RiskTUN: An ICT-based Concept for a Risk-aware Decision Support System for Tunnel Safety

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ABSTRACT

Safety in road tunnels are of utmost importance for the public notion of safety within the road system. In recent years, there has been significant progress in multiple areas of artificial intelligence, sensor fusion and communication technologies. Together with increase in computing power, this has enabled processing capabilities and aggregation of large amount of data from heterogenous sources. This allows for more intelligent decision-making in real-time in presence of risk in a dynamic environment provided by a decision support system. Previous work in this direction do not actively combine risk-awareness, real-timeness, and artificial-intelligence in a dynamic operational environment of a tunnel in operation for decision-making through considering the capabilities that recent technological advancements enable. To address this gap between decision-support systems and state-of-the-art technologies, this paper proposes RiskTUN, a general framework for developing risk-aware decision support systems for the safety of tunnels in operation. RiskTUN architecture allows for integration of various sources of data in a heterogenous environment where various stakeholders (e.g., road users, emergency responders, traffic centers, etc) can be both contributors or the users of the decision support system. There are major opportunities associated with taking better advantage of available data, but challenges are also identified and discussed. System implementations made based on RiskTUN framework are expected to better adapt to the user needs within the area of tunnel safety as technologies evolve.

KEYWORD: decision support, ict, emergency response, risk, tunnel safety

INTRODUCTION

Accidents in road tunnels can and do occur. A fast and effective response by traffic operators and emergency responders can mean the difference between life and death. Recent history has shown that tunnels constitute dangerous environments in case of emergency [1]. Disasters such as the Mont Blanc Tunnel fire (Italy–France, 1999) and the St Gotthard Tunnel fire (Swiss Alps, 2001) have caused many deaths and serious injuries. More recent tunnel accidents in Norway has revealed challenges associated with operators' and emergency responders' lack of dynamic information about vehicles and road users' positioning, safety equipment status and smoke management strategies [2].

The tragedies in mid-Europe and recent accidents have shown the need for an effective emergency response and the serious consequences of incorrect or delayed decision making [1] [3]. Accident prevention is a key factor in tunnel safety but by itself does not address the full extent of the problem since emergencies can still take place. Having an accident-preventative strategy along with a proper emergency management plan – one that maximizes the speed and effectiveness of a response – is vital to minimize the risk of injury and death [1]. Traditionally the decisions by the tunnel operator are based on fixed protocols that may not be suitable for all possible situations during the continuous development of an emergency [1]. At the same time, tunnel operators may have different incoming data at their disposal from each tunnel, since usually every tunnel is an individual entity with its own dedicated infrastructure [4]. When emergencies occur, time becomes a critical factor. The tunnel

operator, in these extreme and stressful cases, must deal with time-critical information and large amount of incoming data, whose processing for making an informed decision can create cognitive load (i.e., intense use of working memory resources) and delays and can potentially lead to erroneous decision making with grave consequences [5].
Moreover, successful emergency response often depends on the efficient collaboration of several actors – e.g., healthcare personnel, firefighters, police and road users – under stressful and time-critical conditions. In such situations, information about the situation, verification, and suitable presentation is highly important. For this reason, the information provided to the actors should be as comprehensible, complete, and prioritized as much as possible [1]. Research has supported that using decision support systems for emergency management in such complex situations can be highly beneficial [1] [6] [7]. Decision support systems are mainly based on automated processes in order to analyze the input coming from tunnel sensors and data, and assist the tunnel operator in making an informed decision in cases of emergency [1] [7] [8]. Figure 1 demonstrates a generic scheme of a decision support system for tunnel safety inspired by [1].

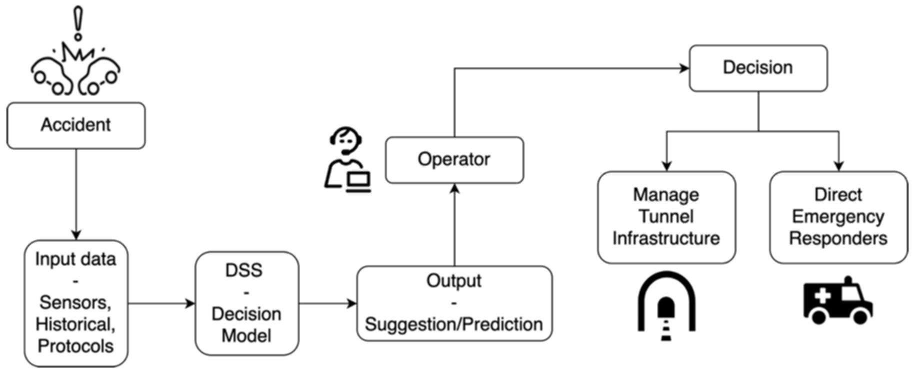

Figure 1 Accident scenario – general functionality of decision support system for tunnel safety inspired by [1].

Significant progress has been made in recent years in several fields – e.g., automation, sensor, communication, and data processing technologies – referred to as Information and Communication Technologies (ICT) hereafter. Hence, these new technologies allow for the aggregate of input data to be automatically gathered from various sources through communication links in order to inform the decision model in a more sophisticated decision support system than those employed previously. This process can potentially make use of Artificial Intelligence- (AI)-based methods for data processing and analytics as well as within the decision support systems' reasoning mechanism.

