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Trends in Enhancement of Safety Aspects of Existing Railway Infrastructure

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Abstract

Since more than 95% of the existing European railway network is older than 100 years, the ageing has unavoidably caused its gradual degradation and there is currently a strong need for risk assessment associated with this type of infrastructure. To increase the safety aspects, as well as to reduce the cost of remediation, railway infrastructure managers need to have more advanced tools on their disposal, since they currently make safety critical investment decisions based on poor data and an over-reliance on visual assessment. As a consequence their estimates of risk are therefore highly questionable and large-scale failures happen with increasing regularity. The paper presents the efforts conducted within the framework of some relevant scientific-research projects funded by the Horizon 2020 programme, whose overall goal is to implement and to further develop state-of-the-art techniques and tools in field of railway infrastructure safety.

1. Introduction

The first railway line in Europe was constructed over 200 years ago and by the time of World War 1, more than 95% of the existing European railway network was in operation [1]. Approximately 215,400 km of rail lines in the EU represent a significant asset for the transportation of people and goods. At the same time, considering the data as fatalities per person kilometre travelled, it can be seen that the safety performance of the rail (as well as air) is by far the safest sector, in comparison to the road and highway sector, Table 1.

Table 1. Fatality risk on passenger transport across the EU-27 (2008-2010) [2]

Transport Mode	Fatalities (per billion passenger km's)
Airline	0.10
Rail	0.16
Car	4.45
Bus/Coach	0.43
Motorised two-wheel	52.59

This is additionally pronounced considering that the safety level of much of the EU rail network is significantly lower than modern highway infrastructure, not just in transit states, but also in the developed ones. The lack of clear strategies and non-investment atmosphere that are further fuelled by the economic crisis, have led to a situation where railways in EU are currently not at an enviable level [3]. For example, in Croatia the railway sector has been neglected for the past 30 years which can be seen through the *'Strategy of transportation development in Republic of Croatia'* [4] since 1999, where it was planned that 5% of GDP will be invested in transportation, and 25% was foreseen for the railway sector. However, only 28% of the foreseen budget was actually invested. At the same time, most of the budget was used for the development of the road and highway network.

The age of the railway infrastructure has unavoidably caused its gradual degradation and there is currently a strong need for risk assessment associated with this obsolete infrastructure, all with the aim of increasing safety and reducing the cost of rehabilitation. Even though the EU Rail Industry employs 800,000 people and generates a turnover of €73bn, there are still significant challenges in regard to prioritising the rail investments in both construction of new and remediation of existing networks. Replacement costs for civil engineering infrastructure items such as rail track, bridges and tunnels are prohibitive. The failure of a single asset results in potential fatalities, large replacement costs, the loss of service for sometimes extended periods and reputational damage. Is not only the ageing of the infrastructure that causes a failure, but other factors also, such as more and more evident climate changes, Table 2.

Table 2. Examples of climate change impact on railway infrastructure

Location of the event	Cause / consequence
 Croatia, east Slavonija, section Drenovci – state border, R105 line, May, 2014. / taken from [5]	floods / significant damage of superstructure and substructure
 Switzerland, ski resort St. Moritz near Tiefencastel, August 2014. / taken from [6]	rain / formation of landslides with impact on railway line (derailment)
 Ireland, Malahide viaduct near Dublin August 2009. / taken from [7]	bridge scour due to river flow / railway bridge collapse

The establishment of a Single European Railway Area (SERA) was seen in the 2011 Transport White Paper [8] as being critical to ensuring long-term competitiveness, dealing with growth, fuel security and decarbonisation in the EU. However, given current economic constraints and the challenges of climate change and population growth it is vital that we maintain safety level and develop optimal ways to manage our rail network and maximise the use of all resources. In past several years, EU has recognized the need for more advanced tools and techniques for increasing the safety of existing railway infrastructure. Therefore, current trends in enhancement of safety aspects will be demonstrated through several ongoing EU innovation and research projects from Horizon 2020 programme.

