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Report

RiskTUN: Risk-aware Decision Support System for Tunnel Safety

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Table of Abbreviations

AI	Artificial Intelligence
AID	Automatic Incident Detection
BLE	Bluetooth Low Energy
BM	Bluetooth Module
DSS	Decision Support System
ER	Emergency Response
FHSS	Frequency-Hopping Spread Spectrum
GPS	Global Positioning System
ISM	Industrial, Scientific, and Medical
KATS	Kapasitetsløft Tunnelsikkerhet
RFID	Radio Frequency Identification
SVV	Statens Vegvesen
UI	User Interface
VTS	Vegtrafikksentralen (Traffic Control Center)

Abstract

Nowadays, technology can be a key tool to improve the effectiveness of emergency management and human safety in road tunnels. The advantage of using decision support systems (DSSs) for emergency management in complex situations is well known. These systems are mainly based on automated processes in order to analyse the input coming from tunnel sensors and data and assist the tunnel operator in making an informed decision in cases of emergency. Moreover, the importance of incident prevention has been recognised. Incident prevention takes place through risk analysis, which has been introduced as a way to calculate the probability for events with a large number of fatalities or material damage to occur in a tunnel. The majority of current road tunnel risk analysis assess physical aspects of the tunnel system and consider several hazards concerning the transportation of dangerous goods through a tunnel.

In this work, we present a theoretical concept around the combination of emergency management and incident prevention through risk analysis in DSSs. The proposed concept addresses the research question "To what degree can we introduce risk analysis in a DSS system, combining it with its emergency management functionality, and how?". The ultimate goal is to provide a conceptualized framework acting as a high-layer description and a guide for the design and implementation of risk-aware DSSs that can be of further use by researchers and practitioners of the field.

RiskTUN is targeting a dual functionality: incident/accident prevention and emergency management. RiskTUN is intended for use and facilitation of the stakeholders' operation. These stakeholders that are involved in tunnel emergencies are as following: i) tunnel operators, ii) emergency responders (fire rescue service, ambulances, etc.), and iii) road users (e.g., passengers and drivers).

The RiskTUN DSS is basing its preventative operation on the collection of input data from the available tunnel technologies/sensors, which are then analysed, and a risk grade is assigned to each vehicle in the tunnel. If the grade is beyond a certain threshold a suggestion for action along with an explanation as to why this suggestion is made, is sent from the system to the operator. Then, the operator can make a decision so that an accident is prevented and inform the road users, emergency responders (if needed), as well as use tunnel's emergency equipment. The same process is followed for the emergency management functionality; however, the risk grade is only used for secondary accidents, e.g., multiple car collision. The indoor positioning system of RiskTUN (mobile application), the RiskTUN navigational mobile application for emergency responders, key performance indicators for tunnel road safety, multi-attribute decision-making (DEXi) models, and sketches of the DSS's user interface are presented and discussed, among others.

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1 Introduction

Norway, being a rather mountainous country, has today more than 1000 road tunnels, while approximately 641 of them are monitored. 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 this report, we direct attention to both the *operational phase* and *emergency response situations*. In the operational phase, a major goal is to maintain continuous control over the system to prevent the occurrence of accidents, keep track of operational and technical status in the tunnels, and sharing information with other relevant actors of the "safety system", e.g. the fire and rescue service and the emergency dispatch ("110 central"). When emergencies occur, *time* becomes a critical factor. Successful emergency response often depends on the efficient collaboration of several actors under stressful conditions, which again is dependent on available decision support. In such situations, information about the situation, verification and suitable presentation is of the essence. The VTSs provide emergency responders and tunnel users (travellers) with information for decision support. In this report, we investigate how to improve both the operational phase and ER situations, by exploiting available and potential information sources to better comply with the needs of different tunnel system actors.

1.1 State-of-the-art

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. These tragedies have shown the need for an effective emergency response and the tragic consequences of incorrect or delayed decision making[1,2] .

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 that maximizes the speed and effectiveness of a response is a critical way to minimize the risk of injury and death[1].

The tunnel operator is the first professional agent to deal with the emergency and inform the tunnel users, supervisor and emergency services regarding the situation[1,3]. In many cases, the decisions of the tunnel operator are based on fixed protocols that *may not cover 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 every tunnel is, usually, 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 data, whose processing for making an informed decision can create *cognitive load*,

[1] Alvear, D., Abreu, O., Cuesta, A., & Alonso, V. (2013). Decision support system for emergency management: Road tunnels. Tunnelling and underground space technology, 34, 13-21.
[2] Burns, D. (2004). Emergency procedures in road tunnels: current practice and future ideas. In: Carvel, R.O., Beard, A.N. (Eds.), The Handbook of Tunnel Fire Safety, vol. 21. Thomas Telford Publishing, United Kingdom, pp. 437–450.
[3] Tesson, M. (2009). Adapting the road tunnel safety devices to the users. In: Proceedings of the 4th Symposium on Human Behaviour in Fire, Cambridge, UK, July, 2009, pp. 375–386.
[4] Kim, H. K., Lönnermark, A., & Ingason, H. (2008). Comparison of Road Tunnel Design Guidelines. In Proceedings from the Third International Symposium on Tunnel Safety and Security (p. 95).

i.e., intense use of working memory resources, and *delays* and can potentially lead to erroneous decision making under stress with grave consequences[5]. Moreover, successful emergency response (ER) often depends on the efficient collaboration of several actors under stressful conditions, which is dependent on available decision support. In such situations, information about the situation, verification, and suitable presentation is of the essence. The tunnel operation center provides emergency responders and road users (drivers and passengers) with information for decision support. For this reason, the information in these critical situations should be as comprehensible, complete, and prioritized as possible[1].

Nowadays, technology can be a key tool to improve the effectiveness of emergency management and human safety in road tunnels. Research has supported that using decision support systems (DSSs) for emergency management in complex situations can be beneficial[1,6,7]. Figure 1 demonstrates their general functionality. These 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[1,6,7]. Moreover, the importance of incident prevention has been recognised[1,8]. Incident prevention takes place through risk analysis, which has been introduced as a way to calculate the probability for events with a large number of fatalities or material damage to occur in a tunnel[9,10]. The majority of current road tunnel risk analysis assess physical aspects of the tunnel system and consider several hazards concerning the transportation of dangerous goods through a tunnel[11].

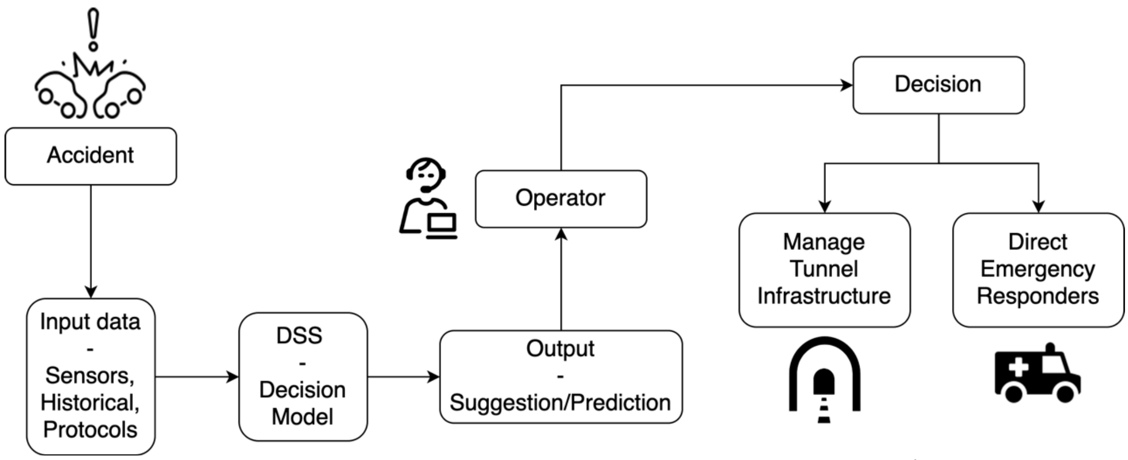

Figure 1: General functionality of DSSs for tunnel safety[1].

[5] Neerincx, M. A., Rypkema, J., & Passenier, P. O. (2003). Cognitive and functional (COLFUN) framework for envisioning and assessing high-demand situations. In Proceedings of CSAPC (Vol. 3, pp. 11-16).
[6] Yoon, S.W., Velasquez, J.D., Partridge, A.B., Nof, S.Y. (2008). Transportation security decision support system for emergency response: a training propotype. Decision Support Systems 46, 136–148.
[7] Yu, L. (2011). A distance-based group decision-making methodology for multiperson multi-critteria emergency decision support. Decision Support Systems 51 (307–315), 2.
[8] Capote, J. A., Alvear, D., Abreu, O., Cuesta, A., & Alonso, V. (2013). A real-time stochastic evacuation model for road tunnels. *Safety science*, *52*, 73-80.
[9] Petelin, S., Luin, B., & Vidmar, P. (2010). Risk analysis methodology for road tunnels and alternative routes. *Journal of Mechanical Engineering*, *56*, 41-51.
[10] Schlosser, F., Rázga, M., & Danišovič, P. (2014). Risk Analysis in Road Tunnels. *Procedia Engineering*, *91*, 469-474.
[11] Kirytopoulos, K., Konstandinidou, M., Nivolianitou, Z., & Kazaras, K. (2014). Embedding the human factor in road tunnel risk analysis. *Process Safety and Environmental Protection*, *92*(4), 329-337.

This work addresses the tasks T4.2 and T4.4 of the Kapasitetsløft Tunnelsikkerhet (KATS) project. T4.2 is about the *integration of mobile information and communication systems* while T4.4 concerns the *development of machine learning models that provide risk indicators for hazardous traffic conditions*. An exploratory research approach is followed in order to perform the aforementioned tasks, leading to a joined technical solution, expressed through a *theoretical concept*. The proposed concept is based on the combination of emergency management and incident prevention through risk analysis in DSSs. Moreover, it addresses the research question "To what degree can we introduce risk analysis in a DSS system, combining it with its emergency management functionality, and how?". The ultimate goal is to provide a conceptualized framework acting as a high-layer description and a guide for the design and implementation of risk-aware DSSs that can be of further use by researchers and practitioners of the field.

