Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Grant Agreement Number 826193

Deliverable 1.1
Report on assessment of effectiveness of conventional safety measures in underground transportation systems and similar confined spaces

Lead authors: KIT (Z. Xu, T. Jordan, M. Kuznetsov)
Contributing authors: UU (D. Cirrone, V. Shentsov, D. Makarov, V. Molkov)
USN (K. Vaagsaether)
FHa (A. Bernad)
IFA (C. Brauner)
URS (P. Russo)
NEN (F. de Jong, J. van den Berg)

Version: 190830
Delivery date for internal review: 1 August 2019
Due date: 31 August 2019
Dissemination level: Public

Deliverable administration						
Work Package	WP1. The state-of-the-art in safety provisions for underground transportation systems and accident scenarios prioritisation					
N. and title	D1.1 Report on assessment of effectiveness of conventional safety measures in underground transportation systems and similar confined spaces					
Type	Report					
Status	**Draft**/Working/Released	Due	M6	Date	31-08-2019	
Comments						

Development and revision			
Version N.	Date	Authors	Description
190404	04-04-2019	Z. Xu, KIT	1st draft ToC
190327	190328	D. Cirrone, UU	Appending ToC with two sub-section titles
190630	190701	D. Cirrone, UU V. Shentsov, UU	Contribution to the subsection “2.4 Underground parking and other confined spaces”
190702	190702	Z. Xu, KIT	Completion of whole draft report
190806	190802	V. Shentsov, UU	Contribution to the subsection “4.5 Blast wave mitigation techniques in tunnels”
190823	190822	C. Brauner, IFA	Text on influence of ventilation on firefighting intervention in tunnels or semi-confined parking places, mainly as subsection 2.2.7, and some open issues
190829	190827	A. Bernad, FHa	Correct some typos and add two citations on ‘rail safety’ and ‘rail tunnel safety’
190829	190828	F. de Jong, NEN J. van den Berg, NEN	Corrections of some minor text errors
190829	190828	K. Vaagsaether, USN	Add “and positive impulse” in last 2nd paragraph of subsection 4.5
190829	190829	P. Russo. URS	Corrections of some minor text errors and improper wording
190830	190830	Z. Xu, KIT	Compiling and finalizing the report

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Acknowledgments

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 826193. The JU receives support from the European Union's Horizon 2020 research and innovation programme and United Kingdom, Germany, Greece, Denmark, Spain, Italy, Netherlands, Belgium, France, Norway, Switzerland.

Summary

Hydrogen risk increases in confined spaces like tunnels comparing to open roads. A purpose of the HyTunnel-CS project is to investigate in-depth the hydrogen behaviours in any confined spaces as traffic tunnels, underground car parks, garages even workstations etc. Safety measures, emergency systems and corresponding regulations and standards are already available for existing traffic infrastructures, while hydrogen powered vehicles are joining gradually in the traffic. Thus, it is necessary to understand the interactions between unexpected hydrogen presence and the risk mitigation systems in the confined infrastructures. The understandings are hopefully used to improve current safety measures and to append additional new measures against hydrogen risks, in order to protect life and property especially when hydrogen vehicles are involved in traffic accidents in e.g., tunnels. Accordingly the regulations, codes and standards for the traffic infrastructures should be updated to be suitable for both conventional and hydrogen vehicles.

Ventilation is one of the most important safety measures in tunnel systems, to discharge the contaminations from the fossil fuel driven vehicle exhausts then to keep the tunnel air quality at a required level in normal operations, and to extract toxic gases and smoke in case of tunnel fires thus to facilitate evacuation, rescue and firefighting activities in fire emergencies.

Various ventilation modes are reviewed for road tunnels, including passive natural ventilation and active mechanical ventilation. The selection of ventilation designs is always case dependent, which are affected by many factors, like local meteorological and geological conditions, engineering feasibility, budget etc. Natural ventilation is suitable only for relatively short tunnels, which normally works in a longitudinal ventilation mode. Mechanical longitudinal and transverse ventilation modes are developed to realize the optimum air quality control in normal conditions and smoke extraction in fire emergencies. It seems that semi-transverse ventilation mode shows merits in air and smoke controls by using its hybrid features from both longitudinal and full transverse ventilations. Where possible, a Saccardo nozzle system can be incorporated in the tunnel design to obtain an optimum ventilation effect due to many advantages of the system, though subject to more construction costs. Based on reviewed experimental and theoretical studies, a critical ventilation flow velocity in the longitudinal direction of a tunnel is recommended as 3.5 m/s. It is sufficient to extract gaseous contaminations and toxic smoke of fire, while it is not too strong to impede the personal evacuation and rescue operation. However, it should be further identified in case of hydrogen dispersion.

Examples of typical modern railway tunnel systems are reviewed to elaborate the designs of ventilation, rescue and intervention systems. Different from road tunnels, rail tunnels have relatively smaller cross section area, which leads to some variation of design comparing to road tunnels e.g., positioning the impulse jet fans for longitudinal ventilation. An integral momentum balance equation modelling the tunnel ventilation flow driven by jet fans and piston effects of moving trains in tunnels is reviewed and elaborated. Both the steady-state and transient solutions of the govern equation provide theoretical tools for hydrogen transport estimations possibly encountered in the coming study in the HyTunnel-CS.

Another application scene of hydrogen vehicle is the underground parking house. The current safety provisions and regulations on such confined spaces are reviewed, which are in principle

natural and mechanical ventilation systems against possible accumulations of hazardous or harmful gaseous emissions from vehicles. In case of hydrogen vehicles, unwanted hydrogen release could occur due to certain failures, when it is using the underground park. The new configuration of the ventilation safeguards should be upgraded by considering the hydrogen presence in the enclosure, to avoid any possible formation of flammable clouds by effective mixing and convection. Empirical correlations about ventilation flow rates are reviewed for a passive natural ventilation mode. Different layouts of mechanical ventilations are discussed e.g. jet fans or induction fans for different application circumstances.

As a conventional fixed firefighting system (FFFS) widely applied in industries, water spray or water mist mitigation measures are reviewed for traffic tunnels. Water injection can decrease fire growth, spread and heat release rate due to its cooling effect. Aqueous film forming foam (AFFF) can be an additive component injected together with water to strengthen the extinguishing effect in some circumstances. On the other hand, the interval distance between spray nozzles or nozzle groups along a tunnel cannot exceed certain value e.g., 50 m recommended by industry, for firefighting efficiency. The interval is relatively small comparing to a tunnel length e.g., dozens km. Due to this reason, the construction and maintenance cost of such a system is normally very expensive. Moreover, the accuracy of fire detection and the timing of activation of spray are two critical points for water spray operation, in order to obtain an effective fire extinguishing in case of tunnel fire emergencies. Water injection into tunnels in fire incidents can bring issues: loss of visibility, loss of smoke stratification if it is formed, decrease of tenability of temperature limit due to increased humidity. These factors will impede the personal evacuation, rescue and firefighting activities of firemen. However, in view of hydrogen safety, water projection into tunnels are beneficial, to break down possible hydrogen stratification and, to inert the hydrogen-air mixture, although the induced turbulence by the injection can enhance hydrogen combustion in certain conditions, as a negative effect. The current status is that installations of water injection systems in traffic tunnels are not widely accepted in the world except Japan and Australia where such installations are prescriptive. The determination on installation of a water spray system should rely on detailed analysis of a specific tunnel and case by case.

The structural integrity of a tunnel being subject to a fire disaster plays a significant role in avoiding collapse and further big loss of life and property. Especially the tunnel concrete lining degradation in high temperatures and counter measures are reviewed. The standard fire scenarios for fire tests, concrete spalling issues, thermal-mechanical models of the concrete component with reinforcement and modern relevant computer simulation software are summarized, supplying useful hints for coming tunnel structure studies in the HyTunnel-CS.

To define meaningful realistic tunnel traffic accident scenarios for the study in HyTunnel-CS, traffic mix and tunnel involved accident characters and occurrence frequencies are reviewed. According to the statistics mostly in European Union, heavy goods vehicles (HGV) are more prone to be involved in tunnel fires than passenger cars. Commercial vehicles in large dimensions including HGVs and bus coaches occupy about 15% of overall traffic mix i.e., one commercial vehicle among every seven vehicles. These large vehicles can increase significantly the congestion of gas flows due to the limited space in tunnels. Statistics show that the occurrence frequency of vehicle fire in tunnels is no more than 0.25 fires per million vehicle-km.

Previous studies on tunnel involved hydrogen issues are reviewed. In particular, the main achievements in the internal HyTunnel project of the NoE HySafe are summarized in both experimental and theoretical work. A general conclusive remark from the study is that the internal parts of any kinds on tunnel ceiling and walls e.g. jet fans, lighting system, power cable ducts, information boards, concaves of lay-bys, emergency telephone booths etc. are potential obstructions which can trigger hydrogen-air flame acceleration even combustion regime transmissions with increasing hazards. The geometrical profiles of tunnels, ventilation configurations and designs of thermal-activated pressure relief device of hydrogen vehicles play important roles to determine the levels of hydrogen risk and the designs of mitigation measures for tunnels.

Certainly more aspects of safety issues while hydrogen vehicles using traffic infrastructures like tunnels and underground parks will be investigated in the HyTunnel-CS project, with a deeper and more broadened view.

Keywords

Hydrogen safety, tunnel safety, ventilation, water mist, hydrogen vehicle, hydrogen dispersion, hydrogen combustion, concrete lining, concrete spalling.

Table of contents

Nomenclature and abbreviations

AFFF	Aqueous film forming foam
ARC	Alcohol resistant concentrate
CCTV	Closed-circuit television
CGH2	Compressed gaseous hydrogen
DDT	Deflagration-to-Detonation Transition
EHSP	European Hydrogen Safety Panel
ETCS	European Train Control System
FCHV	Fuel cell hydrogen vehicle
FFFS	Fixed firefighting system
HGV	Heavy goods vehicle
HRR	Heat release rate
IA HySafe	International Association for Hydrogen Safety
LFL	Lower flammability limit
LH2	Liquid hydrogen
NFPA	National Fire Protection Association (US)
PIA	Personal injury accident
PIARC	Permanent International Association of Road Congresses
PRD	Pressure relief device
pp fibre	polypropylene fibres
QRA	Quantitative Risk Assessment
RCS	Regulation, codes and standards
RTA	Road traffic accident
TPRD	Thermal pressure relief device

List of figures

List of tables

1. Introduction

Tunnels are an increasingly important part of the traffic infrastructure especially in territorially uneven mountain areas. They create challenges for prevention and management of incidents/accidents, fire and explosion protection and security against attacks or sabotage. The use of alternative fuels, including compressed gaseous hydrogen (CGH2) and cryogenic liquid hydrogen (LH2), in tunnels and similar confined spaces creates new challenges to provision of life safety, property and environment protection at acceptable level of risk.

There is yet no understanding among stakeholders whether existing safety provisions in tunnels, underground parking and similar confined spaces would be sufficient to tackle accidents with hydrogen-powered vehicles and trailers transporting compressed or liquid hydrogen. In the absence of sufficient and specific for hydrogen knowledge there is no answer to a question what should be changed in Regulations, Codes and Standards (RCS) if any. This is the motivation of this pre-normative research.

The Task 1.1 of WP1 of the HyTunnel-CS project has the following objectives:

- To share professional information and technical discussion of relevant documentation, reports, case studies, risk assessment methodologies, etc.
- To focus on existing safety provisions for transport in tunnels and other confined spaces like underground and multi-store parking and to analyze their applicability to accidents involving hydrogen-powered vehicles and hydrogen delivery transport.
- To undertake critical analysis of existing incidents and accidents with vehicle fires and explosions in confined spaces, available prevention and mitigation measures, and the state-of-the-art in hazard and risk assessment procedures for road and railway tunnels and other confined spaces.
- To clarify the applicability of currently used safety systems and the procedures to hydrogen.

The unique gathering of professional members in the consortium, e.g., those from European Hydrogen Safety Panel (EHSP) and International Association for Hydrogen Safety (IA HySafe), facilitates to exploit the complementarities of hydrogen safety expertise for tunnels, and to achieve eventually the project goals.

In this task, the state-of-the-art knowledge concerning safety is reviewed for the whole system of underground transportation systems and similar confined spaces, like tunnels, underpasses, underground and multi-story parking structures, garages, maintenance shops, etc. The existing knowledge implemented in contemporary CFD models and simpler engineering tools are also reviewed, which are currently used for hazards and associated risk assessment in tunnels in similar confined spaces.

Only models and tools validated against experiments with hydrogen release, dispersion and combustion can be applied for inherently safer design of tunnels and risk assessment. Therefore previously performed experiments available to partners are analyzed, which can be used to underpin the validation of CFD models and engineering tools from the start of the project. For an in-depth study, considerations are given to both vehicles with moderate hydrogen inventory onboard such as fuel cell cars and buses, and transport with larger inventory like hydrogen tube trailers, liquid hydrogen carriers, trucks, trains, etc.

The hazard mitigation features incorporated into tunnels are generally required to deal with selected design fire scenarios. From the perspective of fire and general hazard control in tunnels, it is important to understand the mitigation features related to tunnel design, ventilation and operational procedures. As the most important safety measure, various ventilation systems are reviewed in Section 2 for road tunnel, rail tunnel and underground structures like car parks. Different tunnel designs, operation procedure, regulations and standards are reviewed with focuses on road tunnel ventilation, smoke control in fire emergencies, and hydrogen safety concerns in case hydrogen vehicles are involved. Cases studies are reviewed to illustrate the configurations of railway tunnel ventilation systems and emergency designs. Theoretical models about jet fan ventilation and piston effect produced by fast moving trains are also discussed. Passive natural ventilation and active mechanical ventilation systems are reviewed for underground parking systems. Codes and standards about the ventilation requirements of underground parking spaces are summarized. Empirical engineering correlations are elaborated to compute ventilation flow rates and hydrogen fraction estimations in case of unintentional hydrogen release in the underground enclosure.

The state-of-the-art status of fixed firefighting systems (FFFS) is reviewed in Section 3, with special focus on water mist system. The interaction mechanism between water injection and the tunnel fires is discussed. The advantages and disadvantages of water injection into tunnel in fire scenarios are summarized.

Section 4 is dedicated to formulate the response of tunnel structure to vehicle fires, with focus on the concrete degradation in high temperatures, including the failure modes of concrete mixes, temperature-time profiles of tunnel fires, and research methodologies etc.

To identify realistic accident scenarios for the hydrogen release and explosion scenarios, it is a key factor to understand the vehicle traffic behavior in road tunnels. The traffic characteristics in tunnels and the types and frequencies of traffic accidents are summarized in Section 5.

Main results of both experimental and theoretical parts of an internal project of HyTunnel in the frame of HySafe are reviewed in Section 6, which provide a base for the further in-depth study in this HyTunnel-CS project.

Finally the whole contexts are summarized at the end as a conclusion part.

2. Review of tunnel safety provisions

2.1 Tunnel design and operation

By literature survey, it is found that the following sources collate a wide range of useful information and provide a good summary of tunnel design, operation and general emergency procedure.

- Fire and Smoke Control in Road Tunnels, published by the World Road Association / PIARC in 1999 (PIARC, 1999).
- The Handbook of Tunnel Fire Safety edited by A. Beard and R. Carvel and published by Thomas Telford in 2005, London (Beard & Carvel, 2005).
- NFPA 502 on Standard for Road Tunnels, Bridges, and other Limited Access Highways (NFPA, 2004, 2008).
- Design Manual for Roads and Bridges, Volume 2, Section 2, Part 9, BD 78/99: Design of Road Tunnels, The Highways Agency et al (1999), The (UK) Stationary Office Ltd. (Highways Agency, 1999).

Although the focus in the above publications is primarily on fire issues, the information is still applicable to general incident or accident scenarios such as hazardous gas dispersion and combustion. Therefore, some information in Section 2 is drawn from these literatures for the hydrogen related safety study in the HyTunnel-CS project. Furthermore, the tunnel safety mitigation features are driven generally by the requirement to deal with the selected design fire scenarios based on existing transport loads and energy carriers. From the perspective of fire and general hazard control, tunnel designs and operational procedures need to address the following issues.

- *Construction materials*

  This addresses the resistance of the tunnel walls and lining materials to fire gases and radiation fluxes. Resistance of concrete to spalling has been of particular interest in recent years, and a number of developments in respect to improved performance have been reported, e.g. addition of fibres into the concrete mix. The structural integrity of tunnel construction is usually designed for and tested in terms of exposure to a specified time- temperature curve, representing the exposure conditions to be expected for the design scenario. The construction may also consider the resistance to the effects of explosion.

- *Detection and surveillance*

  In normal operation, detection of vehicle emissions, e.g. CO, may be incorporated in the tunnel design. Additional ventilation can then be provided to alleviate conditions inside the tunnel. Heat detection is used principally to detect a fire event. Video surveillance, including in the infrared, may be used to detect the presence of smoke, and coupled with appropriate image processing technology may be able to automatically detect the onset of a fire.

- *Ventilation and smoke control*

This is discussed in more detail in next sub-section.

- *Fire suppression*

  There has been much debate, and controversy, over the potential benefits or disadvantages of installing water suppression systems inside tunnels. While actively pursued in some parts of the world, e.g. Australia and Japan, fixed-suppression water systems were considered unproven, and not cost-effective in others, e.g. The World Road Association opposed the introduction of water suppression systems into road tunnels (PIARC, 1999) and earlier editions of NFPA 502 (NFPA, 2004) remained cautious. It is now more widely accepted e.g. NFPA 502 (NFPA, 2008) that water suppression can be an important part of the overall fire safety strategy for a road tunnel, both for life safety and property protection. An alternative to water sprays and mists is provided by aqueous film-forming foam (AFFF), designed principally for extinguishing liquid hydrocarbon fires – see for example (Cafaro, 2005).

- *Egress and tunnel user behaviour*

  The safe evacuation of tunnel users in the event of an emergency has received much attention in recent years, prompted in part by the series of catastrophic fires in a number of alpine road tunnels in Europe, e.g. the Mont Blanc Tunnel fire in 1999. Fraser-Mitchell and Charters (Fraser-Mitchell, 2005) review the current understanding of human behaviour in the event of a tunnel fire. Shields (Shields, 2005) reviews what happened in various recent tunnel fire incidents.

Other emergency facilities are all important like: emergency telephone, pushbutton type information equipment, emergency alarm equipment, escape passage, guide board, radio broadcasting equipment, loudspeaker, observation system (e.g., CCTV), etc. Driving practice and human behaviour of road tunnel users are reviewed by Shields (Shields, 2005) and Egger (Egger, 2005). A recent directive from the European Parliament (European 2004) imposes strict new regulations on the minimum level of safety within the main trans-European road tunnels.

In the background of hydrogen applications in the HyTunnel-CS, an immediate attention should be paid to the ventilation amongst the listed above, in that, both in normal and emergency modes, any accidentally released hydrogen distribution in tunnels is determined by the tunnel ventilation systems and influenced by the traffic and environmental conditions. Secondly, installations of hydrogen detection and water suppression system are also of significant importance, due to the diagnostic function of a hydrogen induced accident at an earlier stage and the interaction between water component and hydrogen combustion at a later stage of accident evolution, respectively.

2.2 Tunnel ventilation

2.2.1 Hydrogen safety concerns of tunnel ventilation

Ventilation is required in tunnels during normal operation to maintain the air quality level by convecting pollutant vehicle emissions and aerosols discharged from internal combustion engines. Additional emergency ventilation is necessary, when tunnel is long enough, to mitigate the effects of the heat and smoke in case of fire events, and to assist in the egress of tunnel users and then to assist firefighting and emergency operations.

Various types of ventilation systems for tunnels are summarized in (Bendelius, 2005). They are further formulated in a closer view of use of ventilation to smoke and heat control in fire accidents in tunnels (Jagger & Grant, 2005).

In view of hydrogen safety, tunnel ventilation is concerned owing to the following two reasons.

- In the dispersion stage of hydrogen after unintentional release in a tunnel, the ventilation function influences strongly the hydrogen distribution, stratification, and mixing with air in the tunnel. Meanwhile the tunnel geometry and adjacent vehicle dimensions and positions play also important roles to form the gas flow field initially driven by the ventilation.
- In the hydrogen combustion stage, after an unwanted ignition of hydrogen release from e.g., a hydrogen powered vehicle, the ventilation changes from normal operation to emergency mode, which influences much on the propagation of hydrogen flames and combustion regime evolutions. As thermal and pressure hazards, the combustion heat even explosion pressure shock waves endanger other hydrogen vehicles in the tunnel and the tunnel structure itself.

Studies on tunnel ventilation performances have been conducted and published, e.g., (Li & Chow, 2003). Many concerns are focused on the thermal and smoke distributions with emergency ventilation modes specifically for fire accident scenarios in tunnels. The situations are directly relevant to hydrogen dispersion. Hydrogen behaves to some extent like the smoke from a fire due to the buoyancy effect caused by the lighter density of hydrogen or smoke than air.

Although ventilation is indispensable for tunnels, it has pros and cons in view of mitigating hazards of hydrogen or smoke/heat of a fire. The positive and negative effects are listed as follows.

Pros:

- Hydrogen concentration in tunnels can be decreased by the vented air, thus the hydrogen-air mixture can escape the flammability or detonability.
- The risky hydrogen-air mixture may be exhausted by the convection flows of ventilation, out of the tunnel through a portal or ventilation ducts.
- Stratification of hydrogen in air can be broken down by ventilation, e.g., jet fans. Thus, locally flammable gas mixture becomes not flammable, or flammable mixture in fast flame regime becomes to a slow flame regime due to the decrease of hydrogen fraction.

Cons:

- In case of large inventory of hydrogen release, the dimension of the flammable hydrogen-air mixture can be increased significantly due to the ventilation function. The mixture is transported from the release location along the tunnel or along the ventilation shafts. Consequently, a larger area and more equipment are endangered by hydrogen combustion risk.
- Turbulence produced by active ventilations may change adversely in certain circumstances the combustion regimes of hydrogen-air mixture. Slow flame can evolve

to fast flame, which can further develop to detonation, due to the turbulence enhancement.

- More neighboring traffics, especially those in the downstream of a ventilation flow, are entrapped in hot smokes from a fire. The amplified thermal threaten, most likely, accompanying loss of visibility, is caused by the strong ventilation.

The exact ventilation performance is determined by the vented flow field in the tunnel and ventilation ducts. Given a tunnel geometry, ventilation device and a hydrogen release, at least a CFD study or even laboratory experiments are required to make meaningful judgement about what is a proper ventilation for a tunnel.

Existing tunnel ventilation systems are categorized basically into three types: natural ventilation, longitudinal ventilation, transverse ventilation. Other variants are also in application such as, semi-transverse ventilation or longitudinal ventilation with Saccardo nozzle. These are reviewed in following sub-sections.

2.2.2 Natural ventilation

The natural convection flow between portals of a tunnel is usually driven by the moving vehicles as a piston effect and by the pressure difference between the two portals caused by distinct meteorological conditions, like differentials in elevation and ambient temperature of wind etc. Certainly natural ventilation is suitable only for short tunnels due to its limited venting capability.

Due to the relatively short length of the tunnel, accumulation of smoke from a fire is supposed to be not a major issue. However, the tunnel structure needs to be fire proof to a specified level. Tunnels without additional ventilation device by using natural convection exist often two-way traffic.

