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Effective and active fire safety systems for railway tunnels

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Abstract:
In the territory of the Slovak Republic, there is a significant number of railway tunnels, some of which are over 50 years old and pose an increased risk to safety in the event of extraordinary incidents, especially fires. Currently, the safety of railway tunnels and the response to extraordinary events in linear structures are key topics. Identifying areas of risk associated with the potential release of hazardous substances transported by rail is a priority, with a primary focus on detecting fires in their early stages directly in railway vehicles.
While fire statistics show a negligible risk of fires in railway tunnels, the development of an early fire detection system has become a current issue to enhance the safety of these tunnels. The mentioned aspects represent fundamental active measures to minimize catastrophic consequences during extraordinary events. The organization of rescue operations requires precise delineation of endangered and anticipated endangered areas, with an emphasis on ensuring conditions for effective rescue work, including the necessary personnel and technical equipment, efficient ventilation, and addressing potential faults in ventilation shafts and closures.
The article elaborates on the methodology of fire ventilation with a focus on its application in existing railway tunnels, which are currently undergoing improvement processes. Emphasis is placed on improving fire ventilation as a higher level of ventilation system.

Key words:
extraordinary event, fire, detection system, railway tunnels

Introduction

Fires, accidents, and other emergency events occurring in road and railway tunnels, large car parks, and multi-story park houses pose significant threats, particularly when a considerable number of people and substantial quantities of flammable substances are involved, impacting a wide area and numerous individuals. Managing such incidents requires the coordinated efforts of the integrated rescue system, including fire and rescue services, ambulances, and civil protection forces. Effectively overseeing the rescue system becomes crucial, considering the complexity of rescue tactics and techniques, firefighting, first aid, emergency supply, and the provision of emergency accommodation. These activities are among the most challenging (Betus et al., 2022; Directive no. 2004/5; PIARC, 1999; PIARC, 1995).

In structures where evacuation conditions for individuals, animals, and belongings are straightforward, the potential loss of life is minimal, health risks are manageable, and the cost of rescue operations, as well as the deployment of forces and resources, is relatively low. The risk of endangering individuals is directly linked to the layout of the building, especially concerning escape routes, the quantity and characteristics of flammable substances, and the number of people and their mobility (Betus et al., 2022; Directive no. 2004/5; PIARC, 1999; PIARC, 1995).

Considering the criteria mentioned above, it is evident that railway tunnels are considerably safer compared to road tunnels. This discussion has been ongoing within the European Union for the past 10-15 years. Given the increasing threat of terrorism, even in our local context, ensuring the efficient and high-quality construction, as well as fire safety in road tunnels, emerges as a crucial aspect of security measures. This emphasis aligns with the directives outlined in the 2004 directive (Betus et al., 2022; Directive no. 2004/5; PIARC, 1999; PIARC, 1995).

The issue of fire occurrence in road and railway tunnels and the management of ventilation during a fire in these tunnels have been thoroughly examined in various publications by different experts. These publications have identified various threats to human life and health in connection with fires in road and railway tunnels, including high temperatures, the presence of various toxic gases and combustion by-products, and low oxygen concentrations. Reduced visibility significantly limits the escape options from endangered areas during a fire and complicates the access of rescue teams to the site of an extraordinary event. High temperatures and a high level of thermal radiation can lead to uncontrolled fire spread and transmission to other areas. For this reason, it has been concluded that ventilation management is essential to ensure life-saving, facilitate evacuation, carry out effective rescue and firefighting operations, prevent explosions, limit damage to tunnel construction and equipment. This means that controlled ventilation is necessary in the event of an extraordinary event and fire in the tunnel (Beard and Carvel, 2012; PIARC, 2011; Cigolini, 2012; PIARC, 2006).

Methodological procedures for extinguishing fires in railway tunnels are defined according to the following philosophy:

- before entering the tunnel tube, the train in which a fire occurs should, if possible, be stopped to prevent the fire from entering the tunnel,
- if a train is passing through the tunnel and a fire is detected in any part or carriage, it should, if possible, exit the tunnel and not stop inside,
- in specific situations (e.g., the occurrence of a fire in a high-speed passenger train, such as the high-speed Paris - Strasbourg line), the train must continue its journey and park the train set outside the tunnel tube. (Beard and Carvel, 2012; Cigolini, 2012; PIARC, 2011; PIARC, 2006; Zumsteg et al., 2012).

