HEAT RELEASE RATES IN TUNNEL FIRES

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ABSTRACT:

This paper examines the dynamics of heat release rates (HRR) in tunnel fires, highlighting their central role in fire development, spread, and safety management. Drawing on experimental studies, computational fluid dynamics (CFD) modeling, and full-scale incident analyses, it investigates how tunnel geometry, ventilation systems, and fuel sources influence HRR. Particular attention is given to differences between fuel-controlled and ventilation-controlled fires, as well as the transitions between these states during incident progression. The re-search outlines HRR variations across vehicle types, from passenger cars to heavy goods vehicles (HGVs), and quantifies the effects of heat feedback, ventilation efficiency, and combustible surface area on fire intensity. It further discusses HRR's critical impact on tunnel ventilation design, fire suppression sys-tem capacity, and structural resilience against thermal stress and spalling. By synthesizing lessons from road, rail, and metro tunnel scenarios, the study underscores that accurate HRR prediction is essential for optimizing safety strategies, guiding emergency response, and mitigating catastrophic outcomes. The findings reinforce that managing HRR—through integrated engineering, opera-tional planning, and real-time control—is fundamental to safeguarding tunnel infrastructure and human life.

KEYWORDS:

Tunnel Fires, Heat Release Rate, Tunnel Fire Development

1 INTRODUCTION

In the intricate realm of tunnel fire safety, this paper weaves together a narrative of cutting-edge research and evolving technologies that shape understanding and approach to managing fire risks in tunnels. By exploring both historical lessons and modern advancements, the goal is to illuminate the complex dynamics of tunnel fires related to the essential strategies needed to safeguard these vital infrastructures.

Robena [1] turned the tunnel into a fiery laboratory where 130 tests would simulate everything from a small car fire to a catastrophic fuel tanker blaze. To create a realistic scenario, steel silhouettes of vehicles filled the tunnel, their presence critical in mimicking how congestion might affect the movement of heat and smoke. As the flames roared, sensors captured every detail—visibility, temperature, airflow, and carbon monoxide levels—all monitored from a control room filled with computer terminals. This wasn't just an experiment; it was a mission to draft new guidelines that would shape the future of ventilation systems, ensuring they could clear up smoke and heat effectively, while also boosting safety in those crucial moments when lives are at stake.

To battle a fire, it is essential to understand how it develops, and that's exactly what Ingason, Li, and Lönnermark [2] set out to do in their study of fire dynamics in tunnels. They discovered that the way air moves through a tunnel—its longitudinal ventilation—can make or break a fire's intensity. By modeling these dynamics, they could predict the spread of heat and smoke, providing critical data for designing better ventilation and suppression systems. Their research wasn't just theoretical; it had real-world implications, underscoring the necessity of comprehensive fire modeling to enhance safety in tunnels across the globe.

The prospect of more tunnel fires cropping up loomed large over Europe, prompting a closer look at how these structures could be better protected. Lottman, Snel, Kaalberg, Blom, and Koenders [3] took up the challenge, focusing on the phenome-non of spalling—where concrete buckles under the intense heat of a fire, potentially leading to catastrophic failure [4]. Their research didn't just stick to the rules; it questioned them, comparing numerical models with full-scale tests to reveal that thermal restraint, not just heat, plays a dominant role in triggering spalling. This insight opened up new avenues for both scientific inquiry and practical engineering, suggesting that approach to tunnel fire resistance needs to evolve.

Predicting when and where a fire will strike is no easy task, but Kammerer, Lehan, and Klampfer [5] believe that a comprehensive risk assessment could tip the scales. They advocate for the integration of probabilistic risk assessment (PRA) methods with deterministic models to create a more robust system for evaluating fire risks in tunnels. Their studies revealed that ongoing risk assessments, adjusted for changing conditions and emerging threats, are crucial throughout the life of a tunnel. By blending these methods, they offer a new approach to tunnel safety—one that's as dynamic and adaptable as the challenges it seeks to overcome.

