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Progress Report on Probability and Consequence Models for Road Infrastructure Element Failure

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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

Progress Report on Probability and Consequence Models for Road Infrastructure Element Failure

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

PEB Project Manager: Tom Casey, NRA, Ireland

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Executive summary

This report is a precursor to the Deliverable D4.2- Report on Risk Optimization in Road Networks. Deliverable D4.2 contains 4 tasks, as shown in Figure 1. This report describes the work performed so far for the first 2 tasks--the probability models and consequence models.

Figure 1: D4.2 Tasks

The first part of the report elaborates the probability models which were recommended in the Deliverable D4.1 in order to calculate the probability of an infrastructure failure. The second part of the report addresses the consequence models of road infrastructure failure. Consequence models are derived after an intensive review of the literature on economic models. Direct consequences of infrastructure failure and indirect consequences due to infrastructure failure are taken into account in these consequence models.

1 Introduction

The Re-Gen objective is to provide Road Owners/Managers with best practice tools and methodologies for risk assessment of critical infrastructure elements, such as bridges, retaining structures and steep embankments, considering the effects of climate change and increased traffic and loads.

To achieve these, one of the objectives in Re-Gen is to develop a risk based methodology for risk assessment. In Deliverable D4.1, risk is defined as probability of failures x consequences, therefore, models both for the failure probability of infrastructure as well as the consequences of the infrastructure failures will be investigated in D4.2 to formulate and optimise risk in the Re-Gen project.

2 Probability models of road infrastructure failure

Probability models recommended from Deliverable D4.1 are taken into account in Deliverable D4.2, and further elaborated in order to calculate the probability of an infrastructure failure.

2.1 Probability model using fault trees

For the probability model, in Deliverable D4.1 it concludes that quantitative risk assessment tools (e.g. fault tree (FT) or Bayesian Belief Networks (BBNs)) are most suitable for quantifying the risk model for road infrastructure failures. Currently in D4.2 we use the FT approach to model and quantify the probability model for Re-Gen project, because this is the most widely used quantitative technique for assessing the probability of system failure in industry. Equally this method is particularly good for determining the causes leading to a failure in the road system, which fits the need for task 4.2. Currently WP4 focuses on developing probability model using FT and WP4 also works together with WP5 to model and calculate the probability of global failure using this approach. If the FT approach cannot cope with the goals that WP4 is trying to reach, then we will use BBN approach as a more complicated approach than FT.

In WP4, the FT approach provides the system probability of failure as a function of all component probabilities. For the component probability, a logistic regression-analysis based on empirical data with covariates (such as age of the road section, maintenance level, traffic intensity, climate stress level etc) is suggested in Equation 1;

$$log\frac{P_i}{1-P_i} = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \quad \text{(Equation 1)}$$

In this model, the regression coefficients can be estimated from the literature or using actual data from road authorities. Currently, we are attempting to gather this data. In the final D4.2 report, recommendations will be provided on the type of data which should be collected for these models. .

3 Consequence models of road infrastructure failure

In Task 4.33, economic models are investigated and derived to model the consequences of infrastructure failure considering the direct cost of rebuilding the infrastructure and the indirect cost of infrastructure failures that affect the operation, possible loss of human life, and impact on surrounding area (i.e. damage to the quality of the environment).

3.1 Consequence models

The consequences of road infrastructure failures must be estimated to evaluate the risk of different infrastructure failures and therefore, to determine the optimal intervention.

