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Pre-Standardisation Document for Advanced Risk Assessment of Railway Infrastructure
Deliverable 1.2

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1 Glossary of Terms

P_f - Failure Probability, defines the probability of a certain limit state being exceeded.

β - Reliability Index, provides a quantitative measure of the reliability of an object with respect to a particular limit state.

β^* - provides a simplified qualitative indicator of risk in the absence of advanced risk assessment.

V_F - Variation Factor, factors used to take account of site-specific influences for which insufficient information is available be incorporated in a detailed quantitative reliability analysis.

C_F - Consequence Factor, factors used to take account of the various consequences of infrastructure failure.

Hazard - dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009).

Consequence - outcome of an event affecting objectives (ISO, 2009).

Risk - The combination of the consequences of an event or hazard and the associated likelihood of its occurrence (ISO, 2009).

2 Introduction

The GoSAFE Rail project will be transformative for asset safety in the rail sector. It will bring together inter-disciplinary experts from risk based asset assessment of infrastructure, Artificial Intelligence, object detection and data management sectors with leaders in network micro-simulation modelling to deliver a Decision Support Tool that will allow a step change for railway infrastructure safety.

This report describes a simplified hazard-based risk assessment procedure which has been developed as part of the GoSAFE Rail project.

The main reasons for evaluation of the safety and serviceability of an existing railway infrastructure include, amongst others:

- changes of use or increase of loads;
- effects of deterioration;
- an extension of the design working life;
- damages as a result of extreme loading events or accidental actions;
- potential damage due to periods of extreme weather
- concern about possible design/construction error or the quality of building materials and workmanship;

In the context of this report, railway infrastructure is assumed to consist of three separate types of structures: bridges, slopes and tunnels. The traditional metric for risk quantification is defined as:

$$Risk = Probability\ of\ Failure\ \times Consequence \quad (1)$$

The formulation of equation 1 can be useful for smaller networks or individual infrastructure elements. This procedure will be applied, developed and exemplified with a case study in GoSAFE Rail Work Package 3. In order to provide an indication of high-risk areas (hotspots) a precursor to advanced risk assessment will be discussed in this deliverable. This procedure provides a simplified qualitative "risk indicator" for infrastructure assets in a coordinated manner without directly quantifying either the probability or the consequences of failure.

For infrastructure objects (bridges, slopes and tunnels) the framework for calculation of this simplified "risk indicator" is defined as shown in Figure 1.

Figure 1: Flowchart

$$\beta^* \propto \beta \times V_F \times CF \quad (2)$$

The β^* value in equation 2 will form the simplified "risk metric" for this framework. While this is not a direct calculation of risk, it provides a crude indication of hotspots which may subsequently be considered in an advanced quantitative risk assessment.

In order to calculate the reliability index (β), a probabilistic approach is required. All data required for stochastic modelling should be acquired based on available data, testing and remote monitoring.

For the various infrastructure objects, a number of "variation factors" (V_F) are approximated and applied. These factors are used to take account of site-specific influences. The calibration of these factors will vary depending on the Infrastructure Manager / assessor's perception of risk

"Consequence factors" (C_F) should also be approximated based on site-specific conditions such as amount of rail traffic, type of rail traffic, location of the asset etc. These factors are used move from a purely hazard-based analysis to one which gives some consideration of the relevant consequences for the infrastructure.

In determining the β^*-value, both the variation factors (V_F) and consequence factors (C_F) should be less than 1.0.

3 Reliability analysis

In traditional design practice, the safety of infrastructure is often evaluated using deterministic approaches, neglecting the site-specific variability and uncertainty of both load and resistance. The advanced assessment procedure developed as part of GoSAFE Rail for risk assessment of a rail infrastructure requires the application of probabilistic approaches. In order to do this, the variability and uncertainty of material properties, asset geometry and condition, as well as the loads acting on the asset must be modelled. There are various models available to represent these parameters as random variables (e.g. normal distribution, lognormal distribution etc.). DESTination Rail Deliverable 2.1 provides a detailed review of this type of stochastic modelling.

Reliability-based structural analysis provides the probability of infrastructure failure (P_f) by considering the likelihood that any particular limit state has been reached. This can be based upon individual element failure, structural failure or network failure by application of system analysis. Limit states for probability-based infrastructure failure analysis are generally divided into Ultimate Limit States, Serviceability Limit States and Fatigue Limit States. Reliability is measured in the current framework by the reliability index (β):

$$\beta = -\Phi^{-1}(P_f) \qquad (3)$$

Where $\Phi^{-1}()$ is the standard normal inverse function.

The failure region of a particular limit state is illustrated in Figure 2 (Krejsa et al., 2013).

