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Risk Assessment Process for Railway Networks with Focus on Infrastructure Objects

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ABSTRACT

When railway infrastructure fails it can result in substantial consequences. These occur because the railway objects are part of a network and the service they provide depends on all objects providing adequate levels of service, simultaneously. Railway managers are interested in executing interventions on their railway network if the levels of risk are unacceptable or if they can execute interventions to reduce the probability of infrastructure failure in a way that the risk reduction is greater than the costs of the intervention.

To determine whether the level of risk related to the infrastructure is acceptable, it is necessary to have a single process to assess the risk related to each object in the railway network in a consistent way and take into consideration the ramifications on the service provided by the network if there is an infrastructure failure. This is something that currently does not exist. Usually the risk related to infrastructure objects is examined inconsistently for objects of different types and with inadequate consideration of the service provided by the network. There has been no attempt to combine them.

In this paper, a process is proposed for estimating the risk related to railway networks based on consistent analysis of possible events for objects of all types. It is the first level of a more comprehensive process in which four levels of the system are considered, i.e. object, section, route and network level, involving increasing complexity, but also accuracy. The proposed process includes a classification of stakeholders, cost types, and event types. It is demonstrated by conducting a risk assessment for all objects in an example network. The advantages and the disadvantages of the proposed process are discussed, as well as the future research being conducted at the section, route and network levels.

INTRODUCTION

The railway networks hold a central role in transport, economy and society, accommodating a demand of 17.8% of freight (Eurostat, 2015a) and 7.6% of passenger (Eurostat, 2015b) in European transport¹. In order to satisfy this demand for the best, Infrastructure Managers (IMs) are responsible to ensure that the

¹Total inland transport in EU-28 in 2013 measured in passenger-kilometers and ton-kilometers, respectively
railway infrastructure is safe, reliable and efficient. Due to the generally expected high levels of risk related to railway infrastructure, and the desire to ensure that these are acceptable, it is useful to have a standardized process to estimate these risks. As it is desired to reduce risks to acceptable levels in the most effective way if the risk levels are unacceptable, it is useful to have a standardized process to determine the optimal intervention programs to be followed to reduce these risks.

Currently, there is a lack of a clear process to assess risk related to railway infrastructure and to determine the interventions to be executed to reduce this risk (Liden, 2015). Most of the existing processes, methods and tools focus on the estimation of risk related to individual objects or type of objects (Papathanasiou et al., 2016). However, railway IMs are required to make decisions considering the level of service of the whole network. In order to enable IMs to identify the intervention program that maximize the net benefit over the whole network, a risk assessment process (RAP) is presented in this paper that enables systematic consideration of all the objects in the network, as well as, the effect of object failures on the level of service of the network.

The process proposed builds on the high level process developed in (Adey et al., 2016) and (Hackl et al., 2015), for the estimation of risk related to infrastructure failures due to natural hazards. This work is based on the RAP in the (ISO 31000, 2009), with an additional focus on the interdependencies in time and space between hazards, objects and networks. The process makes use of a system representation using scenarios built from source, load, infrastructure, network use and societal events, whose probabilities of occurrence and consequences are estimated to estimate risk. The RAP for railway networks presented in this paper is an instance of the general process that is suitable for the assessment of risks related to railway infrastructure. It is made specific by identifying specific events and scenarios for all objects in a railway networks.

To that end, the consistent breakdown of the railway objects in railway networks was used. The railway objects were categorized according to (Profillidis, 2014), which is based on the European Community Regulation 2598/1970 (EU2598/1970, 1970) and on the (EU.343.32.2012, 2012). This breakdown includes 10 categories of railway objects: track and track bed; ground area; switches and crossing; engineering structures; level crossings; passengers and goods platforms and access ways; safety, signaling, telecommunication installations; electricity power supply; lighting installations for traffic and safety purposes; and buildings. The breakdown of the railway network in progressively smaller portions, from network level to object level is proposed to ensure that the process can be used in different situations, e.g. when different levels of detail and accuracy in the representation of the railway network are required. In the instance presented in this paper, a railway network consists of railway lines, each line is the infrastructure connecting two stations and can consist of one or multiple railway routes, each route consists of railway sections and each section consists of railway objects, e.g. a track section on a bridge.