The following can be inferred from the above: if there is a possibility for the train to stop before entering the tunnel tube in case of a fire or the danger of a fire, the train driver must slow down and stop the train in order to avoid risks associated with a fire within the enclosed space and to prevent endangering passengers with the threat of a fire. When implementing this procedure, it is necessary for the train driver to make a decision regarding the possibility of the fire spreading (Beard and Carvel, 2012; Cigolini, 2012; PIARC, 2011; PIARC, 2006).

In the case of the second philosophy, the principle is based on preventing the spread of fire in the tunnel, meaning not entering the tunnel or exiting it in the event of a fire in the train set (preventing the spread of fire in an enclosed space). Applying this philosophy in practice involves ensuring the entire system, whether it be the train set or the environment around the tunnel tube, is equipped with fire detection systems and, ultimately, an appropriate automatic safety system to stop the train (Beard and Carvel, 2012; Cigolini, 2012; PIARC, 2011; PIARC, 2006).

The fundamental requirement expected from the detection system is the ability for the tunnel safety control system to react swiftly to potential fire hazards in a train entering the tunnel. It is necessary to take into account the braking distance that the train requires, typically ranging from 1-3 km, depending on external conditions such as the deceleration value of the track (0.3 – 0.2 m.s-2), the distribution of the train's weight, the reaction time of the detection system, and the delay in the braking process (Beard and Carvel, 2012; Cigolini, 2012; PIARC, 2011; PIARC, 2006).

1 Materials and methods

1.1 Railway Transport Detection System

Fires that could potentially affect railway rolling stock can ignite through a wide range of different sources, depending on the type of carriage, technological equipment, operational conditions, and the properties of transported materials (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

Various experts have analyzed the phenomena of ignition by conducting research on fires in rail vehicles. The goal was to identify the phases of the fire, resulting in the classification of events observed during extraordinary incidents leading to fires in passenger rail vehicles and extraordinary incidents resulting in fires in freight rail vehicles (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

Regarding the cause of fires, electrical issues were predominant in most cases, with the peak released thermal power reaching 50 MW for passenger rail vehicles and up to 150 MW for freight rail vehicles (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

Active fire protection systems equipped on railway vehicles, in some cases, did not detect a slow increase in released thermal power. In the case of freight transport, many times these systems were not even installed (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

When focusing on specific threshold values related to the onset of fires, it is possible to identify a wide spectrum of external sources that may cause false alarms. The measurement of released thermal power (heat release rate - HRR) is strongly influenced by the emissivity of materials characterizing various surfaces of the train, depending on modifications, paint, dust, wear and tear, where this parameter value is usually not available and is quite variable depending on the spectral range and temperature range (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

On the other hand, considering criteria based on temperature measurement, attention must be paid to determining threshold values that take into account uncertainties in identifying the ignition location (internal part, external part) and the possibility that some parts of the train may function normally at higher temperatures (pantograph, brakes, engine, etc.). External factors affecting the detection of the ignition location can also include prolonged exposure of railway vehicles to sunlight, where the detection limits of released thermal power (HRR value) may be exceeded beyond acceptable limits (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

According to the basic concept of the proposed detection system, which should be installed along the railway track (before tunnel portals), it is necessary to note that the system must measure trains traveling at speeds ranging from 80 to 150 km/h, depending on the track, and for high-speed train sets, speeds up to 300 km/h. This last circumstance determines the complexity associated with data acquisition and processing, which can be time-consuming depending on the amount of data, algorithm complexity, and hardware capabilities (Cigolini, 2012; Ingason et al., 2015; Liu et al., 2010; Zumsteg et al., 2010).