2. DestinationRAIL project – Decision Support Tool for Rail Infrastructure Managers

The DestinationRAIL project [9] provides solutions for common infrastructure problems encountered in diverse regions of Europe, e.g. deterioration and scour damage to bridges, slope instability, damage to switches and crossings and track performance [10]. Whilst similar failure modes are seen around the EU, the triggers (precipitation, earthquake loading etc.) are regional.

Fig. 1. Different types of failure on railway infrastructure [10]

To obtain solutions, 15 institutions from 9 European countries (Ireland, Croatia, Norway, Netherlands, Austria, Germany Slovenia, Switzerland and United Kingdom) are working closely together in development of management tools based on scientific principles for risk assessment using real performance measurements and other vital data stored in an Information Management System. The objectives are achieved through a holistic management tool based on the FACT (Find, Analyse, Classify, Treat) principle. These four phases follow the project workflow.

2.1. FIND module

The question which first arises when discussing the safety of railway infrastructure is *'how do we locate and identify risky assets before they fail?'*. The idea offered by the project is to use a combination of remote monitoring, advanced visual assessment, structural health monitoring (SHM) as well as expert judgement to determine the real-time condition of infrastructure assets. These activities are focused towards the development of algorithms to help find so-called 'hot-spots' (critical sections of the rail infrastructure) rather than classifying these after an event. Therefore, the first task includes a review of key problems faced by infrastructure manager's case histories (e.g. slope instability, bridge scour, switches and tracks and structures) followed by the identification of hot-spots. Here, a Ground Penetrating Radar (GPR), Figure 2, is used consisting of antennas measuring at different frequencies in conjunction with complementary seismic and electric tomography (ERT) measurements [11]. This enables a complete three dimensional image of the investigated section and allows detection of anomalies such as ballast pockets due to depression, animal burrows and the distribution of water content.

Fig. 2. Conduction of multi-channel GPR investigations within DestinationRAIL project

Furthermore, the project aims to develop a methodology to continuously monitor critical track infrastructures, such as switches and crossings, using inbuilt sensor technologies. The sensor communicates with passing trains / monitoring trains to inform the status and condition of the switch. A data analysis and storage system was developed and installed, as well the communication system to transfer data in real time. The project thus develops efficient screening methods to determine dynamic properties of railway tracks, locate hot-spots for adverse track deterioration, sources of annoying environmental vibration emission and areas where adverse track response at increased train speed can be expected.

Besides the railway superstructure, the project deals with monitoring of earthworks and other engineering structures along the line. Within these activities, a drone with a digital camera is used, which can perform the rapid assessment of slopes. In particular, using a special software, the digital data can be transformed into a 3D orthographic image of the slope which can be used directly in the stability analysis, Figure 3.

Fig. 3. Drone application for the determination of railway slope cross-sections

To increase the insight into the structure's health and to improve maintenance decision making in regard to engineering structures along the line, advanced structural health monitoring (SHM) concept is developed.

2.2. ANALYZE module

In order to deal with *'how do we determine the real-time safety of existing infrastructure?'* issue, the project introduces an idea of using advanced models updated using monitoring data from FIND module. The advanced probabilistic models are used to assess the current condition and the effect of maintenance intervention on the remaining lifecycle.

Tasks within the activity include the development of a probabilistic framework to facilitate multi-criteria performance optimization of railway infrastructures (i.e. structures, earthworks and tracks). Also, tailored algorithms are developed to perform the statistical information updating provided on the condition of structures, earthworks and tracks. Developed frameworks are used for the assessment of structures, earthworks and tracks.

2.3. CLASSIFY module

To determine safety level and to assign scarce resources, as the next step in the project implementation, a consortium implements an interdisciplinary infrastructure management tool, based on a risk assessment framework. The framework was developed, where the critical aspect, i.e. the Hazard Assessment, was based on the real scientific data included, rather than on a subjective rating system derived from visual assessment.

