FIRE SAFETY IN EXISTING ROAD TUNNELS AND CONFINED SPACES OF HONG KONG

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Fire Safety in Existing Road Tunnels and Confined Spaces of Hong Kong

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

In Hong Kong, buildings and other structures are statutorily required to provide active and passive fire safety provisions as prescriptively stipulated in different Codes and Standards that are in-forcing during the time of construction. However, these designs might not be able to cater for new challenges caused by technology advancement, living habits changes, use of new vehicular construction materials as well as increases in population and traffic volumes. In this thesis, new challenges faced by road tunnels nowadays would be elaborated in detail.

Fire safety provisions in tunnels were reviewed. A horrible fire that happened in 1999 at the Mont Blanc Tunnel caused 39 decreases. The fire was originated from a heavy good vehicle carrying flour and margarine. Post-fire investigation revealed the fire temperature was over 1,300°C and cause extensive structural damage in the tunnel. 15 days were required for cooling down the tunnel to allow the entry of investigation team. Countless serve road tunnel fires had claimed the lives of people and caused huge monetary loss.

Having learnt from the tragic experience of road tunnel fires, researchers suggested that a tremendous amount of heat would be released in a heavy goods vehicle fire occurs inside a road tunnel. Means must be provided for tunnel structure protection and fire spread prevention; while the installation of fixed fire-fighting system is a feasible solution to the problem.

In the first part of the thesis, the integrated performance of fixed water-based fire-fighting systems and a longitudinal ventilation system was studied by performing full-scale burning tests. A section of tunnel under construction, with dimensions of 100m in length, 12m in width and 6.5m in height, was utilized for the venue of full-scale burning tests. Water-spray systems, with or without AFFF foam additives, were used to suppress a 20MW fire in different testing scenarios. The longitudinal ventilation was set at the critical velocity, i.e. a wind speed of $3ms^{-1}$. Diesel or wood pallets were used to fire fuel. Temperature profiles, both in upstream and downstream positions, would be studied and compared. Video camera would also be used to record the development of fire and as well as the movement smoke. Top shield and side shield would be provided to simulate the shielding effect of vehicle compartment and adjacent tall vehicle respectively. A total of eight scenarios with different testing parameters combinations would be conducted for evaluating the coupled performance of water-spray fire-fighting systems and longitudinal ventilation, the activation sequences of these two systems and the shielding effects. These results would be valuable for formulating

statutorily requirements on fixed fire-fighting systems and provide a solid scientific foundation on the holistic assessment in the engineering analysis for road tunnels.

Moreover, the introduction of clean fuel for vehicles also posted new challenges to the road tunnel design. In the second part of the thesis, the explosion and thermal hazards associated with the clean fuel vehicles would be studied through Computational Fluid Dynamics software, namely Flame Acceleration Simulator (FLACS) in a garage and a section of short vehicular tunnel.

A garage with a design commonly seen in Hong Kong was used to demonstrate thermal hazards of vehicles using LPG and hydrogen as fuel. The simulation results on post-explosion pressure and temperature surges could provide in-sight on determining appropriate protection measures for the maintenance garage.

Furthermore, a section of SVT of 12m in length with concealed spaces under the roadways was used to illustrate the explosion hazards of LPG vehicles which further highlighted the problem regarding old / existing designs might not be able to cater for new challenges. Two case studies in road tunnels of Hong Kong were used to intensify the idea. According to the findings, a recommendation was made to strengthening fire safety management as an interim measure.

Through continuous dynamic risk assessment, potential risks and areas requiring strengthening could be identified while the use of performance-based design provides a scientific platform to holistically review the integrated performance of existing active and passive fire safety provisions as well as their synergy with enhanced and tailor-made fire safety management measures.

PUBLICATIONS ARISING FROM THE THESIS

Referred Journal Papers

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J2. C.W. To, W.K. Chow, F.M. Cheng, 2019. Numerical studies on explosion hazards of vehicles using clean fuel in short vehicular tunnels, Tunnelling and Underground Space Technology - Submitted for consideration to publish, June 2019.

J3. C.W. To, W.K. Chow, F.M. Cheng, 2019. Numerical study on thermal hazards of vehicles with clean fuel in enclosed spaces, Building Simulation - Submitted for consideration to publish, August 2019.

Conference Papers

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C2. Y. Huo, C.W. To, C.H. Cheng, W.K. Chow, 2019. Numerical study on explosion hazards of hydrogen cars in garage, 4th Thermal and Fluid Engineering Conference, 14 - 17 April 2019. Las Vegas, NV, USA, Paper no. TFEC-2019-27142.

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CHAPTER 1 INTRODUCTION

1.1 Background of the Study

The utilization of vehicular road tunnels is boosted by the pressing need for efficient transportation networks and the sufficiency of fire safety level in road tunnels has been research focuses for era (CHOW & LI, 1999; Y. Wu & M.Z.A. Bakar, 2000).

The Lion Rock Tunnel, the first-ever vehicular road tunnel in Hong Kong, is commissioned in 1967. Fifty-two years after its opening, more tunnels have been built and it comes to no surprise that different fire safety provisions are found in these tunnels.

Hong Kong is well known for its over-population, together with the rapid economic relationship between the People's Republic of China and Hong Kong, a tremendous increase in trade associated with logistics transportation and heavy traffic load have been observed in the traffic network, including the road tunnels. Moreover, the introduction of new energy source and the increase in vehicle fire size due to the change of construction material also posted new challenges not only to the fire-fighters, but also the fire protection measures of built infrastructures including road tunnels.

Whether the existing fire safety measures of existing road tunnels could be sufficient to cater for the new challenges nowadays still remains the main concern of Hong Kong citizens and researchers.

1.2 Objectives of the Study

In the research, new challenges towards existing tunnels are reviewed with improvements and areas required strengthening would also be studied in details with the following objectives:-

(a) review the key aspects of fire safety requirements for road tunnel as stipulated in different codes and standards;

(b) evaluate the integrated performance of fixed water-based firefighting system with other road tunnel fire safety provisions;

(c) study the explosion hazard of using clean fuel for vehicles and their associated hazard induced to existing road tunnels; and

(d) propose fire safety measures to mitigate the fire risks and explosion hazards in existing road tunnel induced by the new challenges.

1.3 Methodologies

The research methods adopted in this study are as follows:-

(a) literature review on the evolution of fire safety requirements for road tunnel;

(b) full-scale burning tests in a section of road tunnel to study the performance of water-spray system and foam-water spray system, as well as their integrated performance with ventilation system;

(c) clean fuel explosion study by numerical simulation using CFD software, namely FLACS, in different scenarios; and

(d) case studies of past fire road tunnel fire incidents in Hong Kong to unveil the concerns of different stakeholders and areas required further improvement.

1.4 Overview of the Thesis

The thesis has seven chapters with an outline schematically shown in Figure 1.1 as follows:-

(a) Chapter 1 highlights the background of the study as well as outlines the research objectives and methodologies.

(b) Chapter 2 reviews the evolution of fire safety requirements in road tunnel. The changing attitude on the use of fixed water-based firefighting system in road tunnel is emphasised.

(c) Chapter 3 presents the real fire test result on the suppression performance of water spray system and foam-water spray system. Moreover, their integrated performances with other road tunnel fire safety provisions are also evaluated.

(d) Chapter 4 expounds explosion hazards of clean fuel vehicles in enclosed spaces. The explosion phenomenon of clean fuel vehicles in enclosed spaces, like garage, is explored via computer simulation. A computational fluid dynamics software, namely FLACS, is used to simulate different explosion scenarios. (Ogle, 1999; JO & KIM, 2001; Cant, et al., 2004; GexCon AS, 2009)

(e) Chapter 5 further discusses the explosion phenomena of vehicles using clean fuel in short vehicular tunnels by using the FLACS simulation results. (WU, 2012; Middha, 2010)

(f) Chapter 6 illustrates the importance of fire safety management through case studies of two existing road tunnels in Hong Kong; while conclusion and recommendation are presented in Chapter 7.

CHAPTER 2 EVOLUTION OF FIRE SAFETY IDEOLOGY IN ROAD TUNNELS

2.1 Introduction

The construction of vehicle tunnels has been boosted by the pressing need for efficient transportation networks. However, catastrophic fire accidents happened in road tunnels have claimed hundreds of lives and induced million economic losses in different countries. (PIARC, 1999)

2.2 Lesson Learnt from Tragic Experience

Fire at Mont Blanc Tunnel – 24.3.1999

On 24th March 1999, a Belgian heavy goods vehicle (HGV), with flour and margarine on board of the HGV, was on fire in the middle of Mont Blanc Tunnel, which is a main trans-Alpine traffic routes interconnecting France and Italy. Because of its enclosed nature, the fire grew rapidly and spread uncontrollably to nearby vehicles in the road tunnel. After a 53 hours firefighting operation, the fire was eventually under control. Unfortunately, the fire involved 39 deceased which including a fire-fighter of the rescue operation, 31 people taking shelter in their vehicles or nearby refuges, and 7 people trying to escape on foot. A total of 34 vehicles, including 20 HGVs, were burnt in the fire.

Fire at Tauern Tunnel – 29.5.1999

Two months after the Mont-Blanc Tunnel fire, another fire incident, which was caused by the collision of multiple vehicles including HGV containing paint canisters, occurred in the Tauern Tunnel of Austria and claimed 12 lives. The fire grew and eventually 24 cars and 16 lorries were burnt in the incident.

Fire at St. Gotthard Tunnel – 24.10.2001

A fatal fire in the St. Gotthard Tunnel of Switzerland was caused by a traffic accident between two HGVs carrying tires, photographic films and miscellaneous goods caused and claimed 11 lives. The traffic accident caused fuel spillage of one of the involved HGVs. The fuel was then quickly ignited and the fire rapidly spread to two involved HGVs.

Fire at Frejus Tunnel – 4.6.2005

The Fréjus Road Tunnel is connecting France and Italy under Col du Fréjus in the Cottian Alps. A HGV, with tires on board, caught fire in the Frejus Tunnel. Two people died and 17 people were injured in the fire, including 6 firefighters.

The Natural and Environmental Disaster Information Exchange (NEDIES) is a project on information exchanging on natural and environment disaster in the European Union States. NEDIES conducted an in-depth study on large tunnel fires and suggested necessary improvements. Statistics of NEDIES revealed that road tunnel fires have caused numerous deaths and over million economic losses throughout the world. A summary of remarkable tunnel fires are tabulated in Table 1 (Colombo, 2001).

In the old belief of tunnel fire protection, additional fire protection measures, like sprinkler system, would only be required for tunnels that allow the passage of dangerous goods vehicles (DGV) in view of the additional fire risks of dangerous goods and the tragic consequence once the dangerous goods are involved in a tunnel fire. However, the painful experience learnt from the said tunnel fire incidents suggested that HGV, other than DGV, were also highly risky and required special attention.

To better apprehend the risk associated with HGV, a thorough understanding on the fire dynamics of road tunnel fires is of paramount importance.

2.3 Fire Dynamics of Road Tunnel Fires

Unlike compartment fire, the behaviours of tunnel fire would be greatly different due to its enclosed and confined nature (CHOW, 1996; Ingason, 2011).

2.3.1 Comparison of Tunnel Fires and Open Fires

Generally speaking, an open fire would be different from a tunnel fire with the following distinctions (Carvel, et al., 2001): -

- Oxygen is readily available in an open fire. Alike to other confined spaces, the oxygen supply in road tunnels is restricted. A tunnel fire may be developed into a fuel-controlled fire with unreacted air bypassing the burning vehicles or a ventilation control fire where all oxygen is consumed in the combustion zone and fuel-rich gases leave the exit of the tunnel.

- The burning of vehicle is found more vigorous in a tunnel because of the effective heat feedback from tunnel walls and ceiling. The heat release rate (HRR) of a fire in road tunnel is found four times larger when compared with that of an open ground fire.

2.3.2 Comparison of Road Tunnel Fires and Compartment Fires

In a building compartment fire, its maximum HRRs is governed by the ventilation factor, $A_0\sqrt{h_0}$, where A_0 is the area of opening and h_0 is the height of opening (Drysdale, 1992; CHOW & NG, 1994; CHOW, 1997; Walton & Thomas, 2002). Figure 2.1 is a typical compartment fire curve and the flashover stage could be reached in minutes of time.

Because of the lack of confinement of hot gases, as well as the significant heat loss from the fire to the surrounding, a flashover is less likely to occur in a road tunnel fire. Nevertheless, the spread of fire along a queue of preheated vehicles at the downstream of fire may still be boosted by a sudden change in ventilation conditions, such as the activation of ventilation system. (CHOW, 2000)

The maximum HRR of a tunnel fire is affected by multiple factors:-

- Tunnel cross-section area
- Tunnel length
- Tunnel meteorological condition
- Tunnel ventilation method, etc

In a mathematical representation (Carvel, et al., 2001; Carvel & Beard, 2011)

$$\dot{Q}_{tun} = \varphi \dot{Q}_{open} \qquad \text{Eqn. (1-1)}$$

where $\dot{Q}_{tun}$ is the HRR in naturally ventilated tunnel,

$\dot{Q}_{open}$ is the HRR of similar fire in open air,

φ is the geometry factor $\varphi = 24(\frac{W_F}{W_T})^3 + 1$,

W_F is the width of fire object, and

W_T is the tunnel width

2.3.3 Determination of the Combustion Mode

A well-developed compartment fire is generally classified into the pre-flashover stage and the post-flashover stage. The shifting from pre-flashover into post-flashover stage involves a transition from fuel-controlled burning to ventilation-controlled fire with the conditions schematically showed in the Figure 2.2.

Since oxygen supply in road tunnels is limited, the supply of oxygen to support the combustion is largely provided by a ventilation system and the tunnel fire combustion mode is characterised by a ratio of oxygen and fuel supply (Tewarson, 1988; Ingason, 2011).

$$\emptyset = \frac{\dot{m}_a}{r\dot{m}_f} = 3000\frac{\dot{m}_a}{Q} \qquad \text{Eqn. (1-2)}$$

where $\dot{m}_a$ is the mass flow rate of oxygen,

$\dot{m}_f$ is the rate of loss of fuel,

r is the stoichiometric coefficient of complete combustion,

Q is heat release rate

Fuel-controlled fire ratio $\emptyset \geq 1$; while ventilation-controlled ratio $\emptyset < 1$.

2.4 Evacuation Behaviour

In a fire incident, people's evacuation behaviour can be interpreted as their immediate responses towards a complex and fast changing situation in the absence of sufficient information.

2.4.1 Evacuation Behaviour in a Road Tunnel Fire

With a view to better apprehend the human evacuation behaviour during a road tunnel fire, the reactions of people in different notable road tunnel fire incidents are reviewed (Shields, 2008).

Caldecott Tunnel Fire – 7th April 1982

A fire was caused by a traffic accident between a gasoline tanker, a passenger car and a bus. In this tragic accident, seven fatalities were involved in where five stayed in their own vehicles. According to the closed-circuit television (CCTV) record, one of the fatalities attempted to contact the tunnel control centre by an emergency telephone. However, the faulty phone connection made her fail to give a prompt notification of the accident. The fatality then returned to her vehicle and stay in her vehicle that was positioned less than 15 m away from a cross passageway. Sadly, she was deceased in her own vehicle.

Mont Blanc Tunnel Fire – 24th March 1999

Twenty-nine fatalities perished in their vehicles in the devastating fire. After the start of fire, lots of drivers disregarded the road traffic signal and entered the tunnel. Luckily, some of these vehicles could make a U-turn and left the tunnel. However, HGVs failed to make a U-turn and blocked the traffic. Eventually, many vehicles were engulfed by the fire.

Tauern Tunnel Fire – 29th May 1999

Drivers also ignored the traffic signal and entered the tunnel in this fire. Further congestion was caused by misbehaviour of drivers; while some of the drivers preferred to stay in their vehicles and refused to leave. Others looked around and some of them even took photos inside the tunnel during the fire incident.

St. Gotthad Tunnel Fire – 24th October 2001

A traffic accident of two HGVs turned into a tragic fire in which 11 victims passed away in their vehicles. Those vehicles were located far away from the fire origin. Some of them were even at a distance of 2km from the fire. According to the CCTV record, some of these deceased drivers had never left their vehicles. Post-fire investigation revealed that all victims could have enough time for a safe evacuation from the tunnel, if they had chosen to do so.

2.4.1 General Evacuation Behaviour

Studies revealed that evacuation behaviours in tunnel fires were similar to that of compartment fire with both environment factors and evacuee personal characteristics had decisive effects in their reactions to fire (Wood, 1972; CHOW & KOT, 1989; LO, et al., 2000; Bryan, 2002; Proulx, 2002; Nelson & Mowrer, 2002; CHOW & LAM, 2006; CHOW & LI, 2007; CHOW, 2007; Kobes, et al., 2010; KU, et al., 2018).

- Age

  People's ability to resist smoke and other toxic fire products would probably be influenced by age. Moreover, their evacuation performance would be depended on age, which would be degraded for young and old people.

- Aloneness

  People's responses to cues of fires and fire alarms would be directly affected by their statuses of alone or accompanied. The presence of other people is likely to affect one's definition and his/her reaction towards fire cues. In general, it is expected that alone people would react more promptly towards the dubious fire cues. Nevertheless, accompaniment could promote group discussion and decision-making on appropriate actions to be taken. Moreover, other people's presence would assist the communication and warning of an emergency situation.

- Engaging activities

  The evacuees' responses toward evacuation would be affected by the engaged activities during a fire. For example, people might be more resisted to evacuate when he / she was sleeping or showering.

- Environmental conditions

  A decision on evacuation would largely depend on one's instantaneous and accumulative exposure to fire and smoke products. Those, who are experiencing serious threat, i.e. heavy smoke and in close proximity of fire, are most likely to evacuate.