In the world of tunnel fire safety, computational fluid dynamics (CFD) is a powerful tool, but it's not for the faint of heart. Ingason, Li, and Lönnermark [6] dug deep into this complex field, breaking down how CFD divides the tunnel space into countless tiny cells, each one solving differential equations with a mix of solution algorithms and sub-models. But knowing how to operate CFD tools isn't enough, it is necessary to understand the science behind the modeling process. That is what this research delves most deeply into, as it adeptly summarizes the complex world of CFD modeling for the purpose of developing a deeper understanding of tunnel fire safety.

In recent decades, the demand for sustainable, resilient, and low-maintenance construction materials has grown substantially, driven by increasing global urbanization, the effects of climate change, and the rising costs of infrastructure upkeep. Concrete, as one of the most utilized materials in civil engineering, plays a central role in nearly every type of construction, from buildings and bridges to tunnels and dams. However, despite its widespread use and many advantages, concrete has a fundamental vulnerability: its propensity to crack under mechanical loads, environmental influences, and thermal stress.

In the specific context of tunnel fires, this vulnerability becomes a critical safety concern as the confined geometry intensifies heat exposure to the structure. High temperatures and rapid Heat Release Rates can lead to severe structural degradation, most notably through the phenomenon of explosive spalling, where the concrete lining loses its load-bearing capacity. Consequently, understanding the influence of these high temperatures is not merely a material study, but a necessity for predicting the fire's impact on the tunnel's structural integrity and long-term safety.

2 CHARACTERISTICS OF TUNNEL FIRES

In the dim, often claustrophobic confines of tunnels, the dynamics of fire take on a life of their own, distinct from fires in open spaces or traditional buildings. These unique characteristics stem from the interplay of environmental factors, tunnel structure, and the nature of the fire itself. Understanding these characteristics is essential for ensuring safety and effective fire management in such constrained environments [2].

2.1 THE HEAT FEEDBACK LOOP

One of the primary differences between tunnel fires and those in open spaces is the heat feedback mechanism. In open fires, the heat generated by the flames dissipates relatively freely into the surrounding environment. However, in a tunnel, the heat is trapped, bouncing off the tunnel walls and ceiling, which in turn radiates back toward the fire. This creates a feedback loop where the temperature continues to rise, intensifying the fire. The materials lining the tunnel, the cross-sectional area, and the tunnel's ventilation system all influence this heat feedback, often resulting in a fire that grows hotter and more aggressive than it would in an open environment [2].

The interaction between the fire and the tunnel's ventilation system further complicates matters. Tunnels are designed to facilitate airflow, but during a fire, this airflow can cause turbulent patterns, altering the behavior of the flames and smoke. The heat from the fire can create buoyancy forces, especially if the tunnel has a slope, leading to a phenomenon known as "back-layering," where hot gases and smoke flow back against the direction of ventilation. This not only hampers fire-fighting efforts but also poses significant risks to anyone trapped in the tunnel.

2.2 UNPREDICTABILITY OF SMOKE

Smoke behavior in tunnels is another critical characteristic that sets tunnel fires apart. In a typical building fire, smoke rises to the ceiling and forms a layer, gradually descending as the fire grows. However, in a tunnel, the smoke tends to spread longitudinally along the ceiling, creating a thick layer that can stretch for hundreds of meters. The distance this smoke travels depends on various factors, including the size of the fire, the tunnel's cross-sectional area, and the effectiveness of the ventilation system.

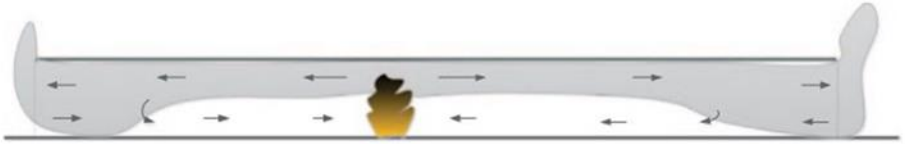

Figure 1: The smoke stratification in a tunnel fire with low ventilation [2]

The presence of smoke is not just a visibility hazard but a life-threatening danger due to the toxic gases it contains. In a confined tunnel, these gases can accumulate rapidly, making evacuation difficult and dangerous. The risk of back-layering exacerbates this problem, as smoke can spread in both directions, complicating rescue operations and increasing the risk for evacuees.