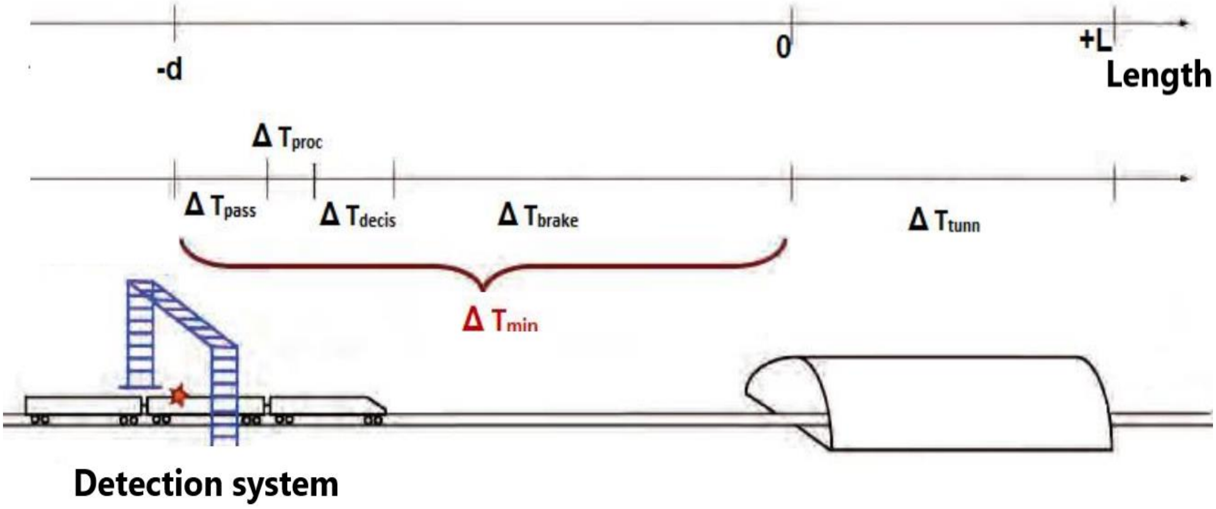

Fig.1 *Fire alarm system considering tunnel location*
Source: Cigolini, 2012

Description of the legend of figure no. 1:

- ΔTpass - reaction time for fire detection (seconds),
- ΔTproc - reaction time for evaluating the detection of physical/chemical variables (seconds),
- ΔTdecis - decision-making reaction time (seconds),
- ΔTbrake - braking time (seconds),
- ΔTtunn - time of passage through the tunnel tube (seconds) (Cigolini, 2012).

1.2 Detection Model

Fires in the initial stage that potentially endanger railway vehicles could be detected by devices installed directly in the railcar, under the car floor, or in the air conditioning system. The detection system itself can also be installed before entering the tunnel tube as a track detection monitoring system (Svnek, 2013; Cigolini, 2012; Hull et al., 2009; Sturm et al., 2012;).

