Quality & Quantity (2023) 57:S249–S270
https://doi.org/10.1007/s11135-020-01003-8

Traffic safety sustainability and population protection in road tunnels

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Published online: 15 June 2020

Abstract
Nowadays, tourism is a phenomenon and every state or continent is trying to offer the most attractive. Transport and related services are currently a key factor in the development and functioning of international tourism. Road transport is the most widespread transport worldwide. Development traffic studies report just under 1 billion motor vehicles in use worldwide today, 1.6 billion in 2020, and 2 billions by 2030. This article deals with the issue of traffic safety sustainability in road tunnels. It describes possible major emergencies that may occur in road tunnel traffic. Based on the analysis of statistical data from the Czech Republic, which deal with major emergencies in the past 13 years, causes of these emergencies, and findings from the screening exercises of the Integrated Rescue System units, measures are proposed to reduce the negative impacts of major emergencies and to improve crisis management, all with an emphasis on the safety of persons and property. The strategic goal is to reduce the number of casualties and the seriously injured in the Czech Republic to the average level of other EU countries. Based on the survey done in lessons to be learnt from training of Rescue System in the Czech Republic are presented.

Keywords Critical infrastructure · Emergencies · Emergency management · Case of emergency · Integrated rescue system · Population protection · Risk · Security sustainability · Traffic accident · Traffic road tunnel · Transport

1 Introduction

Currently, tourism is a dynamically expanding sector, contributing to economic development. The main travel destinations are divided by international arrivals and departures. France has been the first in arrivals for a long time; in 2012 for example, it registered 83 million arrivals. Almost 60% of these arrivals were by road, about 26% by air, 6% by rail,

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and 8% by water. The United States is second with 67 million arrivals. The third place is held by one of the most dynamically growing destinations, China, which recorded almost 58 million arrivals in 2012, 80% of which were by road, 15% by air, and the remaining 5% by water. In 2012, the Czech Republic accounted for about 0.86% of world arrivals. In absolute terms, it is 8.9 million arrivals, which puts our country in the 31st position. The order of states is similar for departures (Palatkova 2014).

Congestion is a major problem especially in road and air transport. The White Paper 2011 document, which contains proposals for European Union action, states that transport infrastructure in the eastern and western parts of the EU is unevenly developed, varies in the quality of infrastructure and services, the density of the transport network and the degree of market opening, and it is necessary to bring it to the same level. In practice, it is necessary to build and effectively use modern transport infrastructure and thereby increase traffic safety (White Paper) (European Commission 2011). The Czech Republic can rank among the countries that have a relatively good quality of transport infrastructure.

Safety on these roads is an important factor not only for the development of tourism. The authors Botlikova and Botlik (2018) conducted an interesting research by correlation analysis concerning the relationship between the quantities of inbound tourism (X) and road safety (Y). They proved that there is a linear dependence between them. In particular, it was found that there is a correlation between the number of foreign guests staying in collective accommodation establishments (or the number of overnight stays) and the number of traffic accidents resulting in death, injuries, or minor injuries. However, this analysis did not find causal relationships, only association relationships were found. It has been shown that changing X (or Y) also changes Y (or X). It was not confirmed whether this change was caused by X or Y; it has not been confirmed whether the number of foreign guests and the number of overnight stays affects road safety or, conversely, whether the increase in the number of participants due to inflows of non-resident drivers does not increase traffic accidents. With the enormous increase in traffic, a question of ensuring its safety arises. Despite the fact that obligations of responsible entities to ensure road safety on all types of transport infrastructure and related objects (including road tunnels) are incorporated into the legislation, the human factor still remains the weakest and riskiest element of the transport process. At the same time, depending on the growing number of motor vehicles on the road, the human factor also increases the risk of traffic excesses (accidents or collisions).

However, a traffic accident is only one of the possible risks that occur in road transport. Other risks, such as leakage of operating fluids (environmental risk), fire risk, and others, may also be related to a traffic accident. As there is a large amount of risks that may happen in connection with vehicle traffic on roads, this article focuses on one specific area—namely the risks arising from traffic in road tunnels, where the conditions are quite different from open road traffic (impossibility of free escape from an enclosed area, accumulation of exhaust gases, smoke during fire, extremely increased effect of heat from fire, etc.).

Statistical data confirm (NS BESIP ČR 2011–2020, 2017) that fewer accidents occur in road tunnels than on roads. This is mainly because drivers in the tunnel are more focused on driving. However, if there is even a slight traffic problem in the tunnel, such as stopping a vehicle for lack of fuel, it is always a great potential danger. If there is a fire in the tunnel, however, then this can have fatal consequences for the persons currently in the tunnel and for the intervening units of the Integrated Rescue System.

Systematic and regular monitoring of potential risks in the area must be done in the management of road tunnel structures. Competent crisis management procedures increase the effectiveness of preventive measures as well as the solution of a major emergency that

has already occurred, with the aim to minimize the negative impacts on the lives, health, and property of affected people. The topic of safety in tunnels has been widely debated in the international scientific and technical community. In this respect the extensive literature was produced and manuals have been developed. Useful information can be found at e.g. https://tunnels.piarc.org/en.

In 2010, 840 million vehicles were registered worldwide, and the projected growth of the number of vehicles at that time was 1.1 billion in 2020. However, the development of increase in vehicles was quicker than anticipated in the original predictions, and therefore the projections for 2020 were later adjusted to 1.6 billion vehicles. Globally, motorization has already exceeded 100 passenger cars per 1000 inhabitants, i.e., there are only about ten times less passenger cars than the planet's population (Bekesiene et al. 2016).

Approximately 260 million passenger cars were registered in EU countries in 2017, motorization has reached 500 passenger cars per 1000 inhabitants, i.e., five times more than the global average. With 83.1%, passenger cars within inland transportation represented the most important mode of passenger transport in all member states (Eurostat 2018). Over 5.7 million vehicles are currently registered in the Czech Republic and the level of motorization reaches the value of approximately 530 passenger cars per 1000 inhabitants. In the passenger transport area, a total of 2837 billion people were transported in the Czech Republic in 2017, of which 2647 billion people were transported using road transport (CSÚ 2019).

Global mortality statistics according to data from 180 countries, processed by the World Health Organization (WHO), report that 1.25 million people are killed on the roads annually and about 50 million are injured during traffic accidents. The ninth most common cause of death is fatal traffic accidents (ČSÚ 2015). 25,300 people died on the roads in European Union in 2017, which, with a ratio of 49 persons to 1 million inhabitants, compared to the world's 174 persons, makes the roads of EU states the 28th safest in the world (Budský 2018).

