 DOI: 10.3217/978-3-85125-883-7-10

SELECTION OF A ROAD TUNNEL VENTILATION SYSTEM USING VENTSIM SOFTWARE

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ABSTRACT

Designing the ventilation of a road tunnel is a demanding process, as it requires considering many aspects. Usually, the ventilation system, devices, and location of the elements are selected based on legal regulations and appropriate guidelines. Nonetheless, it should not be forgotten that each road tunnel is an individual case. The designer's main goal is to ensure safe and comfortable conditions for users. The analysis includes the operation of the ventilation system in a road tunnel for standard conditions and the case of emergency (occurrence of fire). In the study, VentSim software is used. Using this software allows simulating the flow of air during both normal operation and fire conditions. The paper presents the methodology of designing the ventilation system and the carried-out simulations. Based on the results, the operating parameters of the system and its individual components were determined. The model was prepared based on the construction concept, meteorological data for the surroundings, traffic forecasts, and traffic analysis for nearby areas. As the analysis shows, the use of numerical simulation makes it possible to predict airflow for changing conditions, which highly simplifies the designing process and increases the safety of tunnel users.

Keywords: ventilation system, road tunnel, fire, safety.

1. INTRODUCTION

In recent years around the world, numerous new road infrastructure investments have been realized or planned. Frequently in such projects, an issue of overcoming terrain obstacles occurs, including mountains, water reservoirs, and highly urbanized areas. Consequently, it is associated with the construction of new engineering facilities, including tunnels. Increasing needs and technical possibilities results in the construction of more and more modern tunnel facilities. There are several thousand road tunnels in operation around the world. They differ in length, width, construction method, and type of traffic.

During the fire, heat, smoke, and toxic products are generated, which may cause material damage and loss of health or even life of tunnel users. Heat is the cause of damage to the structure and technical installations in the tunnel. A primary hazard to people is the loss of visibility caused by smoke (which makes rescue more difficult) and the toxicity of fire gases. Similarly, fires pose a threat to the environment by emitting toxic smoke components into the atmosphere [1]. In terms of safety, the essential and crucial equipment of the tunnel is its ventilation system. The main tasks of the ventilation are to control airflow, remove fire smoke and gases, and enable the safe rescue of tunnel users [2]. The amount of generated smoke and heat depends on the size of the fire. It is assumed that the production of smoke and heat is proportional to the size of the fire, where smoke and gases are the product of incomplete combustion, and the amount of their emission depends on the combustion mechanism of materials. The larger the size of the fire, the more combustion products are generated. Therefore a larger airflow rate is needed to control the flow and remove smoke and hot gases [3].

This article presents ventilation systems for road tunnels when functioning in normal operating mode and during the fire.

2. CHARACTERISTICS OF FIRE DEVELOPMENT IN A ROAD TUNNEL

When a fire incident occurs, ventilation in the tunnel is started up in the so-called fire mode. The role of the system is to provide a controlled flow of smoke and fire gases in the tunnel and to discharge them outside the tunnel. The creation of a controlled flow of smoke and fire gases allows the evacuation of users with minimal smoke contamination of escape routes, preventing smoke intrusion to the access routes for rescue teams leading to the place of the incident. Typically, one ventilation system is used in tunnels for normal operation, emergency conditions, as well as in fire conditions. Nevertheless, for each operating mode, different ventilation system parameters are provided.

For tunnel ventilation, both natural and mechanical methods are used. In the light of the regulations in force in Poland, natural ventilation is used in tunnels of not more than 700 m in length for unidirectional traffic. For natural-ventilated tunnels with bidirectional traffic, the length of the tunnel should not exceed 500 m [4]. A limitation in the use of natural ventilation in fire conditions is the risk of an uncontrolled process of fire gas flow. According to NFPA [2], three types of mechanical tunnel ventilation could be distinguished, i.e., longitudinal, transverse, and mixed systems. Whereas, Directive [5] introduces the division of mechanical ventilation systems into longitudinal, semi-transverse and transverse. In longitudinal ventilation systems, the air flows along the tunnel, usually from the inlet portal to the outlet portal. The air movement is forced by the operation of fans located inside the tunnel, e.g., jet fans suspended under the tunnel ceiling or fans installed in the supply and exhaust shafts. Typically, longitudinal ventilation is designed, with axial fans arranged inside the tunnel every 60-120 m. This solution does not require routing of ventilation ducts under the roadway or tunnel ceiling. The fans are to ensure smoke removal over the entire length of the tunnel, and speed of air flow through the tunnel should prevent smoke backflow by providing so-called critical speed. Transverse ventilation is used in long tunnels with heavy traffic, as it allows even distribution of air along the entire length of the tunnel and removal of solid and gaseous pollutants emitted by the vehicles. This solution requires routing supply ducts inside the tunnel, usually under the tunnel roadway, and the gas stream is removed through a ventilation duct located under the tunnel's ceiling. In such a ventilation system, air is supplied at the height of vehicle wheels and discharged under the ceiling of the tunnel. Mixed (semi-transverse) ventilation is a combination of transverse and longitudinal ventilation. Ventilation systems in road tunnels are designed for maximum fire power. Figure 1 shows the principle of operation of the longitudinal and transverse systems during a fire.