- External factors

  A poor external environment, such as unfavourable weathers, uneven floors, complex escape routes, dim and noisy environment, would negatively impact on people's decision on evacuation.

- Gender

  In case of fire, people of different genders would react differently towards a fire. Females would favour leaving, notifying others and calling for assistance, while males prefer to extinguish the fire.

- Knowledge and familiarity of escape routes

  Although people would decide to leave when they believe that the extinguishment of fire is not achievable, their choice to leave would be influenced by their familiarity with escape routes. When they are aware of the presence of escape routes or familiar with escape routes, the sense of security may defer their decision on evacuation.

- Location

  The location of evacuee would directly affect the actual travel distance to an exit. Moreover, their location would also affect the time of notification and their interpretation of fire alarms.

- Nearby focal points

  In an emergency or unexperienced situation, people would prefer to seek for directive, supplementary information and guidance available at nearby focal points, such as information board, signature, stage of theatre and screen of cinema. Hence, these focal points could be utilized to provide useful evacuation information.

- Physical ability

  Evacuations of physically impaired people require appropriate guidance and assistance from others. Therefore, the decision on evacuation by impaired people is largely dependent on the availability of suitable assistance and guidance.

- Population and density

  A crowded condition would directly affect the traveling speed of evacuees which is unfavourable to evacuation. Nevertheless, a highly dispersed occupancy would inhabit notification of fire message in the absence of proper fire alarm system or PA system.

- Previous experience

  People with fire experience are found less likely to leave, because they have their preference for other options, like extinguishing the fire or notifying the others, instead of simply escape.

- Staff assistance

  Guidance and clear instructions from staff could speed up the evacuation by shortening the time wasted on clarifying ambiguous fire cues and gathering information on escape routes.

- Social affiliation

  The group behaviour of people with special social affiliation is likely depended on the decision of group leader. Since the group would try to remain intact as far as possible in the evacuation, the flow at junctions would be affected by the group movement and the speed of travel for group evacuation would be dictated by the slowest member of the group.

- Training

  With more training provided, a person would prefer to fight against the fire over leaving the scene of fire.

2.4.2 Tunnel Fire Behavioural Test

The Netherlands Organisation for Applied Scientific Research (TNO) is an independent research organisation focusing on applied science in various disciplines. Other than reviewing evacuation behaviour of tunnel users in past tunnel fire incidents, TNO also conducted a tunnel fire behavioural test in 2002. A mock-up tunnel was built for the test. A vehicle was set to burn in the tunnel and the responses of participants were continuously monitored by CCTVs. (Boear, 2002)

In the absence of effective ventilation, smoke accumulated and filled up the mock-up tunnel. Five minutes after the fire started, people were found halt for evacuation and remained in their own vehicles. People did not start the evacuation until the broadcasting of "explosion danger" announcement. Probably before of the heavily smoke logging situation, some of the people could not leave and returned to their vehicle.

Echoing the lesson learnt from dreadful experience, the tunnel fire behavioural test also suggested that passivity of tunnel users toward evacuation might probably be one of the contributing causes to the fatalities in tunnel fires.

2.5 Fire Test for Determining HRR of HGV in Road Tunnels

As revealed from the tragic consequences of fatal tunnel fires, the HRR of HGV was found far larger than the expectation and fire tests were thence conducted to study the HRR of HGV in a road tunnel fire.

EUREKA 499 Tunnel Test Programme

The experimental results of the Test Programme were shown at Figure 2.3. In the fire tests, a HGV was loaded with 1,994kg of mixed furniture (overall heat content ≈ 87.4GJ) under different longitudinal ventilated conditions. For longitudinal ventilation velocities of 2-3ms^{-1} and 5-6ms^{-1}, the estimated HRR was about 128MW and 120MW respectively (Ingason & Lonnermark, 2005).

Runehamar Tunnel Fire Tests

Four fire tests with mock-up HGV at the Runehamar Tunnel, with the setup as schematically shown at Figure 2.4, were conducted in 2005 to estimate the HRR of HGV fires (UPTUN, 2008d). Details of the fire testes were tabulated at Table 2, while the HRR against Time Curves of the four tests were provided in Figure 2.5. Under a longitudinal ventilation rate of 2.8–3.2ms^{-1}, the peak HRR is found to be 70–203MW. The spread of fire in the mock-up cargo of the HGV was provided in Figure 2.6. Surprisingly, the time required for the fire engulfment of an entire 10m cargo would only require 5-10 minutes.

Fire Tests at Carleton University

Real fire tests were performed in a mock-up tunnel at the Carleton University with dimension 37.5m in length, 10m in width and 5.5m in height as shown in Figure 2.7 (Yoon & Hadjisophocleaous, 2010). In the experiments, the fire sources were shielded by a metal plate with an aim to simulate the in-vehicle fire scenario. As visualized in Figure 2.8, a large amount of stream was generated and resulted in lowering of visibility. Vertical temperature profiles of the tests were provided in Figure 2.9 and the result suggested that the actuation of sprinkler system could effectively cool down the environment and lower the temperature. Heat fluxes against time graphs at different locations of the tests were provided at Figure 2.10. During the actuation of the sprinkler, the measured heat flux is reduced significantly. Once the system was shut, the heat flux quickly resumed.

Different experimental results both suggested that the HRR of a HGV fire in road tunnel was found much larger than our perception (HU, et al., 2006). Such high HRR would unavoidably cause difficulties in designing fire service installations and other safety provisions, particularly the tunnel ventilation system.

Results of different fire tests and researches clearly suggested the fire development in a road tunnel fire could be effectively limited by using the water-based fixed firefighting system. With the updated experimental and research findings, as well as lessons learnt from fatal accidents, numerous national and renowned professional institutions had shifted their attitude towards supporting the installation of water-based fixed firefighting system in road tunnel. The changing stances of the World Road Association (PIARC) and the National Fire Protection Association (NFPA) would be discussed in detail for demonstrating the evolution of views on installing fixed fire-fighting system in road tunnels.

2.6 The World Road Association's View on Installing Fixed Fire-fighting Systems in Road Tunnels

The debate on the suitability of installing fixed fire-fighting systems, such as sprinkler system, in road tunnel had been started in PIARC since 1983 (PIARC, 1983). In the World Road Congress took place at Sydney in 1983, different concerns against the installation were brought up by conferees and the installation of fixed fire-fighting systems in road tunnels was not supported in general.

- Fixed fire-fighting systems, like sprinkler, could not extinguish fire in the motor room or inside the vehicle compartment;
- Steam generated from the discharge might cause injury;
- Smoke layer destratification might hinder escape of evacuee;
- High cost of installation and maintenance;
- Decrease of visibility; and
- Burning flammable liquid might be dispersed by the actuation of fixed fire-fighting systems.

Such an opposing stand remained in the World Road Congress at Brussels in 1987 and at Montreal in 1995. In the World Road Congress 1999 at Kuala Lumpur, PIARC restated that the actuation of fixed fire-fighting systems in road tunnel shall only be started after the completion of evacuation of tunnel users (PIARC, 1999).

In 2008, the PIARC Technical Committee published three publications, namely:-

- Integrated Approach to Road Tunnel Safety (PIARC, 2008a)
- Road Tunnels: An Assessment of Fixed Fire Fighting Systems (PIARC, 2008b)
- Risk Analysis for Road Tunnels (PIARC, 2008c)

According to PIARC, investigations of major tunnel fires found that (PIARC, 2008b):-

- Fire development and spread was faster than expected.
- The temperature inside the tunnel might over 1000°C.
- Smoke generated in the early stage of fire was greater than expected.
- Evacuation behaviour of tunnel users was unpredictable:-
  - Tunnel users did not realize the danger of tunnel fires.
  - Drivers preferred to stay in their vehicles.
  - Tunnel users mistook that staying in vehicles was safer than escape.
  - When they realize how the danger the situation was, it was too late and too dangerous to evacuate.

Smoke could quickly ruin tunnel users' ability on performing self-evacuation. Moreover, a rapidly surging temperature could damage the tenable environment as well as other fire protection systems of road tunnels.

Measures had to be provided to hinder the spread and growth of fire so as to safeguard the safety of tunnel users and emergency responders in both self-rescue and assisted-rescue phases. The installation of fixed firefighting systems in road tunnels might probably be a viable solution to the problem.

The key objectives of installing fixed firefighting system in road tunnel are reducing:-

- the rate of fire growth;
- the HRR;
- the eventual fire size; and
- the risk of fire spread across the vehicles.

Having achieved the above key objectives, a fixed firefighting system could:-

- Reduce the number of casualties and fatalities;
- Maintain a tenable environment for both evacuees and emergency responders; and
- Protect tunnel assets through minimizing damages to its structure element with an aim in preventing post-fire interruption on transportation network.

Since no prescriptive code on the application of fixed firefighting system in road tunnel was readily available, a performance-based approach was thence recommended by PIARC with the following factor, as a minimum, should be taken into consideration:-

- The availability of fixed firefighting system;
- The safety of users;
- The limitation of emergency services;
- The fire resistance of structure;

- The interaction of safety systems in the tunnel; and
- The costs and benefits of installing the fixed firefighting system.

An integrated approach analysis should be adopted to evaluate the coupled performance of fixed fire-fighting system and other fire protection systems.

Moreover, the timing to actuate the fixed fire-fighting system would directly affect its performance and effectiveness. Early actuation of fixed fire-fighting system could effectively limit the spread and size of fire in its incipient stage; however, the evacuation of tunnel users would likely be hindered with evacuees trapped in the tunnel.

Though the discharge of fixed fire-fighting system upon the completion of evacuation could still have volume cooling and surface protection effect, the belated actuation of fixed fire-fighting system might fail to control the fire effectively and would have no effect on life protection of evacuee.

Therefore, the optimum actuation time of fixed fire-fighting system should be critically and scientifically assessed in the said integrated approach analysis. As proposed by PIARC, the controlling and actuation sequent of a fixed fire-fighting system is illustrated in Figure 2.11 (PIARC, 2008b).

2.7 The Stand of National Fire Protection Association towards the Installation of Fixed Fire-fighting Systems in Road Tunnels

NFPA 502 – Standard for Road Tunnels, Bridges and Other Limited Access Highways is firstly published in 1972, which provides fire safety and fire protection requirements for limited access highways, road tunnels, bridges, elevated highways, depressed highways and roadways which are located beneath air-right [1] structure (NFPA, 2011).

Echoing the latest research findings, the Technical Committee on Road Tunnel and Highway Fire Protection of NFPA keeps reviewing the requirements as suggested in the NFPA 502. The latest version is published in 2017.

The revised fire protection and safety requirements in NFPA could provide a glance at the global shifting attitude towards accepting the installation of fixed fire-fighting system in road tunnels.

Having reviewed the past NFPA 502, the technical committee had been introducing considerable new ideas and changes since 2004; namely:-

- Propose new idea on structural protection for road tunnels;

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[1] Air rights are the interest of property in a "space" above the surface of earth.

- Re-evaluate the tremendous HRR of vehicle fires;
- Review comprehensively on tunnel categorization and relevant fire safety provisions, such as fixed fire-fighting system; and
- Introduce the performance-based approach in tunnel design.

2.7.1 Structural Protection for Road Tunnels

In the 2004 edition of NFPA 502, the idea on structural protection was newly introduced (NFPA, 2004). All the primary structure components, no matter built by concrete or steel, shall be scientifically evaluated by engineering analysis to assure those elements could defy the assumed tunnel fires.

While in 2008, NFPA 502 emphasised that the protection of primary structural element, no matter concrete or steel constructed elements, is crucial for the purpose of (NFPA, 2008):-

- Maintenance of tenable environment for life protection and safety;
- Minimalizing the damage to structural elements; and
- Preventing progressive collapse of structural elements and associated economic loss.

As suggested by the 2014 and 2017 edition, the protection of structural elements could also support the accessibility of fire-fighters (NFPA, 2014). It also proposed the primary structural element shall be able to cope with an assumed fire under the Rijkswaterstaat (RWS) time-temperature curve for at least 2 hours without any sign of failure.

In the latest 2017 edition, fire protection features for structural elements are firstly recommended to be included in the engineering analysis of the road tunnel design (NFPA, 2017).

2.7.2 HHR of Vehicles in Road Tunnel Fires

In accordance with updated results from fire tests, the HHR of different vehicle fires in road tunnels was updated as shown in Table 3.

Tunnel ventilation system and other associated fire protection equipment had to remain functional at such a high temperature under fire conditions. Therefore, the design of a tunnel ventilation system is elementarily affected by the designed fire size.

As such, the surge in HRR as proposed in NFPA 502 2008 edition would directly introduce design difficulties in the ventilation systems of road tunnels (NFPA, 2008). NFPA thence proposes the installation of fixed water-based fire-fighting system and makes use of engineering analysis to facilitate the design of road tunnels ventilation systems in the NFPA 502 2011 edition (NFPA, 2011).

With a growing acceptance of installing fixed water-based firefighting system in road tunnels, the experimental HRR of different vehicle fires in tunnels with fixed water-based firefighting system installed as tabulated in Table 4 was also provided in the newly published NPFA 502 2017 edition (NFPA, 2017).

As suggested in the 2017 NFPA 502, AHJ could reduce the value of designing HRR based on the finding of an engineering analysis with considerations on:-

- Activation Time;
- Resilience; and
- Reliability.

2.7.3 Fixed Fire-fighting System

In the earlier version of NFPA 502, a sprinkler provision was not recommended in road tunnels in general, except unescorted transportation of hazardous/ dangerous materials was allowed in the road tunnel.

The reasons for not recommending the installation of sprinkler provision in a road tunnel was clearly stated in the NFPA 502 2004 edition (NFPA, 2004):-

- The sprinkler system is unable to extinguish a fire that is located inside and beneath the vehicles.
- Potential damage caused by the stream generated during the extinguishment process.
- Delayed actuation due to tunnel geometry and non-localized heating to the heat sensing element of sprinkler (CHOW & HO, 1990; CHOW & HO, 1992).
- The stratified layer of smoke is likely to be drawn down to road level by the sprinkler discharge (CHOW & FONG, 1991; CHOW & FONG, 1991; CHOW & FONG, 1993)
- Other tunnel users would be unnecessarily panicked by the accidental discharge of sprinkler

Yet, NFPA proposed in the later 2008 edition that the installation of fixed water-based fire-fighting systems should be allowed in road tunnel to protect the life of tunnel users and maintaining a tenable environment for safe escape as well as assess by fire-fighter. Nevertheless, its integrated performance with other tunnel fire protection systems shall be evaluated.

NFPA also retorted their previous stands in the 2008 edition (NFPA, 2008):-

- The purpose of installing fixed fire suppression system is to hinder the spread of fire across other vehicles instead of fire extinguishment.
- A fixed water-based fire-fighting system could cool the environment and prevent the injuries by stream.
- The delayed actuation of fixed fire suppression system could be prevented by supplementing the detection system by other fire detection technology.
- Biases on sprinkler and other fixed fire suppression systems would introduce panics and smoke stratified layer lowering was not consistent with experimental observation and study findings.

In the NFPA 502 2008 edition, the provision of fixed fire suppression systems is classified as “Not Mandatory Requirement”. However, the installation of water-based fixed fire-fighting systems is proposed as “Conditional Mandatory

Requirement" for tunnels of 1000m or above in the later versions. Engineering analysis shall be used to determine the necessity of such provision.

In the annex of 2011 edition, the technical committee of NFPA supplemented that the objectives of fixed water-based fire-fighting system are (NFPA, 2011):-

- Suppression of Fire
- Control of Fire
- Cooling of Volume
- Cooling of Surface

As suggested by NFPA and other researchers, a fixed water-based fire-fighting system allows (CHOW & SHEK, 1993; CHOW & YAO, 2001a; YAO & CHOW, 2001b; NFPA, 2011):-

- Prevent fire spread across vehicles;
- Maintain and improve the tenable conditions in the tunnel by suppressing the fire and volume cooling so as to facilitate the escape and access of fire-fighters;
- Protect the ventilation system and boost their performance; and
- Lessen the stratification problem by reducing the amount and rate of generating smoke.

2.7.4 Performance-based Approach in Road Tunnel Design

The concept of performance-based approach in road tunnel design was firstly included in NFPA 502 Code in 2011.

In the NFPA 502 2011 edition, the installation of water-based fixed fire-fighting systems is proposed as a "Conditional Mandatory Requirement" for tunnels of 1000m or above in the later versions. Engineering analysis shall be used to determine the necessity of such provision.

The performance of tunnel fire protection measures and fire service installations were highly tunnel geometry dependent, unique and tied in. The use of performance-based design approach could be a systematic platform to comprehensively and scientifically assess their integrated performance with due consideration given to the unique characteristics of tunnel as well as tailor-made fire-fighting and evacuation strategies.

In the latest NFPA 502 2017 edition, the area of concerns of the analysis is updated with emphasises on the holistic and multidisciplinary natures of the analysis. The minimum coverage of engineering analysis as stated in different versions of NFPA 502 were tabulated in Table 5.

2.7.5 Prescriptive Requirement for Road Tunnels in Hong Kong

The prescriptive requirements for road tunnels had been included in the Code of Practice for Minimum Fire Service Installations and Equipment (FSI Code) since 1987. A summary, showing the evolution of fire safety provisions of road tunnels in different versions of FSI Code, was provided in Table 6.

Other than the Fire Services Department, different Government Department must also be consulted in different areas as shown in Table 7.

As required by codes, a dynamic smoke extraction system, which may be incorporated into the ventilating system, shall be provided for road tunnels exceeding 230m in length. Since the installation of ventilation system would require detailed engineering analysis of air flow patterns and aerodynamics, detail reports shall be submitted to relevant authorities (viz. EPD, FSD, EMSD and TD) for approval.

