VENTILATION OF LONG ROAD TUNNELS IN REGULAR AND ACCIDENTAL CONDITIONS OF FUNCTIONING

Nikola Mirković [1]
Predrag Mitković [2]
Ljubo Divac [3]
Slobodan Radovanović [4]
Dragoslav Šumarac [5]

UDK: 624.191.94
DOI:10.14415/konferencijaGFS2017.062

Summary: *In the paper presents the basic principles of ventilation long road tunnels using three different types of ventilation systems. There are presented the basic principles of longitudinal, transverse and semi-transverse ventilation in terms of regular functioning traffic in the tunnel, with special emphasis on safety control and protection measures in the case of accidental situation - a fire in the tunnel. This paper description procedure of design ventilation system in regular and accidental cases on the specific example of long traffic tunnels from aspect energy efficiency applied ventilation solution.*

Keywords: *ventilation, ventilation systems, energy efficiency, accidental situation, fire protection, road tunnels.*

1. INTRODUCTION AND BASIC PRINCIPLES OF TUNNEL VENTILATION

Vehicles on the open road create emissions which are diluted and dispersed through natural surface air flows. Road tunnels create an enclosed space around vehicles where emissions from the vehicles can build up to unacceptable levels without an engineered ventilation system to replace natural surface air flows. The basic principle of tunnel ventilation is dilution of vehicle emissions by providing fresh air and then removing the exhaust air from the tunnel. The exhaust air can be removed via a portal, via a ventilation outlet, or via a combination of both. Longitudinal ventilation is the simplest form of

[1] Nikola Mirković, teaching assistant - PhD student, University of Belgrade, Faculty of Civil Engineering Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, e-mail: nmirkovic@grf.bg.ac.rs
[2] Predrag Mitković, teaching assistant - PhD student, University of Priština, Faculty of Technical Sciences Kosovska Mitrovica, Knjaza Miloša 7, 38220 Kosovska Mitrovica, e-mail: predrag.mitkovic@pr.ac.rs
[3] Ljubo Divac, PhD student, Stucky doo Belgrade, Bulevar Mihaila Pupina 115E, 11070 Belgrade, e-mail: ljubo90@gmail.com
[4] Slobodan Radovanović, teaching assistant - PhD student, University of Belgrade, Faculty of Civil Engineering Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade and Jaroslav Černi Institute for the Development of Water Resources, Jaroslava Černog 80, 11226 Belgrade, e-mail: sradovanovic@grf.bg.ac.rs
[5] Dragoslav Šumarac, professor, University of Belgrade, Faculty of Civil Engineering Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, e-mail: dragosumi@gmail.com

engineered ventilation, and involves the introduction of fresh air at the entry portal and the removal of exhaust air out of the exit portal or a ventilation outlet.

The approach to tunnel ventilation has changed dramatically over time, mainly because of the significant reduction in vehicle emissions. Longitudinal ventilation was once not suitable for longer tunnels due to the need to supply large quantities of fresh air to dilute vehicle emissions. Due it cleaner vehicles, longitudinal ventilation can now readily maintain acceptable air quality in long tunnels, and is generally considered the most efficient and effective tunnel ventilation approach.

For tunnels up to around 500 m in length the natural air flow through the tunnel driven by the movement of vehicles is normally adequate to manage in-tunnel air quality, and forced ventilation is not required. For longer tunnels forced ventilation in the form of fans may be required at times to ensure that air flow rates are sufficient to maintain in-tunnel air quality to required levels. The main air quality criteria considered in tunnel ventilation design are carbon monoxide (CO), nitrogen dioxide (NO_2) and visibility. Even though there are other vehicle pollutants to consider, these three criteria are considered to be the most important for health and safety.

The amount of a given pollutant that is produced in a tunnel per unit time is determined by calculating the total number of vehicles in the tunnel multiplied by the emission rate of each vehicle. In terms of ventilation design, the total number of motor vehicles in a tunnel at any one time is primarily determined by the tunnel length, the traffic density and the traffic speed. The emission rate of a vehicle is dependent on speed and additionally, vehicle type, vehicle age, vehicle condition, traffic conditions and road gradient.

