JEDNOROZMERNÁ ANALÝZA APLIKOVANA PRI NÁVRHU VETRANIA DIAĽNIČNÉHO TUNELA

MONODIMENSIONAL TECHNIQUE APPLIED TO THE VENTILATION DESIGN FOR HIGHWAY TUNNEL

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ABSTRAKT

Príspevok prezentuje analýzu diaľničného tunela s dvoma paralelnými rúrami a hybridným ventilačným systémom s dvomi zónami odsávania dymu, jednou s jediným bodom odsávania a druhou realizovanou so systémom klapiek v medzistrope. Núdzové vetranie je pozdĺžne v prvom segmente a polopriečne v druhom.

1D analýza umožňuje vziať do úvahy faktory, ktoré ovplyvňujú účinnosť ventilácie, ako sú teploty vzduchu a stien tunela, sklon tunela, vztlak vyvolaný zohrievaním dymu a vzduchu, miestne a distribuované tlakové straty, vývoj rýchlosti uvoľňovania tepla, charakteristické krivky ventilátorov a parametre prúdových ventilátorov.

Simulácie poskytujú hodnoty prúdenia vzduchu a teplôt vo vnútri tunelov a vo vnútri vetracích kanálov v rôznych časových krokoch po celú dobu trvania simulácie.

V 1D modeli sú tunely zobrazené ako vetvy charakterizované geometrickými, tepelnými a hydrodynamickými parametrami. Každá vetva je definovaná medzi dvoma uzlami. Uzly sú umiestnené na vonkajšej hranici (na portáloch a na konci úsekov vetrania) a na prípojných bodoch (medzi šachtou a tunelmi, medzi tunelmi, klapkami a medzistropom).

Tento prístup vytvára významné zníženie výpočtových zdrojov potrebných pre model. Okrem toho sú tieto techniky schopné riešiť zložité tunelové a vetracie systémy a zároveň zaručiť presné znázornenie oblasti, kde sa požiar vyvíja. V článku je jednorozmerný prístup aplikovaný na analýzu požiarnych scenárov v diaľničnom tuneli.

ABSTRACT

The present paper shows the analysis of the Višňové Tunnel, an highway tunnel with two parallel tubes and a hybrid ventilation system with two zone of smoke extraction, one with a single point of extraction and the second one realized with a system of dampers and false

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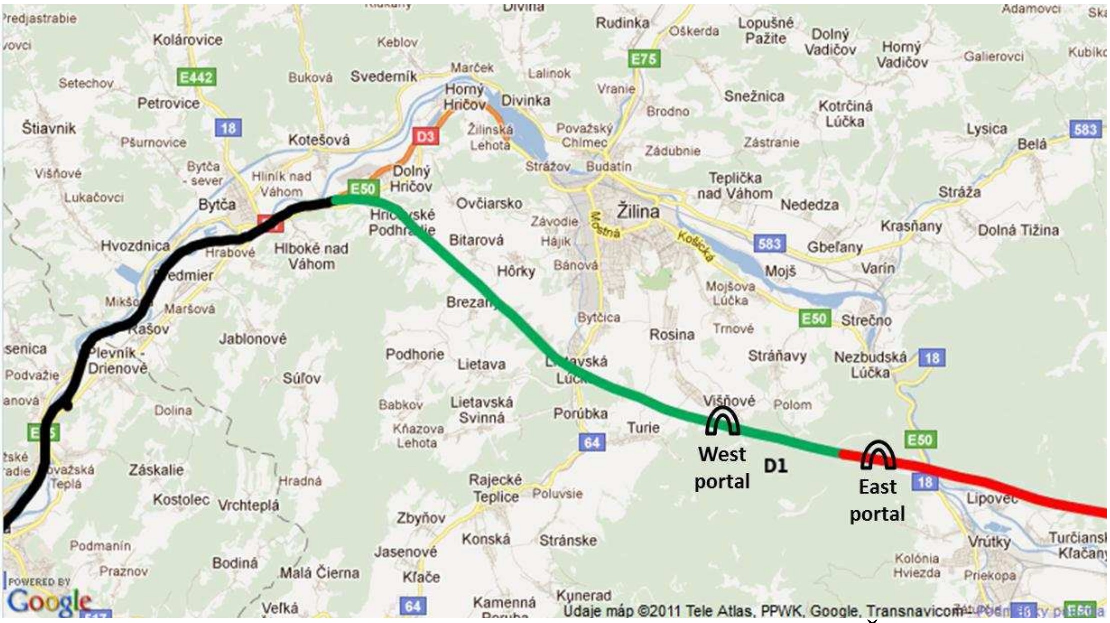
ceiling. The emergency ventilation is longitudinal in the first segment and semi- transversal for the second one.
1D Analysis allows to take into account factors that affect the ventilation effectiveness, such as the air and tunnel wall temperatures, the tunnel slope, the buoyancy effect induced by smoke and air heating, the local and distributed pressure losses, the evolution of the fire heat release rate, the fan characteristics curves and the jet fans parameters.
Simulations provide information about airflow and temperature values inside the tunnels and inside the ventilation ducts at different time steps for the whole duration of the simulation.
In the 1D model, the tunnel is represented through 110 branches characterized by geometrical, thermal and fluid-dynamic parameters. Each branch is defined between two nodes. Nodes are located at the external boundary (at the portals and the ventilation section exits) and at the connection points (between shafts and tunnels, between tunnels, dampers and false ceilings).
This approach is capable of dealing with complex tunnel layouts and ventilation systems and provide a sufficiently accurate representation of ventilation system operation. In this paper, the results of two simulations are presented with the aim of showing the operating condition of the hybrid ventilation system.

