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RESEARCH

Evaluation of the current technologies used for the physical security and safety of selected railway tunnel portals as a case study in the Czech Republic

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Abstract

The security and safety of the railway tunnels require technical measures, information processes, and trained experts. Proper implementation and integration of these elements is crucial to protect lives, property, and the operation of the rail network. The purpose of this study is to identify and describe technological security and safety measures at the portals of selected railway tunnels greater than 1000 m in the conditions of the Czech Republic and their subsequent evaluation. The method of semi-structured interviews with experts with experience in the implementation of security and safety measures was used for the elaboration. SWOT analysis was used to assess the safety level of selected railway tunnels. The evaluation was carried out based on multi-criteria decision making and pairwise evaluation on the principle of Fuller's triangle. The technical solutions of two currently known technological solutions in the case study for accident elimination based on lidar detection supplemented by cameras are characterized by fundamental differences. The solution in the Ejpovice tunnel focuses on the detection of objects in the immediate vicinity of the portal or already entered it. The solution in the Březenský tunnel focuses on a larger detection zone extending tens of meters in front of the tunnel portal and is divided into two parts with different logic, the pre-alarm and the alarm itself. Integration of individual elements into a proactive and automated system that uses modern AI-based analytical algorithms and respects the process and technology specifics of the railway environment is important for the safety and security of the railway tunnel.

Keywords Railway trespassing · Railway tunnels and safety · Train-person crashes · Risk localities

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Introduction

The development of rail transport, the modernisation of transport networks and the interconnection with information systems are linked to high security requirements (Ivančík 2002; Dušek 2015). Rail transport is one of the safest and most efficient ways to transport people and goods. However, even when rail routes are carefully designed and managed, unauthorised access to tracks and tunnels still poses a serious risk to people's lives. Rail tunnel security and safety is a complex issue that requires a combination of technical measures, information processes and training. Ensuring that these elements are properly implemented and integrated is key to protecting lives, property and the sustainable operation of the rail network (Pokorný et al. 2020; Novotna et al. 2020). The authors' paper addresses the issue of protecting the life and health of people who trespass on the tracks and especially in the portal area of railway tunnels and the potential damage to the property of the railway manager and railway operators.

The solution of security and safety on railways with a focus on tunnels and their portals is addressed by experts from several perspectives. One approach focuses on the assessment of the vulnerability of selected key elements of rail transport. One of the criteria assessed is the security of tunnels (Sventekova et al. 2021). Similarly, safety improvement is addressed in the form of a safety plan of the key railway infrastructure element, where scientific methods and system measures are proposed to enhance safety (Hoterová 2019). Another perspective is the emergency supply to safety systems of long railway tunnels. The solution focuses on the operation of a generator to ensure continuity of operation in the event of a power failure to supply safety systems, signalling, telecommunications, emergency lighting, and auxiliary equipment for electrical substations, including associated cooling systems (Lamedica 2019). Another related topic is a wireless sensor network for real time monitoring and controlling of railway accidents (Potdar 2017), online identification method of railway tunnels (Wei et al. 2023) and an intrusion detection system for the protection of railway assets using fiber bragg grating sensors (Catalano 2014).

An interesting approach is presented by a case study in the context of China, which focuses on the efficiency of risk management for tunnel security and safety of megaprojects construction based on system dynamics. The reflection is aimed at improving the efficiency of tunnel safety risk management. The security and safety risk management process is the starting point, which is based on the Observe-Orient-Decision-Action model. The results of the study show that building a comprehensive and continuous risk information network, adapting risk management strategies in real time based on the complexity of risks, and reducing delays in risk management can effectively improve the efficiency of dynamic safety risk management. (Liu 2023). Safety and security in railway tunnels have many specifics and different areas such as complexity of long railway tunnels (Diamantidis et al. 2000), mitigating risks in railway tunnel maintenance (Voicu and Draghici 2023), the risk of a terrorist attack on the railway tunnel and the use of CBRN agents (Ivančík and Nečas 2020; Petersen et al. 2023; Havârneanu et al. 2022) and the possibility of using thermal imaging cameras (Szurgacz et al. 2021). A completely original approach is presented on the example of Canada, where a protecting railway network using remote sensing technology is used (Huntley et al. 2021).

Unauthorized movement on railroad tracks occurs for a variety of reasons, including curiosity, taking shortcuts, loss of orientation, suicidal intent, and others. Regardless of the reason, it is a very dangerous activity that can have tragic consequences. Persons trespassing on tracks and in tunnels face many risks, including the possibility of colliding with a train, falling from a height, or coming into contact with electricity. These accidents can have serious consequences and can lead to serious injury or even death. This not only puts the lives of these people at risk but can also have a negative impact on rail transport as a whole, especially when disruptions are needed for rescue operations.

How can this problem be addressed? In addition to primarily preventive measures such as public education through awareness campaigns and school programmes to help raise awareness of the risks, traditional passive technical measures are offered to increase the level of security such as the installation of physical barriers, fencing and warning signs but also the use of active intelligent technology such as the installation of security cameras with video and audio analytical detection, radars and lidars.

Implementing physical security at the entrance to a railway tunnel is essential to protect the infrastructure and prevent unauthorised access that can affect operational safety. Physical security of the railway tunnel entrance is an integral part of the overall security plan and helps to ensure that the tunnel area is protected from hazards and unauthorised persons. The basic elements of physical security for rail tunnel access include:

- Gates and fences: there should be gates and fences around the tunnel entrance to prevent unauthorised access. Gates should be lockable and monitored.
- Checkpoints: Checkpoints should be located outside the tunnel entrance to carry out security checks on persons and vehicles. Security cameras and possibly metal detectors can be installed here.
- Identification and verification: Staff and persons authorised to enter the tunnel should be identified and verified, for example by means of identification cards with access rights, biometric systems or passwords.
- Presence of security personnel: Security guards may be present around the tunnel entrance to monitor entrances and respond to potential security threats.
- Lighting: Adequate lighting around tunnel entrances is an important feature to help detect suspicious activity.
- Alarms and warning systems: In the event of unauthorised entry or suspicious activity, alarms and warning systems should be activated to alert security personnel.
- Video surveillance: Installing security surveillance systems to monitor the tunnel entrance and surrounding area can be very useful for monitoring and investigating incidents.
- Emergency exits: In the event of an emergency evacuation, safe emergency exits should be available to allow quick and safe exit from the tunnel (Pokorný et al. 2015).
- Employee training: employees should be properly trained in physical security and know how to respond to different security situations.