2. TYPES OF VENTILATION SYSTEMS

In this paper presents the basic principles of ventilation long road tunnels using three different types ventilation systems. There are presented the basic principles of longitudinal, transverse and semi-transverse ventilation.
Longitudinal ventilation in its simplest form comprises of fresh air introduced within the entry portal and exhaust air expelled out of the exit portal. This is shown in Figure 1.

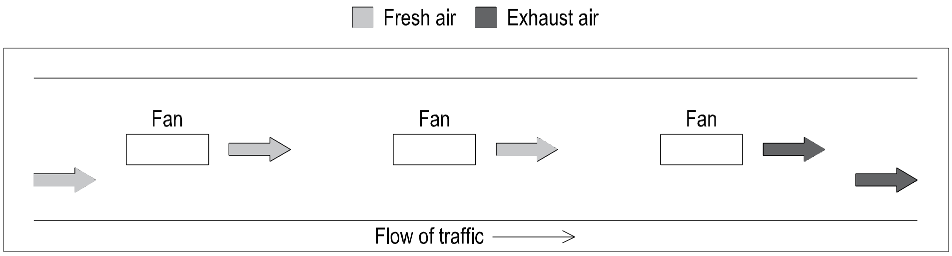

Figure 1. Longitudinal ventilation system

Figure 2 represents the pollution profile along the length of the tunnel. The pollution level increases along the tunnel because this is the direction of air flow, and vehicles continue to generate emissions as they pass from one end to the other.

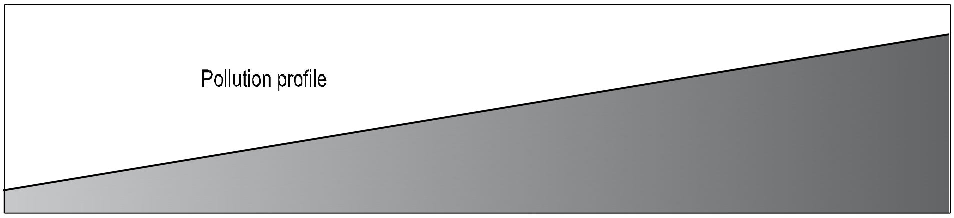

Figure 2. Pollution profile

Transverse ventilation works on the same principle of dilution and removal as longitudinal ventilation, but the supply of fresh air and the removal of exhaust air occurs across the tunnel. This system requires two ducts along the length of the tunnel, one for the supply of fresh air and one for exhausting polluted air (Figure 3).
These ducts can be located both at high level or low level in the tunnel, or one at low level and one at high level.

Transverse ventilation has been used in the past where longitudinal ventilation could not adequately manage tunnel pollutant levels due to much higher pollutant levels in tunnels. Transverse ventilation is also effective in bi-directional tunnels (where vehicles are travelling in both directions in the same tunnel).

For these traffic conditions, the piston effect is cancelled out and the pollutant levels are more evenly distributed along the tunnel length.

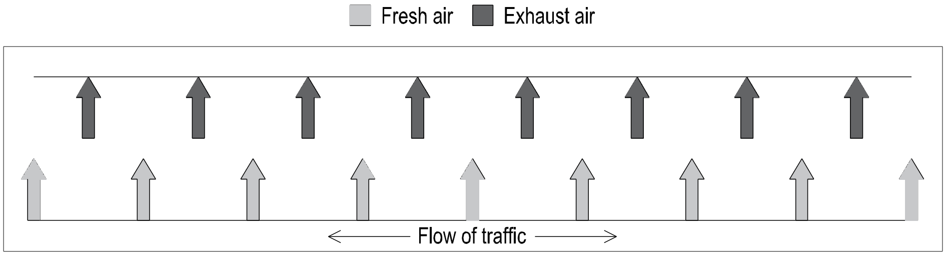

Figure 3. Transverse ventilation system

Semi-transverse ventilation is a combination of both longitudinal and transverse ventilation. Fresh air can be supplied from the portals and be continuously exhausted along the tunnel through a duct along the length of the tunnel (Figure 4).