There were 104,764 registered traffic accidents in the Czech Republic in 2018, with 565 casualties and 27,680 injured. That means that 53 persons per 1 million inhabitants died. The total material damage was estimated at CZK (Czech Crowns) 6.3 billion (Police of the Czech Republic 2019).

The work deals with the description of crisis management procedures in the management of exposed roads transport structures, such as road tunnels longer than 500 m. in the Czech Republic and Brno, respectively. Based on the analysis of risks related to operation in tunnels, according to emergency statistics and comparison of emergencies with procedures for their elimination, the main aim was to propose possible solutions how to improve crisis management by the tunnel manager with emphasis on safety of persons and property.

2 Background and related valid legislation

In this chapter the National Strategy for Road Traffic Safety in the Czech Republic as well as the tunnels structures and road safety conditions are discussed.

2.1 National strategy for road traffic safety in the Czech Republic

In 2010, on the basis of a negative balance of traffic accidents in the Czech Republic (CR) in relation to European Union (EU), the Ministry of Transport developed

the National Strategy for Road Traffic Safety 2011–2020 (hereinafter referred to as "NSRTS"), (NSRTS ČR 2011–2020, 2017) which was approved by the resolution of the Government of the Czech Republic in 2011, with effect from 2012.

The NSRTS is currently the fundamental and only document at government level, which establishes strategic needs to reduce the number of accidents and creates a framework to protect lives and health of citizens in traffic on roads in the Czech Republic. The aim of the NSRTS is to achieve a reduction in the number of traffic accidents and the related number of killed and seriously injured people in road traffic in the Czech Republic to the average level of European Union countries by 2020, compared to 2009—reducing the number of killed by about 60% (to 333 persons) and seriously injured by about 40% (to 2122 persons). See NSRTS 2011–2020, pp. 6, 37 (2017).

The NSRTS is an action plan detailing specific measures, including entities responsible for their implementation. As part of the plan implementation, the Ministry of Transport is obliged to submit an annual report on the evaluation of partial fulfilment to the Government of the Czech Republic.

After the initial period, when the set inter-annual plan to decrease the number of traffic accidents and related phenomena was more or less met, the increase in fatal traffic accidents in 2014 and especially in 2015 resulted in the Czech Republic being placed among the 8 EU countries with the highest risk of accidents with fatal consequences. In response to this drop, the NSRTS Review and Update was prepared and developed, with effect from 2017. The unfavourable development of NSRTS implementation is best illustrated by the Fig. 1, where the x-axis shows the years, the left y-axis shows the number of deaths, the right y-axis shows the number of seriously injured persons.

The dashed line shows the expected development of the number of killed (red one) and seriously injured persons (orange) according to NSRTS. The solid orange line shows the actual development of seriously injured persons. Data from the year 2019 was available only from the first 2 month.

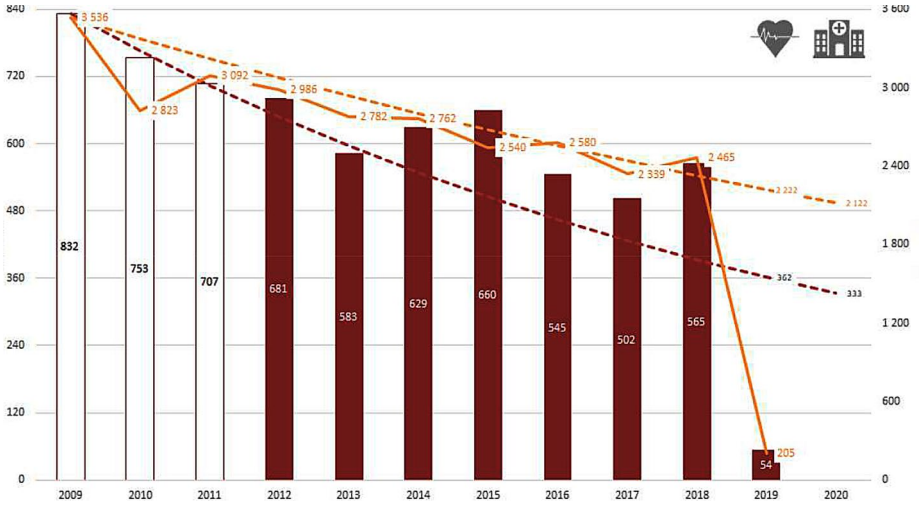

Fig. 1 The unfavourable development of NSRTS implementation. *Source*: (NS BESIP ČR 2011–2020, 2017)

It follows from above that although the NSRTS measures adopted are relatively successful year-on-year in reducing the number of traffic accidents with fatal consequences in the Czech Republic, in comparison with the original plan and the rate with which these accidents are reduced in other European Union countries, the Czech Republic still has much work to do, and the administrators of related transport infrastructure (motorway and road) must constantly aim to evaluate the current situation and more decisively adopt new and more stringent measures to eliminate or accept risks related to the large number of these traffic excesses.

The resolution planning of individual crisis situations in the Czech Republic is based on both general legislation and special sector laws. The general legislation governing activities in the area of preparing for crisis situations consists mainly of laws and government decrees:

No 110/1998 Coll., on the security of the Czech Republic—deals with procedures for threats to sovereignty, territorial integrity, internal order, security of the lives and health of citizens, assets, or the environment of the Czech Republic, depending on the intensity, territorial scope and features of the emergency situations.

The special sector laws, on the basis of which, inter alia, other measures are prepared to deal with crisis situations on roads, include mainly the following laws and decrees:

- No 111/1994 Coll., on the road transport,
- No 13/1997 Coll., on roads.

2.2 Tunnel structures and road safety conditions

Tunnel structures are of great importance when solving complex transport, urban development, and environmental problems of proposed transport routes. These are complicated and technically, organisationally, and financially very demanding transport constructions, where the conditions for the occurrence, development, and progress of dangerous, or rather critical, situations or phenomena greatly differ from the environment of an open road route.

With regard to the high probability of potential risks, it is necessary to secure these structures in terms of construction, technology and organization so that the risks are eliminated, or their effect reduced to an acceptable level. This is done by the relevant legislative, normative, and technical tools. For each tunnel, in addition to the construction documentation, the operational documentation is also prepared, where all aspects of the construction location, and technical and organizational security assurance are evaluated, and where conditions and procedures, on the basis of which the tunnel is built and subsequently operated, are defined. From the point of view of crisis planning, it can be stated that the operational, or rather the safety documentation, substitutes with its content an emergency preparedness plan of a critical infrastructure element for each tunnel construction.