1.2 Objectives

Within the context of the KATS project, we approach the research question above from a conceptual point-of-view by setting the following main objective: *to design and propose a conceptual DSS for tunnel safety featuring a dual functionality, i.e., incident/accident prevention and emergency management*. The objective is based on four main characteristics/sub-objectives (SO):

1. Perform risk analysis of the in-tunnel conditions and each vehicle. This should lead to a risk grade/characterisation for the elements that exist inside the tunnel at a given time.
2. Risk analysis and emergency management being adaptive to every tunnel's available technology/sensors, ensuring its satisfactory-quality performance.
3. Provide suggestions for action to the tunnel operator at the UI level, being based on the element of explainability, i.e., having the system's UI explaining to the tunnel operator how the system came up with a suggestion and what attributes contributed to that. That way the DSS is not treated as a black-box and it enhances its reliability.
4. Provide user-friendly user interfaces (UIs), which alleviate and balance out the cognitive load that may exist in critical situations and that may come from the explainability factor of SO #3, not only for the tunnel operator, but also for other authorities that contribute to emergency management.

The aforementioned SOs are addressed in a conceptualized framework for a new risk-aware DSS for tunnel safety we design and propose, namely RiskTUN.

2 RiskTUN: a conceptual risk-aware DSS for tunnel safety

2.1 Functionality

As stated in the main objective, RiskTUN is targeting a dual functionality: incident/accident prevention and emergency management. This functionality is visualized in (Figure 2). RiskTUN is intended for use and facilitation of the stakeholders' operation. These stakeholders that are involved in tunnel emergencies are as following: i) tunnel operators, ii) emergency responders (fire rescue service, ambulances, etc.), and iii) road users (e.g., passengers and drivers). The RiskTUN DSS 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 DSS for road tunnels currently described in research literature[1,2,8,9,11,12,24], cross-referenced with real-life practices and needs, coming from informal discussion with VTS and Rogaland Brann og Redning personnel.

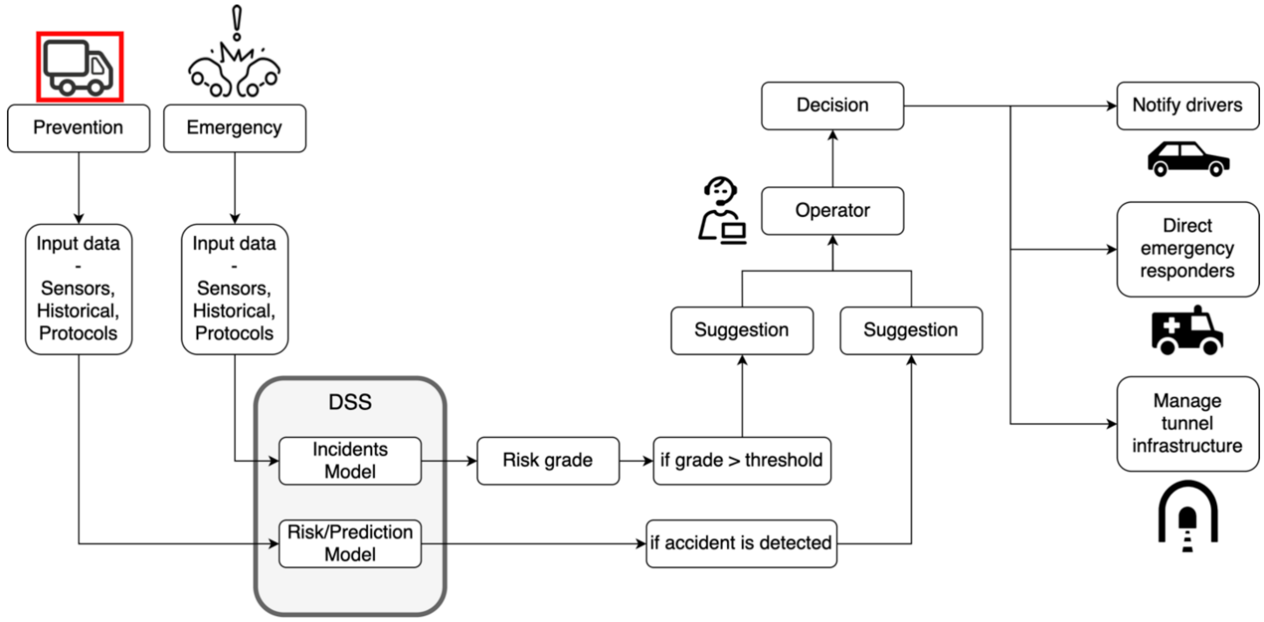

Figure 2: The RiskTUN functionality.

2.1.1 Input data

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. At the same time, this technology should enable a two-way communication, i.e., not only collecting vehicle-related data, but also pushing notifications to the vehicles. To address that, we introduce designs for vehicle positioning and communication in Section 3.

2.1.2 Operation platform

At this stage, the input data are collected, and 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 perspective 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 trusts blindly. The algorithms and artificial intelligence (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

[12] Bjelland, H., Njå, O., Heskestad, A. W., & Braut, G. S. (2018). Emergency Preparedness for Tunnel Fires. In Book of Proceedings Nordic Fire & Safety Days (p. 106-112).

suggestions. The 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 went beyond the DSS functionality and designed an adaptive UI (Section 3.2) 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.

2.1.3 Notifications and navigational assistance

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 DSS 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. A design suggestion on how the RiskTUN positioning and communication technology will be used to push personalized notifications to drivers is described in Section 3. A design suggestion on the navigational assistance that will be provided to emergency responders through the UIs and applications designed in the project is presented in Sections 3 and 3.2.

2.2 Risk factors in tunnels

As stated earlier, 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 herein is based on recent related work on risk factors for Norwegian tunnels[13], as well as international work on the subject, which is presented hereafter. Moreover, the identified risk factors are expressed through multi-attribute decision-making (DEXi) models to be able and provide better guidance for their use in practice.

2.2.1 Primary risk factors

Primary risk factors (Table 1) are the basic ones which apply in every case, producing a risk grade for every vehicle entering a tunnel.

"Black hole" - Tunnel entrance zone

Crash rates are higher in Zones 1 and 2 (Figure 3) and are lower as drivers continue driving inside the tunnel[14,15,16]. This is due to sudden change in visual environment, i.e., the driver adapting to the

[13] Høye, A., Nævestad, T. O., & Ævarsson, G. (2019). Predikering av branner og ulykker i vegtunneler.
[14] Amundsen, F. H., & Engebretsen, A. (2009). Studies on Norwegian Road Tunnels II: an analysis on traffic accidents in road tunnels 2001-2006.
[15] Amundsen, F. H., & Ranes, G. (2000). Studies on traffic accidents in Norwegian road tunnels. *Tunnelling and underground space technology*, *15*(1), 3-11.
[16] Brandt, R., Schubert, M., & Høj, N. P. (2012). *On risk analysis of complex road-tunnel systems*.

dim light condition ("black hole"), and speed variations among drivers[17,18]. In one-way tunnels, the crash rate in zone 1 is larger[14,16].

Table 1: The primary risk factors and the incidents they can cause.

Risk factors → Incidents ↓	"Black hole"	Driving attitude	Highway geometric design	Traffic volume	Vehicle type	Surface conditions
Crash (with or without fire)	X	X	X	X	X	X
Overheating/ Fire without crash				X	X	
Ventilation problem				X		
Road spillages	X	X	X		X	
Respiratory issues						

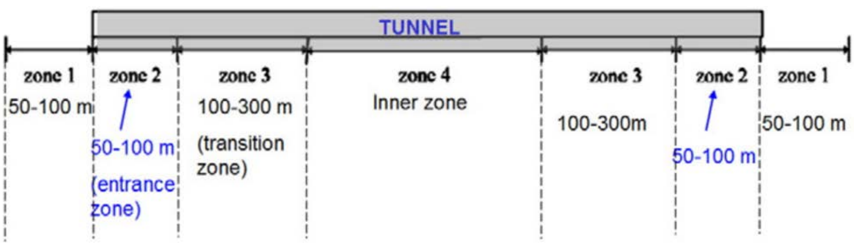

Figure 3: Typical tunnel zones for crash distribution[20].

Driving attitude (high speed and lane changes)
Inside the tunnel (Zone 4 in Figure 4), the most frequent crashes are rear-end crashes, due to aggressive lane changes and high speed (Lu et al., 2014). Drivers who are approaching tunnels (Zones 1 and 2) at high speed are exposed to much higher accident risk[17].

Length of tunnel

[17] Lu, L., Lu, J., Xing, Y., Wang, C., & Pan, F. (2014). Statistical analysis of traffic accidents in Shanghai river crossing tunnels and safety countermeasures. *Discrete dynamics in nature and society, 2014.*
[18] Lemke, K. (2000). Road safety in tunnels. *Transportation Research Record*, *1740*(1), 170-174.

When the tunnel part in the roadway network is small, drivers in general tend to drive more carefully and at a lower speed. The risk of crash in a tunnel is reduced compared with the open road[18,19]. The risk declines or levels out with increasing tunnel length[14].

Highway geometric design
Horizontal curvature and gradient are potential factors that affect vehicle collisions and their severity[20]. Sub-sea tunnels with sharp vertical curvature magnify a driver's feeling of "unease" after entering the tunnel[15]. The risk of accident increases with steepness of grade[14].

Traffic volume
Rear-end accidents occurred most frequently in the wider tunnels with high traffic volumes[15,17]. High traffic volume increases the chances for congestion and causes a lack of ventilation due to the absence of the piston effect in the tunnel[21]. The risk declines or levels out with increasing annual average daily traffic[14].

Surface conditions
Inside the tunnel (Zone 4), two thirds of the crashes occur anyway in dry surface conditions, and only 2.3% occur in slippery conditions other than wet, bare, or ice-covered pavement conditions. These other slippery conditions could be based on unclean surface due to oil, fuel, and other flammable and toxic liquids of dangerous goods' transport[14].

Fire crashes
Fire crashes are less frequent than traffic crashes, even if they might cause catastrophic consequences. Fire incident rate in the tunnel system (Norway and Switzerland) is approximately 30% of the tunnel crash rate (0.036)[16].