As illustrate above, the concept of Performance-based Approach in Road Tunnel Design had already been adapted in Hong Kong for decades. Nevertheless, the codes did not prescriptively require the provision of fixed fire suppression systems for road tunnels in Hong Kong.

CHAPTER 3 FIRE SUPPRESSION PERFORMANCE EVALUATION OF WATER-BASED FIXED FIREFIGHTING SYSTEM IN ROAD TUNNEL

3.1 Introduction

As discussed in the previous sections, a growing acceptance by national and renowned research institutions on installing water-based fixed fighting system was observed. Therefore, intensive research efforts are made in reviewing the fire suppression performance of water-based fixed fire-fighting system in road tunnels.

Apart from the real fire tests for HRR of HGV in road tunnels as mentioned in section 2.5, intense research effort has been devoted to study and evaluate the fire suppression performance of water-based fixed fire-fighting system in road tunnels (Ministry of Transport, 2002; Arvidson, 2003; Setoyama, et al., 2004; Opstad, et al., 2006). A glance of findings is summarized at Table 8.

Though the installation of the fixed fire-fighting system is not compulsory required, according to the prescriptive codes and design manuals, in China and Hong Kong, it is noted that long road tunnels were equipped such systems with due considerations given to its heavy traffic loads and concerns on structural protections (Fire Services Department, 2012; Transport Department, 2001;

National Standard of People's Republic of China, 2014; Industrial Standard of People's Republic of China , 2014; Industrial Standard of People's Republic of China, 2015).

The use of water mist fire suppression system and water-based deluge systems are adopted in Europe and Australia respectively. However, water spray fire-fighting systems or foam-water spray firefighting systems are more common in road tunnels of China. Thus, there is a need to review the performance of water spray fire-fighting system and foam-water spray firefighting system in different fire scenarios (NG & CHOW, 2002; CHOW, et al., 2003; CHOW & LI, 2002; CONG, et al., 2008; LI & CHOW, 2008; LI, et al., 2019).

As emphasised by both NFPA and PIARC, an integrated approach should be adopted to evaluate the coupled performance and effectiveness of fixed fire-fighting system and other fire protection systems. Since tunnel ventilation system is a crucial element in tunnel fire safety (CHOW, 1993; CHOW, 1996; CHOW, 1998; CHOW & LI, 1999; CHOW & LI, 2001; LI & CHOW, 2003; Miclea, et al., 2007; LI, et al., 2009; CHOW, et al., 2010;CHOW, et al., 2015), the effect of ventilation system on the performance of water spray fire-fighting systems and foam-water spray firefighting systems, as well as the effect on fire growth, fire spread and tenability are studied and reviewed in the coming section.

3.2 Experimental Configurations

Full-scale burning tests were performed in a section of road tunnel in the study. The performance of water spray fire-fighting system and foam-water spray firefighting system in suppressing diesel pool fires and wooden pallet fires up to 20 MW, which is commonly seen design fire load in urban road tunnel in China, was evaluated.

Moreover, the coupled performance and actuation sequence of fixed fire-fighting system and longitudinal ventilation system were also evaluated (LI, et al., 2019).

3.2.1 The Tunnel Testing Facilities

The full-scale burning tests were conducted in a section of road tunnel in Shanghai Tongtai Testing Facility with a dimension of 100m in length, 12m in width and 6.5m in height. The photo and schematic drawings of the testing facilities are provided at Figure 3.1 and 3.2

A water spray fire-fighting system in the testing facility is designed to discharge water spray, with and without 3% Aqueous Film Forming Foam (AFFF) additives. The foam solution with 3% AFFF additives was produced in accordance with GB 50151-2010. As schematically shown in Figure 3.2(b), the testing tunnel is divided into four zones of which each is 25 m in length with 5 nozzles evenly distributed on one side wall of the testing tunnel at a height of 4.5m above the ground level.

The working pressure of nozzles is set at 0.35MPa with a spray density of 6.5Lmin^{-1}m^{-2}, which is the common setting for the water-spray fire-fighting system adopted in China according to GB Code.

To holistically evaluate the effectiveness of water spray fire-fighting system in suppressing fire in road tunnels, a comprehensive research and a series of experiment had been conducted in a Joint Research Project. Part of work was reported in thesis.

Temperature measurement in the testing tunnel is made by four thermocouple trees at the following positions:-

- T1: 10m upstream from the fire centre;
- T2: Above the centreline of the fire;
- T3: 10m downstream from the fire centre; and
- T4: 20m downstream from the fire centre.

Type K-thermocouples, each with a diameter of 0.5mm, is set at 6.5m, 5.5m, 4.0m, 2.5m and 1.5m above the ground level in thermocouple trees T1, T3 & T4; while thermocouples are set at 6.5m, 5.5m and 4.0m above the ground level in thermocouple tree T2.

Details of experimental instruments were provided in Table 9.

In this study, the experimental works were focused on investigating the effectiveness of FFFS through temperature measurements. Yet, the investigation through monitoring the structural temperature and radiation were reported in separate report.

For the measurement of longitudinal ventilation velocity, a thermos-anemometer is set at 15m upstream of the fire centre at the level of about 3m above the ground level. Video cameras, both in optical and infrared, are set at both ends to monitor and record the fire development in the testes.

Since 20MW is the design value commonly used in China and Hong Kong, a 20MW fire generated from liquid fuel pans or wood pallets is used in the tests.

The design of fire sources is provided at Figure 3.3. As shown in Figure 3.3(a), the liquid fuel pan has a dimension of 1.5m in length, 1.5m in width and 0.2m in depth. Water of 10mm in depth was provided at the bottom of pan for the protection purpose. To give a heat release rate of about 20MW, a total of six pans with the said configuration would be used in the experiment. (Shanghai Tongtai Fire & Security Co. Ltd., 2008).

Wood pallet stacks, measuring each of 1.2m in length, 0.8m in width and 1.5m in height, are placed along the centreline of the tunnel at a position of 40m away from one end of the mock-up tunnel portal. To provide a HRR of 20MW, a total of eight wood pallet stacks are used. The overall dimension of wood pallet stack cluster measured 4.8m in length, 1.6m in width and 1.5m in height.

The heat release rate was estimated from the Radiation Heat Flux and a detail evaluation of heat release rate was covered in a separate report published by Shanghai Tongtai Fire & Security Co. Ltd in 2008 (Shanghai Tongtai Fire & Security Co. Ltd., 2008), which had proved that the heat release rate would attain the value of 20MW when:-

- about 2/3 of the wood pallet stack was engulfed in flames; and
- 90s after the ignition of diesel pool fire.

Therefore, the FFFS was manually actuated when it was found that about 2/3 of wood pallet was engulfed in flames through monitoring by the IR camera. For diesel pool fire, the FFFS was actuated at 90s after the ignition of fire.

The entire fire source, no matter liquid fuel pan or wooden pallet, could be masked by the water spray coverage.

In order to an in-vehicle fire scenario, a steel plate of 6m in length and 3m in width is set above the fire source to simulate a shielding effect. The photo of the top shield is provided at Figure 3.3(c). A vertical separation of 0.5m is maintained above the fire source (LI & CHOW, 2006).

Besides, a steel plate of 6m in length and 4m in height was vertically erected at a distance of 2m from the fire source to simulate a taller vehicle halted beside the fire vehicle. Photo of the vertical side shield is provided at Figure 3.3(d).

3.2.2 Fire Scenarios

A total of eight fire scenarios is conducted, namely W1 to W4 and D1 to D4 for wood pallet fire and diesel pool fire respectively. The coupled performance of ventilation system and the water spray fire-fighting system or foam-water spray firefighting system as well as the actuation timing of the fixed fire-fighting systems would be evaluated. Details of testing arrangements are provided at Table 10.

Through comparing the result of Tests W1 and D1, the extinguishment effect of foam-water spray system for wood pallet fire and diesel fire could be contrasted. Moreover, insight on the coupled performance of ventilation system and the water spray fire-fighting system or foam-water spray firefighting system could be obtained from the tests. Also, the effect of delayed actuation of ventilation system could be studied by comparing the result of Test W4 with others.

As the discharged water might be blocked the vehicle outer shell and vehicles nearby, shielding effect disguised by the top shield and the side shield are experimentally studied. The effect of the actuation timing of the fixed fire-fighting system is would also be studied on the wood pallet fires scenarios. To inhibit the backlayering of smoke generated by a 20MW fire, a longitudinal ventilation system is set the critical velocity of 3ms^{-1}.

3.3 Test Results

3.3.1 Wood Pallet Stack Fire Test Results

The water spray fire-fighting system was actuated when about 2/3 of the wood pallet stack was involved in fire and fuels, both wood pallet stack and diesel, were not all consumed after the experiments.

The temperature variations as measured at the ceiling and at a level of 2.5m above the floor level for fire scenario W1 to W4 are provided at Figure 3.4 and Figure 3.5.

As demonstrated in Figure 3.4(a), the ceiling temperature directly above the centreline of the fire was immediately deceased from about 550^{o}C to about 450^{o}C in scenario W1 upon the actuation of foam-water spray fire-fighting system. Until the complete extinguishment of wood pallet stack fire, the ceiling temperature stayed at quite a high level.

The volume cooling effect of the foam-water spray fire-fighting system was demonstrated by the significant drop of ceiling temperature at 10m upstream, 10m and 30m downstream of the fire source as shown in Figure 3.4(a).

According to Figure 3.5(a), the temperature as measured in W1 at 2.5m above the floor level was found much lower than the ceiling level, i.e. about 30^{o}C before the actuation of foam-water spray fire-fighting system.

After actuating the foam-water spray fire-fighting system, slight surges in temperature at 2.5m level at 10m upstream, 10m and 30m downstream of the fire source were noted.

The surge in temperature was likely due to the destroying of the buoyancy of hot smoke by the foam-water mixture. The hot smoke was cooled and drawn to a low level upon the actuation of foam-water spray fire-fighting system as shown in Figure 3.6. Nevertheless, the temperature was stayed at a relatively low level, i.e. below 60^{o}C, of which the evacuation would be hindered.

Moreover, the foam-water spray fire-fighting system was found not so efficient in suppressing wood pallet fire where about 6 minutes were required to extinguish the wood pallet fire.

For Scenario W2, longitudinal ventilation of 3ms^{-1}, blown towards the downstream side, was provided to the mock-up tunnel after the ignition of fire. Water spray fire-fighting system was used for fire suppression. Though the distance between the fan and the fire was only 50m, which may be too short for the generation of a uniformly distributed ventilation flow, the back-layering was found successfully prevented in the test. Also, the ventilation flow distribution may not be uniform in a real tunnel fire due to the presence of vehicles and other objects.

The temperature profiles were provided at Figure 3.4(b) and Figure 3.5(b). Snapshots of the experiment were also provided at Figure 3.7.

With the provision of ventilation system, the temperature as measured at the ceiling level and 2.5m level was found largely reduced to below 180°C and 50°C. Such lowering of temperature would be beneficial to both protection of structure and evacuation of tunnel users

It was also noted that the ceiling temperature at 10m downstream from the fire centre was higher than that directly above the fire centre. Therefore, the single zone actuation of fire-fighting system would have a limited effect on improving the tunnel situation, multiple water spray zone actuation would be required for an effective and efficient control.

As shown in Figure 3.7(a), visibility was maintained on the upstream side by the longitudinal ventilation system. Though a disturbance of smoke layer was also noted in this case during the actuation of water spray fire-fighting system, it would still be advantageous for the evacuation process.

In Scenario W3, longitudinal ventilation of 3ms-1, blown towards the downstream side, was provided to the mock-up tunnel after the ignition of fire. Water spray fire-fighting system was used for fire suppression. A top shield was provided to simulate in-vehicle fires. The temperature profiles were provided at Figure 3.4(c) and Figure 3.5(c). Snapshots of the experiment were also provided at Figure 3.8.

In the presence of a top shield, the temperatures as measured at the ceiling and 2.5m level were further reduced to below 110^{o}C and 45^{o}C.

As shown in Figure 3.8(a), the flame was blocked by the steel plate and spilt out from the side of the wood pallet stack. Contrasting Figure 3.7 and Figure 3.8, the extinguishment effect of water spray fire-fighting system was found diminished by the top shield.

Regarding Scenario W4, the experimental configuration would be the same as Scenario W3 except that the actuation of longitudinal ventilation system was delayed to 90s after the actuation of water spray fire-fighting system.

Snapshots of the experiment for W4 were also provided at Figure 3.9. The flame was blown to the downwind side upon the actuation of longitudinal ventilation system.

The peak ceiling temperatures as measured by Scenario W4 were found much higher than those in Scenario W3. For the peak ceiling temperature as measured above the fire source, W4 showed the highest value when compared to that of W2 and W3.

Moreover, the temperature at 2.5m level at the downstream side of the fire centre did not drop after the actuation of water spray fire-fighting system in both Scenario W3 and W4. It was also noted that the high temperature at the downstream side in Scenario W4 had lasted longer than that of W3.

As suggested by the results, an early start of ventilation system could achieve a better control of fire rather than the actuation of water spray fire-fighting system in this fire scenario.

3.3.2 Diesel Pool Fire Test Results

Temperature profiles at the ceiling level and 2.5m level for Scenarios D1 to D4 were provided shown in Figure 3.10 and Figure 3.11 respectively. Snapshots for the experiments in Scenarios D1 and D2 were respectively shown in Figure 3.12 and Figure 3.13.

In Scenario D1, no tunnel ventilation was provided. According to Figure 3.10(a), the maximum ceiling temperature was measured directly above the fire source.

As shown in Figure 3.12(a), a smoke layer was formed before the actuation of foam-water spray fire-fighting system. Upon the actuation of the fixed fire-fighting system, the fire was extinguished in 10s which demonstrated that the foam-water spray fire-fighting system was efficient in suppressing a flammable liquid fire.

In Scenario D2, a longitudinal ventilation of 3ms^{-1} was provided to hinder the smoke backlayering. The foam-water spray fire-fighting system was activated at 400 s. When comparing Figure 3.10(a) and 3.10(b), it was noted that the maximum ceiling temperature was found lower in the presence of ventilation system.

In both scenarios D1 and D2, temperatures were deceased shorter after the actuation of foam-water spray fire-fighting system and the liquid fires were also quickly suppressed.

Top shield and side shield were set up in Scenarios D3 and D4. Since the top shield would hinder the upward movement of heat and smoke, the ceiling temperatures as measured in Scenario D3 were the lowest among four testing scenarios. Due to the top shielding effect, foam-water spray was blocked and the fire suppression time was lengthened.

Because of the distorted movement of heat and smoke by the top shield and ventilation flow, the temperature measured at 2.5m level downstream of the fire was found to be highest among four cases.

Before the actuation of foam-water spray fire-fighting system, the temperature profiles of Scenario D4 were provided in Figure 3.10(d) and Figure 3.11(d).

For Scenario D4, where a side shield was in place, temperatures measured were found to slightly higher than that of Scenario D2 even before the actuation of fixed fire-fighting system which might be attributed to thermal radiation reflected from the steel plate. Nevertheless, similar temperature profiles were observed for D2 and D4 which demonstrated that the side shield, likewise a tall vehicle parked near the fire source, has limited or even no diminishing effect on the fire suppressing capability of a foam-water spray fire-fighting system with nozzles installed at a relatively high level.

3.4 Concluding Remarks

With the painful lesson learnt from the tragic tunnel fire in past years, fixed fire-fighting systems are found having a growing acceptance all over the word (CHOW, 1989). As suggested by renowned researchers and international research institutions (PIARC, 1999; PIARC, 2008b; Mawhinney, 2013; NFPA, 2011; NFPA, 2014; NFPA, 2017), a fixed fire-fighting system could:-

- Suppress /cool down a tunnel fire;
- Limit fire spread across vehicles inside a tunnel;

- Protect structure elements and other facilities inside a tunnel; and
- Facilitate evacuation as well as fire-fighting and rescue by emergency responders.

The full-scale burning test is a practicable tool to evaluate the performance and parameter set for a fixed fire-fighting system. Intense research effort has been devoted to study the performance and effectiveness of sprinkler, water mist, compressed air foam and other technologies for suppressing fires in road tunnels in the past decades (Ministry of Transport , 2002; Setoyama, et al., 2004; Yoshimochi, et al., 2004; Arvidson, 2003; Kawabata, et al., 2004; Opstad & Brandt, 2005; Ingason, et al., 2015; Ingason, et al., 2016).

The effectiveness of fixed fire-fighting system in tunnel fire protection is unarguably well. Nevertheless, concerns on smoke layer destratification and stream generation are still not properly addressed.

The results of fire tests are found in-line with previous findings with the following noteworthy observations:-

- Other than the benefits of inhibiting backlayering of smoke, a longitudinal ventilation system could effectively the ceiling temperature which is helpful for the protection of structural elements. For a non-enclosed fire, the longitudinal ventilation could enhance the extinguishment efficiency of the fixed fire-fighting system to a certain extent. As such, it is reasonable to actuate the ventilation system before or at the same time with the fixed fire-fighting. However, the effect of ventilation speed on the coupled performance of fixed fire-fighting system is not explored.

- The extinguishment effect of fixed fire-fighting for an in-vehicle fire is limited. The flame might even force towards downstream direction by the longitudinal ventilation system. Therefore, the adjacent zone of the fixed fire-fighting system in the downstream direction should also be actuated for the prevention of possible fire spread.
- The effect of tall vehicle parked next to the fire sources is found to be low for a fixed fire-fighting system with nozzle installed at relatively high positions of the tunnel sidewall.
- The discharge from a fixed fire-fighting system might disturb the buoyancy of smoke and cause smoke layer destratification. Nevertheless, a longitudinal ventilation system could enhance the visibility.
- Fixed fire-fighting systems, no matter whether a water or foam-water spray fire-fighting system is, could effectively lower the temperature in the tunnel and achieve the volume cooling effect, which is beneficial for the evacuation as well as fire-fighting and rescue works.
- The foam-water system deems more effective in extinguishing fires involving flammable liquid.