Current technologies to reduce the risk of disruption and improve safety in railway tunnels are based on the EU Commission Regulation concerning the Technical Specification for Interoperability relating to safety in railway tunnels of the railway system of the European Union. The purpose of the EU Commission Regulation is to define a coherent set of tunnel-specific measures relating to the infrastructure, energy, rolling stock, control and safety and operational subsystems and to ensure an optimum level of safety in tunnels in the most cost-effective way (Commission Regulation EU No 1303/2014). For the design and construction of bored and excavated tunnels on railway lines with speeds up to 160 km/h the Czech Technical Standard No. 73 7508 is used in the Czech Republic. The standard also specifies the requirements for underground and surface construction in the zone of effects (Česká technická norma č. 73 7508 / 2002).

Trespassing as an unauthorised access to railway line is a very serious, although often underestimated, traffic safety problem. The total number of road and rail accidents involving pedestrians in the Czech Republic is considered alarming. If we express the ratio of the number of pedestrians killed on Czech roads, we arrive with 131 victims to the number of 0.00123 victims per kilometre of road. In the case of railways, with about 200 pedestrian casualties per year, it is 0.0212 casualties per kilometre of railway line. The relative number of pedestrian deaths per km is therefore 17 times higher on rail. Despite this fact, this problem is not systematically addressed in practice (Skládaná et al. 2018).

In the statistics in the Czech Republic, we see a slightly improving trend in Fig. 1. 163 persons died in collisions between railway vehicles and persons on national and regional railway lines and railway sidings outside level crossings, which is the lowest since the Railway Inspectorate (Drážní inspekce) started measuring this statistic in 2003. There is a very high ratio of rail vehicle-to-person collisions resulting in injury and death in the rail environment. Three out of four of these incidents end in death. Most of these cases occur in places that are inaccessible to the public by Law No 266/1994 Coll. People are often not fully aware of the dangers they face on the railway if they do not comply with the applicable legislation and risk their lives by behaving irresponsibly.

According to Section 4a(2) of Act No. 266/1994 Coll. on railways, all places on the railway and within the perimeter of the railway are inaccessible to the public except (Act No. 266/1994 Coll.):

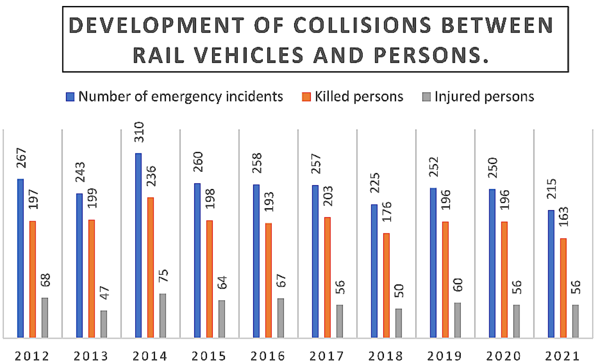

Fig. 1 Development of collisions between rail vehicles and persons between 2012 and 2021 (Drážní inspekce 2021)

- the runway and its perimeter if the runway are on a road;
- the runway and its perimeter at the point where the runway crosses a land road;
- premises intended for public use, platforms and access routes to them and premises in buildings located within the perimeter of the railway, if services related to rail transport are provided therein;
- publicly accessible dedicated roads within the railway perimeter;
- open areas at least 2,5 m from the axis of the track edge.

The phenomenon of unauthorised access to tracks and tunnels has been the subject of many studies in recent years, mainly focused on the consequences of unauthorised crossings of the railway line (i.e. train collisions with persons) and the possibilities of their prevention. For example, in the framework of the international RESTRAIL project (Havârneanu 2016), studies have mostly dealt with the frequency and motivation of trespassers and the factors that influence their actions (Silla and Luoma 2009; Burkhardt et al. 2014). In the Czech Republic, the AMELIA research project carried out in 2016 described the current state of unauthorised access to railway tracks in the Czech Republic and the project provided an overview of basic prevention principles. Regarding the locations and motives of offences, the main risk locations were specified, including railway stops and stations, shortcuts and shortcuts, places of interest (e.g. for railway enthusiasts, but also for vandals and graffiti artists); places near the railway where alcohol and drug users gather or which serve as shelters for homeless people). These risk locations also include railway tunnels (Skládaná et al. 2016).

The purpose of this study is to identify and describe the technological safety measures on the portals of selected railway tunnels in the Czech Republic and their subsequent evaluation.

Within the scientific approach, the research questions were formulated:

Q1 QWhat are the technologies used to ensure physical security and safety of portals of selected railway tunnels in the Czech Republic preventing the entry of unauthorized persons?

Q2 What are the strengths, weaknesses, opportunities and threats in addressing the portal security of two selected railway tunnels longer than 1000 m in the Czech Republic?

Materials and methods

Materials

The railway network in the Czech Republic is characterised by a large number of tunnels. Most of them are quite old and are built using different methods and materials. As this is one of the most demanding civil engineering works, it is necessary to pay particular attention not only to the construction phase but also to the subsequent management and security. This administration and security are provided by the Railway Administration state organisation. (Správa železnic, státní organizace - SŽ). This organisation is the owner and provider of national and regional railway infrastructure owned by the state.

At present, there are 163 tunnels in total under the management of Railway Administration, the total length of which is 49.5 km. Due to the relatively high number, it is obvious that individual tunnels differ in their technical parameters. The shortest tunnel is the Nelahozeves I tunnel with a length of 23.3 m, while the longest railway tunnel in the Czech Republic is the Ejpovice tunnel with a length of 4150 m. The longest single-track tunnel is the Březno tunnel with a length of 1759.2 m, which ranks among interesting construction projects not only in terms of its length, but also in terms of construction technology (the circumferential notch method). The Špičácký tunnel, which is also outstanding for its length of 1747.3 m, is an admirable work given the time of its construction in 1878.

From the point of view of security and safety, the length is the most important parameter. If an accident occurs in a tunnel, timely professional intervention is more problematic than in open terrain. According to Act No 133/1985 Coll. on the establishment of fire safety conditions and the exercise of state fire supervision (Fire Safety Decree), tunnels longer than 350 m are designated as objects with difficult conditions for intervention and therefore increased fire precautions are required. This requirement is already taken into account for new constructions, but especially for the reconstruction of lines of lower transport significance, it means a significant increase in economic demands. In these cases, the arguments for possible reconstruction are very difficult to find. In the rail network, we find mostly shorter tunnels. As shown in Figs. 2 and 128 tunnels are shorter than 350 m, the remaining 33 tunnels are longer. Of these, 8 tunnels are longer than 1000 m.