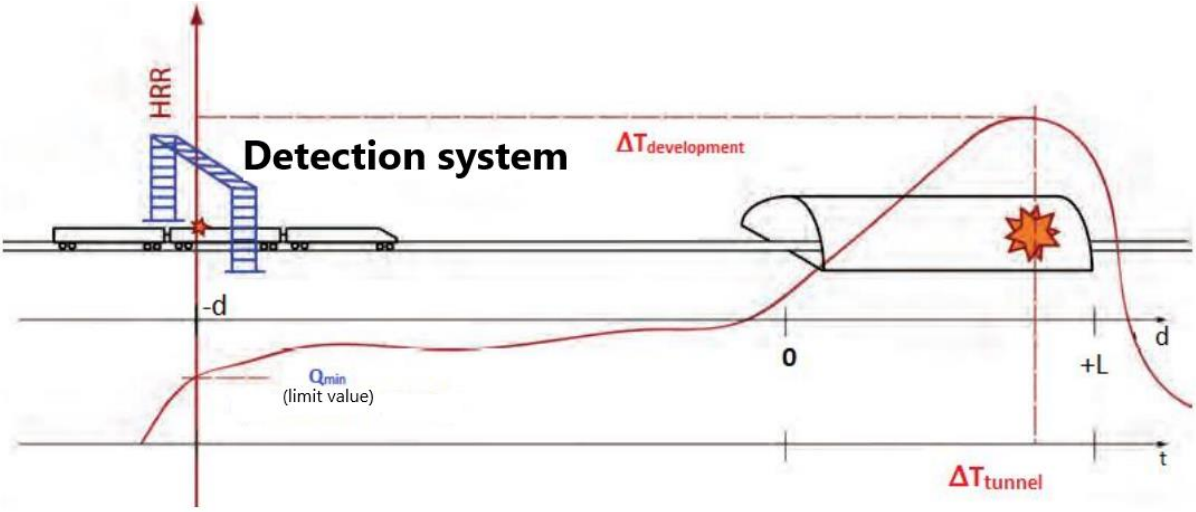

Fig.2 *Curve of Released Thermal Power in Relation to the Distance of the Tunnel Portal to the Detection System*
Source: Cigolini, 2012

Description of the legend of figure no. 2:

- ΔTdevelopments - fire development time (seconds),
- ΔTtunnel - time of passage through the tunnel tube (seconds),
- HRR - heat release rate value (MW),
- Qmin - minimum heat release rate value, the threshold for detection (MW) (Cigolini, 2012).

Considering that a train set usually carries more than 300 passengers in multiple cars (high-speed trains), various types of devices are used to ensure safety, providing better supervision and control over various events that may occur during its operation. Fire detection is crucial and can be considered a complex and challenging issue in railway tunnels (Svnek, 2013; Cigolini, 2012; Hull et al., 2009; Sturm et al., 2012;).

Fire detection in moving trains before the tunnel complex is more complicated inside the tunnel for the following reasons:

- Fire detection due to the speed of the train,
- Quality and reliability of the detection system,
- Detection needs to be performed at two levels,
- Detection must cover all sides of the train, including the undercarriage,
- Piston effect – forced air flow inside the tunnel caused by the moving train (Svnek, 2013; Cigolini, 2012; Hull et al., 2009; Sturm et al., 2012;).

There are three options for fire detection in moving trains before the tunnel portal:

- Fire detection within the train itself,
- Fire detection outside the train in the upper part of the train set,
- Fire detection under the moving train (Svnek, 2013; Cigolini, 2012; Hull et al., 2009; Sturm et al., 2012;).

1.3 Identifying fire in an approaching train

Assuming a train with 300 passengers is entering a tunnel, and applying a philosophy based on various fire elimination proposals, it is necessary to stop the train before the tunnel complex. What are the options for detecting a fire in an approaching train entering the tunnel? Answering this question requires consideration of the parameters for selecting the best detection system currently available:

- The optimal placement of detection devices before the train enters the tunnel,
- The speed of the train before entering the tunnel
- The duration it takes for the train to stop,
- The minimum time required for declaring an evacuation (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

Train Stoppage Time

An average freight train has a length of 400 to 700 meters, and to stop it when the train set, moving at a speed of 80 km/h, is approximately three minutes. From this, it can be inferred that the fire detection device should be placed at least 2 km from the tunnel portal (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

Types of Detection

In general, the following types of detection systems can be used:

- Detection systems within the train set,
- Point detection systems,
- High-sensitivity smoke detection system (HSSD System),
- Standard linear detection system,
- Optical fiber sensor system (Distributed Temperature Sensing - DTS),
- Detection under the train set (before entering the tunnel tube),
- Thermal imaging camera,
- Triple IR detector with a flame sensor (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

Detection based on reaction time:

- Point system (10-30 seconds),
- HSSD system (up to 10 seconds),
- Standard linear detection system (more than 60 seconds, depending on HRR and fire size),
- Optical system (10-60 seconds depending on fire size, max sampling time is 10 seconds),
- Combination of thermal imaging camera and IR system (up to 5 seconds),
- Triple IR detection system (1 second) (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

High Sensitivity Smoke Detection (HSSD) and Distributed Temperature Sensing Systems (DTS)

HSSD is a highly sensitive smoke detection system that uses a central detection unit to draw air through suction pipes into a sampling chamber. The system evaluates the presence of smoke particles in the air by detecting laser beams, allowing it to detect smoke before it is visible to the naked eye (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