As shown in Figure 2.2.1, the configuration of natural convention can be either portal to portal, shaft to shaft or from portal to shaft, in the longitudinal direction of a tunnel.

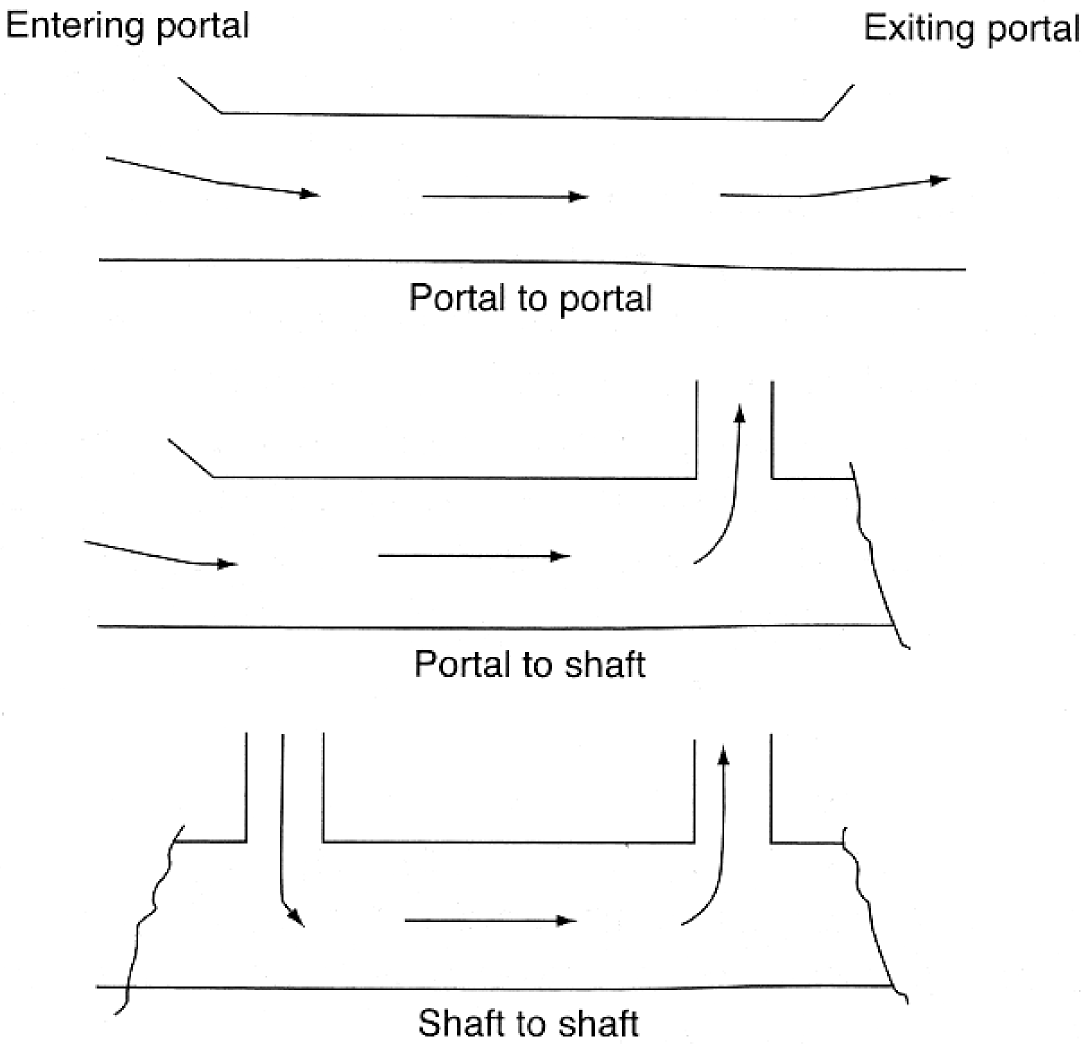


Figure 2.2.1 Natural ventilation modes along longitudinal direction of tunnel (Beard & Carvel, 2005)

The first case, "portal to portal", in Figure 2.2.1 is taken as an example, air enters the tunnel from one portal and exits from the other. The pollution of vehicle emissions is accumulated gradually by the convection air flow from upstream to downstream. If the vehicle emissions are evenly distributed along the tunnel length and the air flow in the tunnel is uniform, both the emission concentration and the air temperature linearly increase along the length of the tunnel, resulting in a most pollutant level of air quality at the exit portal. It is indicated by the solid lines in Figure 2.2.2 that a sudden change in wind direction or the wind velocity can affect adversely the natural ventilation effects along with the vehicle generated piston effect. Such a situation brings a lower air venting velocity and thus elevated contamination of air in the tunnel, as presented by the dashed lines in Figure 2.2.2.

Several factors influence natural ventilation effect by means of influencing the air flow velocity, e.g., the ambient air temperature difference, wind direction and velocity, the structural configuration of the tunnel portals or shafts, etc. Depending on the local traffic density, the maximum allowed length of tunnel is up to 1000 m, where only natural ventilation suffices and no extra mechanical ventilation is equipped.

It is obvious that natural ventilation is not reliable for a relatively long tunnel, because it is insufficient to supply fresh air for tunnel users and to protect them from hazardous conditions e.g., in case of accidental release of chemical poisons or even in a big fire with heavy smoke. Therefore, active ventilation driven by extra power is required, at least in emergency cases, or when the contaminated air by vehicle emissions is too bad to be respired in the tunnel.

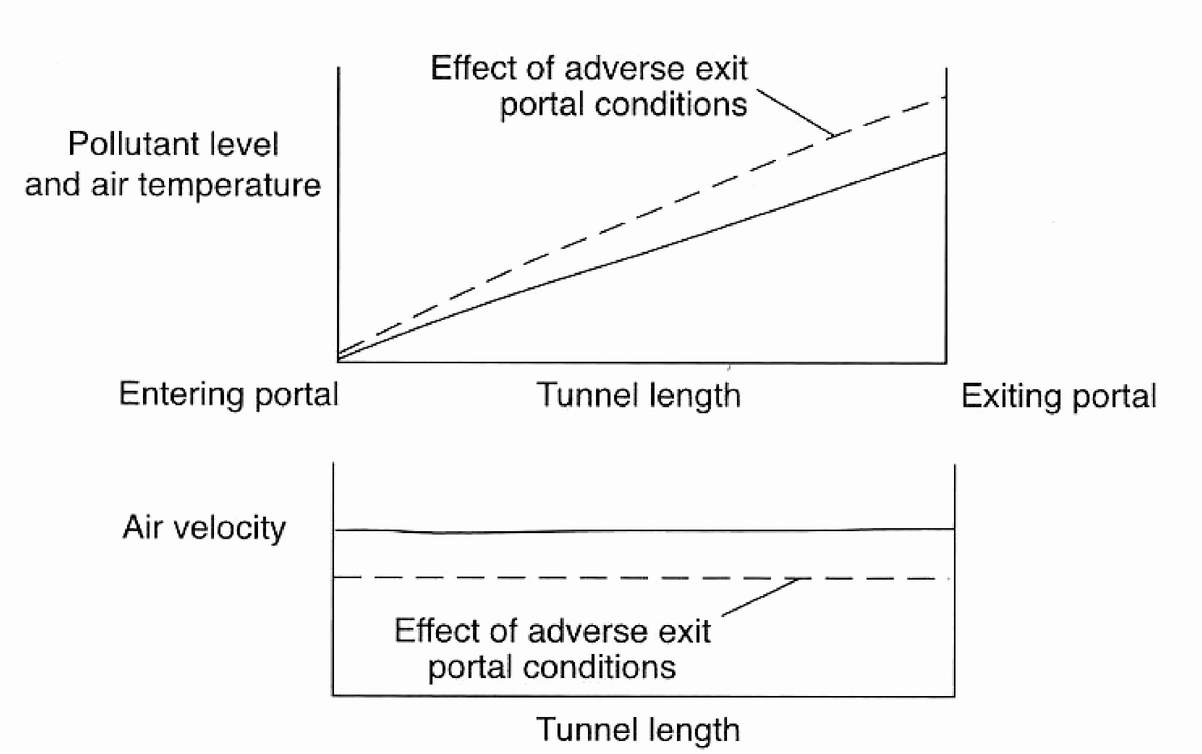


Figure 2.2.2 Natural ventilation flow characteristics in a longitudinally ventilated tunnel (Beard & Carvel, 2005)

2.2.3 Longitudinal ventilation

Active ventilation system for tunnels employs mechanical devices like electric fans, exhaust, and blowers, which removes the exhaust gasses from the tunnel and blows fresh air into the tunnel. Blowing, exhausting and combination of them are the three major functions of a mechanical ventilation system. Depending on the different ventilation airflow directions, mechanical ventilation includes two forms: longitudinal ventilation and transverse ventilation.

The topic of this sub-section is on longitudinal ventilation, which is the most straightforward, usually least expensive, form of mechanical ventilation. In general, fresh air is sucked into the tunnel from one portal, and exhausted from the other. However, in engineering practice, different configurations of longitudinal ventilations can be designed.

- The airflow is driven by a series of distributed jet fans, installed often on the ceiling of the traffic space along the tunnel. In this case exchange of fresh or pollutant air occurs only at the portals.
- The airflow is driven by centralized fans, located normally outside of the traffic space. By this way, air is exchanged through ventilation ducts and shafts.

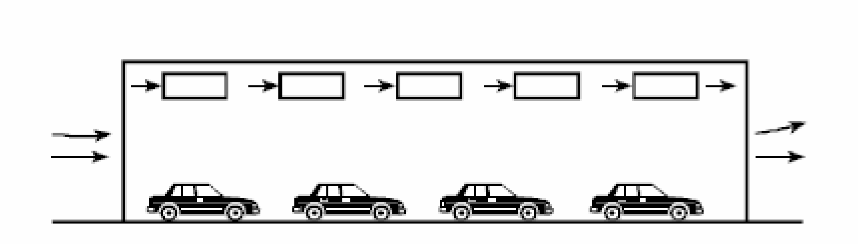
- Based on the last design, i.e., the central fan driven ventilation, an additional Saccardo nozzle is employed to supply a high velocity of air jet. Combined with the piston effect provided by the moving traffic, the fast air jet enhances the thrust longitudinally through the tunnel, to realize a better effect of ventilation.

Variant configurations of mechanical longitudinal ventilations are presented in Figure 2.2.3. Four different models are taken as examples. The forced ventilation airflow in Model (a) is quite similar to that of a naturally ventilated tunnel, certainly with much more resilience to adverse effect caused by meteorological changes at the portals. The air pollution and temperature at the exhausting portal are higher than that at the intake portal, like the tunnel with only natural ventilation.

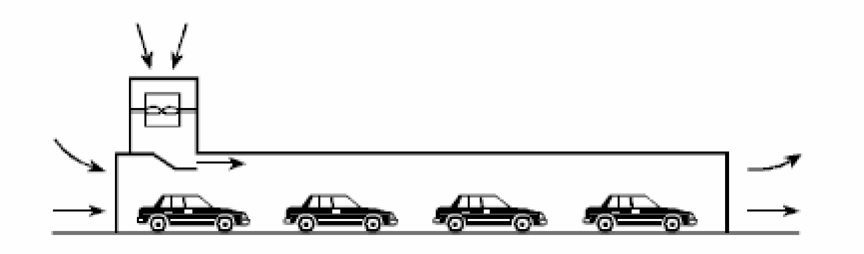
Model (b) shows schematically the longitudinal ventilation with only central fans, which are built outside of the traffic space and can be maintained without interruption to the tunnel users. The longitudinal ventilation in tunnel is driven by the powerful thrust created by central fans, with one portal as inlet and the other as outlet.

Model (c) shows an example of combination use of central fans and Saccardo nozzle, whereby the fresh air is supplied from the Saccardo nozzle and exhaust extracted by the central fans though the shaft. Meanwhile, the portals act also as air inlet or outlet.

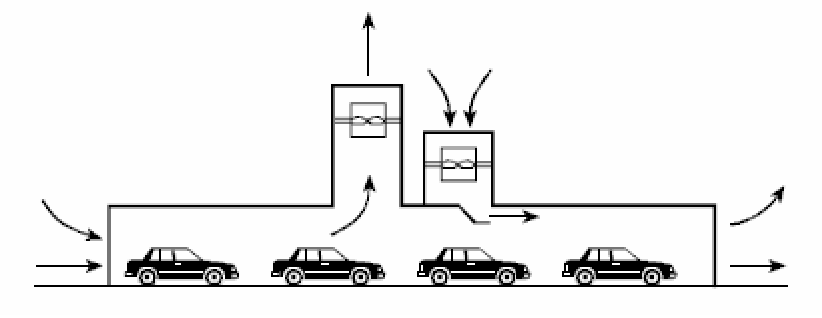
In Model (d) fresh air is supplied from both portals and the longitudinal ventilation flows are from each portal towards the centrally positioned exhaust shaft, where the central fans provides the extraction power. Comparing to Model (a) and (b), the vehicle emissions and smoke, if any, are controlled in a much better way.



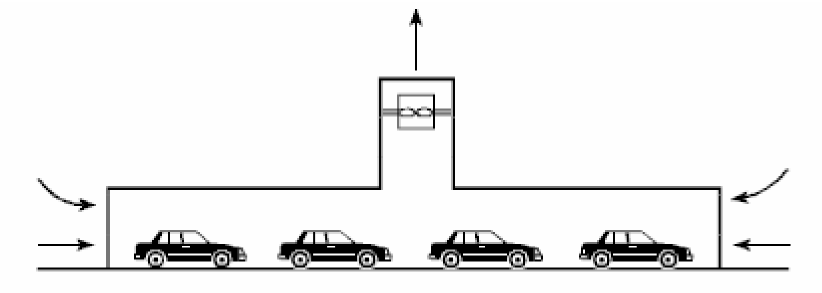
(a) Distributed jet fans (installed in traffic space)



(b) Central fans (installed outside traffic space)



(c) Central fans in exhaust shaft combined with Saccardo supply nozzle



(d) Central fans with exhaust shaft only

Figure 2.2.3 Variants of mechanical longitudinal ventilation (NFPA, 2004)

In normal operation of a tunnel, a longitudinal ventilation flow velocity ranging from 0.5 to 1 m/s typically suffices to exhaust vehicle emissions. However, in an emergency case of e.g., a fire accident, a higher flow velocity is demanded to effectively control the smoke transport from a fire location. This issue is addressed as follow.

A basic design philosophy of a tunnel ventilation system is that, the ventilation should be strong enough in fire emergency to keep the smoke or any hazardous gases moving in one-way direction from the source location to any exit of the tunnel, e.g., downstream portal or exhaust shaft. To satisfy the requirement, the designed ventilation airflow velocity can be lower than a critical value, so-called critical velocity, which is a function of heat release rate of the fire, tunnel geometry and air temperature.

Empirical correlations have been developed to compute the critical velocity, V_c, as shown in Equation 2.2.1 and 2.2.2 (Danziger & Kennedy, 1982).

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f}\right)^{\frac{1}{3}} \qquad Eq. 2.2.1$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c}\right) + T \qquad Eq. 2.2.2$$

where,

V_c is the critical velocity for longitudinal ventilation, m/s,

K_1 is the Froude number factor, taken a value of 0.606,

K_g is the tunnel gradient factor, 1 for level,

g is the gravitational acceleration, normally, 9.81 m/s^2,

H is the height of the tunnel, m,

Q is the heat release rate from the fire, J/s,

ρ is the density of the upstream air, kg/m^3,

C_p is the specific heat capacity of air at constant pressure, J/kg/K,

A is the tunnel cross section area, m^2,

T_f is the average temperature of the hot gases at the fire, K,

T is the ambient air temperature, K.

The correlations are widely used in tunnel design calculations, e.g. in (NFPA, 2004). More general expressions for critical velocity calculation refer to (Hwang & Edwards, 2005).

The computed critical velocities by using the correlations are compared to those obtained by using numerical computer simulations. A tunnel with a cross section of 37.8 m^2 and a height of 4.2 m is taken as an example, which is supposed to be two-lane tunnel. Figure 2.2.4 presents the critical velocity as a function of the fire scale in MW (PIARC, 1999). It indicates a good consistence between the correlations, denoted as solid line, and the computer simulations, denoted as symbols in Figure 2.2.4. It is concluded that the critical velocity is about 3 m/s.

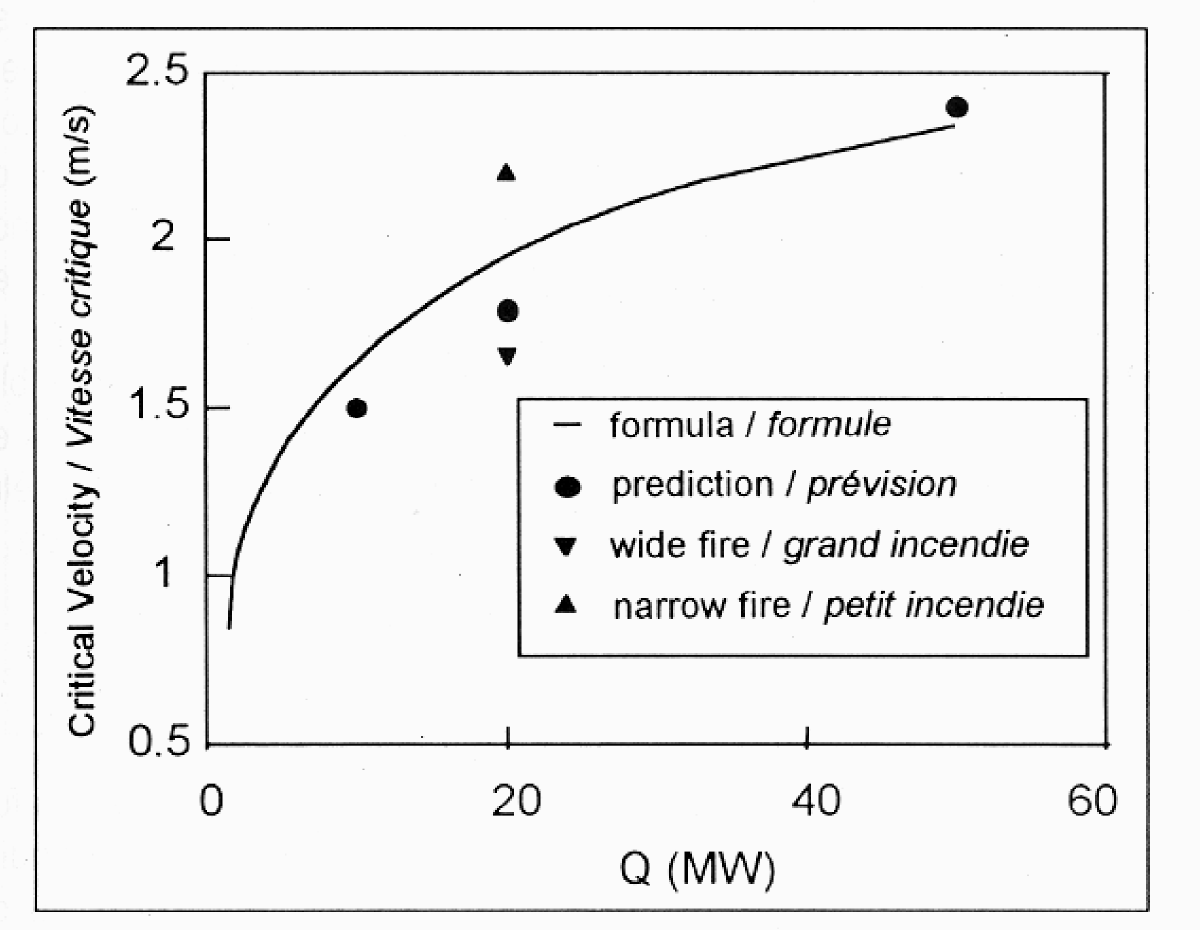


Figure 2.2.4 Computed and simulated critical velocities for longitudinal tunnel ventilation (PIARC, 1999)

The study on the critical velocity was extended to large scale of tunnel fires , e.g., a fire disaster up to 100 MW involved in a heavy goods vehicle (HGV). For such a big fire, however, a larger value of 5 m/s was recommended for the design critical velocity in engineering view. Nevertheless a full scale tunnel experiment study (Lemaire, 2003) showed that the recommended value can be reduced. According to Eq. 2.2.1, $V_c \propto \sqrt[3]{Q}$ for a given tunnel geometry. It is evident that the curve of V_c versus Q flats down quickly along with increasing heat release rate Q. In other words, the critical velocity remains almost constant while the heat release rate (HRR) exceeds certain range. This constant is called “super critical velocity”. Figure 2.2.5 (Wu & Baker,2000) presents the non-dimensional critical velocity (V'') as a function of non-dimensional HRR (Q''), by summarizing a number of experimental data point. The figure clearly shows that a constant velocity appears when HRR exceeds a critical value.

To be conservative, a critical ventilation velocity of 3.5 m/s is generally recommended for most tunnel designs, by covering fire disaster of an HGV in 100 MW. By satisfying the requirement of ventilation velocity, it is assured in principle that the smoke of a fire transports only in one direction from the source to a portal or an adjacent exhaust shaft.

On the other hand, the ventilation flow velocity cannot be too fast, otherwise, people cannot escape safely and cannot perform firefighting activity effectively in such a strong artificial wind. Therefore, the Swedish and Norwegian regulations quote a maximum allowed longitudinal air velocity in the range of 7 to 10 m/s, while NFPA 502 (NFPA, 2004) quotes a maximum value of 11 m/s.

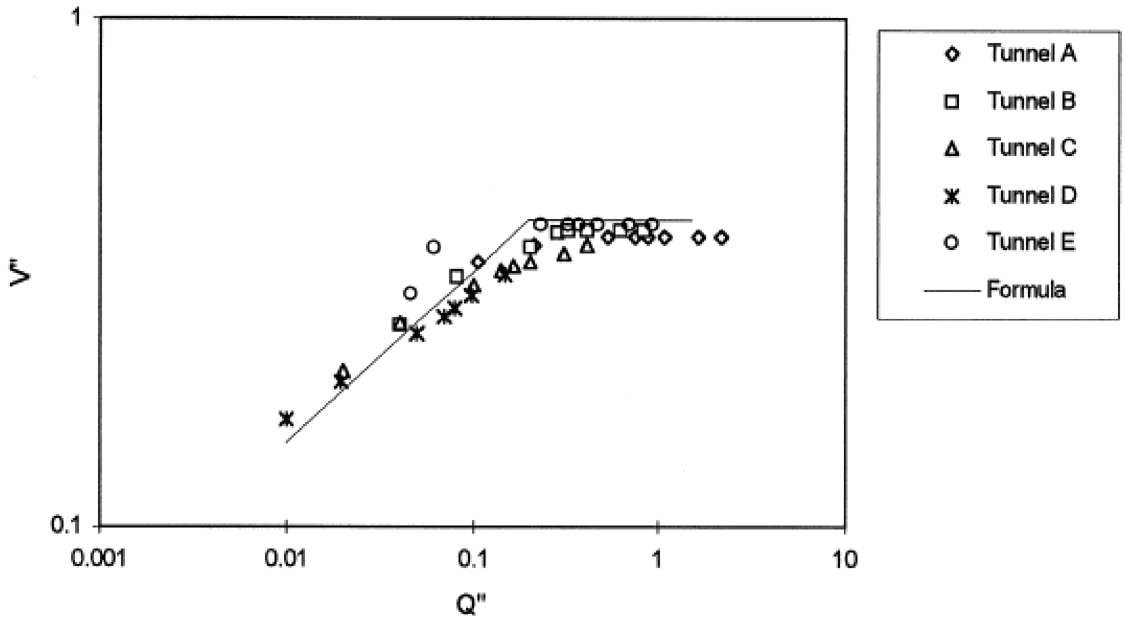


Figure 2.2.5 Non-dimensional critical ventilation velocity as a function of non-dimensional heat release rate (Wu & Baker, 2000). The critical velocity approaches a constant while the heat release rate exceeds certain value.