To the best of authors’ knowledge this is the first attempt to develop such a systematic RAP for estimating the risk related to the railway network due to the states of its objects. In the next chapters the RAP is first introduced and then its application and results on a simple example are discussed. Finally conclusions are drown and further steps outlined.

**RISK ASSESSMENT PROCESS**

The RAP for railway networks, presented in this paper, is considered to be suitable for a railway IM, who would first like to do a relatively simplified complete risk assessment for all objects within the network. It is focused on the relationship between load, infrastructure, network use and societal events for all objects within the network. The process includes four levels of analysis, each with increasing complexity and accuracy in the consideration of the system interdependencies in the system representation resulting in a complete estimation of risk related to the network. In each of the four levels the focus with respect to the
For all the levels of analysis the RAP consists of five tasks, 1) define stress tests, 2) determine approach, 3) define system representation, 4) estimate risk, and 5) evaluate risk.

**Define stress tests.** In this task the stress tests are selected. This involves two groups of high level decisions, decisions regarding the system to be assessed, including the area, time period, and interdependencies between events; and decisions regarding the acceptable level of risk to be considered, including the process that should follow if the risk is estimated unsatisfactorily or if the risk is estimated to be unacceptable. The former group of decisions mainly affects the input of the process, e.g. data required, while the latter affects the output of the process, e.g. level of accuracy of the results.

**Determine approach.** In this task the approach and the resources to be used are determined. Both quantitative and qualitative approaches can be used in all four levels for the estimation of the risk. Depending on the level adopted, the risk is related to the state of single objects, sections, routes and networks, whose probability of occurrence is not influenced by the state of other parts of the infrastructure. This assumption simplifies the estimation of risk, but consequently reduces the accuracy in the representation of the real behavior of the railway network, which affects the accuracy of the risk estimate.

Regarding the resources, the process allows the involvement of various methods, e.g. static or dynamic aided tools, for the estimation of the probabilities and consequences. However, although the selection of the methods and tools can influence the accuracy of the estimation of the risk at each level, it is important to remember that the assumption made at each level sets a limitation on the accuracy of the representation of the real behavior of the railway network.

**Define system representation.** The system representation is defined in this task. This sub-process, consists of five sub-tasks, 1) define boundaries, 2) define events, 3) define relationships, 4) define scenarios and 5) determine models. Each of those tasks are performed according to the level of the RAP that is selected to be used.

*Define boundaries.* All spatial and temporally boundaries are defined at this task, according to the level at which the RAP is conducted. Boundaries include definition of the size of the objects and the time frame over which the load events and infrastructure events may happen, and also the definition of the area to be analyzed when defining network use events and societal events as well as the time frames over which these are to be analyzed. In order to systematically estimate the risk, it is important to keep both the spatial and temporal boundaries consistent for all objects, i.e. at the same level of detail.

*Define events.* All the load, infrastructure, network use and societal events to be included are defined in this task, according to the level at which the RAP is conducted. The load events are defined using the expected loading conditions of the objects, sections, routes and networks, for each level of RAP, respectively. The infrastructure events are defined using only the physical states of the infrastructure.
They are defined taking into consideration the ways in which the objects, sections, routes and networks, for each level of RAP, respectively, can be loaded, as well as, how they will behave when loaded. The network use events are defined using only the characteristics of traffic flow on the network, for all the level of RAP. The societal events, which are the events upon which monetary values are placed, are defined in terms of how humans are affected. The societal events are defined in terms of the difference between the required railway service performance and the actual railway service performance, given specific stakeholders.

**Determine scenarios.** The previously defined events are linked in causal relationships which yield the scenarios to be analyzed, according to the level of RAP.

**Define relationships.** The risk related to the investigated object, section, route or network, for each level of RAP, respectively, is estimated by considering the possible infrastructure events if the load events occur, the possible network use events if the infrastructure events occur, and the possible societal events if the network use events occur.

In order to estimate the probability of occurrence of the scenarios it is, therefore, necessary to determine the relationships between the events. The relationships between load events and infrastructure events are defined using object characteristics, for example in Fig. 1 (left). The determination of the relationships between the infrastructure events and network use events requires knowing the traffic characteristics, for example in Fig. 1 (center). The determination of the relationships between the network use events and societal events requires knowing how society will be affected by changes to service and how it will react to the restoration of the service, for example in Fig. 1 (right).