2.3 FLASHOVER AND FIRE SPREAD

In typical building fires, flashover—a rapid transition where all combustible materials in a space ignite almost simultaneously—is a well-known phenomenon. However, in tunnel fires, flashover is less likely due to the vast volume and geometry of space. The fire in a tunnel loses a significant amount of heat to the surrounding walls, which acts as a heat sink, preventing the buildup of temperatures required for flashover. Nonetheless, localized flashovers can occur within vehicles or compartments inside the tunnel, leading to intense, localized fires that can quickly spread if not contained.

Fire spread in tunnels is particularly concerning. The confined space and the potential for long flame lengths can result in the fire rapidly moving from one vehicle to another, especially if the vehicles are queued up due to traffic congestion. The heat flux— the rate at which heat energy is transferred per unit area—within the tunnel, can reach levels high enough to ignite vehicles or other combustible materials even at some distance from the initial fire. This chain reaction can lead to a large-scale fire involving multiple vehicles, significantly complicating firefighting efforts.

2.4 HUMAN ELEMENT

Finally, the human element adds another layer of complexity to tunnel fires. In an open environment, people have multiple escape routes, but in a tunnel, options are limited. Panic can set in quickly as smoke fills the tunnel and visibility drops to near zero. The narrow confines can become a death trap if the fire spreads rapidly or if the ventilation system fails to clear the smoke effectively. The behavior of drivers and passengers—whether they abandon their vehicles and attempt to flee or remain inside—can dramatically influence the outcome of a tunnel fire incident.

3 FIRES IN DIFFERENT TUNNELS

3.1 FIRES IN ROAD TUNNELS

Fires in road tunnels are among the most dangerous and complex emergencies due to the unique environment and the presence of vehicles carrying potentially flammable materials. These fires typically originate from vehicle malfunctions such as engine overheating, brake failures, or collisions. The confined space of a tunnel exacerbates the situation, trapping heat and smoke, which can quickly turn a small fire into a large-scale disaster.

One of the most challenging aspects of road tunnel fires is the rapid escalation caused by the accumulation of heat and toxic gases. The tunnel walls and ceiling trap heat, which radiates back towards the fire, intensifying the flames. This phenomenon, known as heat feedback, leads to higher temperatures and more aggressive fire behavior than would occur in an open environment. The confined space also allows smoke to build up quickly, reducing visibility and making it difficult for drivers to evacuate safely.

Ventilation systems, while crucial for maintaining air quality in tunnels under normal conditions, can complicate fire scenarios. Depending on their design, these systems can either help by controlling the spread of smoke and heat or worsen the situation by pushing smoke further into the tunnel, potentially trapping people and increasing the hazard for first responders. Back-layering, where smoke and hot gases flow back against the direction of ventilation, is a significant risk in these fires, making it difficult to predict smoke movement and complicating rescue efforts [2].

The presence of heavy goods vehicles (HGVs) in road tunnels adds another layer of risk. Fires involving HGVs tend to be more severe due to the large fuel loads they carry. In incidents where multiple HGVs are involved, the fire can spread rapidly from one vehicle to another, leading to intense heat and long flame lengths that can damage the tunnel structure itself. The low ceiling heights in some tunnels can exacerbate this, increasing the likelihood of continuous fire spread.

Human behavior during these incidents also plays a critical role in the outcome. In the panic of a tunnel fire, drivers may abandon their vehicles, leading to congestion that can block emergency access routes and hinder evacuation. The limited escape options in tunnels, combined with the rapid spread of smoke and toxic gases, can turn a road tunnel fire into a deadly situation in a matter of minutes.