A key aspect in performing efficient risk assessment is the management of the volume of data generated, so the project develops an information management system (IMS) based on smart objects. The IMS holds all the data relating to an individual asset and the network. Risk assessment methodology takes into consideration the probability of occurrence of the events to which the infrastructure objects will be subjected and the probability of the infrastructure objects providing different levels of service following an event. Risk ranking methodology is based on risk assessment methodology. It was developed to provide infrastructure managers with the decision support required to help them optimally allocate limited resources.

As the final step within ANALYZE module, Decision Support Tool (DST) was developed, which will help infrastructure managers in the decision making process in the context of dealing with a number of previously identified and ranked risks. The DST forms the basis for the development of 'pre-standard' or benchmark guidelines which can be used by infrastructure managers and stakeholders to support robust development measures which ultimately mitigate multiple risks that are associated with aging railway networks, increased traffic and climate change impacts, along with decreasing maintenance budgets.

2.4. TREAT module

Having established risk rating through CLASSIFY module, Life Cycle Analysis (LCA) is performed to prioritise investment decisions. The answer to relevant question *'how do we choose the optimal rehabilitation technique?'* is given through the set of construction techniques assessed through Probabilistic Whole Life Cycle Model. The DESTination RAIL project considers methods for the rehabilitation and construction of major elements of infrastructure including bridge abutments, transition zones, embankments and open-track.

This is achievable through two areas:

1. Development of modelling tools to optimise and prioritise maintenance based on a range of possible maintenance regimes, with the ability to constrain the model by cost, risk and operational impacts.
2. Development of novel and innovative maintenance and construction techniques for rail infrastructure including tracks, earthworks and structures. Transferring experience from other sectors and regions, e.g. highways, to the rail domain.

By implementing a holistic DST for infrastructure managers, DestinationRAIL project will (i) reduce the cost of investment by using the IMS to manage the network; (ii) contribute to monitoring and real-times analyses which will prevent unnecessary line restrictions and closures; (iii) lower maintenance costs by optimising interventions in the life cycle of the asset and (iv) optimise traffic flow in the network.

3. GOSafe project – A Global Safety Framework for RAIL Operations

The GoSAFE RAIL project [12] is another ongoing research and innovation project from Horizon 2020 programme and it gathers 10 institutions from 6 European countries (Ireland, Croatia, Norway, Netherlands, Austria and United Kingdom). The consortium consists of experts for risk-based assessment of infrastructure, artificial intelligence, object detection and data management sectors, as well the experts in network micro-simulation modelling [13].

The overall aim of the project is the development of a Network Decision Support Tool which will serve as the basis for the Global Safety Framework which provides integrated solutions to different issues related to infrastructure safety and planning. To achieve this objective, the involvement of railway Infrastructure Managers as full partners in the project is of great importance, since they currently make safety critical investment decisions based on poor data and an over-reliance on visual assessment. As a consequence their estimates of risk are therefore highly questionable and large-scale failures happen with increasingly regularity.

The Global Safety Framework aims to assist infrastructure managers [14] by:

- providing the central data repository of asset registers (geometry, location, etc.;
- integrating key performance indexes (KPIs) related to the current condition, maintenance records, failure history, processed sensor data as well as storing the dynamic data, generated as a result of different analysis, for later use;
- implementing the reliability-based assessment models and life cycle cost models on the object level;
- integrating risk assessment model based on the hazard scenarios and network effects;
- establishing a link between traffic flow model outputs, which makes estimations of traffic disruption impacts based on the planned and unplanned maintenance activities;
- assisting in maintenance decision making by recommending maintenance treatments and maintenance plans as a result of following the procedural flow of defining the scope, objective(s)

The information flow of all components of the Global Safety Framework is given in Figure 4. Other than developing a GSF, the project focuses on other objectives as well. These include (i) developing a range of obstruction detection