Based on the evaluation of the acquired data, and experience from past major emergencies and joint training exercises of the Integrated Rescue System units, there is a gradual development of the legislation and legal norms in force, making the tunnels currently the most secure structures of surface transport in terms of their safety.

The basic possibilities of obtaining information about traffic or technological excess in a tunnel structure are the following:

- video detection,
- video surveillance done by the traffic operator or technology dispatcher,

- from sensors of technological devices by means of the tunnel's control system announcement,
- report from a traffic user using the tunnel SOS phone or a mobile phone.

Although a major emergency in a tunnel is statistically less common, due to the nature of the environment it is much more serious and has a much greater effect on the lives and health of people and the tunnel itself (Malachova et al. 2017; Navrátil et al. 2019; Oulehlova et al. 2015). Examples of the most tragic major emergencies in Europe are for example mass vehicle fire in a tunnel under Mont Blanc in 1999 with 39 victims (Bodart et al. 2004) an accident of 41 vehicles in the Tauern Tunnel with 12 victims, or a bus accident from 2012 in a tunnel near the Swiss town of Sidders with 29 mostly child victims (Lyon and Sanders 2012).

In addition to risks resulting from traffic situations (vehicle stops, fire, dangerous substances leakage, the loss of load, etc.), there are other dangerous situations in tunnels. These are technological excesses directly in the tunnel, i.e. failure of some of the technology crucial to the safety operation of the tunnel. These failures are further subdivided into those that are an immediate risk to traffic users (e.g. fire of cable wiring in the tunnel), and those which are an indirect threat (e.g. air conditioning failure). Other risk factors are traffic excesses in the area in front of a tunnel (e.g. an emergency situation caused by weather—heavy snowfall and frost), resulting in traffic limitation in front of tunnels. Finally, there are also situations that may occur in the operational and technical areas outside the tunnel, such as the failure to connect to a remote control room, failure of variable traffic signs or traffic equipment. A major emergency can also be caused by a terrorist or criminal act, or vandalism (activities aimed at loss of life, causing panic, devaluation or damage to a tunnel structure or it's decommission, intentional damage to equipment that is dealt with according to the legal norm on criminal damage) (Rybansky and Vala 2009; Oulehlova et al. 2017).

The most common cause of a traffic accident is the entry (getting stuck) of an oversized vehicle, the stopping of a vehicle in the tunnel tube, a vehicle on the wrong side of the road, a traffic accident caused by a slow moving vehicle, a fall in the traffic flow speed below the defined limit (congestion), an objection on the road, an animal or person in the tunnel, a dangerous substance in the tunnel, a major control system failure, and others. (Vlkovsky et al. 2017).

The most common dangerous situations detected by the control system or technology dispatcher are technological equipment failures, measurement of monitored quantities does not correspond to estimates, unexpected manipulation of the control system equipment, increase in concentration of $CO/NO/NO_2$ above the alert threshold, or critical limit, increase in capacity above the alert threshold, or critical limit.

For the analysis of the causes, effectiveness of the staff activity, function of the technological equipment, effectiveness of technical and organizational measures in compliance with the requirements of the directive 54/2004/EC and GD No. 264/2009, the following is used:

- video recordings captured by Closed Circuit Television;
- data from the tunnel control system (air velocity, temperature, staff reaction…);
- simulation of the origin and solution of the problem on the tunnel simulator using data from the control system;
- tunnel manager's materials about performed training of the tunnel staff and regular complex tests of safety equipment in the tunnel.

3 Methodology and data set

One of the strategic goals of the government is to reduce the number of casualties and the seriously injured in the Czech Republic to the average level of other EU countries. One important part of achieving this goal is ensuring road safety in road tunnels. In order to do this, the following research questions were set.

3.1 Research questions

Based on the analysis of statistical data from the Czech Republic (which deal with major emergencies in the past 13 years) and based on the findings from the long-term screening exercises of the Integrated Rescue System units focused on road tunnel safety issues and last but not least the results obtained from guided interviews with road tunnel safety experts the authors sought answers to the following research questions:

Question 1 What are the main risk factors that cause accidents most often?
Question 2 What has to be improved or changed in the risk management strategy for effective prevention of accidents in roads tunnels?
Question 3 Is the road tunnel safety level more dependable on the funding of its infrastructure than investments on stakeholders training?
Question 4 If the stakeholders (government, ministry of transportation, ministry of health, education, etc.) of a country give higher priority to take actions design strategies „profession routine "than the traffic safety in roads tunnels will achieves higher safety level? (Which means that after long-term work in one position, the professional is no longer subject to routine and is unable to perceive his mistake).

3.2 Data

In order to understand the studied issue, it is necessary to explain the organization of road transport and the competences of individual administrative bodies for its operation and safety.

In the Czech Republic, road tunnels located on roads (motorways and first-class roads) are managed by the state through the national organization Road and Motorway Directorate of the Czech Republic (RMD CR). Tunnels on second and third class roads are managed by the region on whose territory they are located. Local roads in municipalities are managed by municipalities according to their territorial jurisdiction. The classification of roads into their relevant categories and changes in the category is decided by a competent road administrative authority. The road categories are determined in accordance with the Czech State Standard ČSN 73 6101—Road and Motorway Design, and Law on Roads 13/1997:

Motorway is a road designed for fast long-distance and interstate transport by motor vehicles; it is built without level crossings, with separate points of connection for entry and exit. It is owned by the Czech Republic.

Road is a publicly accessible road intended for use by road and other vehicles, and pedestrians. Roads are divided according to their purpose and transport importance into the following categories:

First-class road—intended especially for long-distance and international transport. Built as an expressway, it is designed for rapid transport and is only accessible to road motor vehicles. It is owned by the Czech Republic.
Second-class road—intended for transport between districts.
Third-class road—designed to connect municipalities with one another or to other roads. It is owned by a municipality.

The data below (in Table 1) are from tunnels managed by the state (RMD CR). The method of obtaining data for the subsequent statistical processing was as follows: The data were collected from RMD CR employees, road tunnel administrators, who, as part of their duties, record data on all emergency situations and accidents that occurred in a tunnel into the company's information system. The authors of this article drew on this database. From Table 1 it is also evident that 4 people have died in Czech tunnels in last 13 years.

