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Some Questions about the Safe Operation of Short Road Tunnels

Omar Lanchava[1,*],

[1] Labor Safety and Emergency Management Department, Mining-Geology Faculty, Georgian Technical University, Tbilisi, Georgia

* Corresponding author: o.lanchava@yahoo.com

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Abstract

The article looks at the statistical data on fires in short tunnels. It notes that about a quarter of road tunnel fires are classified as strong ones. The analysis is made according to the standards of the USA, the leading industrial country in the world. Underground fire scenarios are analysed and it is shown that for descending ventilation flows, there occurs a strong back-layering on the fresh air jet. The reason for this is an algebraic summation of mechanically and thermally induced underground ventilation flows and the insufficiency of the generally accepted numerical value of critical velocity of 3.0 m/s in the case of a great tunnel slope and strong fires. Noteworthy among the fire-fighting measures are equipping the tunnel with measuring devices; training the tunnel service personnel and rescuers; imposing transportation regimes for heavy hazardous cargoes; information support and promotion of the issue.

Keywords: tunnel fire, critical velocity, fire safety standards, numerical modelling.

Introduction

More than 50 new road tunnels are planned to be built in Georgia in the next 3-5 years, some of which are relatively short tunnels. According to the building norms and regulations applicable in our country, tunnels less than 150 m long are ventilated only by natural traction; tunnels with lengths ranging from 150 to 400 m should also receive natural traction, but its sufficiency should be proven by a relevant assessment. Tunnels longer than 400 m need a mechanical ventilation system (Lanchava & Javakhishvili, 2021; Lanchava & Ilias, 2020; Lanchava, 1986). England has similar regulations: mechanical ventilation is not required for tunnels less than 400 m long, while according to the German RABT Standard, tunnels less than 700 m long do not require mechanical ventilation and are mandatory for tunnels longer than 700 m.

In addition, according to many standards, including the RABT and PIARC standards, a ventilation system must be designed for 30 MW fires, and the emergency ventilation system must be capable of mitigating the harmful effects of fires. For natural gas, an approximately 25 MW underground fire scenario demonstrated that the maximum heat release rate is attained in approximately 5 s. Given that most tunnel fires are controlled by ventilation, this power would be sustained until almost complete combustion of fuel. The modelling results also demonstrated that for short tunnels with natural ventilation, the smoke generated during combustion spreads towards the portals at a velocity of 2.5 m/s, which is very close to the generally accepted value of the critical velocity of 3.0 m/s and somewhat indicative of its numerical value.

The issue of fires is a hot topic worldwide, as the general increase in the number of tunnels, which means more intense road traffic, increases the risk of fires. Following major tunnel fires in the world, the European Union has given particular consideration to the Trans-European Transport Network, in which the safety of existing and future tunnels is a top priority. For tunnels of the network longer than 500 m, the European Parliament and the Council of Europe issued Directive EC 2004/54 on the required minimum level of safety. The total length of such tunnels in EU countries is more than 1000 km. The EU countries strongly recommended extending the requirements of the Directive to tunnels that are not part of this transport network, with the organizational and technical requirements for tunnels at a minimum.

December 2021 was marked by the European Commission's proposal for a new Regulation on TEN-T guidelines (COM 2021/821), putting the Black and Aegean Seas on the list of newly harmonized transport corridors. Consequently, the abovementioned road tunnels under construction in Georgia should be considered part of the common European Transport Network.

The abovementioned tunnels are commonly built-in mountainous conditions, and the most difficult sections of roads are now traversed through them; however, in the future, with the construction and commissioning of new tunnels, freight turnover and traffic intensity will increase further. An increase in traffic will immediately increase the risk of fires.

US fire standards

According to Paragraph 11.1 of the U.S. National Fire Protection Association Standard 502, "Emergency ventilation systems and tunnel operating procedures shall be developed to maximize the use of the road tunnel ventilation system for the removal and control of smoke and heated gases that result from fire emergencies within the tunnel" (NFPA 502, 2011).

For tunnels less than 240 m long, Paragraph 11.1.1 of the said Standard provides for safety planning based on engineering analysis, taking into account natural factors, mode of transportation, traffic patterns and other similar indicators and does not provide for not considering the need for emergency ventilation. The standard is one of the best standards in the world, and it is worth considering it, especially if we do not have a similar standard in Georgia.

The NFPA-502–7 test standard was introduced in 1972. In 1980, the NFPA Committee revised the document as a recommended practice and added a chapter on air ventilation, which was introduced in practice at the 1981 NFPA Annual Meeting, a conference-like event.

The 1987 edition included a minor amendment regarding the fire water supply.