Moreover, the importance of incident prevention using decision support has been recognized [1] [8]. Efficient incident prevention requires accurate risk analysis [9] [10]. This necessitates a good understanding of the safety situation in the tunnel – i.e. the system's capability of preventing losses on the short and longer term. However, most current road tunnel risk analysis models only assess physical aspects of the tunnel system or consider hazards related to the transportation of dangerous goods through a tunnel [11]. They are therefore unsuitable for adoption by a decision support system for tunnel safety since they do not capture the dynamic changes in the tunnel and its environment and users – i.e., through dynamic changes in the traffic pattern, tunnel conditions or the evolution of an impending incident – which in turn affects the safety or the risk situation in the tunnel.

Problem statement
We therefore define the notion of *risk aware* decision support system as a system that takes into consideration the dynamic situation of risk using a broad and transparent risk model developed collectively by several stakeholders in its decision model. Using an exploratory research approach, we propose RiskTUN, a theoretical concept that combines the emergency management and incident prevention through introduction of dynamic risk analysis in the decision support system. The goal of RiskTUN is to provide a conceptualized framework acting as a high-level description and a guide for

the design and implementation of risk aware decision support systems that can be of further use by various stakeholders of the tunnel safety field as well as the researchers in the field.

Developing a decision support system is inherently a design task and progress in design projects often occurs by iterations and incremental development. Formulating the design problem is often part of the design task, which is also the case in this paper. Our method is therefore to reflect on our pilot development, and to clarify design problems that needs attention in the next phase. Safety analysis and holding a futuristic perspective, serves as an important basis for the decision support system. We cannot validate, in the traditional sense of the concept, analyses (or models) of the future. This calls for a fundamental analysis of the risk concept, as it is applied in RiskTUN, and how its characteristics and application affect the development prosess. A thorough discussion is beyond the scope of this paper, in which we focus more on the user needs, technology and architecture, but will be provided in a separate work. However, we will provide a summary of user needs in this paper.

User Benefits

In identifying the user benefits we use Norway as an example use-case due to the fact that the country has numerous tunnels within a complex geographical landscape and tunnel safety is of high importance for various tunnel safety stakeholders within the country. Table 1 presents the potential benefit(s) of RiskTUN framework for each stakeholder in Norway.

Table 1 The tunnel safety stakeholders in Norway; user needs and potential benefits from RiskTUN decision support system framework.

Stakeholders	**Potential benefit**
Norwegian Ministry of Transport (NMT)	Decision support to management of traffic safety and tunnel safety regulations. Decision support for administration and communication with the European commission.
Norwegian Public Road Directorate (NPRD)	Decision support to management of traffic safety and tunnel safety regulations.
Tunnel owners/ managers (NPRA, Regional municipalities and Nye Veier)	Decision support on risk-exposed tunnels or elements, to support prioritization of rehabilitation funding. Information about the operational status of tunnels and equipment, to support efficient management and maintenance.
Norwegian Public Road Administration (NPRA), traffic control centers	Decision support for actions to prevent tunnel accidents. Decision support for consequence-reducing actions during tunnel accidents. Workload reduction from automatic alarm management.
Norwegian fire and rescue services	Decision support to prioritize risk prevention activities. Decision support to on-scene emergency management commanders. Decision support to rescue personnel involved in tunnel accidents.
Road users	The road users are intended as the main profiteers of the riskTUN solutions. From a long-term perspective it includes improvements in safety design, traffic management and education. In a short-term perspective, riskTUN will provide road users with decision support to better facilitate for self-rescue in tunnel accidents. Road users will receive targeted (position specific) information, suggested actions, and wayfinding guidance.
Road management and maintenance contractors	Decision support on maintenance intervals for specific equipment in tunnels.
Research institutions	Better understanding of accidents and underlying causes.
Engineering consultants	Data for risk assessments in design of new tunnels.

Our paper's motivation
Our motivation for this paper stems from the emerging need for such decision support system in Norway – a mountainous country with more than 1200 road tunnels spanning across the entire country, 641 of which are being monitored by the Norwegian central traffic center. Keeping the flow of transportation and mobility within Norwegian tunnels safe and efficient is of great long-term strategic importance for Norway and plays an important role in the country's policy on public road infrastructure. In Norway, the operation of the tunnels are presided by five traffic centers across the country known as *Vegtrafikksentralen*, shortly referred to as VTS hereafter. In addition, the maintenance of tunnels by various contractors also needs to be coordinated with the VTS. Therefore, the risk aware decision support system can potentially be deployed at the VTS which can provide emergency responders and road users with necessary information for decision-making.

It is worth noting that our paper's primary focus is mainly on tunnels in operational and maintenance and emergency situations that can arise during these phases. While risk assessment and analysis are also highly important during the design and construction phases and can benefit from informed decisions during operation and maintenance – e.g., in construction of future tunnels – we explicitly choose to maintain our focus on the operation and maintenance phases due to the dynamic aspects of risk for tunnels in operation and maintenance which needs to be investigated on its own merits.

Our paper's contributions
The main contributions of our paper are as follows:

a) We identify the system description and user needs from various stakeholders in tunnel safety.
b) We contribute to EC directive 2004/54/EC which requires best practice risk management approaches for tunnels. While most other decision support models are investigating larger time spans, RiskTUN is focused on real-time and dynamic risk management aspect. The approach taken by RiskTUN is connected to addressing the user needs – e.g., from traffic manager perspective.
c) We investigate various risk factors and associated key performance indicators in road tunnels.
d) Most importantly we provide a conceptual framework on risk aware and dynamic decision support system for tunnel safety.

