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The effect of ventilation in linear underground structures on the rate of fire spread in relation to existing linear fire spread indices in the Slovak Republic

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Abstract

The speed of fire spread and its development in linear underground works, both in operation and during the construction itself, as a mining work represents a significant safety problem. The current legislation of the Slovak Republic, which regulates the dimensioning of forces, means, material equipment, the amount of extinguishing agents and the overall concept of fire response in tunnels, is based on the guidelines from 2003. However, this legislation does not contain relevant provisions regarding the speed of fire spread in mining works, which of course include tunnels, since at the time of its creation; mining works were only in the construction or design phase. Furthermore, the legislation defines the intensity of the supply of extinguishing agent based on theoretical assumptions that do not correspond to the actual results of fire analysis. Experience from real events has shown a significant impact of tunnel ventilation parameters on the dynamics of the fire, its spread and the resulting requirements for intervention forces, resources and the amount of extinguishing agent.
Analyses of tunnel fires since 1 January 2015 indicate that the prescribed amount of extinguishing agent is underestimated. Current standards do not sufficiently take into account the influence of ventilation on fire development or optimal fire ventilation management strategies, which play a key role in the effectiveness of the response and speed of fire extinguishing. These findings point to the need to revise legislative regulations to increase fire extinguishing safety in the above-mentioned mining works, including tunnel structures, and to improve the efficiency of firefighting activities.

Keywords

ventilation, underground structures, mining constructions, tunnel, fire, fire spread rate

Introduction

The development of Slovakia's current transport infrastructure necessitates the construction of a greater number of highway, road, and railway tunnels. Experience from the operation of transport tunnels worldwide, especially those located near or within cities, highlights a high risk of extraordinary events—traffic accidents and collisions—which often result in fires, hazardous substance leaks, and, consequently, threats to human health and loss of lives (Quiju and Chenhui, 2023; Lin and Chien, 2021; Bartabto et al., 2014; Schubert et al., 2012).

The increased risk of extraordinary events in tunnels and at their entrances, particularly traffic accidents involving fires, hazards posed by escaping transported dangerous substances, and extraordinary events on roadways caused by natural disasters, floods, winter calamities, and landslides, is conditioned by the following factors:

- high traffic intensity and the transportation of large quantities of fuel by trucks, as well as the simultaneous transport of hazardous substances, as noted in Caroly's publication (Caroly et al., 2013; Hylender et al., 2022),
- the rapid release of hazardous substances, fire development, and intense smoke production in tunnel structures, along with high temperatures and the threat to a larger number of people who may be affected during the occurrence and progression of an extraordinary incident in a tunnel (Cassea, 2019; Margaryan et al., 2017),
- the complexity of deploying forces and resources, particularly the primary emergency response units of the integrated rescue system, including the Fire and Rescue Service, emergency medical services, territorial (local) rescue systems, civil protection units for regional needs, and units responsible for monitoring and determining the nature of hazardous substance leaks (Khattri et al., 2019; Alvear et al., 2013),
- traffic regulation and diversion measures to redirect vehicles away from the site of the extraordinary event (Dong et al., 2022),
- demarcation of the incident location to ensure a controlled and efficient response (Li and Ingason, 2018),
- evacuation and rescue strategies carried out by emergency medical service providers, where evacuation procedures may vary depending on the specific characteristics of the tunnel, as discussed in research conducted by Storm et al., Caliendo et al., and Yamamoto et al. (Caliendo and De Guglielmo, 2016; Storm and Celander, 2022; Caliendo et al., 2012; Yamamoto et al., 2018).

Negative findings and experiences from traffic accidents in tunnels confirm that the third challenge—the complexity of deploying forces and resources—is still inadequately addressed due to the specific conditions occurring within the tunnel tube, as highlighted by Gehandler in his publication (Gehandler, 2015).

Extraordinary events in tunnels are accompanied by the release of toxic gases, vapors, and mixtures, rapid loss of visibility on escape evacuation routes due to smoke accumulation, an increase in the heat release rate (HRR), a transition from linear to nonlinear airflow within the tunnel tube, and the impact of the ventilation system on the feasibility of rapid and effective rescue operations, as discussed by Boer et al. and Carvel et al. (Boer et al., 2005; Carvel et al., 2001; Li and Ingason, 2017).

These factors hinder access to the fire-affected tunnel tube and complicate the deployment of forces and resources, leading to the risk of rapid fire spread and endangering individuals inside the tunnel (Himoto, 2019; Hansen and Ingason, 2011).

In general, tunnels can thus be characterized as structures with an increased risk of extraordinary events (Oggero et al., 2006; Hansen and Ingason, 2012).

Materials and Methods

Deployment of forces and resources in an emergency situation

According to the applicable legal regulations, the term extraordinary event refers to a natural disaster, accident, catastrophe, Level II public health threat, mass influx of foreigners into the territory of the Slovak Republic, or a theoretical attack. The law characterizes natural disasters, accidents, and catastrophes based on their consequences, deviations from the established state, and the increase in impact (Law No. 42/1994).

PIARC defines an extraordinary event as an abnormal and unplanned incident, including accidents, that adversely affects the operation and safety of a tunnel, as illustrated in Figure 1 (PIARC, 2007).

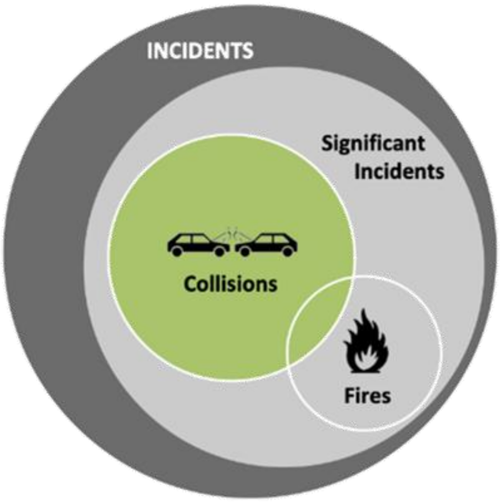

Fig. 1 Illustration of the relationship between incidents, significant incidents, collisions and fires (PIARC, 2007)

Calculation of the deployment of forces and resources under the conditions of the Slovak Republic

Under the conditions of the Slovak Republic, the determination of the forces and resources of the Fire and Rescue Service for mitigating the consequences of an extraordinary event is established in accordance with internal management acts, specifically the Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003.

According to Annex No. 2 (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003), the determination of forces and resources is based on the following factors:

- Free fire development time,
- Response time,
- Fire area calculation,
- Fire spread within the tunnel tube.

