CEDR Transnational Road Research Programme
Call 2013: Ageing Infrastructure Management-
Understanding Risk Factors

Funded by: Denmark, Germany, Ireland,
Netherlands, UK, Slovenia

CEDR
Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

Re-Gen
Risk Assessment of Ageing Infrastructure

Report of the literature review on risk frameworks and definition of road infrastructure failure

Deliverable No. 4.1
June, 2015

Roughan & O Donovan Innovative Solutions (ROD-IS), Ireland
Gavin and Doherty Geosolutions Ltd. (GDG), Ireland
Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
Institut Français des Sciences et Technologies des Transports de L’amenagement et des Reseaux (IFSTTAR), France
Rambøll Denmark A/S, Denmark
Delft University of Technology, Netherlands

Re-Gen
risk assessment of ageing infrastructure

CEDR Call 2013: Ageing Infrastructure Management-Understanding Risk Factors

Re-Gen
Risk Assessment of Ageing Infrastructure

Report of the literature review on risk frameworks and definition of road infrastructure failure

Due date of deliverable: 16/02/2015
Actual submission date: 18/03/2015
Revised with PM comments: 09/06/2015

Start date of project: 01/04/2014 End date of project: 31/03/2016

Author of this deliverable:
Pei-Hui Lin, TU Delft, Netherlands
Pieter van Gelder, TU Delft, Netherlands

Table of Contents

Executive summary

This deliverable consists of definitions of road infrastructure failures and a literature study to summarize the state of the art in appropriate risk frameworks. It benchmarks them with each other and identifies which framework is most suitable for the current project.

As climate change can threaten both a road assets' integrity and functionality, Chapter 2 suggests that the definition of failure in this report should cover structural failures caused by weather, traffic growth, and infrastructure management failures (e.g. asset inspection and asset design); and functional failures such as, for example, failures caused by traffic jams due to extreme weather conditions.

A literature review on various risk frameworks is given in Chapter 3 and Chapter 4. Chapter 3 reviews the qualitative and quantitative risk assessment models in the safety science domain, which in itself represents a state of the art in available risk frameworks. In Chapter 4, specific risk frameworks for roads, which consider the climate change and long term traffic, growth are discussed. Major international reports are reviewed in this chapter.

Chapter 5 concludes that quantitative risk assessment tools (e.g. fault tree or Bayesian Belief Networks) are most suitable for quantifying the risk model for road infrastructure failures. If part of the historical data is not available, structured expert judgment (Cooke, 1991; Cooke & Goossens, 2000; 2008) can be used to quantify this model. This gives us the opportunities to quantify for road assets failures in condition to traffic growths and weather conditions if no historical data is available.

1 Introduction

The majority of infrastructure components for road transport systems were constructed during the 1960s and the 1970s in Europe. Many of the structures built during this period are now in need of repairs or can no longer adequately serve the road user. As infrastructure deterioration caused by heavy traffic and an aggressive environment becomes increasingly significant, this results in a higher frequency of repairs and higher costs to maintain the required service life performance of road infrastructure. Thus, the need for risk-based assessments to priorities risk and optimize budgets/resources for maximized service life performance of road infrastructure is increasingly urgent.

To build a methodology to estimate the risk associated with the failure of an element of infrastructure, definitions of road network failures are provided in Chapter 2. Chapter 3 reviews the qualitative and quantitative risk assessment model in the safety science domain and describes where particular methodologies are relevant to Re-Gen. A state of the art review is performed in chapter 4 to benchmark possible risk frameworks for roads regarding the changing climate and long term traffic growth. Chapter 5 suggests the framework that is most suitable for the current project.

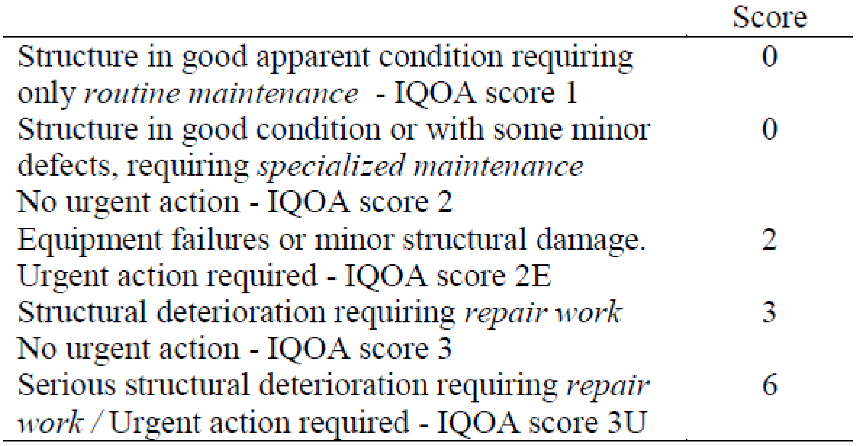
2 Definition of failure

Several areas of the literature are reviewed for definitions of road infrastructure failures.

The U.S. Federal Highway Administration (2011) has developed a framework for improving resilience of bridge design. Failure is defined as *“the inability of a bridge or one of its primary load-carrying components to no longer perform its intended function. For bridges under construction or in service, this framework considers the term failure in two different contexts: 1) collapse and 2) critical defect. Herein, a bridge collapse is the failure of all or a substantial part of the bridge where full or partial replacement may be required. The term critical defect refers to the condition in which the structure has undergone some deformation, section loss, or similar undesirable condition, but has not collapsed and can be repaired or retrofitted.”*

Lacoste et al. (2012) developed a risk analysis approach for identifying, qualifying and quantifying risks in order to preserve post-tensioned girder bridge decks in France. In this article, five different bridge conditions are defined and scored. The condition of a bridge defined in this literature is shown in Table 2.1 which is based on the IQOA scoring system (SETRA 1996).

Table 2.1 The condition of a bridge (Lacoste et al., 2012)



	Score
Structure in good apparent condition requiring only *routine maintenance* - IQOA score 1	0
Structure in good condition or with some minor defects, requiring *specialized maintenance* No urgent action - IQOA score 2	0
Equipment failures or minor structural damage. Urgent action required - IQOA score 2E	2
Structural deterioration requiring *repair work* No urgent action - IQOA score 3	3
Serious structural deterioration requiring *repair work* / Urgent action required - IQOA score 3U	6

Adey et al (2003) develop a risk-based approach to determine optimal interventions for bridges affected by multiple hazards (e.g. traffic load, excessive scour leading to foundation failure). In this paper, they consider that the ability of a bridge to provide an adequate “level of service” to the users may be compromised due to multiple hazards. The failure defined in this paper is the behaviour of the structure resulting in the exceedance of a defined limit state caused by multiple hazards. When the limit states equations are lower than zero (i.e. bridge resistance smaller than hazard effects), it is considered to result in a level of reduced functionality, such as a speed restriction, weight restriction, single lane closure or complete bridge closure. In summary, this work takes into account not only the structure failures but also the probabilities of inadequate level of service due to different hazard effects.

Decò & Frangopol (2011) developed a framework for the quantitative risk assessment of highway bridges under different hazards. This paper defines reliability as the ability of a component or system to perform and maintain its intended performance. The performance of a component is related to its capacity to withstand the applied loads. So the failure of a component or system in their paper also considers the structure performance associated with a specific limit state.

The definition of failure in this report should be able to cover structural failures caused by weather, traffic growth, and infrastructure management failures (e.g. assets inspection, assets design); and functional failures such as failures caused by traffic jams due to extreme weather conditions.

In respect of the literature review in this chapter, the road infrastructure failures defined herein in this report can be summarized as follows:

Structural failures:

- This is defined as an infrastructure that no longer performs, in the permanent state, its intended function or the failure of a component is expected to result in the complete failure of the infrastructure. Structural failures include: 1) complete failure in permanent state (e.g. a bridge collapse due to extreme weather like flooding and scour) and 2) critical defect. This means there may not be a complete failure of the infrastructure, but there is the potential for complete failure. Critical defect refers to the conditions in which the infrastructure has undergone some deformation or section loss, but has not yet completely failed. Infrastructure failures can cause interruption to commercial activities and services, result in significant repair costs, and threaten the safety of human life.

  Complete failure and critical defect can be further classified as
    - Loss of serviceability (minor structural failure or equipment failures that need some urgent repair actions)
    - Structural failure (major structural failure that need some urgent major rehabilitation)
    - Infrastructure collapse/ complete failure (with potential loss of life of several people)

Functional failures:

- This refers to the cases in which the infrastructure cannot provide defined levels of service in the temporary state. For instance, bad weather conditions can have impacts on mobility. Extreme weather conditions can cause congestion and delays. Heavy rain reduces distance visibility. Snow may result in slippery pavements, which reduces vehicle traction and manoeuvrability. These impacts prompt drivers to travel at lower speeds resulting in increased congestion, reduced roadway capacity and increased delay. Extreme weather conditions can also reduce capacity. Capacity reductions can be caused by lane submersion due to flooding and by lane closure due to other extreme weather conditions.

It should be noted that the objective of the Re-Gen project is to provide Road Owners/Managers with best practice tools and methodologies for risk assessment of critical infrastructure elements, therefore the term failure here is not restricted to structural collapse alone, but also refers to the potential of failure occurring. With this definition, the developed tool is able to provide Owners/Managers with the ability to prioritise risk and optimise budgets/resources for the maximised service life performance of an infrastructure.

The aim of next two chapters is to review current methodologies of risk assessment for the overall risk of road infrastructure regarding climate change and long-term traffic growth.

3 Literature review on possible risk frameworks in the safety domain

In this section of the report, risk assessment frameworks in the safety domain are investigated. Risk analysis approaches are widely employed in the safety science domain to identify the various combinations of faults which can lead to reduced safety and can be divided into two types: qualitative risk assessment, Section 3.1, and quantitative risk assessment, Section 3.2. Typical frameworks in this domain are described with a view to highlighting state of the art frameworks which can be used to benchmark frameworks that are possibly of relevance to Re-Gen. The latter frameworks, as described in Section 4.1 of this report, are mostly qualitative or (semi)-quantitative when considering the effects of climate change or traffic growth on roads. As a result quantative methods are ultimately proposed for Re-Gen.

3.1 Qualitative risk analysis

There are several methods available for performing qualitative risk analysis (e.g. expert judgment and tabular methods). Among them, HAZOP (Chemical Industries Association, 1977) is an analytical method used in identifying potential hazards. The HAZOP technique was initially introduced to the chemical industry as a method by which plants could be assessed to determine the potential hazards they presented to operators and the general public. Later it was extended to other types of systems and also to complex operations such as nuclear power plant operation.

HAZOP requires a qualitative inductive treatment by expert panels. The basic concept of a HAZOP study is to identify hazards which may occur within a specific system. This requires a brainstorming session by a group of experts familiar with the design and operation of the system. The team of experts systematically considers each component (e.g. bridge, retaining wall) in the system, applying guide words to determine the possible deviations and consequences of operating conditions outside the design boundary. Figure 3.1 shows the steps to identify the failures for sewer assets (as an example) using HAZOP (Stanic´ et al., 2014).

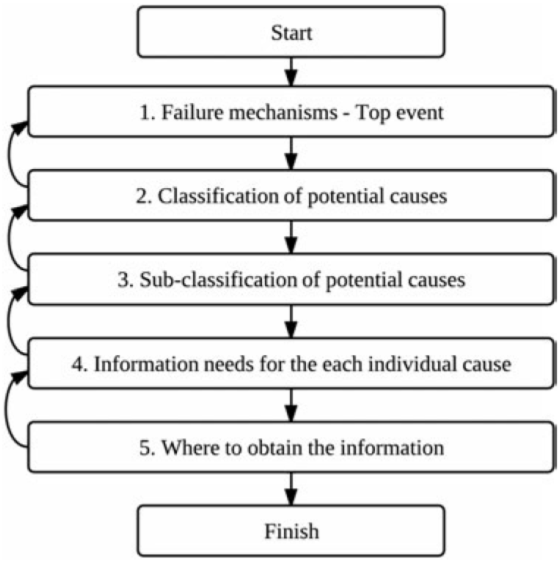
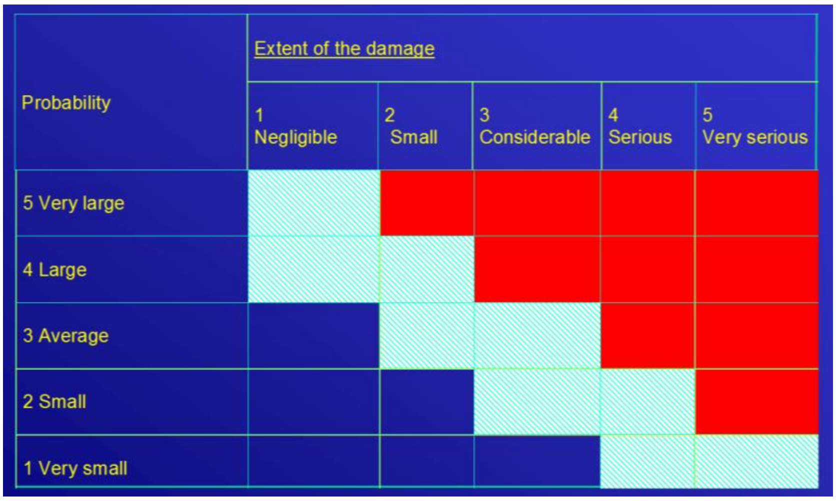


Figure 3.1 Procedural outline followed in sewer failure assessment using HAZOP (Stanic´ et al., 2014)

The output of the HAZOP is a matrix with deviations, seriousness, probability estimates, remedies, and usually, an indication of the costs. The identified risks are prioritized using a pre-defined rating scale. This matrix is then presented to policy makers who then have to decide which remedies to implement and what residual risk to accept.