3.2 FIRES IN RAIL TUNNELS

Fires in rail tunnels present a particularly complex and hazardous scenario due to the nature of the enclosed space, the speed and size of trains, and the potential for large numbers of passengers to be trapped underground. These fires can be triggered by a variety of factors, including electrical failures, mechanical malfunctions, or even external causes such as collisions or derailments.

One of the most significant challenges in rail tunnel fires is the interaction between the fire and the tunnel's ventilation system. Unlike road tunnels, where the primary fire load is fuel from vehicles, rail tunnels often involve the combustion of a wide range of materials, including the train itself, electrical equipment, and passenger belongings. The intensity of these fires can be exacerbated by the tunnel’s ventilation, which may inadvertently fan the flames or spread smoke along the length of the tunnel.

The presence of electrical systems in rail tunnels adds another layer of complexity. Fires can start from electrical short circuits, leading to rapid ignition and the release of toxic gases. In tunnels with electric trains, the power supply can create additional hazards, such as arcing or explosions, which can significantly hinder fire-fighting efforts. The confined space also makes it difficult to manage the spread of smoke, which can quickly reduce visibility and create life-threatening conditions for passengers and crew.

Another critical factor in rail tunnel fires is the speed and momentum of trains. A fire that starts in motion can spread rapidly as the train moves through the tunnel, potentially involving multiple carriages or even sparking secondary fires along the track. If a train comes to a halt within the tunnel due to a fire, passengers may be trapped far from escape routes, complicating evacuation efforts. The smoke and heat generated by the fire can create untenable conditions long before help can arrive, making timely and effective evacuation plans essential.

The design and materials of the tunnel itself also influence the behavior of the fire. Rail tunnels, often lined with concrete, can absorb significant amounts of heat, which may help in preventing flashover but also creates a challenging environment for firefighting. Additionally, the presence of slopes or curves in the tunnel can affect the movement of smoke and hot gases, leading to unpredictable and potentially hazardous conditions.

3.3 FIRES IN METRO TUNNELS

Fires in metro tunnels are particularly perilous due to the high passenger density, the complexity of underground networks, and the potential for rapid smoke and heat spread. Metro tunnels, often deep beneath city streets, create a unique environment where fires can quickly escalate, posing significant challenges for evacuation and emergency response.

Metro fires are usually triggered by electrical faults, such as short circuits or equipment failures, which can ignite cables, control systems, or even the train itself. The confined space of a metro tunnel traps the heat and smoke, creating an environment where fire can spread rapidly along the train and through the tunnel. This can lead to a dangerous build-up of toxic gases, particularly if the fire is ventilation-controlled, meaning that the lack of oxygen results in incomplete combustion and the production of hazardous fumes.

The design of metro tunnels often includes multiple stations, tracks, and emergency exits, which can influence how a fire behaves and how smoke spreads. The presence of numerous underground stations can create a chimney effect, where heat and smoke are drawn upward toward the station exits, potentially putting passengers at risk even far from the fire’s origin. The interconnected nature of metro tunnels also means that smoke can travel significant distances, affecting multiple sections of the network and complicating evacuation efforts.

One of the most challenging aspects of metro tunnel fires is the evacuation process. With trains often packed during peak hours, the prospect of moving large numbers of passengers through narrow tunnels filled with smoke and heat is daunting. Panic can quickly ensue as visibility drops, and the limited space makes it difficult for people to move quickly. The smoke, which can spread both ahead of and behind the fire, can block access to exits, trapping passengers and making rescue operations extremely challenging.

The role of ventilation systems in metro tunnels is crucial but complex. These systems are designed to maintain air quality and remove smoke in the event of a fire, but their effectiveness depends on the location and intensity of the fire. In some cases, ventilation systems can inadvertently spread smoke to other parts of the tunnel network, endangering more lives. The potential for back-layering, where smoke flows in the opposite direction of the intended airflow, can further complicate rescue efforts.