DTS is an optical fiber system based on optoelectronic devices that measure temperature along the cable from optical fibers (up to 10 km). This system provides a continuous (or distributed) temperature profile along the length of the sensing cable rather than at discrete sensing points, which must be predetermined. The response time to generate an alarm event depends on the size of the fire in the tunnel (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

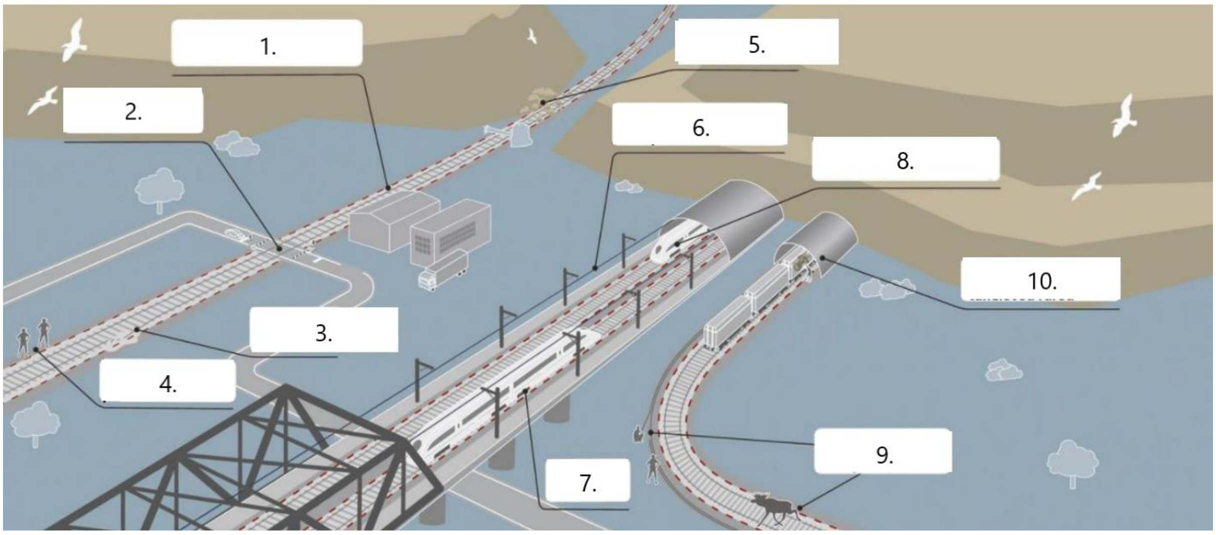

Fig.3 *Detection*
Source: Vouillamoz et al., 2006

Description of the legend of figure no. 3:
1. Temperature increase detection on the track,
2. Crossing detection,
3. Rail damage detection,
4. Warning for track workers,
5. Detection of natural hazards,
6. Pantograph short-circuit detection,
7. Wheel detection,
8. Detection of train speed, position, and direction,
9. Detection of human/animal movement,
10. Fire detection before the tunnel tube (Vouillamoz et al., 2006).

Triple IR3-HD Detector

Triple IR3-HD provides ultra-fast response, high performance, and reliable detection of all types of fires (visible and invisible). The detector offers high-resolution video of the fire event (Vouillamoz et al., 2006; Gill and Britz-McKibbin, 2020; Henelman et al., 1989).

Infrared Thermography

Infrared thermography, based on measuring the heat flow emanating from the external surface or uncovered parts of the train, can be challenging in the first phase of a fire scenario, where the fire is not easily visible to most thermal sensors or detectors due to its origin under protective surfaces (interior, sleeping car, etc.). Infrared thermography relies on detecting dangerous overheating and subsequent ignition based on the thermal flow measurement, typically influenced by significant uncertainty related to the unknown emissivity value of emitting materials (Cigolini, 2012; Tomaskova et al., 2022; Betus et al., 2023).