The 1996 edition included a chapter on the total revision of tunnels, as well as requirements for reviewing the use of new materials in tunnels.

The 1998 edition was revised in cooperation with the Motor Vehicle and Highway Fire Safety Committee. Specifically, practically all the chapters were critically revised, and a new Chapter 7 was added to include research results related to ventilation fire safety testing in the U.S. Memorial Tunnel. This tunnel was no longer in operation at that time and was categorized as an abandoned tunnel. It is located in West Virginia. Following the strong fires in European tunnels, to study air flows and smoke movement, temperature distribution and concentration of toxic gases during fires, the mentioned tunnel was equipped with all types of ventilation systems and measuring equipment, and fires of different powers were tested (Santoianni & Gonzales, 1996). More than 3 million data points were obtained, which were analysed and are presented as graphs and tables in 9 volumes.

The 2001 edition focused on emergency lighting and the optimal spacing of emergency exits. Some important editorial corrections were made. This edition clarifies the rule for applying the standard depending on the tunnel length.

The 2004 edition includes additional requirements for concrete and reinforcement, emergency lighting and emergency exit spacing. Appendix A of the same edition presents the results of new studies from around the world.

The 2008 edition added specific fire testing requirements for tunnel structural members and clarified the classification of road tunnels; additionally, it discussed proper ventilation, a safe environment, and the transportation of hazardous cargo. Annex E also provided a discussion on fixed fire extinguishing systems.

The 2011 revision provides more reasonable requirements for tunnel systems (safety) by tunnel categories. Chapter 9 on water extinguishing systems was added. The document also added materials on system control and periodic testing and updated the appendix on design factors for saving life and material assets.

Analysis of the statistical and factual data of tunnel fires

According to statistical data of long-term observations of tunnel operation in England and France (Bearard & Carvel, 2012; Perard, 1996), Germany (Bauberhorde Highways Department, 1992), Sweden (Ruckstuhl, 1990) and Italy (Arditi, 2003), traffic accidents in tunnels are less frequent than those in open highways. This can be explained by the strict control of tunnels, less weather impact, better night lighting and greater attention of drivers when travelling through tunnels, being in an unusual environment—under the ground.

In addition, underground fires have more severe consequences than open environments because in open environments, the products of combustion—heat, toxic gases and smoke—are more easily dispersed. In tunnels, on the other hand, diffusion processes are limited, and there is a need to control them through ventilation.

According to French statistics, there are typically 1 or 2 fires per kilometer of tunnel for every 100 million passenger vehicles that pass through the tunnel. Similarly, for every one hundred million heavy-duty vehicles—the trailers that will pass through the tunnel—under the same conditions, i.e., per 1 kilometer of tunnel length, according to the statistical average, 8 fires will occur, including 3 strong (up to 100 MW) fires, the consequences of which will be disastrous for human life and tunnel infrastructure.

Based on these statistics, for example, in the Elbe Tunnel (Germany), where 37 million vehicles travel in both directions per year, the probability of a fatal fire is much greater than in the Chakvi-Makhinjauri Twin Tunnels in Georgia, where a maximum of 200,000 to 300,000 vehicles travel in one direction per year; however, considering the total length of the tunnels and the total number of vehicles, as well as the increase in freight traffic that is bound to occur due to heavy vehicles as a result of the Silk Road popularization, the risk of fatal fires in our country will significantly increase, and the country must be ready to prevent it.

We provide an example of just one fire in a medium-length road tunnel to show that despite a high level of preventive safety, fires cannot be completely avoided, and tunnel services must be prepared to mitigate and completely eliminate the harmful effects of expected fires: in the Mont Blanc Tunnel connecting France and Italy, which is 11.6 km long, there have been 18 fire incidents since 1965, i.e., when it was commissioned (Lacroix, 2001). The mortality of these fires was the same as that on March 24, 1999.

A large truck carrying margarine entered the tunnel on the French side at 10:46 pm. After 7 minutes, the driver noticed white smoke from his vehicle and stopped the truck 6.3 km from the portal. Immediately after stopping, the trailer caught fire and emitted black smoke, which started to propagate towards the portal on the French side. The driver immediately ran in the opposite direction. Before the emergency closure of the tunnel, 1 motorcycle, 9 cars, and 18 different heavy vehicles entered the tunnel on the French side after the burning truck, and 8 trailers and several cars entered the tunnel from the Italian portal. None of the latter were injured, but none of those who entered from the French side survived, resulting in 39 victims (including 27 car drivers). After the fire had raged for 53 hours, a 900 m long tunnel section collapsed, and 34 cars were destroyed. Ventilation or communication between the portals was insufficient.