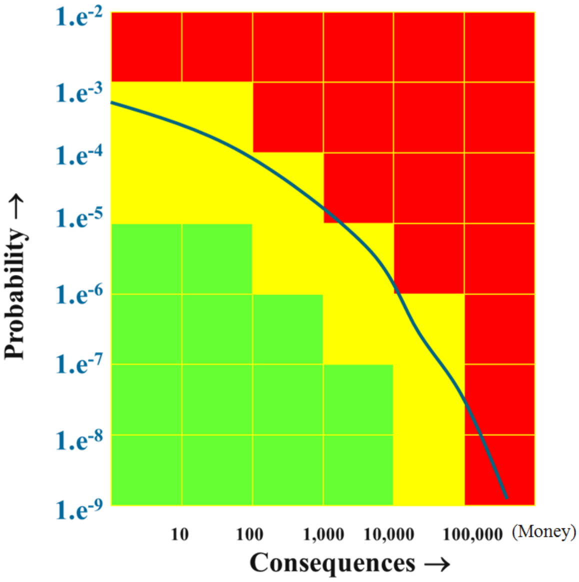
Most of the traditional safety analysis methods, e.g., HAZOP, are qualitative analysis tools or semi-quantitative tools. Likelihood and consequence is scored without using probability distributions or data analysis, unlike in the quantitative method. Qualitative methods often rank the risks on an ordinal scale, e.g. from “low” to “high” and present the various levels of risk using a risk matrix as a risk assessment tool. Table 3.1 and Table 3.2 show examples of risk matrices. Matrices can range from simplistic ‘tables’ with discrete high-medium-low ranking of risk (Table 3.1) to more complex formulations with probabilities and consequences (Table 3.2). Normally these qualitative risk assessments methods are used to identify and rank the importance of the potential hazards, which may critically affect the safety of the system and are commonly used for screening risks to determine whether they need further investigation. They can also be useful in preliminary risk management activities

Table 3.1 Risk matrix



Probability	Extent of the damage				
	1 Negligible	2 Small	3 Considerable	4 Serious	5 Very serious
5 Very large	▨	🟥	🟥	🟥	🟥
4 Large	▨	▨	🟥	🟥	🟥
3 Average	🟦	▨	▨	🟥	🟥
2 Small	🟦	🟦	▨	▨	🟥
1 Very small	🟦	🟦	🟦	▨	▨

Table 3.2 Risk matrix



Most of the risk frameworks which consider climate change with respect to road infrastructure networks constitute some type of risk matrix to evaluate and prioritize risks (see chapter 4 for more discussion). Those events with higher combined likelihood and impact receive higher risk prioritization scores than those with lower rank. Qualitative risk assessment can be used in preparation for a quantitative analysis, such as a fault tree analysis, which will be discussed in the next section.

3.2 Quantitative risk analysis

Quantitative Risk Assessment (QRA) requires the calculation of two components of risk - the probability of adverse event and the magnitude of the consequence.

$$Risk = P(adverse\ event) * C(consequence) \qquad \text{Equation (1)}$$

Methods such as fault tree (FT) and event tree (ET) analysis are core methods of quantitative risk assessment. Fault tree analysis (FTA) is a well-recognized tool for system failure analysis. This analysis method is a top down, deductive failure analysis showing how different factors could combine to cause a systematic failure. This deductive technique focuses on a particular failure event and provides a method to determine the causes leading to a failure in a system. After the qualitative model of the Fault tree is built, it is then quantified using Boolean logic.

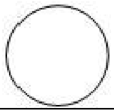
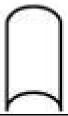
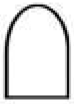
The Fault-Tree/Event-Tree method is the most widely used quantitative technique for assessing the probability and frequency of system failure in industry. This is particularly true in the field of risk analysis of process safety, nuclear power plants or offshore oil platforms. The technique was first developed by H. A. Watson (1961) of Bell Telephone Laboratories during a study for the Minuteman Launch Control System. The importance of the fault tree for system failure analysis is that it describes all causes of the system failure in a diagrammatic way. Hence, the system engineers can easily identify problems in the system.

Since fault tree analysis is a well-recognized tool for system failures analysis and has the potential to be used in Re-Gen study, a detailed description of fault tree analysis is given below.

3.2.1 Fault Tree Diagram

In a fault tree diagram, an undesired state of a system or failure of the system is analysed using Boolean logic. Table 3.3 provides an explanation of the symbols used in the fault tree. The rectangle with the long side horizontal represents a top event and the intermediate event in a fault tree. The circle represents a basic event in the fault tree. Basic events are events that are not further developed in the fault tree. Figure 3.2 shows the Boolean logic of different types of gates used in the fault tree.

Table 3.3 Symbols for Fault Tree Analysis

Symbol	Usage	Usage
	Events	Represents the top event and the intermediate events in the fault tree.
	Basic event	Represents basic events in the fault tree.
	OR gate	OR gate exists if at least one of the input events (preceding events) exists.
	AND gate	AND gate exists only if all of the connected input events (preceding events) exist simultaneously.

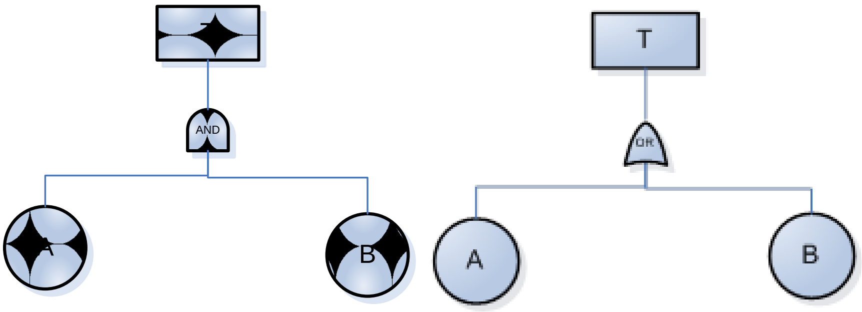


Figure 3.2 Boolean logic

AND gates are used where an event T has two independent events, necessary causes A and B. AND gates exist if only all of the connected input events (preceding events A&B) exist simultaneously.

$$P(T)=P(A)\cdot P(B) \qquad \textit{Equation (2)}$$

The output event associated with the OR Gate exists if at least one of the input events (preceding events) exists.

$$P(T)=P(A)+P(B)-P(A)\cdot P(B) \qquad \textit{Equation (3)}$$

3.2.1.1 Fault Tree analysis

An approach used to model a Fault tree involves five steps, Figure 3.3 (AIChE, 2000; NASA, 2012).

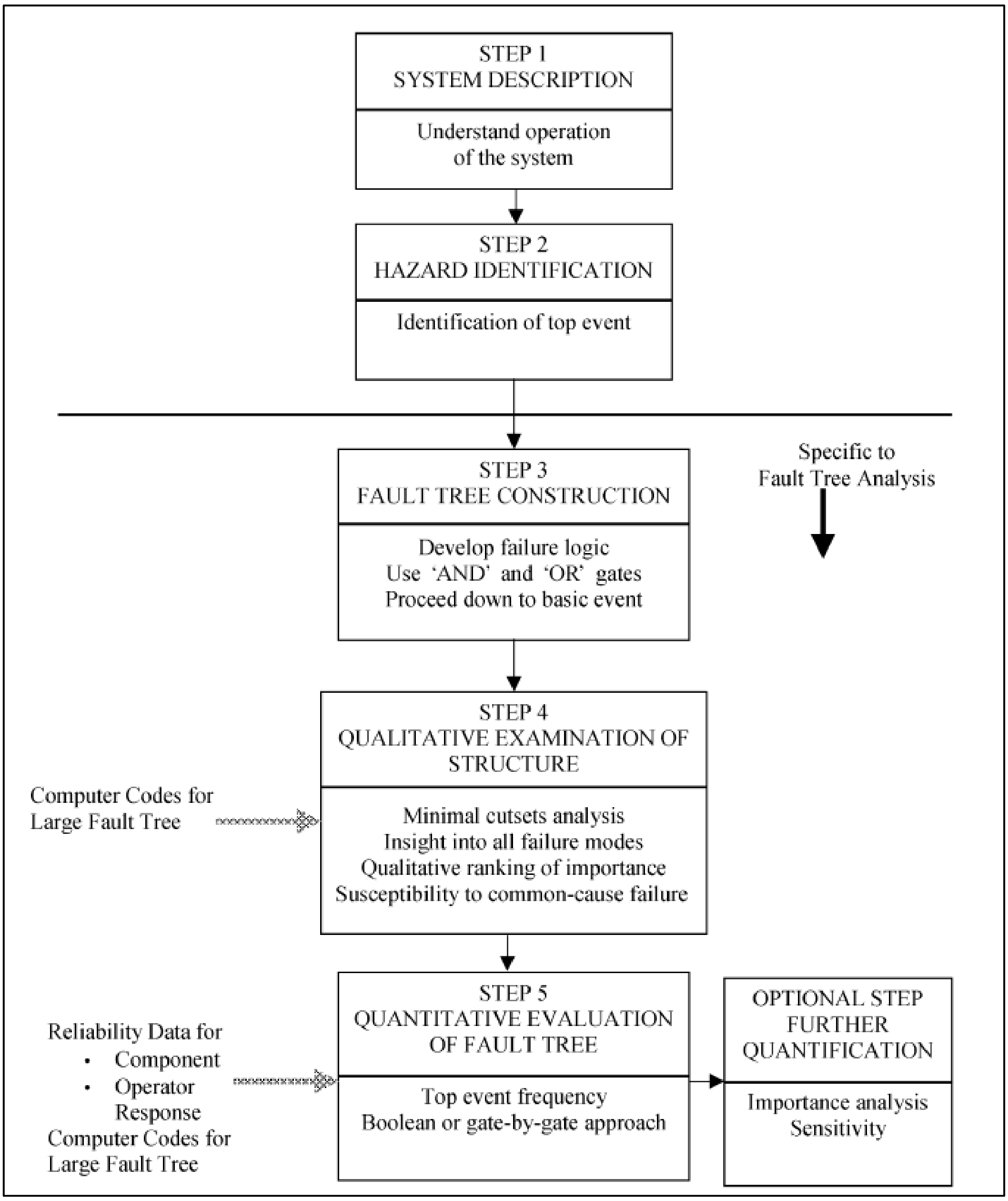


Figure 3.3 Operational steps for fault tree analysis (AIChE, 2000).

Step 1: System description

System analysts can help with understanding the overall system. System designers have full knowledge of the system and this knowledge is very important to avoid missing any cause affecting the undesired event. For the selected event all causes are then numbered and sequenced in the order of occurrence and then are used for the construction of the fault tree.

Step 2: Hazard identification

After identifying an undesired event, causes can be identified through systematic approaches. This can be done by data-driven methodologies (e.g. hazard report, real time simulation) or qualitative analysis (e.g. based on discussion, interview or expert judgement).

Step 3: Fault tree construction
After identifying the top event and having analysed how the system can fail, the fault tree can be constructed to develop failure logic. The fault tree is based on AND and OR gates as described above.

To construct the fault tree, the system failure mode is broken down or developed into subsystem failures, which are in turn further developed into lower resolution events or failures. This process is continued until no further development can take place and the limit of resolution is encountered.

Those events whose causes have been further developed are termed 'intermediate events' and events terminating branches, 'basic events'. The top event of the fault tree is the system failure, which is also an intermediate event. Events in the fault tree are combined using logic gates.

Step 4: Qualitative evaluations of a Fault Tree
After the fault tree has been constructed, significant insights and understanding are gained concerning the causes of the top event. FT itself is a qualitative assessment of the events and relationships that lead to the top event. The minimal cut sets define the smallest list of basic events that is necessary to cause the top event to happen. Once the minimal cut sets are obtained, the quantification of the fault tree is more or less straightforward.

Step 5: Quantification
Quantitative fault tree requires a fault tree and failure data of basic events. To quantify the probability of the top event of the FT, a probability for each basic event in the fault tree must be provided. These basic event probabilities are then propagated upward to the top event using the Boolean logic.

In quantifying the Fault Tree, a top-down approach (reversing the calculations) can be followed. If the probability of the top events of the Fault Trees is known, the top events can be split into events corresponding to unsuccessful performance of each intermediate event. These unsuccessful intermediate events are then further split into the causes of intermediate failure. Each stage requires further information, which is obtained either from the causal distributions above, or from other data sources or judgements.

3.2.1.2 Fault tree example: Analysis in bridge design

The U.S. Department of Transportation (2011) utilizes a fault tree diagram to demonstrate the critical failure path of a bridge. Fault trees allow the bridge designer to graphically see various failure combinations and failure paths and the department uses fault trees for advising bridge designers to consider potential failure scenarios during the design process.

The fault tree diagrams illustrated in Figure 3.4 and Figure 3.5 show the possible failures caused by four different mechanisms: design and/or operation, inspection, construction, and fabrication. The fault tree in this example is established with a Steel Girder Bridge Failure, the top event. The four categories are joined by an “or gate” which means at least one of the conditions can cause a bridge failure. Each of the four basic events in Figure 3.4 is further developed into more detailed fault trees (see Figure 3.5 for design/operation).

The fault trees presented in this document are qualitative. A project specific fault tree is developed by LeBeau and Wadia-Fascetti (2007) for the collapse of the Schoharie Creek

Bridge in the U.S. They use Boolean algebra to quantify the probability of failures of different failure path mechanisms for the collapse of the bridge. Daniels et al. (1991) use fault tree analysis to assess the vulnerability of several steel bridges. These studies show that fault tree can be used as qualitative and quantitative tools for road infrastructure failure analysis.