Free fire development time,

The free fire development time is the period during which the fire spreads without human intervention. The free spread time is determined according to the following formula:

$$t_{vr} = t_{sp} + t_{oh} + t_{do} + t_{br}, \quad (1)$$

Where:
t_{vr} - is the free fire development time (in minutes),
t_{sp} - is the time from the presumed origin of the fire to its detection (in minutes),
t_{oh} - is the time from detection to reporting the fire to the fire alarm center (in minutes),
t_{do} - is the time from the alarm being triggered to the arrival of the fire brigade at the scene (in minutes),
t_{br} - is the firefighting unit's deployment time (in minutes) (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

Response time

Response time is characterized as the time interval from the moment the call for intervention is received until the fire brigade arrives at the scene of the incident:

$$t_{do} = t_v + t_j \quad (2)$$

Where:
t_{do} - is the response time (in minutes),
t_v - is the dispatch time of the fire brigade (in minutes), where for a professional unit, the time is 1 minute,
t_j - is the travel time of the unit to the fire scene (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

Travel time is characterized as the time interval that elapses from the moment the fire and rescue unit departs from its base (station) until it reaches the incident site:

$$t_j = \frac{60 * L}{v_j} \quad (3)$$

Where:
t_j - is the travel time (in minutes),
L - is the distance to the fire scene,
v_j - is the average speed of the fire vehicles, which is 45 km/h (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

Fire area calculation

When calculating the fire area, an estimate or measurement based on available information is used, with the goal of determining the affected area as accurately as possible. This calculation is critical for the efficient management of the intervention, resource allocation, and assessment of the severity of the situation. For the fire area calculation, three variables are used:

- t_1 - is the ignition time, defined as the duration from 0 to 10 minutes,
- t_2 - is the free fire spread time (until the first attack lines are deployed) (in minutes), as shown in Figure 2 (calculated as - $t_2 = t_{vr} - t_1$) (4)
- t_3 - is the fire spread time from the deployment of the first attack lines to the fire's localization (in minutes), where:

$$t_3 = t_r + t_{br}^{Po} - t_{br}^{Pr} + (5 \div 15) \tag{5}$$

Where:

- t_r - is the time difference between the arrival of the first and last fire unit (in minutes),
- t_{br}^{Po} - is the arrival time of the last fire unit (in minutes),
- t_{br}^{Pr} - is the arrival time of the first fire unit (in minutes) (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

According to the above, the fire spreads from its origin at a certain linear speed. The distance of fire spread (fire radius) r is determined by the following formulas:

- during the ignition phase ($t_1 = 0 \div 10$) - $r = 0{,}5 * v_l * t_l$ (6)
- For burning times greater than ten minutes until the deployment of the first attack lines – $r = 5 * v_l + v_l * t_2$ (7)

Where:

- v_l - is the linear fire spread rate (m/min), which is provided in Table 1 of Annex No. 2 of the mentioned instruction (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

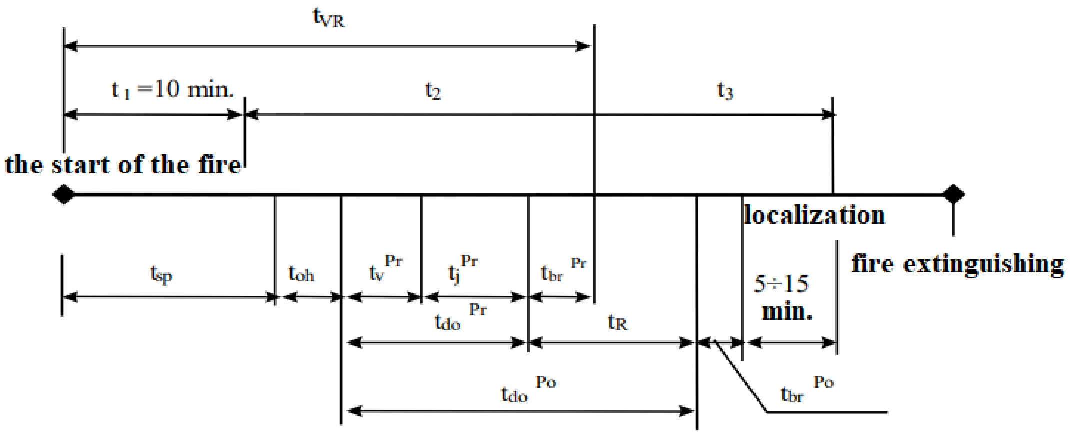

Fig. 2 Time course of fire development (Collection of instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003)

Fire spread within the tunnel tube

Fire spread in a tunnel has specific characteristics and dynamics, which are influenced by the enclosed environment and limited airflow. Fires in tunnels pose a high risk to people, infrastructure, and rescue operations. For the purpose of calculations, fire spread in the tunnel is characterized by a rectangular form, which is the frontal spread of the fire, constrained by constructions with fire resistance, at least on two sides (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

The calculation of fire area is characterized by:

$$S_p = n * a * l \tag{8}$$

Where:

- Sp - is the fire area (m²),
- n - is the number of directions of spread,
- a - is the width of the object (m),
- l - is the distance the fire has spread from the fire's origin (m) (Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003).

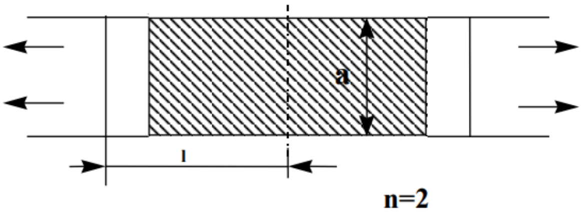

Fig. 3 Rectangular form of fire propagation.

It is important to emphasize that the linear fire spread rate is determined according to the relevant legislation, where for fires in a tunnel, specific conditions prevailing there, such as the rate of released heat flux, ventilation in the tunnel, smoke layer, and back-layering, are not taken into account. Instead, it is tabulated as follows: $v1$ - linear fire spread rate is 0.7 m/min, and the intensity of fire-fighting agent supply to the fire area is tabulated as Ip = 11.1 $l*m^{-2} * min^{-1}$.

Specifics of fires in a tunnel shaft

As Ignason characterizes, when the longitudinal ventilation speed in a tunnel is high, flames occur and spread only on the side of the fire source in the direction of airflow. In contrast, with low ventilation speed, flames occur both before and after the airflow from the fire source. In tunnel fires, the horizontal distance between the fire source and the flame tip is defined as the flame length (Ingason et al., 2005).

