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**Review paper**

# Fire safety in railway and metro tunnels

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**Abstract:** The article presents the development of tunnel infrastructure in the world. Then, the hazards occurring in fires occurring in underground rail transport are characterized and several incidents that have occurred are described. It is also noted that a large role in improving fire safety in tunnels is played by conclusions drawn from experience from incidents that have occurred and by predicting new threats and possibilities of preventing them. Despite equipping tunnels with increasingly modern safety systems, fires, accidents and disasters still occur, as is shown by the given number of fires in tunnels in German-speaking countries that occurred in the years 2013–2023. In addition, the article discusses the current EU requirements aimed at ensuring an optimal level of safety in tunnels in the most economical way. They were developed taking into account scenarios of the most probable events. Ensuring that residual risk is reduced to a low level requires combining all safety layers in the following order: prevention, mitigation, evacuation and rescue. It was also emphasized that the proper selection of non-metallic materials for the construction and equipment of rolling stock and tunnel infrastructure is an important element of effective fire protection. Nevertheless, the required systematic inspections of the condition of vehicle and tunnel equipment, as well as rescue operations exercises according to various scenarios provided for in the Tunnel Emergency Plan, play an important role.

**Keywords:** event scenarios, long railway tunnels, rescue and firefighting operations, technical specification for interoperability, tunnel fires

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# 1. Introduction

The increase in demand for transport services worldwide has forced the acceleration of the development of communication infrastructure, including the construction of new routes, including increasingly longer tunnels, the introduction of modern and faster rolling stock, and the implementation of logistic traffic management systems. However, despite equipping tunnels with modern safety systems, fires, accidents, and disasters still occur and pose an exceptionally high risk to the health and life of people inside them and are the cause of high material losses. On the other hand, the specific conditions inside tunnels (forced air flow and limited heat dissipation) mean that rescue and firefighting operations in underground facilities are among the most difficult and responsible. Therefore, it is necessary to systematically adapt the requirements for ensuring safety to current standards.

# 2. Construction of rail tunnels

The development of tunnel infrastructure in rail transport was initiated in the first half of the 19th century. The oldest railway tunnel in the world was built in 1838-1841 on the Manchester and Leeds line between Rochdale and Hebden Bridge in Great Britain [1].

In later years, more railway tunnels were built. These were:

– Rydułtowy – the oldest tunnel in Poland, 727 m long, built in 1854-1857 [2],
– Fréjus connecting the French Modane in the Arc (Maurienne) river valley with the Italian Bardonecchia in the Dora Riparia river basin, built in 1857–1870; it has one nave with two parallel tracks, 13,636 m long [3].
– Church Hill Tunnel Richmond, USA – 1200 m long, put into operation in 1873 and closed in 1925 due to collapse on a passing work train, which resulted in the death of 4 workers [4],
– Kamionka Wielka Tunnel on the Tarnów – Leluchów line, Galicia (Poland), built in the 1870s, 180 meters long, the tunnel has a curved geometry with a radius of 252 meters.

The oldest metro in the world, on the other hand, began carrying passengers in London on January 10, 1863. Then metro networks were built in other cities (Chicago, USA – 1892, Budapest, Austria–Hungary – 1896, Glasgow, Great Britain – 1896, Paris, France – 1900 [6].

In the 21st century, in the era of dynamic economic development, tunnels have been recognized as a key element of sustainable design of transport networks. Particularly large-scale development of tunneling took place in China, where over 60 tunnel investments were completed, mainly using the TBM method with very large diameter shields [7].

Tunnel investments increase traffic capacity and shorten travel times. This is also important for the environment because it does not interfere with areas of special natural value above ground, and also increases the interest of travelers in using the train instead of the car, which reduces exhaust emissions and thus reduces the carbon footprint. At the same time, the increasing attractiveness of rail travel contributes to a decrease in interest in domestic flights generating carbon dioxide emissions of an average of 244 g $CO_2$/pkm (for a train: 28 g $CO_2$/pkm) [8].

In addition, more and more investments are being made underground due to the dynamic population growth in large agglomerations and limited space [9]. However, it should be taken into account that planning and building in densely urbanized areas requires the use of modern tools that support sustainable development of urban areas and enable minimization of damage. An example is the use of the Leica DS2000 ground-penetrating radar using a new classification algorithm developed by the Military University of Technology team [10].