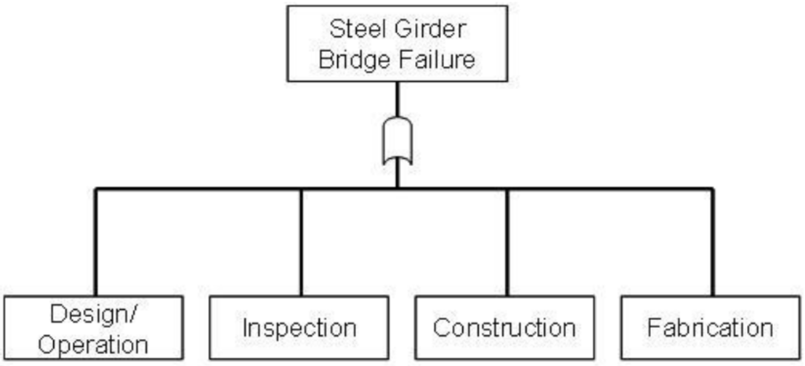


Figure 3.4 Top events of fault tree for steel girder bridge

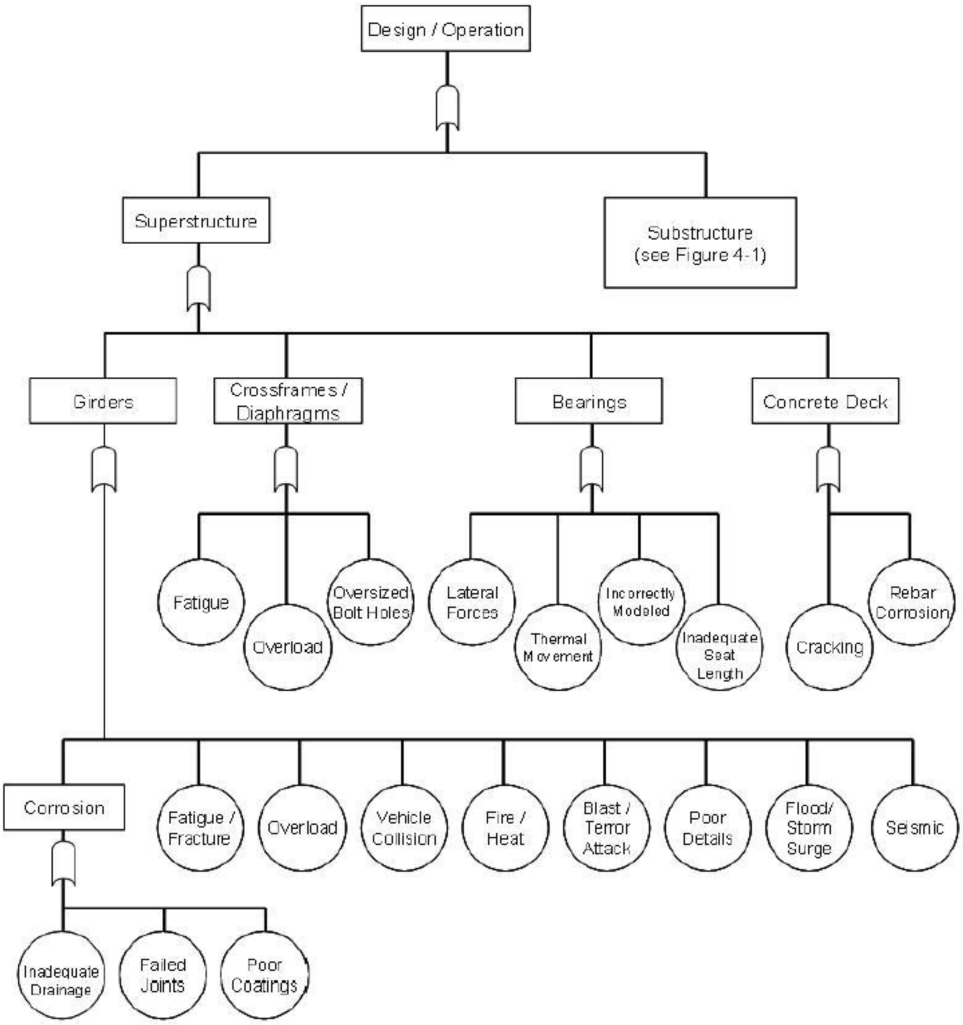


Figure 3.5 Fault tree for design/ operation for superstructures for steel bridge

3.2.2 Bayesian network

Fault trees are the most widely used quantitative technique for assessing the probability and frequency of system failure in industry. However, standard fault tree analyses are not suitable for analysing large systems, particularly if the system has common cause failures and there are interdependencies among the system elements, as in the case of road infrastructure subject to climate change and traffic growth. A Bayesian network (BN), or Bayesian Belief Network (BBN), is an alternative technique with ample potential for application in safety analysis and consists of a directed graph that provides a framework of the logical relationships between variables. The distinct advantages that make BNs more suitable than FTs are their ability to capture the uncertainty of the dependencies between variables and to more easily update probabilities. The quantification techniques of BNs and the logic of systematic modelling for risk can be useful as a reference to model failures of road infrastructure in Re-Gen project.

Quantifying a BN consists of the following steps:

1. List the relevant variables by starting with the objective of the analysis and describe the factors that might influence these objectives.
2. Describe the different variables in precise terms. Each factor can be in one of a number of different states. For instance, “traffic load” might be in one of the states “heavy traffic” or “light traffic”. The states should be exclusive and exhaustive.
3. Construct the qualitative influence model using a directed acyclic graph. This considers the relationships existing between the variables.
4. Quantify the network. This includes assigning conditional probabilities for each variable given each possible combination of states of the variables in the parent nodes. The conditional probabilities can either be derived from historical data or elicited from experts in the field.
5. After a BN is completed for the variables and their relationships, it can be used to answer probabilistic queries about them. This is known as “inference”. For example, the network can be used to find out updated knowledge of the state of a subset of variables (the evidence variables) when other variables have not yet been observed.

The variables in the BN model can be discrete or continuous variables. If the conditional probabilities cannot be derived from historical data, structured expert judgement (Cooke, 1991; Cooke & Goossens, 2000; 2008) can be used to quantify the BBNs model. This gives us the opportunities to quantify for instance bridge failures in condition to traffic growths and weather conditions if no historical data is available.

Bayesian Networks are useful tools in making inferences about uncertain states when limited information is available. BN’s are frequently used for making diagnoses, with applications to medical science as well as various engineering disciplines such as aviation, the chemical industry and the nuclear energy industry (Jensen, 1996; 2001).

Causal Model for Air Transport Safety (CATS) is a project that was embarked on in 2005 by the Dutch Ministry of Transport, Public Works and Water Management to develop an integrated risk model for air transport for the whole flight cycle from (departure) gate to (arrival) gate (Ale et al., 2009). This model contains technical elements (technical failure probabilities), human behavioural factors (failure probabilities in human behaviour), combined with organizational factors (managerial influences). The CATS model converted the different parts of the models into a single Bayesian Network. This allows the model to quantify overall risk, taking into account dependencies, and also to model softer influences, such as human errors and management failures, in a homogeneous manner.

This project is reviewed in Section 3.2.2.1 below. This project is particularly relevant to Re-Gen as the system to be adopted in the risk framework grows larger, as more infrastructure elements are considered in the system. Equally the system has common cause failures and interdependencies among the system elements (e.g. the failures of infrastructure elements may have common cause failure due to the same failures in assets inspection or failures in assets maintenance). In such cases, where there are interdependencies among the system elements, standard fault trees are not very suitable for analysing such systems. The quantification techniques and the logic of systematic modelling for risk can be used as a reference to model failures of road infrastructure.

3.2.2.1 Risk model in aviation (Ale et al., 2009)

Causal Model for Air Transport Safety (CATS) is a project that was commenced in 2005 by the Dutch Ministry of Transport, Public Works and Water Management to develop an integrated risk model for air transport for the whole flight cycle from (departure) gate to (arrival) gate.

Aviation accidents tend to result from a combination of many different causal factors: human errors, technical failures, environmental and management influences. The integrated risk model of CATS contains technical elements (technical failure probabilities), human behavioural factors (failure probabilities in human behaviour), combined with organizational factors (managerial influences). The CATS project approaches this complexity by developing separate causal models for these three aspects.

Figure 3.6 describes the modelling techniques of the CATS project. Event Sequence Diagrams (ESDs) presents the possible accident scenarios. Fault Trees (FTs) describe the conditions and causes of the scenarios. In the base events of the fault trees include events representing technical failures and human errors (e.g. break not applied correctly by pilots). Bayesian Belief Nets (BBNs) is used to quantify the human reliability. The CATS model is thus built on the combination of these three modelling techniques.

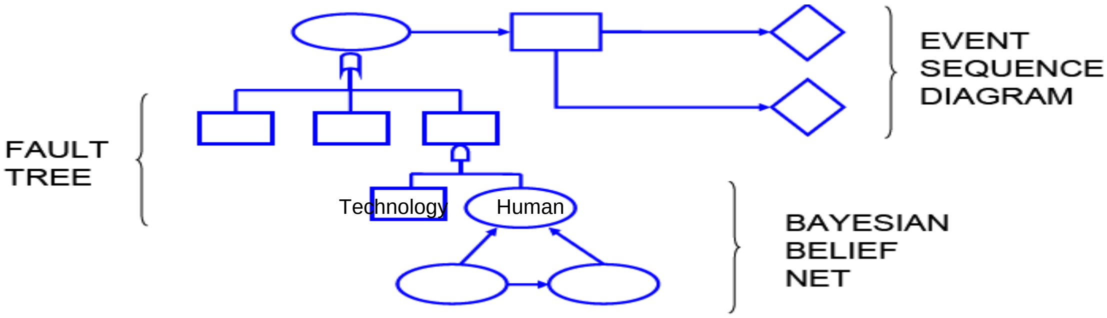


Figure 3.6 The basic constituents of CATS

ESDs is the backbone of the model which consists of 33 generic accident scenarios identified in the aviation industry. The event representation in ESDs is usually kept broad and generic to portray the progress of events over time.

FTs are developed more elaborately to identify technical component failures and/or the combinations of human errors that can lead to an undesired event identified in the ESD. FTs are usually constructed from the analysis of accident descriptions. This analysis is performed by dissecting these accident histories one by one to find potential causes of events already in the causal chain towards a pivotal event in the ESD. This continues until no new events (the failure of an identifiable technical system or a human action) can be established from data.

CATS also incorporates human factors and link a safety management model with the technical model and human model, and then quantify the risk implications of different management changes to prevent accidents.

Human models are developed using the concept of the Performance Shaping Factors (PSF) to deal with human factors. Human error probabilities for general types of tasks are adjusted for the influence of possible circumstances or contexts by the application of PSFs (performance shaping factors) (Swain & Guttmann, 1983). This technique calculates the human error probabilities by identifying the sorts of PSFs external or internal to the individual. Dependencies and interactions between PSFs are easily represented in a BBN structure; therefore the events involving human reliability are often detailed further as BBNs. In the CATS project, human operator models are attached to the fault trees wherever humans are involved in the fault tree events (Figure 3.6).

The management model used in CATS builds on the work done in I-RISK, WORM and ARAMIS (Bellamy et al, 1999; Ale et al 2006; Papazoglou & Ale, 2007). CATS quantified the influences of management actions on human performance, expressed through the quality and operation of the management actions (Lin et al., 2013). The technique, based on paired comparisons, was used to quantify the management influences and to build up a BBN risk model (Lin et al., 2013).

The whole structure of the CATS model as described up to this point is shown in Figure 3.7. All these separate elements in FT and BBNs are then converted into a single Bayesian Belief Net (BBN). This allows the model to take into account dependencies and also to model the softer influences such as management in a homogeneous manner.

The systematic decomposition of failures by technical errors, human factors and management factors proved to be useful in analysis risk and control safety (Ale et al., 2009). As road transportation has similar activities as in aviation i.e. they both consist of considerable engineered systems and the engineered system failures can be caused by design errors, operation errors, and maintenance errors. These errors are then caused by human factors (e.g. human negligence by inadequate inspection) and management factors (e.g. policy for traffic loading over bridge). Therefore, this concept can be used to model failures for road network.

