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Modeling and optimization of road tunnel ventilation with respect to pollutant dispersion and traffic variables

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Abstract: Road tunnels present complex challenges for ventilation due to the accumulation of exhaust gases and heat from vehicles, installations, and the surrounding rock. The primary goal of tunnel ventilation is to maintain air quality by reducing toxic gases such as carbon monoxide (CO), hydrocarbons, and aldehydes to safe levels, as well as to regulate temperature and visibility. This article presents the experimental method and the results obtained in order to evaluate the effectiveness of natural ventilation in a railway tunnel.

Keywords: tunnel ventilation, carbon monoxide (co), exhaust gases, air quality, traffic intensity, fuel consumption, heat emissions, toxic gas concentration, road tunnel safety, altitude effect

1. Introduction

Tunnel ventilation is a critical aspect of underground infrastructure that ensures air quality, temperature regulation, and the safe removal of toxic gases and smoke during regular operation and emergencies. As urban areas expand and the demand for efficient transportation systems increases, the construction of tunnels for roadways, railways, and subways has become more prevalent. Despite the significant development of engineering solutions, tunnels still pose special challenges related to limited space, air movement, visibility, and ensuring human safety. In such conditions, a reliable ventilation system is necessary not only to maintain acceptable air quality, but also to prevent the accumulation of dangerous pollutants such as carbon monoxide (CO), nitrogen oxides (NOx) and suspended particles. During fires or accidents, ventilation becomes a key element of smoke management and evacuation management. Over the past decades, various options for natural and mechanical ventilation have been developed, which are now increasingly complemented by digital monitoring and automation systems. This paper examines promising areas for the development of tunnel ventilation, new technical solutions and their impact on safety and sustainability of operation.

2. Methodology

In order to evaluate the operation of ventilation systems in conditions as close as possible to real conditions, a series of full-size experiments were conducted in a 20 km long railway tunnel. This tunnel, which is part of the Transgorny railway corridor, provided an opportunity to study in detail the behavior of air flows, the spread of gases and thermal processes both under normal conditions and during fire simulation.

The experimental tests were performed at a stable temperature of 22 °C and a relative humidity of 55%. The main objective of the study was to determine the effectiveness of various ventilation schemes, identify the features of the spread of smoke and gas emissions, and compare the data obtained with the results of laboratory experiments and CFD modeling. The tunnel is equipped with a longitudinal ventilation system, including jet fans located at regular intervals, and ventilation shafts at key points. Measurement and control systems were additionally deployed during the tests.

During the experiments, CO_2 was dosed into the tunnel to simulate the exhaust of diesel locomotives, as well as artificial smoke to test the behavior of smoke streams during a fire. The release points were located near emergency exits and in places with the least effective natural ventilation, which made it possible to simulate the most unfavorable scenarios. The co_2 consumption was selected in such a way as to match the load of a diesel locomotive during intensive operation.

A network of sensors, including gas analyzers, thermal imagers, and ultrasonic anemometers, was used to register the environmental parameters. They recorded gas concentrations (ppm), air temperature (°C), and flow velocity (m/s) in real time. A rapid decrease in temperature was observed in the test areas due to forced ventilation, which is an important factor for maintaining safe conditions in emergency situations. In total, over 60 measurement points were installed at different heights and cross-sectional positions throughout the tunnel. All sensor outputs were transmitted to a central control station and analyzed using a LabVIEW-based data acquisition platform.

Three main ventilation scenarios were tested:

1. **Baseline (no active ventilation):** Natural dispersion of CO_2 and smoke without fan assistance.
2. **Partial ventilation (low-speed fans):** Limited fan activation at specific segments.
3. **Full emergency ventilation (high-speed fans):** All jet fans operating at maximum capacity.

Each test scenario lasted approximately 45 minutes, with continuous monitoring throughout the injection and post-injection phases. In the absence of mechanical ventilation, the dispersion of CO_2 was slow and localized, leading to elevated gas concentrations near the emission source. Smoke stratification was observed near the tunnel ceiling, posing a risk to evacuation safety in case of real fire events.

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With low-speed ventilation, pollutant removal was moderately improved, but some areas still showed residual gas pockets. The most efficient outcome was achieved during full-speed ventilation, where airflow exceeded 3 m/s and gas concentrations dropped to safe levels within 10–12 minutes.