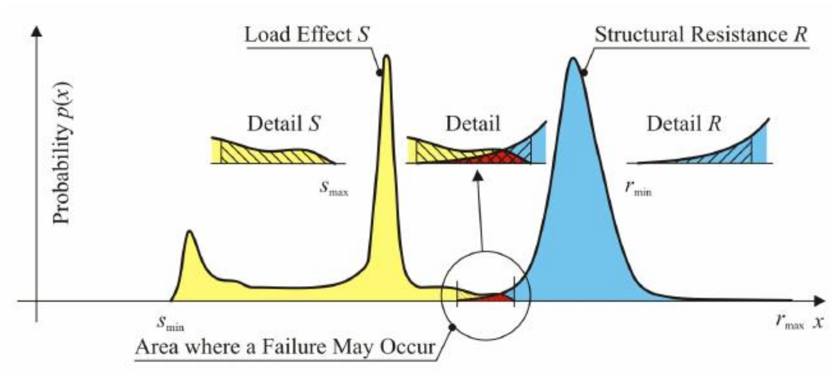

Figure 2: Distribution variables for load and resistance and failure probability (Krejsa et al., 2013)

Traditional deterministic approaches use characteristic values for the various assessment variables. This means that the worst credible loading and resistance variables are applied to the entire assessment, resulting in conservative design of the infrastructure. Likewise, the application of deterministic approaches to existing infrastructure assessment can result in unnecessary and costly repair / replacement, due to the inherent redundancy in infrastructure design.

The most commonly applied reliability assessment methodologies include, First Order Reliability Method (FORM), Second Order Reliability Methods (SORM) and simulation techniques.

FORM is usually used as a starting point for ultimate limit states (DRD, 2004). This is considered the simplest method but its accuracy depends on the linearity of the limit state function. Depending on the limit state function's linearity it may be necessary to check that the use of the analysis method SORM does not give significantly different values of the failure probability.

For serviceability limit states, where the requirement for β is lower than for ultimate limit states, the difference between FORM and SORM can be significant (depending on the linearity of the limit state function). In such cases SORM, or possibly simulation (e.g. the Monte Carlo Simulation method), could be used to provide an accurate calculation of the safety index.

There can be limit states of such complexity that both FORM and SORM are inappropriate. In such cases simulation methods should be considered (Ditlevsen & Madsen 1989).

Reliability analysis is explained in detail in Destination Rail Deliverable 2.1.

4 Bridges

Structural assessment of bridges is often performed when there is a change in use (e.g. heavier vehicles, new lane/track added) or the bridge has been damaged (by natural or human hazards) or deteriorated as a function of time.

4.1 Variation Factors

Many variation factors can influence the risk related to bridges and some of the more frequently considered factors are listed in Table 1. When evaluating a variation factor, an assessor should use a weighting process based on the impact of the particular factor on the risk metric. This decision is, in most cases, based on the expert judgement of the engineer and client experience. It should be noted that it is preferable to incorporate these factors directly within the detailed quantitative reliability analysis.

Table 1 Non-exhaustive list of variation factors for bridges

VARIATION FACTOR	SOURCE
BASIC FACTORS	
• Age of the bridge structure, • Construction materials, • Structural form, • Quality of the structural materials, • Foundation details	• Design documents and reports, • Visual inspections and measurement, • Construction logs, • Laboratory and in-situ testing,
LOAD FACTORS	
• Frequency, speed and traffic loads spectra, • Previous accidents on/under the bridge, • Evidence of deformation, • Live loading, • Evidence of fatigue induced damage (cracking), • High vibrations	• Traffic logs, • Monitoring, • Accident logs (if available), • Visual inspections, • Embedded sensors, • In-situ testing
WEATHER AND ENVIRONMENTAL FACTORS	

VARIATION FACTOR	SOURCE
• Rain and snow events, • Deterioration (variation of cross section, cracking and spalling of concrete cover, variation in bond strength, corrosion), • Wind pressure and its effects on bridge elements, • Solar induced damage, • Geographical Location	• Weather stations / climate models, • In-situ monitoring, • Meteorological data • Visual observations
MAINTENANCE FACTORS	
• Whether design solutions are maintenance friendly or not, • Maintenance timing, quality and type, • Protection layer data,	• Visual observations, • Design documents and reports, • Maintenance logs
OTHER	
• Partial collapse during erection, • Settlement of substructure elements, • Settlement behind/around abutments	• Construction logs, • Underwater visual inspections • Embedded monitoring systems

When evaluating these factors, the engineer should consult design documents and design codes which were valid during the period of the bridge construction. The gold standard of risk quantification involves statistical updating of the variables, based on remote monitoring networks.