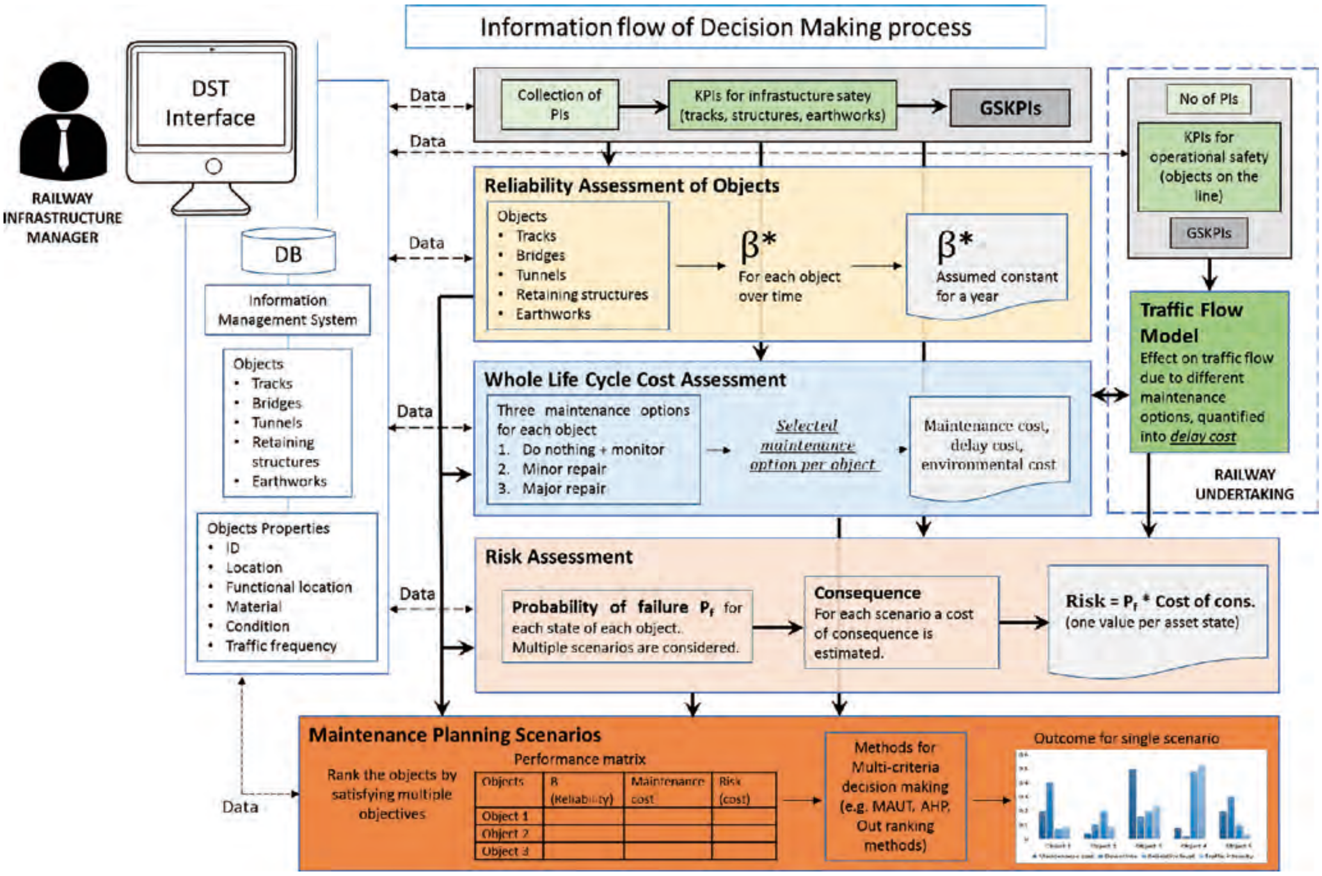

Fig. 4. Global Safety Management Framework developed through the GOSafe project [14] and budget, selecting the assets on network, analysing the assets and budget, selecting the assets on network, analysing the assets.

methods using a combination of vibration based sensor networks, train mounted cameras and lasers in order to identify a range of hazards; (ii) implementation of the machine learning algorithms developed based on the near-miss concept where the usage of low-consequence events to train models will provide statistically significant data for model training and (iii) development of the new safety indicators based on existing concepts and knowledge gained (and validated) from the live safety framework.

