DEVELOPMENT OF (SELF-)RESCUE PRINCIPLES DURING FIRES IN THE OF THE BLANKA TUNNEL COMPLEX

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ABSTRACT: Compared to surface roads, road tunnels are characterized by additional specific hazards resulting from the enclosed cross-section of the structure. From the point of view of personal safety, it is therefore necessary to address fire safety. The Czech regulatory framework addressing fire safety in the first moments, after a fire breaks out, treats road tunnels primarily as non-production facilities (Czech Standardization Agency 2023). This means that they primarily address the safety of pedestrians and do not take into account aspects of road traffic itself, let alone the possibilities of telematic traffic control depending on the current traffic situation. Regulations relating directly to the design and equipment of planned or already operational PK tunnels (Czech Standardization Agency 2013, MD ČR 2025, Ministry of Transport of the Czech Republic 2024) set out requirements for the location of individual structural/technological/telematic elements and the principle of organizational security measures, but for the most part do not address the requirements for mutual interaction in space and time in the event of an emergency. Based on a detailed analysis of the course of more serious emergencies that have occurred during more than ten years of operation of the Blanka tunnel complex, the principles of self-rescue and rescue of persons in the complex have also undergone development. The article describes the gradual implementation of support measures, including the implementation of new technological equipment and the modification of the principles of cooperation and control of individual technological elements and units, as well as road traffic control, also with regard to road traffic safety.

1. INTRODUCTION

The Blanka tunnel complex was presented at the conference in a number of previous years. The aim of this article is to describe how real-life experience has led to adjustments to the principles of (self-)rescue and the implementation of dynamic evacuation sequences for selected technological units, taking into account possible traffic situations in the event of a vehicle fire in the TKB. In addition to fulfilling their primary purpose – supporting the evacuation of people and the intervention of the Fire and Rescue Service – these sequences also seek to take into account road traffic safety in sections of the tunnel complex that are not directly threatened by fire.

Road users in the tunnel need to be protected from the effects of fire, especially from toxic fumes. Obviously, the fewer people there are in the area of the fire, the fewer people are at risk. Therefore, the general aim is to limit the number of people near the fire and to inform those who are already in the fire area and enable them to escape to safe areas. To this end, a number of technological, safety, and telematic devices are installed in tunnels to detect emergencies and activate appropriate responses to these events.

From a traffic management perspective, the primary task after a fire has been detected is to prevent other vehicles from entering the affected area in the tunnel tube where the incident has occurred (the affected tunnel tube). After a fire is detected and a fire alarm is triggered in the tunnel control system and related technologies, vehicles are stopped in front of the fire by activating light signals S 1a and S 8a. Vehicles behind the fire are allowed to leave freely or even preferentially (prioritization of the direction from the tunnel with colliding surface traffic flows). If the tunnel consists of two tunnel tubes, the tunnel tube not affected by the fire (the intervention tunnel tube) is also closed, i.e., the entrance is closed immediately and the light signals S 1a and S 8a are activated in subsequent sections in a gradual evacuation sequence. The affected tube serves as a fire-safe area for people escaping from the affected tunnel tube via tunnel connections, while at the same time, fire brigade units intervene from the opposite direction. From the point of view of tunnel technology management, the aim is to alert people/tunnel users trapped in the tunnel to the imminent danger and provide them with the conditions for self-rescue until the arrival of the fire brigade. This primarily involves activating the local public address system, emergency escape lighting, fire ventilation, and operational information equipment. A description and evaluation of the effectiveness of individual information tools, responses, and user behaviour would fill several more articles. As can be seen from the above, the evacuation process can be divided into two main phases, depending on whether the fire brigade has already arrived in the tunnel (rescue of persons and extinguishing of the fire) or has not yet arrived (self-rescue of users).

When a fire alarm is activated in the BTC control system, whether based on detection by a linear temperature detector or manual activation by a technology dispatcher, the following technological equipment units are activated:

- traffic control,
- emergency escape lighting,
- main tunnel lighting,
- ventilation,
- local radio,
- antenna equipment,
- water management.