CHAPTER 4 NUMERICAL STUDY ON THERMAL HAZARDS OF CLEAN FUEL VEHICLES IN ENCLOSED SPACES

4.1 Introduction

For the sake of environmental protection and global sustainability, clear fuel vehicles have drawn growing concerns all over the world (HUO, et al., 2016a; HUO & CHOW, 2017; NG, et al., 2017).

Liquefied Petroleum Gas (LPG) has been used as vehicle fuel first in 1912. With a growing desire in cutting down the crude oil consumption, the acceptance of LPG vehicle is boosted in the 70s and 80s. Information on the using of LPG vehicles is tabulated in Table 11 (LAU, et al., 1997). LPG is suitable to be used as fuel for a variety of vehicles, such as vans, goods vehicles and buses, but it is limitedly used for taxis and light buses in Hong Kong.

Other than LPG, the appeal for using alternative clean fuels is also increasing with the blooming environmental awareness.

Following the increased usage of clean fuel vehicles, their associated fire and explosion hazard could not be underestimated. On 30th April 2017, a taxi using compressed natural gas as fuel exploded in a fire incident in Buona Vista of

Singapore (The Straits Times, 2017). Four fatalities, including a SCDF officer, were injured. Such a tragic accident posted an alarm on the fire and explosion hazard of vehicles using clean fuel to the general public.

4.2 The Hong Kong Situation

So as to reduce pollutants emitted by vehicular transportations, the Government of HKSAR launched an "Introduction of LPG Vehicle Scheme" in 1999 (LAU, et al., 1997; Electrical and Mechanical Services Department, 2017). The scheme provides incentives for replacing diesel taxis by LPG taxis and replacement diesel light buses by LPG or electric light buses in 2000 and 2002 respectively.

The incentive schemes for LPG taxis and light buses were successfully completed in 2003 and 2005 respectively with 99.9% of taxis and more than 3,100 light buses were transformed to use LPG as fuel.

According to the census data of HKSAR, the number of LPG taxis and LPG light buses in 2017 were 18,152 and 4,031 respectively. (Transport Department, 2017b) With the strong encouragement of the government and growing environmental concerns, the number of LPG fuelled vehicles is expected to increase continuously.

Under Cap.51 the Gas Safety Ordinance of HKSAR, a LPG filling station is considered as a "Notifiable Gas Installation" (Laws of Hong Kong, 2014). A Quantitative Risk Assessment is statutorily required to prove the associated risk of the filling station is within an acceptable level. Besides, proper training focused on the filling operation and responses in case of emergency shall be provided to all operators. Tailor-made safety measures and detailed construction requirements are formulated (Electrical and Mechanical Services Department, 2003).

However, safety problems of LPG vehicle maintenance facilities in Hong Kong were not awakened before a deadly explosion at a garage as shown in Figure 4.1 (South China Morning Post, 2015).

Although hydrogen-fuelled vehicles are still prohibited in Hong Kong, its application is surging all over the world. However, only limited discussions are available on their explosion hazards (Puzach, 2003; Tanaka, et al., 2007; Barley & Gawlik, 2009; Merilo, et al., 2011; Pitts, et al., 2012).

In the coming section, the explosion hazards of LPG and hydrogen-fuelled vehicles in a garage are numerically evaluated in different scenarios by the use of Computational Fluid Dynamics Simulations through a software namely, Flame Acceleration Simulator (FLACS) (CHOW & WONG, 2003; CHOW, 2002; CHOW & CHAN, 2003; CHOW & YIN, 2004; GexCon AS, 2009; HUO, et al., 2016a; NG, et al., 2017; GAO, et al., 2018).

4.3 The Sample Garage

A sample garage, based on the garage configuration commonly seen in Hong Kong as shown in Figure 4.2(a), is used in the simulation. The dimensions of garage are 8.1m (x-direction), 3.6m (y-direction) and 3.9m (z-direction). The computational domain is extended in x-direction for 1.5m as shown in Figure 4.2(b). The extended region allows the following of hot gas and cold air leaving and entering the garage.

A roller shutter, with a height of 3.6m from ground level and capable to withstand a pressure of 0.2 bar, is set at the position x = 8.1m.

The source of leakage is assumed to be a 5-seater taxi with a full tank capacity of 95.5L LPG (48.705 kg) (Electrical and Mechanical Services Department, 2015). The source is positioned at the centre of garage with a coordination of x = 4.05m, y =

1.45m and z = 0.45m. Downward (-z direction) leakage is assumed through a rectangular hole of 0.3m x 0.3m.

The vapour mass flow rate for difference leakage scenarios are tabulated in Table 12 (Van der Schoor, et al., 2013). The assumed scenario is leakage of LPG from a broken hole in the fuel tank with a mass flow rate of 0.21kgs^{-1}. The fully filled tank would be leaked completely in about 231s.

4.4 The Simulation Scenarios

The mesh size used in the simulation is $0.3m \times 0.3m \times 0.3m$. The grid system is shown in Figure 4.2(b).

Preceding researches suggested that the simulation results of FLACS are reasonably close with experimental data for different configurations with a maximum grid size Δx, Δy and Δz (Hansen, et al., 2010):

$$\text{Max}(\Delta x, \Delta y, \Delta z) = 0.1 \times V^{1/3}$$

where V is the cloud volume

For a cloud volume V of about

$$8.1m \times 3.6m \times 2m = 58.32m^3,$$

the maximum grid size would be 0.39m.

Possible effects of surface compression at the roller shutter to the convective flow field are considered by proper assigning of boundary conditions in the computation domain as follows: -

- Boundary: Euler
- Wind Speed: $0ms^{-1}$
- Ambient Temperature: $20^{o}C$
- Ambient Pressure: 1Bar
- Air Composition: 20.95% Oxygen & 71.05% Nitrogen
- LPG Composition: 40% Propane & 60% Butane

Three explosion scenarios are studied in the preliminary studies:-

- C1 Scenario: Ignition at 50s after the start of leakage;
- C2 Scenario: Ignition at 100s after the start of leakage; and
- C3 Scenario: Ignition at 150s after the start of leakage.

Monitor points M1, M2 and M3, are set at coordinates as shown in Table 13 for monitoring of different physical quantities.

4.5 Explosion Pressure

Pressure variations in Scenarios C1 to C3 at M1, where it is located near the roller shutter inside the garage, are provided in Figures 4.3(a) through (c).

In scenario C1, pressure in the garage is growing steadily in the garage because of the accumulation of leaked of LPG. Since the pressure is found smaller than 0.2barg, the roller shutter remains in a closed position. After the ignition at t = 50s, the pressure rapidly surges and reaches to about 0.2barg at about t = 53s which causes the opening of roller shutter and a decrease in pressure.

At the incipient stage scenario C2, a steady increase in pressure is noted. A slight jump at pressure to 0.2barg is noted after the ignition at t = 100s. Following the opening of roller shutter, the pressure dropped immediately.

In scenario C3, the pressure is growing constantly until t = 102s when roller shutter is opened by the over pressure. Following the opening of roller shutter, a drop in pressure is noted. The ignition at t = 150s caused a surge in pressure.

The pressure profiles at M2, which is positioned near the roller shutter outside the garage, are provided in Figure 4.4 (a), showed an increase at the ignition time for all three cases; whilst scenario C2 shows the biggest pressure surge.

The pressure profiles at M3, which is located near the ceiling directly above the ignition point, are provided in Figure 4.4 (b), shower the maximum measured pressure is 0.2barg in all three cases. For cases C1 and C2, the leakage of LPG is not long enough for the pressure to reach 0.2barg. The 0.2barg pressure level is caused by the explosion caused by the ignition of leaked LPG. However, the 0.2barg pressure level in scenario C3 is caused by the accumulation of leaked LPG within the garage.

4.6 Temperature

The transient temperature profiles for scenario C1 to C3 are contrasted in Figure 4.5. The rise in temperature is highly localized near the point of leak and ignition in scenario C1, whereas simulation transient temperature profiles are observed for scenario C2 and C3. A relatively large extent of temperature increase is observed in both cases and the high temperature area propagates upwardly due to the natural hot gas movement.

Though scenarios C2 and C3 showed similar transient temperature profiles, it is found that the hot temperature zone is extended towards +x-direction in scenario C2 which might be due to the higher explosion push the hot gases towards the opening in that direction.

The temperature profiles measured at M1, where it is located near the roller shutter inside the garage, are shown in Figure 4.6(a).

For scenario C1, the maximum temperature at M1 is 302.362K which is occurred at t = 53.2s. For scenario C2, the maximum temperature at M1 is 1791.02K which is occurred at t = 101.0s. For scenario C3, the maximum temperature at M1 is T=462.04K which is occurred at t = 152.8s.

The temperature profiles measured at M2 and M3 are shown in Figure 4.6(b) and 4.6(c) respectively. Among all three monitor points, scenario C2 showed a maximum rise in temperature.

4.7 Horizontal Component of Velocity

The horizontal components of fluid velocity u profiles at the three M1 to M3 are provided in Figure 4.7(a) through (c) while +u expresses a flowing of fluid out from the garage while -u represents a flowing of fluid into the garage.

In all three monitor points, the maximum change in velocity is all noted in scenario C2.

4.8 Effect of Low Level Ventilation

As presented in the previous sections, scenario C2 results in a greater surge in pressure, temperature and velocity than that of C3.

In scenario C3, pressure is steadily built in the garage due to the leak until the pressure is over 0.2barg and the roller shutter is opened by the overpressure. LPG is then allowed to move out of the garage and lessening the explosion consequences in terms of the increase in pressure, temperature and velocity.
To further study the effect of ventilation on explosion, the following scenarios are considered (JO & KIM, 2001; JO & PARK, 2004; Bauwens, et al., 2011; HUO, et al., 2016b):-

- C2-1 scenario: Simulation configuration is exactly the same as C2 where ignition at 100s after the start of leakage. (d = 0m, where d is the distance from the bottom of roller shutter to floor level)
- C2-2 scenario: Simulation configuration is exactly the same as for C2 where ignition at 100s after the start of leakage, except with a gap of 0.3m is located between the bottom of roller shutter and the floor level. (d = 0.3m)

The temperature, velocity and pressure profiles at M1 are shown in Figure 4.8(a) through (c). It is noted that scenario C2-2 where a gap of 0.3m is located at the bottom of the roller shutter, the increase in all three physical quantities, namely temperature, velocity and pressure, induced by the ignition are smaller than the scenario C2-1.

Such observations highlight the importance of low-level ventilation in a LPG garage, which could effectively reduce the damaging consequences of an explosion.

4.9 Thermal Hazard of Hydrogen Vehicles in Enclosed Spaces

In the coming section, the explosion hazard of hydrogen vehicles will also be evaluated by using the FLACS (Crowl & Jo, 2007; Venetsanos, et al., 2008; Rodionov, et al., 2011; Haugom & Friis-Hansen, 2011; Prasad & YANG, 2011; Shirvill, et al., 2012).

The garage used in the simulation has the same geometry as previous sections. With reference to the simulation by Swain, a hydrogen vehicle completely leaks 3.4 pounds hydrogen 100s (Swain, 2001). A mass flow rate of 0.015kgs^{-1} is thence taken in our simulations. Taking the Toyota Mirai as a sample hydrogen vehicle in the simulation, it has a dual tanks system with a combined capacity of 5kg. Having the given mass flow rate, the whole tank could completely be released in about 333s.

The following two scenarios are simulated:

- H1 Scenario: The ignition starts at 333s after the start of leakage.

  The pressure profile as measured at M1, a monitor point near the roller shutter in the garage, in scenario H1 is provided in Figure 4.9. According to the figure, pressure increases steadily in the simulation until the ignition at t=333s where a small jump in pressure is noted. Nevertheless, such increases in pressure is too small to blow open the roller shutter.

- H2 Scenario: The ignition starts at 100s after the start of leakage.

  The temperature profile as measured at M3, a monitor point near the ceiling above the point of ignition, is provided in Figure 4.10; while the transient temperature distributions are shown in Figure 4.11.

  The temperature of hot gas as shown in the transient temperature distribution in Figure 4.11 is found much lower than that of LPG scenario C2 as shown in Figure 4.5. Moreover, the hot gas is accumulated at the upper portion in the hydrogen scenarios and is pushed toward the ends.

In both scenarios C2 and H2, the leaked gases are ignited at 100s after the start of leaks. The temperature in both scenarios as measured at M3, the monitor point near the ceiling above the point of ignition, is contrasted in Figure 4.12. It is noted that the temperature surge is much greater in the case of LPG leak.

To further study the effect of low level ventilation, simulations on scenarios H2-1 and H2-2 are conducted.

- H2-1 Scenario:

  The same configuration is adapted in the simulation as Scenario H2 where the leaked gas is ignited at 100s after the start of leakage. (d = 0m)

- H2-2 Scenario:

  The same configuration is adapted in the simulation as Scenario H2 where the leaked gas is ignited at 100s after the start of leakage, except that a gap of 0.3m is provided between the bottom of roller shutter and the floor. (d=0.3m)

The pressures profiles as measured at M3, a monitor point near the ceiling above the point of ignition, in Scenarios H2-1 and H2-2 are both provided in Figure 4.13(a). In the presence of 0.3m opening, leaked hydrogen could escape from the garage and the pressure as measured by M3 fails to build up in Scenarios H2-2.

Meanwhile, similar temperature profiles as measured at M3 in both Scenarios are shown in Figure 4.13(b). It is noted that the peak temperature at M3 in Scenario H2-1 is slightly higher which is attributed to the possible heat loss to the atmosphere through the 0.3m opening.

4.10 Concluding Remarks

In this section, the explosion hazards of LPG and hydrogen-fuelled vehicles are discussed in this section.

As suggested by Astbury, the major hazard of LPG fuelled vehicle would be the leakage induced by the failure of fuel tanks and piping (Astbury, 2008).

The simulation results in Section 4.8 illustrated the presence of low-level ventilation could effectively lessening the damaging consequences of a LPG vehicle explosion in a garage.

Contrast the scenarios C2 and H2, ignition starts in 100s after the start of leakage in both cases. Though the increase in temperature and pressure are found smaller in the case of hydrogen vehicles, the explosion risk of hydrogen should not be ignored.

Hydrogen has quite a wide range of flammable limits, covered from 4% to 75%; while that of LPG only limits between 2.1 to 9.5%. Moreover, hydrogen's gross calorific value is 158.9MJkg^{-1} which is much higher than that of LPG 50.49MJkg^{-1} (Electrical and Mechanical Services Department, 2015).

The small increase in temperature for the hydrogen explosion scenario is found smaller than that of LPG which is likely because of the large flow rate differences used in the simulations. Provided with a large enough flow rate of hydrogen, the explosion would be damaging as well.

CHAPTER 5 NUMERICAL STUDIES ON EXPLOSION HAZARDS OF VEHICLES USING CLEAN FUEL IN SHORT VEHICULAR TUNNELS

5.1 Introduction

Short vehicular tunnels (SVT) are commonly used measures to mitigate the heavy traffic problem in cities of the Asia-Oceania Region where people are densely populated and traffic loads are heavy (CHOW, 2019).

These SVTs are classified as (LI, et al., 2019):-

- Urban Traffic Link Tunnels, where the travelling speed is limited to low speed, say 20kmh^{-1}; and
- Urban Tunnels, where the speed limit is high.

Hong Kong is well known for its overcrowded population and heavy traffic flow. A SVT, the Connaught Road Central Underpass as shown in Figure 5.1(a), in the dense commercial area of Hong Kong could have an Annual Average Daily Traffic (AADT) flow of over 131,220 (Transport Department, 2017a).

Other than the need for an efficient ventilation system to improve the indoor air quality of SVT, the associated fire hazard could not be overlooked.

Except traffic accident induced fire, serious fire incidents caused by engine overheating, mechanical and electrical fault of vehicles have drawn deep concerns from the general public.

- Double-desk buses in Hong Kong are all air-conditioned. Therefore, it is equipped with good thermal insulation envelopes. In a past accident, the entire envelopes are consumed by fire within 15 minutes (CHOW, 2001). A recent severe fire, as shown in Figure 5.1(b), involving a double-deck bus close to a footbridge has raised lots of public concerns (South China Morning Post, 2019).
- As reported in previous sections, the HRR of HGV is found over 100MW (NFPA, 2017; CHOW, 2018). The HRR would be much higher for fire involving multiple HGVs. It is reported that vehicular bridges are collapse because of the HGV fire (The News Times, 2018; The Guardian, 2018).
- Explosion hazard of vehicles using electricity and clean fuel might result in deadly explosion (HUO & CHOW, 2017; NG, et al., 2017; HUO, et al., 2016a; HUO, et al., 2019; CHENG, et al., 2016; CHENG, et al., 2018).
- Possible explosion threats of flammable clean refrigerants in the vehicles' air-conditioning systems (CHOW, et al., 2017; Kujak, 2017; CHOW & NG, 2016; NG & CHOW, 2014; NG & CHOW, 2015; NG & CHOW, 2015).

- Traffic congestion associated with heavy traffic loads in SVTs would which would promote fire spread among jammed vehicles and result in a larger fire size.

Taking Hong Kong as an example, vehicles conveying dangerous goods are strictly prohibited to pass road tunnel. However, such restriction is not applicable to SVTs and consequences would be devastating should a dangerous goods vehicle is involved in the fire (LI & CHOW, 2000).

