty treatment associated with an event, the better the probability of the phenomenon being studied. Thus, the evaluation of uncertainty coupled with the concept of probability are extremely important in the practical application of reliability problems.

The classical definition of probability of a given event *A* is defined as the ratio between the number of favourable cases, n_A, and the number of possible cases, n_{tot}, provided that the elementary events are equitable:

$$P(A) = \frac{n_A}{n_{tot}} \tag{1}$$

From the frequentist point of view, the definition of P(*A*) is summarized in the frequency with which a given event occurs in a number of experiments. Thus, for an infinite number of repetitions of the experiment, one obtains:

$$P(A) = \lim_{n\to\infty} \frac{f_n(A)}{n} \tag{2}$$

where f_n (*A*) is the number of occurrences of event *A* in *n* replicates of the random experiment.

In the probabilistic field, the parameters representing the information concerning the data of an event, as well as the related uncertainty, are called random variables. These can be classified as discrete or continuous. Discrete random variables are present when they take a quantifiable finite or infinite number of values. On the other hand, the continuous random variables take values in a given range.

In the scope of structural reliability problems, continuous random variables are usually used because they allow for a better adaptation to the uncertainty and variability of the parameters involved. The use of random variables is, in most cases, sufficient to model the characteristics of the values involved in the phenomenon under study, when they are associated with a certain distribution function and respective statistical moments, such as mean and standard deviation.

The description on how to obtain the probability function for evaluation of each random variable is described in Annex 3. Within the SAFEWAY project, random variables will be obtained through this method assuming the available databases.

3.2.3 Reliability assessment

In the past decades, an increasingly interest in reliability for civil engineering structural concepts is visible, mainly to higher computational performances and lower time costs that are now available. The possibility of implementing a certain degree of randomness and uncertainty to structural problems, when considering a stochastic analysis, is also an advantage. Generally, the probabilistic design method may be considered more rational and consistent than the partial factor design.

The concept of structural reliability may be defined by the evaluation of the probability of a determined limit state function being exceeded. The basic reliability problem may essentially be assumed, in probabilistic terms, to be how a certain structure/infrastructure will perform, on a specific period of time and according to defined conditions (Schneider, 1997). Thus, it is possible to define a probability of failure, p_f, as the complementary probability to the definition of reliability, consequently obtaining a quantifiable parameter for the evaluation of a structure/infrastructure's safety.

In a structural reliability problem, the random variables that define and characterize the behaviour of the structure/infrastructure are denominated as basic variables. When choosing the necessary basic variables in order to define a given problem, one must try to find independent variables, although that is not always possible. Modelling of these variables is possible through probability distributions depending of the available information about them, and also their statistical parameters have to be chosen carefully. After obtaining a structural model, this must be confronted with existent information so it can be improved or revised. In the eventuality of insufficient information to describe the probabilistic function or to corroborate the proposed model, one might use a representative expected value, so-called estimate point or, of most likelihood.

The failure of a given element is considered when the value of its resistance *R* is exceeded by the value of the load effect *S* resultant of a determined loading *Q*, on that specific element. Therefore, p_f may be assumed as the probability that the structural resistance *R*, modelled by a random variable with a known probability function $f_R\,(r)$, being inferior or equal to the load effects *S*, equally modelled by a random variable with a known probability function $f_R\,(s)$.

The determination and definition of probability failure and reliability index to be used in WP5 for determination of reliability levels is provided in Annex 4.

A risk is a potential outcome with an adverse consequence of uncertain severity. Risks are characterized by a distribution of probabilities over the range of all possible outcomes or consequence levels. While risks are fully defined by probability distributions over consequence levels, they are often summarized in expected value terms. Risk assessment is the process of obtaining a distribution of probabilities over potential outcomes. This is typically accomplished through some form of systems-level modelling. Fragility curves can also be developed to represent the probability of failure given multiple failure modes and multiple loads, thus this will be addressed in the following topic.

3.3 Fragility curves for human-made hazards

In reliability analysis a more or less understanding of the expected loads or combination of loads magnitudes is taken into consideration under certain known stochastic parameters. However, for assessment of structures under extreme load conditions it is important to explore the range of loads that goes beyond the standard/expected magnitudes to assess the structure behaviour under a more extreme load condition. For example, in seismic engineering the performance of structures under extreme load conditions is a very well understood subject where fragility curves are often used for vulnerability assessment of structures. In literature, the following definitions for fragility curves can be found:

- 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. Compared to nominal failure probabilities estimated from

reliability indices, fragility curves 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 (Schultz *et al.*, 2010).
- Fragility is defined as the conditional probability of occurrence of the event $G_i < 0$, representing that the seismic demand placed on the structure exceeds its capacity, for a given level of seismic intensity. In seismic engineering fragility curves are essential tools for assessing the vulnerability of viaducts. These curves describe the probability that the actual damage to a viaduct exceeds the damage thresholds when the structure is subjected to a specific ground motion intensity (Akiyama, Frangopol and Mizuno, 2014).

As clearly stated above the fragility curve is dependent on the relationship between the capacity (resistance) and the demand (loads and demand), and these, on the other hand, are dependent on the failure mode that can be triggered by a hazard.

Among the human-made hazard events that can take place on the terrestrial transportation system, several different types of failure modes can be triggered. Therefore, the limit state function that should be used for the proper assessment of the fragility of the asset should be carefully set using the correct formulation that represents a probabilistic distribution of the system resistance and the correct loading features related to the human-made hazard under consideration. A set of variables related to the modelling of the limit state conditions to be considered for the outcome of human-made hazards has been compiled in Annex 2, for the purpose of SAFEWAY. These variables are the parameters where thresholds are inferred to obtain the different performance conditions.

For instance, in Figure 6, a set of fragility curve of a system is represented by different resistance probabilistic distribution parameters, namely, the mean value and the standard deviation of the asset resistance. The asset mean resistance value (m_R) can be characterized by different values according to the failure mode or the degradation rate assumed for the assessment. The standard deviation of the resistance probabilistic distribution, on the other hand, is dependent on the level of uncertainty related to the input variables. With this, it is important to mention that the shape of the fragility curve that will represent the system, and therefore its vulnerability, is dependent on the formulation of the problem.

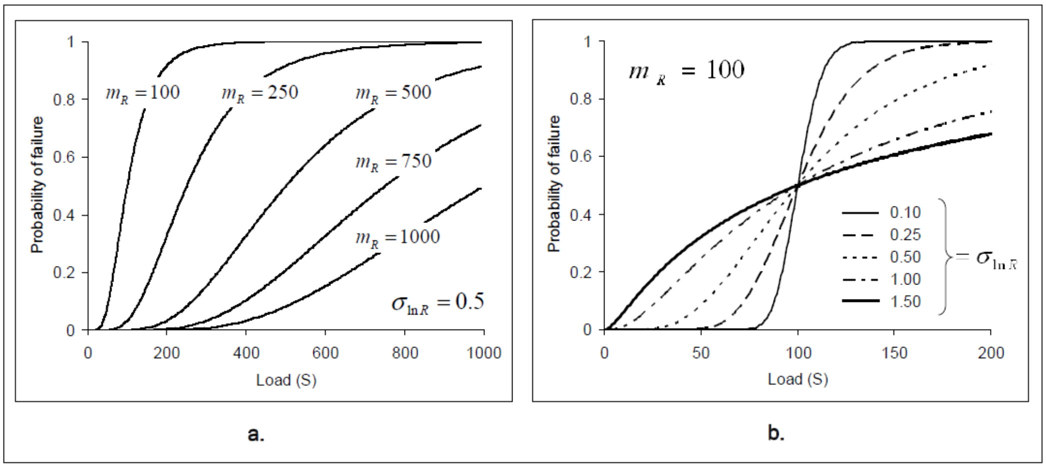


Figure 6: Examples of fragility curves derived from the reliability index. This example assumes a lognormal distribution for the capacity term. In plot a, m_R is varied from 100 to 1000 while σ_{lnR}=0.5 is held constant. In plot b, m_R =100 is held constant while σ_{lnR} is varied from 0.1 to 1.5. (Source: (Schultz *et al.*, 2010))

3.3.1 Collision as an accidental load according to EN-1991-1-7

As one can look to the list of different human-made hazards, presented in chapter 2, vehicle ship and train collision against bridge are usually treated as impact accidental loads acting on the structure, usually as horizontal loads. In the case of research and database related bridges failure, the common element damaged by these hazardous events are the bridge piers and sometimes the bridge deck (Figure 7). Therefore, an attempt to build a fragility curve considering these hazardous events should focus on the capacity of these bridge elements to sustain the effect of lateral forces induced by hazardous event under analysis.

The impact analysis as an accidental load in the standards is clustered into the following groups (EN 1991-1-7, 2011):

1. Impact from road vehicles
2. Impact forklift trucks
3. Impact from trains
4. Impact from ships
5. Hard landing of helicopters

Figure 7: Collision to the substructures or superstructures. (Source: (Sha, Amdahl and Oiseth, no date))

An exemplification of the procedure for the case of ship and vehicle collision against a bridge and how to be implemented within the SAFEWAY project for the implementation of the input variables and determination of the structure fragility is provided in Annex 5.

For a risk analysis of structures subjected to accidental actions, the probability of failure of the structure should be quantified according to its damaged state and the probability of occurrence of the hazard. Therefore, within the SAFEWAY project fragility curves are proposed to quantify the network assets vulnerability to accidental action caused by man.

4. Impacts

As part of the risk analysis, the quantification of impacts on the infrastructure is a fundamental step to obtain risk-based information for a better management of the terrestrial transportation network system. Thus, this chapter will focus on assessing human, economic, environmental, political/social impacts related to human-made hazards.

Annexes 1 and 2 (Table 4 and Table 5) provide the variables for impact quantification related to human-made hazards, which will be used within the SAFEWAY project taking into account the modelling of the different hazards, measurable variables to quantify their impacts on the terrestrial transportation network and how to monetize them according to some sub-input variables. Following, detailed description is provided in order to exemplify the procedure for distinct groups of consequences/impacts on the infrastructure management.