Alternatively, fresh air can be continuously supplied along the tunnel via a duct along the length of the tunnel and exhausted out of the tunnel via the portals or a stack.

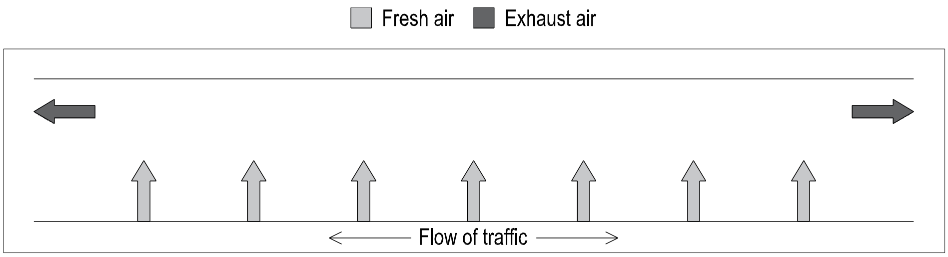

Figure 4. Semi-transverse ventilation system

3. DESIGN OF TUNNEL VENTILATION SYSTEMS IN REGULAR CONDITIONS

The operation of a tunnel ventilation system is designed to meet a set of air quality and fire safety performance requirements under it's expected operating scenarios (ie tunnel length and cross section, traffic volumes and mix). The key air quality performance requirements are:

1. In-tunnel air quality criteria
2. External or ambient air quality criteria
3. Other restrictions, such as limited or no portal emissions conditions.

The in-tunnel air quality criteria, such as CO, NO_2 and visibility limits, specified for a project will be used by ventilation designers to calculate the system capacity (ie how much fresh air is required to flow through the tunnel under different operating scenarios) to ensure that pollutant concentrations do not exceed the criteria. These systems monitor air flows, traffic conditions and pollution levels, and adjust the ventilation rates to suit the prevailing conditions in the tunnel.
Exhaust air can be emitted from tunnels via the portals or via a dedicated ventilation stack where improved dispersion is required to maintain ambient air quality. The basis for the design calculation of the tunnel ventilation system capacity is usually the first year of tunnel opening. This is because emissions in the opening year will generally be higher than emissions in subsequent years. This is because improvements in vehicle emissions occur faster than traffic growth rates [1].

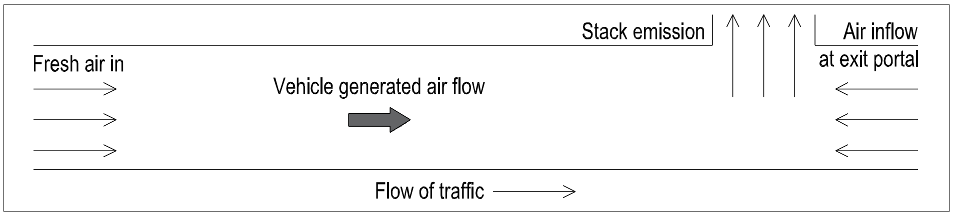

Figure 5. Illustration showing tunnel air flow direction to avoid portal emissions

To meet the zero-portal-emissions condition, all air must be expelled from an elevated ventilation outlet (eg stack), with air drawn in from all portals (Figure 5). In some cases this requires ventilation against the natural direction of air flow due to vehicle movement (ie the piston effect).

The requirement for zero portal emissions leads to a number of design and operation implications:

1. An alternative ventilation outlet is required, such as a stack.
2. Drawing air in from the exit portal increases the quantity of ventilation air required to be discharged through the stack, and can significantly increase the required size of the stack – leading to increased capital and operating costs and visual impacts.
3. The ventilation system will need to be operated all the time, regardless of whether in-tunnel or ambient air quality warrants this operation.
4. A more complex ventilation system is required. Air will need to flow against the traffic direction in parts of the tunnel, between the stack offtake point and the exit portal. This means operating fans against the natural air flow direction in the tunnel.