The results obtained are in good agreement with the data from laboratory installations and calculated CFD models, which confirms the reliability of large-scale experiments as the basis for designing ventilation systems. In addition, they make it possible to refine safety protocols, from sensor placement to fan activation algorithms and optimization of evacuation routes.

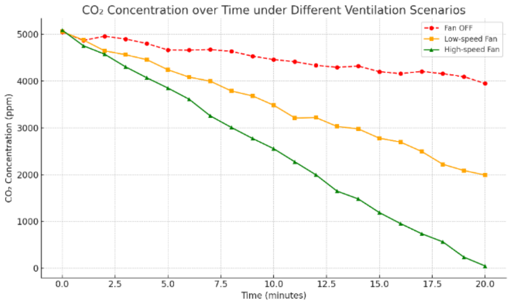

Fig. 1. Change in co₂ concentration under different ventilation operation options

The graph shows that in the absence of ventilation, the concentration decreases extremely slowly, creating a risk of prolonged exposure to polluting gas. Working at a reduced speed accelerates the dilution of CO_2, and the high-speed mode ensures the fastest reduction in concentration, emphasizing the crucial role of active ventilation.

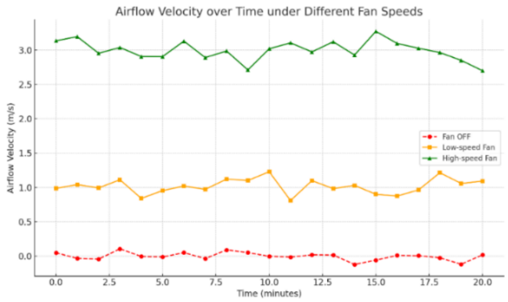

Fig. 2. Air flow velocity at different fan operating modes

When ventilation is turned off, there is practically no air movement. Low speed ensures moderate ventilation, while high speed creates a steady flow of about 3 m/s, which significantly increases the efficiency of air exchange. These results highlight how increased fan power directly contributes to enhanced air movement, crucial for effective tunnel ventilation during both normal and emergency conditions.

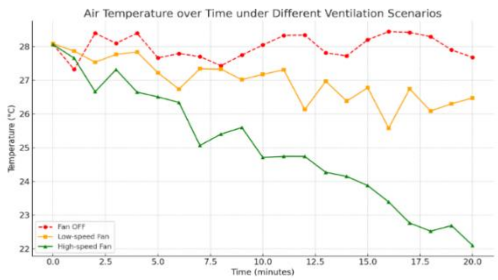

Fig. 3. Change in air temperature over time under different ventilation strategies

This figure shows how air temperature behaves under different ventilation setups. With no ventilation, temperature remains relatively constant and may rise in real fire scenarios. However, both low-speed and high-speed fans introduce cooling effects by increasing air circulation. The high-speed fan notably reduces the temperature more quickly, preventing heat buildup and supporting safer evacuation during fire incidents.

3. Results and discussion

When vehicles move, their engines emit heat and fuel combustion products (exhaust gases), which include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), unsaturated hydrocarbons, aldehydes and a number of other components (nitrogen, oxygen, hydrogen, etc.), as well as soot and fuel and oil vapors. Other sources of heat in tunnels are operating installations, lighting and people in the tunnels [1]. The heat balance is significantly affected by heat exchange between the air in the tunnel and the surrounding rocks. In some cases, underground gases may be released in tunnels [3].

The purpose of ventilation (airing) of tunnels is to ensure such an exchange of air in them that:

1) the concentration of harmful gases is reduced to limits that do not pose a danger to human health;

2) the difference between the air temperature inside and outside the tunnel is reduced to an acceptable size;

3) smoke that affects visibility in the tunnel is eliminated.

These tasks are quite difficult to solve for tunnels. Neutralization of exhaust gases before they are released into the atmosphere is of great importance for road tunnels.

As numerous studies have shown, carbon monoxide is a dangerous component of the air due to its high toxicity and its rather significant content in exhaust gases.

If, through ventilation, the CO content in the tunnel air is reduced to acceptable limits, such hazardous components of the exhaust gases as unsaturated and unsaturated hydrocarbons and aldehydes are also neutralized.

In addition, the smoke in the tunnel is reduced so significantly that normal visibility is ensured when driving in it. Thus, the main gas by which the required ventilation volume should be determined is carbon monoxide (CO).