The percent division of particular types of accidents is illustrated at Fig. 2.

4 Results and gain findings

4.1 Training and instruction of traffic operators and technology dispatchers; training of cooperation within the integrated rescue system units

The organization of tunnels in the Czech Republic is related to a security category which is given by the length of the tunnel and traffic intensity [19], whereby the tunnels are classified as:

- tunnels with permanent active remote monitoring, including traffic control
- tunnels with camera surveillance
- tunnels without monitoring.

Under the management of tunnel structures in the Czech Republic which fall into the security categories requiring monitoring and control, ensuring traffic safety is done mainly from monitoring control centres through traffic operators and technology dispatchers (Ministry of Transport 2004; Potucek 2020).

When managing traffic in tunnels, high demands are placed on traffic operators and technology dispatchers in terms of their expertise, mental resilience, concentration, responsibility in decision-making, and other "soft skills". However, the longer the duration of these activities, the higher the risk of these employees falling into a routine, which leads to a decline in responsibility and concentration.

Therefore, the operational documentation in the „Tunnel Operator Training and Instruction section"(Ministry of Transport 2009) emphasizes continuous and iterative training of tunnel operators, their improvement, and development of new habits when operating and managing a tunnel not only in standard situations, but especially in unusual and emergency ones. The chapter provides guidance and recommendations on the frequency, method, and extent of organizing training and instruction. These guidelines are based on a tunnel administrator's "Training of Tunnel Operators" methodology (ŘSD 2009).

The training of traffic operators and technology dispatchers is also performed within the review or tactical training exercise of fire brigade or Integrated Rescue System units.

Table 1 Causes of road tunnel accidents. *Source*: above mentioned database, adjusted by authors

Cause of the accident/year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Sum
Human or animal in the tunnel tube	16	24	4	7	35	20	42	33	68	62	59	40	10	420
Oversized vehicle	15	14	8	3	24	80	151	38	26	41	41	22	17	480
Accident without injury	63	76	57	49	55	43	66	60	55	59	49	50	21	703
Accident with injury	0	0	0	0	1	7	14	7	8	8/1	6	12	15/2	55
Fire		0	1	1/1	1	1	2	1	4	1	1	1	6	19
Wrong-way driver	1	0	0	0	2	0	5	1	7	3	3	4	2	28
Technology malfunction	10	16	3	0	21	7	13	18	13	14	14	2	5	136
Stopped vehicle	261	281	179	115	301	211	252	161	216	192	192	157	150	2668
Sum	366	411	252	174	440	369	545	319	397	372	365	288	211	4509

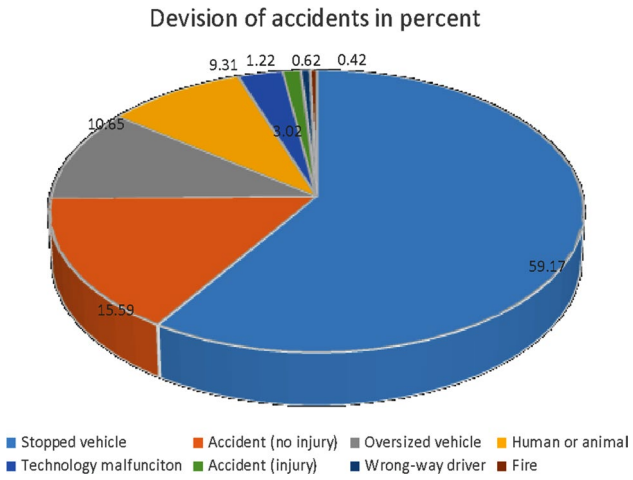

Fig. 2 Percentages of road tunnel accidents by type. *Source*: own

There is no central database of relevant statistical data on accident rate brought about by a specific factor (cause). One reason for the absence of specific data is the multitude or road tunnel administrators—owners.

For this reason and the possibility of obtaining similar data and information about major emergencies, the authors focus on road tunnels in the second largest city in the Czech Republic—Brno. The aim of this article is to propose possible solutions to improve crisis management of tunnel operators with regard to the safety of persons and property. The starting point for achieving the goal of this article is to evaluate the major emergencies statistics and compare their occurrence with the procedures of their elimination, including the findings resulting from simulations on how to deal with major emergencies practiced by Integrated Rescue System units in these tunnels.

The authors focused on tunnels operated in the city of Brno managed by the Road and Motorway Directorate of the Czech Republic, specifically tunnels Pisárky, Husovice, and Královo Pole—see Tables 2 and 3. Due to their location, length, and traffic intensity, all three of these tunnel structures fall into the highest security category, and are subject to Government Decree on Safety Requirements for Road Tunnels over 500 m, (Ministry of Interior 2009) (based on European directive (EUR-Lex 2004). Due to their length and more complicated technical equipment, these traffic constructions put much higher demands on ensuring traffic safety, maintenance, solving all non-standard situations connected with traffic, and crisis management during major emergencies.

4.2 Statistics of emergencies in Brno tunnels

In the operational documentation of each tunnel, in addition to intervention procedures, there are guidelines for recording and record keeping of emergencies and their analyses.

Emergencies are recorded by the tunnel operator in the tunnel records to the Book of Emergencies in prescribed forms.

By 31 January of each following year, the tunnel operator prepares an analysis of emergency situations for each tunnel, in the form of clear tables and comments. The document is stored in the tunnel archive and is permanently available to the needs of the administrator

Table 2 Causes of road tunnel accidents—comparison of Brno city and the Czech Republic. *Source*: data from RMD CR, processed by author

	Czech Republic 2005–2017				Brno 2008–2018			
	Number of cases	Relative frequency	%	Order	Number of cases	Relative frequency	%	Order
Stopped vehicle	2668	0.5917	59.17	1	591	0.6024	60.24	1
Accident (no injury)	703	0.1559	15.59	2	102	0.1039	10.4	3
Oversized vehicle	480	0.1064	10.65	3	174	0.1773	17.74	2
Human or animal	420	0.0931	9.31	4	76	0.0774	7.75	4
Technology malfunction	136	0.0301	3.02	5	12	0.0122	1.22	5
Accident (injury)	55	0.012	1.22	6	10	0.0101	1.02	6
Wrong-way driver	28	0.0062	0.62	7	6	0.0061	0.61	7
Fire	19	0.0042	0.42	8	10	0.0101	1.02	6
Sum	4509	1	100		981	1	100	