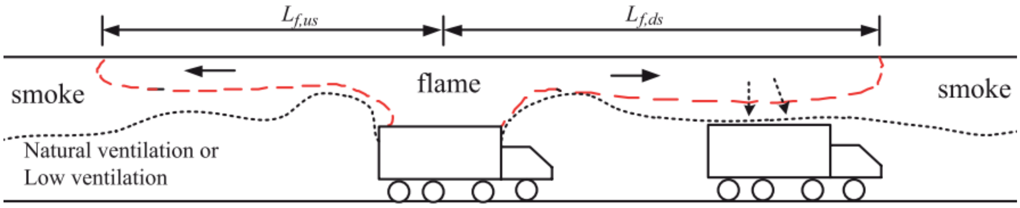

Fig. 4. Flame length in a tunnel fire under low ventilation rate or natural ventilation (source: elaborated by authors)

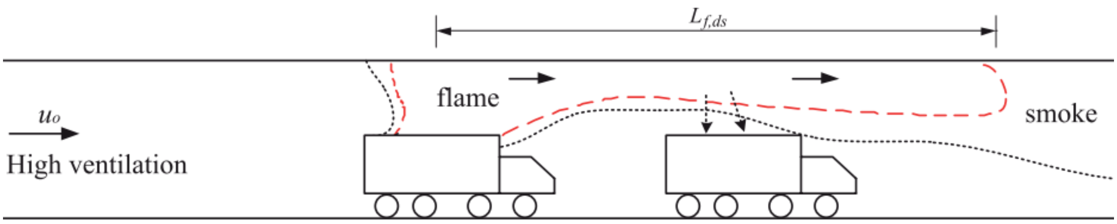

Fig. 5. Flame length in a large tunnel fire under high ventilation rate (source: elaborated by authors)

The flame length Lf, shown in Figures 4 and 5, as defined by Ingason, is the horizontal distance from the centerline of the fire source to the tip of the flame. Depending on the airflow velocity, it is necessary to understand the flame area Lf,ds, which is the area in the direction of airflow, and Lf,us, which is the area against the direction of ventilation or natural airflow (Ingason et al., 2005; Ingason, 2008).

The difference in this distance depends on the type of ventilation. In tunnels with low airflow, as defined in the Technical Conditions of the Ministry of Transport and Construction of the Slovak Republic, TP 049 Technical Conditions – Ventilation of Road Tunnels, the speeds are 1.0 – 1.5 m∗s-1. The flame length and its spread extend beyond the fire source, as shown in Figure 4. These flames are not symmetrically distributed because the speed of smoke formation from the fire source predominates over the low ventilation speeds (Ingason et al., 2005; TP 049).

In contrast, as defined by Ingason, in a tunnel fire with a high ventilation speed greater than 2.0 m∗s-1, the flame only occurs behind the fire source, as shown in Figure 5, compared to fires at low ventilation speeds

(Ingason et al., 2005; TP 049).

According to Li et al., the flame length is one of the most important parameters concerning the fire intensity and subsequent fire extinguishing (Li et al., 2022; Li and Ingason 2017; Wu and Bakar, 2000; Li et al., 2011).

Lönnermark and Ingason, based on their research on flame length in the direction of ventilation airflow, characterized the equation, where, unlike the calculations for deployment of forces and resources in the Slovak Republic (hereinafter only SR), they focused on HRR and the longitudinal airflow velocity. They defined Lf as the distance from the center of the fire, and the equation was characterized as follows:

$$L_{f=}0.02 * \left(\frac{\dot{Q}}{120}\right) * \left(\frac{u_0}{10}\right)^{-0,4} \qquad (9)$$

Where: *

- u_0 - is the longitudinal airflow velocity ($m*s^{-1}$),
- $\dot{Q}$ - is the value of the released heat flux (MW) (Lönnermark and Ingason, 2006).

Lönnermark and Ingason defined this equation based on the HGV-EUREKA 499 test, which is quite conservative since it does not consider the cross-section of the tunnel bore (Lönnermark and Ingason, 2006; Hu et al., 2006).

Lönnermark and Ingason studied flame lengths during the Runehamar tunnel test. The shape of the equation for flame length was estimated using the Alpert equation for ceiling flow temperatures, and uncertain coefficients were determined through regression analysis, which best fit the exponent of 0.8 for HRR (Ingason and Li, 2010; Oka et al., 1995).

Data from the Runehamar tests and some data from the Memorial tests were used in the analysis. The proposed equation was expressed as follows:

$$L_f = \frac{1370 * \dot{Q}^{0,8} * u_0^{-0,4}}{(T_f - T_0)^{\frac{3}{2}} * H^{\frac{3}{2}}} \qquad (10)$$

Where:

- Lf - is the horizontal length of the flames (m),
- $\dot{Q}$ - is the value of the released heat flux (kW),
- Tf - is the flame tip temperature at its end (K),
- T0 - is the ambient temperature (K),
- H - is the height of the tunnel (m) (Ingason and Li, 2010; Oka et al., 1995).

Both of these equations, whether equation 9 or equation 10, suggest that HRR, in addition to ventilation in the tunnel, is one of the key parameters in the fire dynamics within the tunnel and subsequently the overall situation at the fire site. This will determine the necessary deployment of forces and resources for the mitigation of this emergency event (Ingason and Li, 2010; Zeng et al., 2018).

Tf, as the flame temperature (K) chosen in this study, is 1.300 K, where the degree of this flame temperature is consistent with the experimental value of the turbulent diffusion flame (Bailey et al., 2002).

The estimated flame length based on the 500°C and 600°C contours is compared with the correlations (9) and (10) in Figure 6 as a function of the theoretical HRR at an airflow velocity of 2 m/s. Both the prediction and the two correlations show that for a given U0, an increase in HRR increases the flame length. As shown in Figure 7, for a theoretical HRR of 32 MW corresponding to a fire source size of $D = 4$ m, increasing the ventilation speed from 0.5 to 3.0 m/s reduces the flame length, in line with these two correlations. It appears that the predicted flame length seems to be somewhat sensitive to the definition of the visible flame shape (500 or 600°C) for a large-scale fire ($Q > 30$ MW) at low airspeed ($U_0 < 1.5$ m/s) due to significant temperature stratification. A good match between the prediction and correlation (equation (9)) is found for HRR under 30 MW when the visible flame shape is defined using the 600°C contour. For HRR above 30 MW, the quality of the match between the prediction and correlation (equation (13)) deteriorates, as the linear relationship between the flame length and HRR in correlation (9) does not account for the impact of the flame on the tunnel ceiling. While correlation (10) takes the tunnel height (H) into account for the flame's impact on the ceiling, the flame length depends on the flame temperature in a nonlinear relationship. The excessive prediction of flame length from correlation (10) points to the shortcomings of using a constant flame temperature regardless of changes in HRR and ventilation speed (Ingason and Li, 2010; Bailey et al., 2002; Zeng et al., 2018).

