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Mechanics

Multifactorial Dynamic Model for the Analysis and Evaluation of Road Tunnel Fires

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(Presented by Academy Member Elguja Medzmariashvili)

Abstract. The article addresses the limitations of traditional approaches to managing ventilation systems in the event of road tunnel fires, particularly regarding the effectiveness of models based on critical velocity and static Froude number assumptions. It has been analyzed that under real-life fire scenario, where the tunnel geometry, the fire development rate, and thermal pressure vary dynamically, predefined values of critical parameters do not provide an optimal safety strategy. The article presents a multifactorial dynamic model, combining CFD (Computational Fluid Dynamics) simulation, evacuation modeling, and algebraic combination of thermal and mechanical airflows, as well as the impact of a tunnel geometry and gradient on the efficiency of the ventilation. The paper highlights that the mechanical pressure generated by the tunnel fans may be exceeded by the thermal pressure created by a fire, causing back-layering – a reverse spread of smoke and toxic gases, posing threat to evacuation routes. The Froude number (Fr) is given a special consideration, as a dynamic variable indicator, greatly dependent on the temperature and air density. The authors indicate that synchronizing the model with the evacuation procedures presents a basis for an efficient safety strategy – taking into account the pace of human movement, the impact of toxicity threshold and temperature. The article presents a scientific justification of an integrated approach, aimed at designing and operating safer road tunnel infrastructure. *© 2025 Bull. Natl. Acad. Sci. Georg.*

Keywords: road tunnel, Froude number, CFD simulation, fire, critical velocity

Introduction

International guidelines for the design of emergency ventilation systems, as well as the fire safety manual of the United States – one of the world's most developed countries (NFPA 502 Standard, 2023) – concur that the critical velocity of the ventilation airflow constitutes a key technological parameter enabling effective smoke control in transportation tunnels under all fire conditions without any exception. The same idea is also conveyed in numerous scientific studies, among which only the reference literature (Bird and Carvel, 2012) is highlighted. This occurred after the publication of R. Thomas's paper "The movement of buoyant fluid against a stream and the venting of underground fires" (Thomas, 1958). Uncritical acceptance of this premise in contemporary conditions is a significant error, as will be convincingly demonstrated below. Notably, the idea of critical velocity is based on the constancy of the Froude number, while below we demonstrate that the Froude number is not a constant quantity under real fire conditions.

Therefore, under longitudinal ventilation conditions, the critical velocity is adopted as a decisive factor in emergency ventilation strategies for preventing back-layering. Back-layering is the reverse spread of combustion products against the upward ventilation flow, occurring in the air supply section of the tunnel where clean air is expected. This is caused by the high temperature of the combustion products, which results in their lower density and buoyancy due to the buoyant force. This phenomenon poses a significant threat to life safety during evacuation. This phenomenon is particularly pronounced when the airflow moves from a higher hypsometric level to a lower one, while the fire source is located at the lower level.

The critical velocity is the minimum ventilation airflow speed that must be maintained to prevent back-layering. The critical velocity depends on the fire intensity, the tunnel cross-sectional area and slope, as well as other factors. As the dynamic pressure generated by the fire and the corresponding pressure from the fans are summed up algebraically, in order to prevent smoke infiltration into the clean airflow section of the tunnel, the clean air stream must have a velocity higher than the critical velocity. Thus, according to the idea, under longitudinal ventilation system conditions, an airflow with the critical velocity expels smoke and other harmful combustion products from the fire source to only one side, while clean air should be maintained on the opposite side.

In our study (Ilias et al., 2017), using the Clapeyron equation, it was determined that the dynamic pressure generated by a fire at a temperature of 1000℃ in tunnels amounts to 121.6 kPa, which exceeds atmospheric pressure and is eight times greater than the maximum static pressure of the most powerful fans. At this time, the air density is reduced to 0.277 kg/m³. Consequently, in case of a severe fire, it becomes practically impossible to control the ventilation flow using fans, and the direction and volume of air movement will be determined by the thermal depression. This contradicts the idea of critical velocity. Therefore, a preliminary numerical modeling was conducted. The aim of the numerical models was to demonstrate the continuous increase of critical velocity with rising fire intensity (Lanchava, 1982; Lanchava and Javakhishvili, 2021), as well as to highlight the inconsistency between back-layering prevention solely on this concept and the numerical modeling results, alongside with the findings from other studies conducted by us.