1 Introduction

Višňové Tunnel is a highway tunnel composed by two double-lane parallel tubes.



Obr. 1 Poloha tunela na úseku diaľnice D1 b blízkosti Žiliny
Fig. 1 Tunnel location on the motorway D1 near Žilina

Višňové Tunnel is placed along the Motorway D1 in the section between Lietavská Lúčka - Višňové - Dubná Skala, in the district of Žilina, under the Fatra mountain (Fig. 1).
The tunnel is equipped with a hybrid ventilation system that combines longitudinal ventilation in the west portion of the tunnel and a semi-transversal ventilation in the east portion. The two portions are separated by a shaft, which is located at 1.815 m from the West portal and it is equipped with a ventilation central at the ground level, about 110,00 meters above. Extraction from the east portion is operated through 28 dumpers located on false ceiling, for each tube. The false ceiling is ~ 2800 m long and it is connected to a ventilation central located at the East portal.

26 couples of jetfans are installed in the Northern (left) tube, while in the Southern (right) tube there are 34 couples.
This configuration has been adopted to fulfil the specific safety requirements of the Slovak standards and of the Employer.
Ventilation for the normal operation mode is longitudinal and it is mainly obtained taking advantage of the piston effect induced by the vehicles. Some of jet fans are activated in the worst traffic conditions. The shaft and the false ceiling are not active.
The emergency ventilation is longitudinal or semi-transversal according to the fire location. Longitudinal ventilation is applied if the fire occurs in a tunnel segment without the false ceiling. Semi-transversal ventilation is applied if the fire occurs below the false ceiling.
In the **longitudinal ventilation**, smoke can be extracted by the shaft (North or South tube) or it can be pushed out from the West portal, according to the closer option downstream the fire (North Tube), or by the first 3 dampers of the false ceiling (west portal side) (South tube).
In the **semi-transversal ventilation**, smoke can be extracted by 3 dampers downstream the fire in order to achieve smoke confinement in a small portion of the tunnel (North or South tube).
The ventilation system has been verified according to the 1D analysis technique. The emergency operation mode analysis takes into account the most relevant fire scenarios that can occur inside the tunnels.
The normal operation mode analysis has been used to verify the airflow required to dilute the pollutants inside the tunnel, according to the applicable standards.

2 Tunnel characteristics

Višňové tunnel is composed by 2 one-way traffic tubes, the Northern (left) tube and the Southern (right) tube. Inside the Northern (left) tube, traffic flows from East portal to West portal while inside the Southern (right) tube the traffic flows from the West portal to the East portal. Northern (left) tube has a prevalent uphill slope, while Southern (right) tube has a prevalent downhill slope.
Northern (left) tube has a length of about 7.503 m, while the Southern (right) tube has a length of about 7.537 m; each tunnel has 2 traffic lanes. The tunnels shows a main section with a prevalent slope of about 2,3 % and a smaller section, near the West portal, with a lower counter slope.
Both the tunnels have two main different sections characterized to the presence or not of the false ceiling:
Northern (left) tube:

1. A tunnel section, about 4.695 m long adjacent to the West portal, without false ceiling.
2. A tunnel section, about 2.808 m long adjacent to the East portal with a false ceiling.