The implementation of project activities was conducted through several activities, described above.

3.1. Risk Assessment Methodology

Using a combination of remote monitoring, case histories and expert judgement, the key safety performance indicators associated with railway infrastructure are identified. The focus is on the infrastructure including, switches, crossings, tracks, earthworks, tunnels and bridges. Using results from real time monitoring of a case study railway bridge, a probabilistic risk assessment framework was developed. The framework incorporates a unified risk ranking hierarchy to provide infrastructure managers with the decision support required to help them optimally allocate limited resources in a manner which optimises safety. Consequently, rather than just focusing on risk, the framework takes into consideration the availability of resources to reduce risk, the ability to accept or tolerate risks (i.e. the consequences), the effectiveness or availability of interventions to reduce risk and the residual risks following an intervention. The methodology allows different interventions to be compared, taking into consideration their relative costs (both direct and indirect). The tasks within this activity include:

(1) Identification of Global Safety KPIs where consideration is given to how changes in use (increased speed and or loading), climate change etc. might affect the safety performance of infrastructure and cause increased incidence of existing or new heretofore unseen problems;

(2) Monitoring Systems which consider monitoring system for obstruction detection, monitoring system for landslides as well as monitoring system for infrastructure objects. The monitoring system for obstruction detection is particularly interesting since a new system involves multiple sensors mounted on the train, consisting of high-resolution cameras which are in focus of investigation methodology and which are used for acquisition of series of 2D images, large-range LIDAR scanners and near distance and far distance radar, Figure 5;

(3) Assessment and ranking of risks where a probabilistic framework is developed, providing infrastructu-

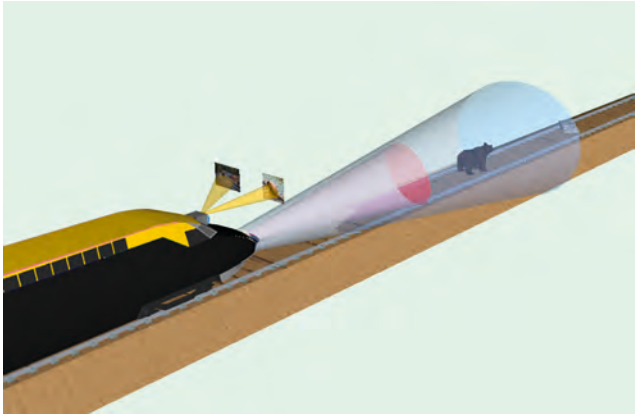

Fig. 5. Train mounted camera system for detecting obstacles [13]

re managers with the facility to optimise budgets/ resources for maximum safety

3.2. Mobility

By application of a suitable algorithm for online optimization of traffic flow, the capacity of bottleneck sections will be increased in comparison to today´s operational practice. This will lead to an increase in punctuality and by the way saving of energy. Today´s production aims to drive as fast as possible in case of receiving the signal aspect track speed. Unfortunately, this leads directly to a conflict when the block in front is not available when passing the closed distant signal. Hence, time and energy are wasted, which is especially critical at bottlenecks. Having an integrated real-time rescheduling algorithm verified by micro-level simulation offers the advantage of reducing track speed to a calculated value when needed; the driver does this and then again accelerate while passing the bottleneck section. This allows an efficient usage of existing capacity, which is not the case at the moment.

The tasks within this activity include:

(1) Micro-planning Simulation where the existing API is used to integrate an algorithm based upon Kronecker Algebra for rescheduling into micro-planning simulation:

(2) System testing in terms of punctuality where the algorithm based upon Kronecker Algebra is tested in terms of punctuality to verify the expected improvements:

(3) Big data integration by establishing an inventory of data sources describing the physical status of a railway network that are available to the railway management authorities that form part of the project consortium.