4. DESIGN OF TUNNEL VENTILATION SYSTEMS IN ACCIDENTAL CONDITIONS

A fire hazard in a tunnel often produces smoke, which is dangerous to the tunnel users, as the visibility is reduced and it may be toxic. In a one-dimensional system, such as a road tunnel, the smoke may spread very fast in one or two directions, threatening the persons situated there. Ideally, the smoke is extracted or directed towards the direction, where no persons are endangered. Smoke control means essentially the control of the longitudinal airflow in the tunnel, either on its own or in combination with a smoke extraction system. Smoke control is primarily in order to ensure the escape of tunnel users from the dangerous area. Secondly, the fire brigade has to be supported by ensuring a smoke-free access to the fire site.
From the point of view of smoke control, there are two basic concepts. In tunnels with pure longitudinal ventilation, the only way for the smoke is through the traffic space itself. In this case, the smoke control system only influences the direction and velocity of smoke movement (Figure 6).

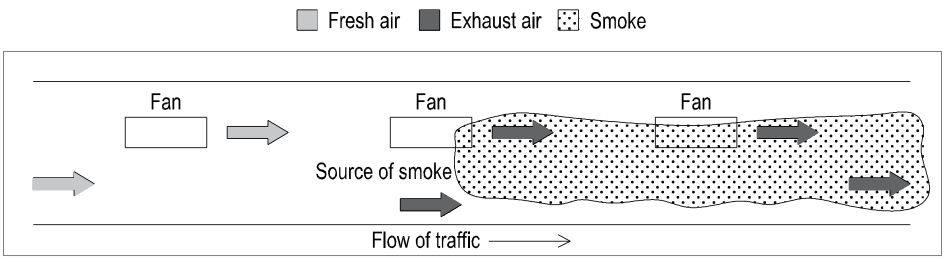

Figure 6. Longitudinal ventilation in case of fire

Using longitudinal ventilation for example in a tunnel with unidirectional traffic, the typical design objective is to prevent smoke from backlayering i.e. to ensure that all smoke is driven in one direction. In that case, the longitudinal velocity must reach at least the so called “critical velocity”. It is inherently assumed that there are no persons downstream of the fire. The situation is quite different in a tunnel with bi-directional or congested traffic. Tunnel users may be situated on both sides of the fire.

With high air velocities, a possible stratified smoke layer underneath the tunnel ceiling would be dispersed over the whole tunnel cross section. Therefore, with a longitudinal ventilation, the intention of the smoke control is to stabilise the airflow at a low air velocity. The goal is to prevent changes in the flow direction and to keep the air velocity low in order to minimise turbulence or large eddy flow.

In longer tunnels, there should be a smoke extraction from the tunnel tube using a separate airduct. Ideally, the smoke is extracted at the point of the smoke source, e.g. at the fire site (Figure 7).

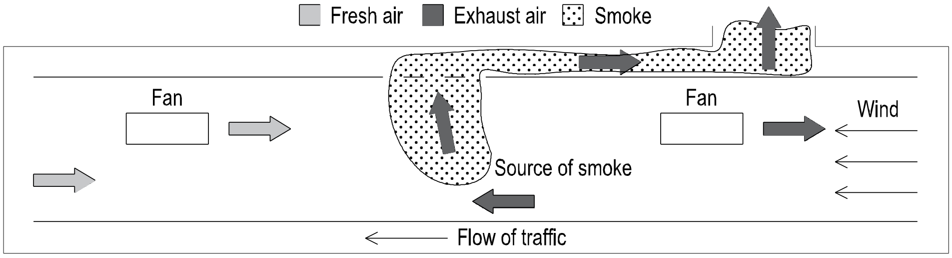

Figure 7. Local smoke extraction system

In the one-dimensional point analysis, the demand for an efficient smoke control means that the airflow in the tunnel tube must be from both sides of the fire towards the extraction point. Wind, meteorological and thermodynamic forces may lead to high air velocities in the tunnel. Even with a powerful smoke extraction, the smoke may pass the extraction point [2].

5. ANALYSIS VENTILATION SYSTEM OF TUNNEL “ŠARANI”

On the section Takovo - Preljina of highway E-763 Belgrade - Požega designed tunnel “Šarani”, a length of about 900 m. In the tunnel designed longitudinal ventilation system with jet fans. The tunnel consists of two separate tunnel tubes. Rating tunnel safety was done on the basis of recommendations issued by the Transportation and Road Research Association, Vienna - Austria, and that RVS 9.261 - Fundamentals (Basics) and RVS 9.262 - Calculating the Fresh Air Demand (Calculation of needed fresh air) [3].