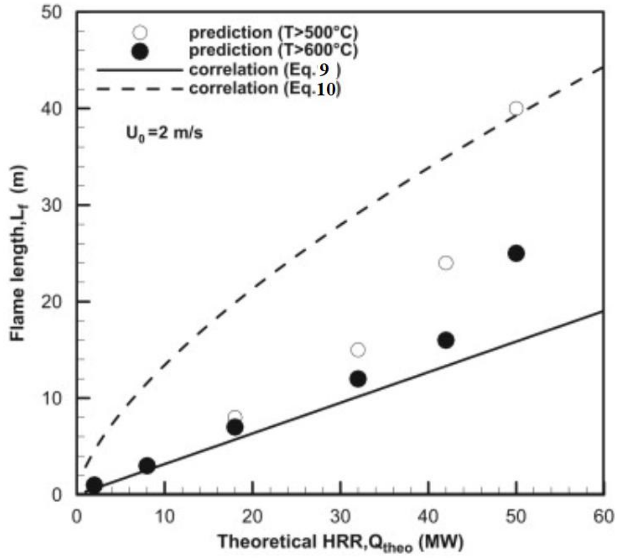

*Fig. 6. Evolutions of the flame length obtained from prediction and correlations as a function of the theoretical HRR at a wind velocity of 2 m*s⁻¹ (Bailey et al., 2002; Zeng et al., 2018)*

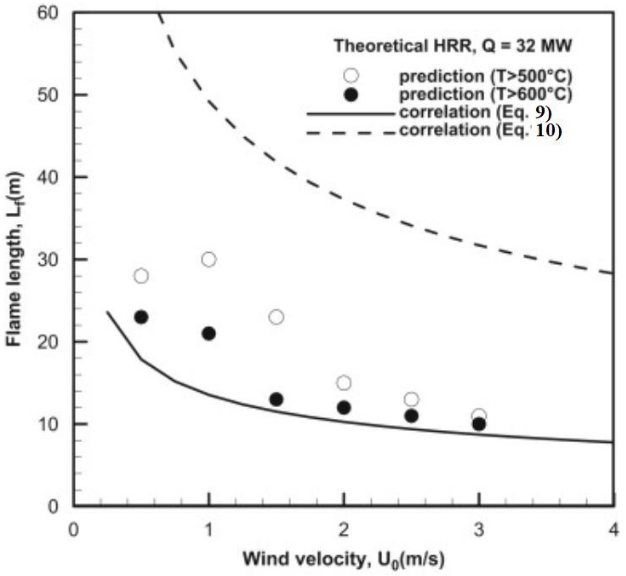

Fig. 7. Evolutions of the flame length obtained from prediction and correlations as a function of the wind velocity for a theoretical HRR of 32 MW (Bailey et al., 2002; Zeng et al,. 2018)

Characteristics of the fire in relation to the airflow velocity

As characterized by Li and Ingason, if the longitudinal ventilation speed is much lower than the critical speed, there are two parts to the horizontal flame areas (Figures 4 and 5). This means that at high ventilation speeds, flames occur only behind the fire. The point of this transition is therefore defined as the longitudinal speed at which there is no ceiling flame in front of the fire source. Accordingly, the "ventilation speed" for flame length is defined as the case with a ventilation speed greater than the transition point, and "low ventilation speed" corresponds to a ventilation speed less than the transition point (Li and Ingason, 2005).

Based on the study by Li et al. and Vauqelin et al., the ratio of the length of the rear layer to the height of the tunnel is related to the ratio of the ventilation speed to the critical speed for a given HRR. At high HRRs, the length of the rear layer depends only on the ventilation speed, regardless of the HRR. Note that the length of the flame against the airflow is part of the length of the rear layer, and fires with ceiling flames correspond only to high HRRs. Therefore, similar to the critical speed, the dimensionless ventilation speed at the transition point is defined as:

$$u_{tp} = \frac{u_{0*tp}}{\sqrt{g*H}} \tag{11}$$

Where:

- u_0 - is the longitudinal air velocity (m.s⁻¹),

- g - is the gravitational acceleration (m.s^{-2}),
- H - is the height of the tunnel (m),
- T_p - denotes the transition point (Li and Ingason, 2005).

And the dimensionless value of HRR was defined as:

$$Q = \frac{\dot{Q}}{\rho_0 * c_p * T_0 * g^{\frac{1}{2}} * H^{\frac{5}{2}}} \tag{12}$$

Where:

- $\dot{Q}$ - is the value of the released heat flux (kW),
- ρ_0 - is the density of the surrounding air (kg/m^3),
- c_p - is the specific heat capacity (kJ/kg K),
- T_0 - is the temperature of the surrounding air (K) (Li and Ingason, 2005).

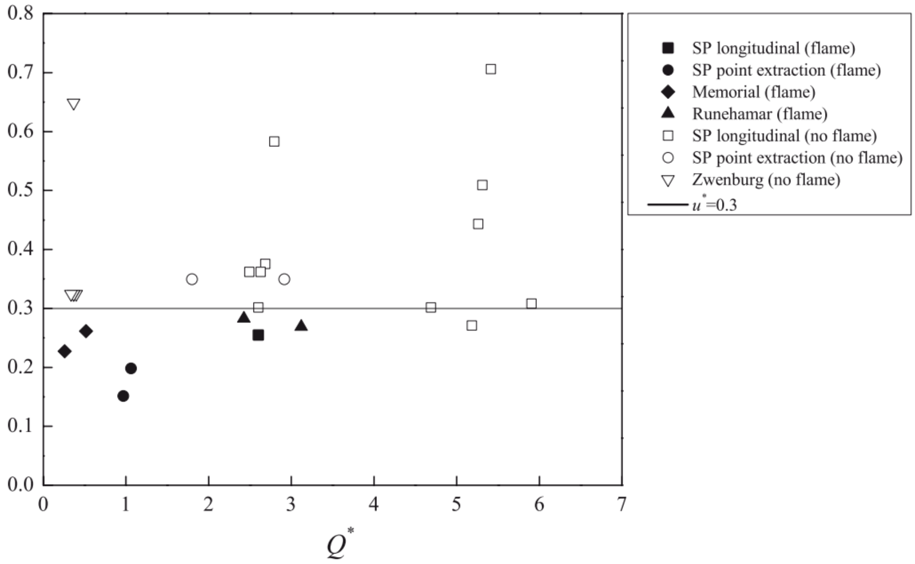

Fig. 8 Transition line between low ventilation rate and high ventilation rate (Li, Y., Z. and Ignason, H. 2005)

Figure 8 shows a graph of data where flame fires were recorded for different types of ventilation in relation to the airflow velocity. The analysis uses data from fire tests in longitudinal tunnels, point extraction tests conducted by Ingason and Li, as well as tests in the Memorial and Runehamar tunnels (Ingason and Li, 2010; Li and Ingason, 2005; Ingason and Li, 2011; Ingason et al., 2011).

The solid data points represent situations where flames were present on the countercurrent side during the tests, and the hollow data points indicate the absence of flames on the countercurrent side for various longitudinal speeds. The data shows a clear transition line between solid and hollow data points. This line can be expressed as: utp = 0.3 (13) (Ingason and Li, 2010; Li and Ingason, 2005; Ingason and Li, 2011; Ingason et al., 2011).

Given that the dimensionless critical speed approaches 0.43 for large fires, the results shown in Figure 8 suggest that the transition point corresponds to a longitudinal speed of approximately 70% of the critical speed. This must be considered when calculating the amount of water needed to extinguish the fire and the number of forces and resources required to handle the emergency (Ingason and Li, 2010; Li and Ingason, 2005; Ingason and Li, 2011; Ingason et al., 2011).