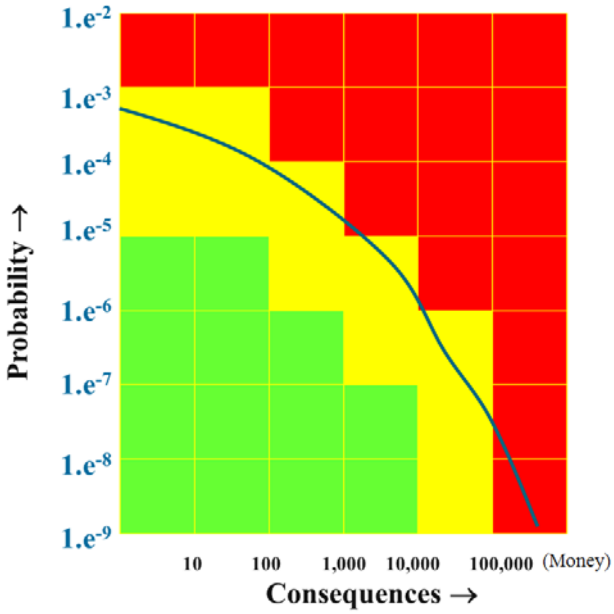
Risk =probability of failures x consequences (Equation 2)

Probability of failures and consequences can be scored quantitatively (using probability distributions or data analysis), or qualitatively (semi-quantitatively). Table 1 and Table 2 show examples of these differences between presentation of various levels of risk/consequence and calculation of risk/consequence. Table 1 shows how risk can be evaluated qualitatively or semi-quantitatively. Consequence is ranked on an ordinal scale with discrete negligible - very serious consequences. Table 2 shows a more complex formulation with consequence calculation in monetary terms. Both semi-quantitative consequence models and quantitative consequence models (described in monetary terms) have been investigated and will be discussed in separate sections in the final version of D4.2.

Table 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 2 Risk matrix (2)



3.2 Consequence model (semi-quantitative)

The literature on consequence models using a semi-quantitative approach for infrastructure failures has been investigated. The evaluation of consequences of a bridge failure can be characterized in terms of serviceability and structure safety and the relevant issues, chosen from the literature (Lacoste., et al., 2012), can be summarised as follows:

a) the importance of the route;

b) the traffic volume;
c) the economical bridge value;
d) the consequences of a service restriction.

The first criteria (a) is the strategic value of the route based on a prioritization of the national road network as follows; very strategic routes (A = 4), strategic routes (A = 2 or 3), and other routes (A = 1). The strategic value of the route is determined by the bridge manager considering the motorways or urban issues, the routes serving a strategic site (e.g. power plant, hospital etc.). The strategic value of the route can be increased by 1 to reflect the local environment, such as, a bridge crossing a high speed track).

Criterion (b) considers traffic volumes (Average Annual Daily Traffic – AADT) over the bridge. Criterion (c) represents the costs of reconstruction or repairs of the bridge. Criterion (D) characterizes the potential impact on the level of service during repairs or replacement. The scales of measurement for different criteria will be discussed in the final version of D4.2.

3.3 Consequence model (monetary term)

The consequence of road infrastructure failures includes the direct cost of rebuilding the infrastructure and the indirect cost of infrastructure failures that affect the operation, possible loss of human life, reputation, and the impact on the surrounding area in terms of damage to the quality of the environment.

The literature on consequence models quantifying in monetary term have been investigated. In Section 3.3.1 direct costs of rebuilding the infrastructure are briefly discussed, followed by indirect costs of infrastructure failures in Section 3.3.2.

3.3.1 Costs for direct consequences

- Cost of Rebuilding a structure can be calculated to the cost of the bridge per square meter of deck surface, Equation 3:

$$C_{Reb}(t) = C_{Reb} * W * L * (1 + r)^t \qquad \text{(Equation 3)}$$

where $c_{Reb}$is the rebuilding cost per square meter (euro/m^2) , W is the bridge width(m), and L represents the bridge length (m). (Deco and Frangopol, 2011)

Further discussion on the parameters and discussion on data collection will be given in the final version of D4.2

3.3.2 Costs for indirect consequences [1]

Several aspects of indirect costs are considered in this section: vehicle operating costs, travel time costs, and accident costs. Each of the equations are given in this milestone. More detail discussions will be given in the final version of D4.2.