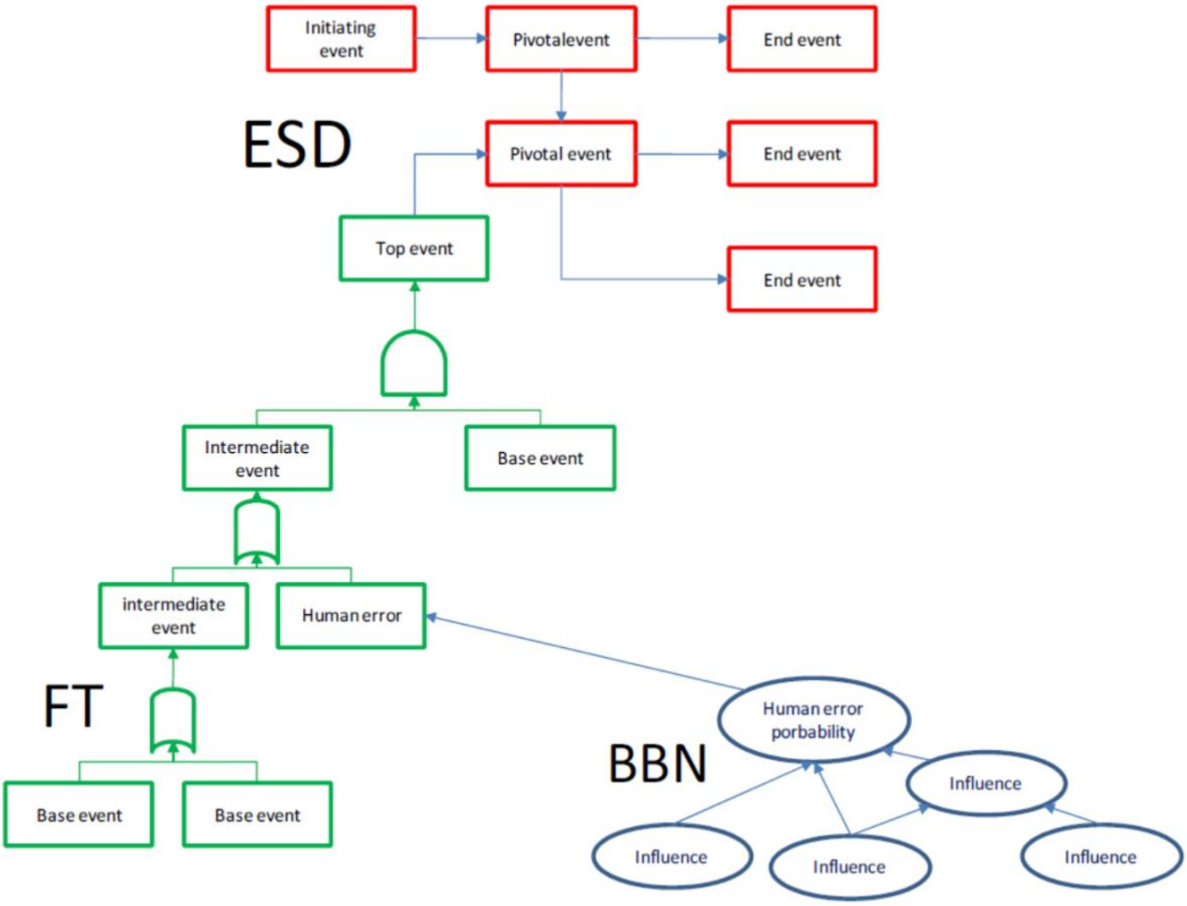


Figure 3.7 The basic constituents of CATS project (Ale et al., 2009)

4 Literature review on possible risk frameworks for roads related to climate changes and long-term traffic growth

This chapter reviews possible risk frameworks for road infrastructure which consider the relationship between climate change and deterioration of the road network, and the relationship for the long-term traffic growth are also reviewed.

4.1 Risk frameworks for roads related to climate changes

In Europe, DVR (2000) observes weather impacts on traffic in general. Bos (2001) and Stiers (2005) research the impacts of weather conditions on road traffic in the Netherlands. Cypra (2006) describes the optimisation of winter maintenance in Germany. Saarelainen (2006) analyses the vulnerability of Finnish transport networks to climate change impacts and discusses adaptation to climate change in the transport sector in Finland. Bengtsson and Tómasson (2008) develop a methodology for risk and vulnerability analysis of a road network in Reykjavik. Sabir et al. (2008) research the welfare effects of adverse weather through speed changes in car commuting trips in the Netherlands. The UK highways agency (2009) executes a risk appraisal, which enables vulnerabilities to be prioritised. The prioritisation provides a basis for developing and implementing adaptation action plans. Chatterton, et al. (2010) analyse the economic costs of the summer 2007 floods in England. Hellman et al. (2010) develop an inspection and maintenance guide for reducing vulnerability due to flooding of roads. WEATHER project (2012) is funded by the 7th framework programme of the European Commission. It aims to analyse the economic costs of climate change on transport systems in Europe and explores ways to reduce the costs in the context of sustainable policy design. RIMAROCC (2012) aims to develop a method for risk management of road infrastructure in relation to climate change. The result of this project is a structured process that supports decisions to be made by road owners in Europe. The method gives guidance on how to identify, analyse, evaluate and treat risks.

The aforementioned studies have investigated the principal effects of climate change and extreme weather events imposed on road infrastructure. However, due to data limitations and the uncertainty of the impact of climate change, most of the studies remain descriptive. Consequently, the review in the following section focuses on those studies that specifically incorporate elements of risk-based practices (e.g. risk analysis, risk assessment) and/or have (semi)-quantitative information relevant to the Re-Gen project.

4.1.1 RIMAROCC (Bles et al., 2012)

The objective of this project is to develop a common method for risk analysis and risk management with regard to climate change for roads in Europe. The method presents a framework and an overall approach to adapt to climate change. Unlike most of the other projects described above, this project clearly defined risk, likelihood and consequence, the components for quantitative risk assessment (QRA) as mentioned in Section 3.1.

RIMAROCC defines risk as the combination of threat, vulnerabilities and consequences.

Risk = a function of [Threat, Vulnerabilities, Consequences]………Equation (4)

-Threat comprises hazard and environmental factors. The hazard is described by climate factors, and the environment (the surroundings) is described by contextual site factors.

Climate factors: those likely to affect road infrastructures are rain, wind, cold/frost, snow, fog, heat, and drought.

Contextual site factors: physical, biological and human factors of the environmental context of the infrastructure. They can be intrinsic risk sources (e.g. unstable ground conditions, trees likely to fall down on the road, etc.), but may also be induced by artificial changes (e.g. soil sealing due to urban development or deforestation of upstream river basins).

-Vulnerabilities describe the properties of the assets or functions of the road system that may be harmed due to climate factors.

In this respect, a road infrastructure can be defined by its technical characteristics (construction standards and designs), its use (traffic), and the environment (e.g. tree alignments). Vulnerabilities include factors from those aspects.

The infrastructure age, design characteristics, used standards, type of maintenance (of the infrastructure and/or its environment) traffic type, traffic intensity can be considered vulnerabilities. An old construction with design mistakes, inappropriate standards, lack of maintenance, unexpected heavy traffic can be considered more vulnerable than a new construction with appropriate design and recent standards. Environment is defined as the environmental assets pertaining to the road system. For example, tree alignments may be considered vulnerabilities, however trees standing near the road, but outside the direct control and responsibility of the road authority, and which are likely to fall down on the road are consider as contextual threat.

-Consequences describe the outcome of the realised threat and include human life and injuries, economic losses, reconstruction cost etc.

The variables described in RIMAROCC are useful in Re-Gen as they determine potential causes leading to the manifestation of a failure within a road system. As such they offer some qualitative analysis for development of a quantitative risk model in our project.

The RIMAROCC guidebook also provides a step-by-step procedure that can be followed through all phases of the risk management process, Figure 4.1. The framework consists of seven steps, each with a number of sub-steps.

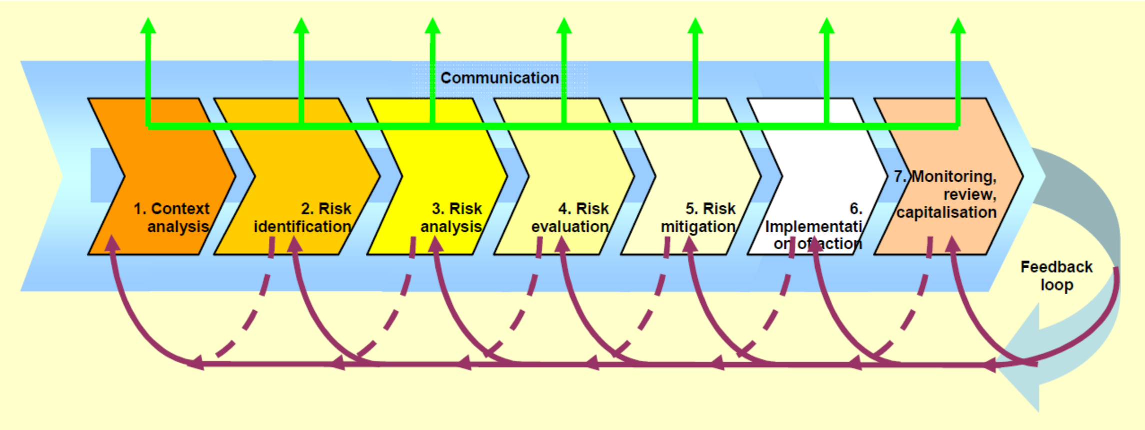


Figure 4.1 RIMAROCC 7 steps

Table 4.1 Scope of steps and sub-steps

Key steps	Sub-steps
1. Context analysis	1.1 Establish a general context 1.2 Establish a specific context for a particular scale of analysis 1.3 Establish risk criteria and indicators adapted to each particular scale of analysis
2. Risk identification	2.1 Identify risk sources 2.2 Identify vulnerabilities 2.3 Identify possible consequences
3. Risk analysis	3.1 Establish risk chronology and scenarios 3.2 Determine the impact of risk 3.3 Evaluate occurrences 3.4 Provide a risk overview
4. Risk evaluation	4.1 Evaluate quantitative aspects with appropriate analysis (CBA or others) 4.2 Compare climate risk to other kinds of risk 4.3 Determine which risks are acceptable
5. Risk mitigation	5.1 Identify options 5.2 Appraise options 5.3 Negotiation with funding agencies 5.4 Formulate an action plan
6. Implementation of action plans	6.1 Develop an action plan on each level of responsibility 6.2 Implement adaptation action plans
7. Monitor, re-plan and capitalise	7.1 Regular monitoring and review 7.2 Re-plan in the event of new data or a delay in implementation 7.3 Capitalisation on return of experience of both climatic events and progress of implementation
Communication and gathering of information	

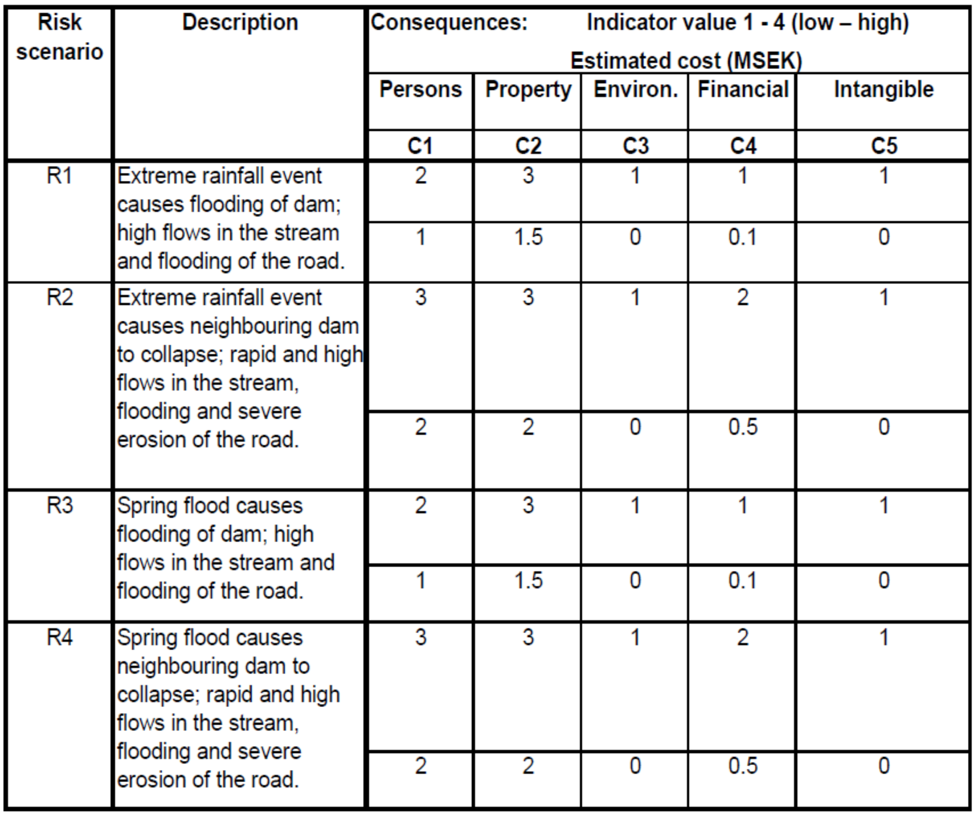
Step 1 determines the possible consequences of climate risks and their related indicators. Step 2 identifies risk sources and vulnerabilities and possible consequence. The objective of Step 3 is to establish risk scenarios, determine the impact of risk, evaluate occurrences and provide a risk overview.

A case study was presented to demonstrate risk scenario and their consequence. As shown in the Figure 4.1, the impact of risk would be determined in relation to the following categories:

- Integrity of people (users and employees) in terms of persons killed or injured;
- Damage to the infrastructure in terms of cost of restoration;
- Operating losses for road managers (revenue, quality of service, image) and for users (loss of time, additional cost of using vehicles);
- Damage to the environment (image and degradation);
- Economic and social consequences for the nation/region/area of influence (impact on modal choices, impact on accessibility of local territories, role of transportation in the global economic system).

Next, the probability or estimated likelihood of risk scenarios is given, Table 4.2. The quantification of the probability is straightforward in RIMAROCC. They use expert judgment to determine the occurrence and consequence.

Table 4.2 Estimated likelihood of risk scenarios in RIMAROCC



Risk scenario	Description	Consequences: Indicator value 1 - 4 (low – high) Estimated cost (MSEK)				
		Persons	Property	Environ.	Financial	Intangible
		C1	C2	C3	C4	C5
R1	Extreme rainfall event causes flooding of dam; high flows in the stream and flooding of the road.	2	3	1	1	1
		1	1.5	0	0.1	0
R2	Extreme rainfall event causes neighbouring dam to collapse; rapid and high flows in the stream, flooding and severe erosion of the road.	3	3	1	2	1
		2	2	0	0.5	0
R3	Spring flood causes flooding of dam; high flows in the stream and flooding of the road.	2	3	1	1	1
		1	1.5	0	0.1	0
R4	Spring flood causes neighbouring dam to collapse; rapid and high flows in the stream, flooding and severe erosion of the road.	3	3	1	2	1
		2	2	0	0.5	0

However, in the field of climate change, probabilities are not available. There is only a small amount of information to determine the actual probability of extreme climate events. Thus RIMAROCC use expert judgment to estimate the likelihood that such an event will appear in the next five, ten or twenty-five years. In practical terms, climate experts today are able to estimate the probability of each climate factor for a specific area. Evolution trends taking climate change into account can be provided from the IPCC report (IPCC, 2013; IPCC 2014), and more precisely from downscaling models. The likelihood of each climate factor in the medium or long run can thus be estimated (RIMAROCC, 2012).