Interaction between Tunnel Ventilation Systems and Fire Dynamics

A tunnel jet fan, capable of generating a pressure of approximately 2000 pascals, is influenced by the presence of a fire during emergency conditions. In the case of descending ventilation, thermal (fire-induced) pressure and mechanical (fan-generated) pressure act in opposite directions, and the pressure difference is defined by the following formula

$$\Delta P = P_f - P_h , \qquad (1)$$

where P_f is the fan-generated pressure, Pa; P_h is the fire-induced dynamic pressure, which increases along with temperature, Pa.

ΔP demonstrates an inversely proportional dependence on the fire heat release rate (HRR). With increasing fire intensity, which corresponds to rising temperature, ΔP decreases. When $\Delta P = 0$, the pressure generated by the fan is balanced by the dynamic pressure induced by the fire. A subsequent rise in temperature results in back-layering of smoke and other toxic combustion products, constituting a critical hazard to life safety during evacuation scenarios. It is of particular interest to identify the intersection point between the fan pressure line – approximately at the level of 2000

Pascal (Fig. 1) – and the rising curve of thermal pressure induced by the fire.

As illustrated in the diagram, under the fire development scenario with a heat release rate of 70 MW, the intersection of the fan pressure line and the fire-induced pressure curve occurs at a point corresponding to a fire intensity of 30 MW. In this case, $\Delta P = 0$. The diagram also shows that the curve is ascending, and accordingly, ΔP continues to increase beyond this point.

The theoretical basis is the Clapeyron equation for the ideal gas state, which is expressed as follows:

$$PV = nRT, \qquad (2)$$

where P is the pressure, Pa; V is the internal volume m^3; n is the gas mole quantity; R is the universal gas constant, J/(mol. K); T is the temperature, K. Internal volume related to the air density is calculated by the formula

$$V = {}^{1}/_{\rho}\,. \qquad (3)$$

If the volume of air (number of moles) remains constant, then pressure and temperature are related by the following formula

$${}^{P}/_{T} = \text{Const}, \qquad (4)$$

which indicates that there is a directly proportional relationship between temperature and pressure, and as temperature increases, the gas pressure rises sharply.

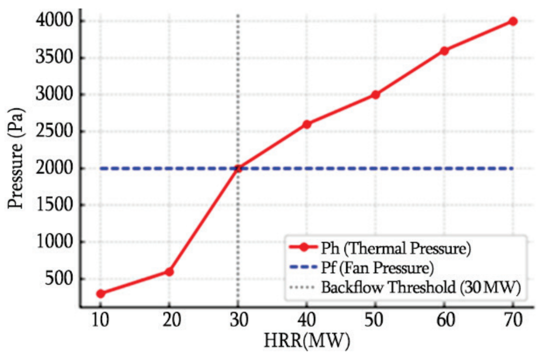

Fig. 1. Dynamics of mechanical and thermal pressures according to fire development.

Thus, if $\Delta P > 0$, the fan pressure prevails over the pressure generated by the fire; if $\Delta P \approx 0$, the fan and fire pressures are balanced, resulting in limited ventilation effectiveness; and if $\Delta P < 0$, the pressure in the fire zone exceeds the fan pressure rendering the fan unable to maintain ventilation and causing back-layering of smoke and other toxic combustion products. This corresponds, as noted, to the case of descending (downward) ventilation. Under conditions of ascending (upward) ventilation, the flows generated by the fan and the fire move in the same direction and reinforce each other, which means that the fan-induced and fire-induced flows are always summed up algebraically.

In tunnel ventilation systems, fans not only serve the function of moving air volumes, but also play a crucial role in creating controlled directional airflow. This controlled flow can counteract buoyant movements caused by fire (to prevent smoke spread along evacuation routes) or, conversely, support evacuation by directing smoke toward designated extraction openings. This controlled airflow is essential for planning safety strategies and evacuation routes.