Based on the specific characteristics of the tunnel, the fire spread in the tunnel is not linear. Therefore, to predict fire spread, an estimate of the heat balance must be performed, considering the probable distribution of the fuel (Hu et al., 2006; Kunsch, 2002; Li and Ingason, 2017).

An important factor is time, specifically the ratio of peak operating intensity to total daily intensity, as this is when fuel in the tunnel space concentrates most rapidly. Time also plays a significant role in the free development period of the fire. The immediate environment of the primary fire is defined as the average distance affected by the flame, characterized by the average flame length (Kurioka, et al., 2003; Oka et al., 1995).

Results

Fires and accidents in tunnels present specific challenges in terms of safety, evacuation, and intervention. Tunnels are enclosed spaces with limited access, where even small incidents can quickly escalate. During the observed period, several events were recorded that required interventions by the Fire and Rescue Service. The following Table 1 defines the interventions in tunnels from February 2, 2015, to November 30, 2021, in the Slovak

Republic, which were used for this research.

Tab. 1. Emergency incidents in tunnels in Slovakia from 2015 to 2021 (source: elaborated by authors)

Date	t_{oh}	t_{do} and time and duration of intervention	Tunnel and length	Type of ventilation	Type of intervention	Activities of fire brigades	On-site specifics
02.02.2015	21:13	21:19 - 3.2. 2015 6:17	Branisko, 4.975	Partially related	Fire	Smoke, 2,500 l	None
29.03.2016	8:08	8:19 - 9:44	Branisko, 4.975	Partially related	Fire	Fire of a cargo vehicle, 2,000 l	None
31.12.2017	12:22	12:27 - 12:56	Bôrik, 999	Longitudinal	Fire	Smoke from the hood, 800 l	None
23.1.2020	6:58	7:04 - 8:47	Bôrik, 999	Longitudinal	Fire	Fire of a passenger vehicle, 2,000 l of water	None
30.11.2021	17:54	17:48	Prešov	Longitudinal	Fire	Smoke, 2,500 l	None

Table 2 illustrates the free fire spread time according to (1) based on the data from Table 1, the fire area according to (8), the required amount of extinguishing agent according to the Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003, where $Ip = 11.1\ l*m^{-2}*min^{-1}$, and the actual amount of extinguishing agent used.

Tab. 2. Comparison of tabulated firefighting agent consumption with actual firefighting agent consumption (source: elaborated by authors)

Date	T_{vr} (min)	S_p (m^2)	l (m)	Tunnel and length (m)	Type of ventilation	Firefighting agent consumption according to 1*	Actual firefighting agent consumption
2.2.2015	6	63	7.5	Branisko, 4.975	Partially related	699.3 l	2 500 l
29.3.2016	11	115.5	7.5	Branisko, 4.975	Partially related	1 282.1 l	2 000 l
31.12.2017	5	52.5	7.5	Bôrik, 999	Longitudinal	582.75 l	800 l
23.1.2020	6	63	7.5	Bôrik, 999	Longitudinal	699.3 l	2 000 l
30.11.2021	6	63	7.5	Prešov, 2.244	Longitudinal	699.3 l	2 500 l
1* - Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003							

As shown in Table 2, in most cases, the actual consumption of firefighting agents is significantly higher than what is suggested in the Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003. For this reason, it was proposed to use Equation (10) for recalculations, where, for the purposes of individual tunnels, the ventilation speed during fires was set at $1.0\ m*s^{-1}$, $1.5\ m*s^{-1}$, and $2.0\ m*s^{-1}$, as suggested by:

$$L_f = \frac{1370 * \dot{Q}^{0,8} * u_0^{-0,4}}{(T_f - T_0)^{\frac{3}{2}} * H^{\frac{3}{2}}} \tag{14}$$

Where:

- $\dot{Q}$ - is the released heat flux value (32 MW),
- Lf - is the horizontal flame length,
- T_f - is the flame tip temperature at its end (1,300 K),
- T_0 - is the ambient temperature (700 K),
- H - is the tunnel height (4.5 m for Branisko and 4.8 m for other tunnels),
- u_0 - is the longitudinal air velocity (1.0 m·s⁻¹; 1.5 m·s⁻¹; 2.0 m·s⁻¹) (TP 049; Bailey et al., 2002; Zeng et al., 2018).

For the purpose of determining the required amount of extinguishing agent for firefighting in a tunnel tube, we will rely on large-scale tests conducted by Ingason and Li, where the intensity of extinguishing agent application (Ip) was set between 4.77 $l*m^{-2}*min^{-1}$ and 22.5 $l*m^{-2}*min^{-1}$ (Wu and Bakar, 2000; Zeng et al., 2018; Schubert et al., 2012).

According to Slovak legislation, Ip is 11.1 $l*m^{-2}*min^{-1}$, which will be used for the purpose of designing the recommended ventilation (see Tables 3 to 7).

Tab. 3. Recommended Ventilation for Tunnel and Extinguishing Agent Consumption (source: elaborated by authors)

2.2.2015 - Branisko	Lf ($m*min^{-1}$)	Consumption of Extinguishing Agent Ip ($l*m^{-2}*min^{-1}$)	Tvr (min)	l (m)	Sp (m^2)	Quantity of Extinguishing Agent According to Lf (l)	Real Extinguishing Agent Consumption (l)
u_{01} = 1.0 ($m*s^{-1}$)	7.44	11.1	6	7.5	63	3 716	2 500 l
u_{02} = 1.5 ($m*s^{-1}$)	6.30	11.1	6	7.5	63	3 147	2 500 l
u_{03} = 2.0 ($m*s^{-1}$)	5.56	11.1	6	7.5	63	2 777	2 500 l

As shown in Table 3, fire ventilation can be divided into three philosophies for design scenarios. The first is the philosophy of maintaining low fire ventilation speeds, where the linear fire spread speed is 11.1 $m * min^{-1}$ according to outdated standards. While new design methods are based on speeds of 7.44 $m * min^{-1}$. The second philosophy is defined by medium fire ventilation speeds, which have a more significant impact on reducing water consumption for fire extinguishing. Subsequently, the last philosophy is based on achieving high fire ventilation speeds, where water consumption for fire extinguishing is significantly reduced compared to classical calculations. From the above, it can be seen that the fire ventilation philosophy and the ventilation itself already have a significant impact on the linear fire spread speed and the extinguishing agent consumption itself.