4.2 Consequence Factors

In order to evaluate consequence factors, consequence analysis is performed. This consists of estimation of the impact of bridge failure on the railway system in question, as well as assessing the likely direct and indirect consequences. Several different factors can be part of this analysis. For example:

- Delay time;
- Frequency of train passages;
- Complexity/cost of repair/replacement;
- Potential hazards to nearby structures/civilians (e.g. nearby houses, stations etc.);
- Potential hazards to railway users (death/injury);
- Indirect costs (e.g. economic costs to freight industry);

As for variation factors, consequence factors should be based on a combination of expert judgement and client experience, and can be based upon a qualitative assessment of impacts.

5 Earthworks

Probabilistic assessments of earthworks are gaining traction in research, as they are ideally suited to accurately describing the inherent heterogeneity of soils. Most of the rail earthworks in Europe are over 100 years old. Only limited knowledge of geotechnical engineering was available at the time of their construction, and the construction techniques were less stringent than presently, leading to relatively high occurrence of failures and a need for stability assessment. As for bridges, a large network of earthworks would require a precise probabilistic hazard and risk assessment for efficient allocation of monetary resources for maintenance.

5.1 Variation Factors

It is often impractical or impossible to include all possible influencing factors in the probability calculations required to derive the initial reliability index. Many variation factors can influence the reliability of a cutting or embankment and some of the more critical factors are listed here. This decision is, in most cases, based on the expert judgement of the engineer and client experience.

It is important to note that due to the wide variation in climatic conditions across Europe and the heavy susceptibility of earthworks to environmental factors, different variation factors and different weights may apply to different networks. It should be noted that it is preferable to incorporate these factors directly within the detailed quantitative reliability analysis.

Table 2 Non-exhaustive list of variation factors for Earthworks

VARIATION FACTOR	SOURCES
BASIC FACTORS	
• Age of the earthwork, • Overall condition, • Degradation rate, • Past repairs, • Historical failure records	• Visual inspections, • Asset databases, • Management/construction logs, • Failure logs, • Third party reports
WEATHER AND ENVIRONMENTAL FACTORS	
• Rainfall characteristics of the area, • Susceptibility to shrink/swell, • Large diurnal temperature ranges, • Water ponding, • Erosion, weathering, ravelling, • Proximity to coast or water courses, • Vegetation cover, • Animal activity	• Meteorological records • Topographical and geological maps • Visual inspections

VARIATION FACTOR	SOURCES
MAINTENANCE FACTORS	
• Drainage type and condition, • Past repairs, • Presence of retaining walls, berms and benches, • Maintenance frequency,	• Visual inspections, • Maintenance logs
OTHER	
• Third party effects	• Visual inspections • Third party reports

5.2 Consequence Factors

In order to evaluate consequence factors, consequence analysis is performed. This consists of estimation of the impact of failure on the railway system in question, as well as assessing the likely direct and indirect consequences. Several different factors can be part of this analysis. For example:

- Clearance between failure source and track;
- Failure’s run-off potential;
- Frequency of train passages;
- Line speed;
- Delay time;
- Complexity/cost of repair/replacement;
- potential hazards to nearby structures/civilians (e.g. nearby houses, stations etc.);
- Potential hazards to railway users (death/injury);
- Indirect costs (e.g. economic costs to freight industry);

As for variation factors, consequence factors should be based on a combination of expert judgement and client experience, and can be based upon a qualitative assessment of impacts.

6 Tunnels

Tunnels face many challenges associated with their extended period of service and changing requirements. In order to ensure continued and efficient use of these assets in the future, it is necessary to manage and maintain them in an appropriate way which is with due regard to, and adequate understanding of, their special characteristics and needs. (McKibbins et al., 2009). These are part of a broad spectre considering that the construction techniques used 50 years ago are rather different than the ones employed today.

6.1 Variation Factors

In the case of tunnel assessment, many different variation factors must be taken into consideration, some of which depend on the construction techniques employed. Because of this, information regarding construction of the tunnel is crucial for a proper variation factor evaluation. This evaluation, similar to the cases of bridges and earthworks, should be based on engineer and client judgement. Some of the variation factors related to tunnel assessment are listed in Table 3 below:

Table 3 Non-exhaustive list of variation factors for Earthworks

VARIATION FACTOR	SOURCE
BASIC FACTORS	
• Construction technique, • Age of the tunnel structure, • Construction material type (used for lining), • Quality of the material (used for lining), • Surrounding soil details	• Design documents and reports, • Visual inspections and measuring, • Construction logs, • Laboratory and in-situ testing of lining and surrounding soil,
LOAD FACTORS	
• Soil pressure, • Water pressure, • Accidents inside the tunnel, • Live loading, • Evidence of time dependant deformations, • Cracks in the lining and surrounding rock	• Monitoring, • Accidents logs (if exist), • Visual inspections, • Embedded sensors, • In-situ testing
WEATHER AND ENVIRONMENTAL FACTORS	
• Rain and snow events, • Deterioration (cracking and spalling of concrete cover, variation in bond strength, corrosion, leaking through tunnel lining), • Rising of ground water levels, • Location	• Weather station / climate models, • In-situ monitoring, • Visual observations, • Piezometers