-Vehicle operating costs:

Vehicle operating costs can be approximated by calculating the detour that users are forced to follow when the bridge is closed/partially closed. This is based on the duration of the detour (days/months) and the length of the detour that users are forced to follow.

A general approach can be described as follows;

$$C_{Run}(t) = C_{Run} * D_{l*} * A(t) * d * (1+r)^t \qquad \text{(Equation 4)}$$

c_{Run} is the average running cost per kilometre (euro/km),
D_l is the detour length(km),
A(t) is the average daily traffic on year t
d is the duration of the detour (days/months), more serious weather impact causes longer duration on the restoration of the infrastructure
r= the annual discount rate of money

Deco and Frangopol (2011) estimate the duration of the detour by considering the implication of economic loss. They assume that if the economic loss is high the repair time is shorter. The time needed to restore the bridge functionality suggested in their paper is assumed to be: 36 months for ADT (average daily traffic) < 100; 24 months for 100 < ADT < 500; 18 months for 500 < ADT < 1,000; 12 months for 1,000 < ADT < 5,000; and 6 months for ADT > 5,000. Given that the ADT is increasing over time, costs are expected to grow over time.

-Travel time costs

Traveling time loss is calculated as cost for users and goods traveling through the detour (based on Stein et al. 1999).

$$C_{travel\ cost}(t) = [C_{AW} * O_{Car} * \left(1-\frac{T}{100}\right) + (C_{ATC} * O_{truck} + c_{goods}) * \left(1-\frac{T}{100}\right)] * [D * A * d]/S * (1+r)^t \qquad \text{(Equation 5)}$$

c_{AW} is the average wage per hour (euro/h),
c_{ATC} is the average total compensation per hour (euro/h),
c_{goods} is the time value of the goods transported in a cargo (euro/h),
O_{car} and O_{truck} are the average vehicle occupancies for cars and trucks, respectively,
S represents the average detour speed (km/h).

-Accident costs

[1] Deco and Frangopol (2011)
Zhu and Frangopol, (2013)
Adey et al., (2003)
Deco and Frangopol, (2013)
Stein et al. (1999)

Consequences evaluated from the previous aspects are only related to commercial losses. However, infrastructure failure due to the extreme weather events and traffic loads may also cause losses, such as human life and environment damage.

To assess accident costs, two paper are cited (Zhu and Frangopol, 2013 & Orcesi and Cremona, 2011):

The French technical guidelines give the value of human life as 1 million euros (Orcesi and Cremona, 2011). Serious and slight injuries are expressed as a percentage of the human life cost: 15% and 2%, respectively (150,000euro and 22,000euro). Orcesi and Cremona (2011) indicate that the accident costs can be found for each route by applying the related accident rate. In Zhu and Frangopol (2013), the safety losses can be estimated by the number of casualties in the bridge failure accident and the implied cost of averting a fatality for bridge engineering (ICAFB). The value of the ICAFB cited in their paper is 2.6 million euros.

The values of the life can be very different in countries. There is now extensive literature on the value of life, which should not be interpreted as the value of any one particular life, but instead, of society's value of saving a "statistical" life. The value of a statistical life (VSL) is the amount of money a person or society is willing to spend to save a life. Understanding the value of life is essential an issue for authorities who make policy. This issue will also be discussed in the final report of D4.2.

4 Risk of infrastructure failure

The risk of infrastructure failure is calculated as the probability of each failure multiplied by the consequence of each specified failure.

Risk of failure= probability of infrastructure failure (calculated from FT) x $[c_{Reb} + C_{Run} + C_{travel\ cost} + C_{accident\ cost}]$ (Equation 6)

5 Conclusions

This report gives a short overview on tasks accomplished so far on probability models and consequence models, a precursor to the Deliverable D4.2 (report on risk optimization in road networks). As risk is defined as probability of failures x consequences, research is being done for these two aspects to evaluate the risk of infrastructure failures. This yields the conclusion that the Milestone M4.1 was successfully completed.

6 Acknowledgement

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