Human impacts can be estimated in terms of number of affected people (e.g. the number of displaced people, fatalities and injuries), economic/environmental impacts in terms of costs/damage in monetary values (e.g. costs of immediate or longer-term emergency measures, costs of restoration of public infrastructure, costs of disruption of economic activity). The political/social impacts will generally refer as example to public outrage and anxiety, social psychological impact, impact on public order and safety, political implications and psychological implications. The political social impacts will have a more detailed description in WP4 deliverables.

When it comes to monetizing the direct and indirect impacts the following Table 1 reflects some recommendations given on the literature. However, nowadays some current works are trying to monetize some of the considered non-market values.

Table 1: Classification of consequences. (Source: adapted from (Acces *et al.*, 2013))

	Market values	Non-market values
Direct	- Physical damage caused by the hazardous event - Costs associated with clean up, rebuilding or repairing	- Human casualties - Ecologic damages - Damage to cultural icons
Indirect	- Loss of mobility - Economic consequences of loss of mobility	- Depressions, Psychological problems - Increased vulnerability; lack of access to service (e.g. regarding social security)

For a general overview of the detailed information contained in this chapter proceed to Annexes 1 and 2.

4.1 Human impacts

A preliminary step to measure human impacts is to estimate or quantify the number of casualties, injuries or displaced people resulting from collapse or any other type of malfunctioning of an infrastructure related to a terrestrial transportation system. For example in (Federal Emergency Management Agency (FEMA), 2003), an empirical relationship for estimating the number of people on or under bridges, NBRDG, is provided as (Imam and Chryssanthopoulos, 2012):

$$\text{NBRDG} = \text{CDF} \times \text{Commuter Population} \tag{3}$$

where CDF is a commuter distribution factor taking into account the percentage of commuters on or under bridges. Suggested values for CDF are 0.02 during peak times and 0.01 otherwise, and the expected number of casualties due to bridge collapse may be taken equal to 7% of the value calculated for NBRDG (Imam and Chryssanthopoulos, 2012). Other models to evaluate human impact and its costs can be found in (Wong, Onof and Hobbs, 2005) where costs for fatalities and injuries are suggested, respectively £800,000 and £200,000.

The cost of fatalities is a contentious subject that is reliant on many dimensions such as ethics, macro-economics, sociology and politics. Nevertheless, this concept is being used all around the globe for estimations and to set priorities on public funding and risk-informed decisions. However, it’s important to highlight that no person life as any price and that common approach usually refer to this matter as the value of a statistical life. Some methods of how to estimate this value are (Lange, Sjöström and Honfi, 2015):

- Output and livelihood approach;
- Life insurance approach;
- Court award approach;
- Willingness-to-pay approach.

4.2 Economic impacts

This section focus on metrics for economic impact quantification due to cut of transportation links. As information related to specific human-made hazards is low, the models for economic impact related to other events that might influence the use, serviceability and performance of terrestrial infrastructures are detailed in order to provide a basis for quantification of the economic impacts. This procedure is to be established as framework for economic impact quantification measurement within the SAFEWAY project, related to human-made hazards.

4.2.1 Cost of immediate or long-term emergency measures

The idea of "cost of immediate or long-term emergency measures" is closely linked to mitigation measures to minimize impacts after a natural disaster (distribution of drinking water, medicines, setting up tents for emergency care, among others). Nevertheless, these concepts can be extended to the scope of human-made hazards if the consideration of the effects is compared. In this sense, the equivalent for the case of loss of land transport links can be:

- removal of debris to operationalize the transport line (cases in which the debris of a fault causes interruption in another line or way of transport);
- definition or indication of new ways to make a detour in a safe and well distributed way;
- reduced track availability to avoid major disasters (limiting number of vehicles, maximum weight, among others).

However, the empirical basis for estimating these costs are still quite weak. There has been little research into cost functions and cost patterns. Event though, in (Furuta, Frangopol and Nakatsu, 2011) the early restoration of road networks after an earthquake disaster has been addressed. In this study, three issues were dealt:

- which groups restore which disaster places – allocation problem;
- what order is the best for the restoration - scheduling problem;
- which restoring method is suitable for which disaster places – allocation problem.

In order to solve the three problems simultaneously, a Genetic Algorithm (GA) was used. Additionally, the relationships among early restoration, minimization of Life-Cycle Cost (LCC), and target safety level of road network were discussed by using Multi-Objective Genetic Algorithm (MOGA). Namely, the following three objective functions were considered:

- Restoring days are minimized.
- LCC is minimized.
- Performance level of road network is maximized.

In that study it was assumed that multiple portion of a road network suffered from damage and cannot function well. The objective was the realization of quick restoration of the lifeline system being intended to determine the optimal allocation of restoring teams, the optimal scheduling of restoring process and the optimal allocation of restoring methods.

For this road network, the following restoration works were considered to be necessary to recover the function:

1. Work (A) – work to clear the interrupted things;
2. Work (B) – work to restore the roads:
    2.1. work to repair the roads;
    2.2. work to reinforce the roads;
    2.3. work to rebuild the roads.

For the links with damage, weighting factors were prescribed which are denoted by W_i (i = 1, . . . , n_L). n_L is the total number of damaged links. Then, the restoring rate after q days, $R^{(q)}$, is expressed as follows:

$$R^{(q)} = \frac{\sum_{i\in J^{(q)}} W_{i} \times l_i}{\sum_{i\in J^{(0)}} W_{i} \times l_i} \tag{4}$$

where l_i is the distance of the i-th link, $J^{(0)}$ is the set of damaged links, $J^{(q)}$ is the set of restored links until q days after the disaster, and W_i is the weighting factor of the i-th link. Then, the objective function can be calculated by using the restoring days and the restoring rate.

The restoring days are calculated for each restoring work, and the minimum days necessary for each work is given as:

$$d = \frac{h}{t_1} \tag{5}$$

where h is the restoration time required to complete the restoration work.

The restoration time was calculated by using the restoration rate for each work which is given as follows:

a) Small damage: damage, there is no difference in capability of each team. The restoration will be completed during a fixed time. Here, 4 hours are assumed.

$$h = h_t \tag{6}$$

b) Moderate damage: there are some differences in capability between teams. However, every team can restore the damage.

$$h = \frac{D}{A} \tag{7}$$

where D is the amount of damage and A is the capability of the team, that is, the restoring amount per hour.

c) Large damage: only some teams can restore, because other teams have no restoring equipment and facility necessary for the large damage.

$$h = \begin{Bmatrix} \infty, & if\ A < A_c, \\ D/A, & if\ A \geq A_c. \end{Bmatrix} \tag{8}$$

where Ac is the minimum capability which the team can work.

The working hours per day of a restoration team are calculated by:

$$t_1 = t_0 - 2t_m - h_c \tag{9}$$

where t_m is the moving time to a site given by:

$$t_m = \frac{L}{v} \tag{10}$$

The shortest distance from the waiting place of the restoration team to the site is considered as L (km), and the moving speed of the team is set to be v (km/h). h_c is the preparation time that is necessary for every work.

In order to find several near-optimal restoration schedules, the concept of multi-objective optimization into the restoration scheduling for earthquake disasters was introduced. The objective functions – restoring days, LCC and safety level – were expressed as follows.

Restoring Days

The relation between restoring days and restoring rate is shown in Figure 8 (Furuta, Nakatsu and Kameda, 2009). The area of the uncoloured portion should be minimized to obtain the optimal solution, because this enables not only to shorten the restoring days but also to restore the important links faster.

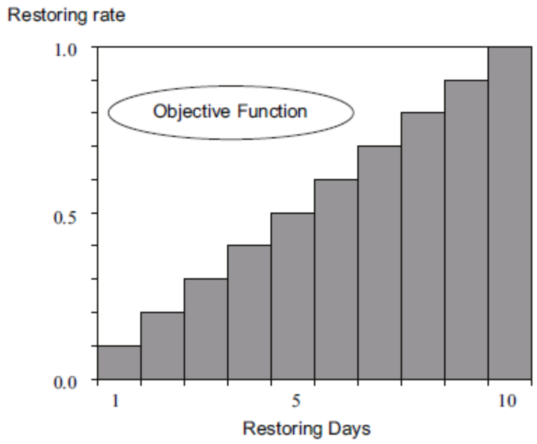


Figure 8: Objective function. (Source: (Furuta, Nakatsu and Kameda, 2009))

Life-Cycle Cost

Life-Cycle Cost (LCC) is defined as the total maintenance cost in terms of road network and all the assets during their lives. Then, restoring cost of each work is defined by:

$$RC = C_b \times D_{degree} \tag{11}$$

where C_b is the basic restoring cost and D_{degree} is the level of damage. The maintenance cost of each work after restoring is defined by:

$$MC = M_b \times D_r \tag{12}$$

where M_b is the basic maintenance cost and D_r is the level of deterioration. Then, the objective function was defined by:

$$LCC = \sum_{i \in J^{(0)}} (RC_i + MC_i) \tag{13}$$

where RC_i is the restoring cost of the i-th link, MC_i is the maintenance cost of the i-th link, and $J^{(0)}$ is the set of damaged links.

Safety Level

Safety level depends on the traffic volume and the condition of links. In this research, safety level (SL) of the road network is maximized, which is defined by:

$$SL = \sum_{i \in J^{(0)}} (I_i + SL_i) \tag{14}$$

where I_i is the importance of the i-th link, S_i is the safety level of the i-th link, and $J^{(0)}$ is the set of damaged links.

With the formulation of the objective function was then possible to use a multi-objective genetic algorithm to generate a custom set of possible solutions. This method enables to compare feasible optional solutions obtained under various conditions and allows the selection of a practical restoration schedule. This framework can, thus, be extrapolated to different event scenarios

4.2.2 Cost of restoration of public infrastructure

Direct losses are a function of the inventory of property in the affected area as well as the damage caused to that property during an incident and the relationship between that damage and the financial value of the property.

Most methodologies for estimation of financial losses comprise a number of common stages, Figure 9, includes: i) the taking of an inventory, ii) a vulnerability analysis, iii) a damage analysis and a loss analysis. The vulnerability analysis, where the loss estimation exercise is carried out must be based on some input from a hazard analysis as well.