Vehicle type associated with fire incidents
The number and type of vehicles involved in tunnel fires are related to the severity of the fires; for example, 46.3% of the 135 fires involved one vehicle under 3.5 tons. In 38.1% of the fires, only one heavy vehicle was involved (above 3.5 tons); 5.2% involved one heavy vehicle and one light vehicle; 5.9% involved two light vehicles or more; and, in 4.5% of the fires, there was no information about the vehicles' involved by fire[22]. Fatalities in road tunnel fires are strongly associated with HGVs[23]; approximately 71% of fatalities in tunnel fires are in fires involving HGVs, 24% regular vehicles excluding trucks and HGVs, and 5% trucks or lorries[24]. Most of the fires are registered in the middle zone of the tunnels. 46.3 % of the fires involved a vehicle under 3.5 tons. In 38.1 % of the fires there was only one heavy vehicle involved. The other fires involved either multiple or no vehicles[15].

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[19] Yeung, J. S., & Wong, Y. D. (2013). Road traffic accidents in Singapore expressway tunnels. *Tunnelling and Underground Space Technology*, *38*, 534-541.
[20] Bassan, S. (2016). Overview of traffic safety aspects and design in road tunnels. *IATSS research*, *40*(1), 35-46.
[21] Petelin, S., Luin, B., & Vidmar, P. (2010). Risk analysis methodology for road tunnels and alternative routes. *Journal of Mechanical Engineering*, *56*, 41-51.
[22] Nævestad, T. O., & Meyer, S. (2014). A survey of vehicle fires in Norwegian road tunnels 2008–2011. *Tunnelling and Underground Space Technology*, *41*, 104-112.
[23] Njå, Å, Kvaløy, J. T. & Njå, O. (2020). Modelling fire occurrences in heavy goods vehicles in road tunnels. Paper to be presented at the ISTSS conference
[24] Beard, A. N. (2010). Tunnel safety, risk assessment and decision-making. *Tunnelling and Underground Space Technology*, *25*(1), 91-94.

Ventilation
The ventilation system is designed in tunnels on the basis of reference fires (defined by standards) that have very higher probability to occur than toxic releases or explosions; as a result the state of not working correctly of the emergency ventilation might show scarce influence on the propagation of temperature and smoke caused by toxic releases with very lower occurrence probability[25].

2.2.2 Secondary risk factors

There are secondary risk factors which do not apply in every case, i.e., are circumstantial. These factors can be the result of primary factors or take place individually.

Table 2: 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	

2.2.3 Incident characteristics

Table 3 describes 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 3: A summary of incidents that can take place inside a tunnel along with their potential outcomes.

Incident	Potential outcomes	
Crash	Fire	No fire
	Spillage	No spillage
	Serious (injuries, fatalities)	Light (rear-end)

[25] Caliendo, C., & De Guglielmo, M. L. (2017). Quantitative Risk Analysis on the Transport of Dangerous Goods Through a Bi-Directional Road Tunnel. *Risk Analysis*, *37*(1), 116-129.

	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

2.2.4 KPIs for risk factors

Followingly, 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.

Risk influencing factor (RIF)	Main indicators	Related sensors	Measurement frequency
- Primary Risk Factors -			
"Black hole"	Position in the tunnel (in meters)	Cameras, Indoor positioning (Bluetooth/RiskTUN app or RFID/AutoPASS)	Constant (every second)
	Direction	Cameras, Indoor positioning (Bluetooth/RiskTUN app or RFID/AutoPASS)	Constant (every second)
Driving attitude	Speed (km/h)/vehicle	Cameras, Indoor positioning (Bluetooth/RiskTUN app or RFID/AutoPASS)	Constant (every second)
	Nr. of lane changes/vehicle	Cameras, Indoor positioning (Bluetooth/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 klm)	Indoor positioning (Bluetooth/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 (Bluetooth/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)

2.2.5 Risk models expressed in DEXi

To illustrate how the incidents types and their risk factors with connected KPIs may be operationalized in a deterministic decision support tool, we include initial models for two of the incident types above expressed in DEXi[26]. DEXi is a computer program for multi-attribute decision making. To use DEXi for decision support, one must make a DEXi model, which is a hierarchical model consisting of a tree structure of nodes, denoted attributes. The attributes are either basic attributes (leaf nodes) or aggregated attributes (branch nodes). For all attributes, a scale is defined to express possible values for the attribute. These values may be ordered, and can represent exact values (like vehicle type, which is one of a given set of values) or values representing an interval (like vehicle temperature).

In addition to a scale, the aggregated attributes also have a utility function describing how different combination of values for their child attributes are used to determine the attribute value (from its scale) for the aggregated attribute. A utility function is expressed as a table with one column for each child attribute, and one column where the attribute value for the aggregated attribute is expressed. There is one row in the table for each combination of attribute values for each child attribute (as expressed in their scale). In the example models described below, the scales of most aggregated attributes, including the root attributes are expressed as risks or danger values.

[26] Bohanec, M., Rajkovič, V.: Multi-attribute decision modeling: Industrial applications of DEX. Informatica 23, 487-491, 1999.

At run time, basic attributes are well suited for getting their values from sensors of real time services. When all child attributes (basic or aggregated) are assigned values, an aggregated attribute may be evaluated, by using its utility function. When all basic attributes in a model are assigned values, the root attribute may be determined (also through its utility function).

Below, we present the DEXi model for two of incident types presented above, i.e., Overheating/Fire without crash and Crash (with or without fire). The structure in the DEXi models vary slightly from the descriptions above.

2.2.5.1 Risk for overheating/fire without crash

Figure 4 shows the tree structure for the DEXi model *Risk for overheating/fire without crash*.

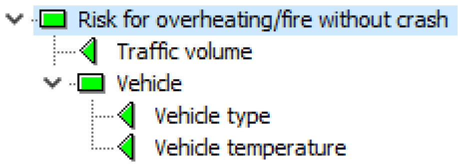

Figure 4: The DEXi tree structure for "Risk for overheating/fire without crash"

The top level risk is influenced by *Traffic volume* and *Vehicle* related risks. The latter is further broken down into *Vehicle type* and *Vehicle temperature*. Different combinations of vehicle type and temperature result in different vehicle risks. In the same way, the risk at the top level varies with different combinations of Traffic volume and Vehicle risk. How these combinations are specified in the DEXi model is described in Figure 5 and Figure 6 below.

	Vehicle type	Vehicle temperature	Vehicle
	30%	70%	
1	<=Diesel car	<=medium	*No risk*
2	<=**Small truck**	*low*	*No risk*
3	*Motorcycle*	>=**high**	Small risk
4	<=Diesel car	**high**	Small risk
5	Petrol car:**Small truck**	medium	Small risk
6	**Large truck**	*low*	Small risk
7	Diesel car:Petrol car	**very high**	Medium risk
8	Petrol car	>=**high**	Medium risk
9	Petrol car:**Small truck**	**high**	Medium risk
10	**Large truck**	medium	Medium risk
11	>=Electric car	**very high**	**High risk**
12	**Large truck**	>=**high**	**High risk**

Figure 5: The DEXi rules for determining the Vehicle risk.

	Traffic volume	Vehicle	Risk for overheating/fire without crash
	37%	63%	
1	***low***	***No risk***	***No risk***
2	***low***	Small risk	Small risk
3	>=medium	***No risk***	Small risk
4	<=medium	Medium risk	Medium risk
5	medium	Small risk:Medium risk	Medium risk
6	>=medium	Small risk	Medium risk
7	<=medium	**High risk**	High risk
8	**high**	Medium risk	High risk
9	**high**	**High risk**	**Very high risk**

Figure 6: The DEXi rules for determining the top level risk.

These rules are expressed using the scales defined for each attribute. These scales are shown in Figure 7 below.

Scales

Attribute	Scale
Risk for overheating/fire without crash	***No risk***; Small risk; Medium risk; High risk; **Very high risk**
├Traffic volume	***low***; medium; **high**
└**Vehicle**	***No risk***; Small risk; Medium risk; **High risk**
├Vehicle type	***Motorcycle***; Diesel car; Petrol car; Electric car; **Small truck**; **Large truck**
└Vehicle temperature	***low***; medium; **high**; **very high**

Risk for overheating/fire without crash

1. ***No risk***
2. Small risk
3. Medium risk
4. High risk
5. **Very high risk**

Traffic volume

1. ***low*** KPI
2. medium KPI
3. **high** KPI

Vehicle

1. ***No risk***
2. Small risk
3. Medium risk
4. **High risk**

Vehicle type

1. ***Motorcycle***
2. Diesel car
3. Petrol car
4. Electric car
5. **Small truck**
6. **Large truck**

Vehicle temperature

1. ***low*** below 90 degrees
2. medium 90-120 degrees
3. **high** 120-150 degrees
4. **very high** over 150 degrees

Figure 7: The scales used in the DEXi model.

All the scales in this DEXi model are ordered, going from low to high-risk values. As can be seen in the figure, the rules for determining how temperature maps to the levels in the scale for Vehicle temperature is also described. When using the model at run-time, sensor reading of temperature needs to be mapped to the scale values before the DEXi model is evaluated.

2.2.5.2 Risk for crash

Figure 8 shows the tree structure for the DEXi model *Risk for overheating/fire without crash*.

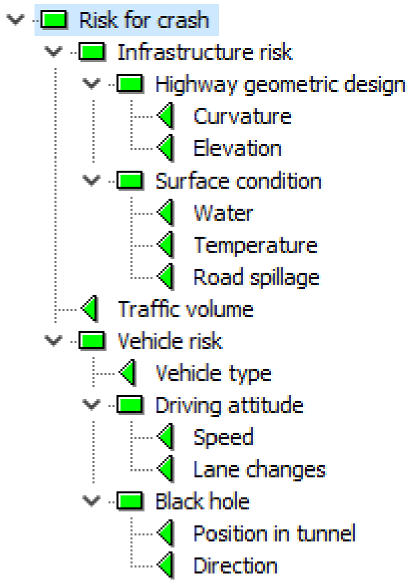

Figure 8: The DEXi tree structure for "Risk for crash".