Importantly, fire does not reach its maximum intensity immediately; rather, a fire that ultimately attains 30 megawatts gradually grows to this value following the heat release rate growth curve, which depends on the type of fuel used, tunnel geometry, and environmental conditions. Thus, during the early stages of fire, ventilation can operate effectively alongside the airflow because the dynamic pressure generated by the fire remains low and mechanical pressure predominates. It is only after reaching a certain threshold that the balance shifts, and the ventilation system must compete with increasingly strong pressures and buoyant flows of expanding gases. Therefore, it is important to analyze not only the final static condition, but also the temporal evolution of ventilation effects under dynamically developing fire conditions.

The main limitation of fan efficiency is thermal resistance. During a fire, the fan is subjected to extreme temperatures, and as the temperature rises, its materials degrade, causing bearings, electronics, and other critical components to fail. If the temperature in the ventilation zone exceeds the design limits (typically around 250-400°C depending on the fan type), the operational lifespan of the fans is significantly reduced, meaning that ventilation remains effective only for a limited period.

Another important aspect is the variability of air density along the length of the tunnel. Closer to the fire, the air is significantly warmer and lighter than the air drawn in from the environment. Therefore, fans operate in environments with varying air densities and consequently different dynamic resistances, which affects their actual contribution to the overall pressure balance. It should also be noted that tunnel ventilation is typically not achieved by a single device; rather, it involves a combination of fans arranged in series or transverse segments, which operate together to influence the airflow. Each of these fans has a different instantaneous contribution, depending on its position, ambient temperature, tunnel configuration, and flow direction.

Thus, the design of ventilation systems must consider not only the fan capacity, but also the tunnel geometry, as the cross-sectional profile directly influences how the supplied energy is transferred to the controlled airflow and how effectively it can resist forces generated by the fire.

In summary, ventilation facilitates overall flow control through directional and pressure effects, which can either act synergistically with the fire-induced flow or, conversely, serve as a fire barrier. To develop an effective system, it is essential to conduct a precise analysis of not only the maximum values, but also the temporal dynamics. In this case, it is considered appropriate to apply the proposition introduced by us implying that thermal and mechanical flows are summed up algebraically in tunnel ventilation systems.

The proposed multifactorial dynamic model must take into account: 1. the time-varying nature of heat release and fire propagation; 2. the deterioration of mechanical ventilation performance in response to fire development, which is especially pertinent to descending (downward) ventilation due to understandable reasons; 3. the tunnel geometry and gradient; 4. algebraic summation of thermal and mechanical flows; 5. the results of advanced CFD simulations, which incorporate the indicated dynamics along with experimental validation of the outcomes, which will enable the design of safer road tunnels by taking these components into account. The aforementioned modeling should also be synchronized with evacuation simulations to ensure the rescue of human lives within the critical time window before the onset of harmful factors (such as high temperature, smoke, toxic combustion gases, and others).

The Froud Number (Fr)

The Froude number is used in engineering and physics to evaluate and compare inertial and gravitational forces. The Froude number becomes particularly important in fire modeling and in determining the effectiveness of ventilation in tunnels. The Froude number indicates whether the ventilation flow has sufficient force to overcome the buoyant rise of hot gases.

The Froude number is generally formulated based on the density or temperature of the ventilation flow.

$$Fr = \frac{u}{\sqrt{gH^{\Delta\rho}/_{\rho_0}}} \text{ or } Fr = \frac{u}{\sqrt{gH^{\Delta T}/_{T_0}}}, \quad (5)$$

where u is the velocity of the ventilation flow, m/s; g is the acceleration due to gravity, 9.81 m/s²; H is the tunnel height, 5.0 m; $\Delta\rho$ is the density differential between the surrounding environment and hot gases, kg/m³; ρ_0 is the ambient air density, 1.2 kg/m³; ΔT is the difference between ambient and hot gas temperature, K; T is the ambient air temperature, 293,2 K. The increase of pressure and temperature are calculated according to the formulas, respectively

$$\Delta\rho = \rho_0 - \rho_h, \quad (6)$$

$$\Delta T = T_0 - T_h. \quad (7)$$

In formulas (6), (7) ρ_h is the air density at temperature T_h, kg/m^3; $T_0 = 293{,}2\,K$ is the ambient air temperature; T_h is the ventilation air temperature under fire conditions K.