The impact on the road system due to extreme climate events are those that likely exceed the infrastructure design standard. As a result, RIMAROCC considers climate events that exceed the design standards of the road infrastructure. In the case of drainage and hydraulic systems for example, the main occurrences to be taken into account will be 10 or 20 years for the drainage system and 100 years for culverts and bridges. However, the likelihood depends mainly on the intensity of specific climate event under study and the vulnerability of infrastructure depends on the design standards and maintenance situations.

If no objective criteria of likelihood can be used (i.e. if there is no information on the climate event threatening to impact on the road system), RIMAROCC recommended that the evaluation is based on climate change trends. As climate change may induce beneficial effects (e.g. a drop in seasonal rainfall and snowfall), likelihood may be scored as +ive or -ive. However, to simplify the scoring, it is recommended to give a value of “0” for climate factors showing improvements in the future.

The evaluation scale suggested by RIMAROCC is as follows:

- Evolution showing improvement for the climate factor (+ or ++): 0
- Evolution showing deterioration for the climate factor (- or --): from 1 (low) to 4 (critical).

RIMAROCC uses different legends (--, -, +, ++) as a measurement scale. Moreover, the probability of road infrastructure damage might be dependent on the climate event coupled with contextual site factors, such as unstable ground conditions, trees likely to fall down on the road, etc. RIMAROCC proposes to describe this occurrence using a conditional probability: Provided the climatic event has occurred, how likely is it that the contextual site factor will occur? By multiplying the probability of the climatic event and the contextual site factor, we obtain the probability of the risk scenario. However, the contextual site factors are not always explicitly present in the risk models. The contextual site factors and their correlations with the other factors (e.g. technical properties of the assets, its traffic use) which leads to the failure of the road infrastructure can be easily represented by BBNs. This is further discussed in section 4.3 of this report.

A case study in Sweden is presented in RIMAROCC to demonstrate the methodology (Bles et al., 2012). Part of the procedure for calculating the likelihood of specific risk scenarios is extracted from the RIMAROCC report and shown below in Table 4.3. Further information on the case study can be found in RIMAROCC.

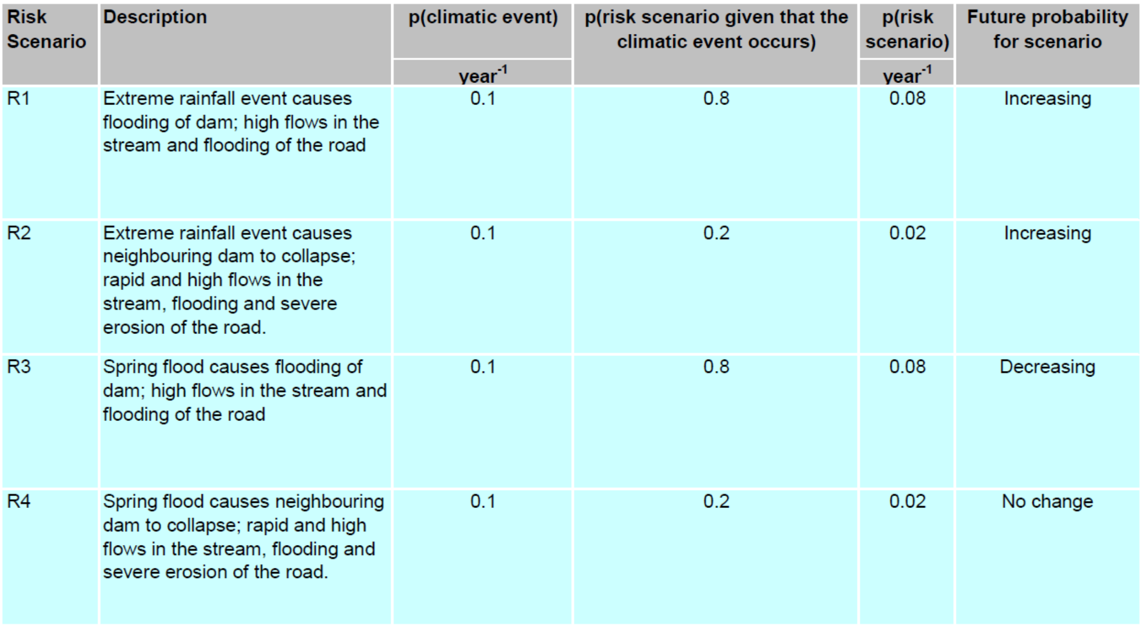
“The frequency of an extreme rainfall event powerful enough to flood the dam is estimated at once every 10 years. Given this event occurrence, the conditional probability of flooding of the road with moderate damage is estimated at $p = 0.8$. By multiplying the frequency of the climate event by the conditional probability, the probability for scenario R1 (0.08) is obtained.

The complementary event for the extreme rainfall event is that the dam collapses; the conditional probability of a dam collapsing and severe erosion is estimated at $p= 0.2$.

Multiplying the frequency of the climate event by the conditional probability results in the probability for scenario R2 (0.02).

The conditional probabilities for the scenarios following an extreme rainfall event is summarised as one."

Table 4.3 case study in RIMAROCC



Risk Scenario	Description	p(climatic event)	p(risk scenario given that the climatic event occurs)	p(risk scenario)	Future probability for scenario
		year^{-1}		year^{-1}	
R1	Extreme rainfall event causes flooding of dam; high flows in the stream and flooding of the road	0.1	0.8	0.08	Increasing
R2	Extreme rainfall event causes neighbouring dam to collapse; rapid and high flows in the stream, flooding and severe erosion of the road.	0.1	0.2	0.02	Increasing
R3	Spring flood causes flooding of dam; high flows in the stream and flooding of the road	0.1	0.8	0.08	Decreasing
R4	Spring flood causes neighbouring dam to collapse; rapid and high flows in the stream, flooding and severe erosion of the road.	0.1	0.2	0.02	No change

4.1.2 WEATHER (Enei et al., 2012)

WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) was an EU funded 7th framework programme project which ran from 2009 to 2012. This project mainly focused on the vulnerability of the transportation sector on climate effects (namely extreme weather events) and the economic costs of climate and extreme weather driven damages to transport.

In Deliverable 2 of WEATHER "the vulnerability of transport systems", (Doll & Sieber ,2011), the researchers focused on the threat caused by weather extremes to the different modes of transport. Damage to the road transport system caused by weather extremes and the wider economic impacts with respect to extreme weather events are investigated in the Deliverable.

In the Deliverable, they introduce the main concept of the systemic risk assessment, illustrated in Figure 4.2. In this figure, risk is a function of exposure and vulnerability. Vulnerability of a network element is defined as its physical sensitivity to extreme events.

Road sector vulnerability towards weather extremes builds on three pillars.

- Impacts on road infrastructures;
- Impacts on transport services and fleet management;
- Impact on users and society, including safety, congestion and delays.

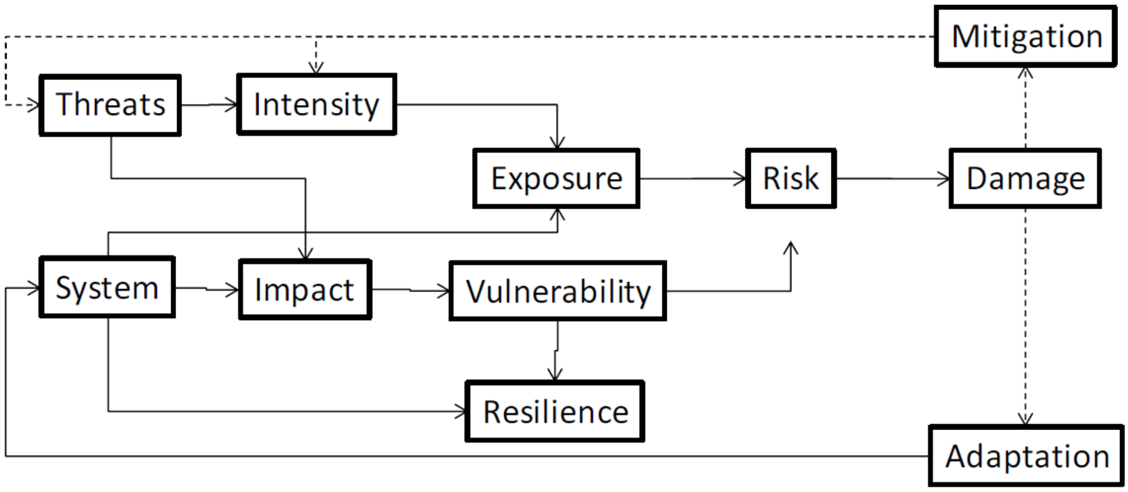


Figure 4.2 Concepts of systemic risk theory

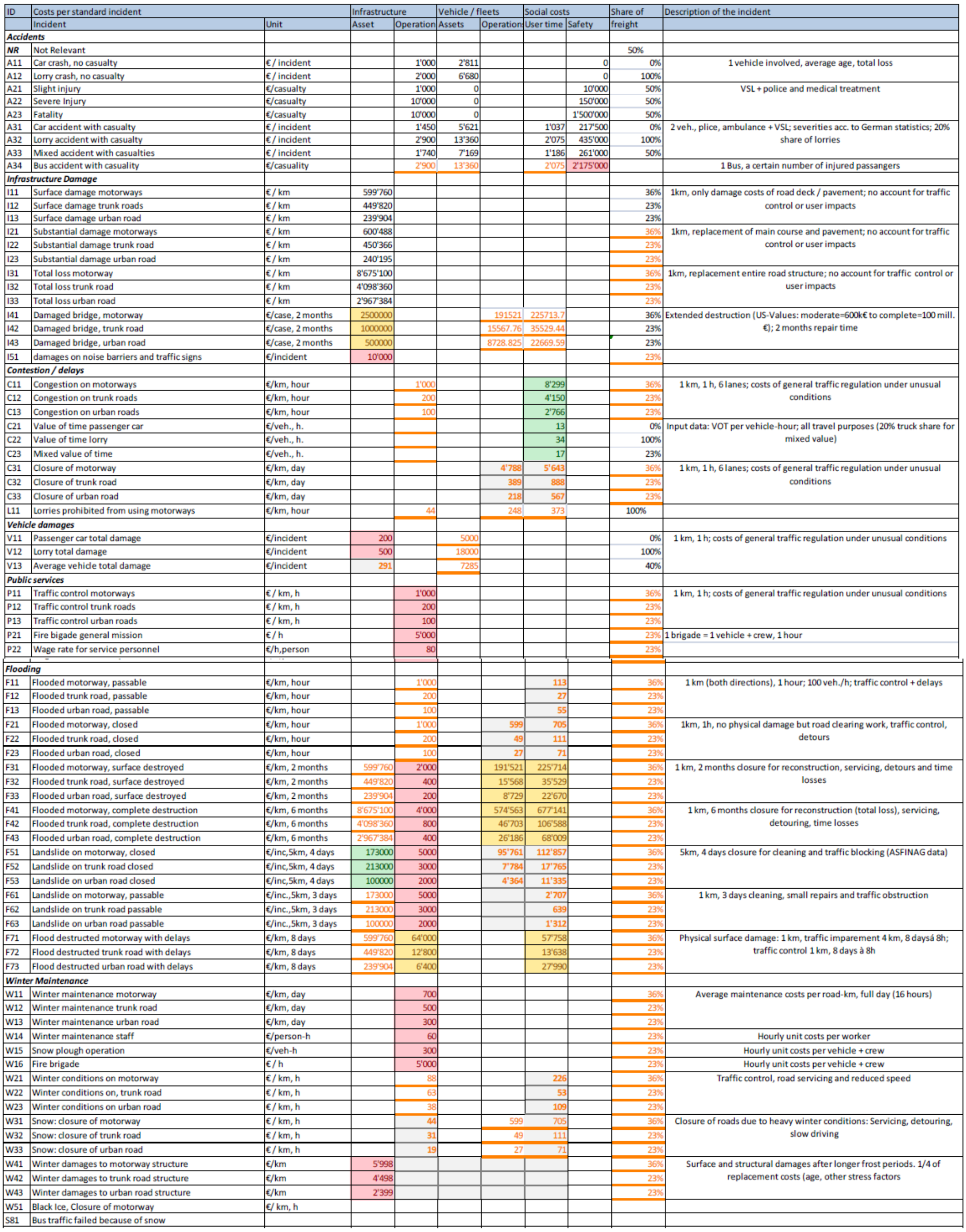
Although the goal of this report does not include the design of a risk assessment tool for transport systems, the information for these three pillars are extensively collected from available statistics, media archives and from transport industries and presented in this report. With a limited amount of data (a problem that is often encountered in quantifying risk model), rich data collected in WEATHER can be very useful for construction of probability /consequence model later in Re-Gen project.

Table 4.4 shows an overall comparison at EU level of the cost assessment of the WEATHER extreme events by transport mode. Table 4.5 provides an overview of the currently used standard incidents and the attached default cost figures. The values within the standard incident table have been set on the basis of extensive literature reviews, transport sector interviews and direct data reports. The mark-ups in the table reflect the data quality (green, yellow and red) or the data source (orange = cross-reference or computed data).