Methods

In order to meet the objective and to develop the basis for the research question, a systematic approach of literature search was used to obtain current information sources, published results and information in the field of railway tunnel security and safety. Furthermore, the method of analysis and synthesis was used, i.e. breaking

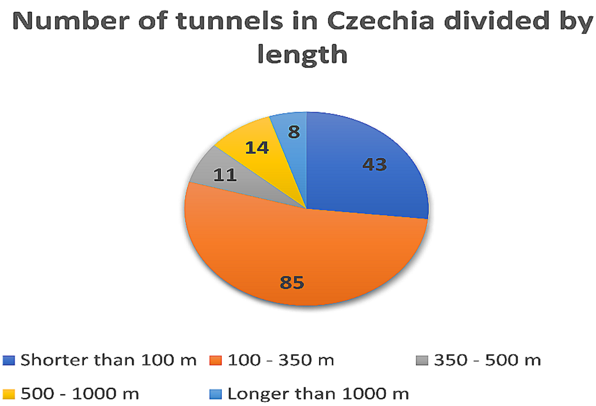

Fig. 2 Number of tunnels in Czechia divided by length (Mastilová 2014)

down the whole into sub-components and combining the individual information into a whole, describing the principles in interdependencies. The above procedure was used in the analysis of the actual information and especially in its synthesis in the final part of the research. Another method used to elaborate the research objective was deduction, a process of reasoning from premises, where a conclusion is reached by proof. The procedure was applied in the elaboration of the findings of the empirical investigation into the summary final part of the research.

As part of the qualitative investigation to gain practical safety experience from the operation of the selected railway tunnels, structured interviews were conducted with staff from the Railway Administration state organisation. (Správa železnic, státní organizace) These included interviews with staff from the Security and Crisis Management Department and staff from the Regional operations departments. The interview method was used as a semi-structured interview to allow the process to respond with additional questions for clarification or explanation of the respondent's answers. This achieved higher accuracy and yield than a fully structured interview. The core of the interview was specific information on the operational safety measures at the selected tunnel. A significant feature was the linking of the information given to specific experience in relation to the reflected security and safety measures of the particular tunnel. The interview was aimed at obtaining the practical experience of the respondents with the safety measures of the selected tunnels.

A SWOT analysis was used to assess the current level of safety assurance of the selected railway tunnels. SWOT analysis is an analysis of strengths, weaknesses, opportunities and threats that originated in the second half of the 20th century in the United States of America. SWOT is an abbreviation from: Strengths, Weaknesses, Opportunities, Threats. It is a versatile analytical technique for understanding and interpreting strengths and weaknesses and for identifying opportunities and threats. It is used in business as a strategic tool that can be used for the development of a company (Fine 2009; Newton et al. 2013).

The SWOT analysis is based on the evaluation and analysis of the current state of the subject/topic under consideration, its internal environment and the current situation of the environment of the subject under consideration, the external environment. The basic purpose is to identify the strengths and weaknesses in the internal environment, i.e. where the subject is good and where it is lagging behind, and the opportunities and threats that are in the external environment and therefore cannot be fully influenced by the subject (Sarsby 2016). First, the strengths that are perceived as internal forces are analyzed. Above-standard skills, knowledge, potential and resources are identified that can be used in the future for the benefit of society and safety within rail transport. Weaknesses are the opposite of strengths. This area mainly includes internal weaknesses of the organisation/issue addressed where better results could be achieved. Opportunities have been selected as potential opportunities for improving the rail safety situation in tunnels based on the selected case study, provided that they are properly exploited. Externalities that could bring success in the future were identified. Threats are external conditions that may make it difficult or dangerous to achieve the objectives. Threats have been identified as aspects that bring negative consequences that must be taken into account and systematically prevented.

To calculate the weighting factor correctly, it was necessary to determine the rating item. The rating was based on multi-criteria decision making. By decision making is meant the selection or classification of the value of one option from the specified criteria. There is a conflict of interest in decision making where it is difficult to prioritize values in socio-economic systems. Different groups of people prefer different consequences of decisions and judgments, and different criteria are offered to assess the degree of optimal decision. For the evaluation of the different features of the SWOT analysis, the criteria of safety options in rail transport in specific tunnel conditions were established.

Results

According to the currently valid decision of the Railway Administration, newly built tunnels longer than 1000 m are secured against unauthorised access. Two tunnels, the Ejpovice and the Březno tunnels, are currently secured in this way. For both tunnels a different security technology has been selected for these purposes. In both cases, the deployed security technologies are in verification operation. In the Ejpovice tunnel from 2017 and in the Březno tunnel from 2020. The technologies used in these tunnels are different and the processing of their outputs is also different. In both cases, the main purpose is to guard the perimeter of the tunnel with an important preventive focus. This involves the detection of objects such as vehicles, people and wildlife. In the following, both technologies will be briefly described. The aim is therefore to compare these technologies. For the comparison, it will use available sources describing these technologies as well as a qualitative method of interviews with people designing, operating and maintaining these technologies.

Ejpovice tunnel

The Ejpovice tunnel, (Figs. 3 and 4), is a railway tunnel on the line 170 Praha-Plzeň between the railway station Ejpovice and the railway stop Plzeň-Doubravka. The construction of the tunnel, started in 2013, was part of the modernisation of the western part of the III national rail transit corridor. The tunnel was put into operation

Fig. 3 The eastern portal of the Ejpovice tunnel (Plzeň.cz Zpravodajský portál 2019)

Fig. 4 The western portal of the Ejpovice tunnel (Plzeň.cz Zpravodajský portál 2019)

in November 2018. The Ministry of Transport of the Czech Republic, or the Railway Administration (Správa železnic), was the client of the tunnel construction, the contractor was the Association MTS+SBT - MTÚ Rokycany-Plzeň (Metrostav and Subterra), the designer was Sudop Praha, and the author of the tunnel implementation documentation was Metroprojekt Praha. The technical supervision of the investor was carried out by the association Inženýring dopravních staveb and SATRA. Geotechnical monitoring was carried out by GEOtest and Angermeier Engineers. Since 15 November 2018, the southern tunnel tube has been in trial operation, both tubes have been in use since 7 December 2018, the maximum permissible speed is set at 160 km/h from September 2019 with a prospective increase to 200 km/h. With its length of about 4150 m, the tunnel is the longest railway tunnel in the Czech Republic. The rails in the tunnel are in special panels, which will allow the passage of rescue workers. Safety walkways run along the sides (Správa 2018).