Table 3 The number of emergencies in Brno tunnels from 1 January, 2008 to 31 December, 2018. *Source*: processed by authors

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Sum
Husovický tunnel												
Human or animal in the tunnel tube	0	5	0	1	0	1	3	4	1	1	1	17
Oversized vehicle	1	4	0	4	0	0	4	1	2	2	4	22
Accidents (no injury)	3	5	2	1	3	4	11	6	7	3	1	46
Accident (injury)	0	0	0	0	1	0	0	0	1	0	0	2
Fire	1	0	0	0	2	1	0	0	1	0	0	5
Wrong-way driver	0	0	0	1	0	1	1	0	0	0	0	3
Technology malfunction	0	0	0	0	1	0	0	1	0	0	1	3
Stopped vehicle	22	30	8	15	20	43	45	33	24	26	11	277
Pisárecký tunnel												
Human or animal in the tunnel tube	1	6	0	1	1	5	3	6	1	2	0	26
Oversized vehicle	2	14	4	2	4	2	1	2	0	0	0	31
Accident (no injury)	6	3	2	1	6	0	4	2	2	3	1	30
Accident (injury)	0	0	0	1	0	0	0	0	0	0	1	2
Fire	0	1	0	1	0	0	0	0	1	0	0	3
Wrong-way driver	0	0	0	0	0	1	0	1	0	0	1	3
Technology malfunction	0	0	0	0	0	1	2	1	0	0	1	5
Stopped vehicle	5	18	8	7	9	13	16	10	10	10	7	113
Královopolský tunnel												
Human or animal in the tunnel tube	ND	ND	ND	ND	4	6	5	8	6	4	0	33
Oversized vehicle	ND	ND	ND	ND	6	15	24	32	1	23	20	121
Accident (no injury)	ND	ND	ND	ND	0	6	6	4	4	4	2	26
Accident (injury)	ND	ND	ND	ND	0	1	0	2	2	1	0	6
Fire	ND	ND	ND	ND	2	0	0	0	0	0	0	2
Wrong-way vehicle	ND	ND	ND	ND	0	0	0	0	0	0	0	0

Table 3 (continued)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Sum
Technology malfunction	ND	ND	ND	ND	0	1	1	1	0	1	0	4
Stopped vehicle	ND	ND	ND	ND	18	32	42	41	45	20	11	209

Královopolský tunnel was first open to traffic in 2012

ND no data

and owner, Ministry of Transport, Brno City Municipality, Regional Authority of South Moravian Region, and International Tunnelling and Underground Space Association/Association Internationale des Tunnels et de l'Espace Souterrain (ITA/AITES).

The statistics below is processed using the Automatic Processing of incidents of tunnels application and shows the frequency and types of emergencies for all the tunnels as a summary or individually for the last 10 years. As reference emergency situations were chosen such situations from the statistics that, based on their nature, threaten the safety, health or lives of traffic users, or that might be a threat to property, and usually require intervention of the Integrated Rescue System units—Table 3.

When looking at the traffic situation in the city of Brno, it can be stated that in 2017 the number of registered vehicles was 243,843 and the level of motorization reached 506 passenger cars per 1000 inhabitants. With regard to traffic in Brno tunnels, the administrator statistics show that an average of 169,000 vehicles/24 h pass through all the tunnels.

In the Czech Republic there were 104,764 traffic accidents, from this there were 2853 traffic accidents in Brno, where 8 people were killed and 833 injured in the year 2018 (Vystrcil 2019).

In addition to the training of tunnel technical staff, the tunnel manager ensures cooperation with the Integrated Rescue System units, especially with the Fire Rescue Service, in organizing screening or tactical exercises, or in familiarizing with the structural layout of tunnel objects and their technical facilities. As part of training of the Integrated Rescue System emergency units, a screening or tactical exercise in one of the tunnels longer than 500 m is carried out on a yearly basis during scheduled maintenance closures of tunnels in Brno, according to the choice of the Fire Rescue Service in the region. Moreover, due to changes of personnel in Fire Rescue Service emergency units, new members of emergency units receive training in the layout of one tunnel structure once a year during the closure of tunnels.

Before each exercise, the Fire Rescue Service prepares a document entitled "Intent of screening/tactical exercise of the Integrated Rescue System units" for a specific situation in a specific tunnel structure. The intent is discussed with authorized representatives of all units and entities involved, including the tunnel manager. The following items are agreed: procedures, technical and transport security in terms of material and personnel resources, establishing competences, cooperation and coordination of the whole event.

In the designated area of the tunnel, props are installed and supernumeraries placed. At a specified time, the exercise is started. Its progress, activities of all participating units in the tunnel tube, and the continuity of reactions of tunnel equipment and dispatch operators, including the duration and method of information transmission, are monitored and assessed after the exercise. The summary of findings and results of the exercise is prepared in the final report "Assessment of a Screening Exercise of the Integrated Rescue System", which also mentions observations, comments on the activities of personnel of particular units during the exercise, and proposed measures or recommendations to the construction manager or supervisor to streamline a future potential intervention in an emergency situation. Since 2012, rescue team exercises have been organized once a year in monitored tunnels in Brno. The exercises suggest the following recommendations: Table 4.

5 Research questions answers

Question 1 What are the main risk factors that cause accidents most often?

Table 4 Screening exercise of the integrated rescue system emergency unit in tunnels in Brno in 2012–2018 *Source*. Own