Since a significant amount of heat is supplied to the tunnel air, which may be unsuitable for a long stay of people in it, the ventilation volume must be sufficient to ensure a favorable temperature regime in the tunnel, such a circumstance may be decisive. Therefore, a verification calculation of ventilation based on heat emissions is always mandatory [2].

The complexity of ventilation of road tunnels depends on their length and traffic intensity. In order to move and distribute large volumes of air along the length of the tunnel, it is sometimes necessary to occupy part of its cross-section for ventilation ducts, to build a whole system of supply ducts and installations.

The cost of ventilation of road tunnels is 10-30% of the cost of the entire structure. Therefore, ventilation issues must be promptly and correctly resolved in a complex of tasks of designing the tunnel as a whole.

In particular, ventilation can have a significant impact on the choice of the tunnel route, the purpose of its cross-section, and the presence of additional entrances - on the organization of work on tunnel excavation. In order to eliminate the harmful effects of gases and, consequently, reduce ventilation costs, in some cases it is rational to switch to electric traction for moving cars with engines turned off along a long tunnel on special rolling stock.

The required ventilation volume in m3/sec per 1 km of tunnel can be represented as a simple relationship:

$$Q = \frac{B}{D}, \quad (1)$$

Where

B is the amount of gas emitted, g/sec;

D is the permissible concentration, mg/l or g/m3.

Uniform standards for permissible concentrations of CO in road tunnels must take into account the dependence of the permissible concentration on the duration of stay in the tunnel, fluctuations in traffic intensity and the altitude of the tunnel above sea level. As studies show, the F factor of CO exposure is manifested not only depending on the concentration of the gas, but also on the duration of stay in a CO-contaminated atmosphere, i.e.

$$F=1000Dt, \quad (2)$$

where

D is the permissible concentration, %0;

t is the duration of exposure, h.

At the same time, numerous studies show that for a long stay, the permissible concentration is 0.11 - 0.20 mg/l (0.09-0.16°/00).

The estimated maximum traffic intensity can only be observed during short periods of time, usually within an hour, when repair work should be stopped; in the event of a traffic stop, the engines should be turned on. Then the duration of stay will be:

for persons in cars moving at a maximum speed of 15 km/h,

$$T = \frac{L_T}{15}, \quad (3)$$

where

L_T is the length of the tunnel

for pedestrians and surveillance personnel (taking into account that in long tunnels in places where personnel are permanently present inside the tunnel, an additional supply of fresh air must be provided) $T = \frac{L_T}{3}$,

During normal (daily average) traffic, the permissible concentration standards should guarantee complete safety of long-term stay of service personnel in the tunnel, as well as the possibility of heavy repair work lasting up to 0.6 hours (without interrupting normal traffic). As studies have shown, with increasing height of the tunnel, the human body becomes more sensitive to CO, since as a result of the change in pressure (volumetric weight of air), the percentage of blood oxygen saturation decreases. The dependence for the permissible concentration of D_H at height H above sea level can be presented as follows:

$$D_H=D-0.01H, \quad (4)$$

where

D is the permissible concentration of CO under normal conditions;

H is the altitude above sea level, km.

The amount of CO emitted by vehicles in a tunnel depends on a number of factors, among which the most important are:

1) the estimated traffic intensity of vehicles in the tunnel (N vehicles per hour);

2) the speed of the vehicle in the column (v_K, km/h);

3) the amount of fuel consumed by the vehicle (q_c, g/sec);

4) the content of carbon monoxide in the exhaust gases.

The last two factors depend on the profile of the track, which indicates the need for differentiated ventilation by volume with dispersed inflow and exhaust for sections with different slopes. Ventilation calculations should be based on vehicles with carburetor internal combustion engines, which continue to be the most common type of engines and produce the highest content of CO in the exhaust gases.

The fuel consumption for each estimated type of vehicle on the considered section of the tunnel with a uniform slope can be determined based on the economic characteristics of the vehicle. More accurate results will be given by a detailed calculation.

You can go to the fuel consumption per second using the dependence

$$q_c = q\frac{v_K}{3600}, \quad 5)$$

where

q is the amount of fuel consumed by the vehicle, g/km;

v_K is the speed of movement, km/h.