As elaborated above, vehicular fires in SVTs not only posted threats to tunnel drivers, but also emergency responders, particularly when the fire dynamics of underground or semi-enclosed tunnels is not clearly understood.

Though fire safety requirements for road tunnels are clearly stipulated in different codes and guides and the fire safety provisions of SVTs strictly follows the regulation and codes at the time of construction, those provisions might not be able to cope with newly emerged challenges nowadays (Fire Services Department, 2012; Transport Department, 2001; TAM, et al., 2015).

In this section, the explosion hazard of a LPG fuelled vehicles inside a SVT is used to demonstrate that an old design may not be able to effectively handle the new fire hazards by using FLACS (GexCon AS, 2009).

5.2 The Sample Tunnel

In our simulation, part of a SVT as shown in Figure 5.2 is the simulation. The length of the simulated section is 12m. Since the simulated SVT is a major transportation route, electric power cables of 11-kV and water supply pipes also run through the space beneath the floor level of the tunnel. The diameters of the water pipes are 1.5m.

Vents on the floors level of the tunnel, as shown in Figure 5.2(b), are provided for ventilation of underground concealed space.

The dimensions of the tunnel in stimulation are 12.0m in length (x-direction) × 6.9m in width (y-direction) × 4.8m in height (z-direction). The concealed space under the tunnel floor is 2.1m in height which is further divided into three connected subspaces. Two of them are 2.1m in width, while the remaining one is 2.7 m in width. Water pipes with dimensions of 1.5m × 1.5m are running through each of these spaces.

Pavements, each of 0.6m in width and 0.3m in height above the floor, are provided on both road sides of the simulated tunnel.

Two vents, each with horizontal cross-section of dimensions 0.9m in length (x-direction) × 0.6m in width (y-direction) × 0.3m in height (z-direction) are provided on both pavements. The vent is positioned at a distance of 5.7m and 5.4m from the ends of the simulated tunnel. A schematic diagram showing the configuration of simulated tunnel is provided in Figure 5.3.

The source of leakage is assumed to be a typical LPG 5-seater taxi with a typical amount of 95.5L (48.705kg) (Electrical and Mechanical Services Department, 2015). It is assumed that the pressure relief valve of the LPG tank is opened after a traffic accident. The mass flow rate of LPG is 0.21kgs^{-1} in –y-direction (Van der Schoor, et al., 2013). The fully-filled tank of LPG would be completely vented out in about 231s. The location of leak is located at coordination x = 6.15m, y = 1.05m, z = 2.25m (0.15m above the tunnel floor level).

At t=250s, the leaked LPG is ignited at the coordination x = 6.15m, y = 0.15m, z = 0.15m, which is located in the concealed space at 1.95m under the tunnel road surface.

The mesh size of the simulation is 0.3m (x-direction) × 0.3m (y-direction) × 0.3m (z-direction) as shown in Figure 5.3(b).

Eight monitor points, namely M1 to M8, are assigned for monitoring the variations of physical quantities in the Simulations. The coordinates of the monitor points are tabulated in Table 14

5.3 Simulation Results

The concentration profile of LPG against time at M1 is provided at Figure 5.4(a).

At t=250s, the concentration of LPG at M1, which a monitor point located at the road level of the tunnel, is about 1% and is found lower than the explosion limit of LPG. Ignition at road level would not induce an explosion.

However, the scenario is still not safe for tunnel users. As shown in Figure 5.4(b), the LPG is found leaked into the concealed space. Since LPG is denser than air, the leaked LPG would accumulate in the concealed space under the tunnel road surface.

After the ignition at t=250s, the transient temperature profile of xz plane at y=0.2m and xy plane at z=2.3m are provided at Figure 5.5.

The temperature variation above road level at M1 is provided in Figure 5.6(a) with a peak temperature measured is 996.2K at 261s.

The temperature variations under the road level at M2 to M8 are provided in Figure 5.6(b) and the maximum temperature is found over 1600K in the concealed space. The pressure variations in the concealed space are shown in Figure 5.7.

5.4 Discussion

A possible explosion scenario, caused by a leakage of LPG from a LPG taxi, is demonstrated in the previous section. It was found that the peak temperature above road level could attain over 900K. Moreover, the temperature of concealed space could attain over 1600K.

Damages to tunnel, though it is repairable, would require the tunnel to be closed for maintenance for a considerable period of time. Taking a fire occurred at the concealed space of Lion Rock Tunnel as an example; the tunnel was closed for two weeks for emergency repairing which leads to a huge loss in economic and disturbs the citizens' lives (Information Services Department, 2013).

Not to mention, high temperature and explosion shock wave could probably induce further traffic accidents and vehicle fires in the tunnel with devastating consequences.

In Hong Kong, buildings shall be provided with fire safety provisions as prescribed in the FSI Code (Fire Services Department, 2012). The code is firstly published in 1954 and recently revised in 2012. The fire safety requirements for road tunnels have been included in the code since 1987.

Though Fire Services Department would review the code from time to time, the pace of code revision may still fail to up-keep with the changes. The introduction of LPG fuelled vehicles sets a good example.

Unarguably, the introduction of LPG fuelled vehicle is an environmentally friendly act which could effectively reduce the pollutant emissions. However, the explosion risk as demonstrated in the previous section is not properly addressed. Even in newly built road tunnels, no measure is required to monitor the level LPG in road tunnels. Though a gas detection system is required by the FSI Code, such system is required to monitor the levels of CO and NO_2 only.

5.5 Importance of Fire Safety Management

Facing the ever changing world with new threats, dynamic risk assessment and fire engineering approach provides a viable mean for existing tunnel and newly built tunnels to upkeep their fire safety level towards new risk, such as the introduction of new energy source and increase in vehicle fire size due to change of living style (CHOW, 2003a; TSUI & CHOW, 2004).

Through periodically review the situation, identify the risk and develop appropriate action plans by tunnel management and AHJ, potential damage could be limited should a risk be materialized.

Taking handling LPG leakage from LPF fuelled vehicle as an example, the tunnel management could make use of portable LPG monitor to thoroughly check the level of LPG as an interim measure. In long terms, they could consider the installation of fixed LPG level monitoring system.

CHAPTER 6 THE IMPORTANCE OF FIRE SAFETY MANAGEMENT IN ROAD TUNNEL FIRE SAFETY

6.1 Fire Safety Management

According to Beard & Scott, the tragic consequences of a disaster could be controlled via management measures (CHOW, 2000; CHOW, 2001; Beard & Scott, 2011; CHOW, 2016). These measures include early crisis detection, rapid response, efficiency mobilisation and action. The development of a controllable / uncontrollable event is schematically shown in Figure 6.1.

As preliminarily discussed in previous sections, proper fire safety management seems to be a viable solution for preparing existing infrastructure, including road tunnels, to cater for new challenges.

British Standards Institution suggests that management measures could be classified into (British Standards Institution, 2008):-

- Prevention measures; and
- Protection / mitigation measures.

6.1.1 Fire Safety Management - Prevention Measures

The purpose of implementing prevention measures is to prevent the occurrence of undesirable events. Taking fire prevention as an example, common measures including ignition source elimination and fire loads reduction.

6.1.2 Fire Safety Management – Protection / Mitigation Measures

The aim of protection / mitigation measures is to lessen the consequences and damaging effect of a tunnel fire through facilitating the evacuation of tunnel users, limiting the spread of fire and extinguishing the fire in its incipient stage.

In the coming sections, two case studies regarding the Cross Harbour Tunnel and the Lion Rock Tunnel in Hong Kong would be used to restate the importance and genuine need of proper tunnel management in road tunnel fire safety.

6.2 Case Study 1: Fire Incident in the Cross Harbour Tunnel (CHT) of Hong Kong

CHT is the first tunnel in Hong Kong. The tunnel is opened on 2 August 1972 to provide a vehicular connection from the Hong Kong Island and the Kowloon Peninsula. The CHT is 1,856m long. It was the longest sunken tube tunnel in Asia by that time. The carriageway of the tunnel has a clear height of 5.1m and a width of 6.6m (CHOW & LI, 2001).

6.2.1 Fire Service Installations of the CHT

Mechanical ventilation is provided through two ventilation buildings located at each portal. Pedestrian cross over facilities, fire hydrant / hose reel system, portable fire extinguishers, emergency lighting, carbon monoxide detectors, CCTV, emergency generator and emergency telephone are installed in the tunnel to satisfy the statutory requirements of the Hong Kong Fire Services Department (CHOW & LI, 2001).

6.2.2 Traffic Statistic of CHT

Being the busiest tunnel in Hong Kong, the annual traffic flow of CHT is 41,527,796 in 2017 (Transport Department, 2018).

As a main route connecting the business areas on Kowloon and Hong Kong Island, it is the most heavily utilised tunnel with a daily average of 113,775 against a design capacity of 80,000 (Transport Bureau, 1998). The overloading caused serious congestion in the CHT and associated approaching roads.

6.2.3 Fire Incident in the CHT

A private car caught fire inside the Kowloon bound tunnel tube of CHT on 29th May 2000. A brief event of incident is summarized in Table 16 (Transport Department, 2000).

Post-incident review highlights the important role of tunnel management in the event of fire:-

- prompt detection of fire and alerting the fire services personnel;
- swift initial response to the incident scene by management staff; and
- well-timed fire confinement and evacuation.

According to the experimental finding of CHEONG (CHEONG, et al., 2013), the growth of an unsuppressed tunnel fire involving HGV is ultra-fast type and the HRR could be as high as 100MW in 10-minute time. The growth of a HGV tunnel fire and interaction among different stakeholders in a tunnel fire are schematically shown in Fig. 6.2.

As illustrated in the above time-line analysis, a timely detection of fire and swift response by tunnel management could be useful in containing a tunnel fire in its incipient stage and hinder its development into an uncontrollable catastrophic fire before the arrival of Fire Services personnel.

6.2.4 Lesson Learnt from the CHT Fire Incident

To fine-tune the existing management measures and figure out important areas in tunnel fire management, criticism from the public on the incident are also reviewed.

In the fire incident, the tunnel controller took more than a minute to detect the fire and the response team required three minutes to reach the incident scene which is longer than the pledged response time of two minutes as specified in the management contract. Moreover, the response team was found not fully complied with the standard emergency procedures. Though the fire was eventually contained, the team members felt uncomfortable and required medical treatment (Transport Department, 2000). Also, tunnel users expressed that they had experienced difficulties during the evacuation, in the absence of sufficient information and guidance.

6.2.4.1 Slow Response by the Tunnel Management

The tunnel management clarified that the delay in the detection of fire was due to the well-worn CCTV system. The situation was expected to be improved after the replacement of monitoring system. Cameras and monitors would be replaced with a coloured system of higher resolution and more monitoring features (including pan and zooming function), in order to enhance the surveillance on traffic movement by controllers at the tunnel control centre.

Yet, the tunnel management explained the stringent two-minute response might be affected by the location and nature of incident.

6.2.4.2 Non-compliance with the Standard Procedures

According to the standard procedures for fire incidents, tunnel staff first arriving at the incident scene shall tackle the fire with breathing apparatus donned. However, the tunnel staff failed to follow the procedure. Besides, the team only used a fire extinguisher instead of a fire hose to control the fire. Not only failing to properly contain the fire, derivation from standard procedures might also put the staff themselves at risk.

6.2.4.3 Unsatisfactory Evacuation

In the fire, over 500 people were evacuated and no injuries were recorded. Most tunnel users were led from the Kowloon bound tube to the Hong Kong bound tube through the emergency cross passage towards the Hong Kong portal. In the absence of public announcement (PA) system, tunnel officers first arriving at the incident scene could still use loud hailers to inform motorists of the incidents and to direct evacuation.

6.2.5 Concerns in Tunnel Fire Management

6.2.5.1 Rapid Incident Detection and Swift Incident Response

Rapid incident detection and incident response are crucial for fire-fighting in road tunnels. The large number of fatalities in tunnel fires is attributed to unexpected fast growth and spread of fire. According to the latest NFPA, the time to reach the peak HHR for tunnel vehicle fires ranged from 10 to 20 minutes. Therefore, it is important for the tunnel management to limit the growth and avoid the fire developing into an uncontrollable extent.

In Hong Kong, all tunnels are statutorily required to install with a CCTV system and all incidents should be detected within one minute. An automatic incident detection system could be used as an aid to relieve the operator.

Experimental results also suggested that the available monitoring time for visual-based detectors was greatly reduced to less than 1 minute for large fires with a quick growth rate due to the significant formation of dense smoke (PIARC, 2008b).

6.2.5.2 Well-established Emergency Handling Procedures

To effectively handle tunnel fire incident, the management must be well planned for the handling procedures for different fire scenarios. Sufficient manning must be provided to carry out the designed procedures. Responding personnel must be clearly specified their designated tasks and duties. Other than the confinement of fire, the procedures must also cover the evacuation of tunnel users. According to the experience of tragic fire incidents and mock-up experiment, tunnel users are found resist to leave their own vehicles even in the presence of heavy smoke. (Shields, 2008; Boear, 2002) Besides, limited information available for tunnel users in case of fire would unavoidably induce unnecessary panic. Therefore, sufficient staff and equipment for announcement shall be arranged to facilitate the information dissemination and evacuation.

6.2.5.3 Proper Training of Tunnel Staff

To ensure the timely and appropriate action taken by the responding staff, proper training on fire-fighting skills. Detailed training schedule by competent personnel must be formulated and conducted to upkeep the proficiency of the initial responders. Emphasis should also be put on the disobedience of laid down guidelines and procedures would not only hinder the efficiency in fire-fighting and rescue, but also endangering their own safety.

6.2.6 Concerns of Emergency Services

In view of the rapid fire growth of the tunnel fire, a close liaison between the emergency services and the tunnel management must be established for effective handling of fire. Being a competent tunnel management, proper housekeeping as well as maintaining the tunnel fire service installations in good working order are always a mere platitude.

According to the past tunnel fire experience, unexpected rapid fire growth and fire spread are observed. The rapid and ever changing tunnel fire situation would unavoidably cause difficulties in estimating the resource requirement as well as the planning of fire-fighting and rescue strategy.

Since all tunnels in Hong Kong are equipped with CCTV system, controllers in the Tunnel Fire Control Centre could make a good use of the system to closely monitor the development of fire and relay the information to the en-routing Officer-in-charge of emergency responders for the advance planning prior to the arrival. With the provision of additional information, like suitable access routes, involved vehicles in the fire and number of casualties from the tunnel management, the planning of strategy could be greatly facilitated.

Unlike conventional building fires in which smoke and fire spread are retarded by fire-resisting compartments, evacuees are directly exposed to the heat and smoke. Besides, a tremendous passenger load of public transports would also lengthen the time required for evacuation. To fully utilize all available time for safe evacuation and ensure the safety of tunnel users, diversion of traffic and evacuation must be conducted immediately upon the confirmation of fire incident. Tunnel management should not adopt a wait-and-see attitude and delay the start of evacuation until the arrival of emergency services, as the condition of the tunnel may be deteriorated quickly.

Unarguably, an early and efficient suppression by the tunnel management at the incipient stage is essential for the confinement of a tunnel fire. However, these first responders should be competent and strictly adhered to agreed handling procedures. Otherwise, they might put themselves at high risk and induced extra burden to the rescue personnel.

Based on the updated results of fire tests, the heat release rate of tunnel vehicle fires has been underestimated over the years. Therefore, it is not surprising that those formerly built tunnels might not be ready for handling such a big fire. Yet, the tunnel management could still make use of fire engineering principles to evaluate the integrated performance of the existing fire safety provisions and management measures in different fire scenarios, which could provide a glance on the effectiveness of existing provisions and allow the emergency services to be better prepared for difference fire scenarios.

6.3 Case Study 2: Fire Incident in the Lion Rock Tunnel

On 8th March 2012, a fire occurred at the service tunnel of Lion Rock Tunnel. The fire was eventually upgraded to No.3 alarm fire and Fire Services members took over eight hours to extinguish the fire. A fire-fighter was injured in the accident. The southbound tunnel was shut down for two weeks which led to a tremendous loss on the economic and affect the lives of many people (TAM, et al., 2015). The fire also raised concerns of the general public on the fire safety of existing tunnels.

6.3.1 Prescriptive Fire Safety Requirement in Hong Kong

In Hong Kong, buildings are required to provide fire service installation according to the Code of Practice for Minimum Fire Service Installation and Equipment (CoP). The requirements of road tunnels have been stipulated in the Code since 1987. The fire service installation as required by different versions of CoP is tabulated in Table 6.

6.3.2 The Lion Rock Tunnel

The Lion Rock Tunnel was firstly opened in November 1967, while the second tube of the tunnel was opened in January 1978. Though the very first version of CoP was published in 1964, the FSI requirements for road tunnel were not prescriptively stated until 1987. Details of fire safety provision of the Lion Rock Tunnel are also provided in Table 17. It is not surprising that the provisions of Lion Rock Tunnel could not meet the latest requirements of CoP.

6.3.3 New Challenges to Fire-fighters

Faulty double-decker buses and goods vehicles caused vehicle fires every now and then (CTS, 2014; The Sun Daily, 2014). Fortunately, the fire took place in an open carriageway instead of inside the tunnel where catastrophic damage would be expected.

Along with the technology advancement and live style change, the construction materials, design, fuel, passenger and cargo loads of vehicles as well as the traffic load and composition of road tunnels nowadays would far different from the initial design which would post new challenges to fire-fighters.

Though the installation of fixed fire-fighting system could alleviate the damaging effects of a tunnel fire, the retrofitting of such system in existing tunnels is found difficult and lengthy in time. Performance-based design and proper fire safety management provide a viable interim measure.