The materials used in the construction of metro tunnels and trains also contribute to the fire dynamics. Trains are often made from materials designed to minimize fire spread, but in an intense fire, these materials can still release toxic gases. Additionally, the concrete walls of tunnels can absorb and radiate heat, affecting the behavior of the fire and the spread of smoke.

3.4 FIRE DEVELOPMENT IN TUNNEL FIRES

In the dim, confined spaces of tunnels, where the walls reverberate with the hum of engines and the distant echo of footsteps, a fire can grow into a monstrous force, almost unnoticed until it is too late. The development of fires in tunnels, unlike in open spaces, is a complex phenomenon influenced by the unique environment that these structures present. The physical characteristics of tunnels, including their geometry, ventilation systems, and the types of vehicles they accommodate, all play crucial roles in determining how a fire will evolve.

In the early stages of a tunnel fire, the flames often start small, perhaps ignited by a malfunctioning vehicle engine or the careless flick of a cigarette butt. But in the enclosed, elongated space of a tunnel, even a small fire can quickly become a significant threat. The fire's growth is largely dictated by two competing factors: the availability of fuel and the control exerted by ventilation systems.

Unlike in open-air fires, where oxygen is abundant and readily available, tunnel fires must contend with a limited supply of oxygen. This scarcity can lead to two distinct types of fire behavior: fuel-controlled and ventilation-controlled fires. In a fuel-controlled fire, there is enough oxygen to sustain combustion, and the fire's growth is limited only by the availability of flammable materials. In contrast, a ventilation-controlled fire occurs when the oxygen supply is insufficient, causing the fire to produce large amounts of smoke and toxic gases, which can be even more dangerous than the flames themselves.

As the fire grows, it interacts with the tunnel's ventilation system, creating complex airflow patterns that can either help contain the fire or exacerbate its spread. In many tunnels, ventilation systems are designed to prevent the back-layering of smoke—a phenomenon where smoke and hot gases move against the direction of ventilation airflow, creating hazardous conditions for both evacuees and emergency responders. To counter this, a critical velocity of air is maintained, typically around 3 to 3.5 meters per second, which pushes the smoke and hot gases in a single direction, ideally towards an exit.

However, the effectiveness of ventilation systems is not always guaranteed. Natural ventilation, which relies on the tunnel's geometry and the external environment, can be highly unpredictable. Factors such as tunnel slope, wind conditions outside the tunnel portals, and even atmospheric pressure can drastically alter airflow patterns within the tunnel. This unpredictability makes it difficult to control the fire and its byproducts, often leading to the dangerous phenomenon of back-layering when the ventilation system fails to achieve the critical velocity needed.

As the fire continues to develop, the tunnel’s physical characteristics start to play a more pronounced role. The heat generated by the fire warms the surrounding air, creating buoyancy forces that can cause the smoke to rise and travel along the ceiling. If the tunnel has a slope, these buoyancy forces can govern the movement of air within the tunnel, potentially leading to rapid changes in the direction and speed of airflow. In long tunnels with little to no slope, natural ventilation is less effective, and the smoke tends to stratify, forming distinct layers of hot, toxic gases at the ceiling and cooler, less harmful air closer to the ground. However, as the fire grows and the smoke layer thickens, this stratification can break down, filling the tunnel with a dense, choking cloud that poses a severe threat to anyone still inside.

One of the most challenging aspects of tunnel fires is the potential for flashover—a rapid and dramatic increase in fire intensity that occurs when all combustible materials in the vicinity simultaneously ignite. While flashover is a common and well-understood phenomenon in building fires, its occurrence in tunnels is less predictable. The elongated shape of tunnels, combined with their high ventilation rates and large heat losses to the surrounding walls, usually prevents the buildup of the necessary conditions for flashover. However, in certain situations, such as within the confined space of a vehicle cabin or a train compartment inside the tunnel, flashover can still occur, leading to a sudden and uncontrollable spread of the fire.