Year of exercise	2012	2013	2014	2015	2016	2017	2018	Tunnel manager's measures
Findings/requirements								
Ensure cooperation for regular training of emergency units	✓	✓						The cooperation then organized continuously
Modification of communication connection for more operational arrival of emergency units	✓	✓						Modifications in effect since 2014
Standardization of radio connection in tunnels, preferably analog connection			✓					Requirement fulfilled since 2018
Equipped tunnel couplings with non-flooded fire main-line				✓			✓	Due to an insufficient width layout of tunnel couplings (narrow tunnels), it is not currently possible to implement these measures
Add equipment to improve analog radio reception for trouble-free connection of fire protection emergency units				✓				Finished since 2018 in all tunnels managed by the Road and Motorway Directorate of the Czech Republic.
Mark all tunnel cross passages with numbers for easier orientation and communication				✓			✓	The cross passages marking is completed in stages
Set up a connection of data from video surveillance of tunnels in Brno to the Regional Operational and Information Centre of Fire Rescue Service in the region for more effective intervention management in case of emergency					✓		✓	Modifications are planned to be done together with the modernization of technological equipment in 2020
Ensure colour differentiation of tunnel tubes for easier orientation of rescue units					✓			Considering the very costly large scale investment, it is necessary to carry out effectiveness evaluation. There is not enough information available to carry out the evaluation yet
Ensure installation of equipment to strengthen analog radio reception					✓			Finished since 2018 in all tunnels managed by the Road and Motorway Directorate of the Czech Republic
Issue information warning alerts during an emergency situation in foreign languages						✓	✓	Only one world language is being considered to be added—English. This measure is planned for 2022
Ensure wider coverage of analog radio reception in tunnel portals						✓		Finished since 2018 in all tunnels managed by the Road and Motorway Directorate of the Czech Republic
Equip the tunnels with Accord Dangerous Routier (ADR) vehicle monitoring system and section speed measurement							✓	Installation of ADR monitoring system in the following 6 years

Table 4 (continued)

Year of exercise	2012	2013	2014	2015	2016	2017	2018	Tunnel manager's measures
Examine the coverage of Pegas digital radio connection in tunnel tubes. During the exercise, the reception was not sufficient (the influence of terrain, location)							✓	Strengthen the digital reception, extend range

Findings from the tunnel manager's perspective/road and motorway directorate Brno

The security of each system depends on its weakest element. And for tunnel operations, this weakest element is precisely the human factor, whose failure cannot, unfortunately, be completely eliminated by any technical or organizational measures. Based on the findings from case studies conducted in the city of Brno, two factors that cause accidents most often were identified. These factors are the performance of tunnel operators (dispatchers) and behaviour of road users (drivers and passengers). See Tables 2 and 3.

Question 2 What has to be improved or changed in the risk management strategy for effective prevention of accidents in roads tunnels?

Under the conditions of the Czech Republic, it is necessary to:

- increase police supervision,
- stricter repression,
- ensure better law enforcement.

Moreover, to extend the area of driving school training for non-professional to the knowledge of how to behave in a tunnel emergency. For professional drivers, highlight this area in the training and also include this topic into final examinations for professional driving licence.

Finally, update and extend professional courses, the evaluation criteria and their regular monitoring for tunnel operators.

Question 3 Is the road tunnel safety level more dependable on the funding of its infrastructure than investments on stakeholders training?

When assessing the implementation of crisis management tasks in the framework of practical training, it was found that in order to efficiently, reliably and quickly fulfil the required tasks, certain technical, constructional, organizational measures had to be taken and ensured in the event of specific emergencies. However, the financial coverage of these measures is an inseparable factor. See Table 4.

Last but not least, the level of road tunnel safety is influenced by tunnel operators (dispatchers). For this reason, it is necessary to determine in the methodology the training of tunnel operators, the content of basic, regular and special training, including the parameters and method of training. Furthermore, determine the professional, qualification, personal and psychological prerequisites of tunnel operators, including evaluation criteria and periodic screening. It is necessary to determine, in the context of the legislation in force, the manner in which tunnel services are to be performed at all types of control centres in continuous operation.

Both these aspects (sufficient financial coverage of all measures and training, training and periodic screening of tunnel operators) affect the safety of road tunnel operations. Both aspects have the same priority, they work in synergy.

Question 4 If the stakeholders (government, ministry of transportation, ministry of health, education, etc.) of a country give higher priority to take actions design strategies „profession routine “than the traffic safety in roads tunnels will achieves higher safety level?

The results from the survey done showed that the human factor failure cannot, unfortunately, be completely eliminated by any technical or organizational measures.

However, it is up to the designer and investor during construction and subsequently during operation to the manager of these buildings, to ensure the necessary organizational measures, using all technical tunnel structures, to minimize the risk of emergencies associated especially with human factor failure (Adamoniene 2018).

The level of road tunnel safety is influenced by tunnel operators. The tunnel manager (the supervisor and the competent authority) should determine, in the context of the applicable legislation, the manner in which tunnel services are to be carried out at all types of control centres in continuous operation. In this way, stakeholders and responsible parties will achieve a higher level of road tunnel safety.

6 Discussion and suggestions

The main goal was to identify main risk factors so that their elimination occurs in increasing of the security of traffic in the roads tunnels. Another goal was to suggest possible solutions to improve security and thus the level of emergency management.

The weakest and most risky link of almost every process is usually the human factor. Based on the findings from case studies conducted in the city of Brno, two factors that cause accidents most often were identified. These factors are the performance of tunnel operators (dispatchers) and behaviour of road users (drivers and passengers).

When managing tunnel structures, we suggest focusing on the prevention of emergency situations, or rather maximum elimination of negative development of situations that have already occurred.

For the first factor:

- a more thorough approach to the training of tunnel operators (dispatchers) with a focus on testing knowledge of procedures in the occurrence of specific situations and flawless operating of tunnel control systems by all members of each shift interchangeably. Furthermore, enshrine this approach in the internal regulations, or, if applicable, implement changes in this area into departmental regulations;
- increase the frequency of spot checks of the operators' (dispatchers') work performance in order to minimize the possibility of developing routinism (professional blindness) and the resulting risk of loss of concentration leading to operators' (dispatchers') mistakes.

For the second factor:

- educate road users, with the aim of raising awareness, on the principles of safe driving in road tunnels, on behaviour, procedures, movement and use of safety tunnel equipment during an emergency situation with the aid of, for example, local or regional media campaigns, public seminars, regular excursions in tunnels for the public;
- extending the training of professional drivers on the principles of safe driving in road tunnels, and their regular training;
- increase the presence of Czech police patrols and proceed more strictly in dealing with traffic offenses—tighten the repressive aspect.

The analysis also showed that the most serious accidents are considered to be accidents involving fire of a heavy truck with dangerous, highly flammable or explosive material. A preventive measure for this issue is thorough monitoring of ADR vehicles (Accord Dangereuses Route). Therefore, the existing tunnels longer than 500 m managed by the Road and Motorway Directorate of the Czech Republic are being gradually retrofitted with the ADR vehicle monitoring system and section speed measurement. In Pisárky, Královo Pole, and Husovice tunnels, the installation of ADR monitoring system is projected to be finished within 6 years.

Another shortcoming that emerged from the research is the fact that there are no evaluation criteria and their indicators that would assess the level of emergency preparedness with emphasis on the safety of health and life of people and property (Svarcova et al. 2015).