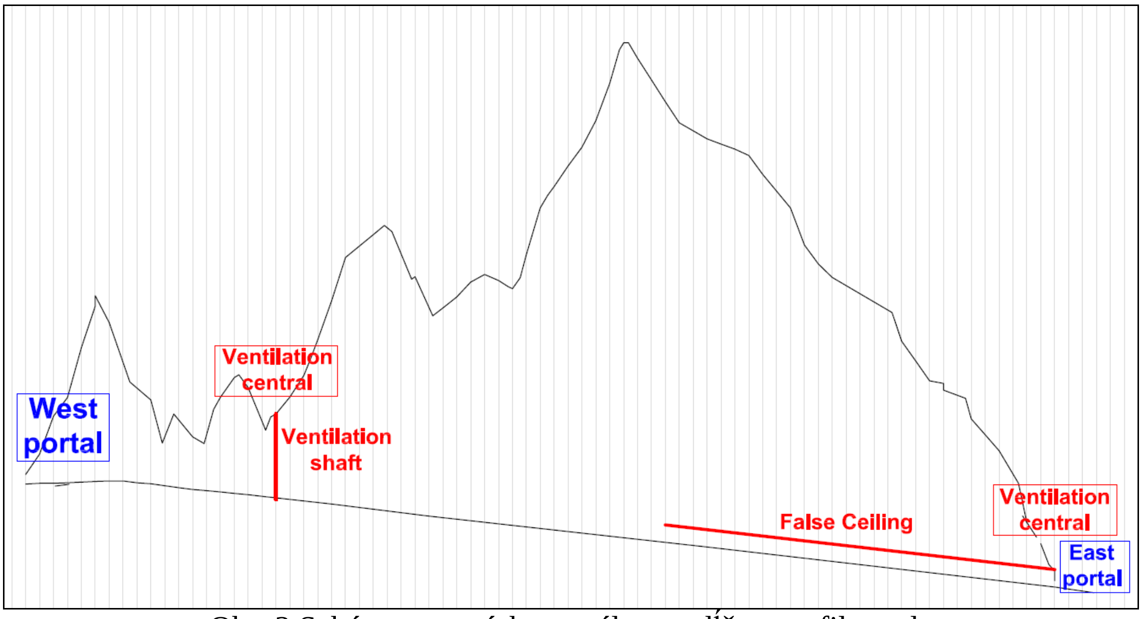
Southern (right) tube:

1. A tunnel section, about 4.715 m long adjacent to the West portal, without false ceiling.
2. A tunnel section, about 2.822 m long adjacent to the East portal with a false ceiling.

In the first tunnel section, longitudinal ventilation is operated with a single extraction point at 1.815 m from the West portal. In the second tunnel section, semi-transversal ventilation is adopted using dampers inside the false ceiling to exhaust the smoke.
The geometric characteristics of the tunnel are listed in Table 1. Figure 2 shows a schematic of the Višňové tunnel.

Tabuľka 1 Základné údaje o tuneli
Table 1 Tunnels characteristics

Tunnel length - Northern (left) tube	7.503 m
Tunnel length - Southern (right) tube	7.537 m
Average transversal section of the tunnel with ceiling	57,4 m²
Average equivalent diameter of the tunnel with ceiling	7,7 m
Average transversal section of the false ceiling	15,8 m²
Average equivalent diameter of the false ceiling	3,4 m
Average transversal section of the tunnel without ceiling	59,3 m²
Average equivalent diameter of the tunnel without ceiling	8,1 m
Average tunnel gradient (east portal to west portal)	~ +2,0 %
Prevalent tunnel gradient (east portal to west portal)	~ +2,3 %



Obr. 2 Schéma vetracích centrál a pozdĺžny profil tunela
Fig. 2 Schematic of the ventilation centrals and altitude profile of the tunnel

In fire emergency cases, traffic has been assumed as blocked behind the fire section according to the traffic direction. The tunnel category was established by the Employer as C1, with no traffic jam, so there is not congested traffic and it has been assumed that there are no vehicles blocked downstream the fire.

3 Emergency ventilation systems and strategies

The hybrid ventilation system, adopted for the Višňové Tunnel, allows to manage all the fire scenario inside the tunnel according to the Slovak standards.
Višňové tunnel is identified in the category C1, according to TP12/2011. This standard, for this kind of tunnel, requires a "*longitudinal ventilation or longitudinal ventilation with punctual smoke extraction*".
The Employer requires, in the tender documents, "*to design and implement in the Tunnel Višňové the longitudinal ventilation with the point (spot) smoke exhaustion in a maximum mutual distance of exhaustion point 3000 meters*".
These requirements mean that inside a tunnel 7.537 m long, at least 2 smoke extraction points are needed. A ventilation shaft at the West side of the tunnel is less complicated to be realize

that a ventilation shaft at the East side of the tunnel due to the thickness of the rocks between the tunnel and the ground level.
A pure transversal ventilation system has not been taken into account due to problems related to the high airflow to be exhausted from a false ceiling on the entire length of the tunnel and to the complexity of the ventilation strategies that must be adopted.
For these reasons, the ventilation system has been realized as an hybrid system with two kinds of smoke extractions:

- The shaft located at 1.815 m from the West portal. This is a punctual and fixed extraction point.
- The false ceiling located along about 2.800 m from the East portal. This is a distributed extraction operated through 3 dampers opened according to the fire locations.

The shaft is a duct that connects the tunnels with the ventilation central at the ground level. It is used only for the emergency ventilation in exhaust smoke. Two great dampers, each one composed by four dampers of 3x2 m, allow to select where the smoke is exhausted, the Northern (left) tube or the Southern (right) tube.
The false ceiling is equipped with 3x2,5 m dampers, spaced 100 m. It is connected to a ventilation central located at the East portal. Dampers are normally closed and they are opened 3 at time. The false ceiling has two different functions according the fire location:

- If the fire is located below the false ceiling, 3 dampers are opened downstream the fire, in order to extract smoke and to confine it in a limited portion of the tunnel. In this case the false ceiling is working in a **semi-transversal ventilation strategy**.
- If the fire is located inside the portion of tunnel without the false ceiling and the propagation direction is towards the East portal, the first three dampers toward the West portal are opened. In this way, these dampers operate as an extraction of the **longitudinal ventilation strategy**.