Table 4 describes the fire in the Branisko tunnel, where the fire area was 111.5 m2. The consumption of extinguishing agent for extinguishing the fire was 2 000 liters, and according to the aforementioned standard it should be 1 282 liters, which is quite underestimated. The data for individual fire ventilation speeds are as follows:

Tab. 4. Recommended Ventilation for Tunnel and Extinguishing Agent Consumption (source: elaborated by authors)

29.3.2016 - Branisko	Lf ($m*min^{-1}$)	Consumption of Extinguishing Agent Ip ($l*m^{-2}*min^{-1}$)	Tvr (min)	l (m)	Sp (m^2)	Quantity of Extinguishing Agent According to Lf (l)	Real Extinguishing Agent Consumption (l)
u_{01} = 1.0 ($m*s^{-1}$)	7.44	11.1	11	7.5	115.5	6 813	2 000 l
u_{02} = 1.5 ($m*s^{-1}$)	6.30	11.1	11	7.5	115.5	5 769	2 000 l
u_{03} = 2.0 ($m*s^{-1}$)	5.56	11.1	11	7.5	115.5	5 092	2 000 l

Also, as shown in Table 4, the decisive influence on the linear speed of fire spread is the fire ventilation, where uniform fire ventilation speeds are defined. The free fire propagation time also has a significant influence, where subsequently, as the fire ventilation speed increases, the amount of extinguishing agent for extinguishing the fire decreases. At high fire ventilation speeds, which can be used in a given case, the consumption of extinguishing agent approaches the actual consumption, in contrast to the original concept, which does not take into account the influence of ventilation on the spread of fire in underground mining structures.

Table 5 defines a fire in the Bôrik motorway tunnel, where the actual water consumption also differed significantly from the tabulated value of extinguishing agent consumption. The philosophies for fire ventilation in the event of a fire are also defined in the aforementioned Table 5, where at higher fire ventilation rates the water consumption for fire extinguishing approaches the actual consumption.

Tab. 5 Recommended Ventilation for Tunnel and Extinguishing Agent Consumption (source: elaborated by authors)

31.12.2017 Bôrik	Lf (m∗min^{-1})	Consumption of Extinguishing Agent Ip (l∗m^{-2}∗min^{-1})	Tvr (min)	l (m)	Sp (m^2)	Quantity of Extinguishing Agent According to Lf (l)	Real Extinguishing Agent Consumption (l)
u_{01} = 1.0 (m∗s^{-1})	7.44	11.1	5	7,5	52.5	3 079	800
u_{02} = 1.5 (m∗s^{-1})	6.30	11.1	5	7,5	52.5	2 622	800
u_{03} = 2.0 (m∗s^{-1})	5.56	11.1	5	7,5	52.5	2 314	800

Underestimated consumption of extinguishing agent when extinguishing a fire in linear underground works, which include tunnels, may result in the fire not being extinguished, subsequently requiring the call of forces and means for extinguishing from the nearest fire station, which increases the time for the fire to spread freely.

Table 6 also shows a fire in the Bôrik motorway tunnel, where the fire area at the time of the fire brigade's arrival was 63 m2. At individual fire speeds of the ventilation device, the value of the extinguishing agent consumption was close to the real consumption, unlike the proposed table value, where the consumption was significantly lower. Specifically, it was only around 700 liters of extinguishing agent, where the real consumption was at the level of 2 000 liters, which is significantly underestimated.

Tab. 6 Recommended Ventilation for Tunnel and Extinguishing Agent Consumption (source: elaborated by authors)

23.1.2020 Bôrik	Lf (m∗min^{-1})	Consumption of Extinguishing Agent Ip (l∗m^{-2}∗min^{-1})	Tvr (min)	l (m)	Sp (m^2)	Quantity of Extinguishing Agent According to Lf (l)	Real Extinguishing Agent Consumption (l)
u_{01} = 1.0 (m∗s^{-1})	7.44	11.1	6	7.5	63	3 716	2 000
u_{02} = 1.5 (m∗s^{-1})	6.30	11.1	6	7.5	63	3 147	2 000
u_{03} = 2.0 (m∗s^{-1})	5.56	11.1	6	7.5	63	2 777	2 000

Table 6 also shows a fire in the Bôrik motorway tunnel, where the fire area at the time of the fire brigade's arrival was 63 m^2. At individual fire speeds of the ventilation device, the value of the extinguishing agent consumption was close to the real consumption, unlike the proposed table value, where the consumption was significantly lower. Specifically, it was only around 700 liters of extinguishing agent, where the real consumption was at the level of 2 000 liters, which is significantly underestimated.

Table 7 defines a fire in the Prešov motorway tunnel, where one of the highest quality ventilation systems has already been dimensioned. Calculations based on individual ventilation strategies also show a significant impact on both the linear speed of fire spread and the consumption of extinguishing agent. The consumption shown, taking into account the individual tunnel ventilation philosophies demonstrates a significant impact on fire extinguishing and is also close to the real consumption of extinguishing agent.

The actual consumption of extinguishing agent in the above case was 2 500 liters of water. For individual strategies for fire ventilation, the consumption at higher fire ventilation speeds is at the level of 2 777 liters of water, which is close to the actual consumption. On the contrary, for classic calculations that do not take into account ventilation in tunnels, it is at the level of 699 liters of water, which is significantly underestimated.

This underestimation can have catastrophic consequences, as fire trucks carry different volumes of extinguishing agent for extinguishing a fire and when applying classic standards, they may not be sufficient to eliminate the fire. For this reason, it is necessary to subsequently send additional units, which results in the spread of the fire.

Tab. 7 Recommended Ventilation for Tunnel and Extinguishing Agent Consumption (source: elaborated by authors)

30.11.2021 Prešov	Lf ($m*min^{-1}$)	Consumption of Extinguishing Agent Ip ($l*m^{-2}*min^{-1}$)	Tvr (min)	l (m)	Sp (m^2)	Quantity of Extinguishing Agent According to Lf (l)	Real Extinguishing Agent Consumption (l)
u_{01} = 1.0 ($m*s^{-1}$)	7.44	11.1	6	7.5	63	3 716	2 500
u_{02} = 1.5 ($m*s^{-1}$)	6.30	11.1	6	7.5	63	3 147	2 500
u_{03} = 2.0 ($m*s^{-1}$)	5.56	11.1	6	7.5	63	2 777	2 500

As is evident from the tables, the flame speed in the direction of ventilation increases due to the ventilation rate, which also impacts the required amount of extinguishing agent, especially when considering the actual response times of firefighting equipment to the fire origin. The proposed ventilation rate in the event of a fire also influences the situation within the tunnel itself. For instance, the minimum rate of u_0 = 1.0 m/s may not be sufficient for the tunnel fire situation, as confirmed by the calculations. Higher velocities, such as u_0 = 2.0 m/s, will significantly affect the fire spread rate in the tunnel and the required extinguishing agent, as demonstrated by actual extinguishing agent consumption during tunnel fires.

Discussion

Ventilation is one of the major measures at underground structure designer's disposal to mitigate the effect of fire and smoke, to aid evacuation, rescue services, and firefighting in a tunnel fire. Fires in linear underground structures as tunnels are can have severe consequences. Examples are the BAKU metro tunnel fire of 1995 (289 fatalities and 265 injuries), the Mont Blanc road tunnel fire of 1999 (all 39 occupants died) and the Daegu subway tunnel fire of 2003 (over 192 fatalities). Life safety is not naturally guaranteed in tunnels, neither is structural stability or traffic continuation. Therefore, a comprehensive risk assessment of existing and new designs is indispensable.