In a tunnel with properly designed longitudinal ventilation, it is an advantage that, the upstream area from the fire location is always protected clear from hot gases and smoke of a fire by forcing them propagating in single direction. In the tunnel fire emergency, people in this region can evacuate or help to make access for fire brigade or firefighting facility.

Meanwhile, it is a disadvantage that the downstream area is always suffering from the smoke and thermal hazard up to next exhaust shaft or tunnel portal. It would be lucky if the vehicles in this region are able to drive out of the tunnel and escape away from the hazardous event. In this sense, a direct judgement comes that, the longitudinal ventilation system is not well suited to two-way tunnel. It is not a good option either to an even one-way tunnel with heavily loaded traffic if traffic jams may occur in the tunnel.

The potential problem regarding to the longitudinal emergency ventilation is illustrated in Figure 2.2.6 (Beard & Carvel, 2005). In the figure, (a) and (b) are the shaft to shaft ventilation, and portal to portal ventilation, respectively, which are in normal operation. (c) and (d) are in fire emergence situation. It clearly shows that smoke issue exist between the fire location and the shaft (c) or between the fire location and the portal (d). The distributed smoke accompanying thermal loads endangers those vehicles submerging in it.

In order to keep both sides of the fire source along a tunnel clear from smoke, another ventilation type, transverse ventilation is preferable, which is introduced in next sub-section.

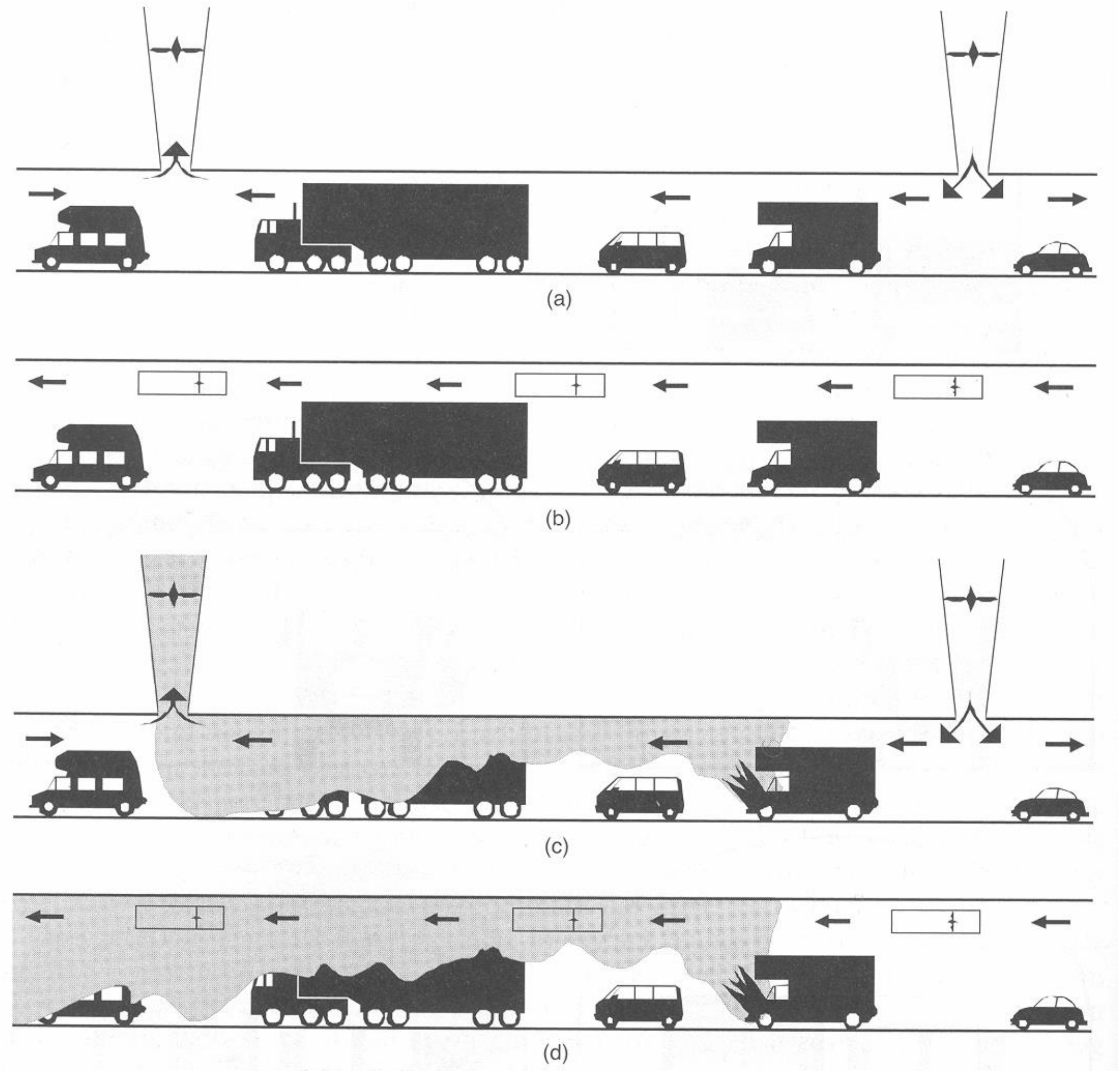


Figure 2.2.6 Smoke distributions in different longitudinal ventilation modes, cited from The Handbook of Tunnel Fire Safety (Beard & Carvel, 2005)

2.2.4 Transverse ventilation

As the name says, the ventilation flow pattern is mainly in the transverse cross section plane of a tunnel equipped with a mechanical transverse ventilation system. The system is characterized by a uniformly distributed fresh air inlets and exhaust outlets along the longitudinal direction of the tunnel. The inlets and outlets are located certainly at different heights as required in the tunnel.

The concept was developed originally for the Holland Tunnel in New York (Lesser, et al, 1987). The cross section of the Holland Tunnel is shown in Figure 2.2.7 as an example. It shows that the fresh air is supplied from the bottom side of the tube and the contaminated air exhausted at the top.

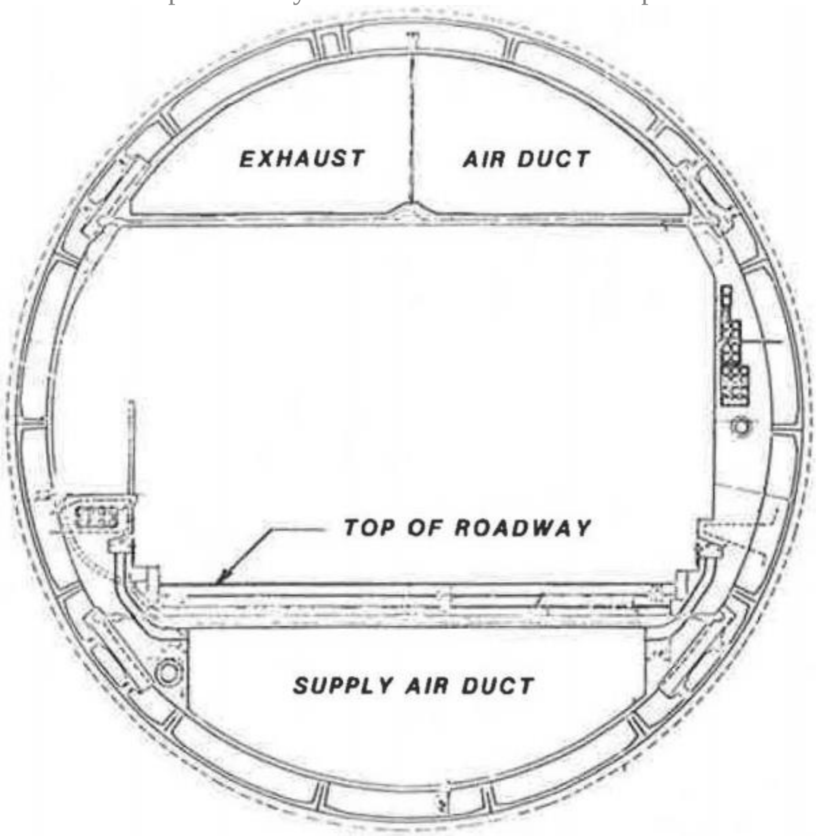


Figure 2.2.7 Transverse cross section of the Holland Tunnel tube (Lesser, et al, 1987)

A scheme of transverse tunnel ventilation is shown in Figure 2.2.8 as an example. Fresh air is sucked by fans into the vertical shaft, then enters the ventilation ducts parallel to the tunnel, where the air is distributed to the uniformly positioned vents on the ducts. The exhausts are collected at the top level of the tunnel. The gathered contaminated gases are extracted outside of the tunnel through another vertical shaft by fans. To balance the air mass and to stabilize the pressure in the tunnel, the electric fans at the inlets and outlets share the same power rate in normal operation of the tunnel.

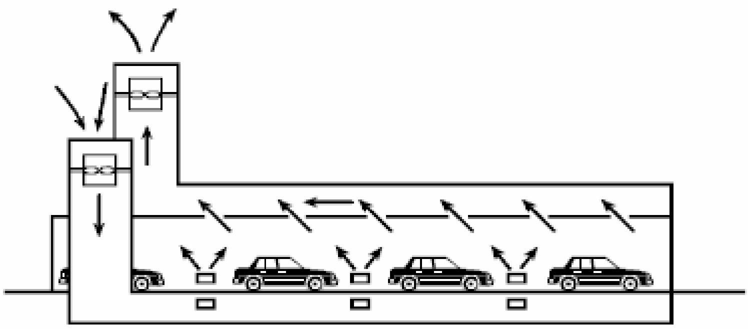


Figure 2.2.8 Scheme of mechanical transverse tunnel ventilation as an example (NFPA 502, 2004)

An advantage of transverse ventilation system is that the pollutant concentration distributes evenly along the length of the tunnel, whereas the air quality can be significantly bad at the exhaust portal in case of longitudinal ventilation, referring to Figure 2.2.2.

However, two potential issues may arise in a transverse ventilation system.

- The gas flow velocity in the supply and exhaust ducts may become excessively. According to (PIARC, 1999), a typical flow velocity of 15 – 25 m/s can be generated in the ventilation ducts at a full power operation.
- In transverse ventilation system, the fresh air is vented in a proper way by considering the traffic direction. Perturbances of atmospheric conditions at portals or instant change of traffic volume inside the tunnel may create of a net longitudinal flow, which is often difficult to control.

Fortunately both the above issues can be solved, at least mitigated, by dividing the tunnel into sections, where ventilation operations and controls are conducted separately section by section. In such a way, the flow velocity in the ventilation ducts can be reduced to a desired level. Meanwhile, the net longitudinal flow of the whole tunnel can be controlled by the relatively independent air supply-exhaust sub-systems at sections.

In case of fire emergency, controls of smoke and heat are always the major concerns. For this purpose, the standard procedure for a transverse ventilation system is to switch on the full capacity mode of the exhaust function in the vicinity of the fire location. Meanwhile, the ventilation configurations in the neighbouring sections can be tuned to minimize any longitudinal flows at the fire place, thus, to avoid smoke and heat propagating along the length of the tunnel.

The most favourite is that the smoke is extracted away from the tunnel through the nearest vents to the fire location, rather than through the distributed vents along the entire section or even the entire tunnel length. In such a sense, exhaust vents designed on the top level of the tunnel are more preferable than those located at a lower height, because the former facilitates to exhaust the light smoke and any other buoyant gas like hydrogen. Therefore, the air supply designed through the ceiling vents in normal operation should be either stopped for a fire emergency, or set to exhaust rather than supply.

On the other hand, air supply in the transverse ventilation system should be also adapted in a fire emergency, to realize a better control of smoke. The transverse air supply, especially in the region of fire, should be decreased to avoid breaking the stratification of smoke layers, if it is already formed in the fire accident. It is obvious that a stratified smoke layer, instead of dispersed smoke in air, provides a clear condition and visibility for evacuation and firefighting operation below the black cloud. It is recommended in (PIARC, 1999) that the air supply rate should be reduced in emergency to half to one-third of full capacity.

2.2.5 Semi-transverse ventilation

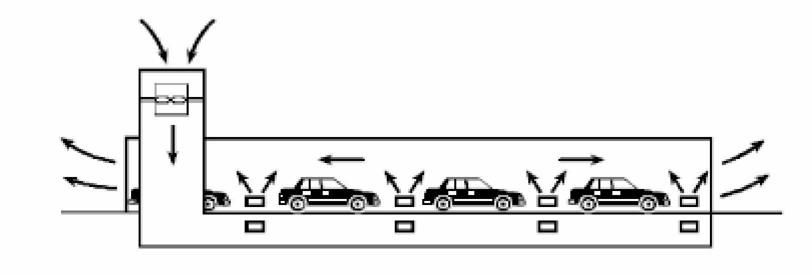
The transverse ventilation addressed in last section features in internal vents on ventilation ducts for air supply and exhaust by ignoring the air exchange at portals. It is called full transverse ventilation. A variant was employed for tunnel ventilation by using both internal vents and portals, called semi-transverse ventilation. It combines the features of both longitudinal and full transverse ventilations, but differs from both of them.

Semi-transverse ventilation has two different modes,

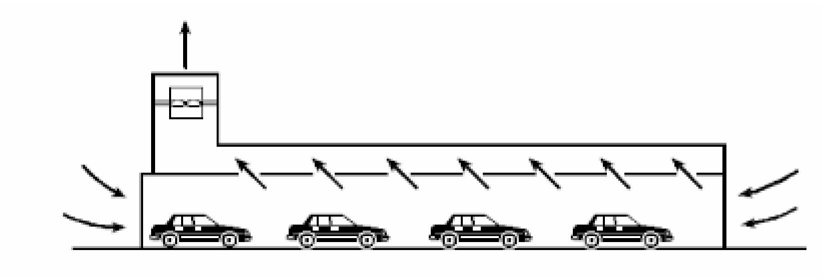
- semi-transverse supply,

- semi-transverse exhaust,

as shown in Figure 2.2.9. In semi-transverse supply system, as illustrated in Figure 2.2.9 (a), fresh air is supplied by internal vents on ventilation ducts, exhausted by portals at tunnel ends. On the contrary, fresh air enters tunnel from portals and exhausted through internal vents in semi-transverse exhaust system, as shown in Figure 2.2.9 (b).



(a) Semi-transverse supply ventilation



(b) Semi-transverse exhaust ventilation

Figure 2.2.9 Two modes of mechanical semi-transverse ventilation (NFPA 502, 2004)

There is a notable difference between the two systems. Due to accumulation effect, the pollution increases from the middle to the exit portals of the tunnel with semi-transverse supply mode, which is similar to the case of longitudinal ventilation system. However, air contamination distribution is approximately even along the length of the tunnel with semi-transverse exhaust mode, which is similar to the case of full transverse ventilation system.

The emergency responses of the two semi-transverse ventilation modes to a fire event are also different in respect to smoke control.

- For the semi-transverse supply mode

  It is recommended in (PIARC, 1999) to reverse the direction of the ventilation flow in a fire emergency, with the portals as fresh air inlets and vents on ventilation ducts as exhaust outlets, because, otherwise, the air vented by the semi-transverse supply system would dilute and disperse the fire smoke. Thus, the evacuation and firefighting operations are benefitted from the changeover of the ventilation functions. The function switch should take place as soon as possible in case of a fire occurrence, because, otherwise, the provided air by the semi-transverse supply system would breakdown the smoke layer and drag the smoke to road surface level in case the vents are located at the ceiling of the tunnel.

Optionally a feasible solution is to design an additional exhaust duct for a fire emergency, with vents located at ceiling level. The duct runs in supply mode in normal operations to enhance refreshing the tunnel, but switches to exhaust mode in emergency cases. This system was employed in the Mont Blanc Tunnel prior to refurbishment following the fire accident in 1999. One of the reasons for the tragedy in the Mont Blanc Tunnel in 1999 was the partial failure to switch the ventilation mode from air supply to smoke exhaust during fire.

- For the semi-transverse exhaust mode

  In case a fire emergency in a tunnel with a semi-transverse exhaust system, the exhaust capacities should be set to maximum, especially those near the fire place, to extract the smoke and hot gases out of the tunnel as quickly as possible.

The capacity of smoke ventilation system is an important indicator for a full or semi- transverse ventilation, while the critical ventilation flow velocity, discussed in Section 2.2.3, dominates the design of a longitudinal ventilation system. For a given design base of fire, with a specific generation rate of smoke and dimension of the fire zone, the smoke exhaust capacity is defined in Europe as the volume of air exhausted per unit length of tunnel involved in fire, briefly, m^3/s exhaust per km of tunnel.

For example, according to French regulations (CETU, 2000), some requirements on the design or performance of a transverse ventilation system for tunnels are listed below.

- Smoke should be constrained and not allowed spreading out of a 400 m zone in an urban tunnel and a 600 m zone in a non-urban tunnel.
- The interval distance between exhaust vents in ceiling is recommended as 50 m, not allowed more than 100 m.
- Smoke exhaust capacity is prescribed between 110 – 155 m^3/s per km by considering comprehensively various factors. Nevertheless, the World Road Association (PIARC, 1999) refers to a lower value of 80 m^3/s per km, with an acknowledgement that this capacity may be inadequate for a large fire involved a heavy goods vehicle.

The different types of tunnel ventilation systems are reviewed with a distinct classification of longitudinal, full transverse or semi-transverse one. However, they can be applied practically in a hybrid way to meet the particular requirements of the tunnel, because every tunnel in the world is unique in terms of meteorological and geological conditions, layout of road, traffic volume and density and so on.

Some of the most sophisticated emergency ventilation systems employ both jet fans to control pollutant and smoke transport longitudinally, and exhaust vents in ceiling to extract smoke transversely. The refurbished Mont Blanc Tunnel adopts such a hybrid system, with running jet fans to confine the longitudinal spread of smoke within a short region of hundreds metres, from where the smoke is exhausted through ceiling vents (Vuilleumier, 2002).

2.2.6 Ventilation by Saccardo nozzle system

As an important auxiliary ventilation tool, Saccardo nozzle is a powerful impulse generator, producing one or more high velocity jets of air to the desired direction. It is mentioned in

Figure 2.2.3 (c) in Section 2.2.3, where the Saccardo nozzle is employed combining jet fans to enhance the longitudinal ventilation of tunnels. Hereby the principle and advantages of Saccardo nozzle are briefly reviewed.

Saccardo nozzles supply fresh air into a tunnel in form of an air jet, which is driven by fans located usually above a portal of shaft outside of a tunnel, as shown in Figure 2.2.10. The air jet contributes most of momentum to the gas flow in tunnel, thus to speed up the ventilation flow. The direction of the jet usually has a shallow angle, e.g. no more than 30 degrees, to the longitudinal axis of tunnel, to optimize the pushing effect and to avoid impinging on the tunnel users.

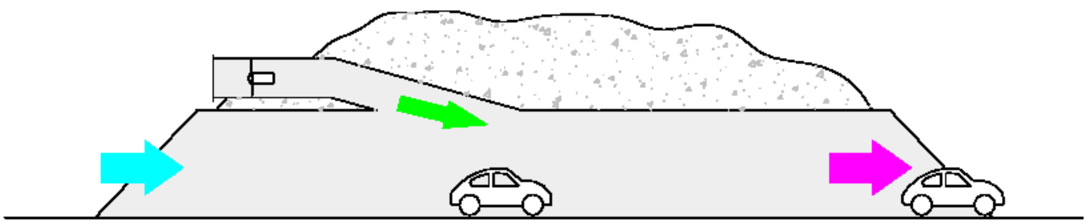


Figure 2.2.10 Saccardo nozzle applied to enhance longitudinal ventilation (PIARC, 2008)

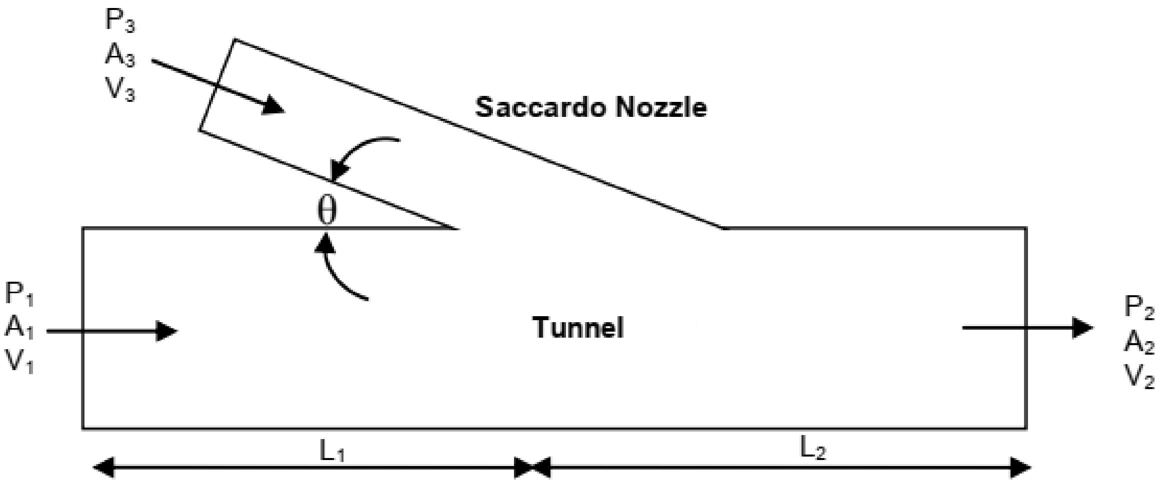


Figure 2.2.11 Momentum balance in longitudinal direction for Saccardo nozzle (Tarada & Brandt, 2009)

By applying the momentum equation to the control volume about the nozzle, as shown in Figure 2.2.11, the integral momentum balance equation in horizontal direction is obtained as,

$$(P_1 - P_2)A_2 = \dot{m}_2 V_2 - \dot{m}_1 V_1 - \dot{m}_3 V_3 \eta \cos\theta \qquad Eq. 2.2.3$$

with an assumption that A_1=A_2, i.e. the area of tunnel cross section stays before and after the Saccardo nozzle, where, (i=1,2,3),

P_i is local static pressure, Pa,

A_i is cross section area of flow path, m^2,

V_i is local gas flow velocity, m/s,

$\dot{m}_i$ is mass flow rate, kg/s,

θ is the angle between the jet direction and the longitudinal direction of the tunnel,

η is installation efficiency, a little more or less than unit, (Tarada & Brandt, 2009).