This standard is unique in that the problem of the calculation needed quantity of fresh air in regular and accident conditions, for example in the fire, is treated in the most complete way. This means that standard takes the view generational age of the vehicle, the impact of altitude, the number of vehicles, distribution vehicles as well as the size and type of the engine and similarly, wherein for each of the required conditions and provides the necessary parameters for the assessment of such conditions. Standard also prescribes a minimum requirement for fresh air in case of fire. Therefore, the quantity of fresh air obtained in calculation for regular conditions compared to the minimum prescribed in accidental conditions, and always adopts a larger value. For project year was adopted 2031., with projected traffic load of 18254 vehicles.

Based on a calculation for the left tunnel tube (Figure 8), with the mentioned methodology has obtained the necessary quantity of fresh air from 22.26 m^3/s for the regime removal of CO and soot. As this quantity of fresh air does not satisfy the requirements for extraction smoke, because not achieved the necessary minimum average speed of 2.5 m^3/s, that is for a selection of fan applicable quantity fresh air of 160.95 m^3/s. After conducted calculation for the selection number of fans for the left tunnel tube for the regime removal of CO and soot, obtained the number of 8 jet fans with a diameter of 650 mm, the individual power of 30 kW, divided into 8 groups of one piece (a total of 240 kW of installed power).

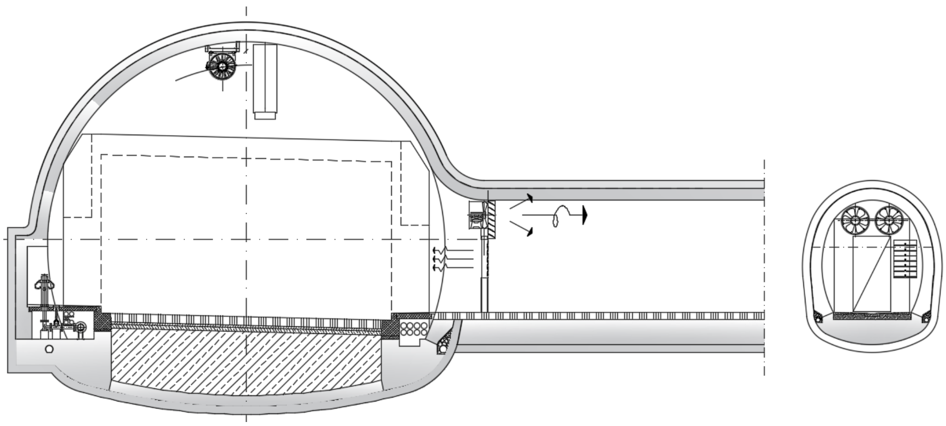

Figure 8. Cross section of left tunnel tube with ventilation system

Based on a calculation for the right tunnel tube (Figure 9), with the mentioned methodology has obtained the necessary quantity of fresh air from 22.89 m^3/s for the regime removal of CO and soot. As this quantity of fresh air does not satisfy the requirements for extraction smoke, because not achieved the necessary minimum average speed of 2.5 m^3/s, that is for a selection of fan applicable quantity fresh air of 160.95 m^3/s.

After conducted calculation for the selection number of fans for the right tunnel tube for the regime removal of CO and soot, obtained the number of 8 jet fans with a diameter of 650 mm, the individual power of 30 kW, divided into 8 groups of one piece (a total of 240 kW of installed power).

Predicted fans are the product of DELTA AIR - Belgrade, type AVT650, diameter of 650 mm, with noise dampers. Selected fans, designed for operating mode of 250°C during 2h. The fans are axial, reversible, with noise dampers. Measuring the concentration of CO or smoke conducted at least two half-tunnels. The direction of all fans is the zone in which it is notified to the increased concentration of CO or smoke. If the alert simultaneously with an increased concentration of CO or smoke is determined and the impact of intense natural flow of 0.3 m/s, then all the fans directed a series of natural airflow. One of the way of evacuation in a fire in one tunnel tube is transverse connection between two tubes. There is a transversal connection provided for the vehicles (these purposes is not considered in case of fire), and two pedestrian transverse connections [4].