The ventilation target changes according to the ventilation strategies.
For the semi-transversal ventilation strategy, the target is to achieve enough airflow on both sides of the fire converging towards it, in order to confine smoke below the extraction dampers. The air velocity on both the sides must be at least 1,5 m/s.
For longitudinal ventilation strategy, the target is to reach the critical velocity upstream the fire. The critical velocity value, defined according to the TP12/2011 formula, ranges between 3,0 and 3,3 m/s.
For both ventilation strategies, reversible jet fans induce a longitudinal airflow according to the direction needed to realize the ventilation targets. They have to overcome the aerodynamic resistances inside the tunnel due to the distributed pressure losses, to the fluid-dynamic resistance of the vehicles, to the buoyancy effects of the smoke and to the pressure differences at the portals.
The ventilation strategy is defined according the following elements:

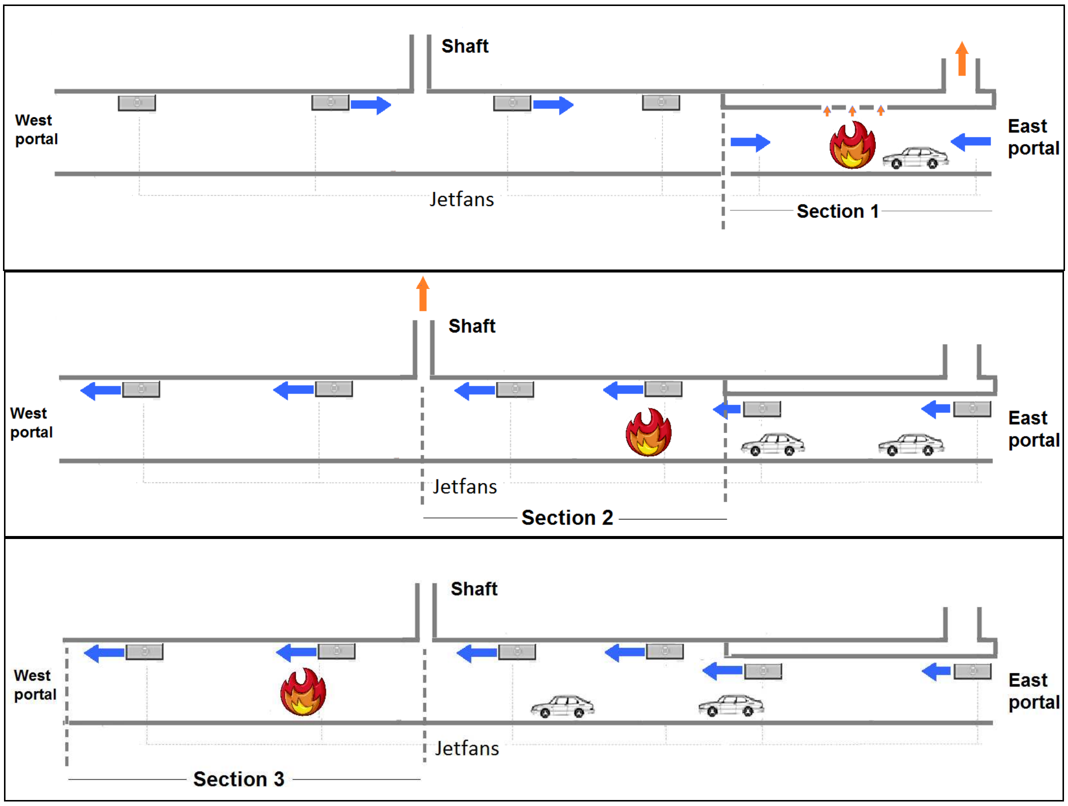
- The fire location.
- The traffic direction of the tunnel where the fire event take place.

Each tube, Northern (left) and Southern (right), has been divided by 3 main ventilation sections characterized by different ventilation strategies as described in Table 2:

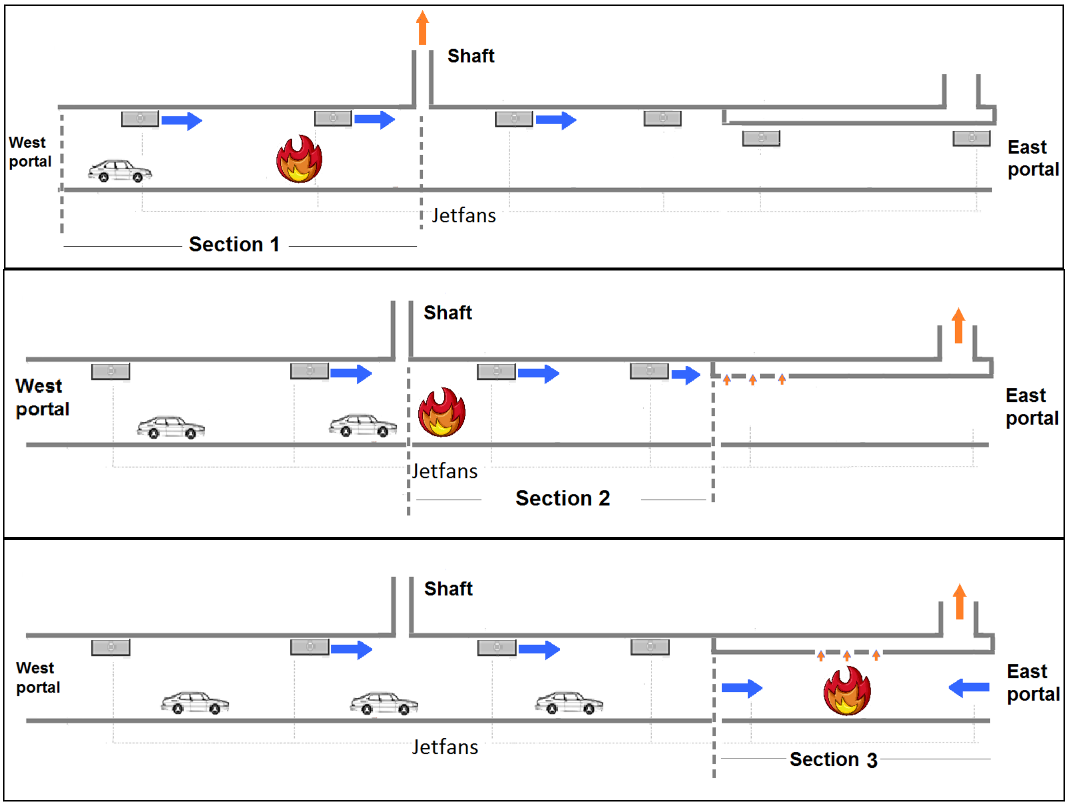
Tabuľka 2 Vetracie stratégie
Table 2 Ventilation strategies

Section	Location	Ventilation strategy	Ventilation target
Northern (left) tube Section 1	about 2.808 m from east portal to section 2	Smoke extraction through the false ceiling.	1,5 m/s on both the fire sides
Northern (left) tube Section 2	about 2.880 m from Section1 to the shaft	Longitudinal ventilation and smoke extraction through the shaft	Critical velocity upstream the fire
Northern (left) tube Section 3	1.815 m from the shaft to the West portal	Longitudinal ventilation	Critical velocity upstream the fire
Southern (right) tube Section 1	1.815 m from the West portal to the shaft	Longitudinal ventilation and smoke extraction through the shaft	Critical velocity upstream the fire
Southern (right) tube Section 2	2.900 m from the shaft to section 3	Longitudinal ventilation and smoke extraction through the false ceiling	Critical velocity upstream the fire
Southern (right) tube Section 3	about 2.822 m from east portal to section 2	Smoke extraction through the false ceiling.	1,5 m/s on both the fire sides

Figure 2 and Figure 3 shows the emergency ventilation strategies for each tunnel section.



Obr. 3 Schéma vetracích stratégií pre severnú rúru
Fig. 3 Schematic of the emergency ventilation strategies - Northern (left) tube



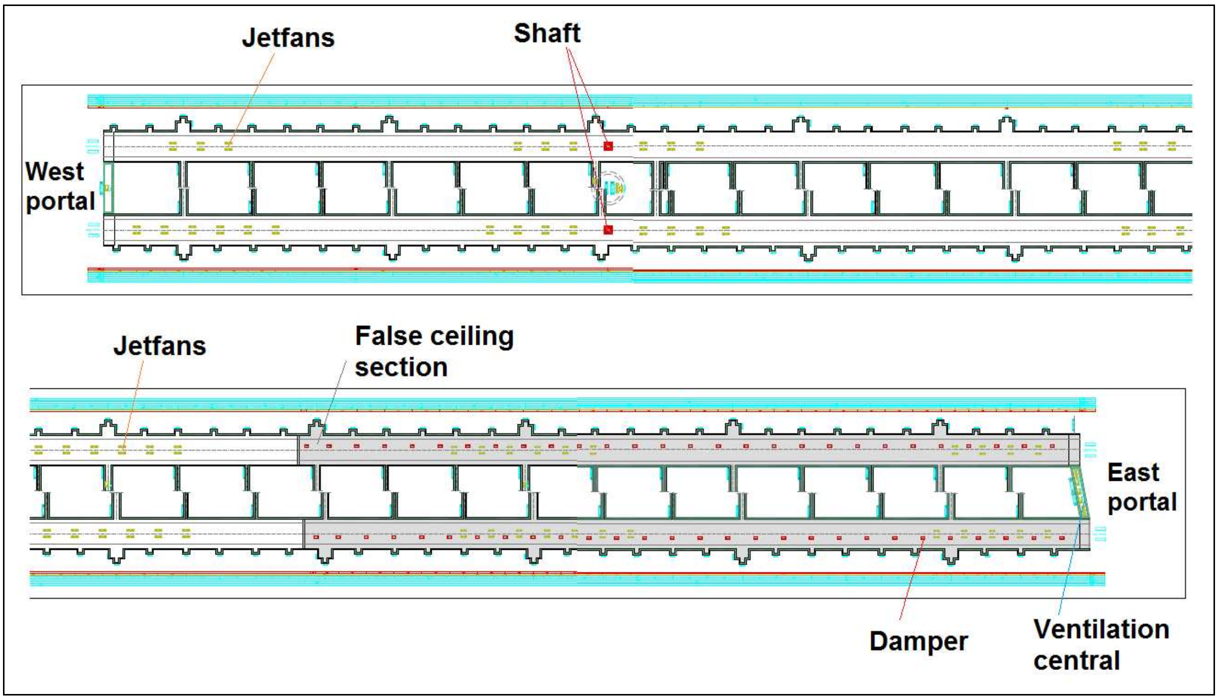
Obr. 4 Schéma vetracích stratégií pre južnú rúru
Fig. 4 Schematic of the emergency ventilation strategies - Southern (right) tube