The top level risk is influenced by *Infrastructure risk*, *Traffic volume* and *Vehicle* related risks. Vehicle risk is further broken down into *Vehicle type*, *Driving attitude* and *Black hole*. Note that Vehicle risk in this model is broken down differently than in the *Risk for overheating/fire without crash model* presented above. This reflects the break-down of the corresponding incident types as described in the risk factor tables described in the preceding sections. As can be seen in Figure 9, driving attitude and Black hole attributes are further broken down. Thus, this the tree for this model is one level deeper than the model for overheating. Furthermore, the Vehicle types are slightly different in the two models. Traffic volume is treated identically in the two models. Infrastructure risk is broken down in two level, one covering important aspects of the geometric design of the tunnel, which is fairly stable over time, and the other covering aspects influencing surface condition, which may vary quite frequently. This means that there are seven aggregated attributes in the model. For each of these aggregated attributes, different combinations of the child attributes result in different risks for these aggregated attributes. How these combinations are specified in the DEXi model is described in Figure 9, Figure 10 and Figure 11 below.

	Vehicle type	Driving attitude	Black hole	Vehicle risk
	40%	34%	26%	
1	**Truck**	**Very dangerous**	<=Dangerous	**High risk**
2	**Truck**	<=Dangerous	**Very dangerous**	**High risk**
3	**Truck**	**Very dangerous**	>=Somewhat dangerous	Medium risk
4	**Truck**	<=Dangerous	Somewhat dangerous	Medium risk
5	**Truck**	Dangerous	Dangerous:Somewhat dangerous	Medium risk
6	**Truck**	Dangerous:Somewhat dangerous	Dangerous	Medium risk
7	**Truck**	Somewhat dangerous	<=Dangerous	Medium risk
8	Car	**Very dangerous**	<=Dangerous	Medium risk
9	Car	<=Dangerous	**Very dangerous**	Medium risk
10	>=Car	**Very dangerous**	**Very dangerous**	Medium risk
11	**Truck**	Dangerous:Somewhat dangerous	***Safe***	Small risk
12	<=Car	Dangerous	***Safe***	Small risk
13	**Truck**	Somewhat dangerous	>=Somewhat dangerous	Small risk
14	<=Car	***Safe***	<=Dangerous	Small risk
15	Car	<=Dangerous	>=Somewhat dangerous	Small risk
16	>=Car	**Very dangerous**	>=Somewhat dangerous	Small risk
17	Car	Dangerous	>=Dangerous	Small risk
18	Car	>=Dangerous	Dangerous	Small risk
19	>=Car	Dangerous	Dangerous	Small risk
20	Car	>=Somewhat dangerous	<=Dangerous	Small risk
21	>=Car	Somewhat dangerous	**Very dangerous**	Small risk
22	***Motorcycle***	**Very dangerous**	>=Dangerous	Small risk
23	***Motorcycle***	<=Dangerous	Dangerous	Small risk
24	***Motorcycle***	Dangerous	<=Dangerous	Small risk
25	***Motorcycle***	Dangerous:Somewhat dangerous	**Very dangerous**	Small risk
26	*	***Safe***	>=Somewhat dangerous	***No risk***
27	>=Car	>=Somewhat dangerous	>=Somewhat dangerous	***No risk***
28	***Motorcycle***	>=Dangerous	>=Somewhat dangerous	***No risk***
29	***Motorcycle***	>=Somewhat dangerous	>=Dangerous	***No risk***
30	***Motorcycle***	***Safe***	*	***No risk***

	Speed	Lane changes	Driving attitude
	52%	48%	
1	**Very high**	<=Moderate	**Very dangerous**
2	<=High	**Many**	**Very dangerous**
3	**Very high**	***Few***	Dangerous
4	High	Moderate	Dangerous
5	Normal	**Many**	Dangerous
6	High	***Few***	Somewhat dangerous
7	Normal	Moderate	Somewhat dangerous
8	***Low***	**Many**	Somewhat dangerous
9	>=Normal	***Few***	***Safe***
10	***Low***	>=Moderate	***Safe***

	Position in tunnel	Direction	Black hole
	53%	47%	
1	**Zone 1**	**In**	**Very dangerous**
2	**Zone 1**	***Out***	Dangerous
3	Zone 2	**In**	Dangerous
4	Zone 2	***Out***	Somewhat dangerous
5	Zone 3	**In**	Somewhat dangerous
6	>=Zone 3	***Out***	***Safe***
7	***Zone 4***	*	***Safe***

Figure 9: The DEXi rules for determining the Vehicle risk.

	Highway geometric design	Surface condition	Infrastructure risk
	39%	61%	
1	**Very dangerous**	<=Dangerous	**High risk**
2	<=Somewhat dangerous	**Very dangerous**	**High risk**
3	**Very dangerous**	>=Somewhat dangerous	Medium risk
4	<=Dangerous	Somewhat dangerous	Medium risk
5	Dangerous	Dangerous:Somewhat dangerous	Medium risk
6	>=Dangerous	Dangerous	Medium risk
7	***Safe***	<=Dangerous	Medium risk
8	Dangerous	***Safe***	Small risk
9	>=Somewhat dangerous	Somewhat dangerous	Small risk
10	>=Somewhat dangerous	***Safe***	***No risk***

	Curvature	Elevation	Highway geometric design
	50%	50%	
1	**High**	**Steep**	**Very dangerous**
2	**High**	Moderate	Dangerous
3	Medium	**Steep**	Dangerous
4	**High**	***Flat***	Somewhat dangerous
5	Medium	Moderate	Somewhat dangerous
6	***Small***	**Steep**	Somewhat dangerous
7	>=Medium	***Flat***	***Safe***
8	***Small***	>=Moderate	***Safe***

	Water	Temperature	Road spillage	Surface condition
	18%	25%	57%	
1	<=Somewhat wet	**Risk of freezing**	**Yes**	**Very dangerous**
2	**Very wet**	**Risk of freezing**	***No***	Dangerous
3	**Very wet**	>=Possible risk of freezing	**Yes**	Dangerous
4	<=Somewhat wet	Possible risk of freezing	**Yes**	Dangerous
5	***Dry***	**Risk of freezing**	**Yes**	Dangerous
6	<=Wet	>=Possible risk of freezing	***No***	Somewhat dangerous
7	<=Somewhat wet	Possible risk of freezing	***No***	Somewhat dangerous
8	Wet	*	***No***	Somewhat dangerous
9	Wet:Somewhat wet	<=Possible risk of freezing	***No***	Somewhat dangerous
10	Wet	***No risk of freezing***	*	Somewhat dangerous
11	>=Wet	***No risk of freezing***	**Yes**	Somewhat dangerous
12	***Dry***	>=Possible risk of freezing	**Yes**	Somewhat dangerous
13	>=Somewhat wet	***No risk of freezing***	***No***	***Safe***
14	***Dry***	*	***No***	***Safe***

Figure 10: The DEXi rules for determining the Infrastructure risk.

	Infrastructure risk	Traffic volume	Vehicle risk	Risk for crash
	28%	35%	38%	
1	**High risk**	**high**	<=Medium risk	**Very high risk**
2	<=Medium risk	**high**	**High risk**	**Very high risk**
3	**High risk**	**high**	>=Small risk	High risk
4	**High risk**	medium	<=Medium risk	High risk
5	**High risk**	>=medium	**High risk**	High risk
6	<=Medium risk	medium	**High risk**	High risk
7	Medium risk	**high**	Medium risk	High risk
8	>=Small risk	**high**	**High risk**	High risk
9	**High risk**	>=medium	Small risk	Medium risk
10	**High risk**	***low***	Medium risk:Small risk	Medium risk
11	Medium risk	**high**	Small risk	Medium risk
12	Medium risk:Small risk	medium	Medium risk	Medium risk
13	>=Medium risk	***low***	**High risk**	Medium risk
14	Small risk	<=medium	Medium risk	Medium risk
15	>=Small risk	**high**	Medium risk	Medium risk
16	Small risk	medium	<=Medium risk	Medium risk
17	>=Small risk	>=medium	**High risk**	Medium risk
18	**High risk**	>=medium	***No risk***	Small risk
19	<=Medium risk	medium	***No risk***	Small risk
20	Medium risk	<=medium	***No risk***	Small risk
21	>=Medium risk	**high**	***No risk***	Small risk
22	Medium risk	medium	>=Small risk	Small risk
23	Medium risk	>=medium	Small risk	Small risk
24	Medium risk:Small risk	medium	Small risk	Small risk
25	Medium risk	***low***	Medium risk:Small risk	Small risk
26	>=Medium risk	***low***	Medium risk	Small risk
27	Small risk	<=medium	Small risk	Small risk
28	>=Small risk	**high**	>=Small risk	Small risk
29	***No risk***	>=medium	Medium risk	Small risk
30	>=Medium risk	***low***	***No risk***	***No risk***
31	>=Small risk	>=medium	***No risk***	***No risk***
32	>=Small risk	***low***	>=Small risk	***No risk***
33	***No risk***	>=medium	>=Small risk	***No risk***

Figure 11: The DEXi rules for determining the top-level risk.

These rules are expressed using the scales defined for each attribute. These scales are shown in Figure 12 below.

Scales

Attribute	Scale
Risk for crash	Very high risk; High risk; Medium risk; Small risk; *No risk*
─**Infrastructure risk**	High risk; Medium risk; Small risk; *No risk*
──**Highway geometric design**	Very dangerous; Dangerous; Somewhat dangerous; *Safe*
───Curvature	High; Medium; *Small*
───Elevation	Steep; Moderate; *Flat*
──**Surface condition**	Very dangerous; Dangerous; Somewhat dangerous; *Safe*
───Water	Very wet; Wet; Somewhat wet; *Dry*
───Temperature	Risk of freezing; Possible risk of freezing; *No risk of freezing*
───Road spillage	Yes; *No*
─Traffic volume	high; medium; *low*
─**Vehicle risk**	High risk; Medium risk; Small risk; *No risk*
──Vehicle type	Truck; Car; *Motorcycle*
──**Driving attitude**	Very dangerous; Dangerous; Somewhat dangerous; *Safe*
───Speed	Very high; High; Normal; *Low*
───Lane changes	Many; Moderate; *Few*
──**Black hole**	Very dangerous; Dangerous; Somewhat dangerous; *Safe*
───Position in tunnel	Zone 1; Zone 2; Zone 3; *Zone 4*
───Direction	In; *Out*

Speed

1.	Very high	More than 20 km/h above speed limit
2.	High	10-20 km/h above speed limit
3.	Normal	0-10 km/h above or below speed limit
4.	*Low*	Less than 10 km/h below speed limit

Temperature

1.	Risk of freezing	Below 0 degrees
2.	Possible risk of freezing	From 0 to +3 degrees
3.	*No risk of freezing*	Above +3 degrees

Curvature

1.	High	Many turns
2.	Medium	Some turns
3.	*Small*	Straight or almost straight

Figure 12: The scales used in the DEXi model.