Currently, the world's longest railway tunnel is the Gotthard Tunnel in the Swiss Alps, which was put into operation in 2016. It is over 57 km long and a passenger train travels through the tunnel in about 20 minutes. Freight trains travel much slower, at a speed of up to 100 km/h [11]. However, other large tunnel investments are being implemented, including:

– Brenner Base Tunnel (BBT), which will connect Innsbruck in Austria with Fortezza in Italy and will be the longest railway tunnel in the world with a length of 64 km, through which high-speed trains will pass [9],
– Koralm Tunnel in Austria is part of the Koralm railway, which is to provide a fast connection between Graz and Klagenfurt. The construction of the 33-kilometer tunnel is to be completed in 2025, the maximum speed for passenger trains will be 250 km/h [12],
– Semmering Base Tunnel in Austria, a 27-kilometer tunnel is part of the Baltic-Adriatic corridor, the project was launched in the 1990s and is planned to be completed in 2028 [13].
– Fehmarnbelt Tunnel – constructed using prefabricated elements embedding technology, will connect Denmark and Germany and will be 18.2 km long, significantly shortening the current 160 km railway crossing through Denmark. The opening is planned for 2029 [9],
– Turin-Lyon Base Tunnel (Mont Cenis Tunnel) – is a key element of the Trans- European Transport Network (TEN-T) and is to improve the freight corridor between France and Italy, offering a real alternative to road transport through the Alps with a length of 57.5 km. Expected completion date 2030 [14],
– Cross-city railway tunnel – will connect the Fabryczny Station in Łódź with the Łódź Kaliska stations (towards Sieradz, Kalisz) and Żabieniec (towards Kutno, Łowicz). The 7.5-kilometer tunnel is divided into two parts – a double-track tunnel from Łódź Fabryczna to Koziny and four single-track tunnels west of the Koziny stop. The investment has been implemented since mid-2019 and the completion of construction and the passage of the first trains is planned for December 2026 [15].
– Tunnel under Łódź city – along railway line no. 85, from the "Retkinia" chamber to the "Fabryczna" chamber, 4.6 km long for high-speed rail, planned start of construction at the turn of 2026 and 2027 [16].
– Męcina – Mordark tunnel – 3.8 km long will be dug on the Limanowa – Nowy Sącz section, passenger trains will be able to travel at speeds of up to 160 km/h, while freight trains will travel at a maximum of 100 km/h, completion of construction planned for 2029 [17].

## 3. Fires in rail and metro tunnels

The improvement of the construction of underground communication routes, which is manifested by their systematic lengthening, as well as the increase in the speed of trains passing through them, entails increased requirements in terms of ensuring safety. The most dangerous events in tunnels include those involving fire. Rescue and firefighting operations in railway tunnels are among the most difficult and responsible. This results primarily from the specifics of the development of the fire itself, which is characterized by a very rapid increase in temperature due to limited heat dissipation and the intensive spread of toxic smoke containing compounds such as: carbon monoxide, hydrogen cyanide, diisocyanates, bicyclic phosphorus esters, nitrogen oxides. The lack of visibility also has a strong psychological effect on the injured and rescuers. Very significant difficulties in conducting rescue operations also result from the limited space of operation. Unfavourable topographic conditions of the tunnel location also affect the extended arrival time of rescue services [18–22].

Fires that occurred in tunnels often caused many deaths and injuries, as well as material losses. Some of the most dangerous were:

- a fire in a subway train in Paris on August 10, 1903 – the cause was a short circuit in the electrical installation in one of the cars, 84 people died [23],
- a fire in a subway tunnel in New York on January 6, 1915 – the fire broke out as a result of a short circuit in one of the electrical boxes in the subway tunnel under Broadway at 55th Street, only one person died, but 210 suffered smoke poisoning [24],
- a fire at the Kings Cross subway station in London on November 18, 1987 – an unextinguished match abandoned by a passenger that fell inside the escalator started a rapidly spreading fire in the garbage there, 35 people died and many were seriously injured. As part of the post-accident conclusions, a number of preventive measures were introduced, including primarily: installation of fire-fighting equipment and a radio communication system in critical locations, replacement of wooden elements of stairs with steel ones, clear marking of evacuation routes, development and implementation of the scope of duties and responsibilities, alarm procedures and training programs for metro staff [25],
- a fire in a metro train in Baku, Azerbaijan, on October 28, 1995 – as a result of an electrical failure, a crowded train caught fire in the tunnel, 289 people died and 265 were injured [26],
- a fire in a mountain railway in Gletscherbahn Kaprun, Austria, on November 11, 2000 – the cause was a failure (overheating and ignition) of an electric heater-blower in the driver's cabin, 155 people died. After this tragedy, the fire safety instructions were changed and the heating system was eliminated [27, 28],
- a fire in the Terfen tunnel near the town of Fritzen in Tyrol, on June 8, 2023. – the ignition occurred after the traction network fell on one of the vehicles in a wagon designed for transporting cars, a total of 33 people were injured by smoke inhalation [29],
- a truck fire in a freight train in the Eurotunnel on 18 November 1996 – the reconstruction of the destroyed 500 m long section of the tunnel took over 6 months. After this incident, automatic fire detection and extinguishing systems were introduced in the tunnel [30].