Throughout the development of a tunnel fire, the interaction between the fire, the tunnel environment, and the ventilation system creates a dynamic and often unpredictable situation. Firefighters responding to such incidents face significant challenges, not only from the heat and smoke but also from the complex and rapidly changing conditions within the tunnel. The unique characteristics of tunnel fires—ranging from the effects of ventilation to the risk of flashover and smoke stratification—require a deep understanding of fire dynamics and careful planning to manage effectively.

In conclusion, fire development in tunnels is a perilous dance of heat, air, and structure. It is a battle against time, where the smallest spark can lead to catastrophic consequences if not quickly and effectively managed. Understanding the nuances of how fires behave in these confined spaces is essential for ensuring the safety of both tunnel users and the brave individuals who fight these subterranean infernos.

4 RESULTS AND DISCUSSION

Heat Release Rate (HRR) is a critical parameter in understanding and managing fire dynamics within tunnels. It represents the amount of heat energy generated by a fire over time and directly influences the intensity, spread, and potential hazards of a tunnel fire. In the enclosed and often elongated environment of a tunnel, HRR becomes even more significant, dictating how the fire develops and interacts with the structure and ventilation systems.

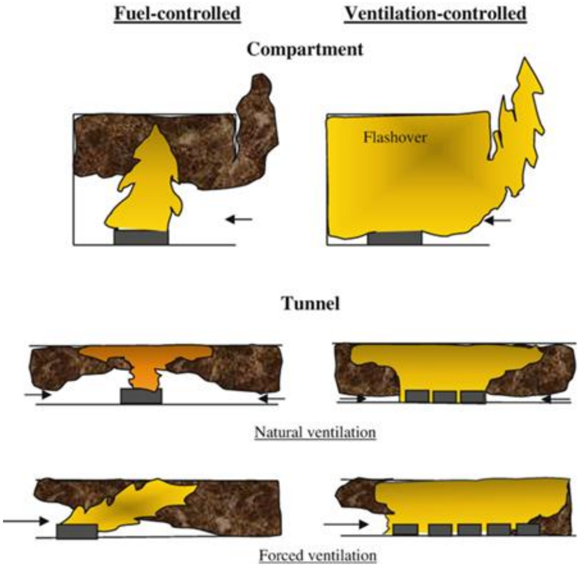

Figure 2: Controlled (left-side) and ventilation-controlled fires in a compartment and a tunnel (right-side) with natural draught (middle) and forced ventilation (lower), respectively [2]

HRR is fundamentally a measure of the power of a fire, typically expressed in megawatts (MW). It is determined by the rate at which fuel burns and the efficiency of combustion. In tunnels, the HRR can vary widely depending on the type of vehicles involved, the materials they carry, the tunnel's ventilation system, and the fire's location within the tunnel. Unlike in open spaces, where HRR can be influenced by a more straightforward supply of oxygen and dissipation of heat, tunnels introduce complexities due to their confined spaces, variable ventilation, and the potential for a fire to spread along a linear path [2].

The HRR is not static value; it evolves throughout the fire's development. Initially, when a fire starts in a tunnel, the HRR is low, but as the fire grows, consuming more fuel, the HRR increases, sometimes dramatically. Understanding the peak HRR, which is the maximum rate of heat release during a fire, is crucial for designing tunnel safety systems, including ventilation, fire suppression, and structural protection.

4.1 HRR IN DIFFERENT VEHICLES

In tunnel fires, the HRR is heavily influenced by the type of vehicles involved, as they are typically the primary source of fuel. Different vehicles have varying amounts of combustible materials, leading to significant differences in HRR.

The HRR for a burning passenger car typically ranges from 3 to 8 MW. This relatively low HRR is due to the limited amount of combustible materials, such as plastics, textiles, and fuel.

Heavy Goods Vehicles (HGVs) including trucks and lorries, can produce a much higher HRR, often exceeding 100 MW. This is due to the large amount of fuel and cargo they carry, which can include highly combustible materials. For instance, the Runehamar tunnel tests demonstrated that a fully loaded HGV could generate an HRR of up to 200 MW under certain conditions.