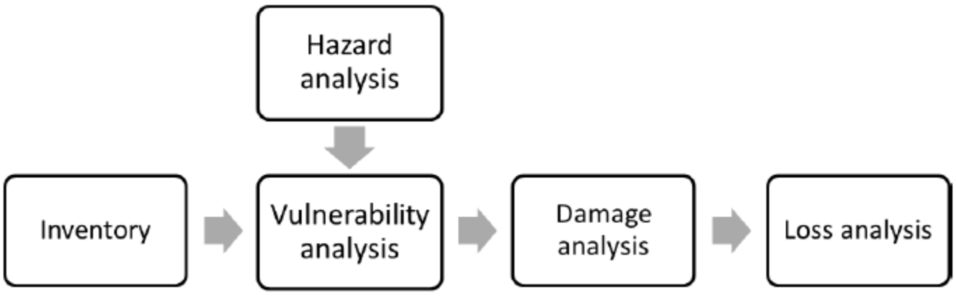


Figure 9: Fundamental stages in loss analysis. (Source: (Lange, Sjöström and Honfi, 2015))

While such a method clearly works based on forecasts or when the exact nature of the hazard is unknown, when an incident occurs the quality of the information about the hazard improves and the hazard analysis could be replaced by details of the incident which is ongoing. This is illustrated in Figure 10.

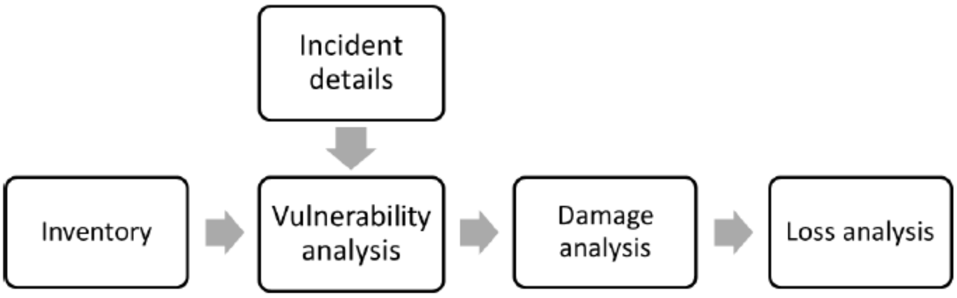


Figure 10: Fundamental stages in loss analysis including hazard analysis. (Source: (Lange, Sjöström and Honfi, 2015))

Based on the hazard analysis or the details of the incident which is ongoing, an engineering assessment must be made to determine if the structures or objects in the inventory is vulnerable to the hazard and if so to what the degree. This kind of assessment however will always be specific to the hazard or event as well as the object in question.

In determining any loss, we can start off with the statement that the total direct loss assuming 100% damage will be 100% of the financial value of the asset which is damaged.

$$direct\ loss = total\ damaged\ area \times \frac{cost}{m^2} \tag{15}$$

Assuming that repair of damage, to any given degree of damage, will be cheaper than replacement of the damaged asset and that the cost to repair is a function of the level of damage which is inflicted on the asset we can express the cost per square meter as a function of the level of damage.

$$direct\ loss = total\ damaged\ area \times \frac{cost}{m^2}(level\ of\ damage) \tag{16}$$

This simple equation requires the identification of the relationship between the cost for repair or replacement and the degree of damage which occurs. In earthquake engineering it is common to define the level of damage qualitatively in the form of Damage Measures (DM). Each DM is conditional on the vulnerability of the asset and conditional on the DM is the consequences, expressed as a Decision Variable (DV). A methodology proposed by FEMA defines four such DM’s, slight, moderate, extensive and complete damage for both the structure and non-structural components. These DM’s for earthquake are shown in the form of, e.g. fragility curves in Figure 11. The practical implementation of this type of classification will require an engineering assessment of the object against the hazard in question relying on either models or engineering judgment.

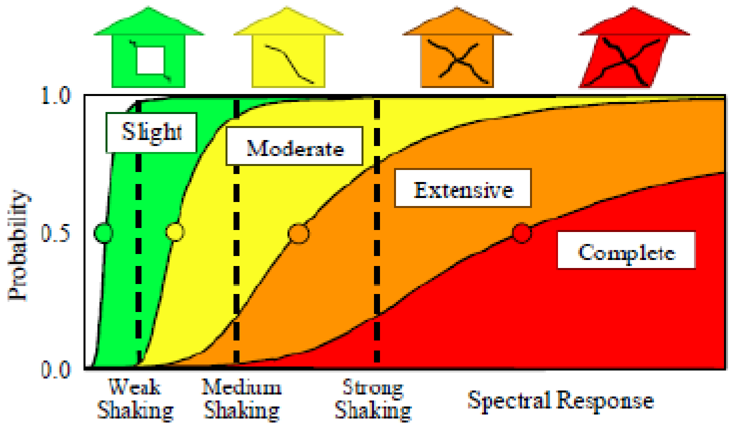


Figure 11: Example fragility curves for slight, moderate, extensive and complete damage. (Source: (Lange, Sjöström and Honfi, 2015))

There are three means of linking the damage to the financial loss as a decision variable: in the absence of data a direct correlation can be assumed between the damage measure and the decision variable, alternatively data may be obtained from component test data or finally from experts' knowledge. In the case of the simplest means of linking damage with cost, i.e. of a direct correlation between damage and cost as a percentage of the unit cost, we can declare decision variables associated with the damage measures. For the 4 described DM's, any one of these methods leads to the simple set of relationships:

- DM(1) => DV(1)
- DM(2) => DV(2)
- DM(3) => DV(3)
- DM(4) => DV(4)

where DM(1) denotes the first damage measure described above, i.e. slight; and DV(1) denotes the decision variable, in this case cost, associated with damage measure 1. The number of discrete damage measures which are defined in any such methodology is purely a question of availability of data and choice of the user. Given these relationships, the direct loss can be given by:

$$direct\ loss = \sum_{area} \frac{cost}{m^2} \times DV|DM \tag{17}$$

For any area which contains multiple structures or assets where the damage can be considered as unit damage as opposed to damage per square meter, the expression scales easily, where n is the number of structures or assets in question:

$$direct\ loss = \sum_{i=1}^{n} cost_i \times DV_i|DM_i \tag{18}$$

The repair cost of a bridge associated with a certain damage state can be considered proportional to the rebuilding cost of the bridge (Mander, 1999)(Stein *et al.*, 1999). S. M. Stein, propose that the repair cost of the transportation network sums up the repair cost of all the bridges in the network (Stein *et al.*, 1999):

$$C_{REP}(t) = \sum\nolimits_{j=1}^{m} \sum\nolimits_{i=1}^{4} P_{BDS_{ij|IM}(t)} \cdot RCR_{ij} \cdot c_{REB} \cdot W_j \cdot L_j \cdot (1+r)^t \tag{19}$$

where c_{REB} is the rebuilding cost per square meter (USD/m^2); W_j is the bridge width (m) for bridge j; and L_j represents the bridge j length (m).

4.2.3 Cost of disruption of economic activity

Indirect loss models are usually divided into one of two categories: unit loss models and input-output based models.

In unit loss models indirect loss estimations are based on aggregate loss data acquired over a period of time and based on large surveys of businesses. The issue with unit loss models is that they are only ever as good as the data set upon which they are based and that higher order effects can only be accounted for in a limited way. Despite this, because of their simplicity they are the principal method of national loss estimation in many countries (Lange, Sjöström and Honfi, 2015).

Input-Output based models on the other hand are based on economic flow within a region and are popular for estimating policy effects of decisions. However, since Input-Output models do not normally account for the behaviour of individuals or companies in times of crises they in reality provide only an estimate of the upper bound of the potential losses. One of the biggest issues in estimating the indirect losses after an incident is uncertainty with regards to the length of time over which fixed assets destroyed by fire were not replaced by extra investment (Lange, Sjöström and Honfi, 2015).

Indirect costs of a link failure in a roadway network can be defined as the financial losses from the increase of transportation costs – time and distance – in a road network [8].

When compared to direct costs, indirect costs can be considerable higher, depending on the dimension of the considered area, the redundancy of the network, but also the consequence of the occurred damages. Therefore, indirect costs are significantly more difficult to determine aggravated by the fact that each type of hazard has a different impact in the network but also in the economic activity of the surrounding areas.

For example, the shipment of goods from industries with high impact on the economy and redistribution of imported goods to the national supply system it's obviously a matter that requires utmost care when compared to a region considered as a residential area. Therefore, it’s very important to carefully assess road networks that supply utility services because the malfunction of the network might come with tremendous consequences.

In (Enke, Tirasirichai and Luna, 2008) is presented an approach to estimate the partial indirect economic loss due to damaged bridges within the highway system from an earthquake by defining an integrated framework. This method, consisting of three connected parts: the HAZUS software, the transportation network model, and the economic module, is presented in Figure 12.