Despite the development of technology for designing and constructing rail vehicles, taking into account the systematic introduction of national requirements since the end of the 20th century, and since 2013 European requirements, including those concerning fire safety, fires in railway tunnels still occur. This is confirmed by the publication of the International Fire Academy [31], which, based on media data (lack of full official statistics), presents the number of fires in tunnels in German-speaking countries (Germany, Austria and Switzerland) that occurred in the years 2012–2023, with the reservation that the actual data may be higher. As it results from the data, in the period under review, the IFA registered a total of 108 fires, including: in Switzerland – 6, in Germany – 88 and in Austria – 14 (including the above-mentioned fire in the Terfen tunel). On the other hand, the number of incidents with significant fluctuations in individual years shows only a slight decrease (Fig. 1).

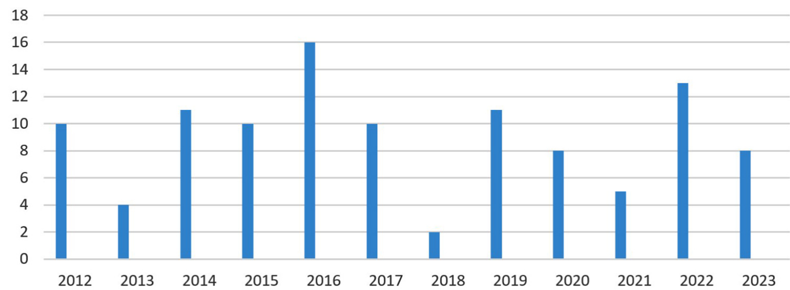


Fig. 1. Fires in railway tunnels in German-speaking countries in 2012–2023 (according to [31])

However, only in 22% of the recorded cases (24 incidents) did rail vehicles or their parts, such as capacitors or brakes, burn. In the remaining cases, rail infrastructure objects such as switchboards, electrical cables, wooden railway sleepers and pavements burned, as well as garbage, luggage or adjacent buildings, from which smoke rose to underground facilities. In six cases, the fire spread to construction machines on tunnel construction sites. In addition, the example from Berlin, given by the German Press Agency dpa, showed that even small fires in tunnels can pose a great risk and require serious rescue and firefighting operations. The described incident took place on September 30, 2022 at the Seestrasse subway station, where a small amount of insulating material ignited. The Berlin fire department sent around 90 firefighters to rescue three people from the smoke-filled areas, extinguish the fire and ventilate the underground railway facilities. At the same time, the analysis of the fires that occurred allowed IFA to state that the majority of fires in the railway sector (60%) occurred in tunnels of metro or suburban railway lines, where, due to the number of stations and stops and the elements of tunnel infrastructure used, there are more potential sources of ignition than in tunnels on long-distance lines [31].

It should be remembered that the course of a fire and its scale depend largely on the type of burning vehicle and on the amount and speed of the incoming fresh air. Information on phenomena occurring during fires in tunnels is provided by the results of analyses of accidents and laboratory tests, as well as tests conducted on a natural scale. Since the 1990s, the results of the above studies have been verified using systematically developed numerical methods enabling computer simulation of fire development in tunnels. The following software:

- CFD (Computational Fluid Dynamics),
- SES (Subway Environment Simulation),

are used in:

- analysis of processes and phenomena occurring during a fire,
- design of tunnels equipped with modern ventilation systems as well as fire detection, signaling and extinguishing systems.

They take into account the temperature distribution and flame propagation speed and the effects of thermal radiation in the tunnel, with different configurations of ventilation systems, taking into account aspects such as:

- safety (evacuation models),
- ventilation efficiency,
- construction and operating costs.

# 4. Role and scope of the SRT TSI

## 4.1. General information

In order to develop unified requirements for individual subsystems of the European rail network, which is a patchwork of the diverse systems of the Member States, the AEIF (French: Association Europeenne pour L'Interoperabilite Ferroviaire) European Association for Railway Interoperability was established in 1995. The association was established by the following organisations:

- UIC (French: Union Internationale des Chemins de Ferroviares) – International Union of Railways,
- UNIFE (French: Union Europeenne des Industries Ferroviares) – International Union of Railway Manufactures,
- UITP (French: Union Internationale des Transports Publiques) – International Union of Public Transport.

In 2003, within the AEIF, the SRT (Safety in Railway Tunnels) Working Group (MANDATE 01/16-MA02 version EN03, 06.03.2003) began its work. The result of the Working Group's work was the publication of the COMMISSION DECISION of 20 December 2007 establishing the first edition of the SRT TSI [32].

In 2005, the role of the AEIF was taken over by the European Union Agency for Railways – EUAR, formerly: European Railway Agency – ERA, (French: Agence ferroviaire européenne) – an agency of the European Union established pursuant to Regulation No. 881/2004 of the European Parliament and of the Council of 29 April 2004 (subsequently replaced by Regulation 2016/796) to act as the European rail market regulator in the technical scope and to provide the Member States of the European Union with technical support for railway interoperability and safety.