As we will show below, one thing is to meet regulatory requirements in terms of the placement and connection of individual technological operating units. Another thing is to implement the logic of their activation and function so that they are as beneficial as possible to all parties involved in the situation at hand.

2. BLANKA TUNNEL COMPLEX – INITIAL SAFETY CONCEPT

As an urban tunnel, the TKB was designed from the outset to allow at least partial congestion without significantly increasing fire safety risks, taking into account the expected traffic situations and traffic density during daily rush hours. This requires an effective system for managing and regulating traffic and evacuating pedestrians. The central brain of the tunnel is the tunnel control system, which connects all detectors and related response devices in technology and transport. After a fire alarm is declared, traffic management implements appropriate scenarios for the automatic closure of all entrances to the complex and the closure and evacuation of individual traffic sections (Brusnice, Dejvice, Bubeneč) in combination with the location of the fire. This means that during evacuation, traffic lights at intersections where tunnel exits lead give priority to tunnel exits so that the tunnel can be evacuated as quickly as possible. The aim of clearing the fire-affected tunnel tube is to limit the number of vehicles in the sections behind the fire, where smoke can spread naturally or be forced by fire ventilation. The aim of clearing the tunnel tube without fire, i.e. an emergency tunnel, is to clear the tunnel of vehicles that could obstruct the arrival of firefighting units or endanger pedestrians who have already managed to pass through the tunnel connections from the fire tunnel to the opposite tunnel.

After the fire mode was activated, traffic control proceeded as follows:

- All entrances from the surface network to both lanes/tunnel tubes at all four interchanges (barriers Z1 + S 13) are immediately closed.
- in the traffic section with a fire (from the disconnection of the exit ramp of the previous traffic section to the following disconnection), traffic is immediately suspended at each such section from the entrances to the lane signal section corresponding to the fire detection location;
- in the traffic areas in the affected tunnel tube, which are located behind the fire in terms of the direction of travel, vehicles are allowed to leave freely via any exit;
- on the traffic lane without fire, the traffic section opposite the affected section shall be closed;

- in unaffected traffic sections located in the direction of travel beyond the section opposite the section with the fire, all directions of travel shall remain open;
- evacuation sequences are gradually activated in the closed sections, which proceed at a constant speed corresponding to approximately half the maximum permitted speed.

In the control of technological equipment after the activation of the fire mode, selected technological units responded in the following automated manner:

- emergency escape lighting immediately turns on in both tunnel tubes along the entire length of both tunnel tubes of the complex;
- The main tunnel lighting immediately turns on to maximum brightness in both tunnel tubes.
- Ceiling lighting at the entrances to escape routes/connections in both tunnel tubes is switched off, except for the lighting of the connection, which is designed by the control system as the most suitable for fire brigade intervention based on the location of the fire;
- Fire ventilation is activated according to the scenario for the relevant fire detection section.
- The local public address system (speakers located in both tubes at the entrances to the cross-passages and in the cross-passages themselves) is immediately activated in both tubes and in the cross-passages. in the tunnel tube affected by the fire and in the connecting passages, it calls for the tunnel tube to be evacuated via the connecting passage; in the unaffected tube, it calls for the tunnel to be evacuated in/against the direction of travel, depending on which portal is closer at that location; the announcements (in Czech only) are repeated cyclically;
- automatic access to FM radio stations whose frequencies are broadcast in the complex. After one playback of the message about the closure of the TKB, the previous tuned station will resume broadcasting.

It is clear from the above that the activation of follow-up reactions by safety devices was approached in the same way as for buildings; everything is activated immediately and in all areas, which is fine in the case of buildings. However, in the context of considering the current traffic situation and road traffic safety conditions in a 5.5 km long tunnel complex with connecting and turning lanes, this raises a number of questions and doubts about the consequences of activation for passing drivers. Tunnel users find themselves in different situations in different sections of the complex. While such a response is appropriate in the area immediately adjacent to the fire, it is not so appropriate in the opposite tunnel tube, where standard road traffic is taking place and users are not immediately threatened by the fire. The escape distances of several hundred meters are also debatable.