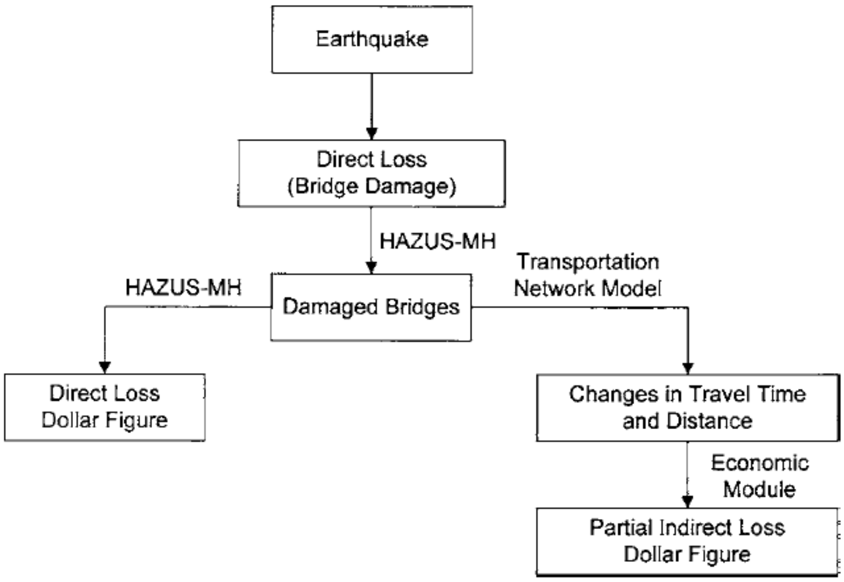
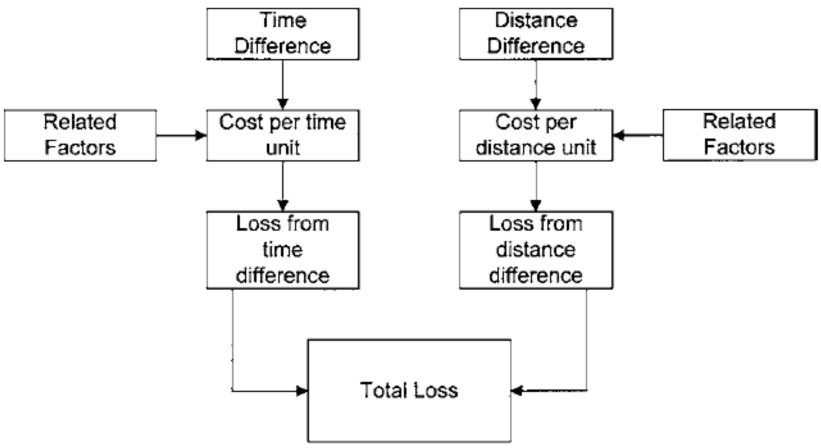


Figure 12: Example framework design. (Source: based on (Enke, Tirasirichai and Luna, 2008)

An earthquake scenario was used to identify the damaged bridges resorting to the multi-hazard HAZUS (HAZUS-MH) software. Based on this information, changes in the transportation network were made to determine the changes in travel time and distance using a transportation network model. Taking the results from the transportation network model as input, the economic module was designed to translate those changes in travel time and distance into a desired output dollar amount representing the partial indirect economic losses. The indirect loss economic module is illustrated in Figure 13.



$$\text{Total Partial Indirect Loss} = \sum_{i=1}^{n}\sum_{j=1}^{n} \text{Loss from increase travel time of route ij} + \sum_{i=1}^{n}\sum_{j=1}^{n} \text{Loss from increase travel distance of route ij}$$

where: i = Route origin zone number

j = Route destination zone number

n = Total number of zones in the study area

Figure 13: Indirect economic loss. (Source: based on (Enke, Tirasirichai and Luna, 2008))

In that study, to aid in the modelling and reduce complexity, some assumptions were made. In Table 2 are presented the considered values of time delayed and increased travel distance.

Table 2: Value of time delayed and increased travel distance (Source: (Enke, Tirasirichai and Luna, 2008))

Value of	Commuting trip	Commercial trip ($)
Time Delayed (h)	60% of income	29.60
Increased distance (km)	$0.28	0.70
Note: Estimates are in year 2004 dollars.		

Typical values which may be used in estimating traffic delay costs for both highway and railway networks are summarised in Table 3. Such values are expected to be different from country to country (Imam and Chryssanthopoulos, 2012).

Table 3: Average European value of time estimates (Source: (Imam and Chryssanthopoulos, 2012))

Mode	Passenger transport	Freight transport
Car	Business: €32.9/person-h Commuting/private: €9.4/person-h Leisure/holiday: €6.3/person-h	Light goods vehicle: €62.6/vehicle-h Heavy goods vehicle: €67.3/vehicle-h
Inter-urban rail	Business: €32.9/person-h Commuting/private: €10/person-h Leisure/holiday: €5/person-h	Full train (950 t): €1135/t-h Wagon (40 t): €47/t-h Average per t: €1.2/t-h

Additionally, (Dong, Frangopol and Saydam, 2013), propose that the indirect costs of an earthquake are the sum of costs weighted by their associated probabilities of occurrence, is related to the running cost of the detouring vehicles and the costs associated with time loss.

In the case of link damage, the users are forced to follow detour. The running costs of a transportation network should sum up the cost of the damage links as follows:

$$C_{RUN}(t) = \sum_{j=1}^{n}\sum_{i=1}^{4} P_{LDS_{ij}|IM}(t)\left[c_{Run,car}\left(1-\frac{T_j}{100}\right)+c_{Run,truck}\frac{T_j}{100}\right]\times K_{ij} \tag{20}$$

$$K_{ij} = D_j ADT_{ij}(t) d_{ij}(1+r)^t$$

where $c_{Run,car}$ and $c_{Run,truck}$ are the average costs for running cars and trucks per unit length (USD/km), respectively.

The monetary value of the time loss for users and goods traveling through the detour can be expressed as:

$$C_{TL}(t) = \sum_{j=1}^{n}\sum_{i=1}^{4} P_{LDS_{ij|IM}}(t)\left[c_{AW}O_{car}\left(1-\frac{T_j}{100}\right)+\left(c_{ATC}O_{truck}+c_{goods}\right)\frac{T_j}{100}\right]\times ADE_{ij}(t)d_{ij}\left[\frac{l_j}{S_D(t)}-\frac{l_j}{S_0(t)}\right](1+r)^t \tag{21}$$

where c_{AW} is the average wage per hour (USD/h); c_{ATC} is the average total compensation per hour (USD/h); c_{goods} is the time value of the goods transported in a cargo (USD/h); O_{Car} and O_{Truck} are the average vehicle occupancies for cars and trucks, respectively; $ADE_{ij}(t)$ is the ADT remaining in the link j associated with damage state i at time t; S_0 is the traffic speed on the intact link j (km/h); and S_D is the traffic speed (km/h) on the damaged link.

On the other hand, (Erath *et al.*, no date) propose a way to quantify the indirect transportation-related consequences of link failures (CI) by defining a methodology to determine:

- Additional travel time (TT) costs,
- Additional driving distance costs, and
- Changes in accident rates and associated total accident costs.

Formally, the additional travel time caused by a link failure is defined as

$$\Delta TT_l = \sum_i \sum_{j\neq i} w_{ij}\left(c_{ij}^{(l)} \cdot c_{ij}^{(0)}\right) \tag{22}$$

where:

w_{ij} = assessed demand weight relation of zone i to zone j,

$c_{ij}^{(0)}$ = travel time from zone i to zone j under normal network conditions, and

$c_{ij}^{(l)}$ = travel time from zone i to zone j under modified network conditions with link l severed.

The additional travel distance (TD) caused by a link failure is defined as:

$$\Delta TD = \sum_i \sum_{j\neq i} w_{ij}\left(d_{ij}^{(l)} - d_{ij}^{(0)}\right) \tag{23}$$

where:

$d_{ij}^{(0)}$ equals the travel distance from zone *i* to zone *j* under normal network conditions and

$d_{ij}^{(l)}$ equals the travel distance from zone *i* to zone *j* under modified network conditions with link *l* severed.

The additional accident costs caused by a link failure are defined as:

$$\Delta AC = \sum_{m} \left(V_{m,t}^{(l)} - V_{m,t}^{(0)} \right) \cdot ARC_t \qquad (24)$$

where

AC = accident costs,

$V_{m,t}^{(0)}$ = volume on link *m* of type *t* in normal network conditions,

$V_{m,t}^{(l)}$ = volume on link *m* of type *t* in network conditions with link *l* severed, and

ARC_t = accident costs per traffic volume on link of type t.

The CI are then given by:

$$CI_i = \Delta TT_l \cdot C_{TT} + \Delta TD_l \cdot C_{TD} + \sum_{t} \Delta AC \qquad (25)$$

where C_{TT} equals the willingness to pay for travel time reductions and C_{TD} equals the average cost for driving a defined distance.

It is important to note that wider (national and international) and long-term losses, as well as production/business losses, require the availability of econometric models, which analyse how detours and delays might affect supply and demand for goods and services in a region, although such estimates are expected to be characterised by a high degree of variability and uncertainty.

4.3 Environmental impacts

The environmental impact shall be assessed as part of the sustainable management of infrastructures. As defined in the Brundtland Report (Brundtland Commission, 1987), the sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs". In this sense, the sustainable infrastructure shall balance social, economic and environmental impacts using a cradle-to-grave approach (European Committe for Standardization, 2006). This last aspect is usually related to the assessment of several indicators (CO_2 emissions, costs, resources depletion, among others) calculated during several stages: production of the building material (cradle), construction of the infrastructure, its use, maintenance and at the end its demolition and waste management (grave). This approach is known with the name of Life-Cycle Analysis. The integral framework requires rather high resources in terms of data needed and calculation effort. To overcome this aspect it is allowed to define narrower boundaries in terms of variables and processes to be considered (Gervásio, 2010). In this study, the life-cycle approach of certain products (i.e. concrete, steel) are assumed as inputs in a very specific analysis related to the impacts of human-made hazard on the environment.

4.3.1 Direct and Indirect Environmental consequences

Concerning the environmental impact of human-made hazards, it is possible to distinguish between direct and indirect consequences, as it is for the economic assessment. The direct effects are basically related to the emissions of pollutants due to the disruptive event (blasts, fires, radioactive release, oil spillage). Furthermore, these consequences depend on the hazard's type, its magnitude and the interactions with the involved infrastructure: e.g. a tunnel fire has different effects on the environment than if it happens on a bridge. Moreover, the magnitude of the consequences is influenced by the boundary conditions represented by the physical and chemical settings of the surrounding environment (Pereira, 2014). For this reason, it is more effectively to analyse and compute only the indirect consequences (i.e. the ones that occur in the after-shock phase). These effects are related to the risks associated to human health and the ecosystem.