Description of the technical solution for portal security and safety

As its length meets the conditions of the Railway Administration's decision on security, the portals on both sides were secured against unauthorised access. The technology chosen here was a laser detection system combined with security cameras. When an object of a certain size or larger is detected, an alarm is automatically triggered. It was sent to the emergency dispatcher's workplace in Rokycany after the start of the trial operation and was transferred to the Central Dispatcher's Workplace in Prague from 15 April 2019. Furthermore, the alarm is sent to the railway firefighters and prospectively also to the dispatching workplace under construction in Pilsen. The above-mentioned cameras are not connected to the laser detection system and serve only for visual information to the workers (Plzeň.cz Zpravodajský portál 2019).

The laser technology is directly connected to the alarm system. As visualized in Fig. 5, the control is provided by a pair of 2D lidar sensors at the end of each tube, which cross-checks the cross-section and the pavements. If objects such as people or animals approach the tunnel, the system detects them and triggers an alarm. As such, trains are detected and can pass through the tunnel without triggering an alarm (SICK Sensor intelligence 2023).

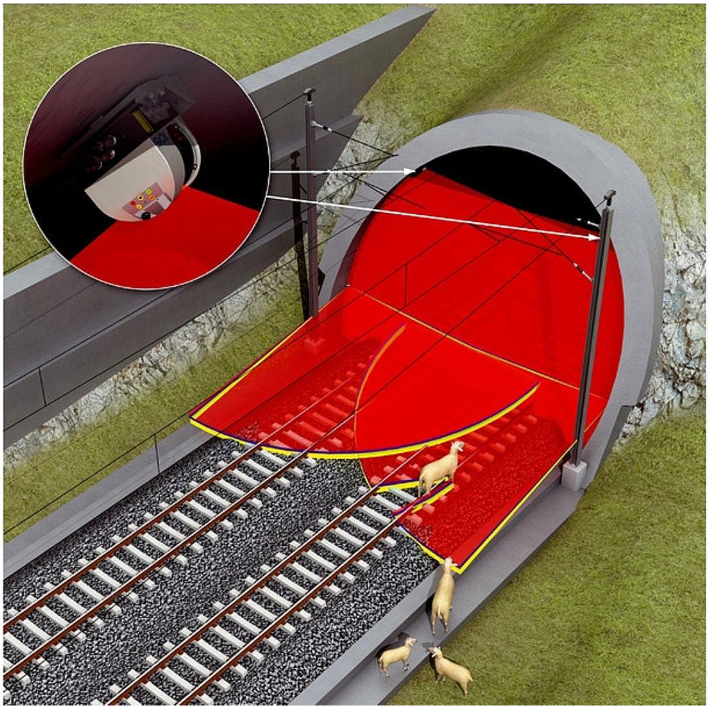

Fig. 5 Visualization of the tunnel portal security system with multibeam 2D LiDar scanners with fan-shaped detection field from the German manufacturer SICK (SICK Sensor intelligence 2023)

The sensors are automatically checked periodically for their functional status and possible contamination. Static multibeam LiDar scanners with a fanned detection field from the German manufacturer SICK are used. They are connected to the Safety Designer configuration and diagnostic software from the same manufacturer. The LMS111 detectors were chosen for the start of the verification operation phase. Over time, this type of detector proved to be not unsuitable for tunnel portals. Therefore, based on operational experience, it was decided to install the model LMS511, which was judged to be more suitable for this purpose (Fig. 6).

Tunnel control system technology is concentrated in two technology rooms in the tunnel portals. The output from the sensors is connected to the ESA electronic railway signalling equipment, which is used to secure and control railway traffic. At the same time, information about the detected alarm is transmitted to other systems (e.g. for automatic switching on of the tunnel lighting). Two alarm levels are set:

- Alarm level 1 is detected immediately after the detection of a breach of any entrance in the portal environment - it lasts for a maximum of 30s.
- Alarm level 2 - is detected automatically after 30s from level 1, if not acknowledged by the operator and is still in progress.

Fig. 6 2D lidar scanner model LMS511 (SICK Sensor intelligence 2022)

Operational experience so far

As mentioned in the previous chapter, the security solution has been in verification operation phase since its introduction. According to the information provided in the guided interviews with the tunnel operator, the security technology has been upgraded several times and its configuration has been tuned in different ways since its launch. For example, the original sensors installed at the start of the verification operation proved insufficient for the use case specifically for the tunnel portals. Therefore, based on operational experience, it was decided to install upgraded models more suitable for these purposes. The types and number of surveillance cameras providing video verification and overview of what is happening at the portals have also been upgraded. Soon after the tunnel started operation (29 December 2018), the tunnel was closed for several hours due to a person being struck inside the tunnel. The person managed to enter the tunnel undetected by safety technology and made it approximately a quarter of the way into the tunnel before colliding with a passing train. In the end, even after several months, police were unable to determine the cause of the security failure or the person's motive for entering the tunnel (Sůra 2019). However, the system does record a relatively large number of false positive alarms which is a major problem for dispatcher processing. These false positive alarms are most often caused by small animals entering the tunnel. (Fig. 7)

Fig. 7 Image from security camera in Ejpovice tunnel - detected animal (Krůta 2019)

Fig. 8 Unauthorised vehicle intrusion into the Březno tunnel - image from the original analogue security camera before the technology upgrade (ČT24 2011)

Březno tunnel

The Březno tunnel is the second longest railway tunnel in the Czech Republic, located on the railway line Lužná u Rakovníka - Žatec - Chomutov near the village of Březno. Put into operation on 1 April 2007, the tunnel is located on the newly built relocation of the section Březno u Chomutova - Chomutov of line 124 from Lužná u Rakovníka to Žatec. In total, 7.1 km of the line was relocated due to the release of lignite deposits for Severočeské doly.

