INNOVATIVE APPROACH TO IMPROVE THE SAFETY OF TUNNELS AND TUNNEL CONTROL CENTRES

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ABSTRACT

Developments in the field of digitalization of the road and its infrastructure are strongly aimed at connected and automated driving. The collection of vehicle mobility data and its use for traffic monitoring and control can make a significant contribution to preventive event detection and the early initiation of protective measures in tunnels. By using real-time risk assessment in tunnels, it is possible to intervene in a controlling manner before the event occurs and thus mitigate or even completely avert negative effects. The potentials arising from mobility data are faced with major challenges, e.g. how to check the integrity of these large volumes of data, and how to select, merge, analyse and evaluate them systematically. Here, the application of Artificial Intelligence is considered as a very promising method. With that in mind, the research project KITT investigated for the first time the possibility of carrying out a risk assessment in tunnels in real time by using weak AI. Furthermore, it was investigated which additional vehicle data from C-ITS could be available in the future in tunnels. It is expected that their targeted use will contribute to a significant increase in tunnel safety and to maintain the availability of tunnels.

Keywords: tunnel safety, real-time risk assessment, artificial intelligence, C-ITS

1. INTRODUCTION

Tunnel control centres play a crucial role in ensuring the availability of the road network. In normal operation, they monitor and control the traffic in tunnels; thus ensure safe and efficient traffic flow. In the event of an incident or emergency, tunnel operators initiate measures to protect road users and the structure as well as support the emergency and rescue services in a coordinating manner. Dealing with incidents in tunnels requires special attention because, unlike on the open road, road users are in a structure that restricts smoke-propagation as well as rescue options. Therefore, events in tunnels have a serious impact on user safety compared to the open route and cause damage to the structure and tunnel equipment. The refurbishment usually leads to long traffic restrictions and often causes considerable additional travel times due to the use of low-performance alternative routes. Therefore, strategies and technical solutions to avoid and mitigate the effects of these events are important for maintaining the availability and safety of tunnels and tunnel control centres.

As a consequence of the big tunnel fires in the Montblanc, Tauern and Gotthard tunnel around 2000 extensive regulations and guidelines have been implemented on European and national level. However, as a result of the introduced minimum safety requirements relevant for road tunnels [1] and the increasing traffic volume, the implementation as well as the complexity of tunnel monitoring and tunnel control systems are steadily increasing. In order to counter this complexity, there has been a trend in recent years for operators to centralize tunnel monitoring and control. Due to the increase in information and communication technologies (ICT), the number of digital points of attack is growing and with it the challenge of ensuring operational safety and the resulting safety of road users.

Nevertheless, digitization harbours great potential for significantly improving tunnel safety and availability. Developments in the field of digitization of the road and its infrastructure are strongly aimed at connected and automated driving. The field of Mobility 4.0 opens up a new possibility: the use of the traffic collective as a fully digitized mobility, information and communication platform. This technology, known as Cooperative Intelligent Transport Systems (C-ITS) is to be regarded as an extension of driving assistance systems. In future, it will make additional information available to infrastructure operators and road users to assess the current traffic or safety situation in the tunnel [2] .

On the other side, the potentials arising from the additional information from C-ITS are faced with major challenges, e.g. how to check the integrity of these large volumes of data, and how to select, merge, analyse and evaluate them systematically. Moreover, the additional information should not lead to a further increase in the workload of the operating personnel in tunnel control centres. If, in the medium term, additional data from C-ITS should be used to improve tunnel safety, concepts must be developed to use them in an appropriate manner. The use of (weak) Artificial Intelligence (AI) offers a promising approach. Potentially it can be used to support operators in assessing the overall situation and making decisions in the event of an incident, as well as in predicting exceptionally dangerous situations. With that in mind, the research project KITT ("Artificial Intelligence to Improve the Safety of Tunnels and Tunnel Control Centres") is investigating for the first time the possibility of utilizing AI to reduce reaction times in event detection and management, mitigate events or prevent them entirely by proactive implementation of real-time safety measures, provide emergency services and tunnel users with targeted information and secure the interfaces of C2I and the communication in the entire network by means of anomaly detection. The main objective is to further increase tunnel safety and to maintain the availability of tunnels. This paper will present the final findings of the KITT project.