Based on Eq. 2.2.3 and using mass balance ($\rho A_1 V_1 + \rho A_3 V_3 = \rho A_2 V_2$), the static pressure difference due to the Saccardo nozzle can be derived as,

$$P_2 - P_1 = 2\varepsilon\left[\varepsilon\left(1 + \frac{\eta\cos\theta}{\alpha}\right) - 2\right]\left(\frac{1}{2}\rho V_2^2\right) \qquad Eq. 2.2.4$$

where, $\alpha = \frac{A_3}{A_2}$, $\varepsilon = \frac{A_3 V_3}{A_2 V_2}$, ρ is air density, kg/m^3.

Eq. 2.2.4 indicates that the downstream pressure increases, i.e., $P_2 > P_1$, due to the thrust of the air jet from the Saccardo nozzle, if $\varepsilon\left(1 + \frac{\eta\cos\theta}{\alpha}\right) > 2$, which is easily satisfied in practice.

Comparing to jet fans, Saccardo nozzles have the following advantages (Bendelius, 1999),

- Tunnel height is reduced owing to external location of the fans.
- The number of turning or moving parts to maintain is reduced.
- System maintenance can be done without disturbing the running traffic in tunnel.
- The noise level in tunnel is decreased.
- The ventilation efficiency of fans is high.

2.2.7 Influence of ventilation on firefighting intervention in tunnels

- Formation of ventilation flow pattern – upstream and downstream

The decisive parameter for firefighting is the formation of an up and a downstream side in relation to the source of the fire. On the downstream side, conditions (heat, vision) can establish, under which firefighting by the fire service is impossible or at least associated with very high risks for the firefighters. On the upstream side, however, there are generally conditions under which the fire services can very quickly achieve an effective extinguishing success.

In road tunnels it is possible on the upstream side to advance up to a few meters to the fire (Blennemann et al., 2005, pp 55, 57). In the Gotthard Road Tunnel on 24 October 2001 seven truck and trailers were on fire. The fire service could penetrate on the upstream side up to a few meters (seen in the direction of flow) to the first source of fire (Brauner et al., 2016, p. 23).

- Stability of ventilation flow

From the point of view of the intervention, it must be ensured for firefighting that the flow does not reverse unintentionally, because, otherwise, the firefighters can be exposed to extreme dangers, such as in the case of freight train fire in the Simplon Tunnel on 9 June 2011 (Heynen, Luginbühl, Stoffel, personal witnesses).

Therefore, a smoke reversal should always be avoided and should never take place without consultation with the emergency services. Likewise a flow reversal can have fatal consequences for self-rescue.

2.3 Ventilation for rail tunnel

2.3.1 Introduction

Mechanical ventilation of rail tunnels especially for trains driven by electric propulsion engines has been widely discussed. It is concluded in general that mechanical ventilation is required only for longer tunnels than 20 km (Gendler et al. 2012), if no specific requirements are prescribed for the thermal-dynamic condition of the air in tunnels. It has been demonstrated by many experimental and theoretical investigations that shorter rail tunnels can be ventilated by natural winds and by fast moving trains due to the piston effects created by them.

Forced mechanical ventilation is needed regardless of the rail tunnel length in some situations, e.g., (a) specific air temperature and humidity are desired for comfort; (b) ice coating formation is not expected in some cold regions; (c) radiation environment needs to be controlled in underground working places in a tunnel, etc.

However, emergency ventilation system is indispensable for a rail tunnel in order to supply safe evacuation of people and a suitable condition for firefighting in case of tunnel fires. If it is either impossible or commercially unacceptable to construct transverse ventilation shafts, longitudinal ventilation by using jet fans is favourite for a rail tunnel, to satisfy the requirements for both normal operation mode and emergency ventilation mode. Nevertheless, transverse ventilation shafts are built, where possible, especially for extremely long modern rail tunnels to realize air injection or air removal from the traffic tunnel.

By the way, permanent ventilation system is mandatory to keep the tunnel air clean from pollution of toxic exhausts of diesel driven locomotives. They still run in some cases, though in an old fashion. In such a case, the configuration and operation of the longitudinal ventilation system are determined by many factors, including: (a) tunnel parameters like length, cross section profile and area etc.; (b) capacity of natural ventilation resulted from the meteorological difference of the atmospheric air at the tunnel portals; (c) traffic volume of the tunnel as well as the maximum allowed travel speed of the rolling equipment, and the types and dimensions of the train.

2.3.2 Longitudinal ventilation for rail tunnels

Jet fans are widely used for longitudinal ventilation of rail tunnels. Different from road tunnels, the dimension and the positioning of jet fans in rail tunnels have some limits, due to,

- relatively small cross section areas of tunnels, e.g., 34 – 55 m^2,
- presence of the overhead trolley line in case of electrically driven engines.

Therefore, only jet fans with smaller diameters, e.g., no more than 900 mm, can be installed directly in the tunnel.

Figure 2.3.1 shows an example of jet fans installed directly in the tunnel. Owing to safety design margin, two jet fans fixed on the side walls of the tunnel are adequate for ventilation function of a rail tunnel for trains with electrically driven engines. However, in case of diesel engine, additional two jet fans fixed on the roof of the tunnel help to strengthen the ventilation capability of exhausting diesel combustion products.

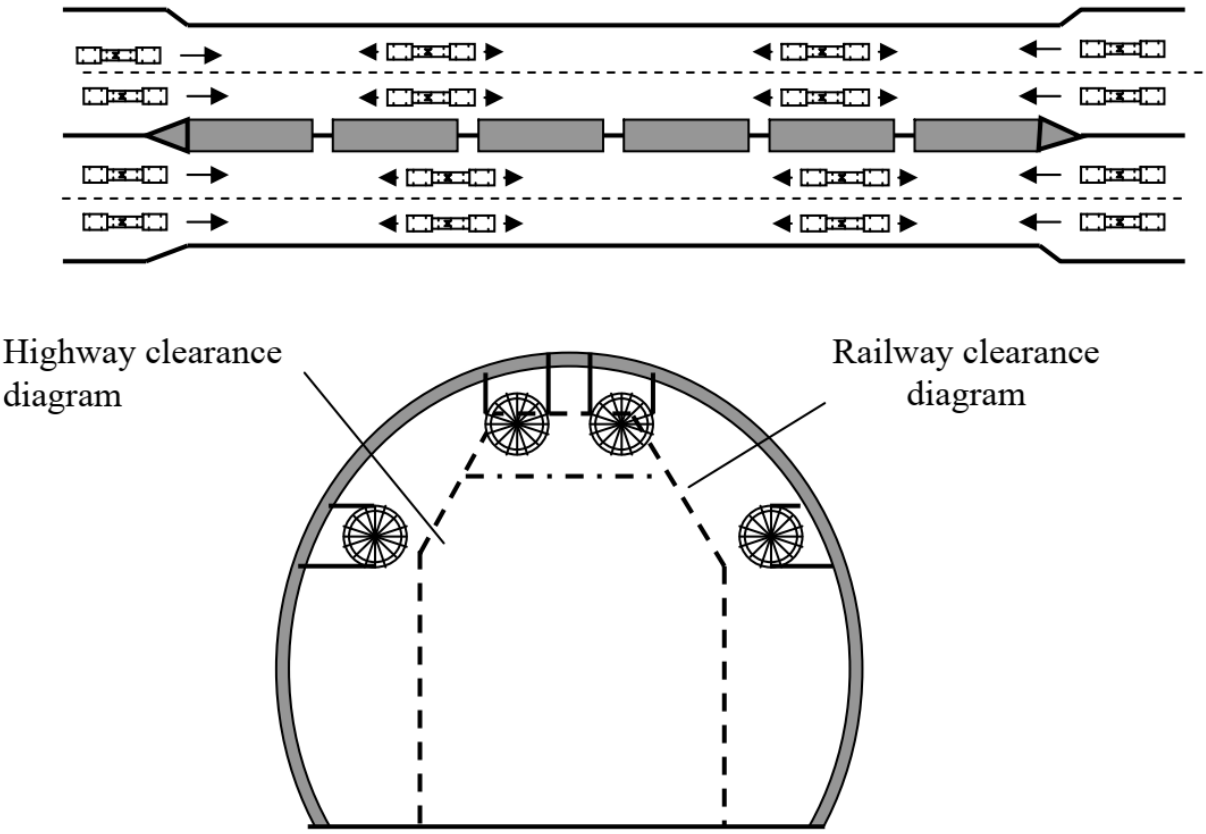


Figure 2.3.1 Jet fans installed directly in the tunnel section for longitudinal ventilation (Gendler et al. 2012)

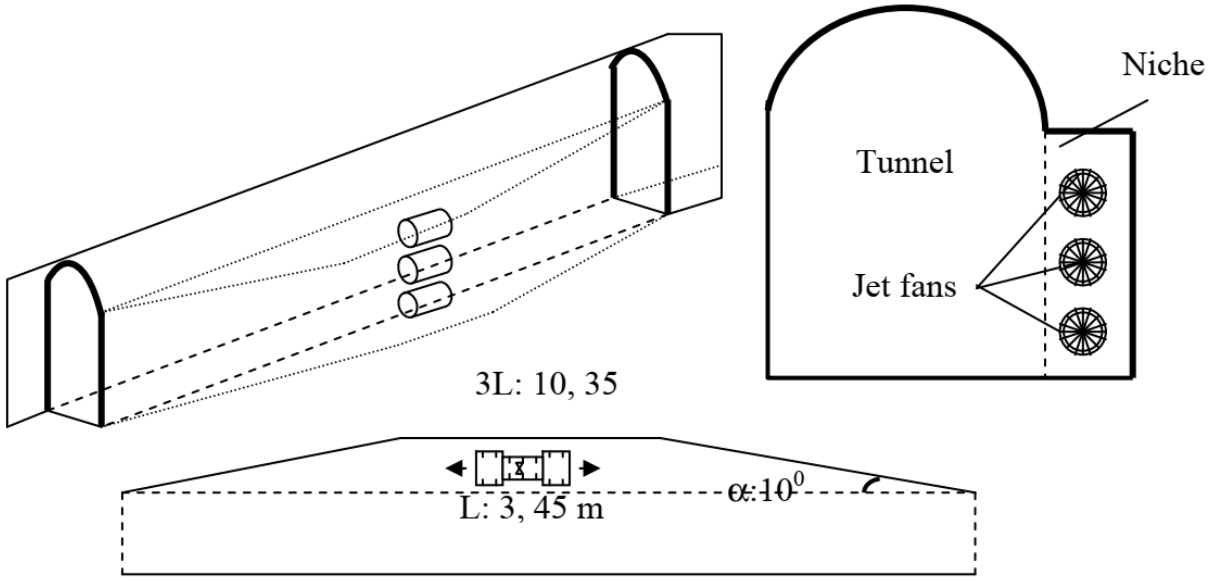


Figure 2.3.2 Jet fan installed in niches constructed in the tunnel side wall for longitudinal ventilation (Gendler et al. 2012)

In some cases a desire of a more powerful ventilation capacity to satisfy a stricter requirement about ventilation, results in new design options to allow more jet fan installations. A widely used option is to locate the jet fans in niches being constructed in the side wall, as shown in Figure 2.3.2. Alternatively, the additional fans can be located in the splayed parts of the tunnel or in special galleries located at the tunnel portals. The determination of the design options must compromise between the construction costs and the ventilation performances.

The geometrical configurations of the niches or galleries should be designed to minimize the pressure drop of the ventilation air flow through the tunnel. The running direction of the fans should be reversible for multiple operation modes.

The technical parameters of the fans should be properly selected by considering the pollution discharge intensity from trains, in a sense of discriminating electrical engines from diesel engines, and how often and how much the air in tunnels are replaced by the piston effect of moving trains. Both natural and operational factors should be accounted while defining the fan ventilation capacities.

A theoretical model (Kunsch, 2002) is set up to analyze the longitudinal ventilation by jet fans in rail tunnel. The model is useful in design calculations for rail tube ventilation.

A section of tunnel is shown in Figure 2.3.3, equipped with a jet fan close to the ceiling. The integral momentum equation in the longitudinal direction is expressed as,

$$\rho L \frac{du_v}{dt} = \Delta p_{ve} + \Delta p_F - \Delta p_R \qquad Eq. 2.3.1$$

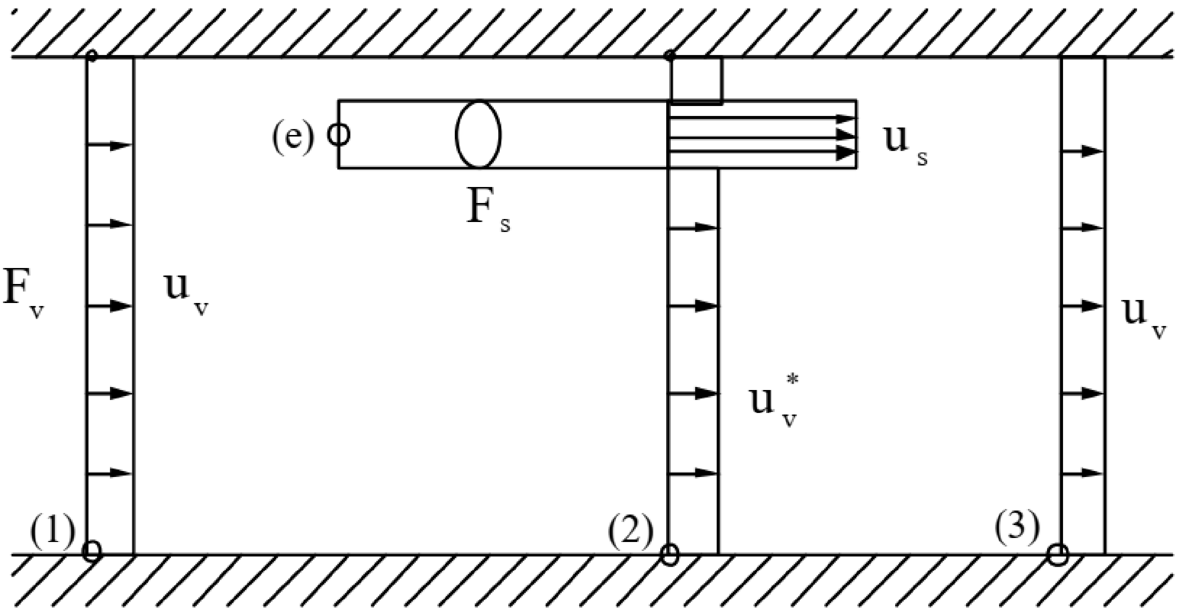


Figure 2.3.3 Theoretical model for longitudinal ventilation with jet fan (Kunsch, 2002)

where,

ρ – air density, kg/m^3,

L – Tunnel length, m,

u_v – ventilation flow velocity, m/s,

Δp_{ve} – pressure increase generated by jet fan, Pa,

Δp_F – pressure difference caused by piston effect due to moving train, Pa,

Δp_R – sum of pressure loss at the entrance portal (Δp_e) and loss due to tunnel wall friction (Δp_w), Pa.

Namely,

$$\Delta p_R = \Delta p_e + \Delta p_w$$

$$\Delta p_e = (1 + \zeta_e)\frac{1}{2}\rho u_v^2 \qquad Eq.\,2.3.2$$

$$\Delta p_w = \lambda \frac{L}{D}\frac{1}{2}\rho u_v^2 \qquad Eq.\,2.3.3$$

Thus,

$$\Delta p_R = \left(1 + \zeta_e + \lambda \frac{L}{D}\right)\frac{1}{2}\rho u_v^2 = a\frac{1}{2}\rho u_v^2 \qquad Eq.\,2.3.4$$

where,

ζ_e – geometrical factor of the entrance portal,

λ – friction coefficient of tunnel wall,

D – hydraulic diameter of tunnel, m,

a – equal to $1 + \zeta_e + \lambda \frac{L}{D}$.

On the other hand, the pressure increase generated by the running jet fan,

$$\Delta p_{ve} = \rho u_s^2 \Phi (1 - \psi) \qquad Eq.\,2.3.5$$

$$\Phi = \frac{F_s}{F_v}, \qquad \psi = \frac{u_v}{u_s}$$

where,

F_s – cross section area of jet fan, m^2,

F_v – cross section area of tunnel, m^2,

u_s – air flow velocity at fan exit, m/s.

The piston effect due to moving trains is formulated as,

$$\Delta p_F = b\frac{1}{2}\rho (v - u_v)^2 = b\frac{1}{2}\rho u_s^2 (\omega - \psi)^2 \qquad Eq.\,2.3.6$$

$$\omega = \frac{v}{u_s}$$

where,

v – train speed, m/s,

b – a factor determined by the geometries of the train and the tunnel. E.g., for a cross-sectional area of the tunnel $F_v = 47$ m^2, if the train is 300 m long, the factor b yields a value of $b = 2.4$ (Gaillard, 1973).

The steady state solution about the ventilation velocity u_v can be obtained by solving the Eq. 2.3.1 – 2.3.6,

$$\psi_{st} = \frac{u_v}{u_s} = \frac{\sqrt{(\Phi + \omega b)^2 + (a - b)(2\Phi + b\omega^2)} - (\Phi + \omega b)}{a - b} \qquad Eq. 2.3.7$$

Based on Eq. 2.3.7, if $b = 0$, namely, without traffic presence in tunnel, the solution becomes,

$$\psi_{st} = \frac{u_v}{u_s} = \frac{\sqrt{\Phi^2 + 2\Phi a} - \Phi}{a} \approx \sqrt{\frac{2\Phi}{a}}$$

by assuming $\Phi = \frac{F_s}{F_v} \ll 1$ in practice.

If $\Phi = 0$ in Eq. 2.3.7, namely, fan is out of running, the velocity due to only piston effect is,

$$\psi_{st} = \frac{u_v}{u_s} = \frac{\omega}{1 + \sqrt{a/b}}$$

The transient solution of the momentum equation Eq. 2.3.1 can be obtained as,

$$\psi(t) = \psi_{st} \frac{1 + Aexp(-t/c_1)}{1 - Aexp(-t/c_1)} \qquad Eq. 2.3.8$$

$$c_1 = \frac{L}{u_s\sqrt{2\Phi a}}, \qquad A = \frac{\psi_0 - \psi_{st}}{\psi_0 + \psi_{st}}$$

where, ψ_0 is the initial value i.e., $\psi_0 = \psi(t = 0) \geq 0$.

The discussion of the solutions can be expanded when required in further study.

2.3.3 Ventilation shafts – semi-transverse ventilation for rail tunnels

Transverse ventilation shafts are quite necessary for efficient ventilation of an extreme long rail tunnel, e.g., longer than 50 km, although such an engineering construction can be significantly costly. In this section, specific case studies are quoted to illustrate the application of transverse ventilation shafts to modern rail tunnels.

A 53.1 km long tube system with two single-track tunnels connected by cross-passages is adopted for the design of Base-tunnel of Lyon-Turin (BLT) on the route from Lyon to Turin (France–Italy), as shown in Figure 2.3.4.

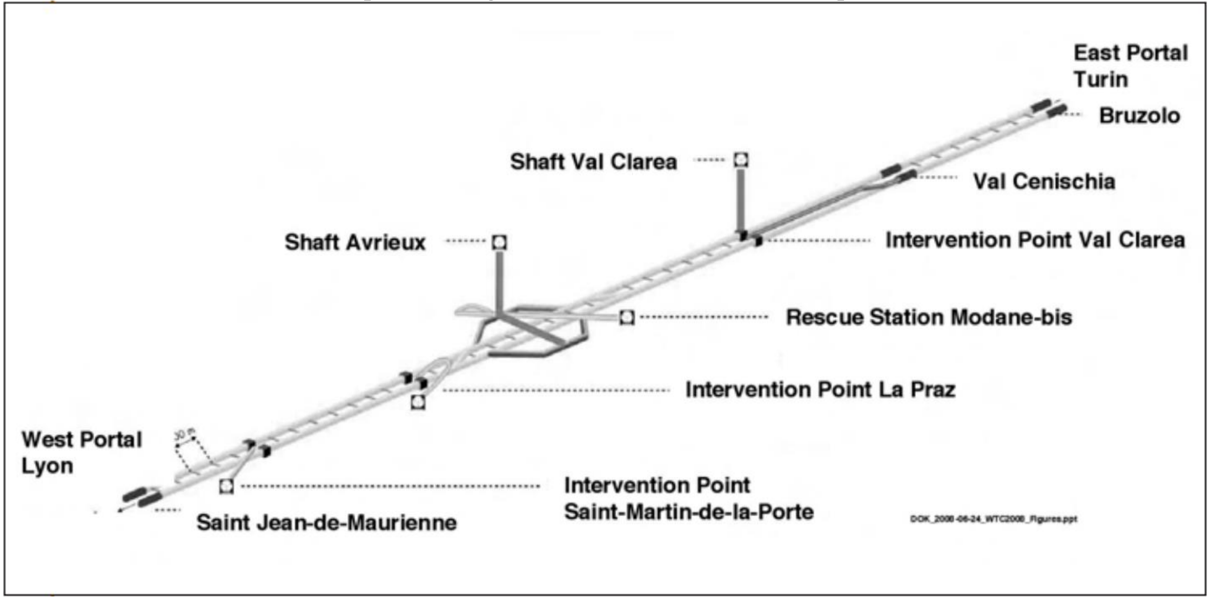


Figure 2.3.4 Design of Base-tunnel of Lyon-Turin (BLT) with two ventilation shafts (Rudin et al, 2008)

According to the figure, two vertical shafts for ventilation, one rescue station and three intervention points are designed at different places along the rail tunnel from west portal in Lyon to east portal in Turin. One shaft is located at the rescue station, supplying maximum protection to passengers from the incident train by venting fresh air in to tunnel or exhausting contaminations from tunnel. Another shaft is located at one of the intervention points.

The rescue station and the intervention points, accessible by road vehicles by access tunnels, are configured as emergency stops for the rescue of passengers from incident trains. These access tunnels act as ventilation channels too in emergency cases. Two tracks for passing trains are equipped at the rescue station for evacuation.

Table 2.3.1 lists the fan stations and corresponding ventilation capacities in the BLT as an example. The fan powers are determined by the tunnel lengths and specific ventilation requirements.

Table 2.3.1 Technical specifications of ventilation fans in Base Tunnel Lyon-Turin (Rudin et al, 2008)

Fan stations	Fan ventilation capacity, m^3/s	
	Air supply	Air exhaust*
Intervention Point: Saint Martin-de-la-Porte	2 x 90	3 x ±200
Intervention Point: La Praz	2 x 90	3 x ±200
Shaft: Avrieux/Modane	2 x 200	6 x ±200
Shaft: de Val Clarea	2 x 120	3 x ±200
Total	1000	±3000

* "±" implies the fan is reversible, namely, it runs in air supply or exhaust mode as required.

The access tunnels to the intervention points act as transverse ventilation tubes in horizontal, while the vertical shafts at two places supply transverse ventilation for the emergency stops and the whole tunnel. The access tunnels provide meanwhile emergency accesses to the tunnel from outside, but the shafts are designed only for ventilation purpose. According to the table, both air supply and air exhaust functions are configured at the overall four transverse ducts. The maximum air supply capacity of the BLT ventilation system is up to 4000 m^3/s, air exhaust 3000 m^3/s.