The Březno tunnel was the longest railway tunnel in the Czech Republic with its 1,758 m until the Ejpovice tunnel (4,150 m) was put into operation. Unlike the Ejpovice tunnel, the Březno tunnel is single-track and non-electrified (Konstrukce Media 2008). However, electrification is planned (Šindelář 2020). There are walking paths on both sides of the tunnel, with recesses every 20 m on one side. The tunnel is served from newly created purpose-built roads leading to both portals. Since its opening, the Březno tunnel has been equipped with basic security with detection of unauthorised access. Due to the low level of security, intrusions by pedestrians, cyclists or even vehicles such as motorcycles and cars were relatively frequent. (Fig. 8)

Description of the technical solution for portal security and safety

The Březno tunnel is a tunnel in the Czech Republic whose length meets the conditions of the Railway Administration's decision on security, therefore the portals on both sides were secured by external security against unauthorised access. As mentioned in the previous chapter, the Březno tunnel has been equipped with basic security with detection of unauthorised access since its commissioning, but it has not proved its worth, mainly due to its low reliability and a large number of false positive alarms. The original solution was based on the use of PIR sensors, optical barriers and floor mats detection to detect the entry of persons. All this was complemented by image verification using analogue cameras. In order to avoid false alarms caused directly by-passing trains, the solution was gradually enriched with technologies that tried to recognize that the object that violated the above-mentioned protection zones was the train itself and therefore should not be registered. These technologies were mainly based on axle counting and estimation of the shape and profile of the train. However, false alarms persisted because the technology did not cope well with different train profiles, different gaps between wagons and their shapes and sizes. They were also severely hampered by the light changes and temperature differences that are typical of tunnels. There was also a frequent entry of animals such as deer, foxes and rabbits. For example, the system had difficulty distinguishing a rabbit from a newly grown clump of grass in front of the tunnel portal. Therefore, in 2019, the Railways Authority began an open tender process to select new technology that would be able to cope with the existing problems and bring a higher degree of security and minimise ancillary complications. In the end, a technology based on a laser detection system combined with security cameras was also selected. In this case it was a more generational and system advanced and enhanced option. A rotating type lidar was chosen to provide a 3D spatial image as opposed to a 2D lidar with fan-shaped beams. The number of lidar detectors was increased from two to three on both portals.

These are multi-channel 3D lidar detectors. They are detectors that emit laser beams into space. Currently, the lidar detectors used are made by Velodyne. These are 16 beam sensors providing data (clouds of points) for volumetric survey in an area up to 100 m in radius (200 m in total diameter) The detection accuracy is 3 cm. The data measured by the lidars are processed and visualized in a 3D map by the volumetric detection system Accur8vision from the Czech software company TACTICAWARE, part of the Swedish multinational concern Hexagon. Each point in the map has its X, Y, Z position given in centimeters relative to the centre of the grid on which the whole map stands. This later allows interaction between all components of the system, i.e. between detectors, cameras, zones and intruders. This eliminates, for example, the complex manual setting of presets for rotating cameras to be called up later when interacting with a detector. Accur8vision knows exactly where the intruder is located and which nearest PTZ cameras are to be rotated towards the alarm event. The operator thus observes all intruders on monitor in real time, seeing their number, positions, sizes, movement speeds and the trajectories of their movements. The entire system is complemented by surveillance cameras. These are both static, monitoring the portals from the outside, and moving (PTZ), used primarily to track detected moving objects, i.e. people or vehicles. The tracking is primarily done automatically directly from the Accur8vision software. Cameras from the Swedish manufacturer Axis Communications are used because of their technological maturity, reliability in specific railway conditions and openness to integration with other equipment, in this case lidar and the Accur8vision 3D volumetric detection system. The solution is also enriched with a radar that serves as a redundant detector in case of failure or maintenance of the lidar units. According to the current regulations of the Railway Administration, the guarding of the portals must be continuously secured. Therefore, when the lidars are out of service (breakdown, maintenance), the radar is used to substitute them, otherwise the Railway Administration's Fire Brigade (HZS SŽ) personnel must be present to take over the guarding during the system outage. For a significant shift towards prevention, the solution has been enriched with connected IP speakers capable of automatically playing pre-recorded warning messages based on detection, or the authorised person can use the speakers for real-time announcements (push-to-talk). (Fig. 9)

The area in front of the tunnel portals is divided into two detection zones. Zone I (pre-alarm) and Zone II. When an object is detected in Zone I, an alarm is automatically raised, and a warning message is triggered in three languages from the installed and integrated IP speakers. In this case, the dispatcher is not proactively warned yet, but passively sees the alarm on his alarm device. In the event of entering the main protected alarm zone I, an alarm is proactively announced at the dispatcher in the

Fig. 9 Security technology for the Březno tunnel portal mounted on a column - lidar, radar, IP horn speaker, PTZ camera tracking the detected object, static camera monitoring the portal - in order from the bottom (Smažinka and Hrinko 2022)

Fig. 10 View of the Březno tunnel portal through the Accur8vision visualization software - the person in the detection zone is displayed both graphically and visually using a rotating camera tracking his/her movement (Hexagon 2023a)

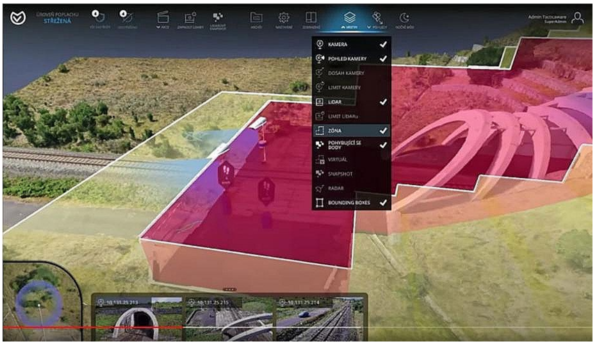

Fig. 11 View of the Březno tunnel portal via Accur8vision visualization software - setting up detection zones (Hexagon 2023a)

Transport Office of the Chomutov railway station. The latter can see what preceded the alarm on the video and either assesses it as a false positive alarm or as an alarm that is not false and takes the necessary actions, in particular steps leading to the stopping of the train and announces the alarm to the Police of the Czech Republic and the Fire Brigade of the Railway Administration (HZS SŽ) Chomutov, that take command of the case. The HZS SŽ also has their own view of the security cameras at the tunnel portals and can actively talk to the IP speakers. In normal operation, the dispatcher has user priority in controlling the cameras, but after handing over to HZS SŽ, they take priority. The dispatchers ensure that all alarms are recorded in the archive. There exists an approved "Operating Rules for the Březno tunnel" documentation describing the processes for recording alarms. The output from the security system can also be monitored in the service room in the building near the emergency exit from the tunnel. It is also partially connected to the Remote Diagnostic Technology Systems (DDTS) system.