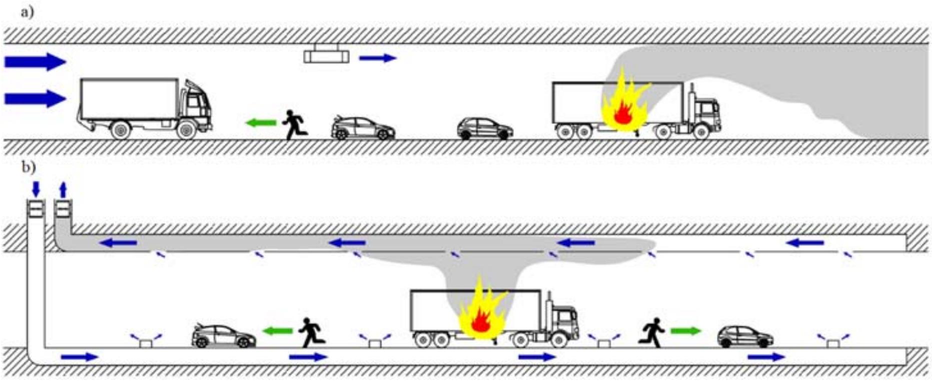


Figure 1: Ventilation of the road tunnels (a) longitudinal system (b) transverse ventilation

3. ANALYSIS OF SELECTED ROAD TUNNEL - CASE STUDY

3.1. Assumptions for calculations

The subject of the analysis in the article is the concept of technical equipment in the ventilation system of the TS-33.7 tunnel on the S6 road. The cross-sections of the ventilation ducts were adopted according to the assumptions presented in Figure 2.

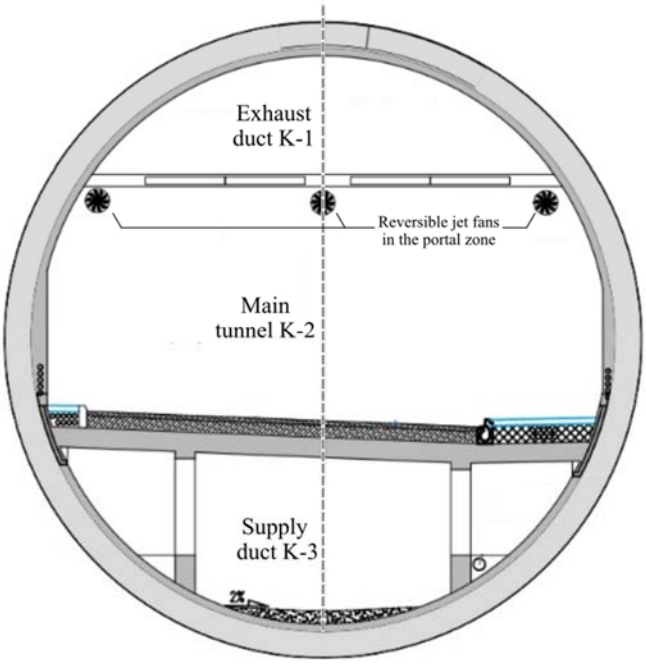


Figure 2: Division of the tunnel cross-section into ventilation ducts

The transverse ventilation system works based on separated functional channels (table 1):