The performance-based design approach provides a platform to scientifically evaluate the integrated performance of existing active and passive fire safety provisions. Synergy with enhanced and tailor-made fire safety management measures, the tunnel safety level could still be maintained at an acceptable level.

6.3.4 Risk Management

Effective from 21st June 2006, all new infrastructure projects in Hong Kong, including road tunnels, are required to conduct a Systematic Risk Management (SRM) process as in Figure 6.4 during its planning stages to identify risks and limit potential damage should a risk materialise (Development Bureau, 2006).

As suggested by the Development Bureau, the level of risk is determined by considering the consequence and likelihood of an incident. The level of consequence is determined by considering different factors including:-

- Financial Implication
- Delay in Construction or Operation
- Life Safety
- Public Concern
- Environmental Consideration
- Social/Cultural Heritage Impact
- Legal Consequences and etc.

The frequency is governed as shown in Table 18, while the level of risk is determined by the risk matrix as shown in Table 19.

It is advisable that the SRM process shall be used to qualitatively evaluate the risk at the existing road tunnels and determine the areas that require further enhancement from time to time. The above SRM process outlined a qualitative method for evaluating the risk of existing tunnels and highlighting the areas that require further enhancement. Nevertheless, a quantitative analysis could provide a numerical evaluation of risks and an objective measurement on the level of improvement.

Due to the complicated fire phenomenon in tunnel fires, the performance of different fire safety provisions shall be holistically evaluated. As suggested by NFPA and other renowned professional organisations, performance-based design approaches provide a scientific platform to assess the overall safety level of road tunnels.

6.3.5 Performance-based Design in Hong Kong

The performance-based design approach, which provides an alternative solution other than the strict adherence to prescriptive requirements, has been widely accepted internationally by the approving authorities.

Seeing the increased complexity of building projects and mega-infrastructures, the demonstration in the equivalency of fire safety standard by performance-based design approaches has been accepted by the regulatory authorities, i.e. Buildings Department (BD) and FSD, since the mid-90s. When there is genuine difficulty in complying with prescriptive provisions, an alternative solution can be adopted and proved through quantitative and qualitative evaluation (CHOW, 2003b; CHOW & CHOW, 2018).

With due consideration given to the uniqueness of these designs, fire safety strategy shall be formulated with reference to (Buildings Department, 1998; Buildings Department, 2011; CHOW, 2015; PANG, et al., 2016):

- Anticipated risk of fire development and spread
- Safe evacuation of occupants
- Minimization of fire and smoke spread
- Facilitation of firefighting and rescue by Fire Services personnel
- Prevention of building collapse as a result of fire
- Role of management

6.3.6 Importance of Management

For as road tunnels, fundamental infrastructures and critical structural elements have already been built, upgrading of active and passive fire safety provisions could not be completed in seconds. The adoption of performance-based design approach provides a pragmatic solution allowing the fulfilment of fire safety objectives through synergy effects of existing fire safety provisions and enhanced management measures.

For example, taking the advantage that CCTV and a 24-hour manned fire control center are mandatory requirements in all tunnels in Hong Kong, the tunnel management should make good use of these available facilities to closely monitor tunnel conditions and take timely actions should any accident occur. Through the implementation of proper management measures to reduce the likelihood or lessen the consequences of a tunnel fire, the fire risk could still be maintained at an acceptable level.

CHAPTER 7 RECOMMENDATIONS AND CONCLUSIONS

7.1 Conclusion

Numerous tragic fires in road tunnel fires have claimed the lives of people and caused huge economic impact (PIARC, 1999). As propelled by these painful experiences, intense research effort devotes to review the HRR of HGV fires in road tunnels (Ingason & Lonnermark, 2005; CHEONG, et al., 2013). With updated research findings, renowned international institutions, like NFPA and PIARC, concur that a tremendous amount of heat would be released in road tunnel fires involving HGV which posted threats to existing road tunnels nowadays (PIARC, 2008b; NFPA, 2017).

Means to protect the tunnel structure and prevent the fire spread must thence be provided, whereas the installation of fixed fire-fighting system is a viable solution to the problems (TAM, et al., 2015).

Since the ventilation system is another core element of tunnel fire safety, the integrated suppression performance of a longitudinal ventilation system and water spray fire-fighting system is experimentally studied on wood pallet fire and diesel pool fire of 20 MW fire under eight different fire scenarios with the following observations (LI, et al., 2019) :-

- The longitudinal ventilation, at critical velocity, could effectively prevent the occurrence of backlayering and lower the ceiling temperature. It could also improve the suppression efficiency of a fixed firefighting system. Nevertheless, the actuation of adjacent spray zone is required on the fire upon operating the longitudinal ventilation system.
- The extinguishing efficiency of fixed fire-fighting system in-vehicle fire is limited.
- The fixed fire-fighting system would affect the buoyancy of the smoke layer and draw it towards the floor level. The effect is undesirable; yet, the situation and visibility are greatly improved by the longitudinal ventilation system operating in critical velocity.
- Foam-water spray is apparently more efficient in extinguishing fires involving flammable liquid.
- Experiment result also suggested that the ventilation system should be actuated earlier than the fixed fire-fighting system for a better fire control.

The information provides solid support for the formulation statutorily requirements on fixed fire-fighting systems in road tunnels and determination of appropriate fire safety provision and strategy of road tunnels.

Other than a tremendous amount of heat released in road tunnel fires, the introduction of clean fuel for vehicles also posted new challenges to the road tunnel design. The explosion and thermal hazards associated with the clean fuel vehicles would be studied through Computational Fluid Dynamics software, namely FLACS in a garage and a section of short vehicular tunnel.

The explosion hazards of LPG and hydrogen vehicles are firstly simulated and compared in a garage with a commonly seen design Hong Kong (TO, et al., 2019b).

The simulation results illustrated the provision of low-level ventilation could lessen the consequences of an LPG vehicle explosion in a garage, whereas the same provision could not lessen the aftermath in the case of hydrogen vehicle explosion.

Moreover, it is noted that the LPG explosion case would result in a bigger surge in temperature and pressure than the hydrogen explosion case when the fuels are allowed to leak for 100s before ignition. Nevertheless, the risk of a hydrogen explosion could not be underestimated.

Hydrogen has a wide range of flammable limits (4-75%) while the flammability limit of LPG only ranges from 2.1-9.5%. The gross calorific value of hydrogen is 158.9MJkg^{-1} which is much higher than 50.49MJkg^{-1} of LPG (Electrical and Mechanical Services Department, 2015).

One of the contributing factors of the difference in the surge in temperature may probably due to the large difference in the flow rates adopted in the simulations. When the flow rate of hydrogen is large enough, the hydrogen explosion would also result in devastating effects.

To formulate proper fire safety measures and appropriate fire-fighting strategy, the main physical phenomena in an SVT fire must be better figured out.

The thermal hazard of LPG taxi explosion is also studied in a section of SVT (TO, et al., 2019a). Since SVT are an important element of major transportation routes, electric power cables of 11-kV and water supply pipes running through the space beneath the floor level of the tunnel are commonly seen in Hong Kong. LPG is assumed to be leaked into the concealed space under the carriageway. Subsequent ignition at a low level of the concealed space, the peak temperature above road level could attain over 900K. Moreover, the temperature of concealed space could attain over 1,600K. The result of the explosion could be damaging.

The explosion simulation also demonstrated the necessity of dynamic risk assessment in alleviating risks arising from new challenges existing infrastructures, like new energy source and power size.

The situation and case studies in Hong Kong were only the opening words to illustrate a long-standing problem worldwide.

Facing the ever changing world with new threats, dynamic risk assessment and fire engineering approach provides a viable mean for existing tunnel and newly built tunnels to upkeep their fire safety level towards new risks, such as the introduction of new energy source and increase in vehicle fire size due to change of living style.

In the long run, permanent measures and infrastructure must be set up to cater for the new challenges. Nevertheless, fire safety management could temporarily alleviate the problem through making dynamic risk assessment with an aim to periodically reassess the situation, determine the new risk, formulate appropriate action to be taken (TAM, et al., 2015).

7.2 Recommendations

Buildings in Hong Kong are statutorily required to provide active and passive fire safety provisions as stipulated in different Codes and Standards which are in-forcing during the time of construction (Buildings Department, 2011; Fire Services Department, 2012). Notwithstanding the above, technology advancement and live style change would unavoidably post new challenges to the fire-fighting works.

Taking road tunnels (CHOW, 2018) as an example, the use of new vehicular materials and an increase in population and traffic volumes, as well as the promotion of alternative energy sources posts challenges the existing designs of road tunnel.

Painful tunnel fire experiences, research and test results have proven tremendous heat would be in road tunnel fires (PIARC, 1999; Ingason & Lonnermark, 2005; CHEONG, et al., 2013; NFPA, 2017).

Hong Kong is well known for its over-population and congested traffic. The traffic volume in road tunnels is unbelievably high (Transport Department, 2018). Since road Tunnel is an indispensable element for the transportation network, proper means of protection must be provided to safeguard public safety.

Echoing the stances of NFPA and PIARC (PIARC, 2008b; NFPA, 2017), the fire test results in Chapter 3 show the provision fixed fire-fighting system in the road tunnel is effective not only in suppressing the fire, but also control the spread, cooling the volume as well as structural surface (LI, et al., 2019). As such, it is recommended that AHJs shall incorporate the provision of fixed fire-fighting system as one of the fire safety requirements of road tunnels.

Notwithstanding with above, the installation, configuration and operation of fixed fire-fighting system are recommended to be supporting by engineering analysis which holistically and scientifically evaluates the coupled performance of active and passive fire protection measures, as well as management measures and emergency services interventions.

The fire test result also suggested that the longitudinal ventilation system should be actuated earlier than the fixed fire-fighting system for a better fire control (LI, et al., 2019). Such information would be useful in determining proper operational procedures and guidelines for the tunnel management and emergency services in case of a fire in a road tunnel.

Other than the tremendous heat released in road tunnel fires, the explosion hazard of a vehicle using clear fuel also post a new challenge to road tunnels. Supported by FDS simulation results by FLACS, low level ventilation shall be provided in road tunnels to lessen the explosion consequences of LPG vehicles (TO, et al., 2019b).

Moreover, the FDS simulation in a section of SVT suggested the LPG explosion consequences in a road tunnel could be tragic. Though the explosion occurred in a concealed space beneath the road surface, the temperature above road level could attain over 900K, not to mention the temperature of concealed space reached over 1,600K (TO, et al., 2019a). As such, measures to monitor for LPG must be provided in road tunnels and its associated concealed spaces to safeguard the public safety.

The emergence of new challenges induced a pressing need to upgrade the hardware of tunnels, like the installation of fixed fire-fighting system could alleviate the damaging effects of a tunnel fire and the installation of LPG sensors in vehicular tunnels could enhance the monitoring of possible threats. However, the retrofitting works of these systems in existing tunnels are difficult and time-consuming.

As a quick relief and interim measures, the fire safety management is obligated to shoulder the responsibility through making dynamic risk assessment with an aim to reassess the situation periodically, determine the new risk and formulate appropriate action to be taken (TAM, et al., 2015).

Reinforcing the dynamic risk assessment, a performance-based design approach provides a platform to scientifically and quantitatively evaluate the integrated performance of existing active and passive fire safety provisions, as well as the synergy effect with enhanced and tailor-made fire safety management measures which upkeep the tunnel safety level to an acceptable level.

AHJs, not only in Hong Kong but also in other countries, are thence recommended to require the tunnel management to review the existing safety level of road tunnels regularly as well as propose the long term and interim remedial measures based on the performance-based design principal.

7.3 Future Studies

To pave the way towards a safer road tunnel design, further studies in the following areas are also recommended:-

- Vehicular fires in road tunnels would unavoidably be involved flammable fuel, such as diesel and gasoline. The test results also suggested that foam-water spray is apparently more efficient in extinguishing fires involving flammable liquid. Nevertheless, the use of foam spray may also adversely affect the evacuation of tunnel users. It is recommended to experimentally investigate the effect of foam spray on the effectiveness of evacuation.
- In the fire tests, only the longitudinal ventilation system at the critical velocity and its effect on the performance of fixed fire-fighting system are studied. The impact of longitudinal ventilation velocity on the performance of fixed fire-fighting system is not studied in detail. It is recommended experiments to be conducted with different longitudinal ventilation velocity so as to figure out the underlying correlation.

- Moreover, only the integrated performance longitudinal ventilation system and the fixed fire-fighting system is considered. It is recommended to extend the experimental study to the transverse and semi-transverse ventilation system.
- Also, our experimental works were focused on discussing the effectiveness of FFFS through temperature measurements. Yet, the discussion may further extend to monitoring the structural temperature and radiation.
- Regarding the CFD simulation regarding garage and SVT, it is recommended that a scale model should be used to validate the predicted results from computer simulations.
- Besides, studies might also include studies regarding the impact of grid size towards the findings and evacuation simulations to evaluate the fire safety levels of the scenarios.

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FIGURES

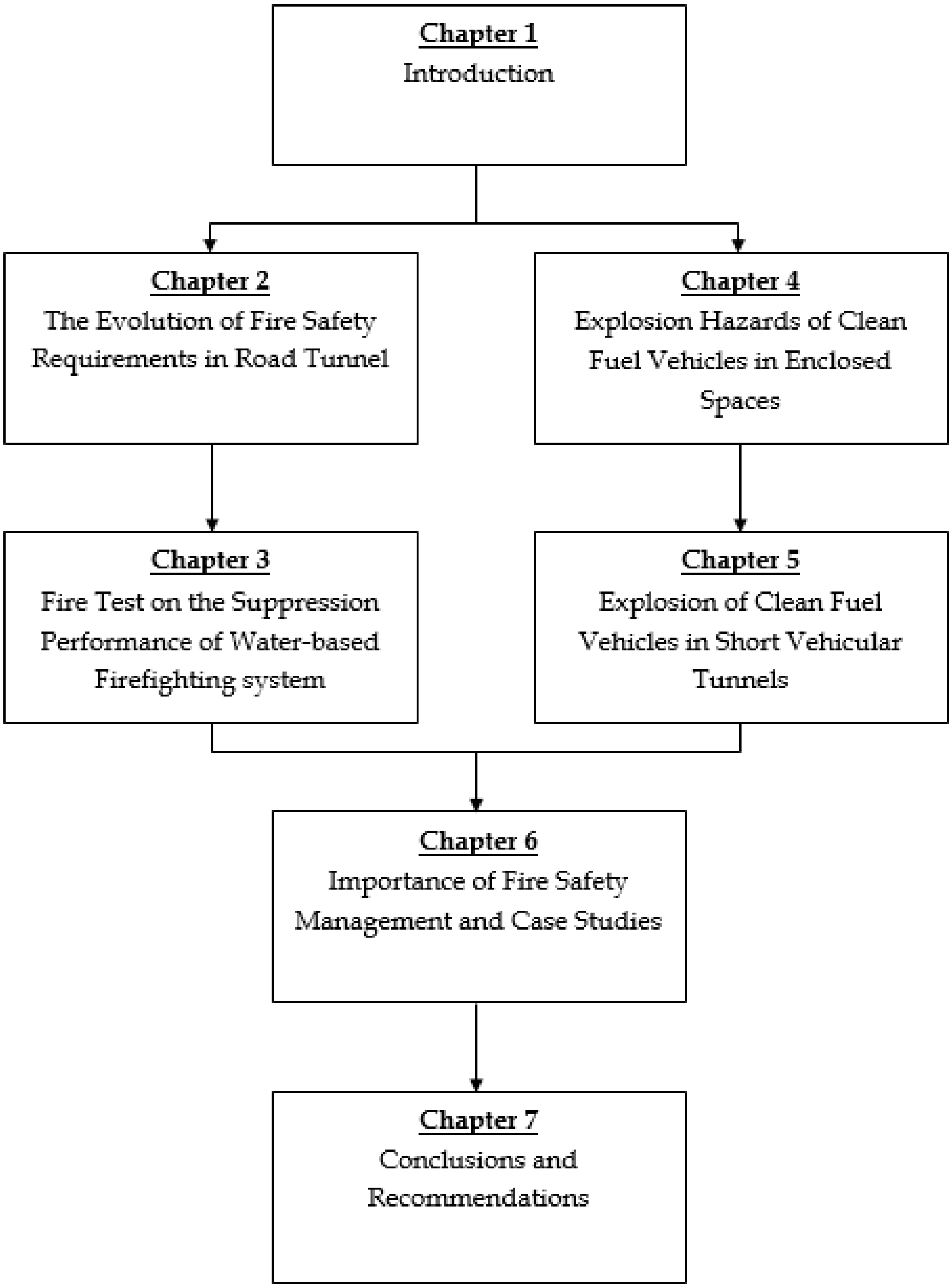


Figure 1.1 Structure of Thesis

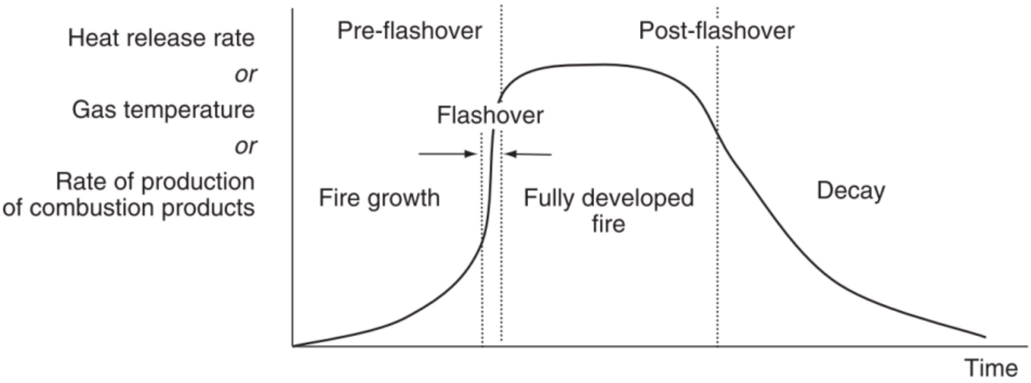


Figure 2.1: Stages of Compartment Fire by Ingason (2011)