**Fig. 1 Examples of relationships between load and infrastructure event (left), infrastructure and network use event (center) and network use and societal event (right)**

**Determine models.** In this task, the models to estimate the probability of occurrence of the scenarios and the values to place on the consequences related to each scenario are determined. There are different types of models that can be used providing different level of detail and accuracy. Examples are structural models to estimate the probability of occurrence of infrastructure events, traffic flow models to estimate the probability of occurrence of network use events and restoration models, to determine the probability of occurrence of the societal events. In the determination of the appropriate models to be used, calibration using existing data is possible. The selection of the models depends on the approach selected, the required accuracy of the result, the available data and the amount of time and expertise available. The probabilities of occurrence of infrastructure events given load events are to be modelled using fragility curves. An example model for estimating the probabilities of occurrence of infrastructure events (defined using track settlement above x mm), knowing the load events (defined using tonnage, T), and the object
characteristics (defined using track stiffness, k), is presented in Fig. 2 (left). Similarly the probabilities of occurrence of network use events given infrastructure events is presented in Fig. 2 (center), and the probabilities of occurrence of societal events given network-use events is presented in Fig. 2 (right). The values of societal events are the sum of the costs of all stakeholders related to them.

Estimate risk. The risk $r$ is estimated in this task using equation (1).

$$ R = \sum_i \sum_j r_{i,j} $$  \hspace{1cm} (1)

The risk $r_{i,j}$ is defined according to the level at which RAP is conducted (e.g., for the object level, $r_{i,j}$ is the risk related to scenario $i$ for object $j$; for the section level is the risk related to scenario $i$ for section $j$, etc).

The risk should be estimated considering the uncertainties involved in the estimation of probabilities and consequences in cost of each scenario. For example, the risk can be estimated, 1) using the mean values of the probability of occurrence and the costs, 2) the values of the probability of occurrence and the costs that are 3 standard deviations above the means, and, 3) the values of the probability of occurrence and the costs that are 3 standard deviations below the means. The three values together give the manager an idea of the uncertainty related to the risk.

Evaluate risk. In this task how the RAP is conducted and the estimated risk are evaluated, by comparing the risk estimated against the defined thresholds and deciding on whether RAP was conducted successfully. Different stakeholders might have different opinions. It is, however, important to decide if the analysis is unsuccessful or if the risk is unacceptable. If the former is decided, further analysis is required. If the latter is decided, then an intervention program is required. If the RAP is considered to be not successful, the analysis can be redone either 1) at the same level of RAP using improved models for the estimation of the probabilities and the costs, or 2) at the next level. If the RAP is considered to be successful, the development of intervention program must be started. If the risk is acceptable that the intervention program will contain no interventions. If the risk is not acceptable the intervention program will contain intervention to modify the risk.

EXAMPLE

The proposed RAP is demonstrated by conducting a risk assessment on the first level for all objects in the example network illustrated in Fig. 3. In this simple network three stations, A, B and C are connected.
Seven switches S1 - S7 allow the change of course. Six track sections are considered, T1, T2, T3, T4, T5 and T6, all being approximately 10 km long. Three bridges allow the railway to pass over a river. They are the bridge B1, at the single track T3 at the route AB and the bridges B2 and B3, at the double track T4 and T5 at the routes, AC and CA respectively. It is assumed that all three bridges have around 50 m span. It is assumed that all double track sections can be used for both directions of traffic if an appropriate switch is provided.

For demonstrating the RAP, the characteristics of the objects, traffic and network considered in the example are presented. It is here considered that there are three possible states for each object, state 1, state 2 and state 3, and that objects are repaired only if an infrastructure event causing them to be in states 2 or 3 occurs. The amounts of time required to repair the object was considered proportional to the state of the object, e.g. to repair a track section being in state 2 are required 5 days while being in state 3 are required 10 days. With reference to traffic, according to the considered timetable 300 passengers per hour and per direction travel between stations A and B and B and C travel, and 600 passengers per hour and per direction travel between stations A and C. Track T6 is used only by freight trains, transferring 2’000 tons of goods per direction per hour. It is also assumed that every day the passenger trains are running for 16 hours, and freight trains for 5 hours.