2. UTILIZATION OF NEW C-ITS DATA

C-ITS allows to exchange information continuously between vehicles and the road infrastructure. Various hardware components are required to enable a wireless communication between individual vehicles and traffic infrastructure. Triggering a message in a vehicle, various kinds of safety equipment, often standard in modern cars, are necessary. This might be rain and light sensors, ESP (Electronic Stability Program) or ABS (Anti-lock Brake System), to name just a few of them. The actual communication then happens via the OBU (On Board Unit). This unit enables the vehicle to communicate with its surrounding environment.

The central elements of C-ITS on the infrastructure are the Road Side Units (RSU), receiving information from the vehicles and transmitting information to the vehicles. Thus, the RSU serves as information transfer point between control centres, traffic infrastructure and vehicles. The networked communication usually takes place via WLAN, in order to establish short-term connections between vehicles and the infrastructure.

In order to enable an efficient data flow and data processing standardization of message formats and interfaces is crucial. The European Telecommunications Standards Institute (ETSI) issues technical standards in the field of ICT. It defines in detail the format of C-ITS-messages. There is a rough classification of message types which provide information continuously or just event-based. In this context, the Cooperative Awareness Messages (CAM) and Decentralised Environmental Notification Messages (DENM) formats used to transmit information are considered particularly relevant in the context of tunnel safety. CAMs contain static and dynamic information on the vehicle status, such as position, direction, speed, vehicle type (car, truck, etc.), propulsion system (battery, gas, etc.), etc. and are transmitted continuously, approx. every second. DENMs are notifications of road users or infrastructure systems sent only in case of safety-critical events with specific event information. Corresponding messages can be e.g. accident type, emergency braking, traffic jam, road works or tunnel closure. Almost all events can be indicated according to the requirements defined in the corresponding standards, except of fire. However, a direct coupling with ambient temperatures of the vehicle can be optionally sent in a DENM, for instance in case of a vehicle breakdown. The available message types are listed in the corresponding ETSI standards for CAM [3] and DENM [4] .

At this point, a distinction between mandatory and optional information has to be made. Mandatory information are basic sets which must be made available in accordance with the ETSI standard. They allow a prompt implementation in tunnel operation, as all C-ITS equipped vehicles transmit this data. Nevertheless, the rapidly advancing technologies in the field of digitization with regard to connected and automated driving call for considering not yet mandatory information at an early stage. Furthermore, detailed definitions already exist in the standards, so that applications already can be built on it.

The collection of vehicle mobility data and its use for traffic monitoring and control can make a significant contribution to preventive event detection and the early initiation of protective measures by tunnel control centres. In contrast to conventional detection systems, which just react to effects of incidents, C-ITS technology allows detecting its causes directly [5] . Furthermore, the additional information source can be merged with other conventional sensor data, i.e. to check plausibility and reduce false alarms respectively. Moreover, the dissemination of additional information to other involved actors, such as emergency services, but also road users, was assessed as having great potential.

3. THE ROLE OF ARTIFICIAL INTELLIGENCE

Processes from the field of Artificial Intelligence (AI) have been the subject of research for many years. Artificial intelligence is understood to be the constructed replica of intelligence that is orientated on the intelligent abilities of humans. In this replication of intelligence, two types of AI have to be distinguished: weak and strong AI.

The weak Artificial Intelligence has no creativity and no explicit ability to learn independently. Its learning skills are mostly reduced to training recognition patterns or comparing and searching through large amounts of data. It can be used to deal with clear defined tasks with a set of predefined methodologies in order to solve more complex but recurring and well-specified problems. The special advantages of weak AI lies in the automation and controlling of processes, but also in speech recognition and processing. Popular examples are text and image recognition, speech recognition, translation of texts, navigation systems, etc. Digital assistance systems such as Alexa, Siri and Google Assistant also belong to this category. The most significant successes have been celebrated with methods based on Machine Learning, which is an approach to achieve Artificial Intelligence by learning from experience in order to find patterns in a range of data.