Paper structure
The remainder of this paper is structured as follows: Section 2 provides a background on already proposed decision support systems for roads and traffic management in general and for tunnels in particular and makes a case for a dynamic risk aware decision support system for tunnels in operation and maintenance. Section 3 provides insight into understanding the risk in road tunnels as a prerequisite to designing a risk aware system. Section 4 presents RiskTUN as risk aware decision support system for road tunnel safety. In doing so, it identifies the actors and user needs, functionalities, risk factors in tunnels and proposes a generic system architecture. Section 5 lays out a detailed discussion on several important aspects related to RiskTUN – i.e., on how to understand the risk in road tunnels, applicability of artificial intelligence in RiskTUN, and design suggestions. Finally, Section 6 concludes the paper and presents the future work.

BACKGROUND

In this section we provide background on the use of decision support systems in the context of road tunnels. First, we investigate the use of decision support for road (and tunnels) in general. Second, we look into related work on real-time decision support for the public roads. Third, we focus on the prior use of decision support for traffic management. Fourth, we discuss the previous initiatives on decision support particularly aimed at road tunnels. Finally, given the limitations of each category, we make a case for our dynamic risk-aware RiskTUN framework for road tunnels in operation.

Decision support systems for road and tunnels
Decision support systems have been considered for use on the maintenance and operation of the road network. For instance, Fancello et al. propose a multi-criteria decision support system model based on

concordance analysis to provide the road administrator with the information on the road segment with the worst safety conditions identified based on variable weighting criteria [13]. Dell'Acqua et al. proposes a decision support system to identify and rank hazardous sites on road networks supporting road administrators in defining infrastructure projects to reduce these sites on the road networks [14]. On the other hand, the SafetyCube DSS project (2015-2018) [15] has developed a decision support system tool aimed at policy makers and stakeholders that identifies numerous road accident risk factors and related safety counter measures extensively [16]. An important aspect of road safety is identifying the Key Performance Indicators (KPIs). This has been addressed by Meißner et al. for use-cases where polices are involved [17].

Real-time decision support on the roads

Mentioned works in previous sub-section focus on general policy and decision making by the road safety authorities and lack real-time response to the events and incidents as they occur on the road, something that is necessary for road monitoring during the operation and maintenance – e.g., for central traffic monitoring center. Zografos et al. propose a real-time decision support system for road Incident Response Logistics as part of an Incident Management System aiming at reducing the incident duration, among other things by producing the shortest route to the incident [18].

Decision support for traffic management

Wismans et al. [19] and Casas et al. [20] offer decision support system for traffic management by providing the short-and medium-term predictions of traffic state based on surveillance systems data and simulation inputs respectively. Moreover, current practices of decision support system for traffic management are laid out by Miller et al. [21]. Other works such as [22] focus on the use of decision support system for active traffic management – e.g., by employing the notion of travel time reliability using a model predictive control method hence allowing for identification of a proper response plan for the reduction of travel time and the improvement of its reliability.

Decision support for tunnels

Use of decision support system in tunnels has been considered in different contexts. For instance, decision support system can be used in guiding the tunnel construction. An ongoing project at the University of Alberta explores the possibility of an automated and integrated decision support system for tunnel construction leveraging real time data to direct tunneling operations in reaction to deviations or irregularities in construction [23]. Another similar ongoing project at the University of Rutgers takes into consideration risk assessment and management in large scale tunneling projects through identification of risky spots along the tunnel as well as quantitative risk assessment [24].

On the other hand, decision support system has also been considered for the operation of road tunnels as explored by Alvear et al. [1] – e.g., by using a predictive model that provides the tunnel operator with the decision recommendations based on the severity of an incident and associated rescue and evacuation times. Capote et al. [8] present EvacTunnel, a real-time stochastic evacuation model for road tunnels. While the decision support model in EvacTunnel is aimed at providing shorter response time, it is exclusively focused on tunnel evacuation during emergency response and does not consider the real-time decision support for prevention nor the involvement of various stakeholders in a dynamic environment. Another example is an earlier European project SIRTAKI that focused on the use of ICT for a generic decision support system in road and rail tunnels [25]. Although many architectural insights from SIRTAKI is still valid the ICT technologies has significantly been revolutionized since the project's conclusion in 2004. Therefore, the need to take into consideration the state of the art and emerging sensor, communication and automation technologies persist though some high-level architectural insights from SIRTAKI can still be relevant today. This is something that RiskTUN aims to investigate.

RISKTUN DECISION SUPPORT FRAMEWORK

The main contribution of the work presented in this paper is RiskTUN, a concept for a risk-aware decision support system for tunnel safety. In this section we present the RiskTUN concept, including stakeholders, their needs, as well as the anticipated functionality supporting these needs. We also outline the most important risk factors that RiskTUN should handle, and a high-level systems architecture.

Identified actors and their needs
The main stakeholders involved in tunnel operations and emergency response are: a) tunnel operators, b) emergency responders (fire rescue service, ambulances, etc.), and c) road users (e.g., passengers and drivers). RiskTUN supports tunnel operators both during day-to-day operation and during emergencies, while emergency responders and road users are mainly supported during emergencies. During day-to-day operation, RiskTUN provides a real-time risk picture for a given tunnel. This picture supports the need for accident prevension, and hightlighs possible risks based on collection and processing on data collected from sensors, systems and services.