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Currently, Commission Regulation (EU) No 1303/2014 of 18 November 2014 [31] as amended (Commission Implementing Regulation (EU) 2019/776 of 16 May 2019 [32], Commission Implementing Regulation (EU) 2024/191 of 8 January 2024 [33]) is in force. The purpose of this TSI is to achieve an optimal level of safety in tunnels in the most economical way. The specification is to enable the free movement of interoperable trains under harmonised safety conditions in the railway tunnels of the TEN network. Ensuring the above, in accordance with the SRT TSI (as shown in Fig. 2), requires the implementation of actions in the following areas in the following order: prevention, mitigation, evacuation and rescue. Combining all safety layers in the above manner (with the greatest effort for prevention) ensures that the residual risk is reduced to a low level.

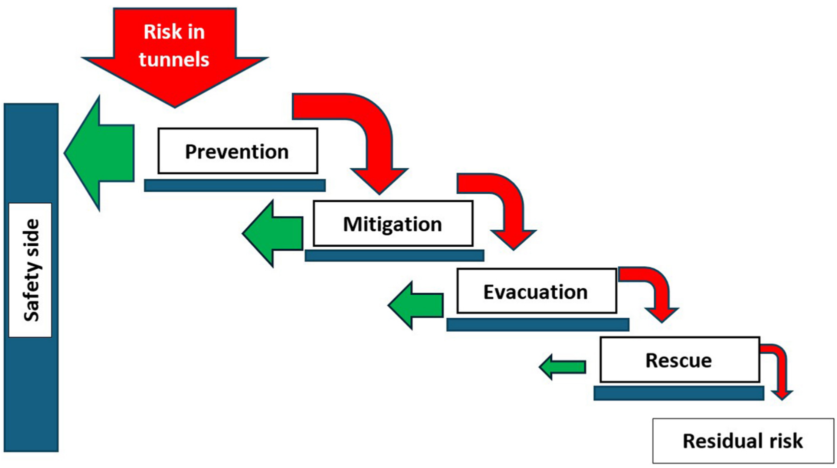


Fig. 2. Safety system in railway tunnels (according to [33])

Safety requirements have been developed taking into account scenarios of the most probable events. They have been classified as:

– "Hot" type incidents, in which we are dealing with a fire, explosion and then fire, emission of toxic smoke or gases. A distinction is made between a variant in which the fire is initiated in the train and a variant in which the fire starts in the tunnel. It is also necessary to take into account the situation in which the fire may occur as a secondary phenomenon as a result of a derailment or collision.

– “Cold” type incidents – i.e. collision, derailment, in which there is no fire and therefore there is no time limit factor resulting from the presence of a hazardous environment caused by the fire.
– and additionally considered – unplanned stopping of the train, without a “hot” or “cold” type incident, for a period longer than 10 minutes, which does not in itself pose a threat to either passengers or staff. However, it may cause a spontaneous, uncontrolled evacuation, exposing people to the hazards occurring in the railway tunnel.

The full scope of the SRT TSI [33] is presented below in 4.1–4.9.

## 4.2. Technical and geographical scope

Clause 1 defines the scope of the specification in relation to tunnels, rolling stock, aspects of rail traffic, as well as the scope of risk covering only specific hazards to the safety of passengers and on-board staff in tunnels, in relation to the subsystems covered. However, it also covers hazards to persons in the vicinity of the tunnel, in the event of which the collapse of the structure could lead to a catastrophe. At the same time, it specifies hazards that this TSI does not cover (health and safety of personnel, financial losses from structural damage, intrusions into the area, acts of terrorism).

## 4.3. Definition of aspect/scope

Clause 2 explains that the tunnel safety system consists of: prevention, mitigation, evacuation and rescue. The combination of these layers in the order given ensures that the residual risk is reduced to a low level. The above hazard scenarios are characterized and appropriate measures are identified to control or significantly reduce them. The role of the rescue services in the event of the above incidents is also described. The next provide definitions of terms used in this TSI.

## 4.4. Essential requirements

Clause 3 specifies the basic parameters of this TSI and their compliance with the essential requirements specified for the individual subsystems and listed in order in Annex III to Directive 2008/57/EC [36].

## 4.5. Characterisation of the subsystem

Clause 4 presents functional and technical specifications of aspects related to tunnel safety, concerning subsystems:

– “Infrastructure” – includes requirements in the scope of: preventing unauthorized access to emergency exits, fire resistance of the tunnel structure and construction materials, fire detection in technical rooms, means of facilitating evacuation (access to a safe area, means of communication in safe areas, emergency lighting on evacuation routes, marking of evacuation routes, evacuation walkways, places intended for fire fighting, emergency communication).