It is possible to rearrange formulas (5) into a form more convenient for manual calculation

$$Fr = \frac{u\sqrt{\rho_0}}{\sqrt{gH\Delta\rho}} \text{ or } Fr = \frac{u\sqrt{T_0}}{\sqrt{gH\Delta T}}\,. \qquad (8)$$

The provided Froude number formulas are applied in nearly all types of CFD simulations to analyze fire dynamics and determine critical flow velocity. The use of the Froude number in tunnel fire scenarios is valid when: 1. the Froude number is a constant value, known as the critical value $Fr_c = 4.5$; 2. at the fire source, the ratio of fresh air to combustion products is 50% to 50%; 3. the width-to-height ratio of the tunnel is 1.6, which corresponds to a tunnel width of 8 meters and a height of 5 meters. It should be noted that these conditions are practically unattainable in real situations. Specifically: 1. the Froude number varies due to changes in temperature and air density and is not a constant value; 2. the fire is neither stationary, nor uniformly distributed; it mostly develops gradually, creating variable zones of heat, smoke, and toxic combustion products, and in many cases, the specified 50%-50% ratio is not maintained; 3. modern multi-lane tunnels are characterized by large widths (15 meters or more), complex geometry, and constant ceiling heights (5 meters), and often do not maintain the specified width-to-height ratio of 1.6. Additionally, the tunnel slope gradient introduces gravitational effects that significantly alter the dynamics of the upward flow, which the standard Froude number does not account for. Once the heat release exceeds 30 megawatts, the thermal flow often dominates mechanical ventilation, changing the flow direction regardless of whether the flow has reached the critical velocity.

Sometimes, the formula is expressed using the inverse form of the Froude number

$$Fr' = \frac{\Delta\rho g H}{\rho_0 u_c^2}\,. \qquad (9)$$

A proportional relationship is maintained between the defined quantities: (5) or (8) and (9) formulas

$$Fr' = 1/_{Fr^2} \text{ or } Fr = 1/_{\sqrt{Fr'}}\,. \qquad (10)$$

The given formulas are applied to assess ventilation strength under conditions of counterflow, where downward ventilation streams oppose the upward movement of hot gases. If $Fr' < 2$, Ventilation remains strong, and reverse airflows are not triggered by the buoyant rise of hot gases. When $Fr' > 2$, under such conditions, the ventilation is insufficient compared to the buoyant force generated by the fire, leading to the reverse flow of smoke and combustion products.

The numerical value of the Froude number changes with the variation in fire intensity, as shown in the Table below. The following quantities were used in the table for the calculations: u – the average ventilation speed, 3.5 m/s; g – gravitational acceleration, 9.81 m/s²; H – tunnel height, 5.0 m; T_h – ambient air temperature, 293.2 K; ρ_0 – ambient air density, 1.2 kg/m³.

Table. Variation of Froude number according to fire intensity

N	Fire intensity Q, MW	Air temperature T_h, K	Air density ρ_h, kg/m^3	Air flow speed u, m/s	Thermal pressure P_h, Pa	The Froude number Fr'
1	10	393	0.896	3.5	~600	1.01
2	20	493	0.715	3.5	~1200	1.62
3	30	593	0.596	3.5	~1800	2.01
4	50	693	0.517	3.5	~2400	2.28
5	70	793	0.459	3.5	~3000	2.47
6	100	893	0.411	3.5	~3600	2.63
7	150	993	0.374	3.5	~4200	2.75

Evaluation of Froude Number Limitations and Justification of Necessity for Multifactorial Modeling

As demonstrated above, while the Froude number remains a critical parameter for evaluating the balance between ventilation momentum and the buoyancy-driven smoke flow, its applicability is significantly constrained under realistic tunnel fire scenarios. The ideal assumptions required for the critical thresholds of the Froude number – such as fixed geometric parameters, uniform gas mixture, and constant air density – are rarely met in the operational practice of modern tunnels.