During an emergency, RiskTUN supports different need for the three types of stakeholders. A tunnel operator provides information for emergency responders and road users. This information will primarily be collected from RiskTUN, but may also come directly from people in or close to the tunnel. In addition to providing information, a tunnel operator will also do various measures like turning on/off or change the direction of fans, close parts of or the entire tunnel, and give audio instructions through car radios and/or speakers in the tunnel. Such measures are executed through existing systems in the tunnel, like the SCADA systems. Emergency responders primarly need as accurate and up-to-date information as possible to respond to an emergency in a best possible manner. This information may come orally from the tunnel operator, and/or through a tailored, mobile version of RiskTUN focusing on the needs of emergency responders. Important information for emergency responders includes the exact type of incident, the location of the incident, the types of vehicles involved, access routes, and temperature in different parts of the tunnel. Road users primarily need information aiding their ability for doing self-rescue. This may come orally from the tunnel operator, from signs and lights in the tunnel, and/or through a tailored, mobile version of RiskTUN focusing on the needs of road users. The most important information are evacuation routes and safety information, like whether they should evacuate the tunnel by driving out (in some direction), stay in the car, or try to walk (in some direction) to a place of safety. RiskTUN is intended for use and facilitation of the stakeholders' need just outlined. Below, we present the main functionality supporting these needs.

Functionality
The functionality of RiskTUN decision support system is visualized in Figure 2. The RiskTUN decision support system is basing its operation on three elements: i) input data, ii) operation platform, and iii) notifications and navigational assistance. The design of these elements is inspired by decision support system for road tunnels currently described in research literature [1] [2] [3] [8] [9] [11] [26], cross-referenced with real-life practices and needs, coming from discussion with representatives from stakeholder organizations.

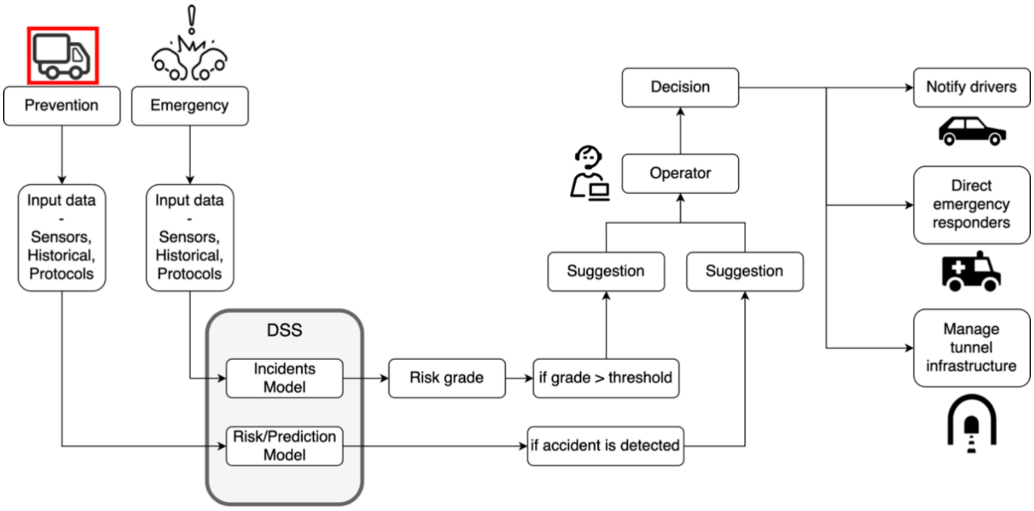

Figure 2 The RiskTUN functionality.

RiskTUN collects input from the available tunnel technologies, i.e., cameras, Automatic Incident Detection (AID) systems, thermal sensors, fire detection systems, phone booths, etc., along with tunnel's characteristics (e.g. length, elevation, direction and angle of turns, etc.). The central element in RiskTUN's input stream is vehicle positioning and communication. There is the need for precise and cost-effective positioning technology of vehicles in tunnel conditions, where global positioning systems (GPSs) do not work [27].

Bluetooth Low Energy (BLE) technology is presently considered as the primary form of wireless technology in mobile devices and has been suggested as one of the most cost-effective and efficient method for indoor positioning when GPS is not available [28]. Other technologies can be used and, potentially, be more efficient. For example, positioning could be done with cameras (normal and infrared) and communication could be done through GSM/xG radio systems. The work of Khademi and Sommer [29] is also a promising alternative, focusing on 5G cellular networks and the new opportunities that arise from their deployment within the tunnels. In a longer timeframe, vehicle-to-infrastructure solutions that are coming and already exist in some modern cars may also be used. In RiskTUN we focus on established technologies that could provide a satisfactory ratio of cost/efficiency, without having to rely on any previously installed tunnel equipment.

When the input data are collected, a risk grade is assigned to every vehicle entering the tunnel for accident-preventative purposes. In case prevention is not possible and an accident does take place, the same data are used to handle the emergency quickly and to assign risk grades for further derived accidents – e.g., to avoid multiple-vehicle collision. The system, based on the tunnel's protocols, suggests respective actions to the user, i.e., the tunnel operator, so that it alleviates the cognitive load coming from drafting action plans in cases of emergency. The suggestions come with the related explanations (explainability) – i.e., data and information that justify the suggestion, thus avoiding creating a "*black box*" system, which the user have to trust blindly. The algorithms and AI applied at this level are of deterministic nature and the tunnel operator is the one making the decisions, deciding to approve or decline the system's suggestions. The User Interface (UI) of the platform is an important element since it must support the cognitive-load relief coming with the explainability of the system. To that end, we have gone beyond traditional decision support system functionality and designed an adaptive UI that produces alerts and shapes itself based on the related emergency. The operation platform facilitates the tunnel operator's access to information and it also coordinates – based on the approved actions by the operator – the output that comes in the form of notifications and assistance for the emergency responders and the drivers.