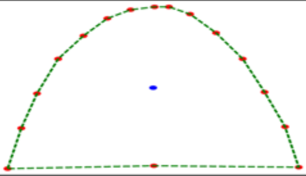
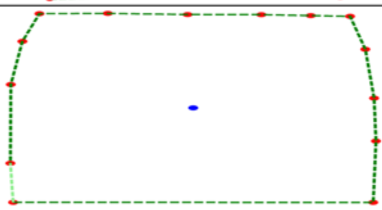
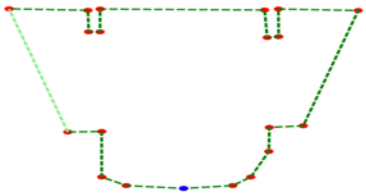
- Smoke exhaust duct **K-1** located under the main ceiling. During normal operation, it is used for exhaust gas extraction along the entire length of the tunnel. During the fire and rescue operation, it allows for the removal of hot air and smoke from the section covered by the fire.
- The main tunnel **K-2**. It is the central space of the tunnel, used to guide vehicle traffic, divided into smoke removal sections with ceiling flaps
- Clean air duct **K-3**. The duct underneath the roadway supplies clean air into the main tunnel K-2 space. The air flows through the duct under the road and is further distributed using transverse ducts with outlets at a height of about 20 cm above the pavement.

Table 1. Characteristic parameters of the ducts/tunnels:

Duct/ tunnel	Cross-sectional area, m^2	Length, m	Volume, m^3
K-1	23,7	5230	123 951
K-2	79,3	5330	422 669
K-3	36,5	5230	190 895

VentSim DESIGN software provided by Howden company was used in this study. Software is a comprehensive package for the design and analysis of mine and tunnel ventilation systems. During the design phase, VentSim enables 3D modeling of the ventilation system, ensuring an understanding of possible solutions. The system performance could be simulated based on expected operating conditions and evaluated to allow for the selection of an optimized design. The mapping of the cross-sectional area for each part was prepared using the Ventsim DESIGN software. Details are presented below in Table 2. For individual cross-sections, the airflow resistance of the ducts was assumed.

Table 2. Mapping of ducts/tunnels

Duct	Cross-section	Cross-sectional area, m^2	Details
K1		23,7 m^2	R= 0,0090 kg/m^7 Concrete duct
K2		79,3 m^2	R= 0,0419 kg/m^7 Concrete tunnel with "blocked" car traffic
K3		36,5 m^2	R= 0,0150 kg/m^7 Irregular duct

The view of the duct connection in the ventilation system model in Ventsim Design is shown in Figure 3. Figure 4 shows the entire model of the road tunnel.

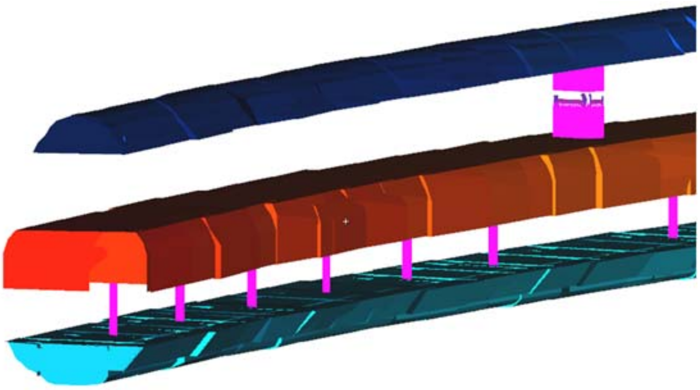


Figure 3: Arrangement of ventilation ducts in the model in the Ventsim Design software

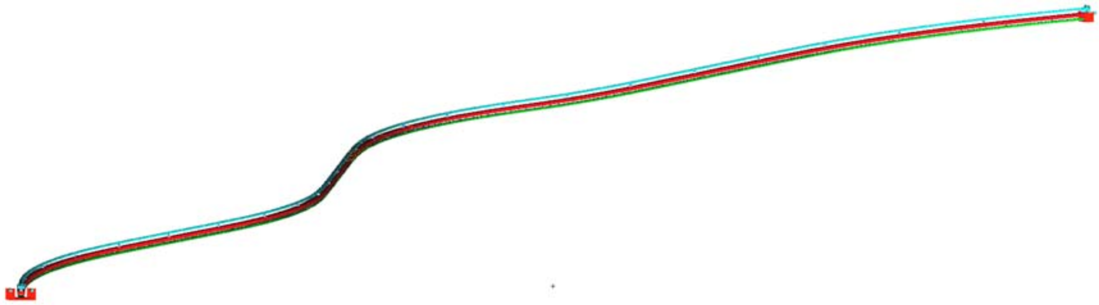


Figure 4: Tunnel model in Ventsim Design software

The view of the ventilation ducts and the mapping of the fan stations are shown in figure 5.