The second type is the strong Artificial Intelligence. However, the realization of a strong AI in practice is not yet within reach. A strong AI can independently recognize and define tasks and autonomously develop and build up knowledge of the corresponding application domain. It examines and analyses problems in order to find an adequate solution – which can also be new or creative.

In KITT the weak AI was developed to support in the following tasks: First, the AI should improve the detection of (potential) critical traffic situations (e.g. slowly driving or stopping vehicles, dangerous driving, congestion, etc.) at an early stage. The improved knowledge about these events can be used to warn the tunnel operators or to adapt the results of the real-time risk assessment by varying the probability of events. Moreover, in this step the AI was used to cope with the big amount of data transmitted by vehicles via C-ITS technology. In particular the continuously transmitted CAMs generate a flood of information that cannot be processed meaningfully and in a reasonable time without machine-supported procedures.

In addition, a major advantage can be seen in sensor fusion, i.e. to meaningfully merge the information from innovative C-ITS with conventional information from tunnel sensors and check its plausibility. On the one hand, a benefit can be expected due to the increased information density. On the other hand, it can be assumed that false alarms can be reduced by plausibility checks from different systems. Overall, this is seen as increasing the efficiency of traffic monitoring and control. However, this step was not (yet) implemented within the project.

Furthermore, AI methods were used to detect security-relevant events (tunnel security and security of the IT systems), i.e. anomalies, at an early stage in time series of sensor and log data.

Finally, a concept for on-the-job learning was developed in KITT. In the future, the experience of operators can be used to continuously improve the performance of the AI modules by learning from the reactions of the operators. However, the improvement of AI components through further learning during operation is a major challenge, especially in safety-relevant application scenarios. It must be ensured that further learning does not lead to a deterioration in the overall system and thus to critical situations.

4. REAL-TIME RISK ASSESSMENT

The main objective of KITT is the improvement of safety of road users. In general, this is achieved through an adequate protection against collisions and fires as well as the optimised handling of self-rescue and emergency response measures. In KITT, however, innovative tools like C-ITS and AI were used to extend common risk assessment methods and investigate the possibility of carrying out a risk assessment of the overall safety situation in road tunnels in real-time and implement fast mitigation or protection measures.

Currently, quantitative risk assessment studies are based on static tunnel parameters (e.g. tunnel length, gradient, cross section dimensions, etc.) as well as on average values of dynamic parameters (e.g. for traffic volume, truck share, driving speed, congestion hours, vehicle occupancy, etc.), leading to annual average risk values. Currently, these risk values are used for example to design the required tunnel equipment, like the ventilation system, or to define consistent operational measures, like the maximum speed limit.

In a real-time risk analysis dynamic data (real-time data) will be used in addition to standard values, leading to a better understanding of the current safety situation in the tunnel. This real-time data originates on the one hand from C-ITS data transmitted from vehicles, on the other hand from existing tunnel sensor systems (see Table 1). This allows for a real-time assessment of safety in road tunnels and an intervention in a controlling manner before the event occurs and thus mitigate or even completely avert negative effects.

Table 1: Overview of different input parameters for the real-time risk analysis and their sources

	Static tunnel parameter	**Tunnel sensor systems**	**C-ITS**	**Processed by AI**
Structural tunnel data	X			
Traffic data		X	X	X
Vehicle data			X	X
Environmental data		X	X	X
Event information		X	X	X
Tunnel equipment status		X		
Incident probabilities	X		X	X
…	…	…	…	…

For the real-time risk analysis existing quantitative risk assessment tools are used and expanded to include additional safety-related information and functionalities (see Figure 1). Both, in Austria [6] and Germany [7] [8] sufficient flexible methodologies for risk assessment are available for this purpose.