4.2 FACTORS INFLUENCING HRR IN TUNNEL FIRES

One of the most significant factors influencing HRR is heat feedback, where the heat produced by the fire is radiated back to the burning fuel, accelerating its combustion. In tunnels, the enclosed space often means that a large proportion of the heat is trapped, leading to higher HRRs. The proximity of tunnel walls and the ceiling to the fire increases this effect, particularly if the tunnel lining is made of materials that can absorb and re-radiate heat.

Ventilation plays a dual role in influencing HRR. On the one hand, adequate ventilation can supply oxygen, which is necessary for combustion and can increase the HRR. On the other hand, if the ventilation is insufficient, the fire may become ventilation-controlled, where the lack of oxygen limits the HRR. In this case, the fire may produce large amounts of smoke and toxic gases, which pose significant hazards even if the HRR is lower than it might be in a well-ventilated fire.

The geometry of the tunnel, including its cross-sectional area, length, and slope, can significantly impact the HRR. A larger cross-sectional area might allow for better heat dissipation, potentially lowering the HRR, while a smaller or more enclosed space can trap heat, increasing the HRR. The slope of the tunnel can also influence the movement of smoke and hot gases, potentially leading to higher HRRs in certain sections of the tunnel.

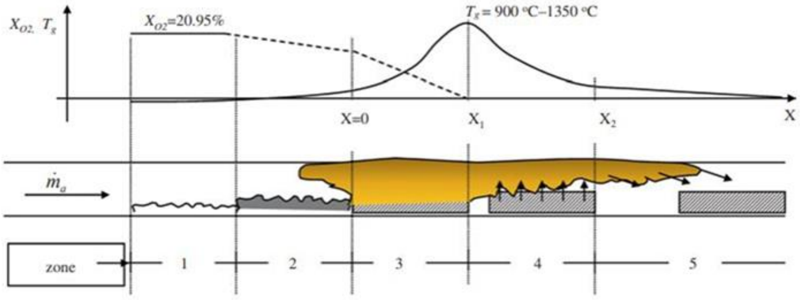

Figure 3: Schematic representation of the burning process of a ventilation-controlled fire in a tunnel [2]

The distinction between fuel-controlled and ventilation-controlled fires is crucial in understanding HRR in tunnel fires. In a fuel-controlled fire, the availability of fuel dictates the HRR, with the fire consuming fuel as quickly as it is available. In a ventilation-controlled fire, the HRR is limited by the amount of oxygen available, which can lead to incomplete combustion and the production of smoke and toxic gases. Tunnel fires can transition between these two states, particularly as the fire grows and ventilation conditions change.

4.3 HRR PER EXPOSED FUEL SURFACE AREA

The HRR can also be examined in terms of the fuel surface area exposed to the fire. This measure is particularly relevant in tunnel fires, where large vehicles or multiple vehicles may present extensive surface areas to the flames. The HRR per unit area is a useful metric for understanding how quickly a fire might spread along a row of vehicles or across the surface of a single large vehicle.

Flammable liquids, such as those found in fuel tanks, can produce extremely high HRRs per unit area, often reaching values above 1 MW/m^2. This high rate of heat release contributes to the rapid spread and intensification of fires, particularly when fuel tanks rupture and spill flammable liquids over a wide area.

Solid materials, such as plastics, rubber, and metals found in vehicles, typically produce lower HRRs per unit area compared to liquids. However, the HRR can still be significant, particularly for materials that are easily ignitable or that burn intensely once ignited. For example, the rubber tires of a truck can contribute a substantial amount of heat to the fire.

In vehicle fires, the HRR per exposed fuel surface area varies depending on the type of vehicle and its contents. For example, a burning truck loaded with flammable cargo will have a much higher HRR per unit area than a passenger car with a typical load of personal items and fuel. Understanding these differences is crucial for predicting fire spread and designing appropriate safety measures.