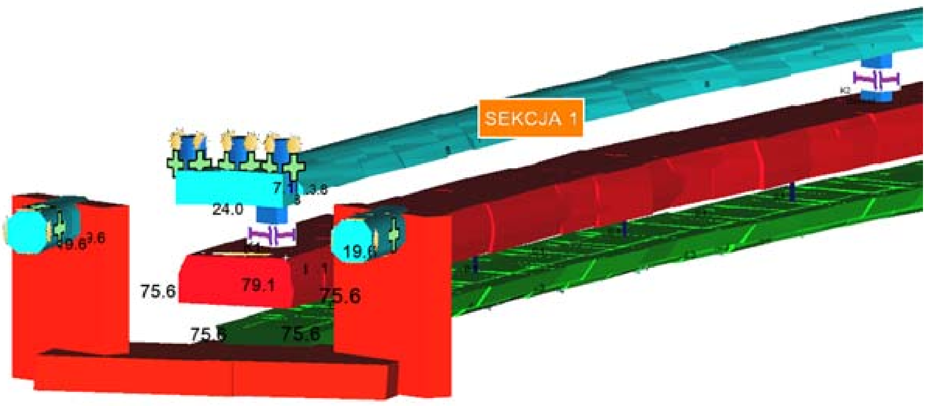
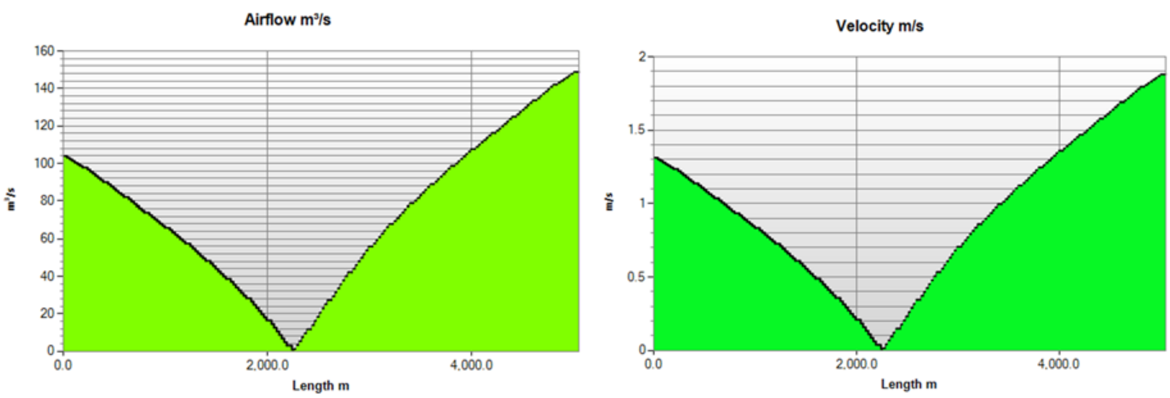


Figure 5: Mapping of ventilation ducts and stations in fans in the Ventsim Design software

The calculations were carried out assuming that the temperature in the summer period is 23 ºC and for the winter period it is -3 ºC. It results from the location of the tunnel. Additionally, west wind with a maximum value of 10 m / s was assumed, which generates a pressure thrust on the portal of 50 Pa.

3.2. Calculations of ventilation parameters

The results of calculations of the airflow and velocity as well as the pressure distribution in the tunnel are shown in Figure 6. The figures show asymmetry in the air distribution and pressure distribution in the tunnel due to the effect of wind. The westerly wind was considered with a barometric pressure difference of 50 Pa between the tunnel inlets.



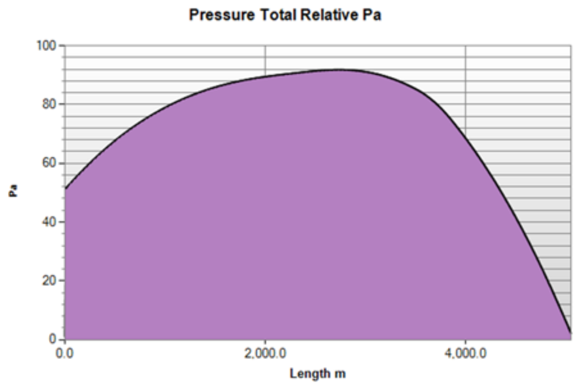


Figure 6: Changes in airflow and velocity, and total pressure distribution in Ventsim Design software

The results of the fan parameters calculation for the airstream of 260 m^3/s in the K1 and K3 ducts are shown in Table 3.