3.3. Decision Support Tool

The development of a decision support tool to support infrastructure and operations managers to plan railway network assets and operations in an integrated manner (or to take the good decisions to manage the safety of the railway system at a global level in each situation) is the main objective of this activity. The decision support tool will be based upon a safety management process that can guide collaborative decision making activities between operations and infrastructure managers. Additionally, the decision support system will be based upon an integrated mobility systematic that allows for quick micro-simulation based experiments to understand different network conditions and to intervene appropriately and timely.

The tasks within this activity include:

(1) Development of mentioned Framework for Global Safety Management

(2) Validation and training of the model where the artificial intelligence algorithms will be implemented to compare the outputs from the risk models (in terms of infrastructure performance) and the network model (in terms of travel times/disruptions etc.) and use the performance as a means of model improvement

(3) Information management and visualization through the development of four java script based Open Source modules that can be used for the development of web based decision support systems

(4) Decision Support Tool which will help infrastructure managers and railway undertakings make robust, cost-effective decisions that increase safety and maximize the network capacity – the decision making process in the context of dealing with a number of previously identified and ranked risks. The tool will be developed to ensure that outputs of previously conducted project activities are practically integrated and used under specific process workflows and modules.

The demonstration projects ensure that the outputs from the project are implemented in the practice of the infrastructure management within and beyond the life cycle of the project. To ensure this, several demonstration sites are chosen: (i) Case Study 1 – The Safety Framework will be tested on a long distance corridor on the TEN-T Network. (ii) Case Study 2 – The Safety Framework will be tested on a complex partial section of the TEN-T Network. (iii) New techniques for object detection will be demonstrated in Norway, Ireland and Croatia.

The project implementation will yield several impacts. Taking into consideration that maintenance of the network and coordination between the infrastructure managers and operators is a determining factor in ensuring safety, the implementation will enable decisions regarding the management of safety for the railway at a global level. Further, the global approach will help evaluate the impact of the new equipment integrated into the existing railway system. It is also assumed that smart planning will significantly reduce delays in long-distance traffic (e.g. from planning, operations and secondary sources such as train connections and reducing the widespread use of speed limits to control risk).

4. SAFE-10-T project – Safety of Transport Infrastructure on the TEN-T Network

In order to ensure high safety performance while allowing longer life-cycles for critical infrastructure across the railway, but also road and inland waterway modes, the SAFE-10-T project [15] takes a step forward from considering critical infrastructure such as bridges, tunnels and earthworks as inert objects to being intelligent (self-learning objects). Consortium of 15 partners from 8 European countries (Ireland, Croatia, Netherlands, Switzerland, Germany, Italy, Belgium and United Kingdom) gathers experts from risk based assessment of infrastructure, artificial intelligence (AI), wireless sensor networks and data management sectors with sociologists and industry groups to deliver a next generation, cross-modal safety model that will be transformative for infrastructure safety [16].

The project considers a number of common problems faced by EU infrastructure managers, leading to the realisation of a number of key policy objectives namely; increased safety and capacity of networks, reduced environmental impact and improved competiveness of the transport networks. It both accurately quantifies the resilience of infrastructure at a node and interchange level on transport networks and allows for investment in rational adaptation strategies, so as to maintain high levels of safety.

The Safety Framework developed in the project, Figure 6, delivers the following:

- Embedded monitoring techniques and data analytics which guide the development of improved probabilistic analyses tools for major infrastructure objects (bridges, tunnels and earthworks) resulting in a much safer infrastructure leading to the near eradication of sudden failures.
- A cross-modal probabilistic network traffic model is developed to assess the effect of maintenance, adaptation and structural interventions and natural hazards on the capacity of the network and the safety of users.
- Life cycle assessments are performed to allow for strategic investment decisions that maximise safety, minimise disruption and allow for the best use of limited resources.
- The end-product is an off the shelf, online safety management tool that will be commercialised by the project partners. A unique feature is the ability to allow infrastructure owners to make informed decisions and to communicate risks to users (road operators, railway undertakings, waterways managers, public transport operators) using modern communication tools. To accomplish this, risk experts work closely with project partners including sociologists, representative bodies and owners.