The ventilation shaft has an airflow capacity of 350 m^3/s.
The east ventilation central provides a variable airflow capacity, ranging between 230 and 290 m^3/s, according to the fire location.
The jet fans installed inside the tunnels are listed in Table 3. Two types of jet fans have been installed, according to the available space below the tunnel roof.

Tabuľka 3 Prúdové ventilátory vovnútri tunela
Table 3 Jet fans installed inside the tunnels

Tunnel	jet-fans configuration
Northern (left) tube	16 couples of 900N jet-fans (32 jet-fans) 10 couples of 700N jet-fans (20 jet-fans)
Southern (right) tube	21 couples of 900N jet-fans (42 jet-fans) 13 couples of 700N jet-fans (26 jet-fans)

Figure 4 shows the locations inside the tunnel of the jet fans, shaft and the false ceiling dampers.



Obr. 5 Poloha prúdových ventilátorov, šachty a odsávacích klapiek
Fig. 5 Location of jet fans, shaft and dampers

4 1D Analysis

The ventilation strategy has been verified through numerical 1D analysis. The software used to perform the analysis is SES [12], a worldwide used designer-oriented tool which estimates airflows, temperatures, and other thermo-fluid-dynamic parameters, for multiple-track tunnel systems.

The tunnel has been represented as a graph composed by 112 nodes and 110 branches. Each branch represents a tunnel segment and it is characterized with geometrical, thermal and fluid-dynamic characteristics. 1D simulations have been performed applying the jet fans characteristics and the airflows elaborated by the ventilation centrals. The fire heat release rate has been considered constant and equal to its design peak value equal to 50 MW. This value is according to the reference [3]**Chyba! Nenašiel sa žiaden zdroj odkazov.**.

Simulations take into account also the heat exchange between the air and the tunnel walls. External ambient conditions have been chosen to take into account the worst conditions for the ventilation effectiveness. If the ventilation direction is according the buoyancy effect direction, air and wall temperatures have been assumed equal to 20 °C, in order to neglect the buoyancy effect. If the ventilation direction is against the buoyancy effect direction, air external temperature has been assumed equal to the lower design value, -5°, and the wall temperature has been calculated according to the geothermal gradient (between 13 and 32 °C), in order to maximize the buoyancy effect.

The total thrust needed has been increased to take into account the maximum allowed pressure difference at the portals equal to 100 Pa.

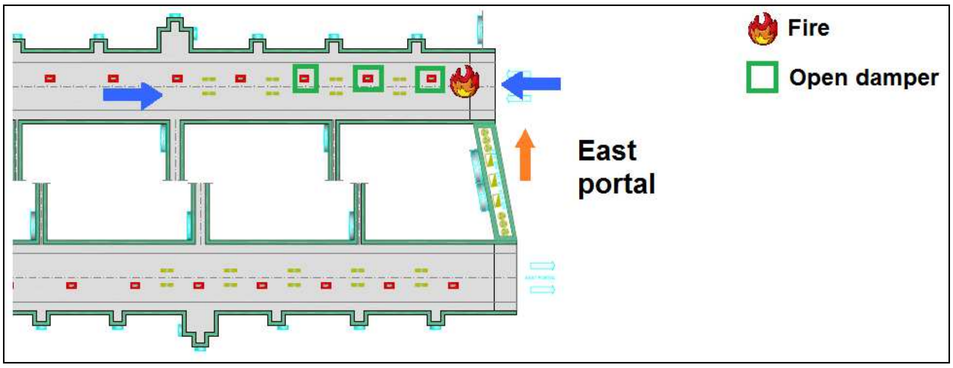
Simulations have been performed for all the worst fire locations inside the tunnel. The worst cases for ventilation effectiveness are determined according the following main factors:

- Fire locations characterized by high exhausted airflows and high smoke temperature at the fan. This is mainly relevant for fire locations near the ventilation plant. Smoke is cooled in the false ceiling due to heat transfer with the walls. If the fire location is near the ventilation central (East portal), the path length of the smoke inside the false ceiling is small, and the cooling effect is lower.