Table 3: Calculations of the parameters of ventilation ducts

System	Airflow of fans	Flow resistance	Total pressure	Summary
Duct K-3 (Supply ventilation)	4 x 65 m^3/s (2 fans on each side of the tunnel)	Pressure loss in ducts: 270 Pa Pressure loss on silencers and outlets: 300 Pa (assumed)	Pc = 570 Pa + 30 % = 740 Pa	740 Pa (at 80% of total stagnation pressure) the volume rate is 65 m^3/s each
Duct K-1 (Exhaust ventilation)	6 x 44,3 m^3/s (3 fans on each side of the tunnel)	Pressure loss in ducts: 816 Pa Pressure loss on silencers and outlets: 300 Pa (assumed)	Pc = 1116 Pa + 30 % = 1450 Pa	1450 Pa (at 80% of total stagnation pressure) the volume rate is 44,3 m^3/s each

The calculations show that for the amount of air which is 260 m^3/s, the maximum pressure loss in the K-3 supply duct is 740 Pa. On the other hand, the maximum pressure loss in the K-1 exhaust duct is 1450 Pa.

3.3. Ventilation analysis for a fire located in the middle of the tunnel (13th section)

A scenario was assumed in which a gasoline tanker accident occurs:

- 0 min - 5 min - Start of fire - burning gasoline at a rate of 0 to 8300 kg/h,
- 5 min - 2 hours and 5 min - constant fire - burning gasoline at the rate of 8300 kg/h,
- Peak fire heat release rate: 101 kW,
- The calculations for 2 open fire dampers,
- The calculations for airflow rate: 260 m^3/s.

Figure 7 shows the location of the fire in the middle of the tunnel for section 13. Figures 8 and 9 show the changes in power and temperature of the fire and changes in the volume rate of air in the ventilation duct exhausting fire fumes, respectively. The performed calculations confirmed the parameters of the designed road tunnel ventilation system.