– "Energy" – includes requirements in the scope of: power supply segmentation, grounding of traction networks or third rail, power supply, used electric cables, reliability of electrical installations.
– "Rolling stock" – takes into account the requirements (in accordance with TSI LOC&PAS [37]) in the scope of: fire prevention measures, material requirements, special measures concerning flammable liquids, detection of hot axle bearings, fire detection and extinguishing measures (portable fire extinguishers, fire detection systems, automatic fire extinguishing systems for diesel-powered cargo units, fire fighting and control systems for passenger rolling stock.
– The interfaces with the Control Command and Signaling (CCS) and Railway Operation (OPE) subsystems were also discussed, as well as the requirements for: the emergency plan for the tunnel, exercises covering evacuation and rescue procedures, shutdown and grounding procedures, providing passengers with information on safety rules and emergency procedures, operating rules for trains running in tunnels, infrastructure and rolling stock maintenance rules, professional qualifications of the train crew and other personnel related to tunnels, and health and safety conditions (including self-rescue equipment).

## 4.6. Interoperability constituents

Clause 5 states that no interoperability constituents are specified in this SRT TSI [33].

## 4.7. Assessment of conformity and/or suitability for use of the constituents and verification of the subsystem

Clause 6 specifies the rules for WE verification of the subsystem.

## 4.8. Implementation

Clause 7 specifies the strategies for implementing the SRT TSI [33] in relation to new, upgraded, renewed and extended tunnels, as well as in relation to rolling stock. Specific cases are also taken into account.

## 4.9. Appendixes

The SRT TSI [33] also contains the following Appendixes:
– Appendix A Standards or Normative Documents Referred to in this TSI,
– Appendix B Assessment of the Subsystems.

## 4.10. Applying the TSI SRT principles in practice

In order to unambiguously interpret the provisions of the SRT TSI [33], ERA has issued an additional document "Guide for the application of the SRT TSI" [38] which provides an interpretation of the individual requirements.

However, when analysing fire safety in rail tunnels, it should be taken into account first of all that fire prevention requires preventing the formation of a combustion triangle (fuel – ignition source – oxidiser). The most important thing is therefore the proper selection of non-metallic materials used for the construction and equipment of rolling stock and tunnels that meet the requirements for flammable and smoke properties (i.e. fuel limitation). Another preventive measure requires avoiding potential sources of ignition, which include, among others: failures in braking systems, electric heating systems, HVAC systems. On the other hand, arson, which was the most common cause of fires in rail vehicles years ago, is fortunately rare now due to the increasingly frequent use of products that meet the requirements. These are passive security measures. Active security measures, i.e. fire detection, signalling and extinguishing at the initial stage of its development, also provide significant support [39]. An important preventive measure is also to systematically raise awareness among railway carriers and infrastructure managers about a number of threats, causes and required controls related to fires in underground tunnels and stations, as reminded by, for example, the ONRSR in Australia [40].

# 5. Summary and conclusions

1. Safety in tunnels, especially in the fire area, is the result of conclusions drawn from experience from events that have occurred and from anticipating new threats and possibilities of preventing them. Tragic experiences force verification of the existing requirements/regulations, as well as development of security solutions and change of approach aimed at avoiding the repetition of similar accidents.
2. The greatest impact on the scale of a fire, its course, and especially the intensity of smoke emitted and the toxicity of its components is exerted by the type, quantity and distribution of non-metallic materials.
3. In order to achieve the optimum level of safety in tunnels in the most economical way and to reduce the residual risk to a low level, it is necessary, in accordance with the provisions of the SRT TSI [33], to combine in the given order actions and measures in the scope of prevention, mitigation of effects, evacuation and rescue.
4. Important preventive actions also include systematic inspections of the condition of vehicle and tunnel equipment, as well as rescue operations exercises according to various scenarios provided for in the Emergency Plan for a given tunnel.

## References

[1] A. Sumara, „Jeden z najstarszych tuneli kolejowych na świecie został odnowiony (One of the oldest railway tunnels in the world has been renovated)", Sektor Kolejowy. [Online]. Available: https://www.sektorkolejowy.pl/jeden-z-najstarszych-tuneli-kolejowych-na-swiecie-zostal-odnowiony/. [Accessed: 16 Nov. 2024].

[2] K. Kubak, „167 lat i 727 metrów. To najstarszy tunel kolejowy w Polsce (167 years and 727 meters. It is the oldest railway tunnel in Poland)", Interia Geekweek. [Online]. Available: https://geekweek.interia.pl/podroze/news-167-lat-i-727-metrow-to-najstarszy-tunel-kolejowy-w-polsce,nId,7155205. [Accessed: 16 Nov. 2024].

[3] „Fréjus Rail Tunnel", Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Fr%C3%A9jus_Rail_Tunnel. [Accessed: 13 Nov. 2024].

[4] „Church Hill Tunnel", Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Church_Hill_Tunnel. [Accessed: 16 Nov. 2024].