To give a complete picture, let us take the following example: given the logic of the tunnel evacuation scenarios, a situation may arise where a vehicle that entered the fire-affected tube of the complex just before the entrance was closed by the fire sequence is allowed to pass through the entire length of the complex, i.e., 5.5 km. The vehicle will travel this distance at the maximum permitted speed of 70 km/h in approximately 5 minutes, or at 50 km/h in approximately 7 minutes (not taking into account the possibility of congestion). Throughout this time, the driver of such a vehicle is illuminated by emergency lights located approximately 1 m above the road surface with a spacing of approximately 12 m, with luminous intensity parameters designed primarily for visibility when the entire cross-section of the tunnel tube is filled with smoke... Not to mention the automated local radio announcements, which also distract drivers (drivers may slow down in an attempt to catch and understand the announcement, creating collision situations). Before the BTC was put into operation, these possible consequences of the immediate activation of the fire sequence for road traffic safety were discussed with the parties concerned, but priority was given to simply complying with fire safety regulations in accordance with existing practices.

Figure 1: Activation of emergency escape lighting

3. ANALYZED EMERGENCIES IN BTC (2015–2025)

Over more than a decade of BTC operation, a number of emergencies of varying severity (personal car/Heavy goods vehicle fires, smoke without flame combustion, traffic accidents with secondary risks) have been recorded, which tested the original concept and provided an opportunity to evaluate the originally set principles and parameters (**Error! Reference source not found.**). These selected events were examined in more detail by the design team beyond the standard requirements. Camera recordings, records of communication between individual components or participants in the operation, and records of the responses and statuses of individual technological units in the control system were used for the evaluation.

Table 1: List of analyzed events with fire mode activation in BTC

Date	Tun.	Burning object/ Source of smoke	Initial detection	Activation of fire mode	Note
May 14, 2019	BTC (BUB)	Passenger vehicle	Smoke detector	Manual (EPS screen)	Only turbocharger malfunction – no subsequent fire.
August 5, 2019	BTC (BUB)	Passenger vehicle	Video detection of the offending vehicle (loss of visibility)	Semi-automatic (smoke detection confirmation)	Only turbocharger malfunction – no subsequent fire.
October 9, 2019	BTC (DEJ)	Passenger vehicle	Video detection of incriminating vehicle (slow-moving vehicle)	Manual	
Nov. 14, 2019	BTC (DEJ)	Passenger vehicle	Video detection of incriminated vehicle (stationary vehicle)	Automatic	The automatic EPS signal was received approximately 3.5 minutes after the vehicle stopped.
January 16, 2020	BTC (BUB)	Passenger vehicle	Video detection of the vehicle in question (stationary vehicle)	Automatically	The automatic EPS signal arrived approximately 2.5 minutes after the vehicle stopped.
Febr. 19, 2020	BTC (BRU)	Heavy goods vehicle	Video detection of the vehicle in question (stationary vehicle)	Manual	Only turbocharger malfunction – no subsequent fire.
May 25, 2020	BTC (BRU)	Heavy goods vehicle	Video detection (of another vehicle stopped at the location)	Automatic	The automatic EPS signal arrived more than 10 minutes after the burning vehicle stopped, approximately 6.5 minutes after

Date	Tun.	Burning object/ Source of smoke	Initial detection	Activation of fire mode	Note
					smoke was detected by video detection.
August 2, 2020	BTC (BRU)	Passenger vehicle	The fire was preceded by the resolution of a vehicle accident.	Automatically	The fire was preceded by an accident response. The automatic EPS signal was received approximately two and a half minutes after the first flames appeared.
December 20, 2020	BTC (BUB)	Passenger vehicle	Video detection of the vehicle in question (stationary vehicle)	Automatic	Preceded by the resolution of another incident. The automatic EPS signal arrived approximately 3 minutes after the vehicle accident.
November 21, 2023	BTC (BUB)	Passenger vehicle	Video detection of the vehicle in question (stationary vehicle)	Manual DT (EPS screen)	The automatic EPS signal arrived almost 5 minutes after the burning vehicle came to a stop.