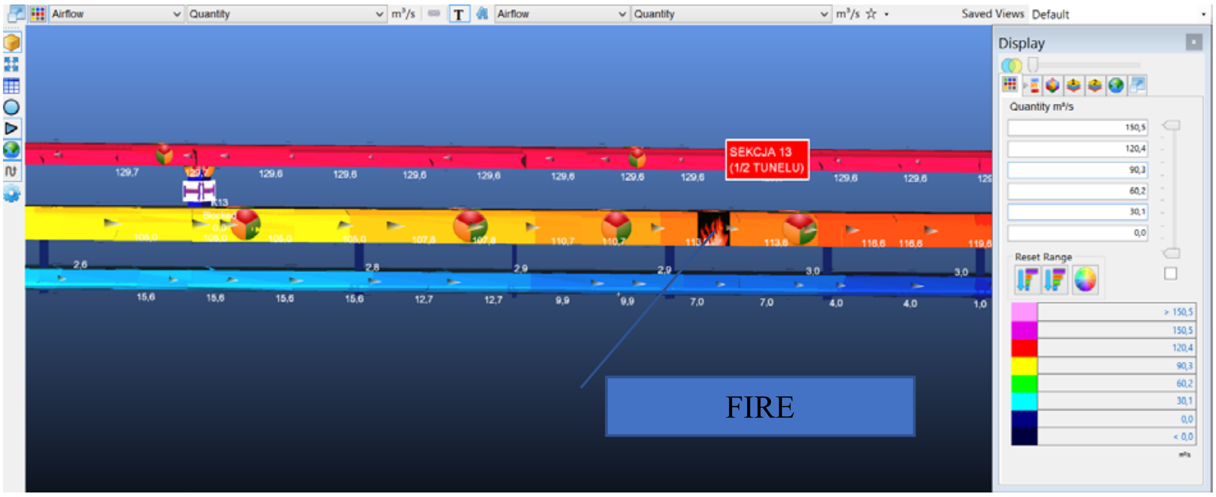


Figure 7: Location of a fire in a tunnel in Ventsim Design

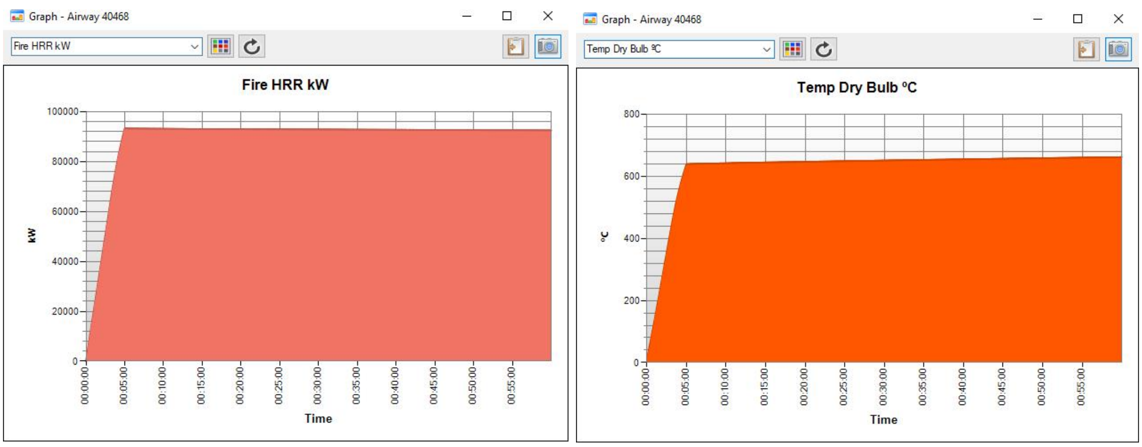


Figure 8: The power of the fire and the temperature changes in the fire location over time

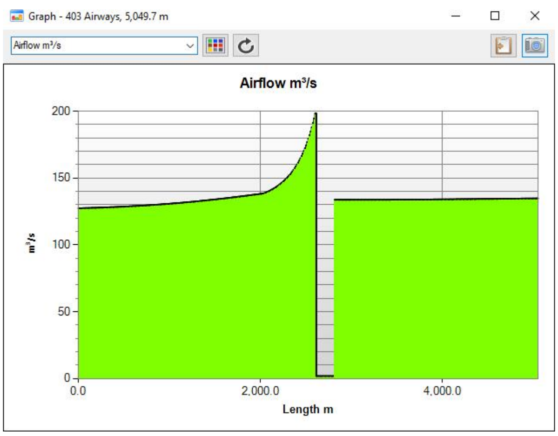


Figure 9: Airflow rate distribution (volume flow) in the exhaust air duct K1.

4. SUMMARY AND CONCLUSION

Regardless of the ventilation system used, the parameters of this system are designed for maximum firepower, taking into account the emission of fire gases produced. The properly designed ventilation system should provide a controlled flow of smoke and fire gases as well as discharge them outside the tunnel. Two primary concepts of fire ventilation solutions are used for these aims. Longitudinal flow is mostly applied for short or unidirectional tunnels, while exhaust ducts are for long and bidirectional tunnels. In Polish conditions, tunnels are usually built as twin-tube tunnels, which allows for unidirectional traffic. The only exceptions are two tunnels: Emilia (in operation) and under Świnna (under construction), which were designed as bidirectional.

In summarizing, it is observed that designers prefer longitudinal ventilation, which is the most likely applied (if the regulations allow it). In the case of the long tunnels where the lengths do not exceed 3000 m, it is proposed to use semi-transverse ventilation with air supply through the ducts under the roadway and air discharge through the tunnel using jet fans installed under the tunnel ceiling. Such solutions are dictated by economic considerations because the installation of longitudinal or semi-transverse ventilation is less expensive than the installation of fully transverse ventilation.

Of course, the implementation of each of the proposed solutions should be adjusted individually to the designed tunnel. Hence, it is necessary to confirm the correctness of the proposed solution in terms of ensuring safe conditions of operation. As the analysis shows, the use of Ventsim Design software allows for determining the parameters of the road tunnel ventilation system and checking its operation during a fire. The occurrence of a fire is the most important test for the designed system. Therefore, checking the operation in this mode is crucial. Based on the simulation, it is possible to determine whether the proposed airflow rate and selected fans could provide the appropriate conditions and meet the assumed requirements.

5. REFERENCES

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[3] NCHPR. 2011. Report no 425, Design Fires in Road Tunnels, ISBN 978-0-309-14330-1.

[4] Regulation of the Minister of Transport and Maritime Economy of 30 May 2000 on technical conditions to be met by road engineering structures and their location (Journal of Laws 2007, no 63, item 735).

[5] Directive 2004/54 / EC of the European Parliament and of the Council of 29 April 2004 on the minimum safety requirements for tunnels in the trans-European road network.