Moreover, the temporal variability of fire development, coupled with changes in the thermophysical properties of combustion products and complex non-uniform geometry, causes significant fluctuations in the Froude number throughout the fire's entire development cycle. Computational Fluid Dynamics (CFD) models typically incorporate this parameter; however, relying solely on the Froude number without accounting for the interactions of multiple sources may lead to overly simplified safety predictions. Therefore, within the framework of the proposed multifactorial model, the Froude number should be considered not as a fixed value, but as a dynamic parameter sensitive to changing conditions. The given conditions include: temporal variation of fire intensity and temperature; changes in tunnel geometry and inclination; variability in airflow direction and its stratification; local gradients of density and pressure. Such model provides a more realistic, robust, and safer basis for the design of tunnel ventilation systems and the coordination of evacuation strategies.

Integrated Modeling for Fire Safety in Road Tunnels

The essence of the problem. CFD methods are used in modeling fires in road tunnels to achieve high accuracy in predicting: temporal variation of temperature fields; smoke propagation; variations in the concentration of carbon monoxide and other toxic gases; changes in visibility; variations in air velocity and flow direction.

CFD modeling requires small time steps (e.g., 0.1 to 1.0 seconds) to accurately capture rapidly changing processes, especially during the initial minutes of fire development. It also takes into account the heterogeneous and dynamic nature of fire spread. Instead of a static, single-point fire source, actual fires often involve multiple ignition points caused by thermal radiation or flame spread to nearby vehicles or infrastructure. Delayed secondary ignitions can occur, leading to the formation of new fire sources at different locations and times.

Evacuation models (such as Pathfinder, Mass Motion, Building EXODUS, Any Logic) primarily use larger time steps (5-10 seconds or more) because human movement occurs relatively slower compared to fire dynamics and temperature changes.

Thus, fire scenarios require high-frequency temporal data (observations at the second level), whereas evacuation models operate on lower-frequency data (observations at the minute level).

Scientific challenges during integration. The temporal resolution discrepancy can be resolved in such a way that integration of both models is realistic and interpretable. The following approaches can generally be employed for integration:

1. Asynchronous time scales – significant processes occur in CFD at each second, while evacuation involves human movement over longer time intervals.
2. Data aggregation – how to represent rapidly changing temperature fields as 'average,' 'maximum,' or 'minimum' values over a given time unit for human evacuation models.
3. Integration methodology via two approaches:
   Unidirectional coupling: CFD results are fed into the evacuation model without feedback;
   Bidirectional coupling: Evacuation modeling results influence the CFD model (e.g., effects of

opened doors, flow variations caused by human movement, etc.)

4. Transfer of critical parameters from CFD to evacuation models for appropriate response actions: visibility, affecting movement speed; temperature, impacting a person's ability to move (e.g., ≥60°C, movement becomes impossible); concentration of toxic gases, influencing risk of poisoning, delays, and stoppages.

Thus, evacuation requirements must be reflected in ventilation priorities, and ventilation should facilitate safe movement. Such a model is essential both for advance planning and real-time response. Based on the above, it becomes clear that ensuring life safety during fires in road tunnels requires the use of fully integrated modeling, which comprehensively encompasses ventilation dynamics, fire development phenomena, evacuation route assessment, as well as the determination of harmful and toxic exposure limits. Conventional single-factor models – such as those based solely on critical velocity or static Froude number – fail to capture variable scenarios under real-life conditions and result in superficial simulation insights. Therefore, the development of a multi-component simulation framework is of a great importance.

Conclusion

Effective ventilation management in road tunnel fire scenarios cannot rely solely on the standard provision of critical velocity. Under real fire conditions, the Froude number, which forms the basis of this model, is not a constant parameter. Without accounting for fire intensity, tunnel geometry, slope gradient, density variations, and other factors, ventilation systems may become ineffective.

Based on numerical modeling and theoretical analysis, it has been demonstrated that:

- Instense fires can generate significant thermal pressure, which exceeds the mechanical pressure of fans, especially under the conditions of downward ventilation;
- The Froude number is variable and often exceeds the critical threshold;
- Ventilation operation is effective only during the early stages of fire, whereas a comprehensive approach is required at the subsequent stages;
- The efficiency of ventilation system is significantly dependant on tunnel geometry and ventilation configuration;
- To ensure safety, ventilation modeling must be synchronized with evacuation modeling.