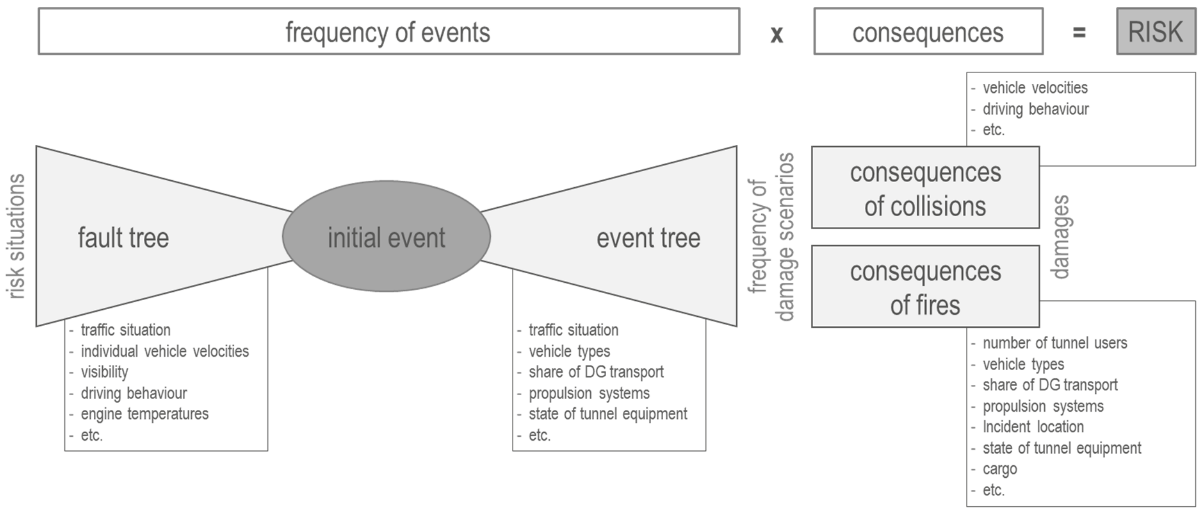

Figure 1: Major elements of a risk analysis extended by real-time information

In the following chapters the process is explained in detail including the potential where C-ITS data can be implemented and where AI can be of support.

4.1. Fault tree analysis to estimate the probability of initial events

When assessing safety in road tunnels using quantitative risk analysis tools, the safety assessment is based on triggering initial events: vehicle breakdowns, collisions, fires. The probabilities of initial events are usually determined using basic statistical data. In the real-time risk analysis the basic probabilities are continuously determined based on the current traffic situation and vehicle data.

A similar approach has been realized in the research project ESIMAS [9] . In the course of this, numerous fault trees were developed illustrating which initial events can be deduced from risk situations. In KITT, the ESIMAS-concept was expanded by data derived from C-ITS communication. Such data was treated as an additional sensor system included in the fault trees. In addition, the AI can enable the early detection of risk situations and thus provide real-time probabilities for the initial events required in the risk analysis. This allows to detect additional causes of events and to recognize initial events or risk situations better and faster.

4.2. Event tree analysis to estimate the frequency of incident scenarios

In the event tree analysis, the frequency of a series of predefined damage scenarios is estimated. Starting from an initial event (for which the frequency is known) various possible chains of events leading to different damage scenarios are developed in several steps (branches of the event tree). Possible branching points are, on the one hand, failure probabilities of tunnel safety equipment and, on the other hand, traffic parameters (e.g. traffic situation), share of vehicle types (e.g. cars, trucks, buses), existing vehicle propulsion systems, share of dangerous goods transport, etc. By quantifying the event tree (absolute probability of initial event and relative probabilities of different branches), the frequency of each individual consequence scenario can be estimated.

4.3. Consequence analysis to estimate the consequences of collisions and fires

In the consequence analysis the effects of the individual damage scenarios are estimated. The basis for the consequence analysis for tunnel collisions is provided by statistical data of tunnel incidents. In many countries statistical values for general tunnel types or individual tunnels are existing. Real-time traffic data can be used to dynamically adapt the standard values based on current traffic data, like vehicle velocities or driving behaviour.

The consequence analysis for tunnel fires is determined by using complex simulation models for fire development, smoke propagation and evacuation behaviour. Thereby, the impairment of tunnel users during evacuation is determined. The fire model implemented in FDS allows for a realistic reproduction of specific energy and smoke releases and determine the effects of a fire by calculating the smoke distribution, the visibility, the CO-concentrations, the temperature and the longitudinal flow velocities in the tunnel over time. Real-time data, like existing vehicle types, the share of Dangerous Goods transport vehicles, the existing propulsion systems or the incident location were used to influence the smoke-propagation results. Due to the complexity and the computational cost of theses three-dimensional simulations it was necessary to pre-calculate a representative set of damage scenarios, which are used during the real-time process.