The selected indicators are the following: (i) the pollution due to the congestion in the alternative roads, following the collapse/damage of an infrastructure; (ii) the pollution due to the reconstruction/repairing of the infrastructure. These variables may be calculated according to average fuel consumptions and emissions of the vehicles with restriction on velocity due to congestion and based on life-cycle assessment of reconstruction/repairing interventions, as it will be developed in the following topics. This can after be converted to CO2 equivalent emissions and a cost can be applied. Other ecological indicators are not considered, since the construction works and traffic emissions are the main responsible for the environmental burden. Indeed, according to the European Institute of Statistics (Eurostat), the transport field and the construction sectors are responsible for the 28% and 36% of the total CO_2 emissions, respectively (Eurostat, 2016).

4.3.2 CO_2 emissions due to traffic congestion

The after-shock scenario is characterized by a damaged structure, which eventually has a damage ratio equal to 1, i.e. is collapsed. The environmental consequences are related to the following activities: (i) evaluation of pollutants on the alternative path; (ii) environmental burden due to repairing works.

The effect of the traffic in terms of CO_2 is evaluated as proposed by Frangopol et al. (Frangopol, Dong and Sabatino, 2017), here modified to explicitly consider the difference of pollutant released before and after the disruptive event. The environmental impact per day is then written as follow:

$$EN_{After} = EN_{Detour} - EN_{Before,O} - EN_{Before,D} \tag{26}$$

Where EN_{After} refers to the after-shock situation. Similarly, EN_{Before} refers to the before-shock condition. It must be noted that this value is computed on both paths: original (O) and bypass one (D), to highlight only the impact of the hazard neglecting the “every-day-pollution”. Finally, the EN_{Detour} is computed on the alternative path in the after-shock scenario.

The Environmental impact is then evaluated as:

$$EN_{Detour} = \sum_{j=1}^{n} L_j \cdot 1day \cdot \left(EM_{CAR}(ADT_j, v_j) \cdot \left(1 - \frac{p_j}{100}\right) + EM_{TRUCK}(ADT_j, v_j) \cdot \left(\frac{p_j}{100}\right)\right) \tag{27}$$

$$EN_{Before,O} = \sum_{i=1}^{m} L_i \cdot 1day \cdot \left(EM_{CAR}(ADT_i, v_i) \cdot \left(1 - \frac{p_i}{100}\right) + EM_{TRUCK}(ADT_i, v_i) \cdot \left(\frac{p_i}{100}\right)\right) \tag{28}$$

Where "n" is the number of the links on the bypass path, "m" has the same meaning, but on the original path. It is assumed that the m-sim link is affected by a failure/damage that reduces its capacity (eventually to zero). L_i and L_j are the length of the D-path and O-path segments. p_i and p_j are the percentage of trucks in the traffic. ADT_i is the average daily traffic in the O-path and D-path, while ADT_j is the total volume of vehicles per day expected on D-path due to the closure of O-path.

The environmental metric is introduced through the emission functions (EM) of cars and trucks. In particular, EM_{CAR} and EM_{TRUCK} represent the kilograms of CO_2 per kilometre released from the amount of vehicles ADT_i and ADT_j , travelling at an average speed v_i and v_j . The amount of CO_2 computed is then reduced according to the traffic composition (p_i and p_j) abovementioned.

If the human-made hazard partially affects the m-sim link capacity, the reduced capacity is taken into account in the modelling of the flow-capacity function; this aspect is accounted inside the link speed value (e.g. a closed lane will substantially decrease the vehicles' speed, especially given that the link demand is constant or increasing).

Concerning the emissions of pollutants, these depend on several parameters, (according to Grote (Grote *et al.*, 2016)): (i) mass of vehicles; (ii) fuel type; (iii) aerodynamics; (iv) particulate filter system; (v) road category; (vi) speed; (vii) acceleration and deceleration rates; (viii) traffic light phasing. Between those parameters, the congestion phenomenon is the most harmful for the environment. This is not a single indicator, but takes into account several of the above cited markers; moreover, it has been proven by Barth et al. (Barth and Boriboonsomsin, 2008) that the CO_2 measured in a constant speed scenario (at 45 km/h) is 40% less than the one released at the same average speed but including the dynamic of congestion. Then it is clear that consider a dynamic road traffic model (RTM) can easily raise the complexity of the framework. Indeed, there are three possible level of detail: (i) macro RTM; (ii) meso RTM; (iii) micro RTM (Grote *et al.*, 2016). The macro-model considers only the aggregated flow parameters, such as the traffic density (veh/km), the average daily speed (km/h) or the volume (veh/h). The micro-model takes into account the interactions between each vehicle and the outputs are typically the paths followed by all automobiles. The meso-models uses instead the technology of the micro-model applied to platoons of vehicles. In this research, since the focus is the overall quantity of pollutant released in a series of roadways, the macro-model was chosen as the most effectively, considering that the more complexity not always lead to less errors (Smit, Ntziachristos and Boulter, 2010). The output of RTMs is the input for the Emission Models (EMs).

The tailpipe discharge can be modelled using different approaches: (i) aggregated measures, such as CO_2 per vehicle's category or average speed; (ii) specific parameters as the road type and the congestion quantification. The latter model family, that explicitly consider the effects of bottlenecks and stop-and-go conditions, are the most accurate ones, even though not the most spread ones. One of those is the European Handbook of Emission Factor for Road Transport (HBEFA), developed under the ARTEMIS project. This database is one of the most complete and can simulate up to 276 different traffic situations (*HBEFA*, no date). The biggest limitation concerns its validity out of the countries in which it was developed (Germany, France, Austria, Switzerland, Sweden and Norway). Between the models that consider only some aggregated parameters, is here cited and recommended the COPERT software, developed with the support of the European Environmental Agency (EEA). COPERT, an acronym to Computer Programme to calculate Emissions from Road Transport, allow to compute the pollutant emissions thanks to a rather large database, whose last update was in 2016 (EEA, no date). The emissions factors are based on the average speed of vehicles, and then multiplied by the volume of daily traffic (ADT). The congestion is implicitly considered, since the emissions collected in the COPERT database comes for each vehicle and vehicle's category from the real drive dynamic tests used for CO_2 computation (EEA, 2016).

4.3.3 CO_2 emissions due to repair works

There is a large variety of infrastructure types, from bridges to tunnels. Those assets have different structural behaviour, management costs and building techniques, but concerning the environmental impact, there are more similarities than expected. Indeed, several studies carried out independently (Huang, Bohne and Bruland, 2015) (Hammervold, Reenaas and Brattebø, 2013), shaped the same conclusion: the material production and construction phase are the highest contributors to the emissions of GHG (greenhouse gasses). This is the reason why in the present study is considered only the reconstruction phase of the damaged infrastructure. The total environmental pollution during the repair activities is evaluated as follows:

$$EN_{Reconstr} = EM_{STEEL} \cdot V_{STEEL} + EM_{CONCR} \cdot V_{CONCR} + EM_{ROAD} \cdot A_{ROAD} \qquad (29)$$

Where, EM_{STEEL} and EM_{CONCR} are the environmental metrics (kg CO_2/m^3) to produce the materials. EM_{ROAD} is the pollution (kg CO_2/m^2) generated for the rehabilitation of each square meter of road surface A_{ROAD}; it takes into account the production of all road materials, for a given asphalt mix. V_{STEEL} and V_{CONCR} are the volume (m^3) of materials used during the repairing works.

There are several databases that consider the Life-Cycle Environmental Analysis of construction materials. The Environmental Metrics (EM) reported in the previous formula are estimated using existing life-cycle analysis databases that were built during the years, and constantly updated. As examples, it can be cited the Ecoinvent dataset (Swiss Centre for Life Cycle Inventories, no date) which is one of the most complete and accurate, specific LCEA from concrete and steel industries (Italcementi, 2007) (World Business Council for Sustainable

Development, 2005) (International Iron and Steel Institute, 2002), international organisation as the Worldsteel Org. (Worldsteel Association, 2017) and ECORCE for LCEA of road's pavement (Jullien, Dauvergne and Proust, 2015).

4.4 Political/Social Impacts

The political/social impacts will generally refer to a semi-quantitative scale, such as for:

- public outrage and anxiety,
- social psychological impact,
- impact on public order and safety,
- political implications,
- psychological implications.

Within the framework of the methodology, each factor measured semi-quantitatively are associated to either an indirect or direct cost. Moreover, the effect is measured in terms of time after the disruptive event has taken place.

The impact related to these events will be analysed within the works of WP4 of SAFEWAY project.

5. Discussion and Conclusions

Striving for holistic risk-based information for infrastructure network management it's important to keep in mind the overall view of the hazardous event that leads to malfunctioning of the network (Figure 14). The infrastructure network is shaped by different types of assets; however, bridges play a crucial role in its efficient operation. Thus, an available and enriched bridge failure database was used to gather useful statistical information concerning this matter. It's also known that the failure of transportation system assets is not the only consequence of the hazardous event, but when it comes to impact on society they have for sure enormous direct and indirect consequences, namely, high fatality and injuries rate, and the downtime (immediate and full unavailability), which is directly correlated to the cost of disruption of economic activities.