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მექანიკა

მრავალფაქტორიანი დინამიკური მოდელი საავტომობილო გვირაბის ხანძრების ანალიზისა და შეფასებისათვის

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(წარმოდგენილია აკადემიის წევრის ე. მემმარიაშვილის მიერ)

წარმოდგენილ სტატიაში მოცემულია საავტომობილო გვირაბების ხანძრის შემთხვევებში სავენტილაციო სისტემების მართვის ტრადიციული მიდგომების შეზღუდულობა, განსაკუთრებით, კრიტიკული სიჩქარისა და ფრუდის კრიტიკული რიცხვის გამოყენებაზე დაფუძნებული მოდელების ეფექტიანობის კუთხით. გაანალიზებულია, რომ რეალური ხანძრის სცენარებში, სადაც გვირაბის გეომეტრია, ხანძრის განვითარების ტემპი და თერმული წნევა დინამიკურად ცვალებადია, კრიტიკული პარამეტრების ფიქსირებული დაშვებები არ ასახავს უსაფრთხოების ოპტიმალურ სტრატეგიას. სტატია გვთავაზობს მრავალფაქტორიან დინამიკურ მოდელს, რომელიც აერთიანებს CFD მოდელირებას, ევაკუაციის სიმულაციას, თერმული და მექანიკური ნაკადების ალგებრულ შეკრებადობას, აგრეთვე გვირაბის გეომეტრიისა და დახრილობის გავლენას ვენტილაციის ეფექტიანობაზე. აღინიშნება, რომ ვენტილატორის მიერ წარმოქმნილმა მექანიკურმა წნევამ შესაძლოა ვერ დასძლიოს ხანძრის მიერ შექმნილი თერმული წნევა, რაც იწვევს უკუდინებას – კვამლისა და ტოქსიკური აირების გავრცელებას საპირისპირო მიმართულებით. აღნიშნული გარემოება ევაკუაციის თვალსაზრისით საფრთხის შემცველია. განსაკუთრებული ყურადღება ეთმობა ფრუდის რიცხვის განხილვას, როგორც დინამიკური, ცვალებადი სიდიდის, რომელიც მნიშვნელოვნად დამოკიდებულია ტემპერატურასა და ჰაერის სიმკვრივეზე. ავტორები მიუთითებენ, რომ მოდელის სინქრონიზაცია ევაკუაციის პროცესთან – ადამიანის გადაადგილების ტემპის, ტოქსიკურობის ზღვრებისა და ტემპერატურული გავლენის გათვალისწინებით – წარმოადგენს ეფექტური უსაფრთხოების სტრატეგიის საფუძველს. სტატია წარმოადგენს ინტეგრირებული მიდგომის სამეცნიერო დასაბუთებას, რომელიც მიზნად ისახავს საავტომობილო გვირაბების შედარებით უსაფრთხო ინფრასტრუქტურის დაპროექტებას და ექსპლუატაციას.

REFERENCES

Bird, A., Carvel, R. (2012). Handbook of tunnel fire safety. Second edition. *Thomas Telford Limited*, 694.

Ilias, N., Lanchava, O., Nozadze, G. (2017). numerical modelling of fires in road tunnels with longitudinal ventilation system. *Quality Access to Success*, *18,* 77-80, Bucharest.

Lanchava, O.A. (1982). Heat and mass exchange in permanent mine workings. *Soviet Mining Science, 18,* 529-532. Novosibirsk, https://doi.org/10.1007/BF02528377.

Lanchava, O., Javakhishvili, G. (2021). Impact of strong fires on a road tunnel ventilation system. *Bull. Georg. Natl. Acad. Sci., 15*(4), 38-45, Tbilisi.

National Fire Protection Association. (2023). NFPA 502 Standard for road tunnels, bridges, and other limited access highways. National Fire Protection Association, Quincy, US.

Thomas, P.H. (1958). The movement of buoyant fluid against a stream and the venting of underground fires. *Fire Research Notes 351*. http://www.iafss.org/publications/frn/351/-1

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