Table 4.4 Generalization of extreme weather events costs for the European transport system (annual data in €m)

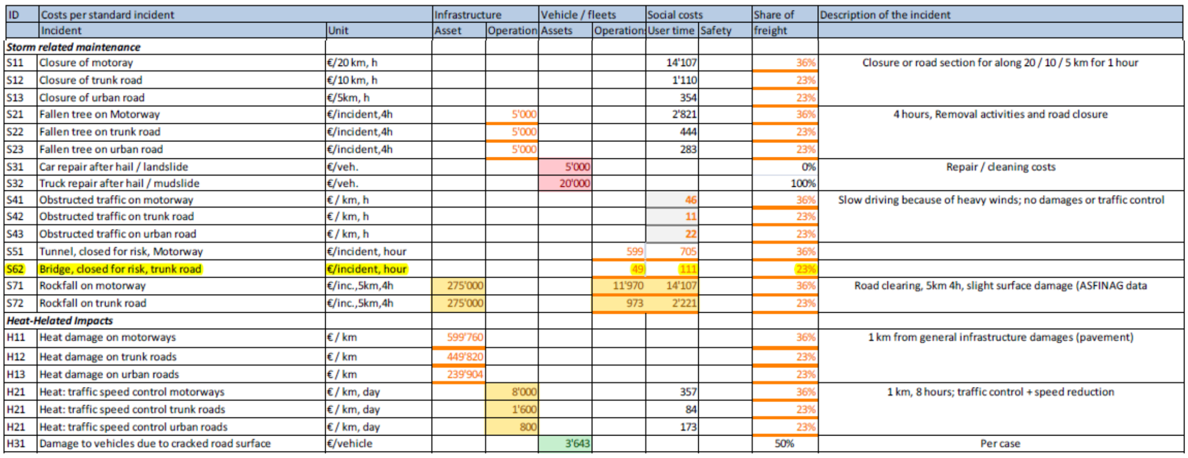
Extreme weather event		Infrastructure Assets (m€)	Infrastructure Operations (m€)	Vehicle Assets (m€)	Vehicle Operations (m€)	User Time (m€)	Health & Life (m€)	Total (m€)
Storm	Road (1)	76,10	22,60	5,10	1,40	63,00	5,90	174,10
	Rail (2)	0,07		12,05		6,28		18,39
	Maritime (5)			2,10	17,98			20,08
	Intermodal (6) (7)	0,53					0,72	1,25
	Air (8)			53,80	34,30	38,40	28,30	154,80
Winter	Road (1)	248,80	126,30	81,30	12,50	125,50	164,90	759,30
	Rail (2) (3)	0,04		3,38		1,60		5,02
	Intermodal (6) (7)	0,21					0,21	0,42
	Air (8)		11,20	12,00	57,70	64,60	1,90	147,40
Flood	Road (1)	630,10	21,90	24,40	30,01	93,70	21,50	821,61
	IWW (4)					4,87		4,87
	Rail (2)	103,66		111,60		67,30		282,55
	Air (8)			3,20	26,50	29,60	0,20	59,50
	Intermodal (6) (7)	0,32					0,10	0,42
Heat&drought	Road (1)						46,90	46,90
Total		1059,82	182,00	308,92	180,39	494,84	270,63	2496,60

Table 4.5 Synthesis of literature findings on delays



ID	Costs per standard incident		Infrastructure		Vehicle / fleets		Social costs		Share of freight	Description of the incident
	Incident	Unit	Asset	Operation	Assets	Operation	User time	Safety		
Accidents										
NR	Not Relevant								50%	
A11	Car crash, no casualty	€ / incident		1'000	2'811			0	0%	1 vehicle involved, average age, total loss
A12	Lorry crash, no casualty	€ / incident		2'000	6'680			0	100%	
A21	Slight injury	€/casualty		1'000	0			10'000	50%	VSL + police and medical treatment
A22	Severe Injury	€/casualty		10'000	0			150'000	50%	
A23	Fatality	€/casualty		10'000	0			1'500'000	50%	
A31	Car accident with casualty	€ / incident		1'450	5'621		1'037	217'500	0%	2 veh., plice, ambulance + VSL; severities acc. to German statistics; 20% share of lorries
A32	Lorry accident with casualty	€ / incident		2'900	13'360		2'075	435'000	100%	
A33	Mixed accident with casualties	€ / incident		1'740	7'169		1'186	261'000	50%	
A34	Bus accident with casuality	€/casuality		2'900	13'360		2'075	2'175'000		1 Bus, a certain number of injured passangers
Infrastructure Damage										
I11	Surface damage motorways	€ / km	599'760						36%	1km, only damage costs of road deck / pavement; no account for traffic control or user impacts
I12	Surface damage trunk roads	€ / km	449'820						23%	
I13	Surface damage urban road	€ / km	239'904						23%	
I21	Substantial damage motorways	€ / km	600'488						36%	1km, replacement of main course and pavement; no account for traffic control or user impacts
I22	Substantial damage trunk road	€ / km	450'366						23%	
I23	Substantial damage urban road	€ / km	240'195						23%	
I31	Total loss motorway	€ / km	8'675'100						36%	1km, replacement entire road structure; no account for traffic control or user impacts
I32	Total loss trunk road	€ / km	4'098'360						23%	
I33	Total loss urban road	€ / km	2'967'384						23%	
I41	Damaged bridge, motorway	€/case, 2 months	2500000			191521	225713.7		36%	Extended destruction (US-Values: moderate=600k€ to complete=100 mill. €); 2 months repair time
I42	Damaged bridge, trunk road	€/case, 2 months	1000000			15567.76	35529.44		23%	
I43	Damaged bridge, urban road	€/case, 2 months	500000			8728.825	22669.59		23%	
I51	damages on noise barriers and traffic signs	€/incident	10'000						23%	
Contestion / delays										
C11	Congestion on motorways	€/km, hour		1'000			8'299		36%	1 km, 1 h, 6 lanes; costs of general traffic regulation under unusual conditions
C12	Congestion on trunk roads	€/km, hour		200			4'150		23%	
C13	Congestion on urban roads	€/km, hour		100			2'766		23%	
C21	Value of time passenger car	€/veh., h.					13		0%	Input data: VOT per vehicle-hour; all travel purposes (20% truck share for mixed value)
C22	Value of time lorry	€/veh., h.					34		100%	
C23	Mixed value of time	€/veh., h.					17		23%	
C31	Closure of motorway	€/km, day				4'788	5'643		36%	1 km, 1 h, 6 lanes; costs of general traffic regulation under unusual conditions
C32	Closure of trunk road	€/km, day				389	888		23%	
C33	Closure of urban road	€/km, day				218	567		23%	
L11	Lorries prohibited from using motorways	€/km, hour		44		248	373		100%	
Vehicle damages										
V11	Passenger car total damage	€/incident	200		5000				0%	1 km, 1 h; costs of general traffic regulation under unusual conditions
V12	Lorry total damage	€/incident	500		18000				100%	
V13	Average vehicle total damage	€/incident	291		7285				40%	
Public services										
P11	Traffic control motorways	€ / km, h		1'000					36%	1 km, 1 h; costs of general traffic regulation under unusual conditions
P12	Traffic control trunk roads	€ / km, h		200					23%	
P13	Traffic control urban roads	€ / km, h		100					23%	
P21	Fire bigade general mission	€ / h		5'000					23%	1 brigade = 1 vehicle + crew, 1 hour
P22	Wage rate for service personnel	€/h,person		80					23%	
Flooding										
F11	Flooded motorway, passable	€/km, hour		1'000			113		36%	1 km (both directions), 1 hour; 100 veh./h; traffic control + delays
F12	Flooded trunk road, passable	€/km, hour		200			27		23%	
F13	Flooded urban road, passable	€/km, hour		100			55		23%	
F21	Flooded motorway, closed	€/km, hour		1'000		599	705		36%	1km, 1h, no physical damage but road clearing work, traffic control, detours
F22	Flooded trunk road, closed	€/km, hour		200		49	111		23%	
F23	Flooded urban road, closed	€/km, hour		100		27	71		23%	
F31	Flooded motorway, surface destroyed	€/km, 2 months	599'760	2'000		191'521	225'714		36%	1 km, 2 months closure for reconstruction, servicing, detours and time losses
F32	Flooded trunk road, surface destroyed	€/km, 2 months	449'820	400		15'568	35'529		23%	
F33	Flooded urban road, surface destroyed	€/km, 2 months	239'904	200		8'729	22'670		23%	
F41	Flooded motorway, complete destruction	€/km, 6 months	8'675'100	4'000		574'563	677'141		36%	1 km, 6 months closure for reconstruction (total loss), servicing, detouring, time losses
F42	Flooded trunk road, complete destruction	€/km, 6 months	4'098'360	800		46'703	106'588		23%	
F43	Flooded urban road, complete destruction	€/km, 6 months	2'967'384	400		26'186	68'009		23%	
F51	Landslide on motorway, closed	€/inc,5km, 4 days	173000	5000		95'761	112'857		36%	5km, 4 days closure for cleaning and traffic blocking (ASFINAG data)
F52	Landslide on trunk road closed	€/inc,5km, 4 days	213000	3000		7'784	17'765		23%	
F53	Landslide on urban road closed	€/inc,5km, 4 days	100000	2000		4'364	11'335		23%	
F61	Landslide on motorway, passable	€/inc.,5km, 3 days	173000	5000			2'707		36%	1 km, 3 days cleaning, small repairs and traffic obstruction
F62	Landslide on trunk road passable	€/inc.,5km, 3 days	213000	3000			639		23%	
F63	Landslide on urban road passable	€/inc.,5km, 3 days	100000	2000			1'312		23%	
F71	Flood destructed motorway with delays	€/km, 8 days	599'760	64'000			57'758		36%	Physical surface damage: 1 km, traffic imparement 4 km, 8 daysá 8h; traffic control 1 km, 8 days à 8h
F72	Flood destructed trunk road with delays	€/km, 8 days	449'820	12'800			13'638		23%	
F73	Flood destructed urban road with delays	€/km, 8 days	239'904	6'400			27'990		23%	
Winter Maintenance										
W11	Winter maintenance motorway	€/km, day		700					36%	Average maintenance costs per road-km, full day (16 hours)
W12	Winter maintenance trunk road	€/km, day		500					23%	
W13	Winter maintenance urban road	€/km, day		300					23%	
W14	Winter maintenance staff	€/person-h		60					23%	Hourly unit costs per worker
W15	Snow plough operation	€/veh-h		300					23%	Hourly unit costs per vehicle + crew
W16	Fire brigade	€ / h		5'000					23%	Hourly unit costs per vehicle + crew
W21	Winter conditions on motorway	€ / km, h		88			226		36%	Traffic control, road servicing and reduced speed
W22	Winter conditions on, trunk road	€ / km, h		63			53		23%	
W23	Winter conditions on urban road	€ / km, h		38			109		23%	
W31	Snow: closure of motorway	€ / km, h		44		599	705		36%	Closure of roads due to heavy winter conditions: Servicing, detouring, slow driving
W32	Snow: closure of trunk road	€ / km, h		31		49	111		23%	
W33	Snow: closure of urban road	€ / km, h		19		27	71		23%	
W41	Winter damages to motorway structure	€/km	5'998						36%	Surface and structural damages after longer frost periods. 1/4 of replacement costs (age, other stress factors
W42	Winter damages to trunk road structure	€/km	4'498						23%	
W43	Winter damages to urban road structure	€/km	2'399						23%	
W51	Black Ice, Closure of motorway	€/ km, h								
S81	Bus traffic failed because of snow									

Table 4.5 Synthesis of literature findings on delays(continued)



ID	Costs per standard incident		Infrastructure		Vehicle / fleets		Social costs		Share of	Description of the incident
	Incident	Unit	Asset	Operation	Assets	Operation	User time	Safety	freight	
Storm related maintenance										
S11	Closure of motoray	€/20 km, h					14'107		36%	Closure or road section for along 20 / 10 / 5 km for 1 hour
S12	Closure of trunk road	€/10 km, h					1'110		23%	
S13	Closure of urban road	€/5km, h					354		23%	
S21	Fallen tree on Motorway	€/incident,4h		5'000			2'821		36%	4 hours, Removal activities and road closure
S22	Fallen tree on trunk road	€/incident,4h		5'000			444		23%	
S23	Fallen tree on urban road	€/incident,4h		5'000			283		23%	
S31	Car repair after hail / landslide	€/veh.			5'000				0%	Repair / cleaning costs
S32	Truck repair after hail / mudslide	€/veh.			20'000				100%	
S41	Obstructed traffic on motorway	€ / km, h					46		36%	Slow driving because of heavy winds; no damages or traffic control
S42	Obstructed traffic on trunk road	€ / km, h					11		23%	
S43	Obstructed traffic on urban road	€ / km, h					22		23%	
S51	Tunnel, closed for risk, Motorway	€/incident, hour				599	705		36%	
S62	Bridge, closed for risk, trunk road	€/incident, hour				49	111		23%	
S71	Rockfall on motorway	€/inc.,5km,4h	275'000			11'970	14'107		36%	Road clearing, 5km 4h, slight surface damage (ASFINAG data
S72	Rockfall on trunk road	€/inc.,5km,4h	275'000			973	2'221		23%	
Heat-Helated Impacts										
H11	Heat damage on motorways	€ / km	599'760						36%	1 km from general infrastructure damages (pavement)
H12	Heat damage on trunk roads	€ / km	449'820						23%	
H13	Heat damage on urban roads	€ / km	239'904						23%	
H21	Heat: traffic speed control motorways	€ / km, day		8'000			357		36%	1 km, 8 hours; traffic control + speed reduction
H21	Heat: traffic speed control trunk roads	€ / km, day		1'600			84		23%	
H21	Heat: traffic speed control urban roads	€ / km, day		800			173		23%	
H31	Damage to vehicles due to cracked road surface	€/vehicle			3'643				50%	Per case

4.1.3 *UK Highways agency climate change risk assessment (UK highways agency, 2009; 2011)*

The U.K. Highways Agency's Climate Change Adaption Strategy and Framework is specifically designed to identify and address climate change risks in highway infrastructure. The Highways Agency's response to the challenge of climate change involves both mitigation (actions to reduce greenhouse gas emissions) and adaptation (changing behaviour so that it is more appropriate to the expected future climate).