With an increase in the height of the tunnel above sea level, the consumption also increases somewhat and can be taken as:

$$q_H = q(1+0.022H). \quad (6)$$

The CO content in the exhaust gases depends on the completeness of fuel combustion, i.e. on the composition of the working mixture, which is characterized by the excess air coefficient a. Under normal operating conditions, it is 0.95 - 0.85; when the engine is idling, a rich mixture is usually used (a = 0.8). To determine the weight amount of CO (in kg) in the exhaust gases, you can use the formula

$$P = 0.14q\left(\frac{c}{3}+h\right)(1-\alpha), \quad (7)$$

where

q is the fuel consumption, kg;

c is the percentage (by weight) of carbon content in the fuel;

h is the same, hydrogen.

Substituting the above average data for the fuel, we find:

$$P = 6.06q(1-\alpha). \quad (8)$$

The result of gas recovery is affected by the altitude of the tunnel above sea level. Initial ratio:

$$\frac{\alpha_H^2}{\alpha_0^2} = \frac{\gamma_H}{\gamma_0}, \quad (9)$$

where

α_H is the coefficient of excess air at a height H above sea level;

α_0 is the same, at sea level;

γ_H is the volumetric weight of air at a height H above sea level, kg/m3;

γ_0 is the same, at sea level, kg/m3.

Using the scale of change of y for air depending on H, it is possible to establish an approximate dependence

$$\sqrt{\frac{\gamma_H}{\gamma_0}} = 1 - 0.045H. \quad (10)$$

Then for any tunnel location:

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$$P_i = 6.06q[1-\alpha(1-0.045H)]. \quad (11)$$

After some simplifications, it is easy to establish that the amount of harmful gas bi (in grams) emitted by a car of this type when driving on a section with a uniform slope is per second:

$$b_i \cong 6.06q_c[1+0.022H - \alpha(1-0.023H)]. \quad (12)$$

Since the amount of CO depends on ik, several possible variants of movement by speed should be considered when calculating ventilation. The total estimated amount of harmful gases per 1 km of tunnel length for a section with a uniform longitudinal profile can be determined if the estimated number of cars (N cars per hour), the proportion of cars moving in opposite directions (A_1N and A_2N), and the composition of the estimated traffic flow, i.e. the proportion of m. cars of each estimated type, are known. In this case, the following conditions must be met:

$$A_1 + A_2 = 1; \quad \sum m_i = 1. \quad (13)$$

Then, knowing the number of cars N/v_K simultaneously located on a section of 1 km in length, we find an expression for the amount of CO (in g/sec) emitted on this section,

$$B\,\frac{N}{v_K}(A_1 \sum m_i b_i^{п} + A_2 \sum m_i b_i^{c})\,, \quad (14)$$

where N is the estimated hourly traffic in the tunnel, cars per hour;

A_1 is the share of cars going uphill;

A_2 is the same, going downhill;

ti is the share of the total flow of cars of this type;

b_i^c is the amount of CO emitted by a car when going downhill;

$b_i^{п}$ is the same, when going uphill.

When all cars move in the same direction, the formula is simplified accordingly:

$$B = \frac{N}{v_K} \sum m_i b_i. \quad (15)$$

The quantities $A_1 \sum m_i b_i^{ц} + A_2 \sum m_i b_i^c$ и $\sum m_i b_i$ express the average amount of CO (in g/sec) emitted in the tunnel by one car, which we denote by p. Then

$$B = \frac{N}{v_K} \rho, \quad (16)$$

The value of N, as well as the coefficients A_1 and A_2, should be assigned based on the near future, since after the expiration of the depreciation period, the fans can be replaced by units with greater productivity, and also taking into account the process of increasing the efficiency of cars and improving their design.

The analysis of various tunnel ventilation systems shows significant advancements in both technology and implementation methods. Traditional mechanical ventilation systems, primarily longitudinal and transverse air supply, are still widely used, but in recent years they have been actively supplemented by intelligent control algorithms and sensor monitoring systems. As modern research in a number of European and Asian tunnels shows, the use of real-time data-based control reduces energy consumption by 20-35%, while maintaining the required air quality indicators both under normal conditions and in emergency situations.