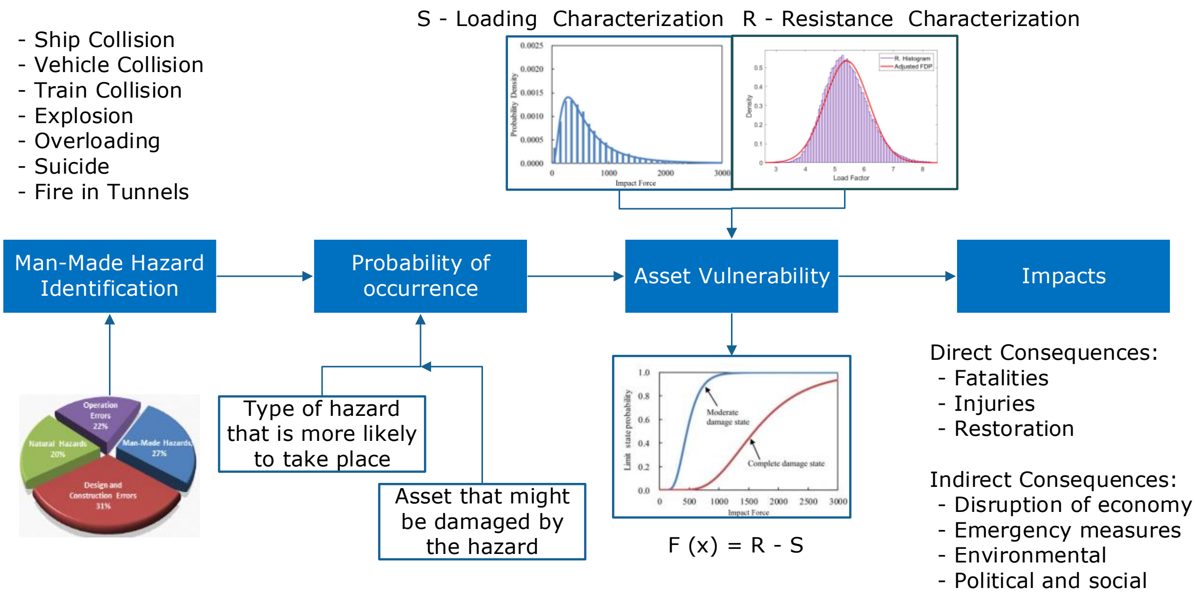


Figure 14: Deliverable 2.2 general framework

For the quantification of human-made hazards possible contribution in malfunctioning of a network system and subsequent impacts, mainly due to bridge failure or any other type of link interruption or partial interruption, it's important to identify the asset's that are more likely to be damaged by certain types of hazard. For instance, bridges crossing highly traffic seaways, roadways or railways, are more likely to be damaged by a ship, vehicle or train collision. Another example is the identification of bridges supplying or close to highly traffic harbours from where heavy vehicles might depart leading to overloading of bridges not suited or was not designed to sustain such loading condition. With this type of screening procedure, a semi-qualitative analysis of the probability of occurrence is achieved.

The vulnerability of structures exposed to a certain hazard can be measured by means of fragility curves representing different damage states that can be reached. The damage states are usually defined by different limit state functions;

therefore, they should be carefully defined for each specific hazard and accordingly to the aims of the analysis. Within this deliverable, where an overall framework for impact evaluation of human-made hazard is presented it's very difficult two go in too much details regarding the fragility curves, especially because there is a wide range of human-made hazard that can be represented by different functions. However, in any case, it will be a function that represents the relationship between the demand and the structural capacities to sustain such demand. Therefore, each scenario of failure should be correctly addressed according to civil engineering good practices and according to the available statistical information, that allows the probabilistic characterization of the safety boundaries.

Related works concerning human-made hazard impact, proposed for this deliverable, are scarce. Thus, the information here presented is mostly extracted and adapted from works addressing other types of hazards. Accounting to expert knowledge and based on the analysed databases, Annexes 1 and 2 were made as to summarize the variables needed for analysis within the SAFEWAY project regarding the construction of suitable fragility curves and quantification of the impacts of human-made hazards on terrestrial transport networks.

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

NETWORKS

Grant Agreement No. 769255

Impact of human-made hazards (D2.2)

WP 2 Risk Factors and Risk Analysis

Deliverable ID	**D2.2**
Deliverable name	**Impact evaluation of human-made hazards on diverse infrastructure types**
Lead partner	UMINHO
Contributors	NGI, IMC

PUBLIC

Annex 1 – General characterization of impacts

The impacts of hazards are within the scope of this deliverable clustered into 4 main sub-fields, namely, human, economic, environmental and political/social impacts. However, the last one is not addressed in this annexe and it's slightly referred in this deliverable.

As described, in Chapter 4 of this deliverable, each one of the impacts is clustered into several sub-groups which are linked to different parameters for monetization purposes of the impacts. In order to provide an overall summary of the different levels of information required for the quantification of the impacts, Table 4 is presented.

Table 4: Impacts on human, economy and environmental with respective monetization groups and sub-variables

Impacts	Sub-groups	Relevant parameters for Monetization	Sub-parameters
Human	- Fatalities - Injuries - Displaced people - People under the bridge	- Cost per fatalities - Cost per injuries - Cost per displaced people	
Economic	- Immediate or long-term emergency measures	- Debris Removal - Alternative paths/detour	- Equipment - Labour Force - Time of detour - Distance of detour
	- Restoration of infrastructure	- Cost of Inspection - Cost of Reconstruction - Cost of Repair - Cost of Demolition	- Material - Equipment - Labour Force
	- Disruption of economic activity	- Restoration time - Detour Paths distance - Changes in accident rates - Additional travel time	- Alternative road moving speed - Alternative road capacity - Disturbed average daily traffic
Environmental	- CO_2 Emissions due to repair works - CO_2 Emissions due to traffic congestion - Emissions of pollutants	- Material production emissions - Detour emissions - Burned materials emissions - Restoration time - Detour Paths distance	- CO_2 emission costs per Kg - Disturbed average daily traffic - Average cars emissions per Km - Congestion rates - Alternative road moving speed - Alternative road capacity

Annex 2 –Overview for impact quantification

In order to provide a general overview of some peculiarities to be taken into account, for the impact assessment described in this deliverable, this annexe was suggested to structure the most relevant information into the Table 5.

An attempt for a general distinction between structural and functional failure of the services provided by the asset is presented. Accordingly, the failure modes and the main modelling variables are suggested. The modelling variable column is concerning the variables for impact quantification rather them the modelling of the hazards. For functional failure, the most relevant modelling variables are usually time and availability. Being the last one the indicator that describes the level of services restriction caused by the hazard. Distinct modelling variables from the previous mentioned variables are targeting inputs for structural impact quantification, although structural failure is followed by a functional failure. For clarification purposes, it must be said that the highlighted modelling variables are not targeting all the impact sub-fields, rather some of them. For further detail on the input variables for overall impact quantification, Table 4 should be addressed.

The "Impact" column should be faced as being a screening procedure of the most relevant fields to be considered rather than absolute information for impact quantification. Especially because, the outcomes of many of the mentioned human-made hazards are enormous, thus, even a small impact in all the subfield should be expected.

The links provided in the last column are intended to be used in further developments, as support, to the impact's quantification procedure.

Table 5: Classification of human-made hazards with modelling variables, failure mode and available databases. Grading should be considered within each event, where "+" means a significant impact and "-" a lower impact compared to the remaining types of consequences

	Hazard Characterization		Asset		Impacts					Available Hazard Database
	Hazard Scenario	Main modelling Variables	Type	Failure Mode	Structural	Human	Economic	Environmental	Social /Political	
Unintentional	Collision of trains	Time/Availability	rail track	Closed or traffic reduction	-	+	+	+ / -	+	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Rail_accident_fatalities_in_the_EU https://erail.era.europa.eu/investigations.aspx https://www.pordata.pt/en/Subtheme/Europe/Rail-403
	Derailments	Time/Availability	rail track	Closed or traffic reduction	-	+	+	-	+	https://erail.era.europa.eu/investigations.aspx
	Suicides	Time/Availability	Rail track / roadway	Closed or traffic reduction	-	+	+	-	-	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Rail_accident_fatalities_in_the_EU#Suicides_on_railways
	Vehicle obstruction	Time/Availability	Rail track / roadway	Closed or traffic reduction	-	+	+	+	-	https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/aar2018_infographics.pdf https://www.pordata.pt/en/Subtheme/Europe/Road-402
	Ship collision against asset	Impact Force	Bridge	Failure, collapse, damaged element	+	+	+	+	+	https://inland-navigation-market.org/archives/?lang=en
	Train collision against asset	Impact Force	Bridge	Failure, collapse, damaged element	+	+	+	+	+	https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Rail_accident_fatalities_in_the_EU https://erail.era.europa.eu/investigations.aspx https://www.pordata.pt/en/Subtheme/Europe/Rail-403
	Vehicle collision against asset	Impact Force	Bridge	Failure, collapse, damaged element	+	+	+	+	-	https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/aar2018_infographics.pdf https://www.pordata.pt/en/Subtheme/Europe/Road-402
	Asset Overloading by live load	Load Value	Bridge	Failure, collapse, damaged element	+	+	+	+	+	http://www.bridgeforum.org/dir/collapse/
	Fire in tunnels	Time/Availability	Tunnels	Closed or traffic reduction/Failure, collapse, damaged element	+	+	+	+	+	https://www.tunntech.com/index.php/what-s-up/incidents/tunnel-fires-database
	Fire vehicle under/over the bridge	Time/Availability	Bridge	Closed or traffic reduction/Failure, collapse, damaged element	+	+	+	+	+	https://effis.jrc.ec.europa.eu/applications/data-and-services/
	Fire evolving to large wildfires	Burned Area/Time/Availability	All	Global Failure	+	+	+	+	+	https://effis.jrc.ec.europa.eu/applications/data-and-services/
Intentional	Strikes/occupancy of lines for manifestation	Time/Availability	Rail track / roadway	Closed or traffic reduction	-	-	+	-	+	---
	Bombing /Explosion (Terrorism Purposes)	Peak pressure force/ Pressure timing	Train station/ Bridges/ Tunnels	Failure, collapse, damaged element	+	+	+	+	+	https://www.start.umd.edu/gtd/ https://www.rand.org/nsrd/projects/terrorism-incidents.html http://www.systemicpeace.org/inscrdata.html
	Fire evolving to large wildfires	Burned Area/Time/Availability	All	Global Failure	+	+	+	+	+	https://effis.jrc.ec.europa.eu/applications/data-and-services/
	Track hazards (Removal of rail track tie bars)	Time/Availability	Rail track	Closed or traffic reduction	-	-	+	-	+	https://erail.era.europa.eu/investigations.aspx

Annex 3 – Probabilistic characterization

The probability distribution function is a function that represents the probability that the continuous random variable X is less than a given value x, given by:

$$F(x) = P(X < x) \tag{30}$$

The probability density function, for continuous random variables, is given by:

$$f(x) = \frac{\partial F(x)}{\partial x} \tag{31}$$

In the definition and characterization of probability density functions the statistical moments are used. These allows to simplify and summarize very large information to only one set of values.