In this research, the authority designed a highways agency adaptation framework model. The model provides a seven stage process that identifies their activities which will be affected by a changing climate. In Stage 4 the UK framework utilises risk appraisal to categorise risk associated with each of the vulnerabilities identified in Stage 3. The following paragraphs specifically explain steps 3 & 4 in this methodology.

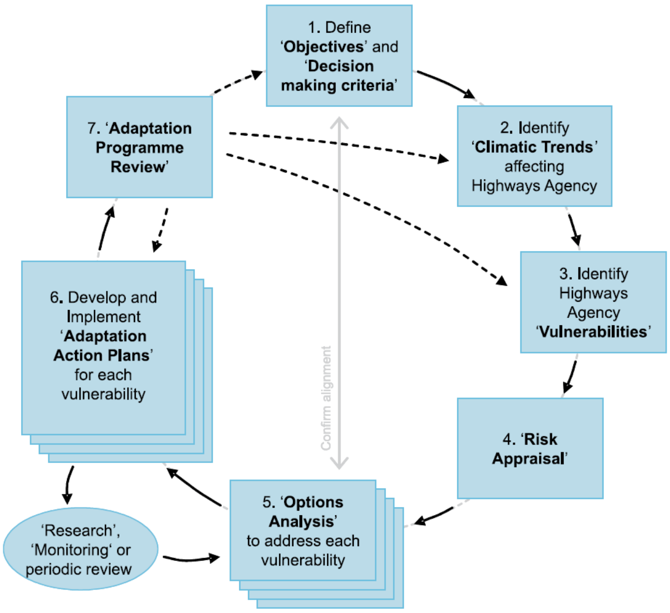


Figure 4.3 Highways Agency adaption framework model (UK highways agency, 2009; 2011)

The first step in completing the vulnerability table is to identify the climate change hazards that may impact on the vulnerable activities. Climate change hazards have been categorised as either primary climatic changes or secondary climatic impacts. The second step is to consider what business activities of the Highways Agency could be affected by climate change. To facilitate the process of identifying vulnerabilities, a vulnerability schedule (Table 4.6) has been produced, which is presented in the form of a matrix (Highways agency's activities affected by climate changes). Within the vulnerability schedule, vulnerabilities have been divided into the categories in Table 4.7, and are further sub-divided into activity-areas for clarity.

Table 4.6 vulnerability schedule

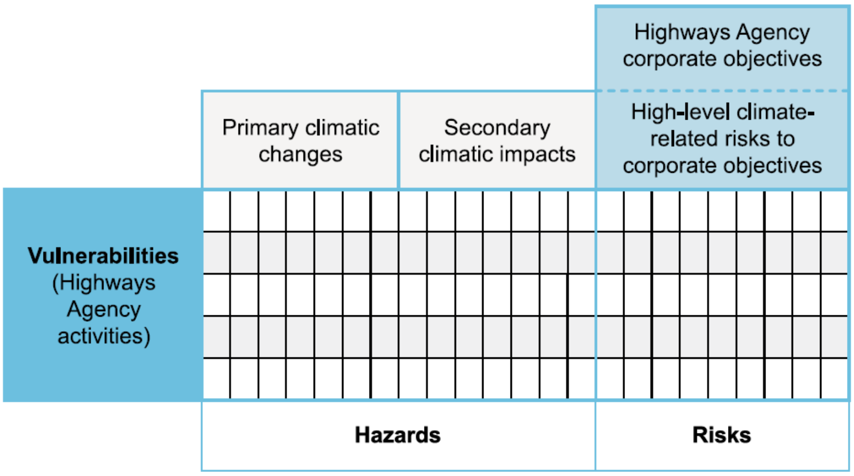
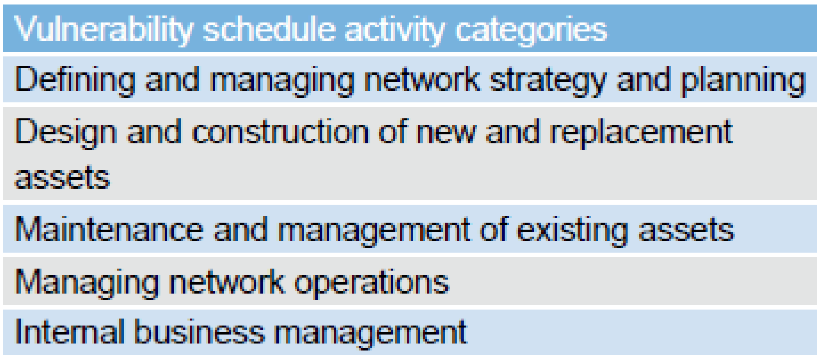


Table 4.7 categorisation of vulnerability schedule activity



Vulnerability schedule activity categories
Defining and managing network strategy and planning
Design and construction of new and replacement assets
Maintenance and management of existing assets
Managing network operations
Internal business management

In the next step, their model uses risk appraisal to categorise the nature of the risk associated with each of the vulnerabilities identified above. It scores the climate change induced risks so that vulnerabilities can be ranked. The primary criteria used to assess vulnerabilities in Highways Agency Report are:

- Uncertainty: A compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity.
- Rate of climate change: A measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity.

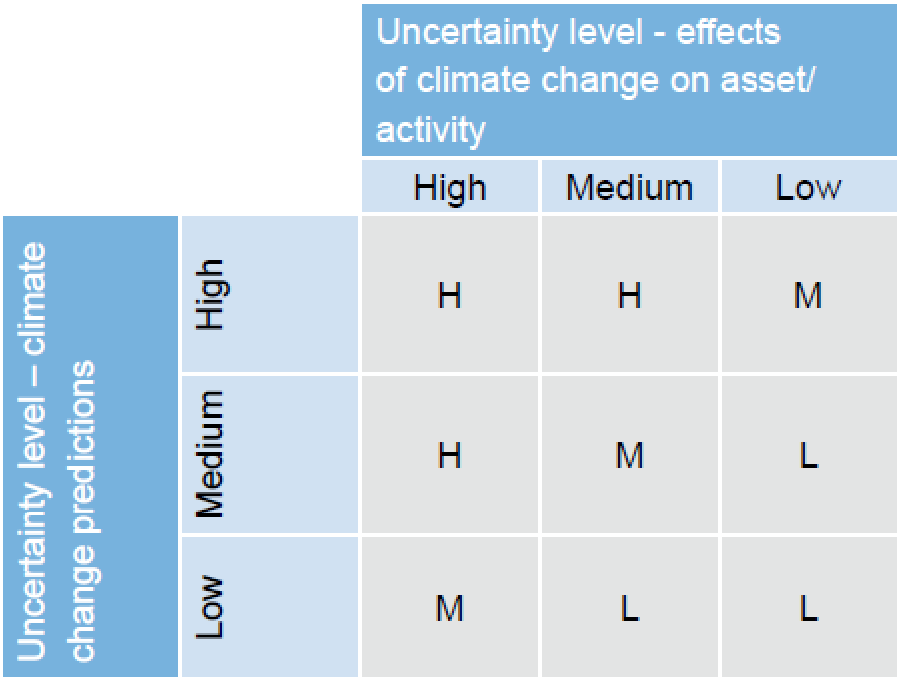
- Extent of disruption: A measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important if it affects a high proportion of the network, or a small number of highly strategic points on the network.
- Severity of disruption: A measure of the recovery time in the event of a climate-related event e.g. flood, or landslip. This is separate from 'how bad' the actual event is when it occurs e.g. how many running lanes you lose; it focuses on how easy/difficult it is to recover from the event i.e. how long it takes to get those running lanes back into use.

The risk appraisal methodology uses multiple criteria, separately and in combination, to prioritise for action. For each vulnerability, a high/medium/low score is assigned against each of the four primary risk appraisal criteria (see Table 4.8-Table 4.11). This is achieved using indicators and reference tables. Scoring is then undertaken based on expert opinion, and necessarily involves some judgement. For instance, scores for uncertainty are determined from uncertainty level of climate change predictions and uncertainty level of effects of climate change on asset/activity. This is similar to the risk matrix that we describe in qualitative risk method in Section 3.1.

The final score generated using the prioritization criteria given in Table 4.12. A score determined for each of the prioritization criteria using the formulae in this table. All these formulae gave a score between 0 and 1.

The risk assessment framework enables the Highways Agency to determine where to focus its adaption plan accordance to climate change.

Table 4.8 Uncertainty matrix



		Uncertainty level - effects of climate change on asset/ activity		
		High	Medium	Low
Uncertainty level – climate change predictions	High	H	H	M
	Medium	H	M	L
	Low	M	L	L

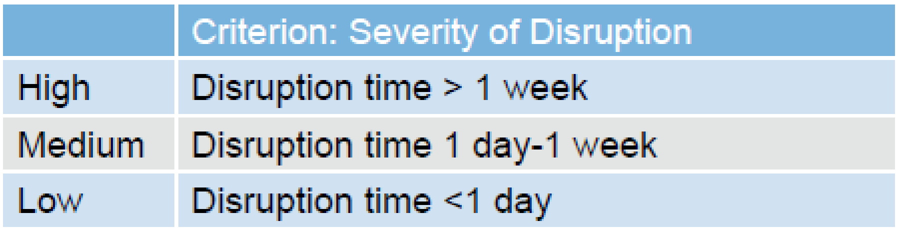
Table 4.9 Rate of climate change matrix

		Asset life / activity time horizon	
		Short term <30 years	Long term >30 years
Time horizon for climate change effects to become material	Short-term (up to 2020)	H	H
	Mid-to-longer term (between 2020 and 2080)	M	H
	Longer-term (beyond 2080)	L	M

Table 4.10 Extent of disruption matrix

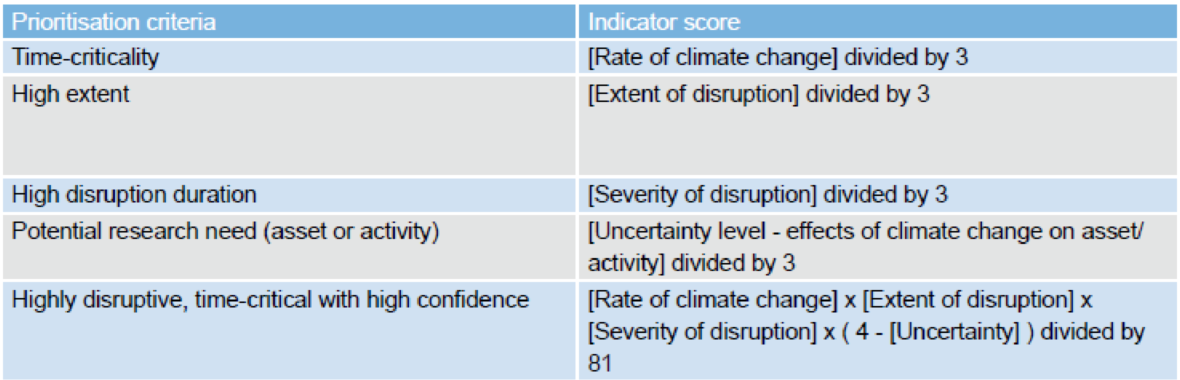
Score	Criterion: Extent of Network Affected
High	>80% of network / users affected, or any specific highly strategic routes/ locations
Medium	20-80% of network / users affected
Low	<20% of network / users affected

Table 4.11 Servility of disruption matrix



	Criterion: Severity of Disruption
High	Disruption time > 1 week
Medium	Disruption time 1 day-1 week
Low	Disruption time <1 day

Table 4.12 Prioritisation criteria and associated indicators



Prioritisation criteria	Indicator score
Time-criticality	[Rate of climate change] divided by 3
High extent	[Extent of disruption] divided by 3
High disruption duration	[Severity of disruption] divided by 3
Potential research need (asset or activity)	[Uncertainty level - effects of climate change on asset/ activity] divided by 3
Highly disruptive, time-critical with high confidence	[Rate of climate change] x [Extent of disruption] x [Severity of disruption] x (4 - [Uncertainty]) divided by 81

4.2 Risk frameworks of road assets under hazards (including long-term traffic growth)

During the service life, different events can occur for a particular structure such as no damage or damage occurrence, maintenance tasks or rehabilitation/repair actions. All these events present a degree of uncertainty (occurrence, quality efficiency…) which allows them to be expressed in terms of probabilities.

This section reviews risk-based approach for road assets failures affected by hazards. Most of the literature reviewed proposes frameworks for the effects of multiple hazards including abnormal traffic loads, similar to the Re-Gen project.

In comparison to the other road assets (e.g. retaining walls & slopes) defined in Re-Gen project, risk-based approaches for bridges are most available in this field. This section thus focuses on the review of a risk-based approach for bridges considering different hazards. However the approach used here can be applied to retaining wall and slopes.

> -Adey et al (2003) design a supply and demand approach to determine the optimal intervention for a bridge subjected to multiple hazards. Bridge failures are not only subject to the structural condition of deterioration with respect to traffic loads. Bridges, however, are affected by multiple hazards, such as flooding and earthquakes. These multiple hazards are considered in the management system when determining the optimal intervention.
>
> A methodology is proposed to determine the risk of inadequate service of a infrastructure:

- Identify hazards that may result in inadequate service;
- Identify failure modes for each hazard;
- Determine limit states equations for each failure mode;
- Estimate probability of the specified levels of inadequate service;
- Determine consequences of the specified levels of inadequate service;
- Estimate risk of having inadequate service;
- Determination of the optimal intervention.

The risk of having inadequate service requires the estimation of the likelihood of inadequate levels of service as well as the consequences of having these inadequate levels of service. This paper presents the methodology to be used when determining the optimal intervention for a bridge affected by abnormal traffic load and flood hazard. The risk-based approach is illustrated using a simple example in which the optimal intervention of two interventions is found.