The system allows electronic identification of a person entering Alarm Zones I or II so that this entry does not trigger an alarm. (So-called "friendly person") This is mainly used for maintenance or inspection needs of the technology and the tunnel itself. Identification can be made with a service card and the system contains a list of persons with approved access. Thanks to the configuration of the volumetric visualisation software Accur8vision, the system is configured so that the trains themselves are recognised as such and can pass through the tunnel without triggering an alarm. (Figures 10 and 11)

Operational experience so far

According to the experience reported during the guided interviews with the tunnel operator, after the launch of the new solution, more alarms were initially recorded due to the relocation of the technology from the tunnel entrance to in front of the portals. This is a logical consequence of the transition from a reactive to a proactive and preventive system. The alarms were caused by the creation of Detection Zones I and II, which reach tens of meters in front of the tunnel portal. Wildlife (deer, rabbits and foxes) are commonly present in these zones and, particularly initially, there was also increased human presence. Paradoxically, the automated voice warning system has become one of the biggest attractions for citizens from surrounding villages and tourists interested in the railway. The increased wave of alarms gradually decreased due to the natural reduction of the mentioned interest of people and also due to the gradual fine-tuning of the lidar technology.

Another source of false alarms at the beginning of the use of the new technological solution was some weather effects. This has also been gradually eliminated both by the configuration of the lidar itself and by the introduced procedural actions of the operator. According to the staff from the Railway Administration, who manage the tunnel, it is not entirely appropriate to compare the number of alarms before and after the change of technology in 2021. In the first case, when the technology was placed inside the tunnel, there was an obvious interest in breaking into the tunnel, which meant stopping operations and thus financial losses. In the second case, the system also reacts to objects that may be just passing by but deters would-be intruders in time. The train dispatcher can monitor everything in real time and can intervene adequately.

In the verification operation, the operator also faced several technical problems related to the use of lidar detectors in specific railway conditions. There were mechanical failures probably related to strong vibrations, large changes in air pressure when the train passes, etc. These problems have now been eliminated thanks to communication with the manufacturer. On the west portal, the setting sun shines directly into the mouth of the portal at certain times of the year. The previous technological solution based primarily on cameras and IR barriers was almost unusable. A solution based on lidars and volumetric surveillance is significantly more effective in these cases.

Evaluation of safety measures of railway tunnel portals

Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis focuses on a critical component of the strategic management process based on the criteria examined and evaluated. The method of analysis is based on the expression and formulation of categories relevant to the tunnel portal, both from an internal and external perspective. SWOT analysis is characterised by its practicality, but it must not be applied uncritically and simplistically. It can lead to strategic errors. A detailed and comprehensive analysis can demonstrate the shortcomings as well as the positives. A SWOT analysis should not be seen as a static analytical tool with an emphasis only on its own output. The analysis should be used as a dynamic part of the management and development planning process.

SWOT analysis provides a qualitative approach to the organization and clarification of multi-layered and interdisciplinary problems in decision-making. The main input for this SWOT analysis is the knowledge obtained by researching the professional literature, conducting interviews with experts in the field of railway safety and tunnels, as well as the experience of the authors of this study with the practical implementation of safety elements in the portals of railway tunnels. On this basis, the critical factors considered for successful analysis are determined. By relating security measures in tunnel portals to their surroundings, it is possible to distinguish between internal factors (strong and weak factors) and external factors (opportunities and threats). To carry out the analysis, it should be noted that the actual current state of the subject is assessed, ideas and assumptions are not included and evaluated.

The indicated strengths and weaknesses, opportunities and threats in the SWOT analysis must be supplemented in the analyses by defining the absolute value determined by the numerical series, the weight factor and the strength of the criterion of the relevant factor. Based on the outputs from this SWOT analysis, it is necessary to make multicriteria decisions. Subsequently, the value of the weight criterion is calculated, which is based on the Fuller triangle, and the determination of the priority of individual elements of the SWOT analysis. The subsequent product of the determined values determines the strength of the individual criterion. The calculation of the SWOT analysis is presented in Tables 1, 2, 3 and 4.

Tunnel Ejpovice

Tunnel Březno

The evaluation and specification of safety and security elements of tunnel portals in selected tunnels in the Czech Republic is summarized in Tables 2 and 4. The obtained results of the SWOT analysis show a prevalence of positive results for both evaluated tunnels. As a result, positive values were found for the evaluated characteristics for the Ejpovice (1.17) and Březno (2.67) tunnels. From this it can be concluded in the overall context that strengths and opportunities outweigh weaknesses and threats. From the point of view of the evaluated and reflected characteristics, these are security measures that aim and are implemented with a positive result. However, there is a difference between the security measures evaluated.

When conducting the evaluation between the Ejpovice and Březno tunnels, it is clear both from the partial and especially from the resulting values that higher values were achieved in the evaluation of the security measures of the portal of the Březno tunnel - a value of 2.67. In contrast, the safety measures of the Ejpovice tunnel portal were evaluated with a value of 1.17, which is lower than the safety measures evaluated for the Březno tunnel. The results of the performed analysis show the relatively high-quality security of both tunnels, but they clearly emphasize the security maturity of the measures implemented at the portal of the Březno railway tunnel.

The outputs from the performed assessment using the chosen methods must be aimed at achieving optimal information in order to design subsequent steps to eliminate risks in real time and economic feasibility. Safety can never be perfectly and completely ensured, and this statement can also be applied to emergent situations related to railway safety measures at tunnel portals. Aiming for absolute security or thinking that serious threats can be completely averted or eliminated is wrong and dangerous. The concept of social vulnerability is used to describe the level of security, which maps, categorizes and measures vulnerability. In addition to strengthening security capacities, it is necessary to create a safe space and an overall safe environment, e.g. in the form of support for security research.

Discussion and conclusion

The basic elements of tunnel safety are four successive phases: prevention, minimizing consequences, evacuation and rescue. Prevention is the most effective and prioritised measure, followed by minimizing the consequences. Together, these safety phases ensure a low level of residual risk. This paper deals mainly with phase prevention - the issue of protection of life and health of persons who illegally move on the railway and disturb it, especially in the area - of railway tunnel portals. the two technological solutions described above from this perspective. Several factors have been selected for comparison, namely the philosophy of the solution, its efficiency, accuracy, technological openness and financial cost.