The output of the system/operation platform will be disseminated according to each emergency and the actions taken/confirmed by the tunnel operator. The target here is to design a decision support system that not only supports the decision-making process of the tunnel operator but of the emergency responder and the road user, as well. Therefore, the system must be able to notify drivers and assist emergency responders in a critical situation. The system will support current protocols which dictate that in case of an accident, vehicles in the tunnel are treated in zones and differently depending on their distance from the accident site – i.e., vehicles closer to the site need immediate attention, etc. Tunnel notification equipment, such as LED displays and illuminated exits can be used for these purposes. Design suggestions on the navigational assistance that may be provided to the stakeholder through UIs and applications designs are presented in the sub-section on Design suggestions.

Risk factors in road tunnels

In RiskTUN, input data from in-tunnel conditions will be collected and a risk grade will be assigned to every vehicle entering the tunnel, for accident-preventative purposes. To do so, there is the need to identify the risk factors that synthesize the risk picture of a tunnel. The identification and synthesis presented below is based on recent related work on risk factors for Norwegian tunnels [36], as well as international work on the subject. We group risk factors into *primary* and *secondary* ones. Primary risk factors are the basic ones which apply in every case, producing a risk grade for every vehicle entering a tunnel. Secondary risk factors do not apply in every case, i.e., are circumstantial. These factors can be the result of primary factors or take place individually. When occurring, both primary and secondary risk factors may lead to different types of *incidents*. In Table 2 and Table 3 we present the primary and secondary risk factors currently identified for RiskTUN, and indicate which risk factors that may cause which types of incidents. In the tables there is one column for each risk factor, and one row for the incidents these risk factors may cause. "Black holes" refer to risks due to sudden change in visual environment – i.e., the driver adapting to the dim light condition ("black hole"), and speed variations among drivers [32] [33] [37] [38]. The other risk factors should be self-explanatory.

Table 2 The primary risk factors and the incidents they can cause.

Risk factors → Incidents↓	**"Black hole"**	**Driving attitude** [30]	**Highway geometric design** [31] [32] [33]	**Traffic volume** [32] [33][30][9]	**Vehicle type** [33] [34] [12] [26]	**Surface conditions** [32]
Crash (with or without fire)	X	X	X	X	X	X
Overheating/ Fire without crash				X	X	
Ventilation problem [35]				X		
Road spillages	X	X	X		X	
Respiratory issues						

Table 3 The secondary risk factors and the incidents they can cause.

Risk factors → Incidents ↓	**Road Spillages**	**Crash**	**Fire**	**Ventilation**	**Pedestrian/ Animal/ Object on the road**
Crash (with or without fire)	X	X	X		X
Overheating/ Fire without crash			X		
Ventilation problem		X	X		
Road spillages		X			
Respiratory issues		X	X	X	

In Table 4 we detail the incidents' characteristics and what kind of outcomes might the aforementioned incidents have. Eventually, there may be a connection between two incidents – e.g., a crash causing a fire. However each incident can also take place on its own.

Table 4 Summary of incidents that may happen inside tunnels along with their potential outcomes.

Incident	Potential outcomes		
Crash	Fire	No fire	
	Spillage	No spillage	
	Serious (injuries, fatalities)	Light (rear-end)	
	Can cause another crash	Can stop traffic	No effect
Spillage	Serious (can cause crashes)	Light (no effect)	
Fire	Regular	Toxic	
Ventilation malfunction	Serious (can cause respiratory issues)	Light (no significant effect)	
People/Animal/Object on the road	Can cause crash	Can stop traffic	No effect

Table 5 Possible Key Performance Indicators for the identified risk influencing factors

Risk influencing factor (RIF)	Main indicators	Related sensors	Measurement frequency
- Primary Risk Factors -			
"Black hole"	Position in the tunnel (in meters)	Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)
	Direction	Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)
Driving attitude	Speed (km/h)/vehicle	Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)
	Number of lane changes/vehicle	Cameras, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)
Highway geometric design	Curvature of turns (degrees)	Tunnel's construction design data, Manual measurements	Monthly
	Elevation (degrees)	Tunnel's construction design data	Annually
Traffic volume	VKM (vehicle X km)	Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)

Vehicle type	Vehicle category (private car, HGV, motorcycle)	AID, details from the RiskTUN app or AutoPASS	Upon entrance
Surface conditions	Temperature (degrees Celsius)	Thermal cameras	Constant (every second)
- Secondary Risk Factors -			
Road spillages	Temperature (degrees Celsius)	Thermal cameras	Constant (every second)
Crash	Vehicles being extremely close to each other or to a tunnel element (e.g., wall)	AID, Indoor positioning (BLE/RiskTUN app or RFID/AutoPASS)	Constant (every second)
Fire	Temperature (degrees Celsius)	Thermal cameras	Constant (every second)
Ventilation	Binary (working/not working)	Ventilation system	Hourly
Pedestrian/Animal/Object on the road	Foreign object in tunnel	AID, Thermal cameras	Constant (every second)

Based on the tables above and RiskTUN concept and functionality, we define the Key Performance Indicators (KPIs) for calculating the risk factors in an objective way. KPIs consist of the main indicators, the related sensors that can capture the main indicators in a, as much as possible, quantitative way, and measurement frequency. The defined KPIs are summarized in Table 5.

System architecture

Figure 3 presents a logical view of the system architecture for RiskTUN. This architecture shows the main component in a decision support system, supporting different types of reasoning mechanisms and both actual sensors being deployed and simulation of sensor values. The core of the architecture is a *reasoning mechanism*. This may be a traditional probabilistic mechanism or a module based on AI/ML. In both cases the reasoning mechanism need a *risk model*. When using AI/ML, the risk model will be built from *training data*, typically log data, including from past events. When using a probabilistic model, the training data plays a less important role, but is still needed to verify that the reasoning mechanism evaluates historical data correctly.