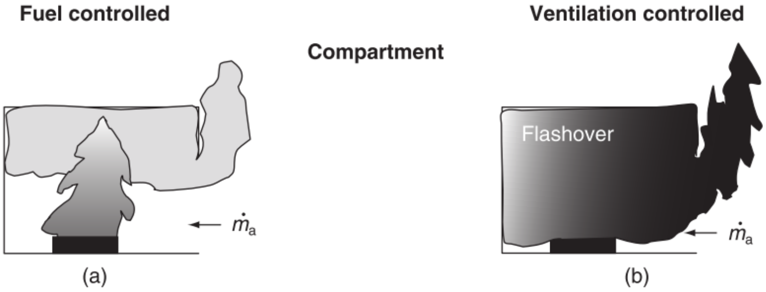


Figure 2.2: Illustration of Fuel-controlled Fire and Ventilation-controlled Fire by Ingason (2011)

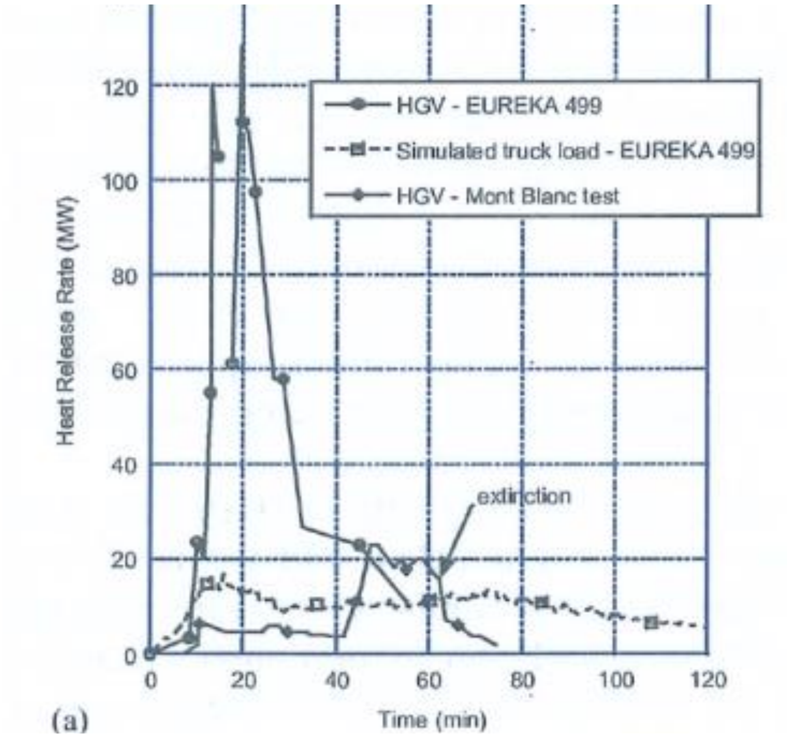


Figure 2.3: Result of EUREKA 499 Tunnel Test Programme from Ingason & Lonnermark (2005)

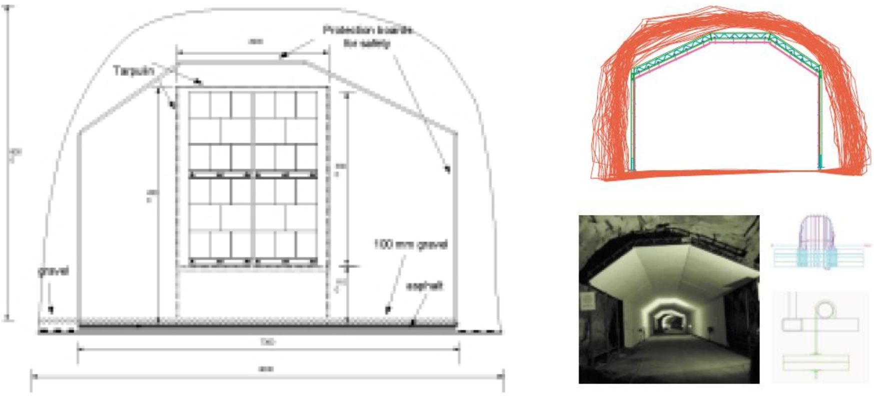
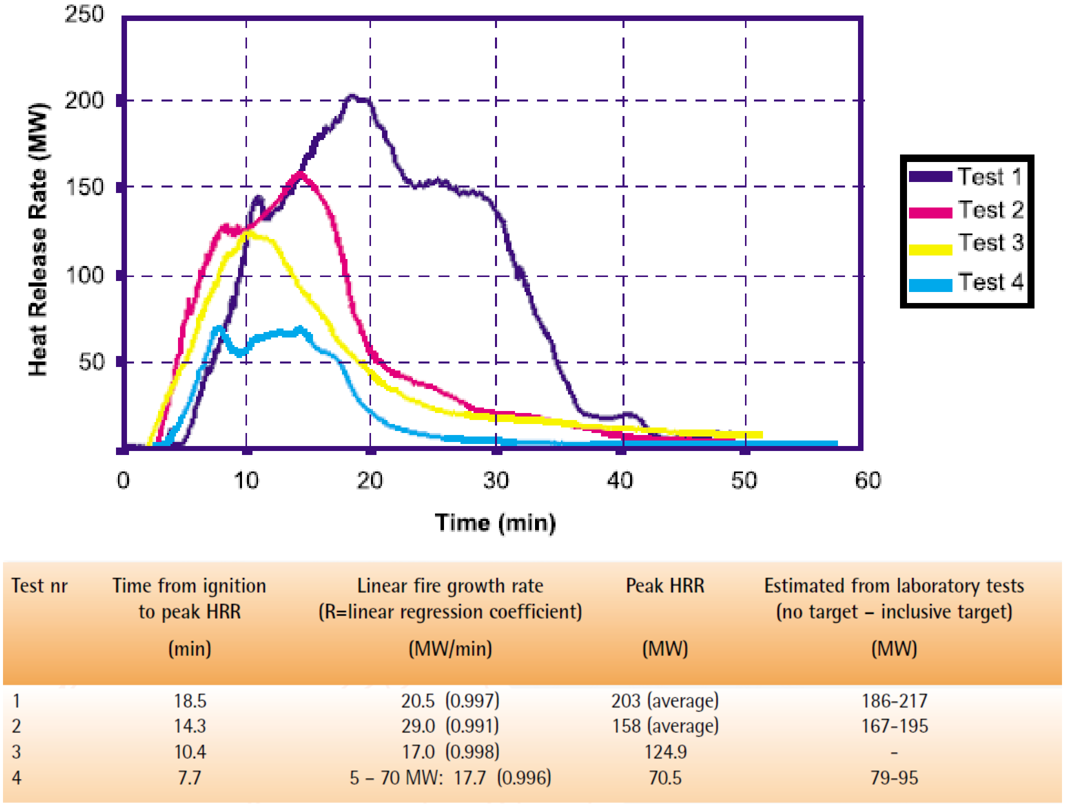


Figure 2.4: Configuration of Runehamar Tunnel Fire Tests from UPTUN (2008)



Test nr	Time from ignition to peak HRR (min)	Linear fire growth rate (R=linear regression coefficient) (MW/min)	Peak HRR (MW)	Estimated from laboratory tests (no target – inclusive target) (MW)
1	18.5	20.5 (0.997)	203 (average)	186-217
2	14.3	29.0 (0.991)	158 (average)	167-195
3	10.4	17.0 (0.998)	124.9	-
4	7.7	5 – 70 MW: 17.7 (0.996)	70.5	79-95

Figure 2.5: Experimental Results of Runehamar Tunnel Fire Tests

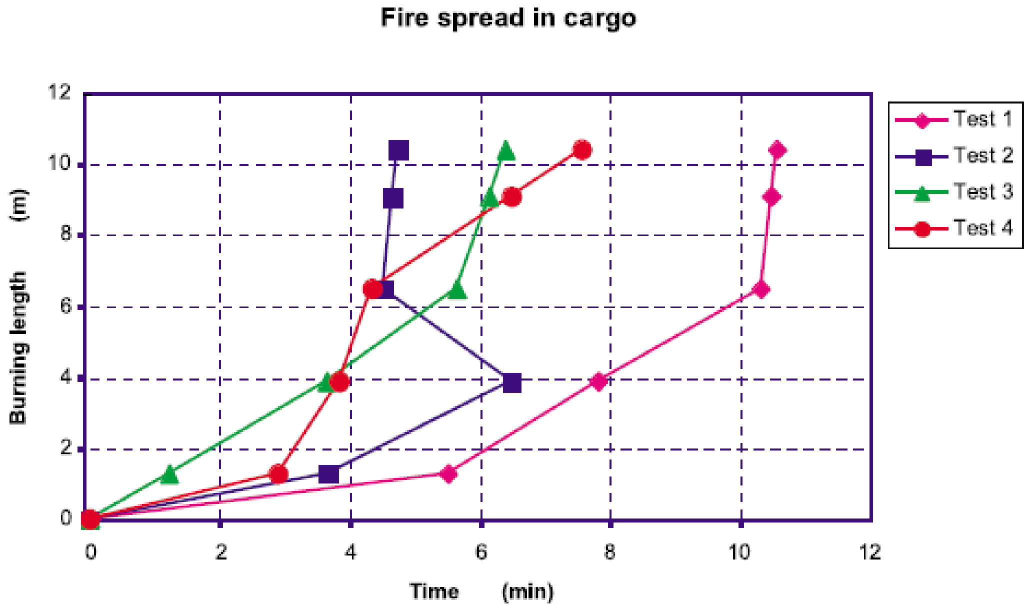
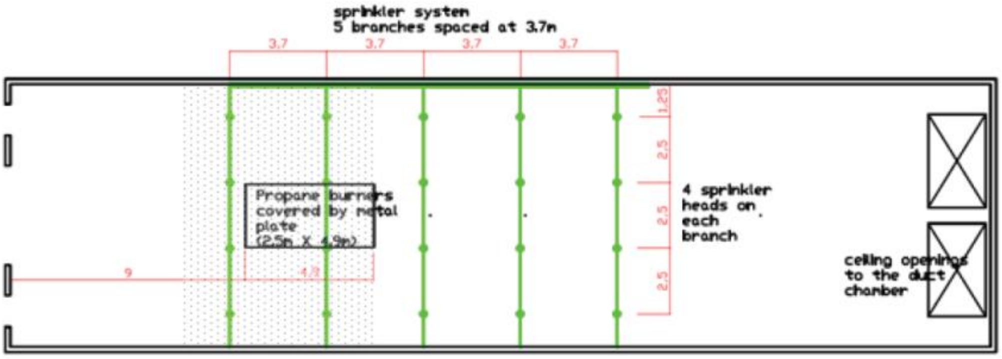
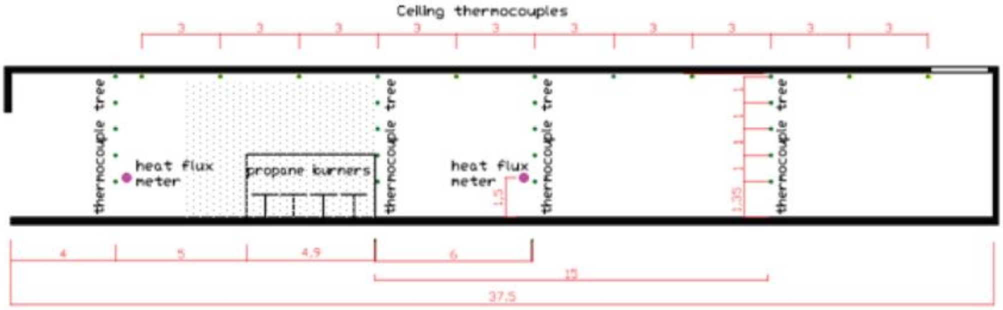


Figure 2.6: Fire Spread Measurements in of Runehamar Tunnel Fire Tests



(a) Sprinkler system (Plan view)



(b) Instrumentations (Section view)

Figure 2.7: Experimental Setup of Fire Tests at Carleton University

Figure 2.8: Fire Tests at Carleton University

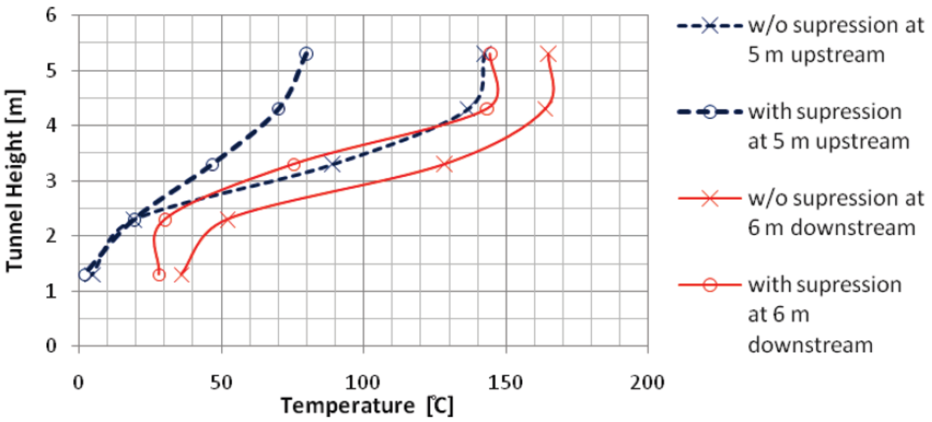


Figure 2.9: Vertical Temperature Profiles of Fire Tests at Carleton University

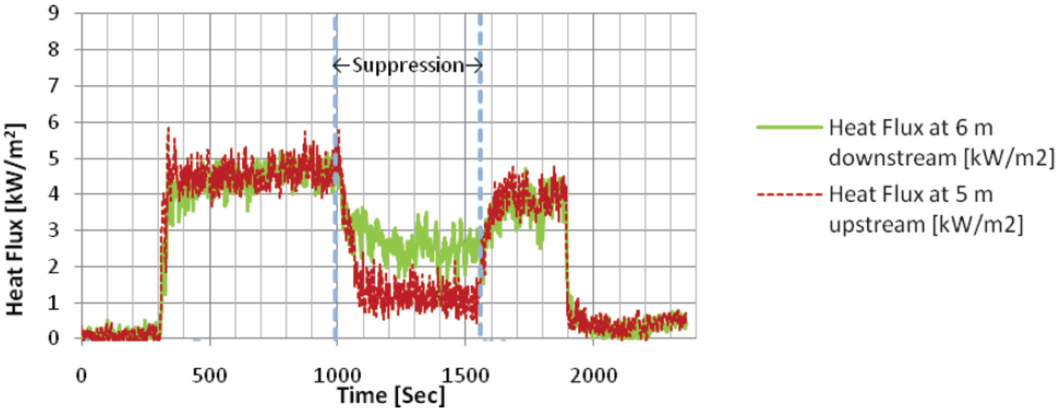


Figure 2.10: Heat Flux Measurement in the Fire Tests at Carleton University

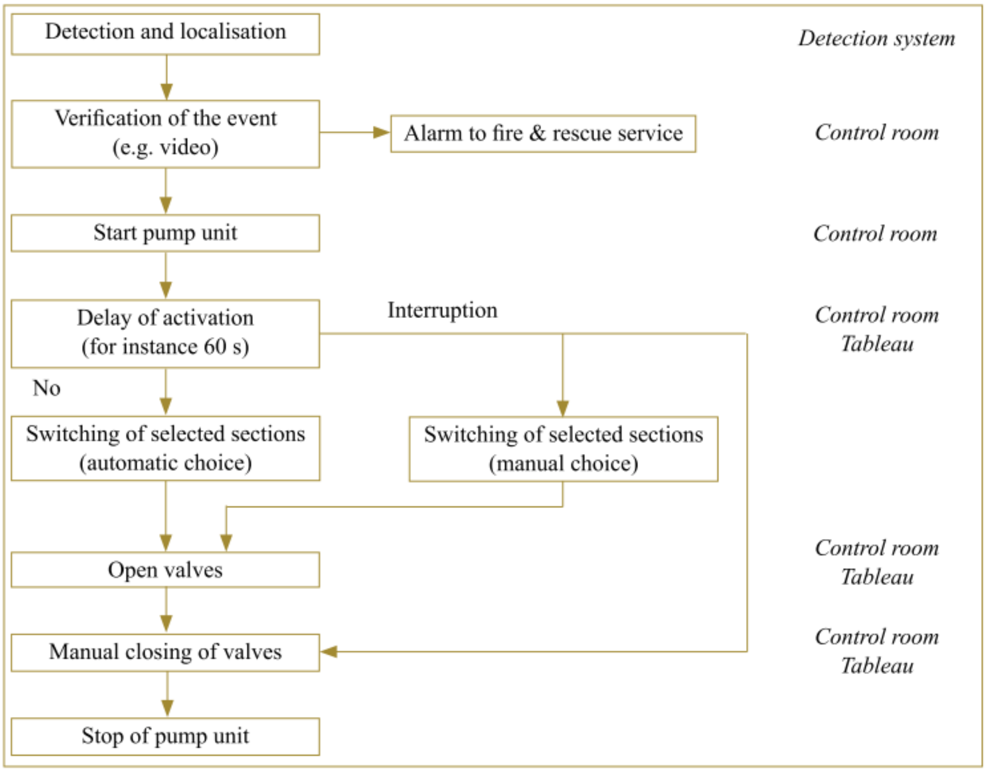


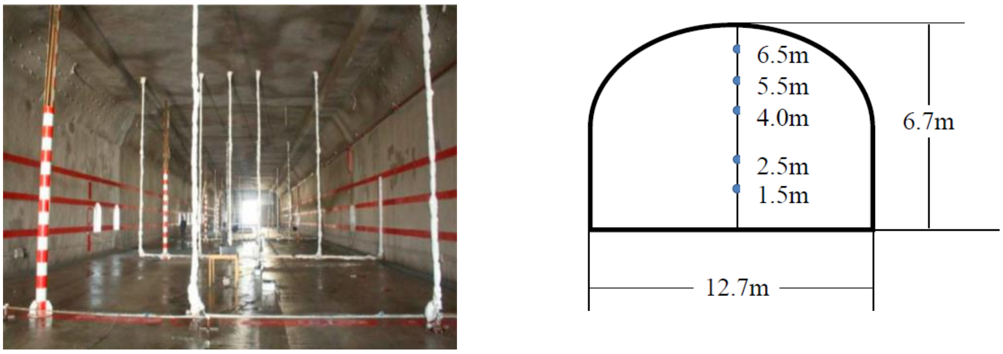
Figure 2.11: PIARC Proposed Controlling and Activating Sequence of a Fixed Firefighting System