Figure 13 also contains details for selected attributes.

2.3 System architecture

Figure 13 gives a logical view of the system architecture we foresee for RiskTUN.

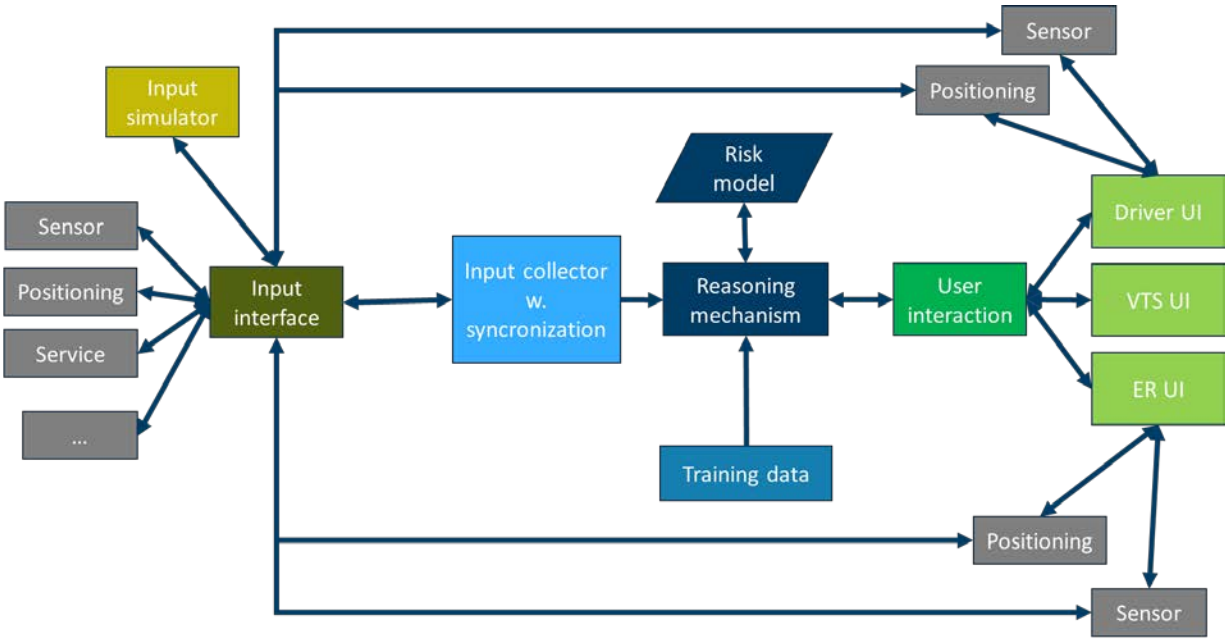

Figure 13: Logical system architecture

This architecture shows the main component in a DSS, 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 a deterministic mechanism like DEXi (see Section 2.2.5) or a module based on AI/ML. In both cases the reasoning mechanism need a *risk model*. When using DEXi, the risk model is a collection of the types of models presented in Section 2.2.5. When using AI/ML, the risk model will be built from *training data*, typically log data, including from past events. When using a reasoning mechanism like DEXi, 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. 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*. Section 3.2 provides examples of such user interfaces, denoted *driver UI*, *VTS UI* and *ER UI* in Figure 22. Users in the tunnel (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.

3 Beyond the DSS: Design suggestions for vehicle positioning, communication, and user interfaces

3.1 Vehicle positioning and communication technology

GPS is the most popular positioning system; however, it is not suitable for indoor positioning[27]. The 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]. In these design suggestions, we described a vehicle positioning and communication system based on BLE. However, it must be noted that 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], within the KATS project, is also a promising alternative, focusing on 5G cellular networks and the new opportunities that arise from their deployment within the tunnels. For the future, we have also to take into consideration the vehicle-to-infrastructure solutions that are coming and already exist in some modern cars. For RiskTUN, we focused on established technologies that could provide a satisfactory ratio of cost/efficiency, without having to rely on any previously installed tunnel equipment.

3.1.1 Bluetooth Low Energy beacons

The Bluetooth technology is originally designed as a short-range wireless connectivity solution for personal, portable, and hand-held electronic devices. Bluetooth employs a fast, Frequency-Hopping Spread Spectrum (FHSS) technology to avoid the interference in the Industrial, Scientific and Medical (ISM) band, in which it is operating, and ensure the reliability of data communications. The typical working distance of Bluetooth ranges from 10m to 100m (Bluetooth 5.0: 40-400 m), depending on the power class of the device. A Bluetooth device assumes the role of either a master or a slave. The master regulates which slave to transmit data and when. In some cases, devices of two types share the common hardware structure and thus may swap their master-slave roles only by altering the core programs. Bluetooth is an industry specification for ensuring compatibility in wireless connectivity of electronic devices, allowing one manufacture's master device to control the slave device made by another[30]. At the same time, BLE is a wireless form of technology with low power consumption, low cost, and easy-to-deploy solution[31,32]. Beacon technology operates over BLE and Bluetooth modules (BM) with a nominal communication range of 100m are embedded in the beacons. Those beacons can be placed on the key points of sites with well-defined position

[27] Li, X., Wang, J., & Liu, C. (2015). A Bluetooth/PDR integration algorithm for an indoor positioning system. *Sensors*, *15*(10), 24862-24885.
[28] Dickinson, P., Cielniak, G., Szymanezyk, O., & Mannion, M. (2016, October). Indoor positioning of shoppers using a network of Bluetooth Low Energy beacons. In *2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN)* (pp. 1-8). IEEE.
[29] Khademi, N. & Sommer, M. (2020). Intelligent & Ultra-Reliable Connectivity for Safety Services in Road Tunnels: A System Architecture. Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference.
[30] Lu, M., Chen, W., Shen, X., Lam, H. C., & Liu, J. (2007). Positioning and tracking construction vehicles in highly dense urban areas and building construction sites. *Automation in construction*, *16*(5), 647-656.
[31] Lin, X. Y., Ho, T. W., Fang, C. C., Yen, Z. S., Yang, B. J., & Lai, F. (2015, August). A mobile indoor positioning system based on iBeacon technology. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 4970-4973). IEEE.
[32] Wang, S. S. (2018). A BLE-based pedestrian navigation system for car searching in indoor parking garages. *Sensors*, *18*(5), 1442.

coordinates (such as entrances) so that they can cover the necessary space with their range[30]. BLE is present in all modern mobile devices (smartphones and tablets) and in combination with beacon technology, they are considered as an appropriate and efficient indoor positioning solution[32]. This solution has been applied in hospital settings[31], shopping centers[28], and indoor car parks[33,32], while various implementations and algorithms for optimized accuracy have been described[34,35].

For RiskTUN, the goal for the indoor positioning system is not only to register the location of each vehicle inside the tunnel but also to be able to notify drivers in case of emergency. The proposed solution utilizes series of BLE beacons throughout the tunnel in strategic places, in a way that their range cover the full length of the tunnel (Figure 14). RiskTUN will present a Bluetooth-enabled mobile application, in the form of either a standalone version or an extension of a popular navigational application like Google Maps, and will ask from drivers to have this application open when entering the tunnel. With their Bluetooth device activated, the BLE beacons would be able to locate them, i.e., locate the moving vehicles, as well as push notifications in case of an emergency, thus establishing two-way contact. The application can also ask/register additional user's details, such as phone number, license plate number, car model, etc., to establish alternative ways of identification and contact. Moreover, with the use of BLE beacons, emergency responders carrying a Bluetooth-enabled application can be tracked and managed more efficiently by the supervising operator.

The implementation of BLE beacons has been tested in Oslo by Google Waze though it is not applied in large scale[36]. Its cost is estimated at $1,200 for 42 BLE beacons required to provide coverage for every mile (1.6 kilometers) within a tunnel[37].

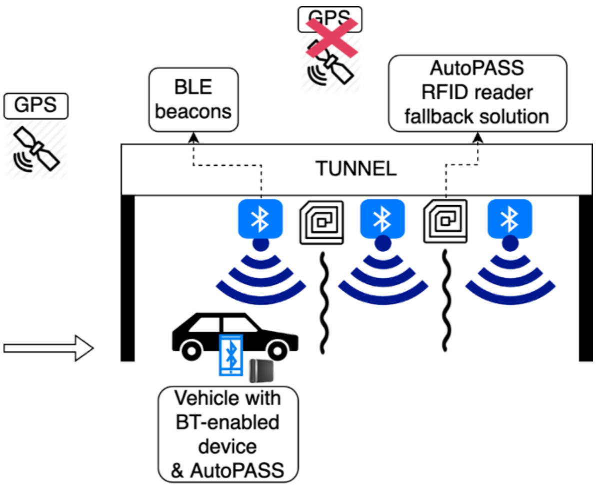

Figure 14: The RiskTUN BLE functionality.