At runtime, the reasoning mechanism works on real time data from *sensors* and *services.* This includes sensors and other mechanisms for *positioning* – i.e., determining the position of vehicles, persons, incidents, etc. AI/ML may be used as part of the processing of sensor data and/or when fusing data from different sensors. The *input interface* makes it possible to use *input simulators* in combination with or instead of real time data. This interface will enable such changes to be transparent to the *input collector* and reasoning mechanism. The role of the input collector is to collocate value from different sources, including to synchronize data with time stamps. The input collector may also do some types of sensor fusion to provide derived and richer information. Any suggestions from the reasoning mechanism are communicated to the users through the *user interaction*, denoted *driver UI, VTS UI* and *ER UI* in Figure 3. Users in the tunnel (e.g., drivers and emergency responders) may be equipped with sensors, including positioning. Information provided by such sensors are also relevant for the reasoning mechanism and is transported through the input interface and input collector.

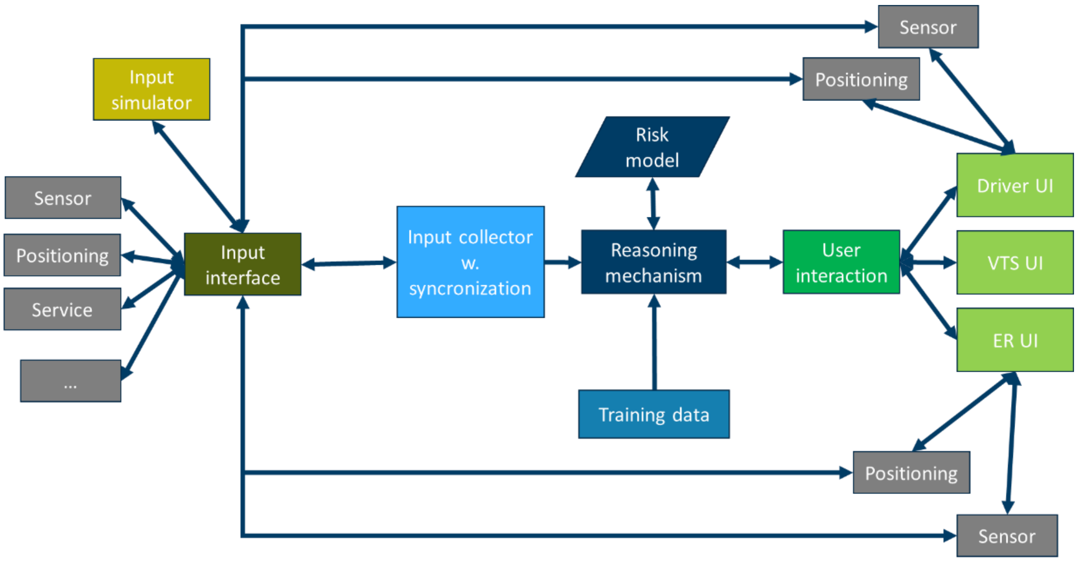

Figure 3 Logical system architecture

DISCUSSION

In this section we elaborate on understanding the risk in road tunnels, provide insight on the applicability of artificial intelligence in RiskTUN, and offer design suggestions for the RiskTUN's UI.

Understanding the risk in road tunnels

Risk analyses of road tunnels became a major issue following the implementation of Directive 2004/54/EC on Minimum Safety Requirements for Tunnels in the Trans-European Road Network, which aims to ensuring a minimum level of safety for road users in tunnels with lengths above 500m on the Trans-European Road Network (TER-N). Risk analysis is introduced as a tool to support both design decisions and tunnel operation. This duality is also made clear in the preparatory work for the directive. For instance, in the European Commission's white paper on European transport policy for 2010, it is specified that the "European Union can help to improve safety both at a technical level and in the way in which tunnels are operated" [39]. In Norway, risk analyses are conducted to support design decisions in all tunnel design projects.

Best practice risk analysis methods for design purposes and assessment of the risk associated with dangerous goods transport through tunnels has been subject to extensive research since mid-2000s. However, implementation and research into risk analysis for tunnel operation, including emergency response, is not equally common, although some examples exist in the literature [1] [8] [40] [41] [42]. No such tool for real-time risk analysis to support tunnel operation and emergency response exist in Norway. By developing the RiskTUN concept, we aim to support decisions to be made in real time by tunnel operators, road users and emergency responders, to both prevent and reduce consequences of accidents. In 2007, the European Parliament commissioned a study on Assessment of the Safety of Tunnels [43], which highlights challenges associated with risk analysis of road tunnels. The study also includes recommendations on how to apply risk analyses in the context of tunnels. Although, the publication is coming of age, it is interesting to note its recommendations and discuss today's status on these issues, in the context of RiskTUN. Some of the recommendations to improve road tunnel safety, which are relevant to the RiskTUN project, are discussed below.

<u>Coordinated European action to collect and distribute information and knowledge</u>: Appropriate and readily available data is essential for any analysis. Beard & Cope [43] calls for a coordinated European action to improve data availability and quality, which includes, inter alia, a uniform system for reporting of incidents, continuous improvements of the knowledge base for dynamic systems (new vehicles, new transport services, climate change, population development, distribution of goods

road/rail etc) and best practice definitions. Presently, it is hard to see that such coordinated action has occurred, which means that the availability and quality of data relevant for detailed risk assessments are scarce. The original concept for RiskTUN, which is described in this paper, implements fundamentally a deterministic risk analysis model, which is inherently vulnerable to incomplete understanding of risk phenomena and dynamicity. Existing tunnels produce extreme loads of potential data, which is presently unstructured and not coupled to models representing risk phenomena, i.e. tunnel fires. A next step for RiskTUN should be to consider whether machine learning methods could be applied to transform the flow of data into appropriate real-time decision support.