In terms of solution philosophy, there are quite significant differences between them. The solution in the Ejpovice tunnel focuses on detecting objects that are in the immediate vicinity of the portal or have already entered it. The solution in the Březno tunnel focuses on a larger detection zone extending tens of metres in front of the tunnel portal and is also divided into two parts with different logic - the pre-alarm and the alarm itself. Furthermore, in the second case, the solution is complemented by automated playback of a warning message from integrated network speakers in order to deter a potential intruder. As far as efficiency is concerned, this is largely based on the already mentioned different philosophy of the solution. The proactive approach of the second solution brings a significantly greater preventive effect due to the larger detection zone, the automated use of network speakers and allows the dispatcher to have a greater overview of what is happening around the portal, which also means a significantly more efficient solution. The second solution (Březno tunnel) is also more accurate, both in terms of classification of detected objects and their physical location in the detection zone. Thanks to the capability of 3D lidar technology, the detected object can be orientationally classified, and thanks to the automated deep integration with the camera system, the object can be reliably visually verified and identified by the dispatcher. The second solution (Březno tunnel) shows a significantly lower number of false alarms. In addition, the object is automatically tracked by a moving camera and the trajectory of its movement can be traced back in time, which is not possible with the first solution.

The technological openness for integration with existing and potential future signalling technologies is difficult to compare objectively. All three manufacturers involved in the two solutions described offer the possibility of integrating their network devices (lidars, cameras, radars, speakers) by accessing their application interfaces. (API) (SICK Sensor intelligence 2021; Hexagon 2023b; Axis Communications

Table 1 SWOT analysis of the security solution of the Ejpovice tunnel portal (own processing)

	Strengths	Weight factor	Assessment	Strength of criteria
Internal environment	1. Lower initial acquisition cost due to the smaller number of technological devices used.	0.50	5	2.50
	2. More robust technology, more resistant to mechanical failures (2D static lidars)	0.17	3	0.50
	3. Easier and faster training and service by staff.	0.17	5	0.83
	4. Lower requirements and costs for maintenance and service due to fewer technologies used.	0.17	4	0.67
	Subtotal			4.50
	Weaknesses			
	5. Lower detection reliability due to the use of older technologies without redundancy. 2D static fan-shaped lidars without backup. No flying objects detection. (e.g. drones)	0.33	-4	-1.33
	6. Smaller scope of integration between the individual technologies used without automated integration with the camera system	0.00	-2	0.00
	7. Less efficiency and economic return with little preventive effect. Without larger detection zones in front of the portals, without deterring potential offenders via automated live announcements using network speakers.	0.50	-5	-2.50
	8. Lower accuracy due to the absence of classification of detected objects and limited information about their physical location in the detection zone without information about the history of their movement.	0.17	-3	-0.50
	Subtotal (total proportion)			-4.33

Table 1 (continued)

	Strengths	Weight factor	Assessment	Strength of criteria
External environment	*Opportunities*			
	9. More extensive fencing and physical security of the perimeter around the portals.	0.33	4	1.33
	10. Existence of emergency connections between the tunnel tubes for emergency events.	0.50	5	2.50
	11. Good accessibility of emergency boarding area to tunnel portals.	0.17	3	0.50
	12. Ease of use of the technology and information system.	0.00	1	0.00
	Subtotal (total proportion)			4.33
	Threats			
	13. Proximity to a populated agglomeration (Pilsen) and the greater number of potential intruders.	0.00	-1	0.00
	14. The long length of the tunnel without an emergency exit (shaft) complicates the intervention of the Integrated Rescue System units during emergencies.	0.17	-2	-0.33
	15. Twin-tube tunnel, which doubles the security requirements of its portals	0.33	-3	-1.00
	16. High operating speed of passing trains (160 km/h with the vision of increasing to 200 km/h)	0.50	-4	-2.00
	Subtotal (total proportion)			-3.33

Table 2 Resulting values of the SWOT analysis – tunnel Ejpovice (own processing

Internal environment (S+W)	0.17
External environment (O+T)	1.00
Total (difference)	**1.17**

2023). However, the depth and width of integration used in the second solution (Březno tunnel) is significantly greater. Here, the outputs from lidars are networked and application-specific with security cameras, radars and networked speakers.

In terms of the financial cost of the solution, the exact comparison is again complicated. They cannot be quantified precisely, both because of the lack of knowledge of exact acquisition costs and because we are comparing a two-tube and a one-tube tunnel. If we try to compare the acquisition costs for a single tube, the solution used in the Březno tunnel is clearly more expensive. This is due to the amount of technology used and the construction of extra poles to place them outside the tube. However, given the preventive effect of this solution, it would be interesting to compare the costs in the long term if the costs of traffic shutdown in the event of an alarm were included. Generally speaking, both solutions described are among the leading solutions for securing railway tunnel portals in Europe. Most tunnels lack similar kind of security and safety systems or are equipped only with passive camera systems or physical barriers such as fences and walls.

Both solutions for securing railway tunnel portals, which are the main subject of this paper, are still in the verification mode phase of operation since their commissioning. Verification operations are a specific feature of the approval process for railway communication and signalling equipment (Karban 2003) According to information from interviews with representatives of the Railway Administration, the evaluation of the verification operation is planned and the selected solution, or rather the selected solution philosophy, will become the standard for tunnel portal security. According to information from the Railway Administration, new standards for tunnel protection in terms of physical security and safety are currently being prepared and the Railway Administration is elaborating a new directive which will also specify the minimum requirements and standards for tunnel portal security and safety. It is clear that the use of automatisation is the appropriate way to improve reliability, efficiency and prevent safety. For example, simply increasing the number of security features (e.g. detectors and cameras) does not necessarily bring greater efficiency.

There is also the use of modern security detection technologies such as sound and image analysis, which, especially with today's use of artificial intelligence based algorithms (AI), are able to cope with the difficult specificities of the rail transport environment (Smažinka and Hrinko 2022). It is important to integrate the individual elements into a proactive and, as far as possible, automated system that uses modern AI-based analytical algorithms and respects the process and technological specificities of the railway environment. From this perspective, it appears that an important aspect for the selection of the technology is also the independence from the security and safety equipment used in the specific tunnel or the openness to connect to different security equipment used on the railway.