The first indication of the consequences of the original settings of the technological units was provided by a verification exercise conducted by the emergency services units in 2016. As stipulated by legislation (Česká republika 2001), the verification exercise is not announced in advance to the participating organizations, and the tunnel is not closed to traffic before the exercise. Although the exercise was carried out at night, the activation of the fire sequence in the tunnel complex and the immediate suspension of traffic in the simulated fire section resulted in a number of vehicles (including foreign participants) being trapped. This made it possible to observe the authentic reactions of motorists; among other things, tunnel operators had the opportunity to practice their English skills when communicating via the SOS cabins in the tunnel. A positive finding from the exercise in terms of evacuation was that the local radio announcements were sufficiently clear, as many people in vehicles in the section with the simulated fire obeyed the automated local radio calls for evacuation. As requested, they left the affected tunnel tube, passed through the tunnel connection to the unaffected tunnel tube, and followed the radio instructions to the portals of the tunnel complex. Since the simulated fire was located in the 3 km long Bubeneč tunnel, in the worst case, people had to walk approximately 1.5 km to the portals. Locating the people and transporting them back to their vehicles took up a significant part of the entire exercise. In view of this direct experience with the march, questions arose again as to whether the principle of guiding people to the tunnel portals is necessary from the point of view of fire safety.

The first actual vehicle fire occurred in October 2019, i.e., more than four years after the start of trial operation, about a week before its completion. This was followed by five fires within 15 months. Another fire occurred almost three years later. From the list of dates of individual events, it is clear that the classic probabilistic approach to risk assessment on a statistical basis is not entirely appropriate for assessing the safety level of a tunnel. In general, it is more appropriate to focus on the analysis of individual event scenarios because, as practice has confirmed, the devil is in the details. Each event has unique conditions, developments, and ways of resolving the situation, both from the perspective of tunnel users and from the perspective of tunnel control room operators or responding emergency services.

1. FINDINGS FROM THE ANALYSIS AND IDENTIFICATION OF PROBLEMS WITH THE ORIGINAL SYSTEM

As the analysis of events has shown, self-preservation and the reactions of people in the first moments after the fire alarm is activated can take many forms, from ignoring the light signals to remaining in the vehicle in place or evacuating on foot to turning the vehicle around and leaving the tunnel in the opposite direction (Fig. 3, Fig. 4, Fig. 5, Fig. 6). In many respects, the position of those involved in relation to the fire and the direct visibility of the imminent danger also play a role. When the danger is visible, people react more quickly. The length of the evacuation route has already been discussed above, and events have shown that evacuation to an open space is not necessary. On the contrary, the subsequent search for evacuated persons has proven to be time-consuming and organizationally demanding.

Drivers' compliance with light signals is another separate issue to be addressed. In general, despite the signals, motorists at the scene of a fire tend to leave the tunnel within a certain time regardless of the status of the light signals. This time depends on the extent of the fire and, above all, the amount of smoke produced; if it is no longer possible to see through the smoke, drivers stop and do not continue. If they assess the situation as dangerous to drive through, they stop their vehicles at a sufficient distance from the burning vehicle, i.e., at least 10 m. In some cases, drivers reversed away from the fire to get as far away from the burning vehicle as possible. However, there have also been cases where drivers who wanted to help the occupants of the burning vehicle stopped behind the burning vehicle in the direction of travel. This procedure is appropriate in the event of a vehicle breakdown or accident, when the person providing assistance is protected from traffic by the vehicle with the problem, but not in the event of a fire, when the person providing assistance is exposed to developing smoke, which usually moves in their direction due to the piston effect or ventilation.