Open source: the recommendation from Beard & Cope [43] is especially concerned with open and readily available source codes computer models and code. The key is to provide transparency into modeling and modeling assumptions, as well as not commercialize the safety of tunnels. Since 2007, there has been an immense development in data processing capacity of computers, which has paved the way for machine learning methods in many societal areas. A shift from deterministic and probabilistic risk models to introduction of deep learning networks, calls for new ways to handle transparency and explainability of decision support systems. In a previous study [44], we conducted an analysis of a new "best practice risk assessment software" for tunnel design projects, and pointed to several challenges, including black-box behavior, limiting assumptions associated with the concept of risk, and issues associated with flexibility and dynamicity connected to the commercial interests of the developer. RiskTUN stands at risk of meeting the same challenges and due considerations should be made in the further development process to provide transparency, explainability and flexibility for the user in the context of a constantly changing world.

Appropriate regulatory framework: the major point of Beard & Cope [43] back in 2007, is that a tunnel design and management regime based on model-based risk analyses, is quite a paradigm change. Traditional safety management in the tunnel industry is built on experience-based prescriptive solutions and procedures. Although existing Norwegian, and European through the EC Directive, regulations open for risk-based decision making, the old paradigm has a strong foothold. For the RiskTUN development project, this means that successful implementation is far from only a technical issue. Adaption of regulations, with special emphasis on European regulations on the use of AI for safety critical decisions, might be necessary. More important might be the cultural change within the tunnel industry necessary to trust recommendations provided by a decision support system based on real-time risk analysis.

Independence of analyst and system: according to Beard & Cope [43], risk assessments should be conducted by a person who is independent person of the system under scrutiny and checked by another independent person. A similar formulation is implemented in the EU directive on tunnel safety (2004/54/EC). In the case of RiskTUN, or any other real-time data-based risk analysis tool, on can ask who is performing the analysis? A deterministic or probabilistic model is pre-determined by the developers, which certainly fulfills the independence criterion. An AI-based decision support system is similarly built by the developers, although one can discuss whether the decision support system is doing the analysis itself. Still, there is independence between the analyst and the system under consideration. However, a major benefit of risk analysis is the possibility of including local, project-specific, and context-specific knowledge into the assessment. Another recommendation from Beard & Cope [43] which highlight this is that measures should be taken to establish a healthy mixture of prescriptive requirements, qualitative risk assessments and quantitative risk assessment in decision-making on safety. In many cases, the best provider of qualitative, local and context-specific knowledge will be persons associated with the system under scrutiny – e.g., the tunnel operator at the control center. Consequently, we question the general recommendation of independence. On the contrary, we are explicitly calling on the user to support the decision support system with its own personal risk analysis. A tunnel operator who blindly initiates actions based on the independent decision support system would be a dangerous operator.

Criteria for acceptability of risk should be explicitly decided: ever since the early morning of risk analyses, risk experts have cried their need for explicitly stated risk acceptance criteria. The idea is that without such criteria, risk analyses are futile and insipid. However, risk analyses are conducted in every Norwegian tunnel design project and are still considered useful [45], without any nationally stated risk acceptance criteria. Hence, we question the validity of the general recommendation. However, RiskTUN would ideally become a tool that constantly supervises the risk level of hundreds of tunnels. It seems rather clear that it is of vital importance to strike the appropriate balance between sensitivity and specificity to not overload the tunnel operators with red flags or risk reducing recommendations.

Consider specific hazards associated with road tunnels: according to Beard & Cope [43], steps should be taken to consider specific hazards associated with tunnels and underground spaces. This includes considering whether measures adopted for non-malicious acts are adequate for malicious acts, reduce deaths and injuries from common traffic, i.e. non-fire accidents, address the challenge of heavy goods vehicles in tunnels and prevent hydrogen-powered vehicles from passing through tunnels. The latter serves as a reminder of the loss potential associated with hydrogen and other new energy carriers introduced in tunnels now and in the future. Still, the recommendation of a prohibition of hydrogen in road tunnels seems rather unrealistic in 2023, considering climate change and the move towards sustainable transport systems. Similarly, malicious acts have gained increased attention since 2007 and a more digitized and interconnected transport network increases vulnerability to both physical and digital malicious acts. RiskTUN is currently considering safety of road users. Future development steps should carefully consider whether it cover issues such as malicious acts and the dynamicity connected to technology, energy carriers and climate change.

Applicability of artificial intelligence in RiskTUN

The use of AI is envisioned in RiskTUN framework and is an important part of it. AI can potentially be applied in various components of RiskTUN architecture. For instance, AI can be applied to sensors and services – i.e., at the edges of the architecture (see Figure 3). An example of this is the use of AI in automatic incident detection sensors. In addition, AI can also be used for the reasoning mechanism by leveraging the training data. Providing a set of training data representative of different scenarios and dynamic conditions in a road tunnel has been a major challenge. However, when *aggregate* of data over *many* tunnels across an entire country and over *long time-span* and from *various sources* (e.g., road-side sensors, vehicles, etc) are leveraged, a more representative set of training data can be derieved. In addition, it is expected that in the future, as connected (and automated) vehicles become more prevalent on the road system, more publicly available vehicular data become available. The privacy regulations and scope of data types, sharing and access policies and methods are out of scope of this paper and require a separate work.