[5] E. Stachura, „Wiecie jaką ma długość tunel kolejowy w Kamionce Wielkiej? (Do you know how long the railway tunnel in Kamionka Wielka is?)", Sądeczanin. [Online]. Available: https://sadeczanin.info/wiadomosci/wiecie-jaka-ma-dlugosc-tunel-kolejowy-w-kamionce-wielkiej-wideo. [Accessed: 16 Nov. 2024].

[6] Ł. Załuski, „Najstarsze metro świata – gdzie jest i kiedy powstało (The oldest metro in the world – where is it and when was it built)", National Geographic Polska. [Online]. Available: https://www.national-geographic.pl/historia/najstarsze-metro-swiata-gdzie-jest-i-kiedy-powstalo/. [Accessed: 15 Nov. 2024].

[7] W. Qiu, X. Dong, L. Su, X. Xue, and K. Zhang, „Development and consideration of Chinese super-large diametel shield tunel", *Archives of Civil Engineering,* vol. 70, no. 1, pp. 473–486, 2024, doi: 10.24425/ace.2024.148923.

[8] M. Wojtkiewicz, „Emisje z transportu: czas na zmianę paradygmatu (Transport Emissions: Time for a Paradigm Shift)", Teraz Środowisko. [Online]. Available: https://www.teraz-srodowisko.pl/aktualnosci/emisje-transport-kolejowy-drogowy-lotniczy-GHG-11142.html. [Accessed: 15 Nov. 2024].

[9] M. Ciupińska, „Tunele kluczowym elementem zrównoważonych sieci transportowych (Tunnels are a key element of sustainable transport networks)", NBI – Portal Inżynieryjny. [Online]. Available: https://nbi.com.pl/archiwum-nbi/tunele-kluczowym-elementem-zrownowazonych-sieci-transportowych/. [Accessed: 16 Nov. 2024].

[10] K. Pasternak and A.S. Fryskowska-Skibniewska, „Automatic classification of underground utilities in Urban Areas: A novel method combining ground penetrating radar and image processing", *Archives of Civil Engineering*, vol. 70, no. 2, pp. 59–77, 2024, doi: 10.24425/ace.2024.149851.

[11] „Najdłuższy i najgłębszy. Wszystko o tunelu Gotarda (The Longest and Deepest. All About the Gotthard Tunnel)", Rynek Kolejowy. [Online]. Available: https://www.rynek-kolejowy.pl/wiadomosci/szwajcaria-otwarcie-tunelu-gotarda-76807.html. [Accessed: 8 Nov. 2024].

[12] „Austria: Kolejowa inwestycja stulecia gotowa w połowie (Austria: The railway investment of the century is halfway ready)", Rynek Kolejowy. [Online]. Available: https://www.rynek-kolejowy.pl/wiadomosci/austria-kolejowa-inwestycja-stulecia-gotowa-w-polowie-116284.html. [Accessed: 7 Nov. 2024].

[13] M. Dobel, „The Semmering Base Tunnel: overcoming the Alps", RailEngineer. [Online]. Available: https://www.railengineer.co.uk/the-semmering-base-tunnel-overcoming-the-alps/. [Accessed: 6 Nov. 2024].

[14] L. Cech, „Ambitne tunele kolejowe w Europie w budowie (Ambitious rail tunnels under construction in Europe)", RAILMARKET. [Online]. Available: https://pl.railmarket.com/news/insights/19825-europe-s-ambitious-railway-tunnels-under-construction. [Accessed: 6 Nov. 2024].

[15] M. Juśkiewicz, „Tunel średnicowy pod Łodzią. Wiceszef MI: pociągi pojadą w 2027 roku", PAP. [Online]. Available: https://www.pap.pl/aktualnosci/tunel-srednicowy-pod-lodzia-wiceszef-mi-pociagi-pojada-w-2027-roku.

[16] D. Długosz, „Najdłuższy tunel kolejowy w Polsce. Plac budowy przekazany (The longest railway tunnel in Poland. Construction site handed over)", Interia Geekweek. [Online]. Available: https://geekweek.interia.pl/technologia/news-najdluzszy-tunel-kolejowy-w-polsce-plac-budowy-przekazany-wy,nId,7588517. [Accessed: 6 Nov. 2024].

[17] „Ruszyły przygotowania do budowy tunelu kolejowego (Preparations for the construction of a railway tunnel have begun)", Limanowa.in. [Online]. Available: https://limanowa.in/aktualnosci/ruszyly-przygotowania-do-budowy-tunelu-kolejowego/72618. [Accessed: 6 Nov. 2024].

[18] J. Radziszewska-Wolińska, „Bezpieczeństwo pożarowe taboru szynowego (Fire safety of rolling stock)", *Problemy Kolejnictwa*, no. 133, pp. 111–124, 2001.

[19] J. Radziszewska-Wolińska, "Passenger train fire in a tunnel", in *Proceedings of the Second International Conference LONG ROAD and RAIL TUNNELS, 09–11 May 2002, Hong Kong*. Kempston, UK: Tunnel Management International Ltd., 2002, pp. 109–118.