-Orcesi and Cremona (2011) presents a probability-based approach to optimise maintenance strategies for bridge networks. Most of the bridge management systems are focused on condition features to ensure a minimum safety level. Their location on the road network, the consequences of inadequate service due to maintenance actions are therefore not taken into consideration. These multiple criteria should be considered when scheduling maintenance activities. A supply and demand approach (Adey et al. 2003) is combined with a probability-based formulation of the inspection and maintenance activities (Thoft-Christensen and Sorensen 1987, Madsen et al., 1989, Sorensen 1993) to overcome these limitations. By balancing the probability of occurrence and the optimal maintenance actions solution corresponding to the branch of the maintenance/rehabilitation event tree with the lowest cost, optimal intervention times are determined and optimal actions are identified to reach all the constrains at the end of the planning. The theoretical and numerical developments are applied on a part of the French road network managed by the Road Directorate of the Ministry of Ecology, Sustainable development, Transport and Housing.

-Decò & Frangopol (2011) provides a rational framework for the quantitative risk assessment of highway bridges under multiple hazards. The proposed framework includes the estimation of the effects of multiple hazards including abnormal traffic loads, environmental attacks, scour, and earthquakes. Risk is a crucial indicator to be considered when managing structures of significant importance such as highway bridges. It associates the consequences of a structural failure or malfunction with the probability of bridge failure. Time-dependent total risk, as an indicator of the life-cycle performance and as an estimation of the consequences of potential failures, has been calculated. The effects in terms of failure probabilities and occurrence of consequences of most common hazards (abnormal traffic loads, environmental attacks, scour, and earthquakes) are investigated.

Moreover, structural redundancy has been modelled and implemented by introducing a risk modifier coefficient. A high level of system redundancy corresponds to high possibilities of providing warnings of partial or complete failure. The risk modifier coefficient reduces and increases risk for redundant and non-redundant structures. These assessments contribute to the evaluation of risk considering the traffic flow and the local economy at the bridge location.

Considering the failure probabilities caused by long term traffic growth, the equations formulated in the previous mentioned literature (particularly in Adey et al. 2003 and Decò & Frangopol 2011) are very useful for Re-Gen project. The equations are associated with a specific limit state varies with respect to time due to the increasing live load effects by the growing demand of increasing traffic volume.

Moreover, considering the risk optimization of a road network, the context of supply and demand approach described in previous literature consists of balancing management costs (network supply) with users' costs induced by diversions and congestions in case of structural failures or weather hazard. These approaches are particularly well suited for providing an efficient answer to the users' demand and will be used herein as a reference for the formulation of the risk optimization of road network when several criteria have to be considered in Re-Gen project.

5 Conclusions

The objective of Re-Gen is to provide Road Owners/Managers with best practice tools and methodologies for risk assessment of critical infrastructure elements, such as bridges, slopes, and retaining walls. As one of the goals is to prioritise critical infrastructure for maintenance and repair, the structural failure defined in this report is an infrastructure that no longer performs, in the permanent state, its intended function or the failure of a component is expected to result in the complete failure of the infrastructure. Structural failures include: 1) complete failure in permanent state and 2) critical defect. This can be caused by weather, traffic growth and infrastructure management failures (e.g. assets inspection, assets design). This report also suggests the definition of failure in Re-Gen project to cover functional failures such as failures caused by traffic jam due to extreme weather conditions.

Possible risk frameworks are reviewed in Chapter 3 and Chapter 4. Chapter 3 reviews the qualitative and quantitative risk assessment model in the safety science domain. Chapter 4 reviews the risk framework for roads regarding the changing climate and long term traffic growth. Major international reports are reviewed in these chapters.

The Literature review related to climate change shows most of the risk frameworks are primarily qualitative or semi-quantitative. They often rank the risks on an ordinal scale and present the various levels of risk using risk matrix as a risk assessment tool. Methods such as fault tree (FT) and event tree (ET) analysis are core methods of quantitative risk assessment. This method is particularly good to determine the causes leading to a failure in the road system. However, when the system grows larger and the system has common cause failures and there are interdependencies among the system elements, standard fault tree are not very suitable for analysing such systems. In this case, BBNs are useful tools in making inferences about uncertain states when limited information is available. The method of CATS project which was modelled with BBNs (reviewed in section 3.2.2.1) can be useful to model failures for road infrastructure failures.

Chapter 4 reviews risk-based approach for road asset failure affected by natural hazard and abnormal traffic load. Considering the failure probabilities caused by long term traffic growth, the limit state equations formulated in the literature (particularly in Adey et al. 2003 and Decò & Frangopol 2011) are very useful for Re-Gen project.

In summary, if data is available, this report suggests using quantitative risk assessment tools (e.g. fault tree or BBNs) to model risk of road infrastructure in respect of climate change and long term traffic growth. The sources listed in Chapter 3 and Chapter 4 can be used as a reference for quantifying part of the fault tree model or BBNs model proposed in this deliverable. If the historical data is not available, structured expert judgment (Cooke, 1991; Cooke & Goossens, 2000; 2008) can be used to quantify this model.This gives us the opportunities to quantify for road assets failures in condition to traffic growths and weather conditions if no historical data is available.

6 Acknowledgement

The research presented in this report/paper/deliverable was carried out as part of the CEDR Transnational Road Research Programme Call 2013. The funding for the research was provided by the national road administrations of Denmark, Germany, Ireland, Netherlands UK and Slovenia.

7 References

Adey, B., Hajdin, R., Brühwiler, E.(2003), Risk-based approach to the determination of optimal interventions for bridges affected by multiple hazards, Journal of Engineering structures, Volume 25, Issue 7, Pages 903-912.

A. L. C. and Smith, E. (2006). "Towards a causal model for air transport safety – an ongoing research project,." SAFETY SCIENCE 44(8): 657-673.

AIChE (2000). Guidelines for chemical process quantitative risk analysis, 2nd edition, New York, USA.

Ale, B. J. M., Bellamy, L. J., Cooke, R. M., Kurowicka, D., Lin, P. H., Morales, O., Roelen, A. L. C. and Spouge, J. (2009). Causal Model for Air Transport Safety (final report). Den Haag, Netherlands, Ministerie van Verkeer en Waterstaat

American Association of State Highway and Transportation Officials (AASHTO) (2008). AASHTO LRFD Bridge Design Specifications, 4th Edition with 2008 Interims, Washington, D.C.

Bellamy, L. J., Papazoglou, I. A., Hale, A. R., Aneziris, O. N., Ale, B. J. M., Morris, M. I. and Oh, J. I. H. (1999). Developmenet of an integrated technical and managmeent risk control and moniitoring methdology for managing and quantifying on-site and off-site risks, I-Risk main report. EU Contruct number ENVA CT96-0243, Ministry of Social Affairs and Employment, Den Haag. Den Haag Ministry of Social Affairs and Employment.

Bengtsson, J. and Tómasson, B., (2008). Vulnerability and risk analysis of the road infrastructure in Reykjavik, Project Number VR7RA, Vegagerðin, Island.

Bles, T, Ennesser, Y, Fadeuilhe, J, Falemo, S, Lind, B, Mens, M, Ray, M., Sandersen, F (2012). Risk Management for Roads in a Changing Climate (RIMAROCC), Deltares report 1205568-000-GEO-0007, Version 2.

Bos, J.M.J. (2001). Door weer en wind, Gevolgen van perioden met extreem weer voor de verkeersveiligheid, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV, R-2001-23, Leidschendam.

Chatterton, J., Viavattene, C., Morris, J., Penning-Rowsell, E., Tapsell, S. (2010). The costs of the summer 2007 floods in England, Department for Environment, Project: SC070039/R1.

Chemical Industries Association (CIA), (1977). A guide to hazard and operability studies, Alembic House, London.

Cooke, R. M. (1991). Experts in Uncertainty: opinion and subjective probability in science, New York: Oxford University Press.

Cooke, R. M. and Goossens, L. H. J. (2000). Procedures guide for structured expert judgment. Technical Report EUR 18820. Brussels, Belgium, European Commission.

Cooke, R. M. and Goossens, L. H. J. (2008). "TU Delft expert judgment data base." Reliability Engineering & System Safety 93(5): 657-674

Cypra, T. (2006). Optimierung des Winterdienstes auf hoch belasteten Autobahnen, Berichte der Bast, Verkehrstechnik Heft V135.

Daniels, J.H., Ressler, S.J., Fisher, J.W. (1991). "Vulnerability Assessment and Ranking of Steel Bridges," Transportation Research Record 1290, Transportation Research Board, National Research Council, Washington, D.C. pg 16-24.

Decò, A. and Frangopol, DM., (2011). Risk assessment of highway bridges under multiple hazards, Journal of Risk Research, 2011

Doll, C. and N. Sieber (2011): Vulnerability Assessment for Road Transport. Contribution to Deliverable 2: Transport Sector Vulnerabilities within the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework program of the European Commission. Project co-ordinator: Fraunhofer-ISI. Karlsruhe, 30.9.2010

DVR (2000). Wind und Wetter. Wie das Wetter auf den Menschen wirkt. DVR-Report 2000, nr. 4. p. 8-11. Deutscher Verkehrssicherheitsrat e. V., Bonn.

Enei, R., Doll, C., Klug, S., Partzsch, I., Sedlacek, N., Nesterova, N., Kiel, J., Rudzikaite, L., Papanikolaou, A., Mitsakis, V., (2012). Weather Extremes: Impacts on Transport Systems and Hazards for European Regions (WEATHER), European 7th RTD Framework Programme 2012 (http://www.weather-project.eu/weather/index.php)

Hellman, F., Knud, A. P., Hansson, K., (2010). Inspection and Maintenance guide for reducing vulnerability due to flooding of roads, Report 4 May 2010, Danish Road Institute, Swedish National Road and Transport Research Institute, SWAMP, Storm Water prevention – Methods to Predict damages from water stream in and near road pavements in lowland areas, Project Nr. TR80A 2008- 72545.

IPCC (2013) *Climate Change 2013 - The Physical Science Basis, contribution to AR5.*

IPCC (2014) Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/

Jensen, F. V. (1996). An introduction to Bayesian networks. Springer

Jensen, F. V. (2001). Bayesian networks and decision graphs. Springer

LeBeau, K.H. and Wadia-Fascetti, S.J. (2007). "Fault Tree Analysis of Schoharie Creek Bridge Collapse," Journal of Performance of Constructed Facilities, Vol. 21, No. 4, pg. 320-326.

Lacoste, C., Corfdir, P., Neiers, S., Aubagnac., C., Delahaye, E., Paillusseau, P. (2012) Application of risk analysis for the preservation of post-tensioned girder bridge decks, Bridge Maintenance, Safety, Management, Resilience and Sustainability – Biondini & Frangopol (Eds), Taylor & Francis Group, London, ISBN 978-0-415-62124-3

Lin, P.H. (2011). Safety Management and Risk Modelling in Aviation, Delft, Netherlands, ISBN: 9789079787326 (doctoral thesis).

Madsen, H.O., Sorensen, J.D., and Olesen, R., (1989). Optimal intervention planning for fatigue damage of offshore structures. In: Proceedings of ICOSSAR 89, San Francisco, 2099-2106.

NASA (2002). Fault Tree Handbook with Aerospace Applications, NASA Office of Safety and Mission Assurance NASA Headquarters Washington, DC 20546.

Orcesi, AD, Cremona, CF (2011), Optimal maintenance strategies for bridge networks using the supply and demand approach, Journal of Structure and Infrastructure Engineering, Vol. 7, No. 10, October 2011, page 765–781.

Papazoglou, I.A., Ale, B.J.M., (2007) Logical Model for Quantification of Occupational Risk, Reliability Engineering & System Safety, Volume 92, Issue 6, June 2007, Pages 785-803.

P.H. Lin, A.R. Hale, C. van Gulijk (2013). A paired comparison approach to improve the quantification of management influences in air transportation, recommend to be accepted after minor revision, Journal of Reliability Engineering & System Safety 113(1).

Saarelainen, S. (2006). Adaptation to climate change in the transport sector. FINADAPT. Working Paper 8, Finnish Environment Institute Mimeographs 338, Helsinki.

Sabir, M., van Ommeren, J., Koetse, M., Rietveld, P., (2008). Welfare Effects Of Adverse

SETRA (1996). IQOA: Quality image of structures, (in french), SETRA press, Bagneux, France.

Stanić, N., Langeveld, J., Clemens, F., (2014). HAZard and OPerability (HAZOP) analysis for identification of information requirements for sewer asset management, Journal of Structure and Infrastructure Engineering, Vol. 10, No. 11, 1345–1356.

Weather Through Speed Changes In Car Commuting Trips, VU University, Department of Spatial Economics, Amsterdam, the Netherlands.

Sorensen, J.D., (1993). Reliability-based intervention planning for structural systems. Reliability and Optimisation of Structural Systems, B-12, 31–46.

Stiers, T. (2005). Studie van de impact van weercondities op de verkeersveiligheid op uurniveau. Limburgs Universitair Centrum, Faculteit Toegepaste Economische Wetenschappen, Leuven.

Swain, A. D. and Guttmann, H. E. (1983). A handbook of human reliability analysis with emphasis on nuclear power plant applications. NUREG/CR-1278, Sandia National Laboratories, Albuquerque, NM.

Thoft-Christensen, P. and Sorensen, J.D., (1987). Optimal strategies for intervention and repair of structural systems. Journal of Civil Engineering Systems, 4, 94–100.

US Federal Highway Administration (2011), Framework for improving resilience of bridge design, Publication No. FHWA-IF-11-016.

UK Highways Agency (2011), Highways Agency Climate Change Risk Assessment.

UK Highways Agency (2009), Climate change adaptation strategy and framework.

U.S. Department of Transportation Design (2011). Framework for Improving Resilience of Bridge Design, Publication No. FHWA-IF-11-016.

Wall, T. and Meyer, M.,(2013). Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector, Transportation research board of the national academies.

Watson HA, (1961). Launch control safety study, Bell Telephone Laboratories, Murray Hill, NJ, USA.