The collaboration during exercises of rescue teams, in cooperation with the tunnel administrator (Road and Motorway Directorate of the Czech Republic), belongs to the preparation of a potential emergency situation solution and is one of the aspects/tasks of crisis preparedness of stakeholders. However, there is no methodology for evaluating the level of emergency preparedness of the entire system (technical equipment, technology, human factor, etc.) (Svarcova et al. 2016; Rybansky 2007; Tušer and Navrátil 2020).

By analysing the data and information obtained, the authors identified the most significant shortcomings related to traffic safety and emergency management in road tunnels. Subsequently, they proposed possible solutions to improve crisis management by the tunnel manager with an emphasis on the safety of health and lives of people and property. The preparation of methodology is one of the future tasks.

7 Conclusion

Nowadays, there is a high level of equipment quality of tunnel structures in the Czech Republic with technical means for ensuring safety. Out of all types of transportation structures, tunnels are considered to be the most secure structures in terms of transport safety. However, it is not possible to view tunnels as isolated objects, but as a part of transport and telematics system in a given area, they must communicate with traffic centres, operational centres of the Integrated Rescue System, integrate connections with respect to traffic control not only inside the tunnel structure, but also on connecting roads, where they must react to a traffic situation that could be kilometres away from the tunnel. Tunnel structures could be considered some kind of "living organisms", because even road users driving their vehicles inside the tunnels could be considered a part of the tunnel structure. They must also cooperate with tunnel systems, follow the traffic signs information, react to changes, etc. However, the safety of any system depends on the weakest link. For tunnel traffic, the weakest link is the human factor, whose failure cannot be, unfortunately, completely eliminated by any technical or organizational measure.

Nevertheless, it is up to the planner and investor during the construction, and later the structure administrator during the operation of the tunnel, to ensure necessary organizational measures, using all technical means of tunnel structures possible, to minimize the risk of emergency situations connected especially to the failure of human factor.

One of the research questions was also the solution of the emergency preparedness of a subject (tunnel) and its level. Specifically, if there are criteria (standards) that could evaluate the level of emergency preparedness for emergency or crisis situations, such as the preventative measure ex ante.

The problem has two layers.

The first is the technical and technological preparedness of a tunnel (entity) for traffic in standard, unusual, and emergency traffic situations. This is generally addressed in the Technological Equipment of Road Tunnels document (TP98/2010-Z-1), and modified for specific conditions in the fire safety solution of a structure (Kelemen et al. 2018), and in risk analysis of a specific tunnel. The tunnel is integrated into a safety category and equipped with technology accordingly (Tauferová 2001).

The second layer is organizational and includes safety documentation of the tunnel (part A of the operational documentation) and fire control documentation, or, if known or expected, specific risks. Furthermore, it includes the "Emergency Plan" of a particular tunnel, connected to a regional emergency plan for tunnels with a high fire danger level. Entities responsible for the security policy and safety in the Czech Republic are the Ministry of Transport for highways, and regional authorities for 1st class roads, etc.

The tunnel administrator is responsible for implementing the measures in practice. The evaluation of tunnel preparedness for a crisis or emergency situation can be carried out in several ways. From tactical, screening exercises to tests of fire safety equipment according to applicable regulations. An integral part of the evaluation is also the training of tunnel operators (dispatchers). It is a complex process, consisting of several parts. TP229/2010 can also serve as guidelines.

Apart from the aforementioned general criteria for evaluating preparedness, there are a number of variables that relate to a particular tunnel and cannot be precisely predicted, let alone generalized into an evaluation system. Every tunnel is a unique transport, construction piece of work with specifics that cannot be fully and accurately covered by universal evaluation criteria. However, if a certain evaluation scale could be compiled and filled with specific data in an accepted and useful output during regular tunnel inspections(for example once a year), it would contribute to increasing transport safety in road tunnels, as part of the preventative measures ex ante.

The authors believe that the creation of a universal set of criteria is unlikely, the solution may possibly be to set criteria and their indicators directly, always for a specific tunnel.

Acknowledgements Irena Tušer thanks her AMBIC College, Prague for its support.

Author Contributions Conceptualization, methodology and investigation I. Tušer and Š. Hošková-Mayerová; formal analysis I. Tušer and Š. Hošková-Mayerová; data resources, I. Tušer; writing–original draft preparation, writing–review and editing, I. Tušer and Š. Hošková-Mayerová; project administration and funding acquisition, Š. Hošková-Mayerová.

Funding This research was supported within the Project DZRO K217, supported by the Ministry of Defence in the Czech Republic.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

Adamoniene, R.: Management presumptions and possibilities of human resources formation. In: Bekesiene, S., Hoskova-Mayerova, S. (eds.) Challenges to National Defence in Contemporary Geopolitical Situation (CNDCGS' 2018), pp. 157–166 (2018)

Bekesiene, S. Hoskova-Mayerova, S., Becherova, O.: Accidents and emergency events in railway transport while transporting dangerous items. In: Proceedings of the 20th International Scientific Conference Transport Means 2016, Book Series: Transport Means—Proceedings of the International Conference, pp. 936–941 (2016)

Botlikova, M. Botlik, J.: Influence the safety of road infrastructure on incoming tourism (2018). https://vslg.cz/wp-content/uploads/2018/06/9-botlikovabotlik.pdf

Bodart, X., Marlair, G., Carvel, R.: Fire in road tunnels and life safety: lessons to be learnt from minor accidents. In: 10th International Interflam Conference, Edimbourg, pp. 1517–152 (2004)

Budský, R.: Tým silniční bezpečnosti, (In Czech), (Road Safety Team), Parlamentní listy.cz. https://www.parlamentnilisty.cz/zpravy/tiskovezpravy/Tym-silnicni-bezpecnosti-V-roce-2017-zemrelo-na-silnicich-EU-25-300-lidi-531702. Accessed 11 Dec 2019 (2018)

ČSÚ 2015: Měsíčník Českého statistického úřadu. Statistika & my. Praha, Česká republika: Český statistický úřad (In Czech), Czech Statistical Office (2015). http://www.statistikaamy.cz/2015/12/kazdy-rok-zemre-na-silnicich-125-mil-osob/. Accessed 5 Jan 2020