This fire could have been easily avoided if normal operating conditions had been provided. Later, there was friction between the tire and the truck body. The heat generated dissipated as the truck drove in the open environment, but due to the reduced heat transfer to the environment in the tunnel, the tire overheated and ignited.

Using the example of the above case, we can visualize the mechanism of the emergency situation, which is very close to the classical definition: there was a deviation from the normal course of a naturally occurring process, an accumulation of an abnormal situation until reaching its culmination, and then relief and damping.

Fire protection of tunnels less than 400 m long is a problem because they usually do not have a mechanical ventilation system. Tunnels up to 700 m long, due to the traction induced by fire, have a greater probability of ventilation system collapse than longer tunnels. The fire traction in this case will increase due to the low aerodynamic resistance of the tunnel and hence the easy provision of an air supply sufficient for complete combustion (Lanchava et al., 2007; Lonnermark & Ingason, 2008). A similar opinion about fire intensification is given in (Ingason, 2010; Bajwa et al., 2009). In particular, at ventilation flow velocities between 2 and 4 m/s, the fire intensification effect is associated with more intense natural ventilation as the fire attempts to better ventilate, i.e., to obtain oxygen for combustion. For clarity, we should note that the length of the tunnels in the mentioned works is not limited, but only the velocity range is defined. The velocity of the flow caused by the natural traction induced by vehicle traffic will be approximately within the specified range in short tunnels.

Special attention should be given to fires in short tunnels resulting in human deaths. Although we do not yet have long or very long tunnels in Georgia, the issue of short tunnels is very important, as confirmed by world experience and evidenced by the following examples: the Newhall Pass Tunnel (USA) between Los Angeles and San Francisco (166 m long): the accident occurred on October 12, 2007, when a truck collided with a sidewall and another truck travelling at high speed collided with it, immediately causing a major fire, which was strengthened by natural traction induced by wind. Twenty-three people were injured as a result of the accident. Despite the shortness of the tunnel, it took 24 hours to bring the fire under control.

An unnamed tunnel on the B 31 Highway (Germany), 200 m: the accident occurred on Christmas Day in 2005, when a passenger car collided with an oncoming vehicle and a fire broke out, in which four young people aged 18-23 were burnt and five others died of their injuries (Ingason, 2010).

The Viamala Tunnel (Switzerland), 700 m: The accident occurred on September 16, 2006, when a bus and two cars collided. A fire broke out immediately, and two more cars caught fire. Nine people died, and 5 were seriously injured. The Cabin Creek Hydro Power Plant (USA), 150 m: On October 2, 2007, a chemical used to purify water spontaneously ignited. Five people died as a result of the inhalation of toxic compounds (Bajwa et al., 2009).

Numerical modelling of the critical velocity

In longitudinal ventilation, the critical velocity in the emergency ventilation strategy is accepted as the decisive factor in preventing back layering. Back-layering is the propagation of combustion products on a fresh air stream. This phenomenon mainly occurs on the descending ventilation flow when there is reverse air movement in the part of the air-supply tunnel where the fresh air should be. This is caused by the high temperature of the combustion products, which results in less density and floating due to buoyancy. This is a very dangerous occurrence in terms of saving lives by evacuation.

The critical velocity is the minimum velocity to eliminate back-layering that must be assigned to the ventilation flow. The critical velocity depends on the fire strength, tunnel geometry, type of ventilation system used in the tunnel, and other factors. Since the dynamic pressure induced by fire and the similar pressure induced by jet fans are algebraically summed, to avoid smogging the clean jet portion of the tunnel, the clean air jet must have a velocity higher than the critical velocity. Therefore, with a longitudinal ventilation system, a jet moving at a critical velocity will drive out smoke and other harmful combustion products from the hearth of the fire to one side only, and there should be fresh air on the other side.

Many works, including the abovementioned US Standard (NFPA 502, 2011; Santoianni & Gonzales, 1996; Beard & Carvel, 2012), indicate that a 3.0 m/s critical velocity is sufficient to prevent back-layering in transport tunnels during fires, which, in our opinion, is incompatible with the scenarios of underground fires, which are realized through numerical simulations (Lanchava & Ilias, 2020; Lanchava et al., 2017).

Using the Clapeyron equation in our work, it was determined that the dynamic pressure induced by a fire at a temperature of 1000°C in tunnels is 121.6 kPa, which exceeds the atmospheric pressure and is 6 to 8 times greater than the maximum static pressure of the most powerful fans. In this case, the air density drops to 0.277 kg/m3. Consequently, in the case of strong fires, it will be practically impossible to control the ventilation flow with fans, and the air direction and supply will be determined by the depression induced by the fire (Lanchava et al., 2022a; Lanchava et al., 2022b; Lanchava & Ilia, 2017). This statement is valid considering that mechanically (with the use of fans) and thermally (by fire) induced ventilation flows are algebraically summed up.