By considering different possible operational modes of the tunnel, the air exhaust fans are reversible, i.e. they can supply or exhaust air as required. The tunnel operation is remotely controlled from a tunnel control centre.

The tunnel ventilation runs principally in three modes: normal operation, maintenance mode, incident mode. Corresponding ventilation requirements in different modes have to be satisfied by the technical configurations of the ventilation devices.

- Normal operation

In principle the piston effect of the moving trains through tunnels is adequate to cool down the air in the rail tunnel. Additional ventilation is needed only if the tunnel is extremely long or the tunnel is in a special geological condition. In such a situation the piston effect induced air exchange may be inadequate. For an instance, the heat radiation from surrounding rock in the tunnel, plus the heat from technical devises, can heat up the tunnel air remarkably. In order to guarantee a comfort temperature, even humidity, in tunnels, regular operation of ventilation system is necessary to limit the tunnel temperature below, e.g., 35 °C. Even a water cooling system is additionally designed along the BLT tunnel. On the contrary, heating may be needed to avoid ice forming e.g., in some rigid region in Russia.

- Maintenance mode

To ensure occupational health and safety of the staff members working in the offline rail tunnel, the ventilation system can be controlled to supply and exhaust air for the construction region in the tunnel. In some cases combination of open or close of tunnel gates can bring temporarily ventilation effects too.

- Incident mode

In case of fire in passenger train or freight train in tunnels, the ventilation operation must be switched to incident mode, to meet the following requirements.

- The waiting area for train passengers at the emergency stop should be protected in fire emergency, primarily against overpressure caused by excessive air supply from outside, e.g. by the fast moving train in the non-incident tube, and against smoke accumulation in the waiting area.
- Smoke propagation into the non-incident tube should be avoided, because it may be used as a part of evacuation route.
- If incident train stops at the emergency stop, the rescue and evacuation conditions are optimized by fresh air supply and smoke extraction through the connected access tunnels or transverse ventilation shafts.
- If incident train stops unluckily outside of emergency stop, the non-incident tube should be supplied with fresh air to prevent any smoke propagation from the incident tube to

the non-incident one. Meanwhile, appropriate measures are implemented near the fire location in the incident tube to mitigate the situation e.g., maintenance of possible smoke stratification, directed displacement of smoke, thinning of smoke, minimization of the smoke propagation etc.

- If incident train stops in a single-track section of e.g., Loetschberg Base Tunnel (Rudin et al, 2008), the rail tube is kept safe by operation of ventilation ducts located in an additional service tunnel running parallel to the rail tunnel length.

Besides tunnel ventilation, different safety devices and measures are applied in rail tunnels e.g.,

- In form of light: signing of escape routes, emergency lighting, handrail, video system e.g., CCTV.
- In form of sound: loudspeakers systems, telephone.
- In form of electrics: hotbox detection unit, load displacement sensor, fire detectors, gas alarm sensors, European Train Control System (ETCS).
- Safety designs: emergency stops, cross-passages, closing doors, water/ foam extinguishing equipment, smoke extraction system, access control etc.

In view of firefighting intervention to rail tunnel fires, access from the upstream side is always more convenient and beneficial for a firefighting service to distinguish the fire source. Logically the hot temperature and bad vision in the downstream is not a good working condition for firefighters.

There are few practical experiences with train fires in tunnels. However, it succeeded, e.g. in the train fire in the Hirschengraben Tunnel on 16 April 1991, to fight a train fire from the upstream side effectively (Mundwiler, personal witness).

Thus avoiding ventilation flow reversal is critical to firefighting. Only few rail tunnels are equipped with stationary ventilation systems, which is why most railway tunnels are expected to reverse their flow due to meteorological or other influences. So it needs to be clarified how an existing flow direction can be effectively stabilised by the use of large mobile ventilators in case of rail tunnel fires.

2.4 Underground parking and other confined spaces

Ventilation systems in underground parking and other confined spaces may have multiple aims. The following discussion will mainly focus on underground car parks. The major scope is to provide fresh air and remove pollutants to prevent health injuries in a normal working condition. Carbon monoxide is one of the main controlled contaminants, as it involves the major health hazard. Other contaminants contributing to a poor air quality are nitrogen oxides and sulphur oxides, etc. Many design guidelines are available in literature and they may change according to the issuing country. UK regulations require ventilation systems to be designed to limit the level of carbon monoxide to an average concentration of 30 parts per million over an eight-hour period and to peak concentrations in determined locations to less than 90 parts per million for intervals of time less than 15 minutes (The Building Regulations, 2010). These requirements can be achieved by means of either natural ventilation or forced ventilation, according to the specific design of the space.

2.4.1 Passive/ natural ventilation

Natural ventilated spaces are generally provided with permanent and well distributed openings. The specific design of the system depends on multiple factors, such as the layout of the car park, the dimensions and position of the air vents, the location of neighbouring buildings, etc. UK regulations indicate that naturally ventilated car parks should be provided with openings with a total area equal to at least 5% of the floor area. 25% of the opening area should be located on each of two opposite walls (BS 7346-7:2013). In case of a fire in the car park, natural ventilation can be also suitable for smoke clearance from the space and creation of smoke-free routes for facilitating the escape of the occupants or the firefighters' approach to the accident scene.

Indoor release of hydrogen is a typical accident scenario for hydrogen and fuel cell systems. Natural ventilation of buildings is the flow generated by temperature/density differences and by the wind (Linden, 1999). Brown, (1962) and Brown & Solvason, (1962) conducted a series of analytical and experimental studies with exchange flow through the rectangular opening in a vertical wall. They suggested that the volumetric flow rate, Q, through a half of a single rectangular vent, during natural ventilation of air in a building is:

$$Q = C_D \frac{W}{3} \sqrt{\left(g \frac{\Delta\rho}{\rho} \right)} H^{3/2}, \qquad \textit{Eq. 2.4.1}$$

where H (m) is the height of the opening, W is the width of the opening, C_D is the discharge coefficient which represents the streamline barrier for the flow, the reduced gravity described as $g(\Delta\rho/\rho)$ can be changed to g' , where g is the acceleration due to gravity and $\Delta\rho/\rho$ is the density fraction due to temperature difference and $\Delta\rho=(\rho_{ext}-\rho_{int})$ is the density difference, where ρ_{ext} and ρ_{int} are the densities of the fluid remote from the wall outside and inside the enclosure respectively. The area of the opening $A=WH$, thus taking onto account all changes Eq. 2.4.1 will be as follows:

$$Q = \frac{1}{3} C_D A \sqrt{g' H} \ . \qquad \textit{Eq. 2.4.2}$$

The assumption used for derivation of this equation for natural ventilation of air is the equality between volumetric flow rate of air entering and leaving an enclosure through the vent. This implies that only half of the vent area is occupied by gases flowing out. This is a typical approximation for natural ventilation of air under normal conditions of building operation. However, this is definitely not applicable for comparatively large unscheduled releases of flammable gas, e.g. from hydrogen or fuel cell system, when at flow rates above a certain limit the whole vent area can be occupied by flowing out hydrogen.

The same results were obtained by Shaw & Whyte, (1974) and Wilson & Kiel, (1990). One year later (Dalziel and Lane-Serff, 1991) stated that Eq. 2.4.2 provides a reliable estimation for the imposed flow needed to arrest flow in one direction. Then Linden (1999) showed that the mixing ventilation occurs when cold air enters at high level or hot air enters at low level, which could be simply modelled by a single opening, and volumetric flow rate through it will be as follows:

$$Q = C_D A \sqrt{g' H} \ . \qquad \textit{Eq. 2.4.3}$$

Coefficient 1/3 was dropped in Eq. 2.4.3 that generated future uncertainties in the selection of value of the discharge coefficient C_D by other researchers (three times smaller values of C_D can be expected just to compensate the removal of the coefficient 1/3).

Cariteau & Tkatschenko (2013) rewrote the equation without 1/3 in terms of the volumetric fraction of hydrogen in air, X, to carry out the comparison with their experiments on helium release in an enclosure with one vent, as:

$$X = \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3}, \qquad \textit{Eq. 2.4.4}$$

where Q_0 is the volumetric flow rate of release, and the reduced gravity is $g' = g(\rho_{air} - \rho_{H2})/\rho_{air}$. The accuracy of Eq. 2.4.4 (Cariteau and Tkatschenko, 2013) for natural ventilation to predict gas concentration has been compared in the study by (Molkov et al., 2014) and an exact solution for gas concentration in conditions of passive ventilation has been derived. Equation for passive ventilation was written in the form convenient for comparison with Eq. 2.4.4 for natural ventilation of air in a building:

$$X = f(X) \cdot \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3}, \qquad \textit{Eq. 2.4.5}$$

where function $f(X)$, which defines the difference between the approximate solution for volumetric fraction of hydrogen by natural ventilation Eq. 2.4.4 and the exact solution of the problem by passive ventilation theory presented in Eq. 2.4.5, is:

$$f(X) = \left(\frac{9}{8} \right)^{1/3} \cdot \left\{ \left[1 - X \left(1 - \frac{\rho_{H_2}}{\rho_{air}} \right) \right]^{1/3} + (1 - X)^{2/3} \right\}. \qquad \textit{Eq. 2.4.6}$$

Function *f(X)* gives the deviation of the exact solution of the problem within the assumptions, i.e. Eq. 2.4.5 for passive ventilation, from the approximate solution for unscheduled release of gas, i.e. Eq. 2.4.4 for natural ventilation of air in buildings. **Error! Reference source not found.**Figure 2.4.1 shows the change of *f(X)* with hydrogen volumetric fraction in air (solid line) compared to *f(X)*=1 for natural ventilation (dash line).

Figure 2.4.1 demonstrates that *f(X)* can be twice more than one for small volumetric fractions of hydrogen and twice less than one for very high volumetric fractions. This means that hydrogen concentrations predicted by Eq. 2.4.4 for natural ventilation can underestimate real values twice for low and overestimate twice for very high concentrations. **Error! Reference s ource not found.**This would have serious safety implications.

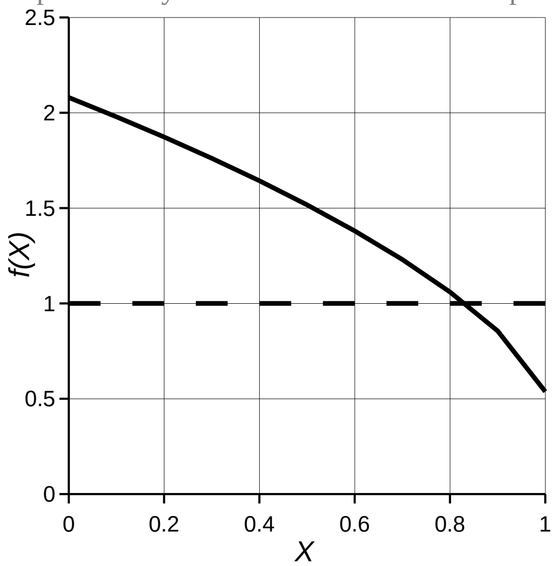


Figure 2.4.1 Function f(X) for passive ventilation (solid line) and for natural ventilation (dash line)

Detailed model derivation and validation against experiments is presented in (Molkov et al., 2014).

According to (ATEX, 2001) the limits for non-catastrophic loss of hydrogen accidents are:

Zone 0: Continuous leakage – 25% LFL = 1% H_2 vol;

Zone 1: Operational release – 25% LFL = 1% H_2 vol;

Zone 2: Occasional leakage – 50% LFL = 2% H_2 vol;

Based on the Norm (CEI EN-60079-10, 2004) ventilation requirements in the enclosures hosting a fuel cell in the event of the leak for the hydrogen concentration in air is not to exceed 50% of the lower flammability limit (LFL). A maximum allowable concentration of 25% LFL is indicated in ISO/DIS 19880-1 and NFPA 2.

Hussain et al. (2019) performed CFD simulations on a hydrogen release from a 700 bar onboard storage in a typical car park. The considered natural ventilation system followed the British Standards (BS 7346-7:2013). Results showed that a release from a TPRD with diameter 3.34 mm formed a flammable cloud that covered large part of the car park of dimensions LxWxH=30x28x2.6 m. A cloud with concentration 1% enveloped the car park along all its length. On the other hand, a hydrogen release through a 0.5 mm TPRD produced a limited flammable cloud with ~2 m maximum extension for 4% hydrogen mole fraction. In this case the cloud with hydrogen concentration higher than 1% covered approximately a length of 15 m. A reduction of this area was observed when the release was directed downwards.

If the natural ventilation in areas containing hydrogen systems is not sufficient to provide air quality with hydrogen concentration below 2% by volume, the additional source of forced ventilation required (Cerchiara et al., 2011).

2.4.2 Active ventilation

The spaces where an adequate natural ventilation cannot be provided are equipped with mechanical systems to fulfil the ventilation requirements. This circumstance can be found in underground car parks or enclosed car park storeys. In normal working conditions, the mechanical ventilation systems shall ensure at least 6 air changes per hour (ACH) in the main parking area. In the zones where vehicles may stop with running engines, a local ventilation shall ensure at least 10 changes per hour (BS 7346-7:2013). In case the mechanical ventilation is combined with permanent natural ventilation, they should respectively ensure 3 air changes per hour and an overall opening area of 2.5 % of the floor surface.

In the event of a fire, the exhaust ventilation system shall be designed to provide 10 air changes per hour. Given the presence of multiple vehicles in close proximity, a further risk is given by the fire spread from a vehicle to another one. The main aim of the ventilation is to clear the smoke produced by the fire for facilitating the escape of the occupants and the access to the scene of first responders. Furthermore, the ventilation system acts reducing the smoke density and temperature during the fire. To achieve this aim, it can be used either a ducted mechanical extraction system or an impulse ventilation system.

The ducted mechanical extract system shall have an independent power supply. The extraction fans should initiate immediately after a fire is detected through one or more of the following systems:

- Smoke detection;
- Detection of rapid rise rate of heat;
- Multi-criteria fire detection;
- Sprinkler flow switch.

The extract ducts design shall ensure that there is no recirculation of smoke into the building, entrance of smoke into the escape routes and neighbouring buildings. A velocity lower than 5 m/s shall be maintained in the escape routes to not impede the occupants escape. The extracting ducts should be distributed evenly throughout the car park and in height, providing 50% of the extraction points at a lower level and 50% at a higher level, as showed in Figure 2.4.2. The system should be constituted by two independent parts to ensure its redundancy in case of failure. The systems should be tested to perform correctly while extracting fumes at high temperature. UK regulations indicates that the equipment should be tested according to the BS EN 12101-3, which requires suitability for operation at 300 °C for at least 60 minutes. When the extraction fans are located within the building, they should be protected by a structure with fire resistance of at least 1 hour.

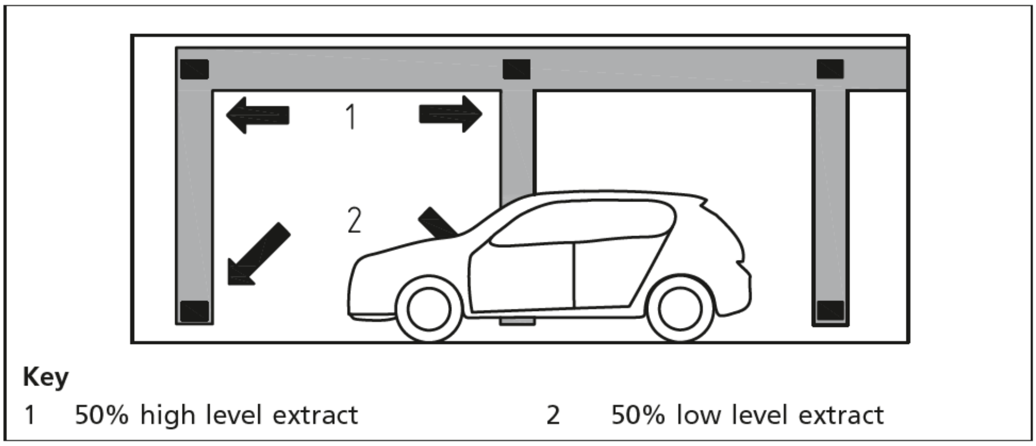


Figure 2.4.2 Typical mechanical ventilation using a ducted smoke clearance system: section view (BS 7346-7:2013)

The impulse ventilation system, also called jet fan system, should support the ducted mechanical extract system if both present. The aim of the system is to direct the smoke towards the extraction points. It should be designed to not move a volume of air greater than the amount that can be managed by the extract fans. The impulse fans may be initiated with a time delay depending on the design of the car park, the extract and impulse fans location, etc., to not obstruct the escape of the occupants. The fans should meet the same requirements as the traditional ducted mechanical extract system in terms of air change per hour. The two main typologies of fans are described below, and they are showed in Figure 2.4.3:

- Jet thrust fan: the axial flow fan is inserted in a cylindrical silencer. The inlet and outlet are located at the two extremities. This type can provide up to 50N thrust and is suitable for car park with small or medium size.
- Induction fan: the centrifugal fan has the inlet located at the bottom of the system and the outlet located on the reduced lateral side. This type can provide up to 100N thrust and is suitable for car park with medium or large size.

Figure 2.4.3 Jet thrust fan (left) and induction fan (right) (Parking Network, 2019, Colt, 2019)

An impulse ventilation system may be designed to aid the firefighters response to the fire. In this case, it should ensure a visibility of 10 m at 1.7 m above the ground in the space up to 10 m far from the fire position (BS 7346-7:2013).

In case of an accident scenario involving the leakage of hydrogen from a FCHV, the ventilation system may affect the dispersion of the gas in different ways according to the characteristics of the imposed flow.

Tamura et al. (2012) performed experiments on the dispersion of a hydrogen release from the bottom section of a vehicle. The volumetric flow rate was equal to 2000 Nl/min. The hydrogen concentration was measured around the vehicle immersed in a forced air flow directed laterally or frontally to the vehicle. The authors observed that a forced wind with velocity 2 m/s failed to achieve an effective dispersion of the gas. Conversely, the hydrogen cloud with concentration equal or higher than LFL enlarged. Tamura et al. (2014) investigated the same release scenarios with an air flow velocity equal or higher than 10 m/s. The blowers were activated 2-3 minutes after the start of the release. They were found to aid the dispersion of hydrogen to values below the LFL. The incidence of ignition decreased in presence of forced ventilation. When the ignition succeeded, the blast wave probes located on the sides of the vehicle recorded a maximum overpressure of 1 kPa, significantly lower than the 6 kPa recorded in absence of ventilation. Overall, Tamura et al. (2012) showed that an air flow with velocity higher than 10 m/s significantly reduces the consequences from an unintended hydrogen leakage. However, regulations may impose as requirement a lower velocity to not impede the escape of the car park occupants.

Requirements and recommendations will change according to the analysed enclosed space. For instance, Brzezi´nska (2018) reported the requirements for battery rooms according to BS EN 62485-2014 as follow. The ventilation flow should be defined according to calculations of the possible hydrogen emission and the volume of the enclosed space. The locations of the air inlet and outlet shall ensure the best conditions for the air exchange. The ventilation openings shall be located on opposite walls or with a minimum separation distance of 2 m if they are located on the same wall.

In parking spaces, the ceiling height is usually much lower than in tunnels, the heat load of the firefighters accordingly much higher. Thus, the heat removal by ventilation is a significant support to firefighting activity.

Due to the design or structural diversity of these spaces, universal statements can be hardly made. The tactical possibilities vary considerably. It needs to be clarified, in any case, how the ventilation can be supported quickly and effectively by the use of large mobile fans.

2.5 Regulations, codes and standards

Recently published EU Directive 2004/54/EC by the European Parliament and of the Council is on *Minimum Safety Requirements for Tunnels in the Trans-European Road Network* (European Union, 2004).

Both the NFPA 502 by the US National Fire Protection Association (NFPA, 2008) and the PIARC by the World Road Association (PIARC, 2008) are widely cited codes. Further published and widely used Report 05.11.B *Cross Section Design for Uni-Directional Road Tunnels* and Report 05.12.B *Cross Section Design for Bi-Directional Road Tunnels* by the World Road Association, summarize the tunnel design requirements in selected countries.

Regulations and standards especially regarding tunnel ventilation and smoke control are partially identified in the preceding content of the report. Instead of a full review of regulations, codes and standards (RCS) for tunnels, which will be done in D1.4 (*Critical Analysis of RCS for Safety in Tunnels and CS)*, some relevant important issues are briefly outlined hereby. Other detailed aspects like escape passages, cross-bore access, refuge shelters etc. for egress in emergency are considered not directly related to the research topic in HyTunnel-CS.

- Allowed maximum length of tunnel with only natural ventilation

  The maximum length of tunnel that requires no mechanical ventilation varies from 200 m to 800 m, depending on different countries, traffic densities, tunnel gradients, urban or rural locations etc. The new EU Directive (European Union, 2004) prescribes that '*mechanical ventilation system shall be installed in all tunnels longer than 1 000 m with a traffic volume higher than 2 000 vehicles per lane*'. It is hereby proposed that any tunnel longer than 400 m should be equipped mechanical ventilation, otherwise, natural ventilation is thought adequate.

- Restrictions on mechanical longitudinal ventilation

  Mechanical longitudinal ventilation is either discouraged or forbidden in two-way or congested tunnels, and risk analysis are required in these cases if a design with only longitudinal ventilation is accepted. Transverse or semi-transverse ventilation is, however, the preferred option for two-way or congested tunnels, usually with a high traffic volume.

  For one-way tunnels in countryside, longitudinal ventilation is generally accepted in tunnels of any length. In this case, other engineering limitations may dominate the tunnel design. For an instance, the air quality levels should remain acceptable at the exit portal, unless intermediate shafts are constructed for ventilation.

- Restrictions on ventilation air flow velocity

  As formulated in Section 2.2.3, there is generally a maximum allowed ventilation air flow velocity within a tunnel, which should be no less than the minimum critical velocity, meanwhile, not exceed certain limits to protect human activities in emergency. The upper limit about the velocity is quoted in a range of 7 to 11 m/s in respect to means of evacuation. The lower limit is suggested as 3 or 3.5 m/s with an aim to maintain smoke stratification as long as needed in emergency cases.

- Restrictions on dimensions and distances of tunnel cross-sections

  Two geometry forms of cross sections are often chosen for the traffic space in tunnels, rectangular profile ("box") and arch profile ("horseshoe"). Stipulations about minimum clearance distances, bore widths, provisions about sidewalk passage, etc. are included in regulations. Cited from BD 78/99 (Highway Agency, 1999), Figure 2.5.1 and Figure 2.5.2 show examples of box and arch profile cross-sections of tunnels, respectively.

Regarding the rail traffic system, a general scope directive on rail safety can refer to the Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 (European Union, 2016). The rail tunnel safety regulation can refer to the Commission Regulation (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union (European Union, 2014).