[33] Rodríguez, G., Canedo-Rodríguez, A., Iglesias, R., & Nieto, A. (2019). Indoor positioning and guiding for drivers. *IEEE Sensors Journal*, *19*(14), 5923-5935.
[34] Cheung, K. C., Intille, S. S., & Larson, K. (2006, September). An inexpensive bluetooth-based indoor positioning hack. In *Proceedings of UbiComp* (Vol. 6).
[35] Li, X., Wang, J., & Liu, C. (2015). A Bluetooth/PDR integration algorithm for an indoor positioning system. *Sensors*, *15*(10), 24862-24885.
[36] Waze teams up with MTA, Port Authority to ease tunnel navigation (2019), https://abc7ny.com/traffic/waze-teams-up-with-mta-port-authority-to-ease-tunnel-navigation/5111411/
[37] Waze finds way to keep drivers on track in tunnels (2016), https://www.timesofisrael.com/waze-finds-way-to-keep-drivers-on-track-in-tunnels/

3.1.2 AutoPASS

The disadvantage of the BLE beacon solution may be visible in cases that drivers do not have a smartphone or when they have their Bluetooth device deactivated. Therefore, there is the need for an additional solution that could offer indoor position and two-way communication, thus making the suggested indoor positioning and communication technology, described herein, a hybrid. As a secondary solution, radio frequency identification (RFID) can be used. RFID systems rely on two main components to fulfill their objective. A reader coupled with an antenna that interrogates multiple tags. The tags should be activated by the interrogation and reply by sending a unique identification string back at the reader. The use of RFID for indoor localization has been studied extensively. Due to its lower cost and its technical capabilities, RFID system has been widely adopted as an attractive technology for many significant applications such as asset tracking, industrial automation, and homecare and healthcare systems[38,39]. In Norway, the majority of cars carry an RFID tag in the form of the AutoPASS, an RFID tag used for the payment of toll fees[40]. Norwegian toll stations operate in the way we suggest being applied in tunnels for indoor positioning. Naturally, the frequency of RFID readers will be higher in the tunnels' case to cover the full length of the tunnel. Apart from the vehicle location, AutoPASS can provide all its registered information, such as license plate number. The challenge in this case is establishing contact with the driver in case of emergency. The phone number of the AutoPASS owner/driver can be registered in the device details or a similar functionality can be developed in the shape of an online form. By having a phone number assigned to the registered AutoPASS, then the driver can be directly or indirectly (in case the vehicle owner is not the driver) contacted.

3.1.3 Privacy

From a privacy point-of-view, the collected information will fall under current privacy regulations for tunnel-related collected data since similar information (e.g., vehicle position, license plate number) can be collected today by tunnel cameras, which exist in many tunnels in Norway, even in a not-so-accurate way. At this point, we must emphasize that we address and cover the private collection of data, i.e., their use is permitted by tunnel operators, and not for distributing collected data publicly. Where additional information is requested (e.g., car model) this will be provided by the user, naturally with having his/her approval (e.g., through the RiskTUN BLE mobile application).

3.2 User interfaces

As stated in Sections 3.1.1 and 2.1.3, the RiskTUN DSS will utilize data coming from a Bluetooth-enabled mobile application for drivers and it will also push notifications to them and provide navigational assistance to emergency responders. At the same time, collected data should be visualized in the Operation Platform (Section 2.1.2) and enable the tunnel operator to decide on the appropriate course of action to prevent or tackle an emergency.

In this section, we describe the UIs for i) the RiskTUN BLE mobile application, ii) the Operation Platform, and iii) the mobile application providing navigational assistance to emergency responders.

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[38] Saab, S. S., & Nakad, Z. S. (2010). A standalone RFID indoor positioning system using passive tags. *IEEE Transactions on Industrial Electronics*, *58*(5), 1961-1970.
[39] Bekkali, A., Sanson, H., & Matsumoto, M. (2007, October). RFID indoor positioning based on probabilistic RFID map and Kalman filtering. In *Third IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob 2007)* (pp. 21-21). IEEE.
[40] https://www.autopass.no/AutoPASS

The presented visualizations are of preliminary nature and come in the shape of low-prototyping sketches.

3.2.1 UI of the RiskTUN BLE mobile application

This UI follows the paradigms of prevalent navigational applications (e.g., Google Navigation, Waze) and offers a top-down view of the tunnel (Figure 15 andFigure 16).

Figure 15: A UI prototype of the RiskTUN BLE mobile application for a vehicle inside the tunnel.

Figure 16: The UI when a notification is pushed through the RiskTUN BLE app.

3.2.2 UI of Operation Platform

The UI for the Operation Platform uses a tabulated approach. The UI is designed in a way that resembles current UIs of operation platforms so that there is some consistency and familiarity with it

(Figure 17 to Figure 21). The "AI Suggestions" are the system's suggestions to the control operator for action and they are visualized as a separate tab, however these suggestions can be embedded in the other tabs, depending on the preferences of the tunnel operators.

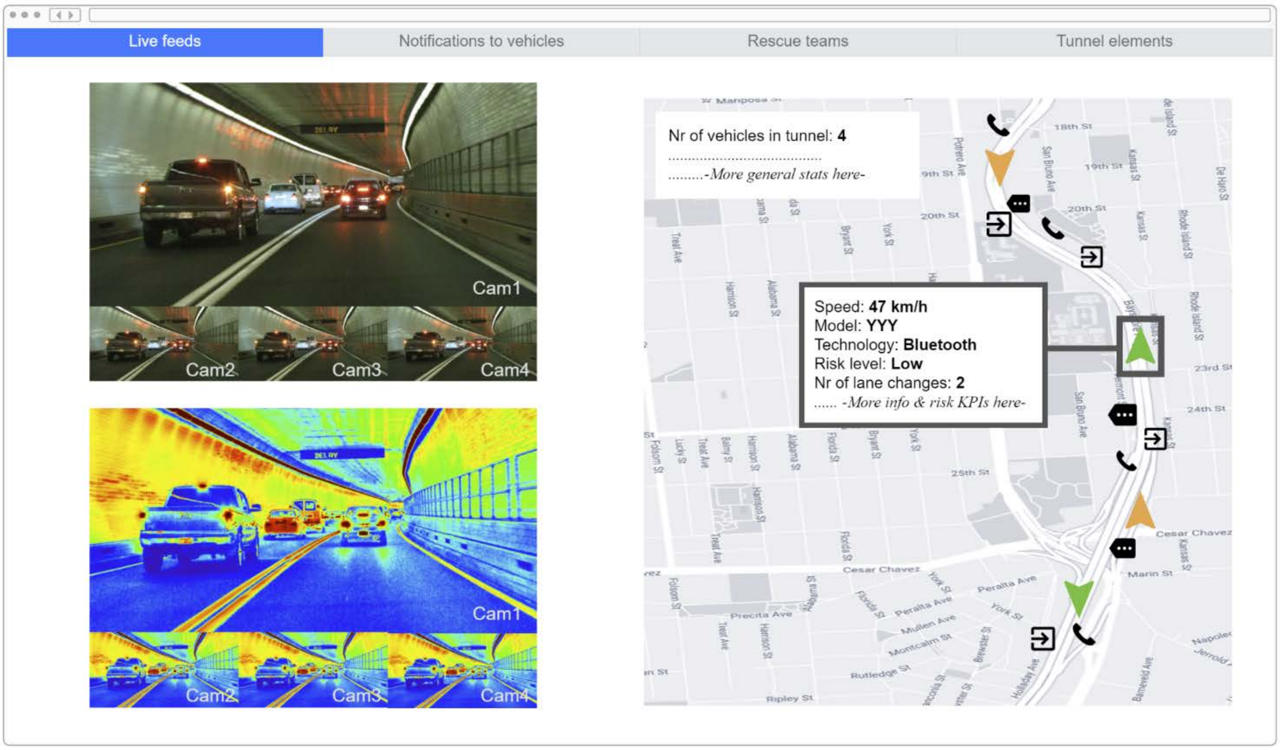

Figure 17: A UI prototype for providing an overview of live feeds, such as real-time vehicle positioning, thermal cameras feed, and regular cameras feed[41].

[41] The camera image used in this figure is licensed under CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/deed.en) and is created by Ben Schumin (https://commons.wikimedia.org/wiki/File:Fort_McHenry_Tunnel_Bore_2.jpg). At the lower iteration of the image a heatmap filter is applied.

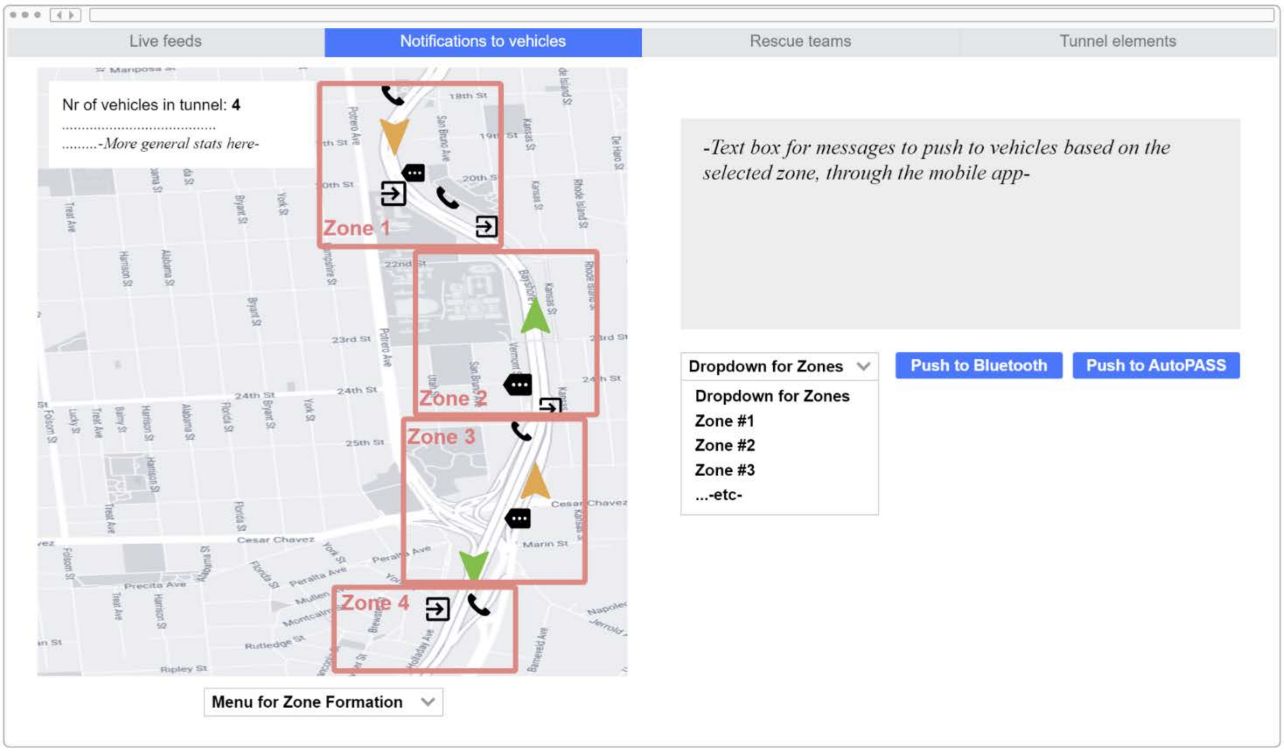

Figure 18: A UI prototype for pushing notifications to drivers.