RiskTUN can be somewhat considered as a safety-critical system, as it provides recommendations for safety-critical situations in road tunnels – e.g., to the VTS operator or emergency responders. European Commission's proposal (COM(2021) 206 final) [46] lays down harmonized rules on AI and among other things discusses specific mandatory rules for high-risk AI systems. The AI mechanisms implemented in RiskTUN, particularly in the system core (i.e., reasoning mechanism) should therefore allow for explainability of the recommended decisions, and human operator oversight.

Design suggestions

As RiskTUN is a framework and not an operational system, the actual UI design of the functionality for the stakeholders is not specified. Still we provide some early sketches of possible UIs for mobile applications for road users and emergency responders. For the RiskTUN functionality to be useful for tunnel operators it needs to be integrated into the operational systems used by the tunnel operators today. As different tunnel operators use different operational systems, we do not provide design suggestions for tunnel operators. In Figure 4, we present example UIs (low-fi prototyping sketches) for a possible driver application (left) and a possible mobile application for emergency responders.

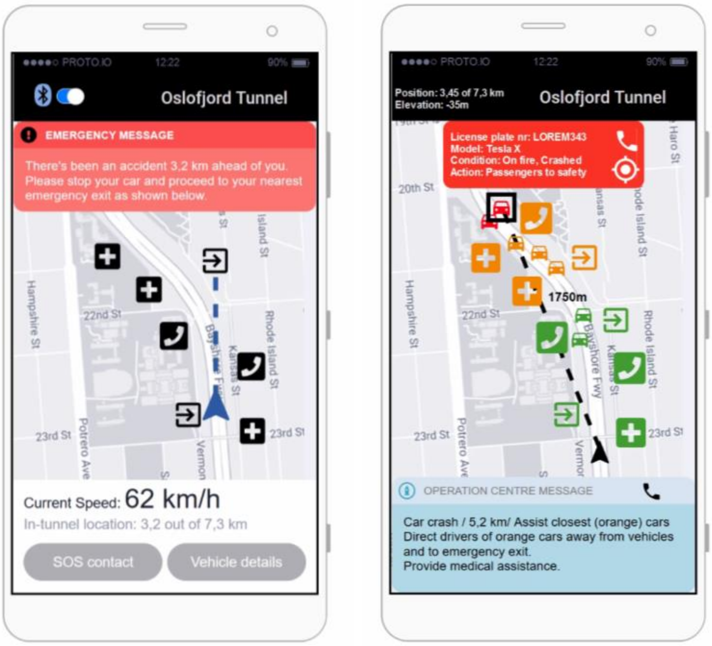

Figure 4 UI prototypes of the RiskTUN mobile application for road users (left, including an example notification), and for emergency responders (right, providing navigational assistance)

This UIs follow the paradigms of prevalent navigational applications (e.g., Google Navigation, Waze) and offers a top-down view of the tunnel. One implementation option for these applications is to provide them as plug-ins to navigation systems used by road users today, either on mobile phones or to in-car navigation systems. For emergency responders, an additional channel of communication between the operator and the emergency responders can be established through a mobile application that displays messages from the operation center and the position and additional information on vehicles inside the tunnel. It can also display the vehicle zones based on which different protocols are applied and the vehicles are treated accordingly. In the right part of Figure 4, the colors of the cars represent the zones; with red signifying the vehicles that were involved in the accident, the orange icons being the vehicles and tunnel equipment in the vicinity, and the green ones are the ones away from the accident site and in a safer place. At the same time, the operator can also see the position of emergency responders and have a better overview of the situation. From our discussion with emergency responders, it is a common practice for rescue team members to carry mobile devices.

Potential contributions to EC directives

As previously mentioned, the EC directive on minimum safety in road tunnels 2004/54/EC, was a major trigger for widespread application of tunnel risk analyses and risk model development within tunnel safety, and consequently fundamental for the RiskTUN work as well. However, a successful development and implementation of RiskTUN, or similar tool, has the potential of developing new knowledge about tunnel safety, by identifying leading indicators that lead to accidents, coupling of data to accident phenomena and identifying weak linkages (high risk tunnel systems) in the road system. RiskTUN has thus the potential of supporting development EC regulations and best practice risk analysis methods for road tunnels.

CONCLUSIVE REMARKS AND FUTURE WORK

In this paper we presented RiskTUN, a risk-aware decision support system for tunnel safety during operation and maitainence phases. RiskTUN's idea is motivated by the emergence of new ICT technologies, and the aggregate of data that can be leveraged in an intelligent way for better decision making. New opportunities arise when various tunnel safety stakeholders are involved in the process. For doing so, we have identified the potential benefits and user needs of each stakeholder. Further we have identifies the risk influencing factors in road tunnels through a literature study and insight gained from various stakeholders and laid out potential KPIs associated with these factors in order to form a risk picture. RiskTUN's system architecture allows for the use of AI/ML both in reasoning mechanism as well as within sensors and services. Our work in this paper is primarily focused on motivating the RiskTUN idea and laying out the system architecture. A more detailed exploration of the risk ontology, understanding risk in the context of road tunnels and the issue of uncertainty and its relation to risk assessment is out of main scope of this paper and will be presented in a separate work. While our proposed RiskTUN idea is a generic decision support system framework, real-life implementation work inspired by it will be undertaken by us in the future through collaborative initiatives with various tunnel safety stakeholders in Norway.

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