The proposals for the intensity of the supply of extinguishing agent when extinguishing fires are based, as already explained, on the standards and fire tests from 2003. In the mentioned period, there was no concept of solving the elimination of fires in underground mine workings, where there are specific conditions for the development and spread of fire.

The influence of ventilation on the speed of fire spread is an important parameter and, on the other hand, it also has a significant impact on the result of extinguishing the fire.

From the research of fires in underground mine workings, ventilation and ventilation speed are important aspects for extinguishing the fire. The strategies for fire ventilation themselves, as mentioned in the individual calculations, show that there is a limit where the influence of ventilation has a positive effect on the speed of fire intervention and also on the amount of extinguishing agent.

Also, as stated in the scientific work of Sturm et al. (Sturm et al., 2017), who focused on ventilation philosophies and the regulation of combustion products, ventilation is an important aspect for solving fire scenarios in linear underground works, where individual philosophies have an impact on the very stratification of hot combustion products. This is also proven by the calculations of the effect of ventilation during firefighting work, where speeds of 2 meters per second achieve excellent results in solving individual fire extinguishing scenarios with regard to the consumption of extinguishing agent.

Conclusion

The primary goal of fire ventilation of underground line works is to ensure the safe evacuation and rescue of people. Consequently, the ventilation system of underground works, which include tunnels, must enable effective intervention by fire brigades. In general, it can be stated that the design and management of ventilation systems in tunnel tubes in the event of an emergency with a fire outbreak is an extremely sensitive issue, influenced by a whole system of factors. The way the ventilation system is controlled during an emergency with a fire outbreak is an individual matter that can be determined based on the assessment of all predictable event variants and influencing factors.

The basic values for the decision-making process (whether to activate ventilation immediately after a fire outbreak) are the direction and speed of airflow inside the tunnel tubes and at the tunnel portals (critical variables). It is not possible to determine a general speed and direction of ventilation for all tunnels, as the effect of ventilation can be negative if people are present in areas with smoke.

Based on practical experience and calculations, the following conclusions can be made:

- In the case of very small fires, especially during the ignition phase, the intensity of ventilation affects the reduction of the immediate heat release rate (HRR),
- Increasing the ventilation speed leads to a reduction in HRR and a decrease in the water required for firefighting,
- When sizing and designing forces and resources for dealing with the aftermath of an emergency fire event, these forces and resources must be adapted to the specific ventilation system, where different speeds significantly affect the fire situation,
- The development of a fire in a tunnel tube must take into account the speed of flame spread in the direction of airflow, where the spread rate in tunnels is entirely different and many times higher than the linear fire spread rate under laboratory conditions, as stated in Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003,
- Based on the results, it is necessary to ensure a significantly larger volume of extinguishing agents for firefighting units, which has been proven in real fires,
- Firefighting plans for tunnels must be designed, where ventilation in tunnel tubes will have a significant impact on the forces and resources required.

References

Alvear, D., Abreu, O., Cuesta, A., Alonso, V. (2013). Decision support system for emergency management: Road tunnels. Tunneling and Undrerground Space Technology, 34, 13-21. https://doi.org/10.1016/j.tust.2012.10.005.

Bailey, J., L., Forney, G., P., Tatem, P., A., Jones, W., W. (2002) Development and validation of corridor flow submodel for CFAST. Journal of Fire Protection Engineering, 12 (3), 139 – 162. DOI: 10.1177/10423910260620473.

Bartabto, L., Cascetta, F., Musto, M., Rotondo, G. (2014). Fire safety investigation for road tunnel ventilation systems – An overview. Tunnelling and Underground Space Technology, 43, 253 - 256. http://dx.doi.org/10.1016/j.tust.2014.05.012.

Boer, L., C., van Zanten D., W. (2005). Behaviour on tunnel fire. Springer Berlin Heidelberg, Berlin, Heidelberg, 91–98. http://dx.doi.org/10.1007/978-3-540-47064-9_8.

Carvel, R., O., Beard, A., N., Jowitt, P., W, Drysdale, D. D. (2001) Variation of heat release rate with forced longitudinal ventilation for vehicle fires in tunnels. Fire Safety Journal, 36(6), 569–596. http://dx.doi.org/10.1016/S0379-7112(01)00010-8.

Collection of Instructions of the Presidium of the Fire and Rescue Service of the Slovak Republic No. 39/2003.

Cassea, Ch., Carolyb, S. (2019). Analysis of critical incidents in tunnels to improve learning from experience. Safety science, 116, 222 – 230. https://doi.org/10.1016/j.ssci.2019.03.015.

Caliendo, C., De Guglielmo, M., L. (2016). Quantitative Risk Analysis on the Transport of Dangerous Goods Through a Bi-Directional Road Tunnel. Risk Analysis an international journal, 37, 116 - 129. https://doi.org/10.1111/risa.12594.

Caliendoa, C., Ciambellib, P., De Guglielmoa, M., L., Meob, M., G., Russob, P. (2012). Simulation of People Evacuation in the Event of a Road Tunnel Fire. Procedia - Social and Behavioral Sciences, 53, 178 - 188. https://doi.org/10.1016/j.sbspro.2012.09.871.

Caroly, S., Kouabenan, D.R., Gandit, M. (2013). Analysis of danger management by highway users confronted with a tunnel fire. Saf. Sci, 35 – 46. https://doi.org/10.1016/j.ssci.2013.06.006.

Dong, S., Wang, K., Jia, C. (2022). A Study on the Influence of Rail Top Smoke Exhaust and Tunnel Smoke Exhaust on Subway Fire Smoke Control. Sustainability, 14, 4049. https://doi.org/10.3390/su14074049.

Gehandler, J. (2019). Road tunnel fire safety and risk: a review. Fire Science Reviews, 4(2), 114 – 123. https://doi.org/10.1186/s40038-015-0006-67of.

Hylender, J., Saveman, B., Gyllencreutz, L., Westman, A. (2022). Time-efficiency factors in road tunnel rescue as perceived by Swedish operative personnel – an interview study. International Journal of Emergency Services, 11(2), 312 - 324. https://doi.org/10.1108/IJES-03-2021-001.

Himoto, K. Quantification of cross-wind effect on temperature elevation in the downwind region.

Hansen, R., Ingason, H. (2011). An engineering tool to calculate heat release rates of multiple objects in underground structures. Fire Safety Journal, 46(4), 194 – 203. http://dx.doi.org/10.1016/j.firesaf.2011.02.001.

Hu, L., H., Huo, R., Peng, W., Chow, W., K.; Yang, R., X. (2006). On the maximum smoke temperature under the ceiling in tunnel fires. Tunnelling and Underground Space Technology, 21, 650 – 655. https: //doi:10.1016/j.tust.2005.10.003.