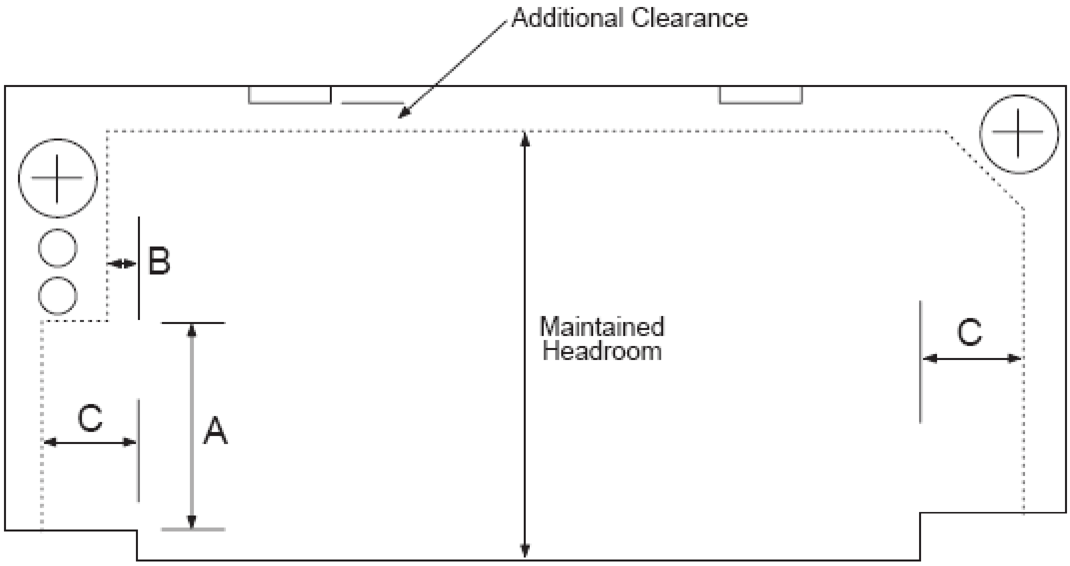


Figure 2.5.1 Example of box profile cross-section tunnel, from BD 78/99 (Highways Agency, 1999)

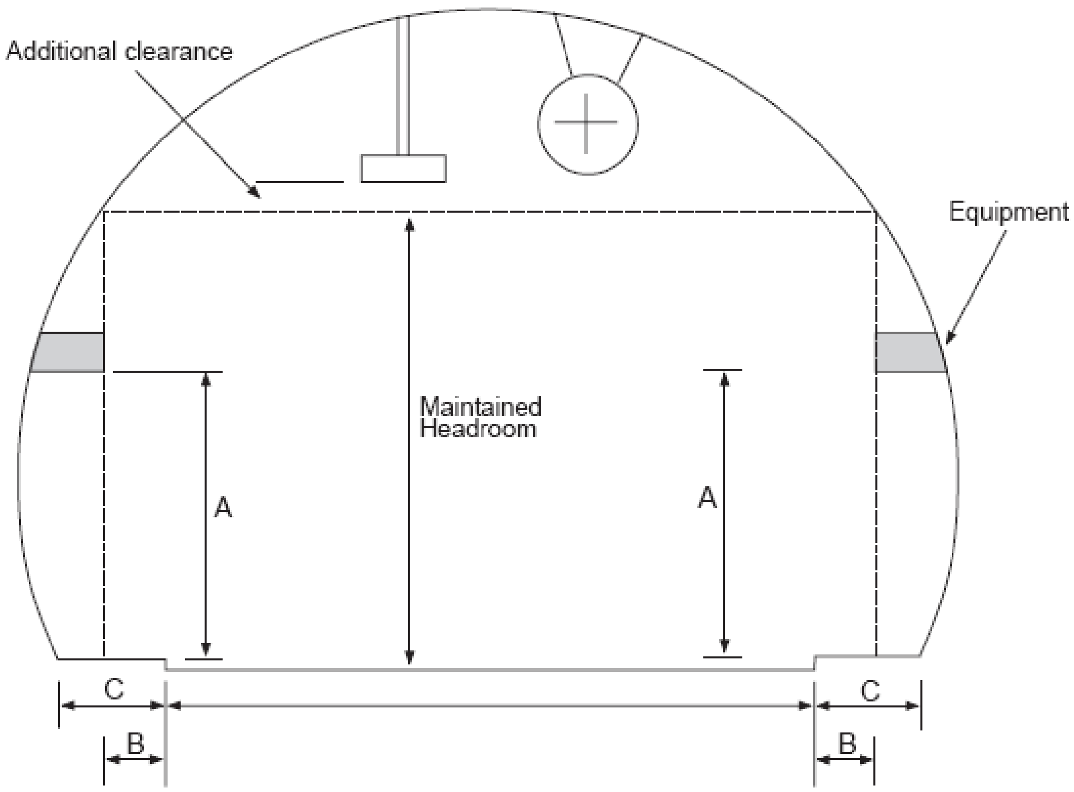


Figure 2.5.2 Example of arch profile cross-section tunnel, from BD 78/99 (Highways Agency, 1999)

Table 2.5.1 Minimum dimensions in the box and arch profile cross-section tunnels, from BD 78/99 (Highways Agency, 1999)

Dimension*	Description	Box profile, mm	Arch profile, mm
A	Walkway headroom	2300	2300
B	Width of verge with full headroom	600	600
C	Width of verge	1000	1000

* Where, “A”, “B” and “C” refer to Figure 2.5.1 and Figure 2.5.2.

- Road surface construction

  Road surfaces are typically either exposed concrete, or have an asphalt or bituminous covering. However, regulations may not allow asphalt or bituminous coverings, e.g. in Spain, as it is considered that they may contribute to fire spread, or they may be degraded.

- Road drainage

  Drainage of water, fuel or other spills is included in the tunnel design by including a transverse gradient (i.e. downwards towards the side of the tunnel bore). Typical values between 0.5 % and 2.5 % may be specified. Provision for prevention of the spreading of hazardous spills is generally required where hazardous cargoes are allowed to use the tunnel. This may be in the form of gutters or other measures, and there is likely to be a requirement for liquid sumps.

- Maximum tunnel gradients

  The maximum tunnel gradient is generally specified in national guidelines, and may vary depending on traffic density and means of ventilation. Typical maximum gradients are 5 % to 6 %.

- Traffic control

  Hazardous cargoes are generally controlled, e.g. escorted in groups. For general vehicle use, there may be recommended minimum separation distances, e.g. the distance covered in 2 s is stated in the new EU Directive (European Union, 2004). Overtaking is prohibited in general, especially in two-way tunnel bores. Stopping, turning and reversing are prohibited too, except in case of emergency or congestion. Drivers may be recommended to turn on their radios so that emergency information can be relayed.

  Additional speed limits may be applied in tunnels if necessary, e.g. where the lanes narrow inside the tunnel. It is generally accepted, however, that imposing additional speed restrictions on main highways serves no benefit and may unnecessarily disrupt the traffic flow. Namely the tunnel should be built appropriately to serve the highway where located. In the event of a vehicle fire starting, it is recommended, if possible, for the driver to drive the vehicle out of the tunnel.

3. Water injection

3.1 Introduction

Tunnel safety becomes more and more a concern since the occurrence of tunnel fire catastrophes like the one in Mont Blanc Tunnel in 1999. New methodologies are constantly being developed to cope with tunnel fires. A noticeable fixed firefighting system (FFFS) is water extinguishing system. Nevertheless, such an equipment may bring benefits only if it is applied properly with integration to other conventional safety measures. FFFS can indeed mitigate fires e.g., decrease temperature, but it causes in certain circumstance new risks too. Thus, the certainty and accuracy about FFFS against tunnel fires needs to be further investigated.

3.1.1 Tunnel fire and tunnel safety

Technical failures of fuel system or electrical system in vehicles can cause spontaneous ignition of combustible substances. Almost all tunnel fires led to fatalities due to the limited space in tunnels. Three major risks of tunnel fires are,

- loss of visibility,
- toxic smoke,
- high temperature.

The heat release rate (HRR) of a vehicle fire in a tunnel ranges from a few MW to 200 MW, depending on the type of the vehicle. The HRR may exceed 200 MW in a worst case e.g., a burning HGV transporting significant amount of hydrogen, or hydrocarbon fuel or other combustible substance including solids e.g., pure metal of aluminium.

In case of fire emergency in tunnels, operations of safety measures are expected to reach the following objectives,

- To allow self-evacuation,
- To improve the tenability time,
- To ease the rescue activity,
- To protect the infrastructure.

3.1.2 Status of FFFS application in tunnels

The world Road Association states in its latest report (PIARC C3.3, 2008) that the main objectives of water projection system in tunnel are to decrease,

- growth rate of fire,
- HRR of fire,
- fire size,
- possibility of fire spread between vehicles.

However, it is emphasized in (PIARC C3.3, 2008) that, before installing a water projection system, it is necessary to,

- identify its reliability and costs,
- identify its interaction with other safety elements,
- identify when, where and by whom the system should be activated,
- guarantee the accuracy of fire detection to prevent mistake activations.

Therefore, application of FFFS in tunnels is limited around the world except Japan and Australia, where the installation of FFFS in tunnel is prescriptive. No more than 20 tunnels are installed or planned to install FFFS in the world up to 2010 (CETU, 2010). It may be explained by the diversities of aerodynamic characters of tunnels and the features of tunnel fires. Thus, the determination of FFFS installation in a tunnel is mostly depending on case analysis.

3.1.3 Research activities on FFFS

Numerous research projects about tunnel safety were launched especially since the Mont Blank Tunnel fire in 1999. Among them, the most well known are,

- European project UPTUN – cost effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels.
- SOLIT project – the Safety Of Life In Tunnels, a German project.
- Hagerbach tests in A86 West tunnel – a Swiss study, etc.

3.2 Constitutions of FFFS

3.2.1 Extinguishing agent and water mist

Table 3.2.1 supplies a good summary about the different extinguishing agents suitable to different classes of fires. The extinguishing efficiencies are indicated as “good”, “limited” or “bad”.

Table 3.2.1 Extinguishing agents for different fires (CETU, 2010)

	Class A	Class B	Class C	Class D
Inert gas	Bad	Good	Good	Only specific liquid or powder agents are suitable
Inhibiting gas	Bad	Good	Good	
BC powder	Bad	Good	Good	
ABC powder	Good	Good	Good	
Water spray	Good	Limited	Bad	
Water with tenso-active, spray	Good	Good	Bad	
Foam	Limited	Good	Bad	

where,

Class A – solid material fires with ashes after burning e.g., woods,

Class B – liquid fires,

Class C – gas fire,

Class D – metal fire.

Tunnel fires of traditional vehicle traffic are mostly in class A or B, which water spray is seemingly a good choice. According to the table, however, water agent is not efficient to extinguish a hydrogen fire by considering the background of HyTunnel-CS. As the topic of this section is on water projection in tunnels, the following formulations focus on water agent.

Different water droplet sizes can be generated by changing the spray pressure and nozzle geometry. Based on the American standard NFPA 750, water mists are classified into three types depending on the droplet sizes (D),

Class I – D ≤ 200 µm,

Class II – 200 µm ≤ D ≤ 400 µm,

Class III – 400 µm ≤ D ≤ 1000 µm.

Bigger droplets as Class III are suitable for extinguishing solid material fires, because liquid water can splash directly on the solid surface to impede the burning. In case of gas fires or tunnel fires where combustible surface can not be approached directly by water spray, the water mist in Class I with smaller droplets is a better option due to its large surface-to-volume ratio and dispersion character in the whole gas volume. In other words, the combustion can be suppressed by the dispersed water mist even in the region shielded by solid structures from water spray. So the following discussion focuses on only mist in Class I.

3.2.2 Constitution of water mist system

Manual control instead of thermo-fusible device is recommended for tunnel water mist system. For an improved efficiency, the system must be operated by section and by remote control. Apparently the water mist droplets can vaporize fast then cool down the hot environment if temperature is high enough in a favourite area of the fire centre. Outside of the area water mist does not function effectively. Thus, manufacturers recommend,

- a distance for water mist section of 30 – 50 m.

By comparison,

- interval distance for smoke extractions of 400 – 600 m,
- distance between emergency exits of 200 – 400 m,
- interval distance of jet fan groups in longitudinal ventilation of 100 m,

the water mist zone is quite limited in length. A scheme of water mist system for tunnels is shown in Figure 3.2.1. The estimated cost for such a water mist system is about 2 million Euro per km of tunnel. The maintenance cost is about 40 000 Euro per km of tunnel per year (CETU, 2010).

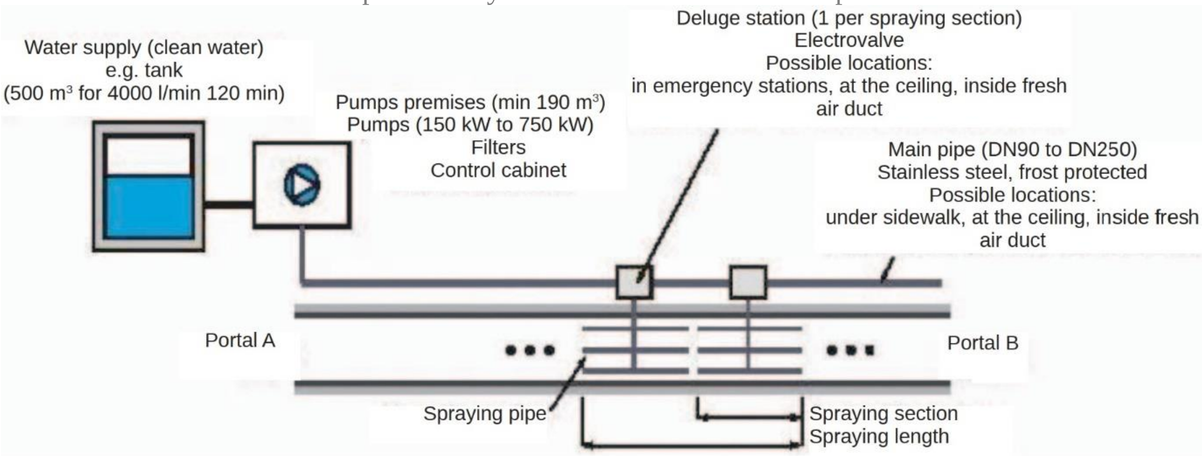


Figure 3.2.1 Scheme of a water mist system in tunnels (CETU, 2010)

3.3 Effects of water mist based FFFS on tunnel environment

Numerous studies are conducted to investigate the performances of water mist system in tunnel. It is straightforward to quote Table 3.3.1 from (CETU, 2010) to present the mitigation effects of such a FFFS system.

Table 3.3.1 Mitigation effects of water FFFS in tunnel fires (CETU, 2010)

	Certain improvement	Probable improvement	Uncertain effect	No effect	Certain deterioration
Temperature and radiation	Decrease in temperature and radiation heat flux				Decrease in tenability limit of temperature due to increased humidity
Fire spread	Limitation of fire spread on solid fuel		Limitation of fire spread e.g. liquid fire in a tilt tunnel		
HRR of fire		Decrease in HRR			
Toxicity of gases		Decrease in toxic gas emissions	Risk of acid generation	Purging of toxic gases	Loss of stratification if initially present
Visibility				Purging of soot	Limited decrease in visibility if no smoke is present; Loss of stratification

					if initially present

For example, the temperature distributions along the tunnel at different cross sections are shown in Figure 3.3.1 in the study (Cesmat, 2008). Temperature decreases in the fire area is observed in the simulations. The same study shows in Figure 3.3.3 that visibility in the tunnel lost more than 50 % due to the presence of water mist.

Decreased radiation heat flux resulted from water mist injection into the tunnel is seen in the Figure 3.3.2, cited from the study (Guigas, 2004).

The timing of the activation of a water mist system is a critical issue to optimize the mitigation effect in a fire incident. The system can be activated,

- as soon as fire is detected in tunnel,
- after rescue services have arrived,
- after all tunnel users have left tunnel.

Analysis on the interactions between water mist and tunnel users and tunnel itself, at different stages of a fire incident e.g., self-evacuation phase, rescue intervention phase etc. are of great importance, but exceeds the scope of HyTunnel-CS.

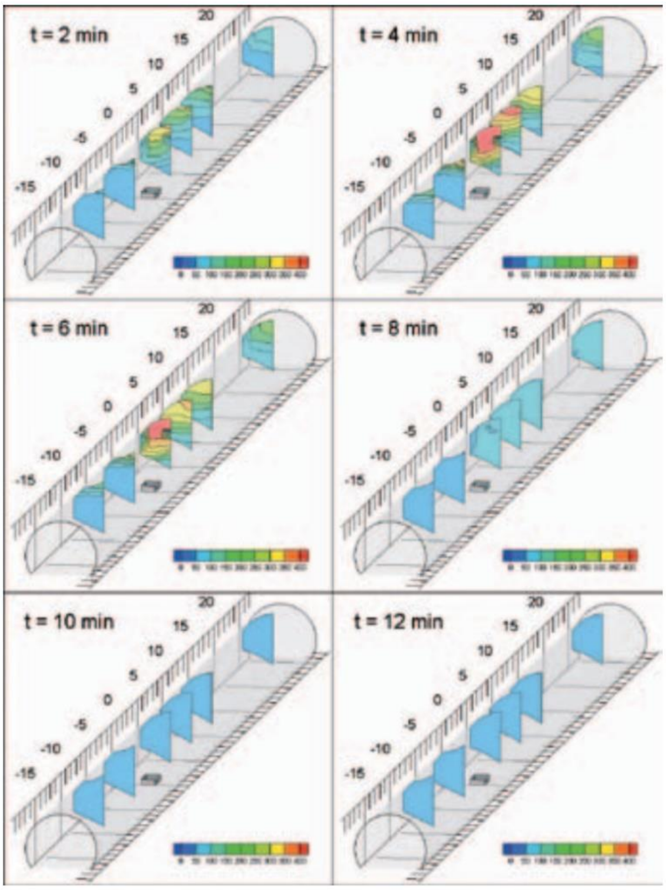


Figure 3.3.1 Decreasing temperature showing cooling effect of water mist (Cesmat, 2008)

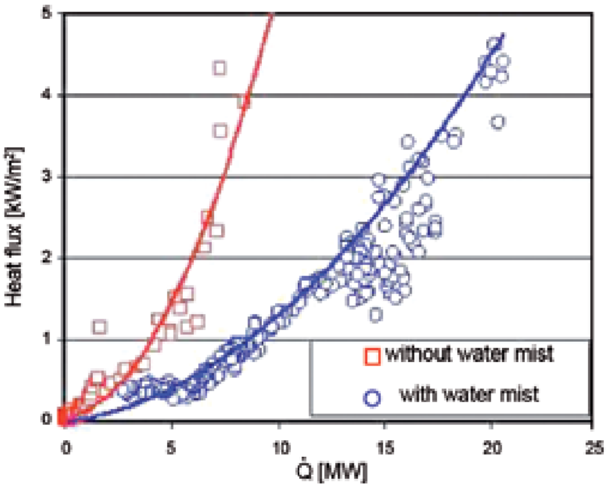


Figure 3.3.2 Decreased radiation heat flux due to water mist (Guigas, 2004)

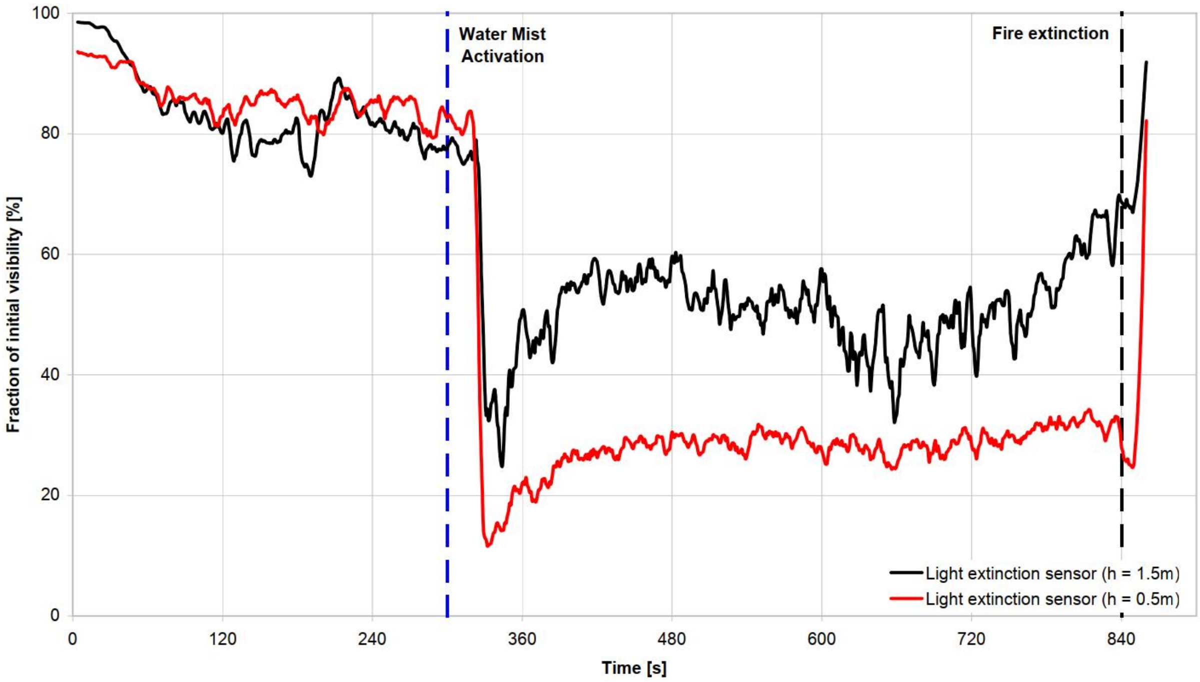


Figure 3.3.3 Decreased visibility due to water mist (Cesmat, 2008)

3.4 Other studies on water mist in tunnels

The interaction between water mist and tunnel fires are studies in many cases. Ingason et al have investigated the water spray interaction on liquid spillage fire in a sloping tunnel by experiments (Ingason et al, 2015). The experiment mimics a tank leakage induced fire incident in a road tunnel. It is an interesting finding that, the addition of a 3% AFFF-ARC foam concentrate into a spray with a water density of 10 mm/min reduced the total heat release rate of a gasoline spill fire by 50%.

The influence of water droplet size on smoke layer thickness, temperature and CO distributions are studied in (Yang et al, 2018). An obvious result is that the smoke layer thickness was increased by the water mist. The temperature distribution in vertical direction was reversed by the spray to upside down, i.e., a lower temperature on top and a higher temperature on bottom. The CO concentration behaves similarly to the temperature, namely, a lower concentration on top and a higher concentration on bottom, clearly due to the drag effect of the water spray.

4. Structural protection

Tunnel fire can pose serious threaten to structural integrity, which has been proven by many engineering practices e.g., Channel Tunnel fire 1996, Mont Blanc Tunnel fire 1999, Great Belt Tunnel fire 1994 (during construction) etc. The concept of fire safety includes fire prevention, fire protection, maintenance and evaluation for different stages of a tunnel application. Fire prevention means normally in design stage, an optimal design of tunnel to avoid fire incident e.g., the layout of one-way traffic lane avoids head-on collision. Active fire protection measures consist of mechanical ventilations, water mist projections, emergency response etc., which are discussed intensively in Section 2 and 3. Another type of protect measures are passive ones, like less flammable and high temperature endurable tunnel linings etc. Logically all the safeguards and devices needs to be maintained in function. Their effectiveness needs to be evaluated. Structural integrity provides the base for operations of all other safety systems in a tunnel. As the topic of this section, the tunnel structural integrity is in the scope of “fire protection”.