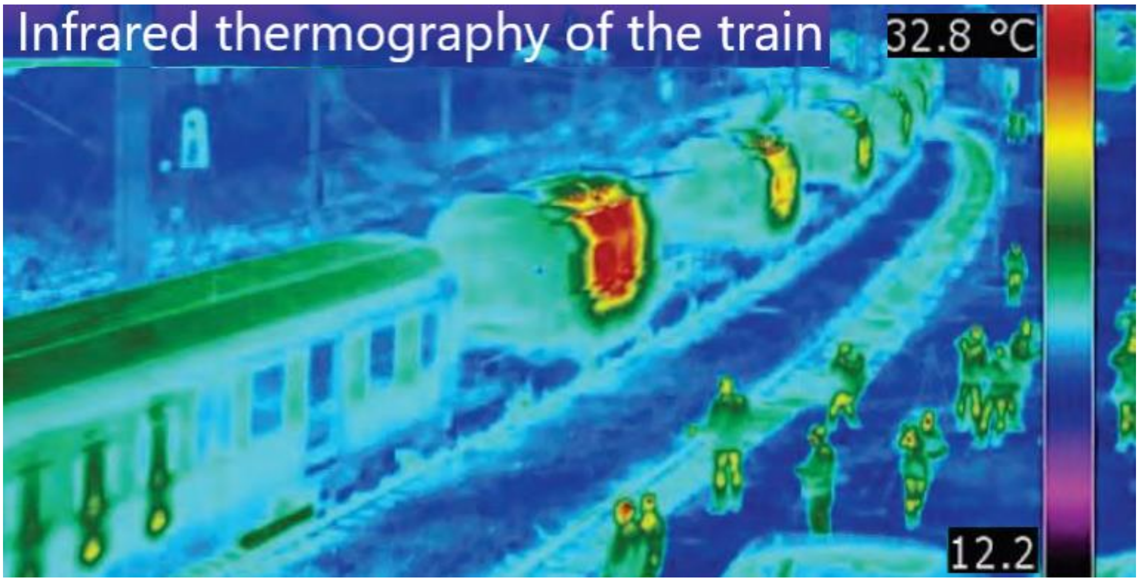

Fig.4 *Infrared thermography of the train*
Source: Cigolini, 2012

2 Results and discussion

The main challenge in external fire detection in an approaching train is identifying the fire when the train passes a control point several kilometers before the tunnel portal. Within various projects worldwide, nine fundamental fire detection systems have been investigated, representing five currently available detection technologies for tunnel applications (Beard and Carvel, 2012; Liu et al., 2010; Coca et al., 2010; Vouillamoz et al., 2006; E. 12127-1; EN ISO 9151).

Tab. 1 *Comparison of Individual Detection Systems*
Source: Liu et al., 2010

Technology	System Labeling	System Information
Linear Detection	D – 1L1	Fiber Optic Linear Detection System
	D – 2L2	Analog Linear Detection System
Optical Flame Detection	D – 3F1	IR3 Flame Optical Detector
Video Detection	D – 4C1	Visual Fire and Smoke Detection System
	D – 5C2	Visual Flame Detector
	D – 6C3	Visual Fire Detection System
Point Detection	D – 7H1	Thermal Detection Temperature System
	D – 8H2	Thermal Detector with Anticipated Speed
Air Sampling Detection	D – 9S1	Air Sampling System

As for the comparison of different systems, the response time of detection systems was examined before entering the tunnel portal at various longitudinal air flow velocities in the railway tunnel. For different design fires, the response times of detection systems are depicted in Figure No. 6, and the placement of these systems is shown in Figure No. 5 (Beard and Carvel, 2012; Liu et al., 2010; Coca et al., 2010; Vouillamoz et al., 2006).