Hansen, R., Ingason, H. (2012). Heat release rates of multiple objects at varying distances. Fire Safety Journal, 52(0), 1 – 10. http://dx.doi.org/10.1016/j.firesaf.2012.03.007.

Ingason, H. (2008). State of the Art of Tunnel Fire Research. Fire Safety Science, 9, 33 – 48. http://dx.doi.org/10.3801/IAFSS.FSS.9-33.

Ingason, H. (2005). Tunnel Fire Dynamics. Springer Science Business Media. New York, 509 pgs. DOI: 10.1007/978-1-4939-2199-7_9.

Ingason, H., Li, Y., Z. (2010). Model scale tunnel fire tests with longitudinal ventilation. Fire Safety Journal, 45, 371 – 384. https://doi.org/10.1016/j.firesaf.2010.07.004.

Ingason, H., Li, Y., Z. (2011). Model scale tunnel fire tests with point extraction ventilation. Journal of Fire Protection Engineering, 21(1), 5 – 36. https://doi.org/10.1016/j.firesaf.2010.07.004.

Ingason, H., Lönnermark, A., Li, Y., Z. (2011). Runehamar Tunnel Fire Tests. SP Technicial Research Institute, Borås, Sweden. https://doi.org/10.1016/j.firesaf.2014.11.015.

Jamamoto, K., Sawaguchi, Y., Nishiky, S. (2018) Simulation of Tunnel Fire for Evacuation Safety Assessment. MDPI Journal, 4(2), 12. https://doi.org/10.3390/safety4020012.

Khattri, S.K., Log, T., Kraaijeveld, A. (2019). Tunnel Fire Dynamics as a Function of Longitudinal Ventilation Air Oxygen Content. Sustainability, 11, 203. https://doi.org/10.3390/su11010203.

Kurioka, H., Oka, Y., Satok, H., Sugawa, O. (2003). Fire properties in near field of square fire source with longitudinal ventilation in tunnels. Fire Safety Journal, 38 (4). 319 – 340. https://doi.org/10.1016/S0379-7112(02)00089-9.

Kunsch, J., P. (2002). Simple model for control of fire gases in a ventilated tunnel. Fire Safety Journal, 37(1). 67 – 81. DOI: 10.1016/S0379-7112(01)00020-0.

Law No. 42/1994 Coll. on Civil Protection of the Population, as amended.

Li, J., Liu, W., Li, F. Y., Chow, W., K., Chow, C., L., Cheng, C., H. (2022). Scale modelling experiments on the effect of longitudinal ventilation on fire spread and fire properties in tunnel. Tunnelling and Underground Space Technology, 130, 104725. https://doi.org/10.1016/j.tust.2022.104725.

Lönnermark, A., Ingason, H. (2006). Fire Spread and Flame Length in Large-Scale Tunnel Fires. Fire Technology, 42(4), 283-302. DOI: 10.1007/s10694-006-7508-7.

Li, Y., Z., Ignason, H. (2010). Study of critical velocity and back-layering length in longitudinally ventilated tunnel fires. Fire Safety Journal, 45, 361–370. https://doi.org/10.1016/j.firesaf.2010.07.003.

Li, Y., Z., Lei, B., Ingason, H. (2011). The maximum temperature of buoyancy-driven smoke flow beneath the ceiling in tunnel fires. Fire Safety Journal, 46(4), 204 – 210. https://doi.org/10.1016/j.firesaf.2011.02.002.

Li, Y., Z., Ingason, H. (2017). Effect of cross section on critical velocity in longitudinally ventilated tunnel fires. Fire Safety Journal, 91, 303 – 311. DOI: 10.1016/j.firesaf.2017.03.069.

Lin, L., Ch., Chien, F., Ch. (2021). Lessons learned from critical accidental fires in tunnels. Tunnelling and Underground Space Technology, 113, 103944. https://doi.org/10.1016/j.tust.2021.103944.

Li, Y., Z., Ingason, H. (2018). Overview of research on fire safety in underground road and railway tunnels. Tunnelling and Underground Space Technology, 81, 568 – 589.

Margaryan, A., Littlejohn, A., Stanton, A., N. (2017). Research and development agenda for Learning from Incidents. Safety science, 99, 5 – 13. http://dx.doi.org/10.1016/j.ssci.2016.09.004.

Oggero, A., Darbra, R. M., Muñoz, M., Planas, E., Casal, J. (2006). A survey of accidents occurring during the transport of hazardous substances by road and rail. Journal of Hazardous Materials, 133(1–3), 1–7. http://dx.doi.org/10.1016/j.jhazmat.2005.05.053.

Oka, Y., Atkinson, G., T. (1995). Control of smoke flow in tunnel fires. Fire Safety Journal, 25(4), 305 –322. DOI: 10.1016/0379-7112(96)00007-0.

PIARC (2007) Integrated approach to road tunnel safety (2007R07). World Road Association. La Défense cedex, France.

Quiju, L., Chenhui, L. (2023). Exploration of road closure time characteristics of tunnel traffic accidents: A case study in Pennsylvania, USA. Tunnelling and Underground Space Technology, 132, 104894. https://doi.org/10.1016/j.tust.2022.104894.

Schubert, M., Høj, N., P., Ragnøy, A., Buvik, H. (2012). Risk Assessment of Road Tunnels using Bayesian Networks. Procedia - Social and Behavioral Sciences, 48, 2697 – 2706. DOI: 10.1016/j.sbspro.2012.06.1239.

Storm, A., Celander, E., A. (2022). Field evacuation experiment in a long inclined tunnel. Fire Safety Journal, 132, 103640. https://doi.org/10.1016/j.firesaf.2022.103640.

Sturm, P., Beyer, M., Rafiei, M. (2017). On the Problem of Ventilation Control in Case of a Tunnel Fire Event. Case Studies in Fire Safety, 7, 36-43. DOI: 10.1016/j.csfs.2015.11.001.

The technical conditions of the Ministry of Transport and Construction of the Slovak Republic, Road Transport and Civil Engineering Section, TP 049 - TECHNICAL CONDITIONS FOR VENTILATION OF ROAD TUNNELS.

Vauqelin, O., Telle, D. (2005). Definition and experimental evaluation of the smoke "confinement velocity" in tunnel fires. Fire Safety Journa, 40, 320 - 330. https://doi.org/10.1016/j.firesaf.2005.02.004.

Wu, Y., Bakar, M., Z. (2000). Control of smoke flow in tunnel fires using longitudinal ventilation systems – a study of the critical velocity. Fire Safety Journal, 35(4), 363 – 390. DOI: 10.1016/S0379-7112(00)00031-X.

Zeng, Z., Xiong, K., Lu, X., Weng, M., Liu, F. (2018). Study on the smoke stratification length under longitudinal ventilation in tunnel fires. International Journal of Thermal Sciences, 132, 285 – 295. DOI: 10.1016/j.ijthermalsci.2018.05.038.