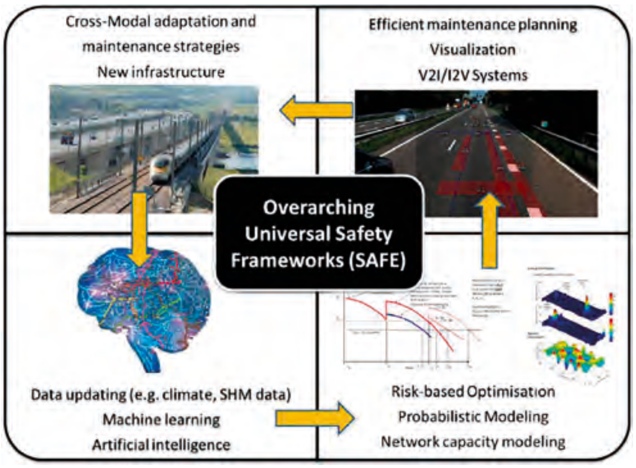

Fig. 6. Information flow in the SAFE-10-T project [16]

The implementation of project activities is conducted through several activities, described above.

4.1. MAP (modelling and monitoring)

The objective of this activity is to develop protocols for advanced real-time assessments of the condition of transport infrastructure assets (bridges, tunnels and earthworks). Probabilistic methods are developed to incorporate results from monitoring to facilitate safety assessments so as to evaluate infrastructure resilience. Under this activity, a Resilience Assessment guideline is developed for resilience ranking of transport infrastructure. Advanced assessment techniques are combined with the machine learning algorithm as well as the network analysis of subsequent activities to demonstrate the probabilistic consideration of infrastructure resilience. Advanced safety analysis of bridges, tunnels and earthworks develops a probabilistic basis for assessment of bridge structures for various travel modes, a probabilistic based displacement model for tunnel safety which estimate the probability of failure (considering a serviceability limit state) of the structure and probabilistic framework which evaluates the stability of earth slopes (cuttings, embankments and dykes). Embedded Monitoring Systems develops a series of methods for self-monitoring of critical infrastructure objects in order to optimise the structural safety of models.

4.2. FLOW (multi-modal traffic flow model)

This activity focuses on smart planning and mobility of multi-modal networks, where existing macro-simulation models are applied for planning and testing in cooperation with railway and road operators in order to identify safety conflicts. The first step is to identify users and to determine their demands for different modes of transport (road, rail waterway) followed by the development of a macroscopic traffic model for a multi-modal transport network, using the existing traffic flow model for railways and extending this to other modes of transport

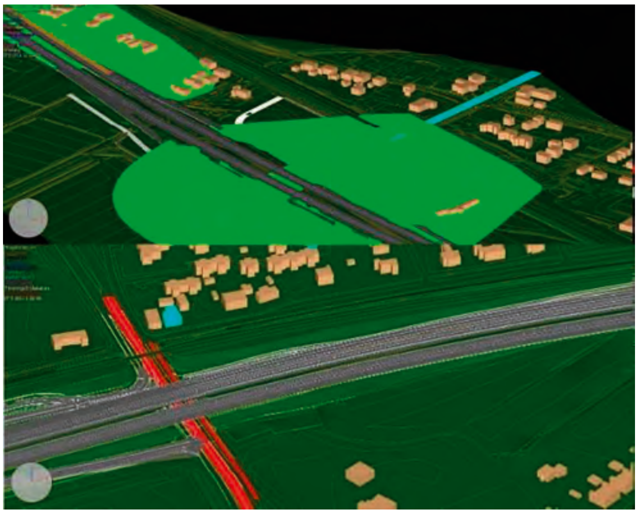

Fig. 7. Visualization of conflicts on nodes and interchanges of different networks [16]

(roads and waterways). Next, a map-based visualization of conflicts caused by insufficient capacity or critical infrastructure failures is developed where users will be able to identify conflicts (e.g. hot spots, maintenance overlaps, and capacity gaps) and develop safety management plans accordingly, Figure 7.