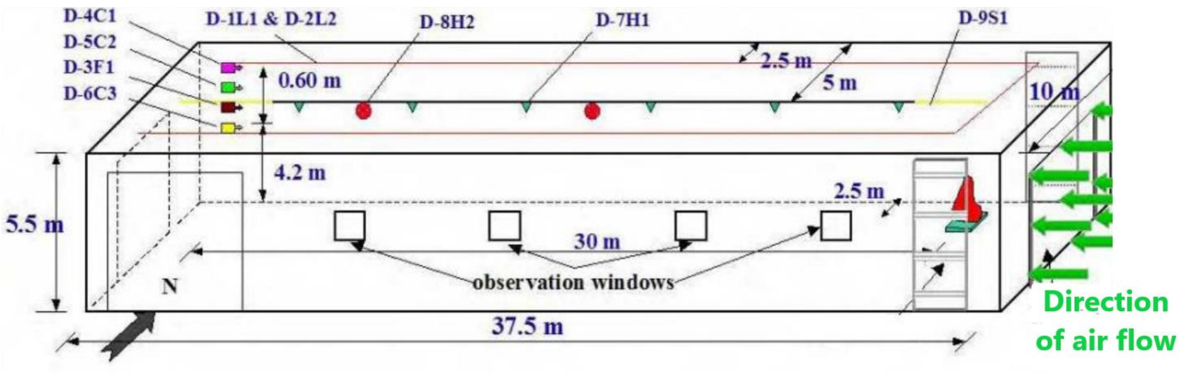

Fig.5 *Localization of Detection Systems*
Source: Ingason et al., 2015

From Figure No. 6, it can be inferred that linear detection systems had the fastest response time for all air flow speeds. Systems utilizing a field of view had issues with fire detection, and to address this problem, multiple types and combinations of detection systems can be employed. Video detection systems, including flame and smoke characteristic-based detection, demonstrated better performance in terms of fire detection, but they had more false alarms during environmental tests. Point detection systems for heat were unable to detect small fires with a released thermal power of up to 1,500 kW (Beard and Carvel, 2012; STN EN 469, 2021; Coca et al., 2010; Vouillamoz et al., 2006).

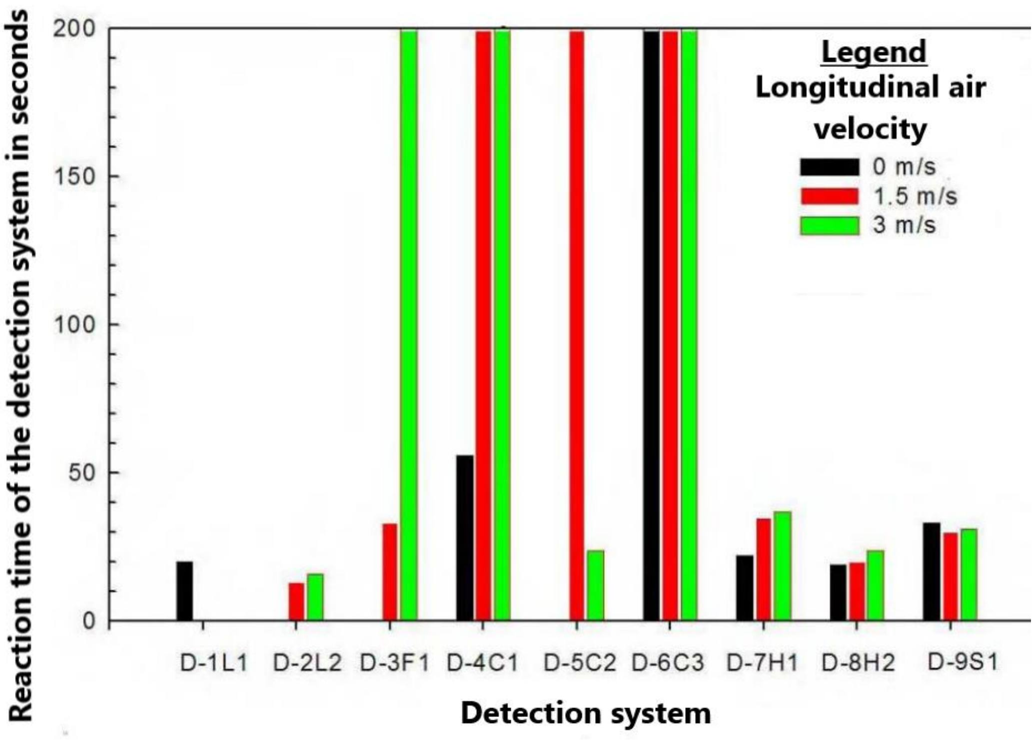

Fig.6 *Response time of detection systems in the designed fire for various air flow speeds*
Source: Vouillamoz et al., 2006