Let X be a continuous random variable in the probability density function f(x), the first moment, that is, the mean value (also known as expected value) is given by:

$$\mu_X = E(X) = \int_{-\infty}^{\infty} x \cdot f(x)dx \tag{32}$$

The second central moment, the variance is given by:

$$\sigma_X{}^2 = Var(X) = E\left[\left(X - E(X)\right)^2\right] = E\left(X^2\right) - E^2(X) \tag{33}$$

where σ_X is called the standard deviation.

To analyse the dispersion of a probability distribution, around its expected value, the coefficient of variation (CoV) given by the ratio of the standard deviation to the mean value may also be used:

$$CoV(X) = \frac{\sigma_X}{\mu_X} \tag{34}$$

The coefficient of variation, being a dimensionless value, is presented as a more robust parameter in the comparative analysis of dispersion between distributions of probabilities than the standard deviation.

In order to analyze the degree of dependence between two random variables, X_i and X_j, covariance is used, this being a parameter given by:

$$C_{X_iX_j} = E\left[\left(X_i - \mu_{X_i}\right)\left(X_j - \mu_{X_j}\right)\right] \tag{35}$$

Analysing eq. (33) and eq. (35), it is verified that the variance is a particular case of covariance since:

$$C_{X_iX_i} = Var\left(X_i\right) \tag{36}$$

Given the concept of covariance it is possible to define correlation coefficients between random variables, given by:

$$\rho_{X_iX_j} = \frac{C_{X_iX_j}}{\sigma_{X_i}\sigma_{X_j}} \tag{37}$$

It is only possible to define a correlation coefficient between random variables if both standard deviations are finite and nonzero. The correlation coefficients take values in the interval between -1 and 1, respectively in cases where there is a decreasing linear relation or a linear increasing relation. The closer the correlation coefficient is to the extremes, -1 and 1, the stronger the degree of correlation between the variables. For independent variables the correlation coefficient is null, but the opposite is not necessarily true since the correlation coefficient is only sensitive to linear dependencies between two variables.

After several observations in the nature of several events, it is found that the distributions of probabilities of continuous random variables tend to exhibit characteristic behaviors.

Annex 4 – Probability of failure and reliability

The probability of failure may be expressed by one of the following ways (Melchers, 1999), which also shows that the limit state function can be formulated in different mathematical ways:

$$p_f = P(R \leq S) \tag{38a}$$

$$P(R - S \leq 0) \tag{b}$$

$$P(R / S \leq 1) \tag{c}$$

$$P(\ln(R) - \ln(S) \leq 1) \tag{d}$$

$$P[g(R, S) \leq 0] \tag{e}$$

where $g(\ )$ defines the limit state function which probability of exceedance is identical to the probability of failure. The safety margin M is consequently stated by:

$$M = R - S \tag{39}$$

When both R and S are given by normal random variables, with means μ_R and μ_S and variances σ_R^2 and σ_S^2, respectively, the probability of failure according to (Cornell, 1969) may be stated as:

$$p_f = \Phi\left[\frac{-(\mu_R - \mu_S)}{\left(\sigma_S^2 + \sigma_R^2\right)^{1/2}}\right] = \Phi(-\beta) = 1 - \Phi(\beta) \tag{40}$$

where $\beta = \mu_M/\sigma_M$ is defined as reliability index and $\Phi(\ )$ represents the standard normal distribution function. In this case, it is visible that p_f increases when either one of the variances increase or when the difference between means of R and S decreases.

The basic concept of structural reliability accounting the random variables R and S with respective distributions $f_R(x)$ e $f_S(x)$, is presented in Figure 15, as well as the distribution that characterizes the safety margin M, where the failure region $M \leq 0$ is presented in shadowed.

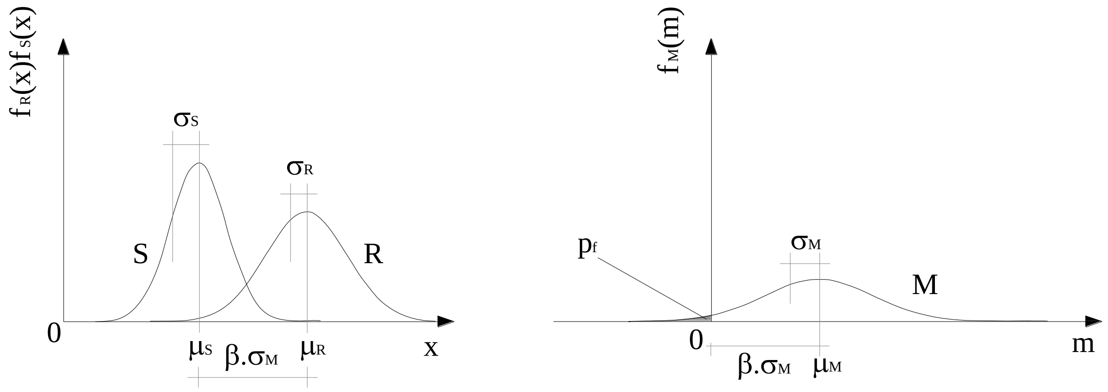


Figure 15: Structural reliability basic problem and safety margin distribution. (Source: adapted from(Schneider, 1997))

Through the graphical representation of the reliability index β, its definition can be inferred as the number of times the standard deviation may be included between the mean of *M* and the origin. The relation between β and p_f, according to eq. (40), is shown for different values in Table 6.

Table 6: Relation between β and pf according to eq. (40)

Probability of failure: p_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Reliability index: β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

When the stochastic variables are non-normally distributed or the failure function is not too non-linear, the probability of failure may be stated as:

$$p_{\mathrm{f}} = P(g(X) \leq 0) \cong \Phi(-\beta) \quad (41)$$

where $\Phi(\ )$ is the standard normal distribution function.

The stochastic reliability methods due to their probabilistic nature, when applied to structural engineering problems, allow considering a large amount of information about the basic variables involved in the safety assessment of an existing structure. In structural reliability applications, often is necessary to consider the characteristic values of demand and resistance, and thus in the large majority of cases the solution is found in the probability distribution extremes. This type of problems is usually denominated as tail sensitivity problem. Accounting this premise, it is verified that p_f is extremely sensitive to the probabilistic parameters chosen for the probability distribution, and thus the importance of correctly define and calibrate the probabilistic model according to the existing data.

In order to design both for ultimate and serviceability limit states, diverse target reliability indices are established for various structural situations by considering different consequences classes, reference periods of time and relative cost of safety measures. For example, the European standard EN 1990 (CEN, 2002) refers three reliability classes RC1, RC2 and RC3 associated with three consequences classes CC1, CC2 and CC3. The definition of the three reliability classes is given in Table 7, and the correspondent minimum target values for the reliability index β regarding ultimate limit states are stated in Table 8. RC is normally related directly to CC.

Table 7: Definition of consequences classes. (Source: adapted from (NP EN 1990:, 2002))

Consequences classes	Description	Examples of buildings and civil engineering works
CC1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible	Agricultural buildings where people do not normally enter, greenhouses
CC2	Medium consequence for loss of human life, economic, social or environmental consequences considerable	Residential and office buildings where consequences of failure are medium
CC3	High consequence for loss of human life, or economic, social or environmental consequences very great	Grandstands, public buildings where consequences of failure are high

Table 8: Recommended minimum values for reliability index β for ultimate limit states (Source: adapted from (NP EN 1990:, 2002))

Reliability Class	Minimum values for β	
	1-year reference period	50-year reference period
RC1	4.2	3.3
RC2	4.7	3.8
RC3	5.2	4.3

Annex 5 - Ship and vehicle collision

The bridges primary mechanism to resist the stress and forces induced by horizontal loads are the substructure, i.e., bridge columns and the foundation. The outcome of impact action on structures can be determined by a dynamic analysis or characterized by a correspondent static force (Figure 16).

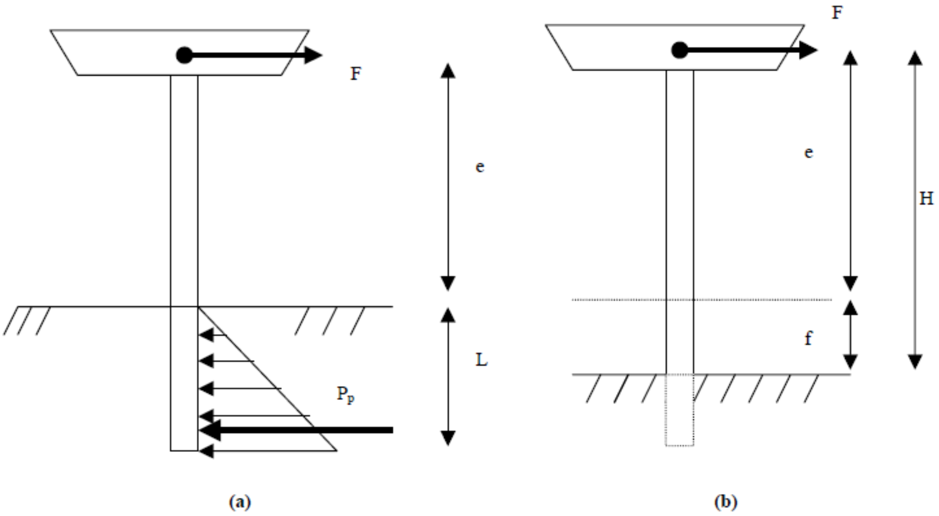


Figure 16: Free body diagram of bridge foundation system: (a)free body diagram for a short pile, dominant failure mode is tipping at base; (b) diagram for long pile, dominant failure mode is bending at distance *f* below soil level. (Source: (Ghosn, Moses and Wang, 2003))

For any of the previous possibilities (static and dynamic analysis), relevant information that should be used as input data for the analysis are:

- Impact velocity of the impacting object;
- Mass distribution;
- Deformation behaviour and damping characteristics of impacting object and the structure;
- Angle of impact;
- Construction of the impacting object;
- Movement of impacting object after collision
- Area of resulting collision force
- Height of the collision.

Regarding the static impact forces of vehicles some indicative information for the analysis can be obtained according to the category of the road traffic that might be responsible for the hazardous event (Figure 17).