4.1 Degradation of concrete in fire

Concrete mixes differ from each other due to different manufacturing processes and various environmental factors e.g., climate, physical or chemical erosion. A general trend is to make more durable and stronger concrete with lower porosity and permeability (Beard & Carvel, 2005). When concrete is subject to high temperature, the function of concrete degrades due to the following reasons.

- Spalling of concrete

The water practically in the pores of concrete body becomes vapour quickly if concrete temperature exceeds 100 °C. The vapour pressurizes the tiny chambers, which finally bursts while the vapour pressure exceeding the containing capability of the concrete pore. It is called “spalling”.

If temperature rises to 400 °C, a component in concrete, $Ca(OH)_2$ starts to dehydrate,

$Ca(OH)_2 \rightarrow CaO + H_2O$.

Owing to the reaction, the concrete strength decreases and the produced H_2O will strengthen the spalling process of the concrete.

If temperature rises to 575 °C, another component of concrete, quartz starts a mineral transformation process with an effect of swelling of material.

If temperature rises to above 800 °C, limestone starts to decompose,

$CaCO_3 \rightarrow CaO + CO_2$.

The product of gas CO_2 accelerates further the concrete spalling process because the porosity is not enough to contain the gases. Meanwhile the concrete strength becomes weaker and weaker.

- Degradation of steel

The thermal loads have also effects on the metal reinforcement in concrete. The loadbearing capacity of steel reduces significantly while increasing temperature due to thermal expansion.

If temperature is as high as 700 °C, the loadbearing capacity of steel decreases to 20% of the value at normal temperature. The low carbon steel has a blue brittleness issue at a temperature of 200 °C – 300 °C.

- Decoupling between concrete and steel reinforcement

Both steel and concrete expand in an increasing temperature. However, the characters of the two expansion ratios become remarkably different if temperature is over 400 °C. The difference causes decoupling between the two different kinds of materials and then damaging the stresses in the mix (Beard & Carvel, 2005).

Critical deterioration occurs in concrete, which may lose structural function completely, if temperature is over 600 °C. Concrete starts to melt at an ultra-high temperature of 1200 °C. The physicochemical processes of concrete subject to thermal loads from normal to high even ultra-high temperatures is shown in Figure 4.1.1 (Khoury, 2000).

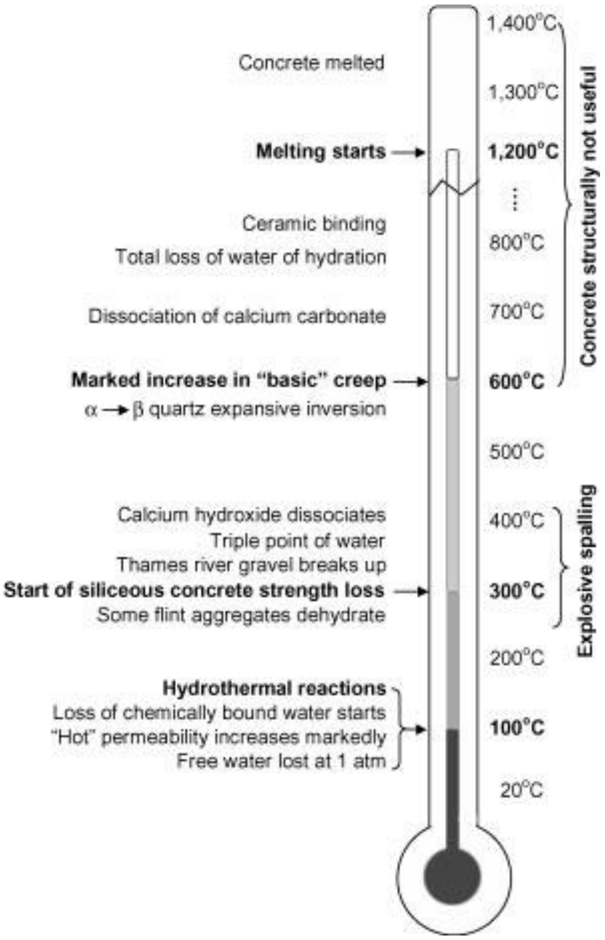


Figure 4.1.1 Physicochemical processes of concrete in normal temperature up to ultra-high temperature (Khoury, 2000).

Therefore, the fire protection measures are either to delay the build-up temperature in the concrete of the tunnel lining or to mitigate the effect of excessive heat flux in the lining. Active fire protection measures are elaborated in previous sections like tunnel ventilation and water mist system etc. Passive measures are generally in one of three forms (Beard & Carvel, 2005),

- A secondary cementitious layer applied to the tunnel surface.

- Cladding made out of protective materials fixed onto tunnel surface.
- Addition of certain fibres into the concrete mix to render it more fireproof.

4.2 Tunnels fire scenarios

Different fires present different characters on temperature evolution along time, thus pose different severities to facilities. Fires are categorized into three kinds: building fires, hydrocarbon fires and tunnel fires. Accordingly corresponding standard fire scenarios were established based on real fire experiments, for testing, modelling and design purposes. These standards are shown in Figure 4.2.1 as different temperature-time curves.

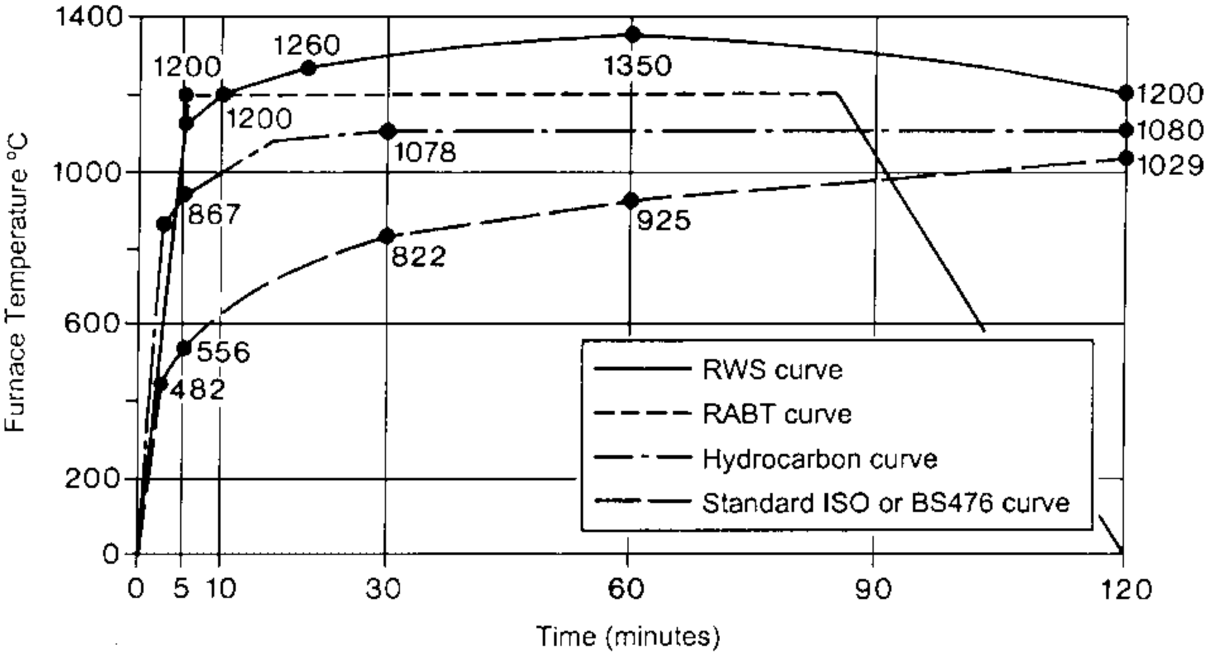


Figure 4.2.1 Fire scenario standard: RWS – Tunnel fire standard in The Netherland; RABT – Tunnel fire standard in Germany; Hydrocarbon curve – oil industry standard; BS476 – ISO building fire standard (Khoury, 2000).

It is worth to mention for HyTunnel-CS that, the RWS fire curve was defined by the Rijswaterstaat (RWS), the TNO Centre for Fire Research and the Dutch Ministry of Public Works. This RWS curve stands for the most severe hydrocarbon fire in tunnels, with a rapidly growing temperature exceeding 1200 °C in 10 minutes, peaking at 1350 °C in 1 hour, decreasing to 1200 °C in 2 hours. The extreme curve is intending to simulate a tunnel fire of a petrol tanker lorry with a thermal load of 300 MW during 2 hours. Another tunnel fire standard – German RABT curve is less severe.

The key parameters of vehicle fires about maximum temperatures and maximum heat release rates are summarized in Table, as an important result of EUREKA project (Haack, 1998).

Table 4.2.1 Key vehicle fire parameters – maximum temperature and heat release rate (Haack, 1998)

Type of vehicle	Max. temperature, °C	Max. heat release rate, MW
Passenger car	400 – 500	3 – 5
Bus/ lorry	700 – 800	15 – 20

Heavy goods vehicle (HGV) with burning goods (not petrol or other hazardous goods)	1000 – 1200	50 – 100
Railway coaches	800 – 900	15 – 20

Three real cases of tunnel concrete lining damage caused by fires are summarized in Table 4.2.2, cited from (Khoury, 2000). It is noticeable that the fire durations in three cases are significantly longer than the standard scenarios, which is caused partially by the difficulty the fire brigade encountered in accessing and extinguishing the tunnel fires.

Table 4.2.2 Concrete lining damage in tunnel fire accidents (Khoury, 2000)

Tunnel	Concrete strength	Maximum Temp. °C	Fire duration, h	Length affected	Segment depth affected
Great Belt (1994)	76 MPa, 28 day	800	7	16 segment rings (1.65 m long) damaged in crown	Up to 68% spalled in layers along 10 segments
Channel (1996)	110 MPa, mature	1100	9	500 m with 50 m severely affected by spalling	Up to 100% of segment thickness spalled showing grout
Mont Blanc (1999)	Not reported	1000	50	900 m; tunnel crown most affected	Not reported

4.3 Failure modes of tunnel concrete lining

The very detailed failure mechanisms of concrete mix and reinforcement subject to high temperature are reviewed in (Khoury, 2000). The failure modes of concrete structures of tunnels exposed to fires are summarized as follows,

- loss of bending strength,
- loss of tensile strength,
- loss of bond strength,
- loss of shear strength,
- loss of torsional strength,
- loss of compressive strength and,
- spalling of the concrete.

Given a fire scenario e.g. the RWS curve, a qualified design of a concrete structure for fire resistance should satisfy the following requirements,

- The overall dimension of the section of a concrete element should be adequate to keep the heat transfer through the element within a prescribed limit.

- The concrete cover to the reinforcement should be sufficient to keep the reinforcement temperature below critical value, for a long enough time period as required for fire resistance.

4.4 Fire resistance assessment of concrete structure

4.4.1 Experimental method

Although it is normally expensive to conduct fire testing of a concrete element or assembly, numerous studies or projects were dedicated to research the topic on fire resistance of concrete structures exposed to certain temperature-time standard curve.

Following the Channel Tunnel fire 1996, for example, a series of fire tests for tunnel concrete lining were commissioned to evaluate the performances of different concrete materials exposed to credible fire scenario (Shuttleworth, 2001). A test specimen of concrete without any additive fibre in the mix showed a clear evidence of explosive spalling after 20 minutes of exposition to a standard fire scenario, as shown in the left piece of Figure 4.4.1, while another piece of specimen with polypropylene fibres (pp fibres) added in the cement did not suffer damages at all, subjected to the same fire scenario.

Figure 4.4.1 Concrete specimens with and without additive polypropylene fibres subjected to a standard fire scenario, showing distinct performances (Shuttleworth, 2001)

The main findings of the study (Shuttleworth, 2001) are,

- Additive polypropylene fibres into the high strength concrete mix with low permeability exhibits a remarkably reduced risk of explosive spalling when exposed to severe hydrocarbon fires.

- Additive steel fibres did not improve the fire resistance performance of the concrete in absence of polypropylene fibres in the mix.

- The retained strength of concrete towards the face exposed to the severe RWS hydrocarbon fire, where the internal temperatures exceeded 800 ºC, was in the region of 75% of the comparative cube strength of the mix.

The results of another experimental study (Kaundinya, 2007) confirmed the conclusion that the bearing tunnel structure can be protected against extreme fire effects by adding plastic fibres into the mix, also by optimising the concrete composition and selecting the aggregates.

- In the context of HyTunnel-CS, however, the hydrogen fire seems pose much more severe condition to the tunnel structure due to the high adiabatic flame temperature of hydrogen-air (2210 ºC). Although it can be a little lower in real tunnel environment, the peaking temperature of hydrogen fire is still much higher than that of the RWS curve. Fortunately the duration of a hydrogen fire is not counted as hours but minutes by considering e.g., the hydrogen release time from a pressure relief device (PRD) of a hydrogen vehicle.

4.4.2 Theoretical method

Analysis methods by using computer codes are widely accepted nowadays. Based on fire engineering and physical modelling, computer software can simulate numerically the behaviours of tunnel structure subject to fire in different structural conditions until collapse, which is in normal case difficult for a fire test.

General professional software for thermal mechanical simulation includes, e.g., ABAQUS, ANSYS, ADINA (ADINA R & D, Inc.), PAFEC (UK), LUSAS (UK) etc.

Fire-dedicated finite element computer programs are available e.g., FIRES-T3 (UC Berkeley, US), TASEF-2 (Sweden), TEMPCALC (Sweden) etc.

The first professional fire-dedicated concrete software, FIRES-RC, was firstly developed in University of California in 1974. Later follow-ups include e.g., CONFIRE (Norway), STABA-F (Germany), CEFICOSS (Belgium), STRUCT (UK) and the recent FIREXPO, developed in 1999 by the Bouygues Group.

European Commission founded the development of the HITECOSP code (HIgh-TEmperature COncrete SPalling), it is a fully coupled multiphase model, capable to predict the behavior, and potential for spalling, of heated concrete structures for e.g., tunnel fires and nuclear reactor applications (Khoury, 2000).

4.5 Blast wave mitigation techniques in tunnels

Among other challenges the information on blast wave mitigation by existing structural elements, e.g. ventilation ducts and openings, emergency exits, passes between parallel tunnels is practically absent. The most of energy from the blast is used to demolish the car rather than it's displacement, so in order to reduce a blast wave strength in the near field due to loss of mechanical energy of compressed gas the simulation of destruction of the vehicle after tank rupture is required and this is the subject of an ongoing research. The CFD study to simulate decay of a blast along a tunnel, without mitigation measures has been carried out in (Shentsov et al., 2018) and (Shentsov et al., 2019). Next step is to add/try mitigation measures outlined in review of currently used explosion mitigation techniques.

Work by (W. Fondaw, 1993) has shown the shock mitigating effects of low-density foam. The optimal foam thickness depends on the length of the tunnel and how much shock mitigation is required. About 1.25 kg of C-4 explosive in 2 m diameter tunnel provided the blast. The tunnel with 10 cm of foam shows over 50% reduction in the peak overpressure compared to the tunnel without foam. The tunnels with 20 and 30 cm of foam show even more reduction of 70% and 78% respectively. In the plain tunnel, the overpressure exceeds the lung damage threshold (82 kPa) values for about the entire length of the tunnel. But with 10 cm of foam, the overpressure drops below this threshold at around 30 m and with 20 cm of foam it drops below at about after 25 m.

(Hager and Naury, 1996) predicted the pressure dynamics for a storage chamber, a secondary tunnel, and a primary tunnel inside an underground storage facility, they determined the effects of tunnel length, and effect of boundary conditions on peak shock pressures and time duration of pressures, also compared measured and predicted pressure time-histories with the following results:

- For straight tunnels, the peak pressures attenuated slowly along the length of the tunnel. Responding media modelled by a cylinder in which the chamber and access tunnel are embedded was 7.8 m in radius and 115 m in length located along the tunnel walls caused minimal change in the predicted peak pressures.
- For the tunnel complex consisting of different tunnels and chambers, responding media reduced peak pressures by 10 to 30%.
- Predicted peak pressures by Autodyne exceed the measured pressures by at least 100% nearfield meaning and by ten times higher than the measured pressure at junctions, which could be explained due to be resulted reflected pressures at the tunnel junction.

The mitigating effect of a water wall on the generation and propagation of blast waves of a nearby explosive has been investigated using a numerical approach by (Cheng et al., 2005) it was shown that the water-to-explosive weight ratio 1–3 is practical for applications. This amount of water can reduce the peak overpressure by about 30–60%.

(Kumar et al., 2009) presented and extensive overview on the dispersion and explosion hazards research conducted as part of HyTunnel, together with other published work, and provided a better understanding of the potential hazards associated with hydrogen vehicles in road tunnels.

(Pennetier et al., 2012) in their study determined numerically and experimentally the position of this transition zone along the tunnel when during the wave propagation, after multiple reflections on the tunnel's walls it will behave like a one-dimensional wave using scaled model.

(De et al., 2013) studied the role of compressible protective barriers (made of polyurethane foam) and rigid barriers (made of concrete) in reducing the impact of a surface explosion and beneficial effects of both compressible and rigid barriers has been shown.

(Koneshwaran, 2014; Koneshwaran et al., 2015) numerically investigated the effect of the surface explosion above the buried tunnel on different depths. They were looking into the amount of TNT that can be safety exploded above tunnel surface and the modelling techniques could be useful in application for the internal explosions too.

A series of in-situ tests were carried out by (Zhang et al., 2016) in far field to study the blast mitigation effect of a water filled plastic wall. Test results show that the mitigation effect of water filled plastic wall is remarkable. The numerical simulations were also performed water wall scaled height and water/structure scaled distance on the overpressure reduction are discussed and analysed.

Work by (Pavan Kumar et al., 2017) studied the shock wave propagation through the shock tube numerically and the interaction of shock wave with perforated plates was observed. It was shown that the shock wave pressure drops as it passes through the perforated plates. The percentage pressure drop varied from 43.75% to 26%. Hence, the perforated plates can be used to attenuate shock/blast waves.

Small scale tests were performed by (Homae et al., 2018) to study mitigation effect from water in a bag (water bag) placed inside the tube to reduce the blast wave, caused by explosion. The blast pressure outside the tube was measured and examined. The results demonstrated that the peak overpressure and positive impulse was mitigated for 33-45 % by the water bag. It was concluded that the information obtained from the research can be extensively applied to the explosion in closed places, such as subsurface magazines, underground magazines, and tunnels, for mitigation of blast wave.

Among blast impact mitigation measures there are several approaches available in the literature to decrease the vulnerability of structural integrity e.g. wrapping the tunnel with flexible and compressible barrier consisting of a layer of polyurethane foam, introducing energy absorbing flexible honeycomb elements between radial joints of the tunnel etc. As for the mitigation of the blast strength on the people this could be archived by compressible porous foams, ventilation openings and presence of evacuation lanes to route the blast way, use of perforated plates for blast shielding, etc. The level of congestion is also affecting the strength of the blast, so this also have to be considered.

5. Review on vehicular traffic accident characters

Study on traffic characteristics in tunnels is important to define realistic accident scenarios for the HyTunnel-CS hydrogen release scenarios. This section is dedicated to discuss vehicle behaviours in tunnels and the traffic accident frequencies.

Hereby it should be claimed by the author that, most of the content in this section is cited or modified based on Chapter 3 of the HyTunnel Final Report (Kumar et al, 2009). It is regarded to have the same value for the HyTunnel-CS.

5.1 Traffic mix

When considering hydrogen releases in tunnels one factor that may influence the resulting dispersion and possible combustion of the released hydrogen is the traffic mix in the tunnel, i.e. the proportion of commercial vehicles. The traffic mix may affect the release scenario due to the following two points,

- the effect of commercial vehicles on air flow velocity in tunnels while traffic is flowing,
- commercial vehicles causing significant obstructions in tunnels which could influence the combustion regime depending on the proportion of the tunnel cross-section and total tunnel volume that they account for.

For the purposes of this report commercial vehicles are considered to be a combination of trucks heavier than 3.5 tonnes and buses or coaches, the former corresponding to a typical definition of a "heavy goods vehicle" (HGV).

As heavy goods vehicle predominates in the commercial vehicle category, it is proposed that the notional commercial vehicle is approximated by the following dimensions, a length of 15 m, a width of 2.55 m and a height of 4.0 m.

The traffic mix is influenced by many factors and national average values may vary substantially when compared with specific roads because of the type of road, and the strategic value of the road in terms of freight transport or particular local conditions such as significant industrial concentrations.

Based on a variety of road traffic statistics, the proportion of commercial vehicles averages 7% in the EU increasing to 9% on major roads and increasing further to approximately 15% if only motorways are considered. However, specific roads can have proportions of commercial vehicles as high as 25% - 30% (Mouchel Consortium, 2001).

Minimum EC safety requirements for Trans-European Road Network tunnels assume a baseline traffic mix including 15% heavy goods vehicles (European Commission, 2002).

On the basis of the aforementioned it is proposed that generalised modelling should allow for 15% of the vehicles in the tunnel being commercial vehicles, i.e. approximately 1 commercial vehicle in every 7 vehicles, with randomly generated positioning of the commercial vehicles within the overall traffic flow.

5.2 Effects of commercial vehicles on air flow velocities in tunnels

Zalosh et al investigated the dispersion of natural gas releases in naturally ventilated tunnels in the US (Zalosh el al, 1994). The study provides limited information on the effects of commercial vehicles on air movements in naturally ventilated tunnels. Traffic mix details are not provided for any of the tunnels considered in the study. However, for one of the tunnels an indication of the effects of commercial vehicles on air velocities is provided. The effects of commercial vehicles were considered to be significant for an individual 10 second velocity measurement but much less significant when individual 10 second measurements are averaged over the 80 - 100 second measurement period used. It was considered that the traffic mix could have a significant effect on the overall air flow. Individual air velocities are not provided in the report to allow the effect of commercial vehicles to be identified.

It is clear that, any effect of commercial vehicles on the overall air flow would be related to the proportion of commercial vehicles in the traffic flow and could be significant for key routes with 25% - 30% commercial vehicles.

5.3 Traffic accidents

Road traffic accidents (RTA) are in general the result of a chain of events caused by failures, i.e. deviation from the intended, in any or all of the principle elements of the road traffic environment including drivers, vehicles, road and surroundings. The road layout and interactions between users have a significant effect on the accident rate. In the UK, 60% of personal injury accidents involving road users occur at or within 20m of junctions, and 84% of those accidents at or near junctions occur within built-up areas (Department of Transport, 1993). Road traffic accidents are basically of three types,

- Vehicle - vehicle conflicts,
- Vehicle - hard object conflicts, e.g. bridge piers,
- Vehicle - soft object conflicts, e.g. human.

Factors influencing the degree of damage include the type, size, weight and construction of the vehicles and objects involved, the relative velocities of the vehicle(s) involved and the angle of impact. In tunnels, the factors influencing safety are indicated in Figure 5.3.1 (UN ECE, 2001).

Many road users consider road tunnels to be special elements of the road infrastructure that generate feelings of concern for their personal safety (Norwegian, 1997). In others words, they perceive a higher risk. The perception of increased risk is in part due to entering a darker confined space, but also due to well known tunnel accidents such as the relatively recent Mont Blanc Tunnel fire in 1999, Tauern Tunnel fire in 1999 and Gotthard Tunnel fire in 2001. In terms of traffic accident frequencies, studies indicate that tunnels are either at least as safe as, or not noticeably safer than, open roads. Nevertheless, if accidents do occur in road tunnels, the potential exists for more severe consequences than on the open road.