Following the RAP introduced in the previous chapter for the first level - object level – the risk related to this simple network was estimated. In terms of stress tests the example aims to define the acceptability of risk of the network over a timeframe of one year. The acceptable level of risk - risk related to cost due to object restoration and delays - is considered to be less than 500’000 monetary units (m.u.). It is also required that the risk related to an individual object or section should be below 10% of the acceptable level of risk, which is 50’000 m.u. and the risk related to a route should be below 20% of the acceptable level of risk, which is 100’000 m.u. The estimation of risk was performed using quantititative approach.

Fig. 3. Example network N
With reference to events definition in this example four types of load events, e.g. the monthly precipitation, related to the corrosion of bridges, and the average river flow speed, related to the scour at the foundation of the bridges, and five types of infrastructure events, e.g. track settlement, and corrosion and scour of bridge, were considered. Each type of infrastructure event was considered to occur at each scenario in different levels, e.g. track differential settlement below 7‰, between 7‰ and 12‰ and above 12‰. Each level of infrastructure event was probabilistically associated with one state of the object under investigation for each scenario. For the entire example network, traffic restriction was considered as the only network use event with three levels, traffic according to the timetable, traffic partially restricted and traffic completely restricted at certain part of the network. Three types of societal events were considered, i.e. no action, repairing, replacing the object. Three stakeholders were considered to be affected by the social events; the owner, suffering the economic impact of the repair or replacement; the passengers, suffering the economic impact associated with time lost due to the infrastructure failure; and the freight costumers, suffering the economic impact associated with time lost or lost connectivity due to the infrastructure failure.

With the events defined 58 meaningful scenarios were developed combining all possible types of events for each object based on the object, traffic and network characteristics. The relationships were defined as follows, these between load events and infrastructure events were defined using object characteristics; these between infrastructure events and network use events were defined using traffic characteristic based on the flexibility of the timetable; and these between network use events and societal events were defined using the expected interventions based on the level of the infrastructure events involved in each scenario. With the scenarios defined the probabilities of the occurrence of each event in the scenario and the cost of each scenario were then estimated. The risk related to each object was computed according to equation (1).

**Results of the risk assessment.** The risk for the network was estimated to be 257'186 m.u., out of which that 76% (195'360 m.u.) is associated with the track, 2% (5'674 m.u.) is associated with the bridges and 22% (56'152 m.u.) is associated with the switches. The risk is considered acceptable and only the risk related to the scenario associated with the track section T6 being in the state that requires replacement exceeds the threshold set for the individual objects, even when considering low estimates.

The risk related to the sections of the network can be estimated by summing up the individual risks associated with the objects including in each section. The section where the track section T6 is located resulted exposed to high risk, above the 10% of the risk threshold., as well as the section including the objects T3, B1 and S7 and the section including the objects T4, B2 and S3. If the RAP is considered to be not successful, the analysis can be redone either 1) at the object level using improved models for the estimation of the probabilities and the costs, e.g. re-estimating the probabilities of the scenarios related to sections 3 and 4, or 2) at the section level, if it is estimated that the risk assessment conducted at this level was lacking accuracy at the representation of the real network interdependencies. The risk related to the routes of the network was estimated by summing up the individual risks associated with the objects including in each route. The indirect routes of the network, i.e. routes AB and BA through station C and routes BC and CB, all using the track section T6 are related to risk above the threshold of 100'000 m.u..

**CONCLUSION**

The proposed RAP, although still in preliminary stages, allows the estimation of the risk over an entire network taking into consideration all the objects in the network. This is achieved using scenarios that are built by chains of events where particular attention is paid to the relationships between the load and the infrastructure events, between the infrastructure events and the network use events, and between the network use events and societal events. The RAP is also set to be conducted in four levels of complexity. The possibility to conduct the risk assessment in four levels allows the IMs to assess the risk, every time
related to the whole network, adapting the effort to the desired accuracy for the estimate. The application of the first level of the RAP introduced in this paper on a simple railway network was presented. The example application has demonstrated that the process can be used to assess the overall risk related to a railway network, and to identify the specific objects that are responsible for eventual high risks related to sections, routes and lines of the network.

From the standing point of these results, two main future steps are envisioned for improving further the presented RAP for railway networks: (i) extending the application on the simple network presented in this paper to the section, route and network levels, and (ii) applying the process on a more complex network, i.e. a real railway network. This will first require to work on the expansion of the process in terms of the section, route and network levels, and then, to apply the process to assess the risk related to the infrastructure of a large scale railway network.

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