Category of traffic	Force F_{dx} [a] [kN]	Force F_{dy} [a] [kN]
Motorways and country national and main roads	1000	500
Country roads in rural area	750	375
Roads in urban area	500	250
Courtyards and parking garages with access to:		
- Cars	50	25
- Lorries [b]	150	75
[a] x = direction of normal travel, y = perpendicular to the direction of normal travel.		
[b] The term "lorry" refers to vehicles with maximum gross weight greater than 3,5 tonnes.		

Figure 17: Indicative equivalent static design forces due to vehicular impact on members supporting structures over or adjacent to roadways. (Source: (EN 1991-1-7, 2011))

A more advanced assessment of the ability of the structure to sustain impact forces can be achieved by considering the impact dynamics and the non-linear behaviour of the material. The impact dynamics can be divided into two groups, i.e. hard impacts and soft impacts, where the first one is characterized by the fact that the energy of the impact is mainly dissipated by the impacting object (the structure is considered rigid and immovable) and the second by the fact that the impacted structure deforms in order to absorb the impact energy.

The maximum resulting dynamic interaction force for a hard impact can be given by the following equation:

$$F = v_r \sqrt{k\, m} \tag{42}$$

Where:

F is the dynamic interaction force of the impact;

v_r is the equivalent elastic stiffness of the object (i.e. the ratio between force and total deformation);

m is the mass of the colliding object.

Type of road	Mass m [kg]	Velocity v_o [km/h]	Deceleration A [m/s²]	Impact force based on (C.1) with $v_r = v_0$ F_0 [kN]	Distance d_b [a] [m]
Motorways	30 000	90	3	2 400	20
Urban areas [b]	30 000	50	3	1 300	10
Courtyards					
– cars only	1 500	20	3	120	2
– all vehicles	30 000	15	3	500	2
Parking garages					
– cars only	1 500	10	3	60	1

[a] Road in areas where the speed limit is 50 km/h.

[b] The value of d_b may be multiplied by 0,6 for uphill slopes and by 1,6 for downhill slopes (see Figure C.2).

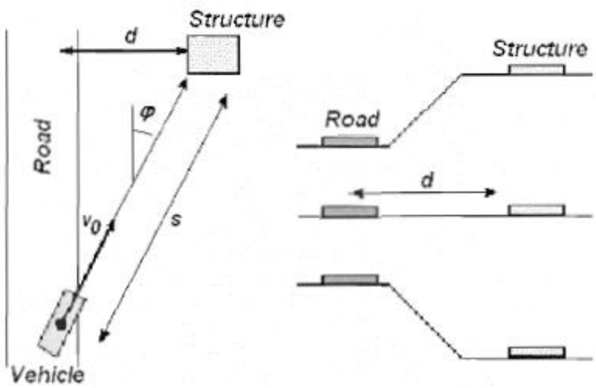


Figure 18: Design values for vehicle mass, velocity and dynamic impact force. (Source: (EN 1991-1-7, 2011))

The previous equation and consequently the values given in Figure 18 gives the maximum dynamic force value on the outer surface of the impacted object, but this force might give rise to dynamic effect within the object. In this case dynamic amplification factor (on other words the ratio between dynamic and static response) is 2.0. However, for more accurate analysis this amplification factor can be obtained through more detailed investigation.

Concerning the probabilistic parameters of the collision force calculation some is given in Figure 19.

Variable	Designation	Probability distribution	Mean value	Standard deviation
v_o	vehicle velocity			
	- highway	Lognormal	80 km/h	10 km/h
	- urban area	Lognormal	40 km/h	8 km/h
	- courtyard	Lognormal	15 km/h	5 km/h
	- parking garage	Lognormal	5 km/h	5 km/h
a	Deceleration	Lognormal	4,0 m/s^2	1,3 m/s^2
m	Vehicle mass – lorry	Normal	20 000 kg	12 000 kg
m	Vehicle mass – car	----	1 500 kg	--
k	Vehicle stiffness	Deterministic	300 kN/m	--
φ	Angle	AC1 Rayleigh AC1	10°	10°

Figure 19: Indicative data for probabilistic collision force calculation. (Source: (EN 1991-1-7, 2011))

Based on general formulation for impact assessment of object against a structural element the following formulation is proposed in the literature for computation of the probability of failure due to vehicle collision:

$$P_f = N \int [P(F > R)] \frac{b}{\sin\varphi} f(\varphi)\, d\varphi \qquad (43)$$

Where:

$N = nT\lambda$ is the total number of initiating events in the period under consideration,
n is the traffic intensity,
λ is the vehicle failure intensity (number of incidents per vehicle km),
T is the period of time,
b is the width of the structural element or two times the width of the colliding vehicle, whichever is the less,
φ is the direction angle,
$f(\varphi)$ is its probability density function,
R represents the resistance of the structure,
F is the impact force.

For ship collision against solid structures some indicative values for the dynamic forces due to ship impact on in land waterways and sea waterways is available in the literature, for the absence of a dynamic impact force analysis (Figure 20 and Figure 21). Normally on inland waterways the collision is considered a hard impact with the kinetic energy being dissipated by elastic deformation of the ship itself. Recommended indicative values for the dynamic amplification factor are 1.3 for frontal impact and 1.7 for lateral impact. For the computation of the probability of failure due to ship collision the following equation is proposed.

$$P_f = N \int \{P(F_{dyn}(x) > R)\}\, dx \qquad (44)$$

Where:

$N = nT\lambda(1 - p_a)$ is the total number of initiating events in the period under consideration,
n is the number of ships per time unit (traffic intensity),
λ is the probability of a failure per unit travelling distance,
T is the reference period (usually 1 year),
p_a is the probability that a collision is avoided by human intervention,
x is the coordinate of the point of the fatal error or mechanical failure,
F_{dyn} is the impact force on the structure following from impact analysis,
R is the resistance of the structure.

CEMT[a] Class	Reference type of ship	Length ℓ (m)	Mass m (ton)[b]	Force F_{dx}[c] (kN)	Force F_{dy}[c] (kN)
I		30-50	200-400	2 000	1 000
II		50-60	400-650	3 000	1 500
III	"Gustav König"	60-80	650-1 000	4 000	2 000
IV	Class „Europe"	80-90	1 000-1 500	5 000	2 500
Va	Big ship	90-110	1 500-3 000	8 000	3 500
Vb	Tow + 2 barges	110-180	3 000-6 000	10 000	4 000
VIa	Tow + 2 barges	110-180	3 000-6 000	10 000	4 000
VIb	Tow + 4 barges	110-190	6 000-12 000	14 000	5 000
VIc	Tow + 6 barges	190-280	10 000-18 000	17 000	8 000
VII	Tow + 9 barges	300	14 000-27 000	20 000	10 000

[a] CEMT: European Conference of Ministers of Transport, classification proposed 19 June 1992, approved by the Council of European Union 29 October 1993.

[b] The mass m in tons (1 ton = 1 000 kg) includes the total mass of the vessel, including the ship structure, the cargo and the fuel. It is often referred to as the displacement tonnage.

[c] The forces F_{dx} and F_{dy} include the effect of hydrodynamic mass and are based on background calculations, using expected conditions for every waterway class.

Figure 20: Indicative values for the dynamic forces due to ship impact on inland waterways. (Source: (EN 1991-1-7, 2011))

Class of ship	Length ℓ= (m)	Mass m^a (ton)	Force $F_{dx}^{b,c}$ (kN)	Force $F_{dy}^{b,c}$ (kN)
Small	50	3 000	30 000	15 000
Medium	100	10 000	80 000	40 000
Large	200	40 000	240 000	120 000
Very large	300	100 000	460 000	230 000

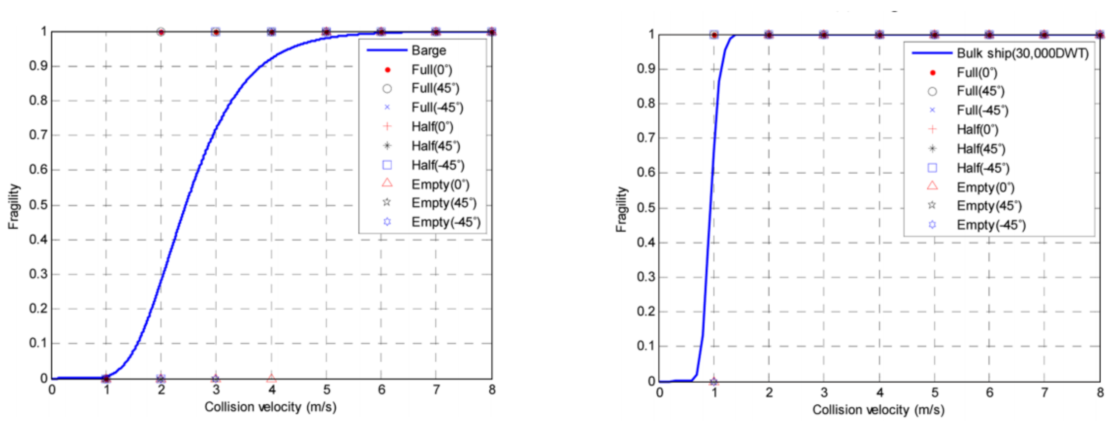
[a] The mass m in tons (1 ton = 1 000 kg) includes the total mass of the vessel, including the ship structure, the cargo and the fuel. It is often referred to as the displacement tonnage. It does not include the added hydraulic mass.

[b] The forces given correspond to a velocity of about 5,0 m/s. They include the effects of added hydraulic mass.

[c] Where relevant the effect of bulbs should be accounted for.

Figure 21: Indicative values for the dynamic interaction force due to ship impact for sea waterways. (Source: (EN 1991-1-7, 2011))

Looking into the literature very few works are found concerning fragility curves were the main action force is given by impact of a vehicle, ship or train. The very few related works that were found, the structure under assessment is an offshore wind turbine where the impacting object are ships, from where the fragility curves given in Figure 22 was extracted just for exemplification purposes, but which can be formally extrapolated to different assets where the demand event is the impact from a collision.



(a) (b)

Figure 22: Collision fragility curve (a) 850 tons ship, (b) 30,000 tons ship. (Source: (Cho and Kim, 2013))