ČSÚ 2019: Veřejná databáze. Český statistický úřad (In Czech), Czech Statistical Office, https://vdb.czso.cz/vdbvo2/faces/cs/index.jsf?page=vystup-objekt&pvo=DOP05-D&z=T&f=TABULKA&skupId=1613&katalog=31028&pvo=DOP05-D&c=v3~8__RP2017#w (2019). Accessed 15 Jan 2020

European Commission: White Paper—Roadmap to a Single European Transport Area—towards a competitive and resource efficient transport system. http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P7-TA-2011-0584+0+DOC+XML+V0//CS (2011). Accessed 27 Jan 2020

EUR-Lex: Access to European Union law (In Czech Přístup k právu Evropské unie.) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32004L0054 (2004). Accessed 01 Jul 2019

Eurostat 2018: Eurostat—statistical office of the European Union. (European Commission), Available online: Eurostat: https://ec.europa.eu/eurostat/data/database. Accessed 15 Feb 2019 (2018)

Kelemen, M., Szabo, S., Vajdova, I.: Cybersecurity in the context of criminal law protection of the state security and sectors of critical infrastructure. In: Bekesiene S., Hoskova-Mayerova S. (eds.) Challenges to National Defence in Contemporary Geopolitical Situation (CNDCGS' 2018) pp. 100–104 (2018)

Lyon, R., Sanders, J.: The Swiss bus accident on: lessons for pre-hospital care. Crit. Care **16**(4), 138 (2012). https://doi.org/10.1186/cc11370

Malachova, H., Oulehlova, A., Kincl, P.: SIMEX Simulation tool—"Accident" crisis scenario and crisis management entities' exercise, In: Communication and Information Technologies (KIT). In: Barath, J., Dedera, L., Ockay, M. (eds.) Slovakia, pp. 83–89 (2017)

Ministry of Transport 2004. Technological equipment of road tunnels. (In Czech: Technologické vybavení tunelů pozemních komunikací; Technické podmínky TP98). http://www.pjpk.cz/data/USR_001_2_8_TP/TP_98.pdf

Ministry of Transport 2009. Operation, management and maintenance of tunnels. Technical conditions, TP 154, http://www.pjpk.cz/. Accessed 5 Nov 2019 (2009)

Ministry of Interior, Czech Republic (2009). (In Czech Nařízení vlády č. 264/2009 o bezpečnostních požadavcích na tunely pozemních komunikací delší než 500 metrů.) https://aplikace.mvcr.cz/sbirka-zakonu/SearchResult.aspx?q=264/2009&typeLaw=zakon&what=Cislo_zakona_smlouvy. Accessed 05 Feb 2020

Navrátil, J., Sadovská, V., Švarcová, I.: Health risk assessment of combustion products from simulated residential fire. Stud. Syst. Decis. Control **104**, 15–23 (2019). https://doi.org/10.1007/978-3-319-54819-7_2

NSRTS 2011–2020: National Road Safety Strategy of the Czech Republic 2011–2020. Ministry of Transport, BESIP (In Czech: Národní strategie bezpečnosti silničního provozu ČR 2011–2020, BESIP). https://www.dataplan.info/img_upload/7bdb1584e3b8a53d337518d988763f8d/nsbsp-020_vc_ap_final.pdf. Accessed 15 Dec 2019 (2017)

Oulehlova, A. Malachova, H., Rezac, D.: Use of simulation in cooperation training of critical infrastructure entities. In: Distance Learning, Simulation and Communication 'DLSC 2015', pp. 103–112 (2015)

Oulehlova, A., Malachova, H., Rezac, D.: Risks evaluation in preparation of crisis management exercise. In: Distance Learning, Simulation and Communication 'DLSC 2017', pp. 143–153 (2017)

Palatkova, M.: Mezinárodní turismus: analýza pozice turismu ve světové ekonomice, změny mezinárodního turismu v důsledku globálních změn, evropská integrace a mezinárodní turismus. (In Czech), (International tourism: analysis of the position of international tourism, changes in international tourism in the

globalization of change, European integration and international tourism) Praha: Grada. ISBN 978-80-247-4862-7 (2014)
Police of the Czech Republic: Accident statistics (In Czech: Statistika nehodovosti), https://www.policie.cz/clanek/statistika-nehodovosti-900835.aspx?q=Y2hudW09Mg%3d%3d (2019). Accessed 5 Jan 2020
Potůček, R.: Life cycle of the crisis situation threat and its various models, studies in systems. Stud. Syst. Decis. Control **208**, 443–461 (2020). https://doi.org/10.1007/978-3-030-18593-0_32
Rybansky, M., Vala, M.: Relief impact on transport. In: ICMT'09—International Conference on Military Technologies 2009. Brno, Czech Republic. ISBN 978-80-7231-649-6 (978-80-7231-648-9 CD) (2009)
Rybanský, M.: Effect of the geographic factors on the cross country movement during military operations and the natural disasters. In: International Conference on Military Technologies, University of Defence, Brno (Czech Republic), pp. 590–596. ISBN 978-80-7231-238-2 (2007)
ŘSD: Road quality policy, (In Czech Politika jakosti pozemních komunikací). http://www.pjpk.cz/metodicke-pokyny-smernice-a-dalsi-technicke-pre/ (2009). Accessed 3 Feb 2020
Svarcova, I., Ptacek, B., Navratil, J.: Psychological intervention as support in disaster preparedness. Crisis Manag. Sol. Crisis Situat. **2015**, 317–320 (2015)
Svarcova, I., Hoskova-Mayerova, S., Navratil, J.: Crisis management and education in health. Eur. Proc. Soc. Behav. Sci. **16**, 255–261 (2016). https://doi.org/10.15405/epsbs.2016.11.26
Tauferová, M.: Požárně bezpečnostní řešení stavby. (In Czech), (Fire safety solution of the building). Vytápění Větrání Instalace **2001**(1), 19–21 (2001)
Tušer, I., Navrátil, J.: Evaluation criteria of preparedness for emergency events within the emergency medical services. Stud. Syst. Decis. Control **208**, 463–472 (2020). https://doi.org/10.1007/978-3-030-18593-0_33
Vlkovsky, M., Ivanusa, T., Neumann, V., Foltin, P., Vlachova, H.: Optimizating cargo security during transport using dataloggers. J. Transp. Secur. **10**(3–4), 63–71 (2017). https://doi.org/10.1007/s12198-017-0179-4
Vystrčil, P.: Crisis management and emergencies in traffic tunnel constructions (In Czech), Bachelor Thesis, p. 61, Vysoká škola Karla Engliše, A.S., Brno (2019)