Clearing traffic from tunnel sections to surface intersections during daylight hours is extremely problematic due to the already heavy traffic at adjacent intersections. The original setting of evacuation sequences at a constant evacuation speed proved to be inappropriate, as the sequences "overtake" vehicles moving on exit ramps, and after the sequence ends, the exit preference ends and the evacuation slows down even more.

The intention to mark the most suitable access route for arriving fire brigade units proved to be correct. However, the technical design in the form of lighting fixtures on the ceiling above the entrance to the tunnel connection for this purpose was completely insufficient. In the flood of surrounding lights activated to maximum brightness at the time of the fire brigade's arrival, these identification lights were lost. It was clear that if the purpose was to be fulfilled, the system would need to be modified.

Figure 2: When the connecting section is closed, drivers wait for the original direction to reopen instead of driving up the ramp.

Figure 3: User responses in the area near the fire – example 1

Figure 1: User reactions in the area near the fire – example 2

Figure 5: User reactions in areas further away from the fire – example no. 1

Figure 6: User reactions in areas further away from the fire – example no. 2

2. REASSESSMENT OF SELF-RESCUE PRINCIPLES, CREATION OF DYNAMIC EVACUATION SEQUENCES

The above findings have shown that the existing universal, statically set procedures and methods of activating fire sequences do not cover the diversity of scenarios in the development of the traffic situation and the event itself (location, intensity and direction of smoke spread, traffic conditions). It was clear that the (self-)rescue system needed to be made more robust, intuitive for users, and without creating additional risk situations.

The findings from the investigation of significant extraordinary events to date were presented to representatives of tunnel operators (Czech Police traffic operators, dispatchers from Technická správa komunikací hl. m. Prahy, a.s.) and the Prague Fire Department at a joint meeting in June 2020. At the same time, the designers submitted a proposal for measures to improve both self-rescue conditions and the management of Fire Department interventions. The first change was to the system for identifying the Fire Department's emergency connection, with a flashing beacon added to each entrance to the connection. The designers also developed the logic of so-called **dynamic evacuation sequences**, which:

- partially adapt the responses of tunnel systems to the current traffic situation in individual tunnel sections and direct responses primarily to where they are most needed,
- distinguish between the affected and intervention tunnel tubes and adjust the modes of fire safety equipment and traffic in a differentiated manner;
- strive to adapt as much as possible to the intuitive perception and comprehensibility of the motoring public.

The principles of evacuation have been modified as follows:

- People from the affected tube are directed to the emergency (evacuation) tube, or in the case of sections between the portal and the first/last escape route, to the open space in front of the portals.
- People who reach the emergency tube are asked to remain there until the arrival of the rescue services.

In order to help evacuees decide on the correct evacuation route, the selection of the correct emergency exit was supported by the installation of dynamic green strip lights, located at a height of approximately 0.5 to 2 m on the outside of the vertical edges of the walls of the emergency route entrances in the tunnel tube (Fig. 7). These lights became part of the emergency escape lighting system and were connected to the tunnel control system. In standard conditions, each entrance is illuminated by continuously lit lights. The functionality of the lighting at the moment of a fire alarm in the tunnel is as follows:

- in the affected tunnel tube in the section with activated traffic suspension (from the fire site back to the entrances to the section), the lighting at the entrances will switch to alternating lighting with a frequency of 1 Hz.
- In the rest of the traffic section where the fire was declared, the lighting of the relevant entrance will switch to alternating lighting with a frequency of 1 Hz only after a period corresponding to the speed of the evacuation sequence has elapsed – in case there is congestion in the section behind the fire, for example (however, the actual traffic evacuation sequence will not be activated in this section – to allow vehicles to exit).
- In other traffic sections of the affected tunnel tubes, the lighting of the relevant entrance will switch to alternating lighting with a frequency of 1 Hz in parallel with the progress of the traffic evacuation sequence.
- In the emergency (evacuation) tube, the lighting of the entrance to the connecting passage, evaluated by the control system as an emergency entrance for the fire brigade, will switch to alternating lighting with a frequency of 2 Hz. Other lighting at the entrances to the emergency tube will remain stable, as in the standard state.