This statement contradicts the idea of critical velocity. Therefore, we carried out an experimental numerical simulation of a tunnel up to 100 m long. The purpose of the experiments was to demonstrate the steady increase in critical velocity as the fire power increased, as well as the unreasonableness of relying on the given concept in the attempt to avoid back-layering in accordance with the numerical modelling.

The velocity profiles obtained from the numerical simulations are shown in Fig. 1. To illustrate the increase in critical velocity, two jet fans are used to create a descending ventilation flow. The cross-sections are given depending on the distance from the lower portal as follows: Figure N1 - lower portal; Figure N2 - distance of 20 m from the lower portal; Figure N3 - distance of 60 m from the lower portal; and Figure N4 - distance of 80 m from the lower portal. The numbers of the curves correspond to the time intervals from the beginning of the experiment: 1 - τ= 60 s; 2 - τ= 80 s; 3 - τ= 100 s; and 4 - τ= 120 s. A negative velocity value in all velocity profile graphs indicates the movement of the ventilation flow towards the lower portal, and a positive value indicates the movement of the ventilation flow towards the upper portal.

Curve 1 in Plot 1 of Fig. 1 shows that before the fire starts, the air flow moves toward the lower portal, and the velocity epure has a classical shape. Two jet fans are running simultaneously at the upper portal. As soon as a fire starts, the situation changes immediately (curves 2, 3 and 4): now, the air direction and intensity are more strongly determined by the dynamic pressure induced by the fire, and the impact of the fans tends to decrease. It should be noted that all the velocity profile plots presented show that the pressure change propagates at the speed of sound, causing the corresponding results to change at the same rate.

Based on the above, it is necessary to distinguish the following cases: 1. When it is possible to develop life-saving emergency ventilation designs based on the available classical knowledge; and 2. When the available knowledge is no longer sufficient to realize similar projects, new study results are needed to develop a new approach to the problem.

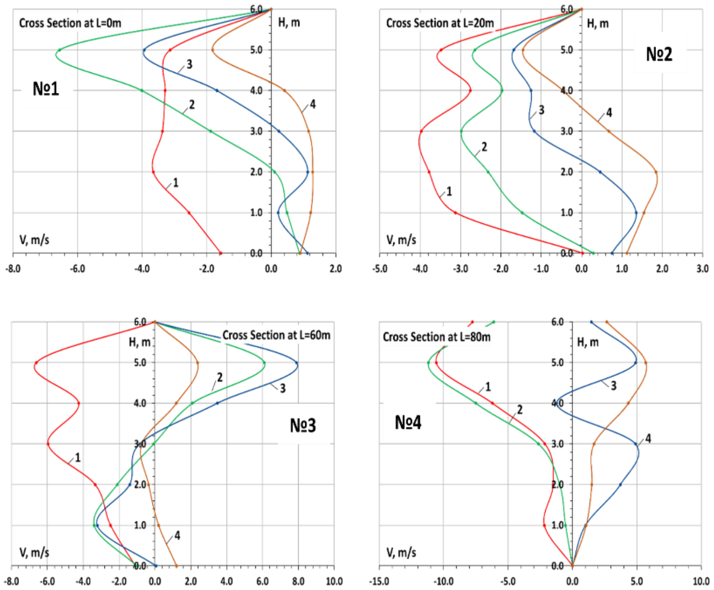

Figure 1. Velocity profiles of the descending ventilation flow with two operating jet fans. The curves correspond to time intervals: 1 - τ= 60 s; 2 - τ= 80 s; 3 - τ= 100 s; 4 - τ= 120 s.

Conclusion

Based on the results of the modelling of fires in short road tunnels and the analysis of statistical indices, it can be concluded that short tunnels, which are allowed to operate without a mechanical ventilation system as per effective standards, need an emergency ventilation system, which will be triggered in the case of fire.

Training of tunnel maintenance personnel and rescuers should be based on scenarios of fires of various strengths with time-varying rates of heat, smoke and carbon monoxide generation. Much attention should be given to strict observance of traffic safety rules; overtaking moving vehicles in tunnels should be prohibited in all instances and should be achieved. At the same time, we consider it advisable to establish a schedule for the movement of hazardous cargo and mandatory inspection of the relevant vehicles before they enter a tunnel.

Competing interests

The author(s) declare that they have no competing interests.

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ORCID iD

Omar Lanchava https://orcid.org/0000-0003-4249-9404

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