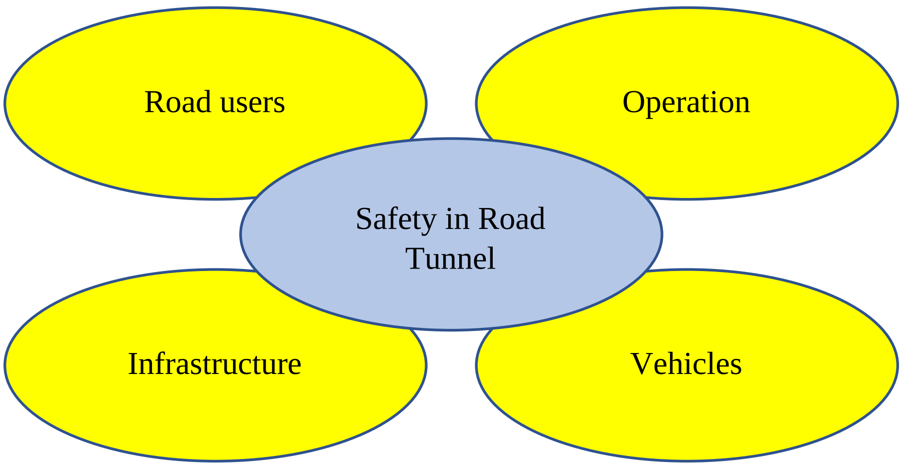


Figure 5.3.1 Factors influencing safety in road tunnels (UN ECE, 2001)

5.3.1 Tunnel characteristics affecting traffic accidents

Many of the factors that contribute to traffic accidents on open roads are absent or of reduced significance in tunnels, including,

- Traffic in tunnels is shielded from to adverse weather conditions, e.g. rain, wind, snow, ice.
- Tunnels often have reduced speed limits.
- Steady lighting conditions.
- Restricted overtaking either by physically separate traffic flows or by regulation.
- Normal absence of junctions or reduced occurrence of merging or diverging traffic flows in the majority of tunnels.
- No stopping.
- Normal absence of pedestrians or bicycles.
- More concentrated drivers due to unusual surroundings/perception of danger.
- High standard road alignments imply often less severe curves and shallower inclines, except for water crossings.
- The reduction in hazard exposure increases in longer tunnels.

However, some additional hazards may exist in tunnels, including,

- A fire in a tunnel may have more severe consequences than an equivalent fire on an open road.
- Confinement if a vehicle leaves the carriageway.
- Confinement causing traffic jams thus blocking the carriageway in the event of a vehicle break down.
- Poor visibility due to built-up vehicle emissions.
- Poor lighting transitions between tunnel and open road including blinding sunlight at tunnel exits.
- Hypnotic lighting in long tunnels.
- Inadequate lighting.

Additionally longitudinal gradients greater than 2.5% increases the frequency of breakdowns by up to five times with a related increase in the risk of further incidents (UN ECE, 2001).

Some possible scenarios that could result in a traffic accident in a tunnel include,

- Vehicle related incidents
    - Fire in tunnel
    - Accidents
    - Breakdowns

  - Debris on road
  - Over-height vehicles

- Non vehicle related incidents
  - Lighting failure
  - Ventilation failure
  - Pumping failure
  - Emergency telephones out of order
  - Pedestrians in the tunnel
  - Animals in the tunnel
  - Vandalism
  - Terrorist attack

- Traffic queues
  - Traffic queues due to other causes, e.g. volume of traffic

- Vehicle loadings
  - Hazardous loads
  - Slow moving loads
  - Wide loads
  - Abnormal Indivisible Loads

- Weather hazards
  - Fog
  - Rapid, air vapour condensation on windscreen, mirrors, etc
  - High winds
  - Ice
  - Snow
  - Flood
  - Dazzle

- Planned maintenance
  - Lane closures
  - Carriageway closures
  - Tunnel bore closures
  - Total closure
  - Contraflow operation
  - Temporary signing

5.3.2 Accident statistics

As with most publicly available road traffic accident (RTA) statistics most of the available data is based on police reports of personal injury accidents (PIA) resulting in personal injury or death, including at least one moving vehicle. The available statistics are often very wide ranging and detailed, however, they have a number of limitations and the following accidents may not be included,

- Damage-only accidents without human casualties,
- Accidents not reported to the police or not reported within a given time limit,
- Reported accidents that are not recorded.

In order to use PIA data to estimate the probability of a hydrogen release following a traffic accident, it has to be assumed that personal injury relates to vehicle damage, i.e. intrusion into the vehicle structure. Such assumptions are misleading for following important reasons.

- PIA statistics do not describe the degree of damage incurred by the accident vehicles.
- PIA statistics do not indicate which part of the vehicle was damaged, e.g. front, rear or side.
- There is not a clear relationship between the severity of personal injuries and vehicle damage.
- Accidents under reporting are a significant issue, as not all accidents are reported to the police regardless of any legal requirement to do so. The degree of under reporting varies inversely to the severity of the accident. Very few, if any, accidents resulting in a fatality do not become known to the police, however, a significant proportion of non-fatal injury accidents are not reported to the police.
- PIA statistics, however, supply a reasonable basis for comparing the relative frequency of accidents in tunnels.

The sources of publicly available RTA statistics for tunnels are from a number of studies focussing primarily on Norway, Germany, Switzerland etc. (UN ECE, 2001; Norwegian, 1997; Amundsen et al, 2000; OECD, 2006; Haack, 2002; Salvisberg et al, 2004). The available statistics do not differentiate between types of vehicles, i.e. private or commercial vehicles.

5.3.3 Accident frequencies

Statistics indicates that the tunnel involved road traffic accident (RTA) is significantly less frequent than that of open road.

The traffic accidents on Switzerland’s national road network during 1992 – 1999 were analysed in the report (OECD, 2006), which tells the average accident rate in tunnels is 0.35 per million vehicle-km, compared to 0.47 on open roads.

Similar statistics was done in Norway with a result that, the frequency of personal injury accident (PIA) in tunnels is half of the average road accident frequency, at a rate of 0.15 per million vehicle-km, referring to the last two bars in Figure 5.3.2 (OECD, 2006).

A German statistics on the RTA rates during 1993 – 1997 concluded a similar result that tunnel accident frequency is about half of that for open roads (Haack, 2002), where accident types are differentiated in the study. The frequency of PIA in tunnels is 0.074 – 0.141 compared to 0.147 – 0.315 for open roads; the frequency of only property damage accident in tunnels is 0.328 – 0.249 compared to 0.619 – 0.983 for open roads.

The road traffic accident frequencies are summarized in Table 5.3.1.

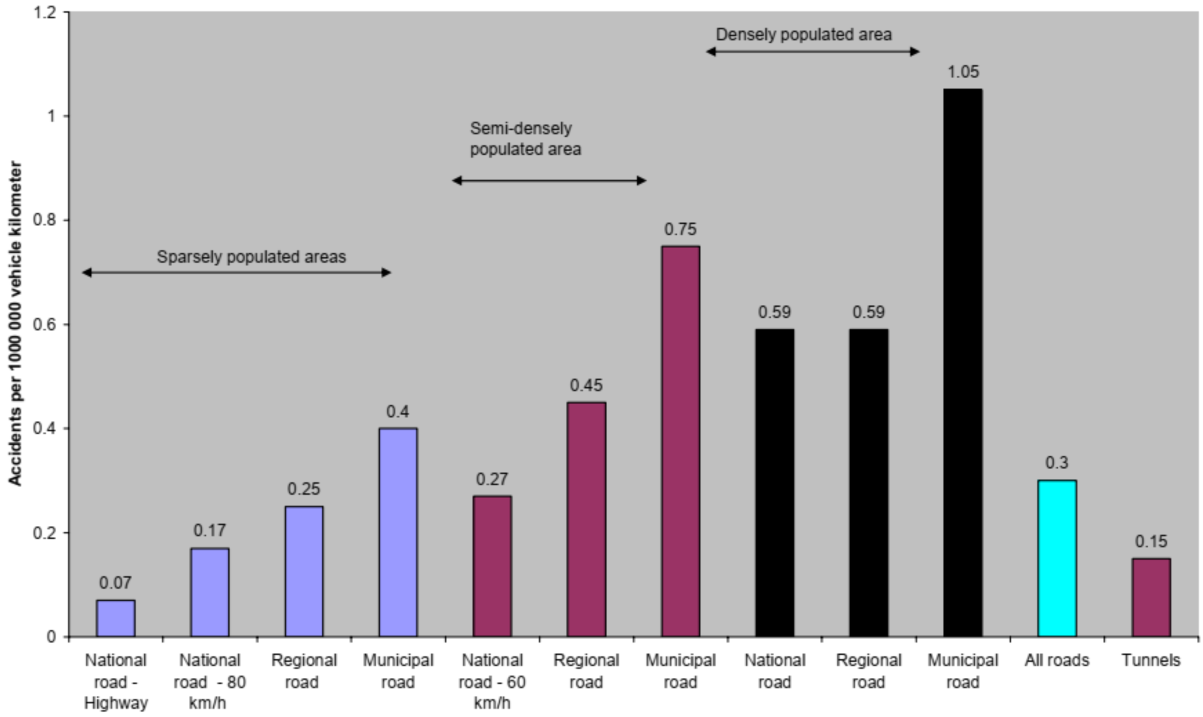


Figure 5.3.2 Number of accidents per annum per million vehicle kilometres in Norway (OECD, 2006)

Table 5.3.1 Traffic accident frequencies

	Accident rate, per million vehicle-km			
	Switzerland	Norway	Germany (PIA)	Germany (Property damage only)
Tunnel	0.35	0.15	0.074 – 0.141	0.328 – 0.249
Open road	0.47	0.30	0.147 – 0.315	0.619 – 0.983
Percent of ‘Tunnel’ over ‘Open road’	75	50	50 – 45	53 – 25

The variation of accident frequency in different parts of tunnels was analysed in (Norwegian, 1997; Amundsen, 2000), supplying a result in Table 5.3.2. It is interesting that the 50 m open road right before entering a tunnel is more risky than in the tunnel, while, the first 50 m in the tunnel has the highest accident frequency.

Table 5.3.2 Accident frequencies in different sections of a tunnel (Norwegian, 1997)

Tunnel zone	Description	Accident rate, per million vehicle-km

1	*50 m in front of tunnel openings*	*0.30*
2	First 50 m inside the tunnel openings	0.23
3	Next 100 m inside the tunnel	0.16
4	Mid-zone (remainder of the tunnel)	0.10
2 – 4	Tunnel	0.13

The relationship between accident frequency and tunnel length is cited from (Norwegian, 1997), as shown in Table 5.3.3. It clearly shows a decreasing accident frequency along with an increasing tunnel length.

Table 5.3.3 Accident frequencies in tunnels with different lengths (Norwegian, 1997)

Tunnel length, m	Accident rate, per million vehicle-km
0-100	0.35
101-500	0.21
501-1000	0.15
1001-3000	0.11
>3000	0.05
Average	0.13

The traffic accident frequency may be influenced by other factors, e.g., traffic volume and traffic density. The tunnel accidents vary in different types and severities. These are in a secondary position by considering the context of HyTunnel-CS. However, vehicle fires in tunnel are of great importance in view of hydrogen safety. The topic is addressed in next section.

5.4 Vehicle fires

Vehicle fire is the most important scenario in a tunnel accident, due to both thermal loads and the toxic gases or smokes released from the fire. In case of a hydrogen vehicle involved in a tunnel fire, potential risk of hydrogen explosion exists.

A vehicle fire in a tunnel may be caused by a traffic accident, a technical failure of the vehicle or a human activity like smoking in the car. A direct reason of the fire may be the failure of the fuel system or electrical system of the vehicle, besides other accidental factors.

5.4.1 Vehicle fire frequency on normal roads

According to the study (Haack, 2002), the statistic frequency of vehicle fire on general traffic roads has a rate of 0.02 fires per million vehicle-km in central Europe.

5.4.2 Vehicle fire frequency in tunnels

Limited data are available for tunnel fire accident statistics. In the same study (Haack, 2002), fire accidents were counted for individual tunnels, e.g., the Gotthard Tunnel in Switzerland. It is found that the heavy goods vehicles (HGV) are more prone to be involved in tunnel fires than passenger cars. The accident statistics in the Gotthard Tunnel suggests an estimation of 0.04 fires per million vehicle-km for all vehicles and 0.06 fires per million vehicle-km for HGV.

A survey conclusion in (UN ECE, 2001), cited from a PIARC study in 1999, indicates that the vehicle fire frequency in tunnels is not higher than 0.25 fires per million vehicle-km. It is proven again that HGVs contribute more to vehicle fires in tunnels than cars. Moreover, fire frequency in urban tunnels is higher than in none-urban tunnels. Forty percent of the tunnels in survey never had a fire.

6. Main results of internal HyTunnel in HySafe

6.1 Background

In the frame of European Network of Excellent on Hydrogen Safety (HySafe), the safety issue of hydrogen vehicle as a tunnel user is identified as an important topic in the Phenomena Identification and Ranking Table exercise. Therefore, a so-called HyTunnel internal project was conducted in HySafe.

For selected scenarios, the potential hydrogen hazards posed by hydrogen vehicles confined in traffic tunnels were investigated both experimentally and theoretically. Especially the phenomena of hydrogen release from a compressed tank, hydrogen dispersion in air and hydrogen combustions in different regimes in a confined space like tunnels were studied. Some results were obtained based on the limited work (Kumar et al, 2009).

6.2 Experimental results

6.2.1 Effect of congestion and ventilation on hydrogen explosions

The stoichiometric hydrogen-air mixtures were ignited in the test facility, the overpressure produced by the hydrogen combustions were measured under different conditions of congestion or ventilation. The main outcomes are,

- Increased congestion at earlier stage let to a maximum hydrogen explosion overpressure, but a further increase of congestion at a later stage resulted in a reduced overpressure.
- In case of low hydrogen release rate, more congestion in the chamber created the highest explosion overpressure. On the contrary, in case of high release rate of hydrogen, less congestion created the highest overpressure of hydrogen explosion.
- Increasing ventilation rate caused a decreasing maximum hydrogen explosion overpressure.

These results imply that a hydrogen vehicle running in a tunnel with accidental release of hydrogen can produce, in case of ignition, destructive overpressures being able to destroy e.g., tunnel facilities, although the hydrogen cloud occupies only a few percent of the confined volume. On the other hand, fast flame and even deflagration-to-detonation (DDT) may occur in such a hydrogen release scenario.

6.2.2 DDT in stratified hydrogen layers

To mimic the real stratified hydrogen distribution on the ceiling of a tunnel after an accidental hydrogen release from a vehicle occurs, a semi-confined test chamber were set up. Hydrogen combustions in the stratified layers were observed and measured. The major conclusions are,

- Only slow flame was found in smooth channel without obstructions, but three different combustion regimes may be distinguished in obstructed channel.
- A new finding on the DDT criteria for a stratified distribution of hydrogen in air is that, the dimension of the confinement should be larger than 7.5 – 15 times the detonation cell size (λ). This differs from the conventional “7λ criteria” for homogeneous hydrogen-air mixtures.

6.3 Theoretical CFD studies

The CFD studies mainly focus on two issues on hydrogen behaviours in tunnels,

- hydrogen dispersion in tunnels, simulating the activation of pressure relief device (PRD) of a hydrogen vehicle,
- combustion and explosion of the dispersed hydrogen cloud in tunnels.

Tunnels with both arched profile and rectangular cross sections were determined as the geometrical models for CFD simulations. Both liquid hydrogen (LH_2) and compressed hydrogen (CGH_2) were taken into account as release sources from different types of vehicles. Main findings are as follows,

- The predicted dimension of hydrogen cloud dispersed from a LH2 car release is smaller than that from a CGH2 vehicle, although the release inventory of gaseous hydrogen is less than the liquid hydrogen. Nonetheless, the hydrogen concentrations in the larger clouds is relatively small, implying a less severe explosion risk. In other words, those releases from LH_2 may bring more severe consequences, but the conclusion needs to be further clarified.
- Comparing to the case of rectangular tunnel, the flammable cloud in the tunnel with arched profile cross section has less hazard. This may be explained by the larger distance between the PRD of vehicle i.e., the source location, and the tunnel roof of the arched tunnel. The larger distance results in a more dilution before the release jet impinges on the ceiling. In view of hydrogen safety, the arched profile seems to be a safer configuration of traffic tunnels than the rectangular one.
- A blowdown simulation of 5 kg hydrogen released from a 350 bar pressure vessel through a 6 mm diameter PRD suggests that, a smaller diameter of PRD may reduce the resulted hydrogen explosion hazard.

However, an inconsistence between two simulation results was regarding to the tunnel ventilation effect on flammable cloud size. One study indicates the variation of ventilation flow velocities within 1 – 4 m/s causes little influence on the sensitivity of the hydrogen clouds. However, another study manifests that, a low ventilation as 1 m/s brings a significant reduction of flammable cloud size. This issue is proposed to be further studied and verified in the HyTunnel-CS.

In general, open issues of hydrogen involved in traffic tunnels and underground parking places should be addressed in the HyTunnel-CS:

- What essential hazards exist when hydrogen enters cross-ventilation systems (ducts and electrically operated fans) in traffic tunnels and underground parks.
- What are the serious differences, if any, in the mechanism and development of the fire ignition / explosion between vehicles powered
  - with hydrogen,
  - with petrol / diesel,
  - with liquefied petroleum gas,
  - pure electric.

7. Conclusions

As the first sub-task (Task 1.1) of work package WP1 in the HyTunnel-CS, the safety provisions for traffic infrastructures with confined boundary conditions like traffic tunnels, underground parks etc. are reviewed with hydrogen concerns, by considering the application scenarios that hydrogen powered vehicles are using the infrastructures. Accidental hydrogen releases in confined traffic infrastructures pose potential risk of combustion and explosion, challenging the existing safety provisions of e.g. tunnels. Hydrogen dispersion and combustion, including fast flame and detonation, are certainly affected strongly by current mitigation systems like ventilation or water spray in tunnels.

Therefore, ventilation systems of road tunnels, railway tunnels and underground parks are described in sequence, and followed by the review of water mist system as an import fixed firefighting system in tunnels and buildings. Next, tunnel structural response to a fire incident and safety measure to protect tunnel concrete lining against high temperatures are discussed. Features of road traffic accidents and statistics on tunnel fire accidents are reported. Previous studies on hydrogen issues relevant to a confined spaces like tunnels are reviewed. The main conclusive remarks are summarized in form of following highlights.

<u>Ventilation</u>

- Ventilation of road tunnels
  - Every road tunnel is unique due to many factors, like local meteorological and geological conditions, engineering feasibility for construction, capital budget etc. Thus, the determination of ventilation mode choice must depend on specific case study.
  - Natural ventilation is suitable only for relatively short tunnels e.g., 1 km depending on the local traffic density.
  - Semi-transverse ventilation mode shows merits in air and smoke controls by using its hybrid features from both longitudinal and full transverse ventilations. As an important auxiliary design, a Saccardo nozzle system can be incorporated in the tunnel design to obtain an optimum ventilation effect due to many advantages of the system.
  - A critical ventilation flow velocity in the longitudinal direction of a tunnel is recommended as 3.5 m/s. It is sufficient to extract gaseous contaminations and toxic smoke of fire, while it is not too large to impede the personal evacuation and rescue operation.

- Ventilation of railway tunnels
  - Rail tunnels have relatively small cross section area, thus the piston effect generated by moving trains are not ignorable particularly in single-track tunnels.
  - Impulse jet fans for longitudinal ventilation must be positioned with cares about the rather limited height of the rail tunnel and with attention to the power lines normally on the tunnel roof for electric locomotives.
  - The solutions of an integral momentum equation about tunnel ventilation flow by modelling of piston effects of moving trains are discussed, which supplies a

theoretical tool for hydrogen transport estimations possibly encountered in the coming studies.

- Ventilation of underground parks
  - The current safety provisions and regulations on such confined spaces are reviewed, including both natural and mechanical ventilation systems against possible accumulations of hazardous or harmful gaseous emissions from vehicles.
  - Empirical engineering tools for natural ventilation flow rate estimations are reviewed for bounded spaces like underground parks. Corresponding formulas with corrections due to hydrogen presence are also available.

<u>Water injection</u>

- As a conventional fixed firefighting system (FFFS), water spray or water mist mitigation systems are widely applied in buildings. However, it has pros and cons when it is applied in traffic tunnels.
- Water injection can decrease fire growth, spread and heat release rate due to its cooling effect. Aqueous film forming foam (AFFF) can be an additive component injected together with water to strengthen the extinguishing effect in some circumstances.
- The construction and maintenance cost of water mist system for tunnels can be remarkably high.
- The accurate detection on a tunnel fire and the timing of activation of spray are two critical points for water spray operation, in order to obtain an effective fire extinguishing in case of tunnel fire emergencies.
- Disadvantages of water injection into tunnels include, loss of visibility, loss of smoke stratification if it is formed, decrease of tenability of temperature limit due to increased humidity, which influence adversely evacuation, rescue and firefighting activities.
- Advantages of water injection in view of hydrogen safety include, breaking down possible hydrogen stratification and making the hydrogen-air mixture inert to combustion. Nonetheless, the turbulence brought by water injection can intensify hydrogen combustion and enlarge potential hazard.
- Installation of water spray are not accepted in worldwide. So far no more than 20 traffic tunnels are installed or planned to be installed a water spray system. The decision on the installation must reply on specific case study.

<u>Tunnel structure</u>

- The mechanism of concrete tunnel lining degradation like spalling in fire scenarios is reviewed. The standard temperature-time profiles standing for different scenarios for fire tests are summarized.
- Previous studies manifest that additive polypropylene fibres into the high strength concrete mix with low permeability exhibits a remarkably reduced risk of explosive spalling when exposed to severe hydrocarbon fires. By comparison, it is interesting that the additive steel fibre cannot improve the fire resistance performance of the mix without the polypropylene fibres.

- Thermal-mechanical models of concrete with reinforcement and modern relevant computer simulation software are summarized.

Traffic accident statistics

- Heavy goods vehicles (HGV) are more prone to be involved in tunnel fires than passenger cars.
- Commercial vehicles in large dimensions including HGVs and bus coaches occupy about 15% of overall traffic mix i.e., one commercial vehicle among every seven vehicles.
- Occurrence frequency of vehicle fire in tunnels is no more than 0.25 fires per million vehicle-km.

Internal HyTunnel in HySafe

- The main achievements in the internal HyTunnel project of the NoE HySafe are summarized in both experimental and theoretical aspects.
- A concluding remark is that, the internal parts of any kinds on tunnel ceiling and walls e.g. jet fans, lighting system etc. act as obstructions of gas flows, which can initiate hydrogen-air flame acceleration even combustion regime transmissions with increasing explosion hazards.
- The geometrical profiles of tunnels, ventilation configurations and designs of pressure relief device of hydrogen vehicles are the key variables to determine the levels of hydrogen risk and the designs of safeguards for tunnels.

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