The functions of the tunnel complex's technological equipment have been adapted to the above evacuation principles as follows:

- It is generally assumed that after a fire is declared in the tunnel traffic area via the BTC control system (either after automatic detection or after activation by the technology dispatcher), people from vehicles in the affected tunnel tube caught in the section with activated traffic suspension (from the scene of the incident back to the entrances to the section) will be asked to leave their vehicles and then directed primarily by local radio announcements or text messages on the operational information devices, which were activated when the fire alarm was declared. Announcements and information are immediately provided in the affected tube only in the specified section. In other traffic sections, announcements for individual escape routes will be activated in parallel with the progress of the traffic evacuation sequence. In the rest of the traffic section with a fire (without stopping traffic, behind the fire), the local radio announcement will be activated at the speed of the evacuation sequence – in case there is congestion in the section behind the fire (however, the actual traffic evacuation sequence will not be activated in this section – to allow vehicles to leave).

- The local radio announcement in the section in question directs people to the nearest escape route/connection, or in the case of sections between the portal and the first/last escape route, to the open space in front of the portals (or this behaviour is assumed given the intensity of the announcement volume).
- If there is an escape route between the affected tube and the emergency (evacuation) tube, the local radio in the escape route directs people to the second tunnel tube. The announcement in the escape route is activated only after a person from the affected tube enters the escape route based on the Alarm security and emergency system signal.
- In the intervention (evacuation) tube, the announcement for the relevant escape route is activated with the evacuation sequence; if a person enters the escape route from the affected tube or escape route before the sequence is activated, the announcement is activated based on the Alarm security and emergency system signal.
- Local radio announcements have been modified and supplemented with English and German versions.

Figure 2: Example of the installation of green dynamic strip lights in TKB

The latest modification was made to the traffic control system – the logic of the clearance sequences was changed. Currently, the sequences no longer proceed at a constant speed, but the procedure depends on information from video detection – the sequence only proceeds to the next step after video detection confirms that the following section is free of detected events. This modification gives vehicles exiting the tunnel longer preference at the surface traffic light-controlled intersection into which they are clearing, resulting in faster tunnel clearance. On the other hand, this modification has a negative impact in that it places higher demands on traffic operators when monitoring the overall situation in the complex.

As can be seen from this list, significant changes have been made to the technological equipment and individual logical connections for dealing with fire emergencies. Unfortunately, the Fire and Rescue Service representative could not be persuaded to implement all the proposed modifications, and the activation of emergency escape lighting remains the same as in the original solution, with immediate activation along the entire length of the tunnel tubes.

3. CONCLUSION

The recommended measures resulting from the analysis of emergency situations have mostly been gradually implemented in the technological equipment of the tunnel complex. The settings of the fire safety sequences and links are repeatedly verified during prescribed coordination functional tests of fire safety equipment (Ministry of the Interior 2001). Fortunately, opportunities to verify the effectiveness of the sequences in practice are rare (a fire occurred only in November 2023 after some of the modifications had been made, and from the point of view of the aspects monitored, everything went smoothly). In light of previous experience, the transition from the original static evacuation procedures to dynamic evacuation sequences in the BTC can be considered a significant qualitative shift in terms of fire safety.

From a road safety perspective, the situation has only improved partially, as the Fire and Rescue Service's requirement for immediate activation of emergency escape lighting along the entire length of the tunnel tubes remains. The authors' goal is to continue to address this issue in the future and to gather sufficient data for the targeted implementation of dynamics in both main and emergency escape lighting.

The use of modified self-rescue principles is also expected in the planned reconstruction of the Strahov Tunnel and in the design of new tunnel structures on the inner Prague Ring Road. However, in order to achieve the goals of Vision Zero in road tunnels, we can only hope that with the development of C-ITS in combination with autonomous vehicles, the need for pedestrian evacuation from tunnels will gradually disappear altogether.

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