Noticeable changes are also taking place in the direction of greening tunnel infrastructure. Auxiliary fans powered by solar panels, braking energy recovery systems in railway tunnels, as well as materials with reduced emissions during operation are increasingly being used. The combination of such solutions provides a measurable reduction in the carbon footprint. Computational methods also play an important role: CFD modeling is widely used to analyze air flows, the spread of gases and smoke in the event of a fire, which helps optimize design solutions and response plans.

The discussion highlights the impact of urbanization and climate change. In megacities with heavy traffic and rising ambient temperatures, the load on ventilation systems is increasing. In such conditions, hybrid schemes that combine elements of natural and mechanical ventilation become especially effective, especially in long and complex tunnels.

In general, the results show that the development of ventilation systems requires constant technological improvements and the interaction of specialists from different fields. Modern ventilation has long been beyond the "mechanical" provision of air exchange — it is becoming part of an integrated infrastructure related to traffic management, energy and safety

4. Conclusion

Ventilation systems play a key role in ensuring safety, maintaining air quality and efficient operation of road and railway tunnels. As the complexity of tunnel constructions increases and the requirements for sustainable development increase, such systems must adapt to new environmental, technological and regulatory challenges. Advanced sensor technologies, artificial intelligence techniques, and the integration of renewable energy sources are making a significant contribution to this transformation. The transition to electric transport will also influence the design of future systems, creating both new capabilities and new safety requirements. The implementation of these approaches requires close coordination of engineers, technologists, environmentalists, and risk management specialists.

Rapid engineering technology will define the future of the tunnel ventilation systems in a very large part. The longer and more intricate the tunnels, particularly in hilly and densely populated locations, the more the smart and dynamic ventilation plans are demanded. The generation of systems that will be created will be completed with automatic algorithms, constant monitoring and devices to adjust the air flows according to the traffic load, the level of pollution and the characteristics of the emergency. With the help of the IoT sensors, it will be possible to monitor the microclimate and the air quality inside the tunnel in a more precise manner throughout the entire length of the tunnel.

The system of ventilating the tunnels will enter the world of the so-called smart cities: it will be connected with the traffic control system, environmental surveillance points and emergency response centers. According to the case, the system can automatically be improved to increase air exchange, eliminate smoke or gases that are harmful in case of congestion or an accident. The integration will deliver centralized management, enhance reliability, and enable the maintenance of equipment based on a forecast.

The presence of electric and hybrid transport will also cause a decrease in the concentration of diesel engine emissions, and the change in the ventilation requirements.

Nevertheless, such risk factors as battery overheating or certain emissions during electricity vehicle ignition will emerge. These features will be required to be considered by the ventilation systems, which will be expected to offer protection based on the new accident scenarios.

As ventilation is among the most energy-consuming systems of the tunnel operation, a lot of focus will be put on its optimization in the future. The introduction of high efficiency fans, frequency drives and energy recovery systems will also help in saving a lot of energy. There will be an increased importance of integration with the sources of renewable energy in order to decrease the carbon footprint.

The CFD techniques of the modern and future will be a significant design tool. They enable the possibility of forecasting air movement, temperature patterns and spreading smoke in different conditions. As part of AI, these models may be applied to operational testing of design solutions and the creation of real-time response scenarios.

Safety remains a key aspect. It should be not only the removal of smoke in the event of fire, but also the maintenance of directed air flows, the creation of safe zones, and also effective work in the event of power failures or interruptions. Other levels of redundancy will be visible in the systems.

Besides this, ventilation should also be more health and comfort sensitive to people both users and maintenance employees. Since the requirements of microclimate will increase, it will be necessary to fine-tune the microclimate and continuously monitor the parameters.

In construction of tunnels in high altitudes, the ventilation systems should consider the characteristics of low atmospheric pressure and low oxygen composition. This influences the functionality of the equipment as well as air exchange calculations. The quantity of the projects devoted to such conditions will grow in the future.

Another important feature will be modularity. The design of the ventilation complexes will be in this manner, so that it can be easily extended or modified with the increase in the traffic load without significant construction activity.

Lastly, creation of the regulatory framework will be a major factor. The energy efficiency, reliability, emissions and air quality requirements are anticipated to be tightened gradually and will provoke the innovation of new solutions This will also require more cooperation between the civil engineers, environmental scientists, health professionals, and policymakers. International best practices and cross-disciplinary research will be necessary in developing holistic, safe and futuristic ventilation measures of tunnel infrastructure

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