Several future railway tunnels are planned in the Czech Republic, especially on the railway corridor IV. Some of them will exceed a length of 1000 m and will therefore be equipped with portal security according to the valid decision of the Railway

Table 3 SWOT analysis of the Březno tunnel portal security solution (own processing)

	Strengths	Weight factor	Assessment	Strength of criteria
Internal environmen	1. High reliability of detections thanks to the use of state-of-the-art 3D lidars additionally redundantly backed up by radio frequency radar in case of failure or servicing of the primary lidars	0.33	4	1.33
	2. Greater depth and breadth of integration between the individual technologies used - all integrated into one logical unit.	0.50	5	2.50
	3. Greater efficiency and economic return due to emphasis on prevention. Use of larger detection zones in front of portals, repelling potential criminals with automated or live announcements using network speakers.	0.17	4	0.67
	4. High accuracy due to automated classification of detected objects and accurate information about their physical location in the 3D detection zone, including information about their movement history. Detection of an objects flying into the tunnel. (e.g. drones)	0.00	2	0.00
	Subtotal			4.50
	Weaknesses			
	5. Higher initial acquisition cost due to the greater number of technological devices used.	0.50	-4	-2.00
	6. Possible increased service costs due to greater sensitivity of 3D rotating lidars to shocks and vibrations near the railway track.	0.00	-1	0.00
	7. Higher requirements for training, qualification and competence of operators.	0.33	-3	-1.00
	8. Higher requirements and costs for maintenance and service due to the greater number of technologies used.	0.17	-2	−0.033
	Subtotal (total proportion)			-3.33

Table 3 (continued)

	Strengths	Weight factor	Assessment	Strength of criteria
External environment	*Opportunities*			
	9. High publicity thanks to the modern technology used will reduce the courage of intruders in the long run.	0.50	5	2.50
	10. The length of the tunnel is relatively short and the tunnel is equipped with an emergency exit (a shaft with a staircase) about halfway along its length - this makes it easier for the Integrated Rescue System units to intervene in an emergency.	0.17	4	0.67
	11. Single-tube non-electrified tunnel = lower track speed.	0.00	2	0.00
	12. The portals are relatively far from the populated agglomeration	0.33	5	1.67
	Subtotal (total proportion)			4.83
	Threats			
	13. Proximity to a populated area and the greater the number of potential intruders.	0.00	-1	0.00
	14. The automatic playback of warning messages attracts people's curiosity and temporarily increases the number of intruders.	0.17	-2	-0.33
	15. The operator's natural distrust of new technologies.	0.50	-4	-2.00
	16. The fencing around the tunnel portal perimeter is not that robust.	0.33	-3	-1.00
	Subtotal (total proportion)			-3.33

Table 4 Resulting values of the SWOT analysis – tunnel Březno (own processing)

Internal environment (S+W)	1.17
External environment (O+T)	1.50
Total (difference)	**2.67**

Administration organization in the Czech Republic. For example, there is a well-known plan for the construction of tunnels in the Nemanice I - Ševětín section, where two tunnels are planned: Hosínský, 3120 m long, and Chotýčanský, which will become the longest railway tunnel in the Czech Republic thanks to its length of 4775 m. Furthermore, it is planned to build the Podkrušnohorský tunnel with high-speed line parameters, which will be located on the new Dresden – Prague railway connection. According to the chosen option, it is to be at least 26 km long, of which 11.7 km on Czech territory (Drážní inspekce 2021). Although the paper looks at the security of railway tunnels primarily from the perspective of protecting life and health of people and trespassing prevention, it is appropriate to consider security also from a broader perspective of safety with a view to possible future challenges.

Rail transport is an important element of infrastructure and can, as we have unfortunately witnessed in recent years, be the target of attacks by other states or entities. Some countries may seek to actively disrupt the rail infrastructure of other countries, which can have serious security and economic consequences. States try to defend themselves against these activities in various ways. One of these is to increase the safety and security of rail infrastructure, including improving cyber security and establishing security rules and standards. With new technologies on the part of potential tunnel security intruders must also come a response on the part of the security technologies used. One particular challenge, for example, is the automatic detection of drones. Today's drones are potentially capable of flying into a tunnel to threaten traffic. Similar challenges must also be taken into account when choosing security technologies and solution for the future.

This paper deals primarily with the technological possibilities to reduce the number of fatalities and injuries due to trespassing in the area of railway tunnel portals. Secondarily, it also focuses on reducing losses and protecting the assets of the Railway Administration organization and railway operators. The number of train-person collisions in the Czech Republic is relatively high. Many of these accidents are concentrated in the area of railway tunnel portals. Therefore, the paper focused on modern safety technologies used for safety and security of railway tunnel portals in the Czech Republic. The paper described the technical solutions of two currently known technological solutions for the elimination of these accidents based on lidar detection supplemented by cameras and some other technologies as radars and horn speakers. Although these solutions are similar at first sight, their comparison showed significant differences. These are due to the different philosophy of the two solutions, with one solution being significantly more focused on prevention than the other. The comparison also focused on efficiency, accuracy, technological openness and financial cost. One solution is also significantly more accurate from several perspectives. Firstly, the number of false alarms, in terms of classification of detected objects (people, animals, vehicles) and also in terms of the physical location of the detected objects in the detection zone and the recording of the object's trajectory.

In the perspective of openness for integration, both solutions appear theoretically similar, as the manufacturers of the components of these solutions claim the possibility to access application programming interfaces (APIs). However, one of the solutions already practically uses deep integration between a larger number of these components (lidars, cameras, radars, loudspeakers) in an automated way. (Control of rotating cameras using lidar or radar data, automated playback of voice warnings when entering a zone, etc.). The financial cost cannot be quantified precisely due to the comparison of different types of tunnels (one and two-tube tunnel). However, one solution is clearly more expensive due to the amount of technology used and the construction of additional columns to place them outside the tube. However, given the preventive effect of this solution, it would be interesting to compare long term costs if the costs of shutting down in the event of an alarm were included. An analysis of the Total Cost of Ownership (TCO) of the different solutions would be a good topic for a follow-up study. In general, the two solutions described in this paper are among the most advanced rail tunnel portal safety and security technologies in Europe. Most of the tunnels are completely lacking this kind of security or are equipped only with passive CCTV systems or physical barriers such as fences and walls.

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Declarations

Competing interests The authors declare no competing interests.

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