VARIATION FACTOR	SOURCE
MAINTENANCE FACTORS	
• Drainage (type, condition, maintenance data), • Vegetation growth/clearance, • Maintenance timing and quality,	• Visual observations, • Design documents and reports, • Maintenance logs, • Drainage testing
OTHER	
• Delamination of the tunnel lining, • Falling or loose parts of tunnel lining, • Insufficient clearance	• Lidar data, • Visual inspections, • Monitoring

6.2 Consequence factors

Similar to the case for bridges and earthworks, tunnel failure in most cases means closure of a railway section, which can have significant impacts on the network. In order to estimate this impact, further consequence analysis should be performed taking into account several factors, some of which are:

- Delay time;
- Frequency of train passages;
- Complexity/cost of repair/replacement;
- Potential hazards to nearby structures/civilians (e.g. nearby houses, stations etc.);
- Potential hazards to railway users (death/injury);
- Indirect costs (e.g. economic costs to freight industry);

As for variation factors, consequence factors should be based on a combination of expert judgement and client experience, and can be based upon a qualitative assessment of impacts.

7 Updating Risk Assessment

Chapters 4, 5 & 6 describe the variation and consequence factors considered for evaluation of β^* values for railway infrastructure. Their values are judgement based and depend on the experience of the engineer who is evaluating them and the information that he/she is provided with.

Ideally, structures should be constantly monitored, allowing variation and consequence factors to be continuously updated from embedded monitoring and neural networks, eliminating the need for subjective judgement from engineers/inspectors.

Monitoring can be applied to continuously update probabilistic modelling and risk calculation. For example, an SHM system installed on a reinforced concrete beam and slab bridge may consist of the following:

- Weigh-In-Motion (WIM) system;
- Weather Station;
- Corrosion detection probes installed on the bridge soffit;

The WIM system can be used to calibrate a Finite Element model of the structure, allowing an accurate assessment to be performed. Measured live loading from passing trains are monitored, allowing continuous updating of the failure probability of the structure. Meanwhile, pre-defined limits of the percentage of section loss in the steel rebar, wind and temperature can be built into the software to allow continuous updating of the variation factors in the calculation. Finally, information on consequence factors can also be updated. For example, a more accurate calculation of the bridge use (number of trains per day) can be determined from the SHM system, by measuring unplanned / un-timetabled passages.

Artificial Intelligence (AI) plays an important role in this system as it can be used to update reliability calculation, predict future degradation of the structure and advise on steps that should be taken in order to avoid incidents caused by structural failure. The last point consists of adjusting the risk as it reaches critical values, by interventions such as increased monitoring, maintenance or repair. In the GoSAFE Rail project, machine learning algorithms are developed based on the near-miss concept. The whole system, once properly calibrated, is completely autonomous which means that it decides when certain rail infrastructure assets should be closed/repaired due to high risk in that section. It also performs all the operations necessary for informing the affected personnel.

Aside from providing live information, the system will play an important role in predicting degradation and by extension, risk to a certain infrastructure asset. In this way, incidents connected to structural failure, which usually fall under the category of major incidents, can be prevented and avoided. The prediction part of the system depends on how the system is calibrated and how much data is provided during the machine learning process. After the initial learning process, the system will be equipped with self-learning algorithms and will be able evolve over time as the amount of available data grows.

8 Conclusions

The GoSAFE RAIL project will be transformative for asset safety in the rail sector. It will bring together inter-disciplinary experts from risk based asset assessment of infrastructure, Artificial Intelligence (AI), object detection and data management sectors with leaders in network micro-simulation modelling to deliver a Decision Support Tool (DST) that will allow a step change for railway infrastructure safety.

In this deliverable, a methodology was provided to give an indication of a simplified qualitative risk metric which is adaptable to the level of information available.

The methodology employs variation factors and consequence factors, both of which depend upon the type of the structure for which they are calculated. Chapters 4, 5 & 6 give suggestions on which variation and consequence factors should be taken into account for bridges, earthworks and tunnels, respectively. Their evaluation and importance mainly depends on judgement-based decisions made by the assessor. Variation factors are divided into several groups depending on their nature (e.g. basic factors, load factors, weather and environmental factors, maintenance factors, and other).

In Chapter 7, a brief explanation is given on how the framework proposed in the GoSAFE Rail project should be applied and how it should provide support to the railway IMs and engineers involved in maintenance of railway infrastructure. It consists of an autonomous AI system which is able to make decisions based on hazard assessment for each structure.

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