4.4 THE ROLE OF HRR IN TUNNEL FIRE SAFETY

HRR is a critical factor in the design and implementation of fire safety measures in tunnels. It directly influences the selection and design of ventilation systems, fire suppression systems, and structural protections. Understanding HRR helps engineers predict the intensity and duration of a fire, as well as the potential for fire spread and the production of hazardous smoke and gases.

The design of tunnel ventilation systems relies heavily on HRR predictions. Adequate ventilation is needed to control the spread of smoke and hot gases, to maintain visibility for evacuees and emergency responders, and to prevent the buildup of toxic gases. Ventilation systems are designed to handle specific HRRs, and an underestimation of HRR can lead to inadequate ventilation, increasing the risk of catastrophic outcomes.

HRR also guides the design and placement of fire suppression systems, such as sprinklers or deluge systems. These systems must be capable of reducing the HRR effectively, either by cooling the fire, starving it of oxygen, or directly extinguishing it. The higher the predicted HRR, the more robust the fire suppression system needs to be.

The structural integrity of the tunnel during a fire is another critical consideration influenced by HRR. Tunnels must be designed to withstand the high temperatures associated with significant HRRs without collapsing or losing their functional integrity. This involves selecting appropriate materials for tunnel linings, reinforcing structures to handle thermal stress, and ensuring that critical infrastructure, such as emergency exits, remains accessible during and after a fire. Additionally, the thermal stress on the tunnel structure can lead to spalling of concrete and other structural failures if not properly accounted for in the design phase [7].

5 CONCLUSIONS

The Heat Release Rate (HRR) is a fundamental aspect of tunnel fire dynamics, directly influencing fire development, spread, and the associated risks. Understanding the factors that affect HRR—such as vehicle types, ventilation, and tunnel geometry—is essential for designing effective fire safety systems in tunnels. Accurate predictions of HRR help ensure that tunnels are equipped to handle fires safely, protecting both the load-bearing structure and the people who use it. Whether it's through robust ventilation, effective fire suppression, or structural resilience, managing HRR is at the heart of tunnel fire safety engineering.

REFERENCES

[1] Robena, J. N. (1995). Tunnel fire testing to evaluate ventilation systems. Public Roads, Winter 1995, 58(3)

[2] Ingason, H., Li, Y., Lönnermark, A. (2015). Tunnel Fire Dynamics. Springer, New York, ISBN: 978-1-4939-2198-0, DOI: 10.1007/978-1-4939-2199-7

[3] Lottman, B.B.G., Snel, A.J.M., Kaalberg, F., Blom, C.B.M, Koenderset, E.A.B. (2021). Spalling Mechanism: Key for Structural Fire Resistance of Tunnels. Structural Engineering In-ternational 31(3):1-8, https://doi.org/10.1080/10168664.2020.1796556 (2021)

[4] Bidžević, I., Džidić, S. (2024). Fire Spalling of Concrete. In: Karabegovic, I., Kovačević, A., Mandzuka, S. (eds) New Technologies, Development and Application VII. NT 2024. Lecture Notes in Networks and Systems, vol 1070. Springer, Cham. https://doi.org/10.1007/978-3-031-66271-3_68 (2024)

[5] Kammerer, H., Klampfer, B., Lehan, A., Wahl, H. (2023). Innovative approach to Improve the Safety of Tunnels and Tunnel Control Centres. Conference: 10th International Symposium on Tunnel Safety and Security ISTSS 2023, At: Stavange

[6] Ingason, H., Li, Y., Lönnermark, A. (2024). CFD Modelling of Tunnel Fires. In book: Tunnel Fire Dynamics, DOI: 10.1007/978-3-031-53923-7_17

[7] Džidić, S. (2015). Otpornost betonskih konstrukcija na požar, Internacionalni BURCH Univerzitet Sarajevo, Bosnia and Herzegovina, ISBN 978-9958-834-47-9