- Fire locations involving high pressure losses inside the false ceiling. If the fire is in the tunnel portion without the false ceiling and extraction is operated using the false ceiling dampers, smoke flows along the maximum path length inside the ceiling, causing the highest pressure losses.
- Fire locations involving high pressure losses inside the tunnel. The worst cases for the pressure losses inside the tunnels are those requiring the activation of the maximum number of jet fans to overcome all the forces that act against the longitudinal ventilation direction (distributed pressure losses, buoyancy effect, vehicles aerodynamic resistance, etc).

A total number of 10 scenarios have been computed. In this paper the results of two 1D analyses are presented.

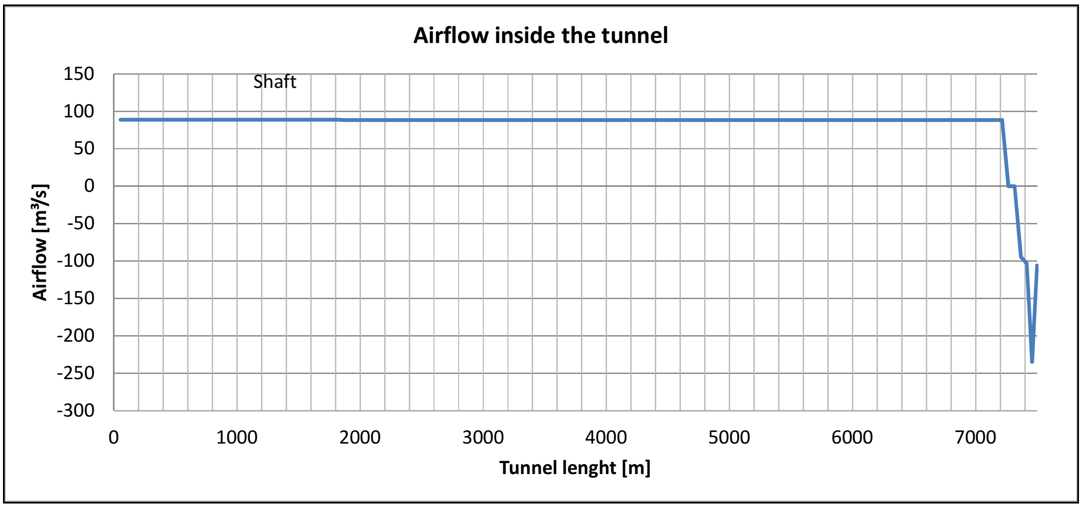
Fire case near the portals. In this case, fire is simulated at the East portal of the northern tunnel (traffic direction from east to west). This case represents one of the worst scenarios due to the airflow that must be exhausted by the fans at the ventilation central of the East portal. For that case semi-transversal ventilation is applied. Table 4 shows the configuration of the ventilation system. In this case the strategy consists in achieving smoke confinement in the three dampers located downstream the fire with respect to traffic direction. Figure 6 shows that velocity becomes 0 at the second dumper. An air flow of about 90 m^3/s flows from west to east, while an air flow of about 100 m^3/s enters through the east portal.



Obr. 6 Požiar v blízkosti východného portálu - konfigurácia
Fig. 6 Fire near the East portal. Ventilation configuration

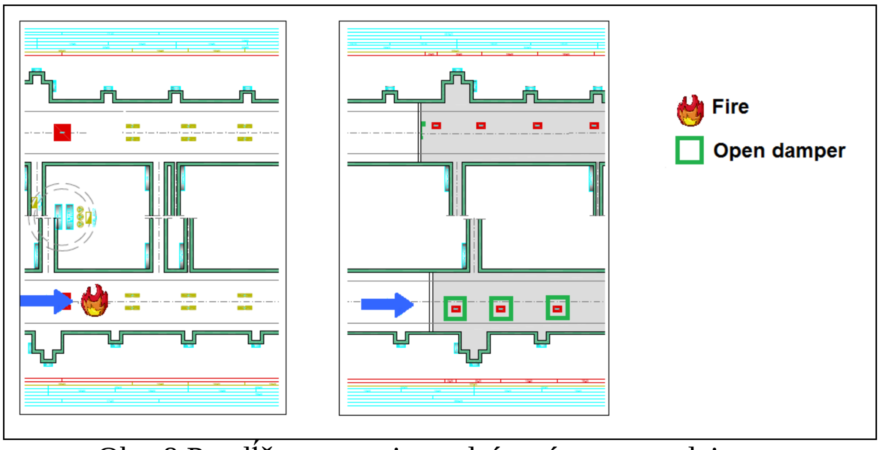
Tabuľka 4 Požiar v blízkosti portálu – konfigurácia vetrania a výsledky
Table 4 Fire near portal – Ventilation configuration and results

Fire scenario configuration	Simulation results
- Airflow Exhausted by east ventilation station: 290 m^3/s	- Temperature at the ventilation central fan: 140 °C
- Airflow Exhausted by ventilation shaft: Not active	- **Air velocity from the West portal: 1,54 m/s**
- Active jet-fans pushing air from west to east portal: 13 x 2 x 900 N	- **Air velocity from the East portal: 1,84 m/s**
- Target: 1,5 m/s on both the fire sides	- **Ventilation requirement: Verified**



Obr. 7 Prúdenie vzduchu v tuneli. Kladné hodnoty predstavujú prúdenie od západu na východ
Fig. 7 Case 1N – Airflow inside the tunnel. Positive values means that the air flows from the West to the East portal.