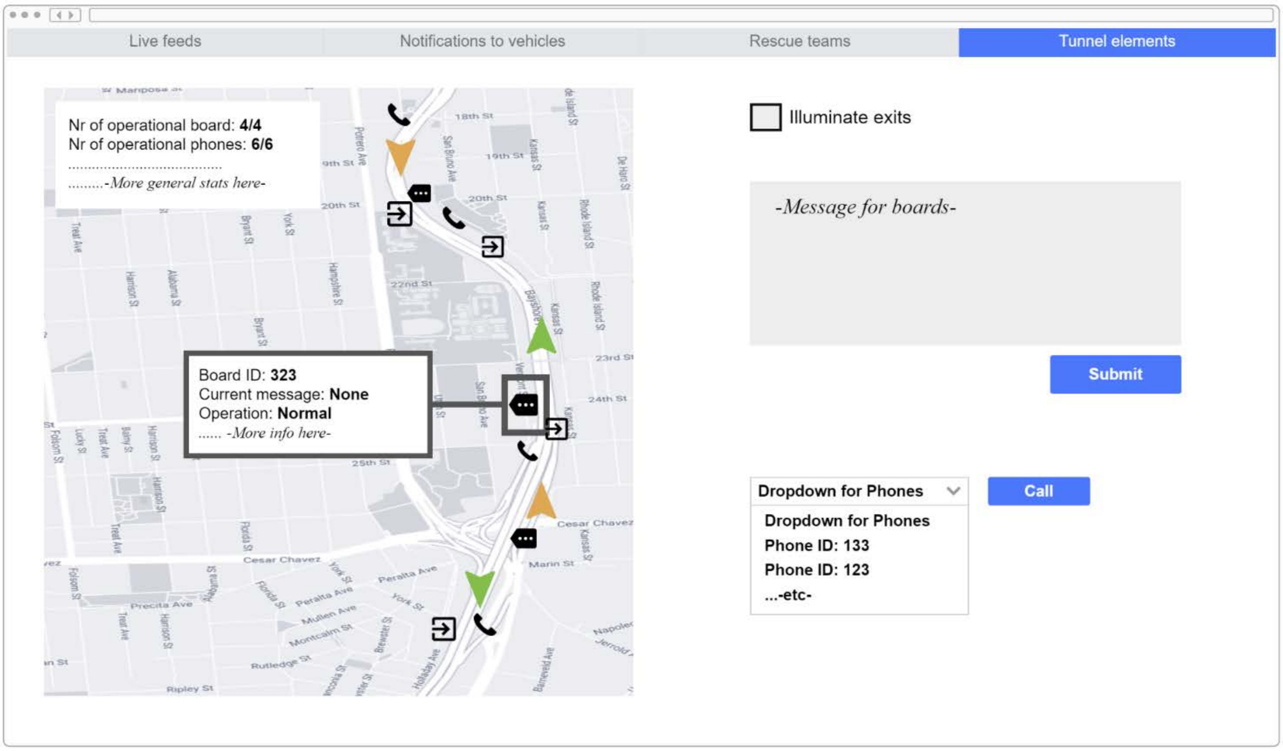

Figure 19: UI for controlling the tunnel equipment, such as LED displays, phones, and illuminated exits.

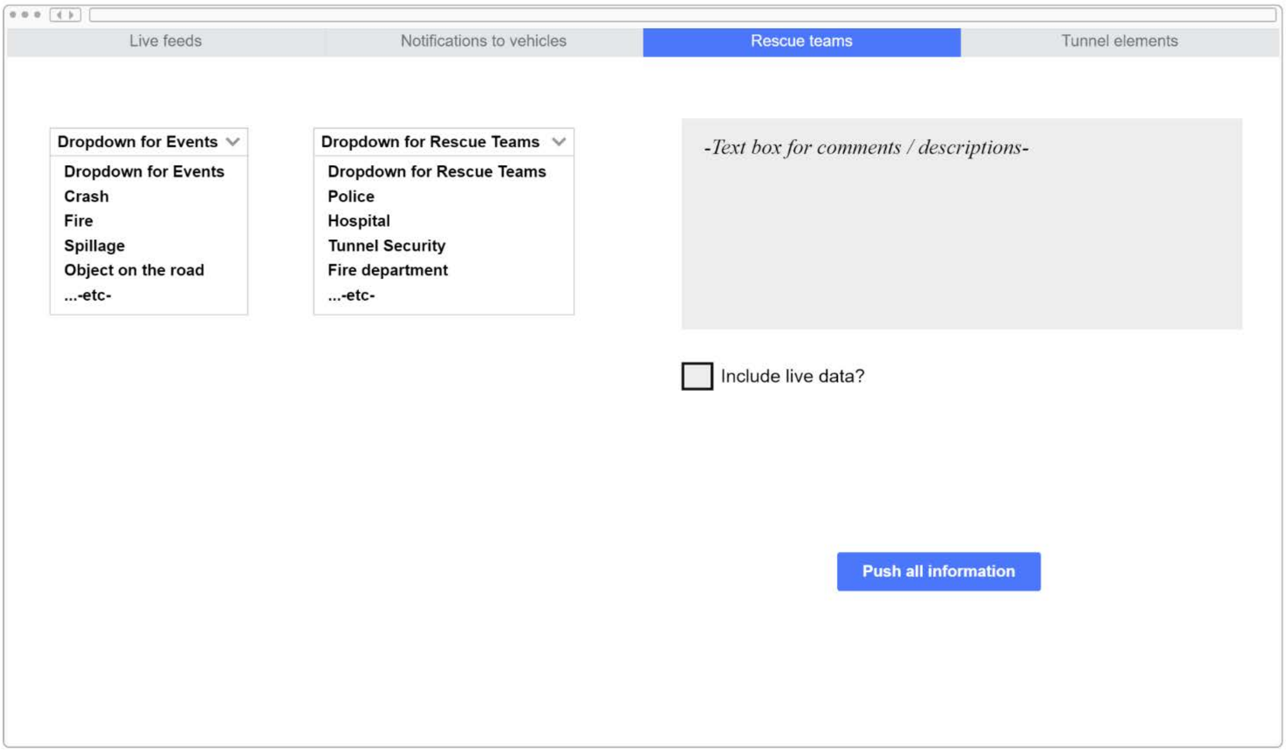

Figure 20: UI for managing the communication with the emergency responders.

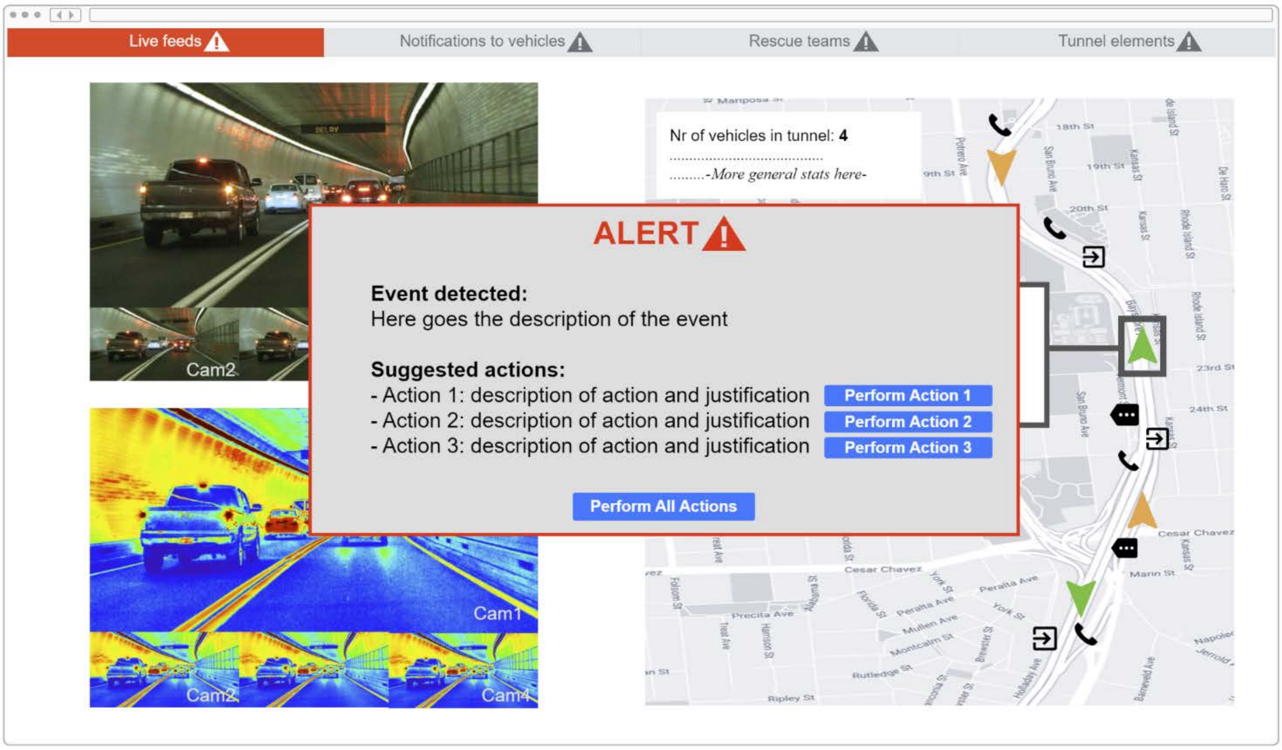

Figure 21: UI for alerts and visualizing the system's suggestions (based on deterministic AI algorithms) along with their explanations[41].

3.2.3 UI for emergency responders' navigation

In case of emergency, 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 (see Section 2.1.3). On the medium-fidelity prototype of Figure 22, 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 (i.e., Rogaland Brann og Redning), it is a common practice for rescue team members to carry mobile devices.

Figure 22: UI prototype for the mobile application that provides navigational assistance to emergency responders.

4 Example scenario

- A truck enters the tunnel and the RiskTUN app assigns it a high-risk grade for fire incident, being a HGV.
- The thermal camera follows the truck and the RiskTUN system analyses the real-time thermal camera data to detect that the vehicle is overheating.
- Then the Risk/Prediction model of the DSS activates the prevention protocol and provides the suggestion to the operator for an ER vehicle (e.g. tunnel's security team, fire department, etc.) to supervise the situation and, if possible, to stop the vehicle.
- The operator approves the suggestion, and the ER team is notified, however the vehicle gets on fire.