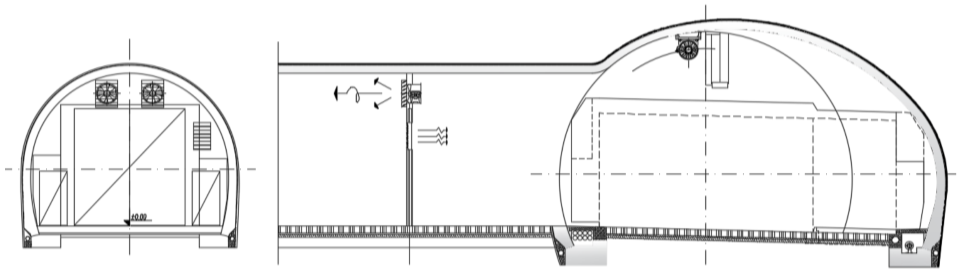

Figure 9. Cross section of right tunnel tube with ventilation system

6. CONCLUSION

The largest contributor to the energy consumption of a long road tunnel is the operation of the ventilation system. With respect to tunnel ventilation, megawatt hours per tunnel kilometre (MWh/km) can be used as an indicator of operational energy consumption. This compares energy consumption in megawatt hours (MWh) per year to tunnel length. When tunnel length and traffic volumes are equal, the key drivers of energy consumption are the complexity of the ventilation system and whether portal emissions are allowed or restricted. Also, the control of the longitudinal airflow during a fire in a tunnel is the key for an effective fire ventilation with or without smoke extraction. In theory, the control of the longitudinal velocity may be rather simple. However, in practice the application of an automatic control routine sets new demands to the reliability of the control routines and instrumentation. It cannot simply be assumed that the anemometers give adequately reading to permit an automatic control. Consequently, it is paramount firstly to calibrate the measurement instruments and secondly to conduct plausibility tests prior to each iteration of the automatic control. Otherwise, a rather good smoke extraction can be destroyed and the survival conditions for the tunnel users deteriorate.

REFERENCES

[1] Nakahori, I.; Mitani, A.; Vardy, A.: *Automatic control of two-way tunnels with simple longitudinal ventilation*, 5th International Conference 'Tunnel Safety and Ventilation', Graz, **2010.**

[2] P. Pospisil, R. Brandt: *Smoke control in road tunnels,* Conference Significance of Tunnels in Transport, **2005.**

[3] Fire in Tunnels – *Technical report, Part 2: Fire Safe Design - Road Tunnels*, EU, **2004.**
[4] *Glavni mašinski projekat ventilacije i kontrole dima u tunelu "Šarani" na autoputu E-763 Beograd – Požega, sektor II: Ljig – Požega, deonica 3: Takovo – Preljina*, Saobraćajni institut CIP d.o.o. Beograd, Belgrade, **2011.**

VENTILACIJA DUGIH SAOBRAĆAJNIH TUNELA U USLOVIMA REDOVNOG I INCIDENTNOG FUNKCIONISANJA

Rezime: *U radu su predstavljeni osnovni principi ventilacije dugih saobraćajnih tunela primenom tri različita tipa ventilacionih sistema. Prikazane su osnovne postavke longitudinalne, transverzalne i polu-transverzalne ventilacije u uslovima redovnog funkcionisanja saobraćaja u tunelu, sa posebnim naglaskom na kontrolu bezbednosti i mere zaštite u slučaju pojave incidentne situacije – požara u tunelu. Ovaj rad opisuje postupak projektovanja sistema za ventilaciju u uslovima redovnog i incidentnog funkcionisanja tunela na konkretnom primeru dugog saobraćajnog tunela sa aspekta energetske efikasnosti primenjenog ventilacionog rešenja.*

Ključne reči: *ventilacija, ventilacioni sistemi, energetska efikasnost, incidentna situacija, zaštita od požara, saobraćajni tuneli.*