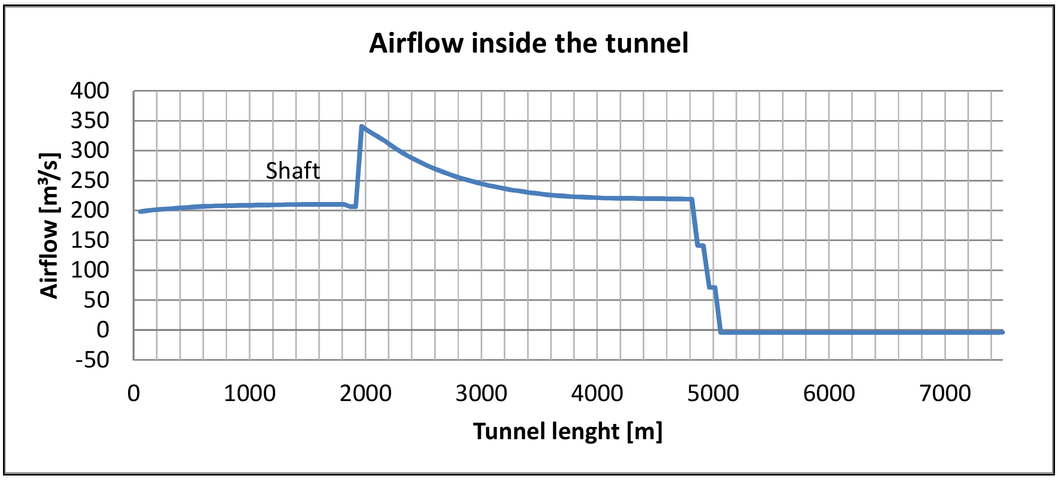
<u>Fire case with high pressure losses inside the ceiling.</u> Fire is considered on the southern tunnel at 1950 m from the west portal. The longitudinal ventilation strategy is applied. Since the shaft is upstream the fire, smoke is extracted through the false ceiling. This case represents one of the worst for the pressure losses inside the false ceiling. Table 4 shows the operating condition of the ventilation system. Using this configuration, about 200 m^3/s of air enters the west portal, as shown in figure 6. This corresponds to a velocity of 3,48 m/s achieved upstream the fire site. Exhausts are then extracted from the first three dumpers of the east portion.



Obr. 8 Pozdĺžne vetranie s odsávaním cez medzistrop
Fig. 8 Longitudinal ventilation. Extraction from the false ceiling

Tabuľka 5 Pozdĺžne vetranie s odsávaním cez medzistrop – konfigurácie vetrania a výsledky
Table 5 Longitudinal ventilation. Extraction from the false ceiling – Ventilation configuration and results

Fire scenario configuration	Simulation results
- Airflow Exhausted by ventilation central: 260 m^3/s - Airflow Exhausted by ventilation shaft: Not active - Active jet-fans pushing air from west to east portal: o 16 x 2 x 900N o 7 x 2 x 700N - Required critical velocity: 3,3 m/s	- Temperature at the ventilation central fan: 10 °C - **Air velocity upstream the fire: 3,48 m/s** - **Ventilation requirement: Verified**



Obr. 9 Prúdenie vzduchu v tuneli. Kladné hodnoty predstavujú prúdenie od západu na východ
Fig. 9 Airflow inside the tunnel. Positive values means that the air flows from the West to the East portal.

1D analysis allows to verify that the ventilation system is able to reach the ventilation targets for all the representative fire cases.

5 Conclusion

This paper presents the hybrid ventilation system which has been designed for the Višňové tunnel. This ventilation system allows one to manage fire events using the jet fans and two extraction options: the ventilation shaft and the false ceiling. With this configuration it is possible to reduce the airflow that is elaborated by the ventilation plants during a fire emergency and to reduce the complications related to the presence of a false ceiling extended all along the tunnel length. Indeed the pure transversal ventilation strategy would lead to more complex ventilation strategies.

False ceiling has been designed for a portion of the tunnel, in order to fulfil the requirement on the mutual distances of the smoke extraction points but avoid a second ventilation shaft on the side presenting higher mountain.

Various 1D simulations have been performed in order to show that different ventilation strategies, longitudinal and semi-transversal, can coexist inside the same tunnel. Two of the analyzed scenarios are presented in this work, showing the different use of the false ceiling: to confine smoke in the vicinity of the fire or as a point of extraction of the longitudinal ventilation strategy.

6 References

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