- The RiskTUN DSS is constantly analyzing data from the thermal camera and the indoor positioning (Bluetooth) due to the vehicle's prior high-risk grade. The system registers the fire and a new protocol for tackling an emergency situation is in place.
- New suggestions coming from the Incidents model of the DSS and based on the tunnel protocols are created, e.g., send safety vehicles/fire rescue to the accident site, push notifications to drivers and treat them in safety zones, illuminate emergency exits.
- The operator evaluates and approves these suggestions.
- Vehicles inside the tunnel are tracked by the RiskTUN mobile app or the AutoPASS and they are treated in zones, e.g., vehicles closer get notifications to go to emergency exits, ones far away are advised to stop.
- Tunnel's LED displays are used to display messages and tunnel's directional aids (green lights) are also illuminated.
- Rescue teams arrive (e.g., fire rescue).
- The RiskTUN DSS has already collected the accident information that the operator provided to the system along with all the additional necessary information for emergency responders to operate (evaluated and approved by the operator), e.g., location of accident, location of vehicles in vicinity, location of tunnel equipment.
- Emergency responders use their RiskTUN mobile app to get navigational assistance and locate drivers.

5 Opportunities, vision and high-level R&D roadmap

The described concept sets the following opportunities for its target users:

Tunnel operators

- Dual functionality for DSS: The RiskTUN functionality can lead to systems that will enable tunnel operators to have real-time risk analysis' results and to perform emergency management through the same system.
- Improved decision-making: By getting informed system suggestions for taking action along with explanations about the suggested actions, tunnel operators can instantly evaluate the application of the protocol and make an informed decision.
- Training: The RiskTUN concept can be used to develop virtual DSSs to train tunnel operators in simulated environments and create customised traffic and alarms to study the tunnel operator's reaction and response time.

Road Users

- Increased road safety: The risk analysis of the RiskTUN concept can prevent accidents and its emergency management features can notify drivers about accidents, as well as ensure better informed and prepared rescue operations.

Emergency responders

- Improved response and safety: The mobile applications for providing navigational assistance described herein could potentially decrease response time since responders could locate victims more accurately. Moreover, their safety could get improved since their position would be constantly visible.

The long-term vision is to realize a system like the one described in this report, and to have it deployed into a significant portion of Norwegian tunnels, i.e., the tunnels in Norway in which it is relevant to have such a system. The relevance must be judged based on factors like length, complexity, and traffic in the tunnels.

Realizing a system based on the concept from this report will require work in a number of steps, including research and prototype development, product development, and deployment into the chosen tunnels. Conducting these steps will require a time frame of more than ten years. In this report, we restrict ourselves to suggest a roadmap for the first steps, i.e., research and prototype development.

The vision for the R&D phase is to implement a prototype that uses the RiskTUN DSS concept to showcase how we can make tunnels safer by looking into real-time risk indicators and sensory data. To reach this R&D vision, we propose a high-level plan. It is divided into three-time frames, i.e., short-term (1-3 years), mid-term (3-6 years) and long-term (6-10 years) activities. In the two first time frames we suggest addressing the problem domain both top-down and a bottom-up. Top-down activities should detail the concept, architecture, use cases, risk models etc. Bottom-up activities should implement demonstrators and prototypes of different parts of a future RiskTUN system. Such feasibility studies should act as proof-of-concept for these different parts. It is envisioned that the top-down and bottom-up activities will "meet"/merge in the long-term R&D activities.

For the activities in all three-time frames, it is important to have active involvement of stakeholders, particularly road authorities (SVV/VTS), emergency response actors and vendors of systems used by these stakeholders today. Representatives of these stakeholders should be partners in possible R&D projects. Their mail role will be to give requirements and participate in assessing and validating suggestions and technical implementations. They will also play an important role in providing realistic data needed for training and validation of risk models and AI/ML modules. Road users should also be involved. This may either be done in an ad-hoc manner by involving ordinary people when testing demonstrators and prototypes, or by involving organizations like Trygg Trafikk and NAF in possible R&D projects, either as partners or through formal cooperation. It is anticipated that results obtained in the activities outlined below will be taken over by and commercialized by system vendors in parallel with the R&D activities.

5.1 Short-term R&D activities

Suggested top-down activities in this time frame are:

- Detail the RiskTUN concept and architecture, particularly study how to integrate the suggested functionality into existing systems used at VTS.
- Develop and validate detailed risk models for a subset of the risk factors and incident types identifies in Section 2.2. The risk factors and incident types to focus on should be prioritized in cooperation with stakeholders, particularly SVV/VTS.
- Study which sensor types that may be used to support the selected risk factors and incident types, and how data from these may be used and combined to obtain as much relevant knowledge as possible.
- Investigate which areas AI/ML may be used to make better sense of sensor values. This should also include temporal aspects.
- Study GDPR related challenges.
- Make detailed plans for mid-term R&D activities.

Suggested bottom-up activities in this time frame are:

- Experiments with integration of indoor positioning systems, e.g., BLE (Section 3.1.1).
- Develop proof-of-concept implementation of sensor fusion and AI/ML-based reasoning for a combination of indoor positioning and other selected sensors.
- Develop prototypes of the applications described in Section 3.2.1 and 3.2.3.
- Develop prototype of deterministic/probabilistic DSS based on the risk models.

To be able to conduct the bottom-up activities in this time frame, it is preferable to have access to tunnel testing facilities or to be able to set up simple experiments in real tunnels. If this is not possible to achieve, it is envisioned that it may be possible to conduct experiments partly in simulators/emulators, or in non-tunnel real-life environment (for example for testing BT sensors, radar, etc.). For some of these activities, it will also be possible to use data collected from tunnels (e.g., video of vehicles) as an alternative to real-time data from sensors.

The most relevant project types for short-term R&D activities are national cooperation and/or innovation projects financed by the Norwegian research council, as well as master theses.

5.2 Mid-term R&D activities

Suggested top-down activities in this time frame are:

- Suggest a technical interface between RiskTUN and existing systems used at VTS.
- Develop and validate detailed risk models for a the remaining the risk factors and incident types identifies in Section 2.2, and possible additional ones. This includes development of risk grade calculation formula (Section 2.2.4 and 2.2.5).
- Study which sensor types that may be used to support the selected risk factors and incident types, and how data from these may be used and combined to obtain as much relevant knowledge as possible.
- Specify how AI/ML may be used to make better sense of sensor values in the areas identified in the short-term R&D activities. This should also include temporal aspects.
- Investigate intelligent ways of communicating between involved stakeholders and technologies. This should include car-to-car communication and exploiting new opportunities like reasoning on the edge when using 5G.
- Propose solutions to GDPR related challenges.
- Make detailed plans for long-term R&D activities.

Suggested bottom-up activities in this time frame are:

- Implementation and integration of UIs, including the ones describe in Section 3.2.
- Creating/adapting open language for input/output data to connect to DSS.
- Perform testing in realistic environments and conditions.
- Develop prototype of AI/ML-based DSS based on the risk models.
- Implement proof-of-concept of technical coupling between RiskTUN and exiting systems used at VTS.

To be able to conduct the bottom-up activities in this time frame, it is necessary to have access to tunnel testing facilities or to be able to set up simple experiments in real tunnels. This may be supplemented with experiments in simulators/emulators, or in non-tunnel real-life environment, as well as using data collected from tunnels (e.g., video of vehicles) as an alternative to real-time data from sensors.

In addition to national cooperation and/or innovation projects financed by the Norwegian research council, and EU projects (Horizon Europe) are highly relevant for mid-term R&D activities. If possible, partners with available tunnel testing facilities should be sought.

5.3 Long-term R&D activities

Suggested activities in this time frame are:

- Detailed specification of technical interface between RiskTUN and existing systems used at VTS.

- Prototype implementation of open language for input/output data to connect to DSS.
- Risk grade formula evaluation, setting thresholds for grades and evaluating its sensitivity and specificity.
- Develop prototype of full-fledge DSS based on risk models combining deterministic/probabilistic models and AI/ML, taking GDPR challenges into account.
- Prototype implementation of technical coupling between RiskTUN and exiting systems used at VTS.
- Proof-of-concept implementation of communicating between involved stakeholders and technologies, including use of car-to-car communication and exploiting new opportunities like reasoning on the edge when using 5G.
- Perform testing in realistic environments and conditions.
- Suggest plans for industrial development of the RiskTUN DSS and deployment of it in tunnels.

To be able to conduct the activities in this time frame, it is necessary to have access to tunnel testing facilities as well as to be able to set up experiments in real tunnels.

In addition to national cooperation and/or innovation projects financed by the Norwegian research council, EU projects, and private-public partnership are relevant for long-term R&D activities.

5.4 Impact from suggested R&D activities

The RiskTUN system will generate *societal impact* through solving both an information overload and scarcity problem, to make better tunnel safety decisions in normal operation and ER situations. The VTS constantly receives alarms from sensors and equipment in tunnels. Some alarms are important indicators of increasing risk; the majority are “false positives”. The latter generate noise for the operators and direct attention from more important issues. In Norway, there are four regional VTSs, and a limited number of operators, who are responsible for the operation of more than 600 road tunnels. The real-time risk model will help tunnel operators make sense of available sensor data and information, dynamically direct attention to high-risk tunnels, and support the enforcement of safety constraints to keep the Norwegian tunnel system in a safe state. The RiskTUN model is also a learning tool for critical processes subjected to societal control, where different system stakeholders could use the model for improving e.g., tunnel safety design regulations, maintenance procedures, training/ER programs/protocols, and accident investigations.

In *emergency response situations*, time becomes a critical factor and safety is dependent on efficient collaboration among the system’s actors. Drivers, dispatch operators and incident commanders need to make safety critical split-second decisions that will also affect other parties. RiskTUN works on the premises of the involved actors to improve timely, verified and user-adapted information. Improved situational awareness, through analyzing sensor data, enables better planning and less stressful situations for incident commanders. Adapted information will help drivers evacuate safely on their own, which reduces the workload for emergency responders, who can direct efforts to where it matters most. The potential impact is saving lives and reduce injury potentials.

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