For most detection systems, it was challenging to respond to small fires under the vehicle. In this case, the flame and heat generated during the fire were shielded by the vehicle, making fire detection difficult. With an increase in the size of the fire, more detectors with shorter detection times responded to the fire. The response time of individual systems was delayed under air flow conditions. In the case of fires behind the vehicle, the response time of heat detection systems increased with the increasing air flow speed. For optical fire detectors and visual alarms, it was challenging to detect a fire under air flow conditions due to the inclination of flames towards the vehicle and disruption of the flame structure. In air flow conditions, the response time of the visual detection system was further delayed (STN EN ISO 13688, 2013; Liu et al., 2010; Coca et al., 2010; Vouillamoz et al., 2006).

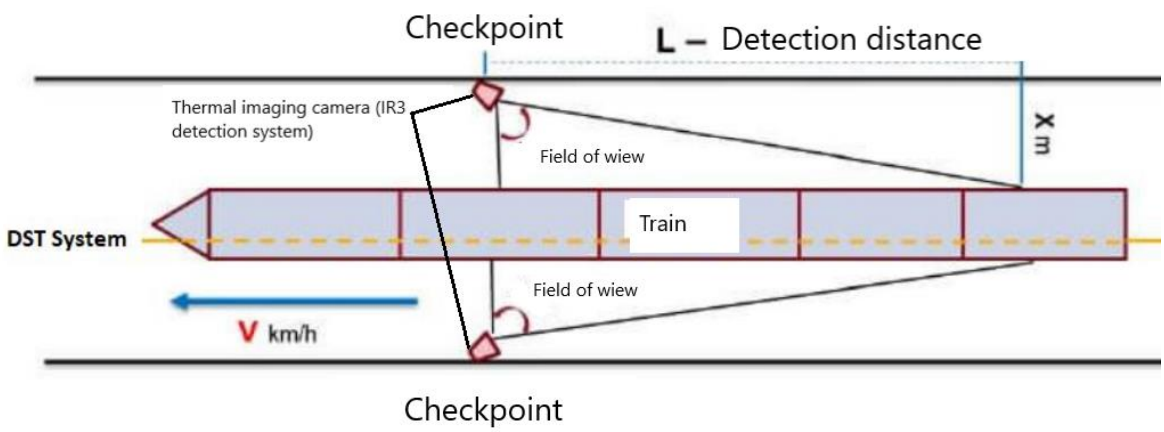

Fig.7 *Detection system design*
Source: Ingason et al., 2015

In the actual detection of fires before entering the tunnel portal, the combination of various types of detection systems appears to be the most effective, such as combining fiber optic linear detection system (DST) and IR 3 DH detection. It is necessary to exclude false alarms through the internal detection of individual physical and chemical accompanying phenomena during the onset of a fire, where the air sampling detection system seems to be the most suitable system (Beard and Carvel, 2012; Liu et al., 2010; Coca et al., 2010; Vouillamoz et al., 2006).

3 Conclusion

To handle the significant number of variables influencing the measurement process and the need to establish reliable criteria, it is essential to find a compromise between higher measurement reliability and appropriate data processing. Obtaining extensive field data (such as measuring temperature and heat flux on moving rail vehicles) and defining suitable correlations between warning variables can be a valid alternative solution compared to using expensive sensors. This may be the only way to determine which methods to implement.

By using appropriate algorithms for processing acquired data, simulating models of sensor principles, and employing suitable indicators of efficiency, it is possible to select the optimal technology for fire detection.

The fire detection system should provide an alarm declaration based on individual levels corresponding to the respective threshold levels. The highest level should trigger a direct (automatic) intervention in the security system and subsequent train stoppage. Direct intervention in the signaling system assumes the highest level of integrity necessary for the safety function (such as fire detection). However, any false alarm would have an unacceptable impact on operations. Therefore, one of the key activities in system development is to quantitatively assess the rate of false alarms and establish acceptable values through appropriate methods focused on minimizing systematic errors.

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