[20] E. Gierski, *Problemy działań ratowniczo-gaśniczych w tunelach kolejowych (Problems of rescue and fire-fighting operations in railway tunnels)*. Kraków: Szkoła Aspirantów Państwowej Straży Pożarnej, 1996.

[21] M. Łukomski and G. Sztarbała, „Pożary w tunelach (Fires in the tunnels)", in *Konferencja SECUREX 2002*. Poznań: COB-R METALPLAST, 2002, pp. 183-194.

[22] S. Nawrat and S. Napieraj, *Wentylacja i bezpieczeństwo w tunelach komunikacyjnych (Ventilation and safety in communication tunnels)*. Kraków: AGH – Uczelniane Wydawnictwa Naukowo-Dydaktyczne, 2005.

[23] R. Carvel and A.N. Beard, Eds. *The handbook of Tunnel Fire Safety*. London: Thomas Telford Ltd., 2005.

[24] Bowery Boys, "The Horror Underground: New York's first subway disaster – during rush hour, one hundred years ago today", BoweryBoys. [Online]. Available: https://www.boweryboyshistory.com/2015/01/the-horror-underground-new-yorks-first.html. [Accessed: 16 Nov. 2024].

[25] D. Fennell, "Investigation into the King's Cross Underground Fire", Department of Transport UK, 1988.

[26] W. Urbanowicz, „Metro na Kaukazie – Baku (Metro in the Caucasus – Baku)", Transport Publiczny. [Online]. Available: https://www.transport-publiczny.pl/wiadomosci/metro-na-kaukazie–baku-1021.html. [Accessed: 16Nov. 2024].

[27] J. Ranecki, „Śmiertelna pułapka (Death trap)", *Przegląd Pożarniczy,* vol. 2001, no. 3, pp. 18–19, 2001.

[28] K. Kęciek, „Piekło w sercu góry (Hell in the Heart of the Mountain)", Tygodnik Przegląd. [Online]. Available: https://www.tygodnikprzeglad.pl/pieklo-sercu-gory/. [Accessed: 16 Nov. 2024].

[29] „Austriacki tunel kolejowy w ogniu, 33 osoby z nocnego pociągu NightJet ranne (Austrian railway tunnel on fire, 33 people from NightJet night train injured)", Kurier Kolejowy. [Online]. Available: https://kurier-kolejowy.pl/aktualnosci/42606/austriacki-tunel-kolejowy-w-ogniu–33-osoby-z-nocnego-pociagu-nightjet-ranne.html. [Accessed: 16 Nov. 2024].

[30] „Tunel pod kanałem La Manche – cała masa ciekawostek (The Channel Tunnel – a whole host of interesting facts)", StatkiHistoryczne.pl. [Online]. Available: https://www.statkihistoryczne.pl/tunel-pod-kanalem-la-manche-cala-masa-ciekawostek/. [Accessed: 16 Nov. 2024].

[31] "Tunnel fires from 2012 to 2023: Statistics from media reports", IFA Magazine. [Online]. Available: https://www.ifa-swiss.ch/en/magazine/detail/tunnel-fires-from-2012-to-2023-statistics-from-media-reports. [Accessed: 16 Nov. 2024].

[32] EU, "COMMISSION DECISION of 20 December 2007 concerning the technical specification of interoperability relating to 'safety in railway tunnels' in the trans-European conventional and high-speed rail system *(notified under document number C(2007) 6450)* (Text with EEA relevance), (2008/163/WE)", EUR-Lex. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2008.064.01.0001.01.ENG. [Accessed: 16 Nov. 2024].

[33] EU, "COMMISSION REGULATION (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union", EUR-Lex. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.356.01.0394.01.ENG. [Accessed: 16 Nov. 2024].

[34] EU, "Commission Implementing Regulation (EU) 2019/776 of 16 May 2019 amending Commission Regulations (EU) No 321/2013, (EU) No 1299/2014, (EU) No 1301/2014, (EU) No 1302/2014, (EU) No 1303/2014 and (EU) 2016/919 and Commission Implementing Decision 2011/665/EU as regards the alignment with Directive (EU) 2016/797 of the European Parliament and of the Council and the implementation of specific objectives set out in Commission Delegated Decision (EU) 2017/1474 (Text with EEA relevance)" (revoked), EUR-Lex. [Online]. Available: Implementing regulation – 2019/776 – EN – EUR-Lex. [Accessed: 16 Nov. 2024].

[35] EU, "Commission Implementing Regulation (EU) 2024/191 of 8 January 2024 correcting certain language versions of Regulation (EU) No 1303/2014 concerning the technical specification for interoperability relating to safety in railway tunnels of the rail system of the European Union", EUR- Lex. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R0191. [Accessed:16 Nov. 2024].