The results of the smoke-propagation simulations were combined with an evacuation simulation. Thereby, the accumulated effect of the noxious substances and the visibility were determined for each time step, resulting in survival rates for each tunnel user. With that, parameters like the number and position of tunnel users, the evacuation time, the walking speeds or the escape route lengths can be assessed. Real-time data like vehicle position, traffic volume, bus share or vehicle occupancy can be used to estimate the number and position of people in the tunnel and influence the results of the evacuation simulation.

4.4. Risk evaluation and visualisation

The risk in the tunnel is the combination of the estimated consequence and frequency of each individual damage scenario. In the risk assessment the collective risk of all tunnel users is estimated, represented by the statistical number of fatalities in the tunnel per year. The real-time risk is evaluated by using a relative approach: The real-time risk value of the tunnel is compared to the risk value of an idealised reference tunnel exactly fulfilling the relevant guidelines and standards. If the risk of the assessed tunnel is below or equal to the risk of the reference tunnel, the tunnel is considered to be sufficiently safe. If the risk of the assessed tunnel exceeds the risk of the reference tunnel, additional risk-mitigation measures are required.

The real-time risk and appropriate risk-mitigation measures are visualised to the tunnel operator on a specific platform. A similar graphical user interface has been realized in the research project ESIMAS [9] and was further developed in KITT.

5. LEGAL AND ETHICAL ASPECTS

The current legal situation with regard to the above-mentioned range of topics is already very extensive. The equipment and operation of road tunnels are covered in Austria [10] and Germany [11] by special safety regulations, which also implement European requirements. The Austrian Road Tunnel Safety Act [12] also contains specifications for tunnel surveillance using video surveillance, and therein already specifications for data minimization. In the area of cyber and information security the extensive European requirements (NIS Directive) have also been implemented nationally. In the area of data protection law and privacy, the legal framework is largely specified by the European legal framework (especially GDPR) and is also specified and implemented in the national DSG (Austria) and BDSG (Germany).

However, due to the technical development in the field of automation and networking in traffic an evaluation and possibly an adaptation of the current legal situation may be required. C-ITS provides for an extensive data exchange between vehicles, but also between vehicles and infrastructure. The collection and aggregation of a large amount of individual data, but also the additional communication channel that is opened up as a result, which can result in new security gaps, require not only technical innovation but also a legal framework that is dynamic on the one hand, in order to be able to take technical progress into account, and on the other hand, sufficiently specific to comply with fundamental rights and the rule of law and to ensure legal certainty.

A major objective of KITT was a review of all relevant legal as well as ethical aspects arising from new developments within this project. For that, two Universities from both, Austria and Germany, each specialised in privacy, liability law and legal informatics conducted extensive analyses in this area.

6. CONCLUSION AND OUTLOOK

At the time of the preparation of this paper, the project is almost finished and a final demonstration of the KITT modules in a German road tunnel is planned in the near future. At the current stage of the project, it is clear that this project is to be designed with great perspective, but the relevance requires this early step due to the rapidly advancing digitization in the area of connected and automated driving. The requirements from the point of view of tunnel safety must be formulated at an early stage, as they may well deviate from those of the open road. This addresses infrastructure operators for the development of the necessary technical infrastructure and integration into existing monitoring and event management concepts as well as the development of competences of system users and vehicle manufacturers who include safety aspects and the requirements derived from them in their design when providing information to the infrastructure. This opens up potentials that can contribute to improving road safety. For tunnel monitoring, concepts for targeted data fusion and plausibility checks can be expected to provide opportunities for better incident prevention.

For the interpretation of the large amounts of data, methods such as AI are needed that make them manageable. At the same time, it can be assumed that improvements in the case of incident management and explicitly for self-rescue can be achieved through the possibility of individualised responses.

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