As the final step within this activity, an economy and environmental impact analysis is performed. Here, a whole life cycle model (WLCM) is developed with the aim of integrating owners, users and societal costs related to transport infrastructure. The purpose of the model is to determine economic and environmental impacts (cost benefits) of planned developments and unplanned (e.g. hazards, failures) disruptions followed by the cost benefit of structural and maintenance interventions.

4.3. SAFE (Global Safety Framework)

The focus of the project is in the development of a multi-hazard, risk-based safety framework to manage multi-modal transport networks. The framework enables infrastructure managers, state and private funding agencies and policy makers to make decisions related to infrastructure objects that maximise safety and investment and consider network performance. Big Data Management activity provides the core BIM platform to collect, correlate, and make available data from multiple sources for the entire project and specifically for integration with the work undertaken in Machine Learning and the Decision Support Tool tasks.

Through the development of a Machine Learning Algorithm an improvement of risk assessment at the object and network levels will result. At the object level, the approach combines SHM information with climate and traffic predictions in order to assess structural health. At the network level, machine learning will allow users to forecast infrastructure demand at a higher precision than previous solutions, hence enabling risk-based optimization at the level of the network planner. As a final step, a Decision Support Tool (DST) is developed, which will help infrastructure managers make robust, cost-effective decisions that increase safety and maximize the network capacity.

4.4. DEMO (demonstration case studies)

Through this activity the R&D providers will demonstrate the project outputs on real demonstration case studies on road, railway and waterway networks operated by the three agencies (partners on project). These demonstration projects ensure that the outputs from the project are implemented in the practice of infrastructure management within and beyond the life of the project. The chosen demonstration sites are; (i) Case Study 1 – North Sea – Baltic Corridor, as an example of the long distance corridor on the TEN-T Network. (ii) Case Study 2 – Mediterranean Corridor – focusing on the Rijeka harbour, Figure 8, as an example of a complex partial section of the TEN-T Network. (iii) Case Study 3 – Urban interchange and node where different modes meet and where the failure of critical infrastructure components (e.g. bridges, tunnels) would cause multiple hazards.

Fig. 8. The Rijeka port as one of demonstration sites within SAFE-10-T project

In regard to the project impact, the implementation will contribute to near eradication of infrastructure-caused accidents. It will also increase readability and forgiveness of the transport infrastructure by providing warnings to user when risk levels exceed certain levels (KPI's), prove the effectiveness of long-term, predictive maintenance systems and it will deliver a number of how-to guideline documents for different stakeholders. An increase in infrastructure safety performance will also contribute to the achievement of sustainable development in the sector and will minimise effects on climate changes via the improvement of traffic smoothness.

Conclusion

The paper presents several ongoing H2020 projects which have a similar overall objective – enhancement of safety aspects of railway infrastructure. Additionally, these projects offer the railway infrastructure more advanced tools for their critical investment decisions. The DestinationRAIL project, GOSafe project SAFE-10-T project provide solutions for common infrastructure problems encountered in diverse regions of Europe. The tools and techniques such as embedded monitoring, advanced modelling and simulations, transition to intelligent (self-learning) infrastructure objects, risk assessment based on probabilistic models, big data information management systems, safety management framework and decision support tools are in focus of these ongoing projects recognized by the European Commission for their innovation aspects. The performed activities clearly demonstrate current, but also future trends in increasing the safety aspects of the railway infrastructure as one of most important modes for transportation of people and goods.

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