[36] EU, "Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the interoperability of the rail system within the Community (Recast)", EUR-Lex. [Online]. Available: Directive – 2008/57 – EN – EUR-Lex. [Accessed: 16 Nov. 2024].

[37] EU, "Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European Union", EUR-Lex. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.356.01.0228.01.ENG. [Accessed: 16 Nov. 2024].

[38] "Guide for the application of the SRT TSI", European Union Agency for Railways. [Online]. Available: https://www.era.europa.eu/system/files/2022-11/Guide%20for%20the%20application%20of%20the%20SRT%20TSI%20-%20new%20version%202019%20%28EN%29.pdf. [Accessed: 16 Nov. 2024].

[39] J. Radziszewska-Wolińska, „Bezpieczeństwo pożarowe transportu szynowego (Fire safety of rail transport)", in *Magazyn Kultury Bezpieczeństwa UTK*. Warszawa: UTK, 2019, pp. 172–183.

[40] „Safety Message: Fires in tunel and underground stations", ONRSR Portal. [Online]. Available: https://www.onrsr.com.au/safety-essentials/safety-messages/safety-message-fires-in-tunnels-and-imderground-stations. [Accessed: 8 Nov. 2024].

## Bezpieczeństwo pożarowe w tunelach kolejowych i metra

**Słowa kluczowe:** akcje ratowniczo-gaśnicze, długie tunele kolejowe, pożary w tunelach, scenariusze zdarzeń, techniczna specyfikacja interoperacyjności

### Streszczenie:

W artykule przedstawiono rozwój infrastruktury tunelowej na świecie zwracając uwagę, że systematyczne wydłużanie tuneli i jednocześnie zwiększanie prędkości przejeżdżających przez nie pociągów, niesie za sobą konieczność zaostrzania wymagań w zakresie zapewnienia bezpieczeństwa. Do najgroźniejszych zdarzeń w tunelach należą te, w których występuje pożar. Podkreślono, że akcje ratowniczo-gaśnicze w tunelach kolejowych należą do najtrudniejszych oraz najbardziej odpowiedzialnych z uwagi na bardzo szybki wzrost temperatury oraz intensywne rozprzestrzenianie się toksycznego dymu. Podano przykłady kilku zdarzeń jakie miały miejsce na świecie w tunelach kolejowych oraz tunelach metra. Przebieg pożaru i jego skala zależy w dużym stopniu od rodzaju palącego się pojazdu oraz od ilości i prędkości dopływającego świeżego powietrza. Informacji na temat zjawisk zachodzących w czasie pożarów w tunelach dostarczają wyniki analiz zaistniałych wypadków oraz badania laboratoryjne, jak również badania prowadzone w skali naturalnej. Rezultaty powyższych badań są często weryfikowane z wykorzystaniem systematycznie rozwijanych metod numerycznych (CDF, SES). Przeprowadzona analiza wykazała również, że mimo wyposażania tuneli w coraz nowocześniejsze systemy bezpieczeństwa, pożary, wypadki i katastrofy nadal mają miejsce jak wynika z ilości pożarów w tunelach krajów niemieckojęzycznych jakie wystąpiły w latach 2012-2023. W artykule omówiono także aktualne wymagania unijne mające na celu zapewnienie optymalnego poziomu bezpieczeństwa w tunelach w najbardziej ekonomiczny sposób. Zostały one opracowane z uwzględnieniem scenariuszy najbardziej prawdopodobnych zdarzeń. Zakwalifikowano je jako:

- incydenty typu „gorącego", w których mamy do czynienia z pożarem, wybuchem i następnie pożarem, emisją toksycznego dymu lub gazów. Rozróżnia się wariant, w którym inicjacja pożaru następuje w pociągu oraz wariant w którym pożar zaczyna się w tunelu,
- incydenty typu „zimnego" – czyli zderzenie, wykolejenie, w których nie ma pożaru,
- oraz dodatkowo rozpatrywane – nieplanowe zatrzymanie pociągu, bez incydentu typu „gorącego" lub „zimnego", przez czas dłuższy niż 10 minut, które nie stanowi samo w sobie zagrożenia ani dla pasażerów, ani dla personelu ale może stać się przyczyną spontanicznej, niekontrolowanej ewakuacji.

Zapewnienie sprowadzenia ryzyka rezydualnego do niskiego poziomu wymaga połączenia wszystkich warstw bezpieczeństwa w następującej kolejności: zapobieganie, łagodzenie skutków, ewakuacja i ratownictwo. Podkreślono także, iż właściwy dobór materiałów niemetalowych przeznaczonych do budowy i wyposażenia taboru oraz infrastruktury tunelowej, stanowi istotny element skutecznej ochrony przeciwpożarowej. Nie mniej, ważną rolę odgrywają wymagane systematyczne przeglądy stanu wyposażenia pojazdów oraz tuneli, a także ćwiczenia działań ratowniczych według różnych scenariuszy przewidzianych w Planie Awaryjnym tunelu.

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