(a) External View of Test Tunnel (b) Ventilation Fan

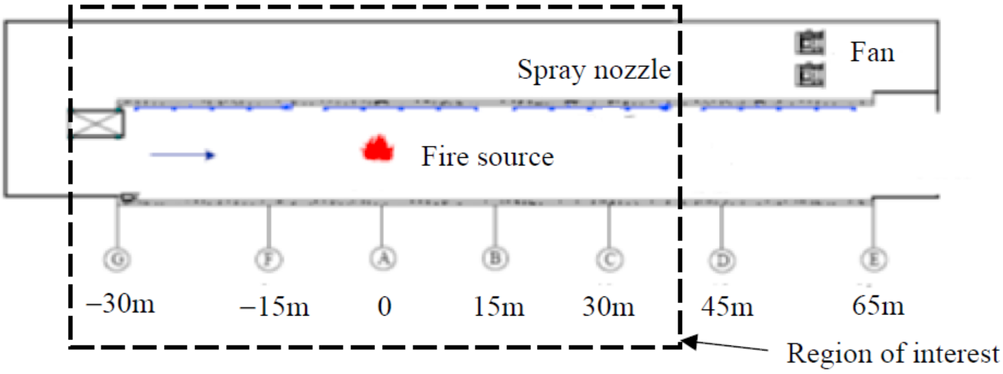
(c) Internal View

(d) CCTV (e) Large Scale Electric Balance

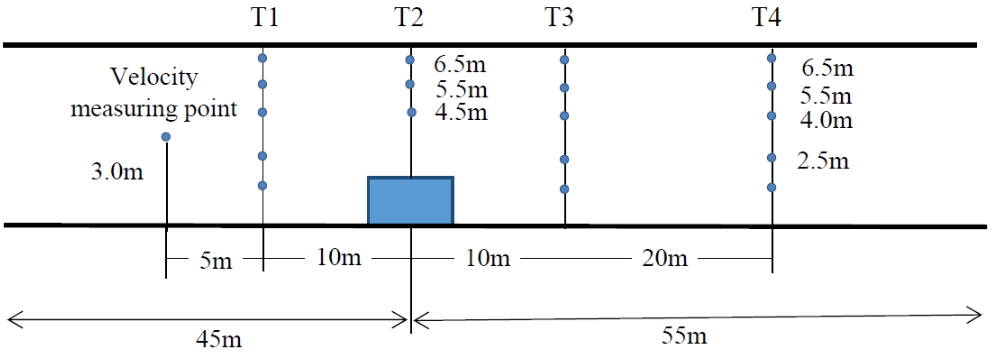
Figure 3.1: The Testing Tunnel



(a) Inside View (b) End View



(c) Schematic Layout Plan



(d) Measurement Points in Region of Interest: Front View

Figure 3.2: Full-scale Burning Tests Setup in the Tunnel

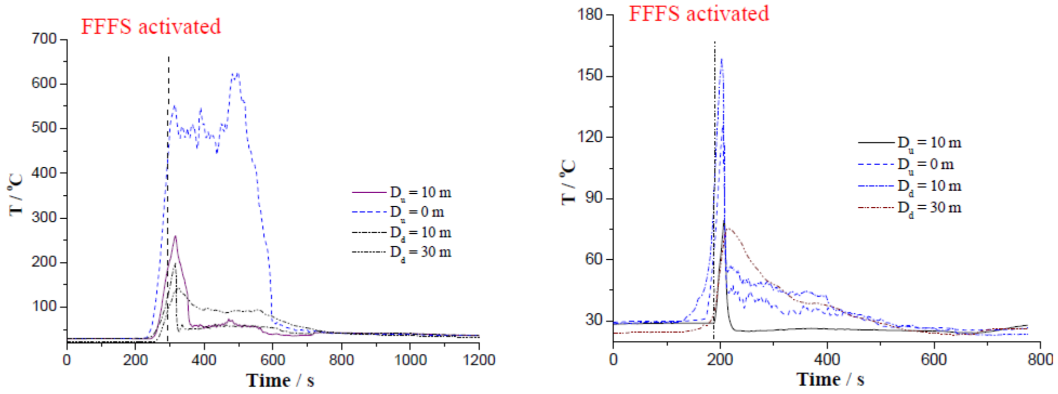
(a) Diesel fuel pan

(b) Wood pallet

(c) Wood pallets stack under a top shield

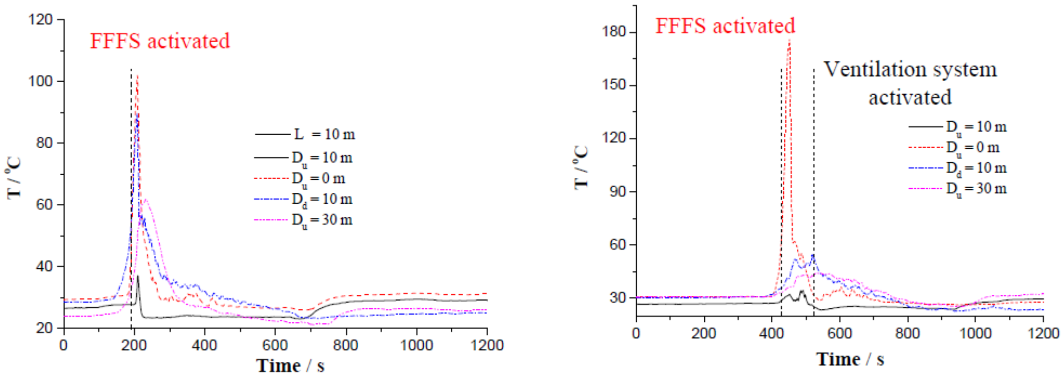
(d) Pool fire source with a side shield

Figure 3.3: Fire Sources in the Experiment



(a) W1

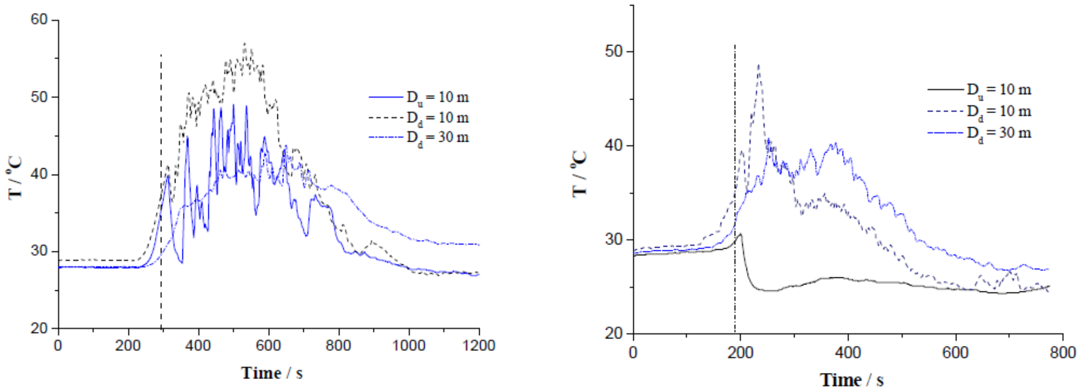
(b) W2



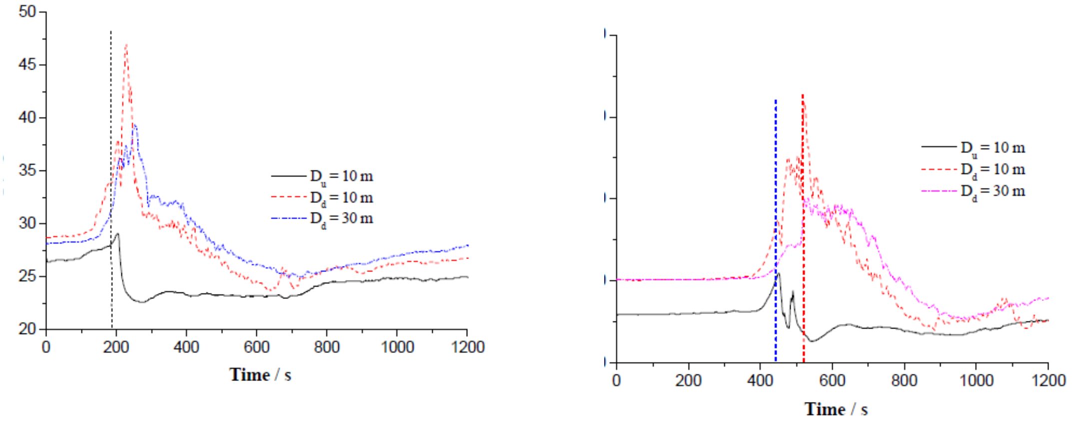
(c) W3

(d) W4

Figure 3.4: Transient Ceiling Temperature for Wood Pallet Fire Tests (Du=upstream, Dd=downstream).



(a) W1 (b) W2



(c) W3 (d) W4

Figure 3.5: Transient Temperature at 2.5m above the Tunnel Road Surface for Wood Pallet Fire Tests

(D_u=upstream, D_d=downstream)

(a) FFFS activated

(b) 60 s after activating FFFS

(c) 120 s after activating FFFS

(d) 180 s after activating FFFS

(e) 240 s after activating FFFS

(f) 300 s after activating FFFS

Figure 3.6: Fire suppression Events in Scenario W1

(a) Flame blown to the downwind side

(b) FFFS activated

(c) 60 s after activating FFFS

(d) 120 s after activating FFFS

(e) 180 s after activating FFFS

(f) 240 s after activating FFFS

(g) 300 s after activating FFFS

Fig. 3.7: Fire suppression Events in Scenario W2

(a) Wood pallet burning with the top shield

(b) FFFS activated

(c) 60 s after activating FFFS

(d) 120 s after activating FFFS

(e) 180 s after activating FFFS

(f) 240 s after activating FFFS

Figure 3.8: Fire Suppression Events in Scenario W3

(a) FFFS activated

(b) 60 s after activating FFFS

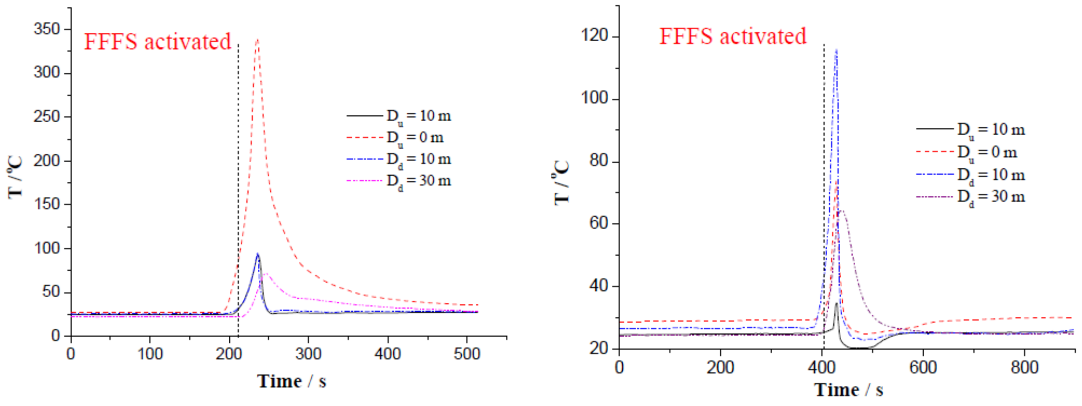
(c) Ventilation system activated at 90s

(d) 120 s after activating FFFS

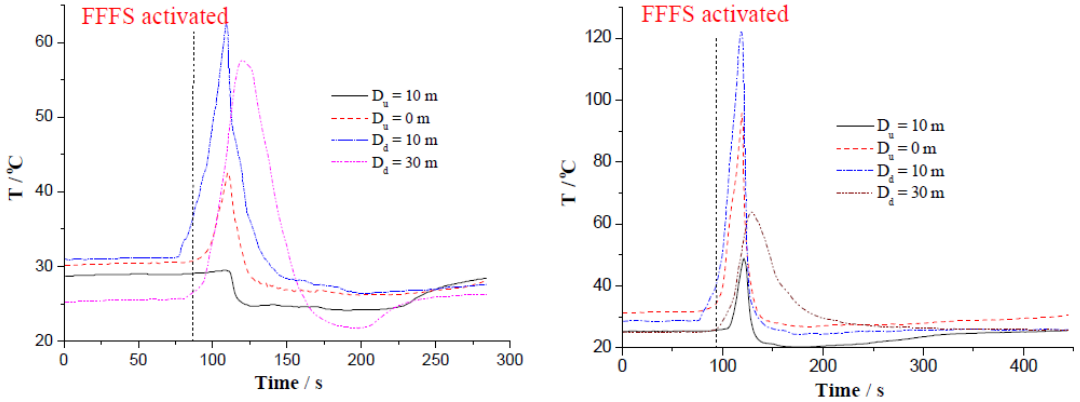
(e) 240 s after activating FFFS

(f) 300 s after activating FFFS

Figure 3.9: Fire Suppression Events in Scenario W4

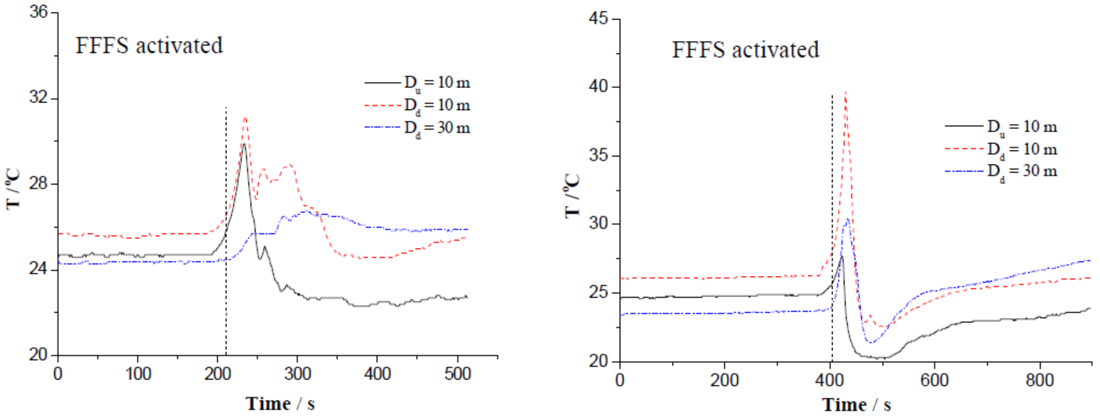


(a) D1 (b) D2

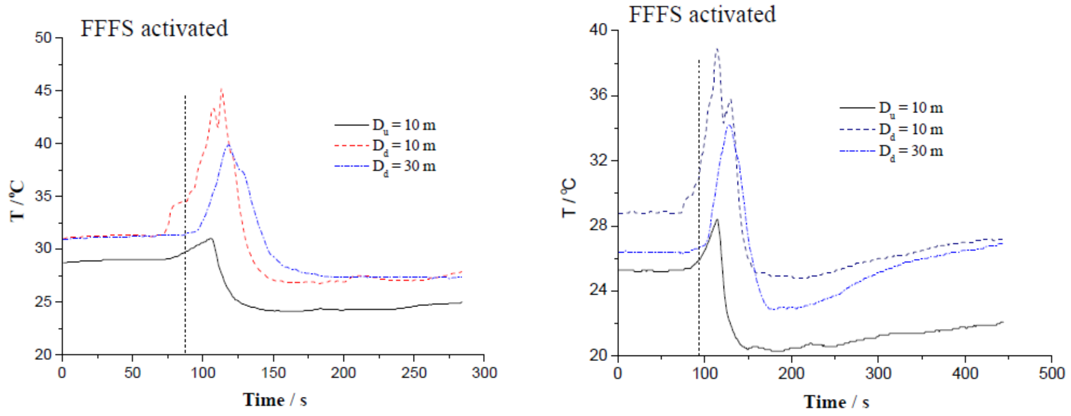


(c) D3 (d) D4

Figure 3.10: Transient Ceiling Temperature for Diesel Pool Fire Tests (D_u=upstream, D_d=downstream).



(a) D1 (b) D2



(c) D3 (d) D4

Figure 3.11: Transient Temperature at 2.5m above the Floor for Diesel Pool Fire Tests (D_u=upstream, D_d=downstream).

(a) Smoke layer formed

(b) FFFS activated

(c) 8 s after activating FFFS

(d) Fire extinguished at 10 s after activating FFFS

Figure 3.12: Fire Suppression Process in Scenario D1

(a) Smoke backlayering prevented

(b) Flame blown downward

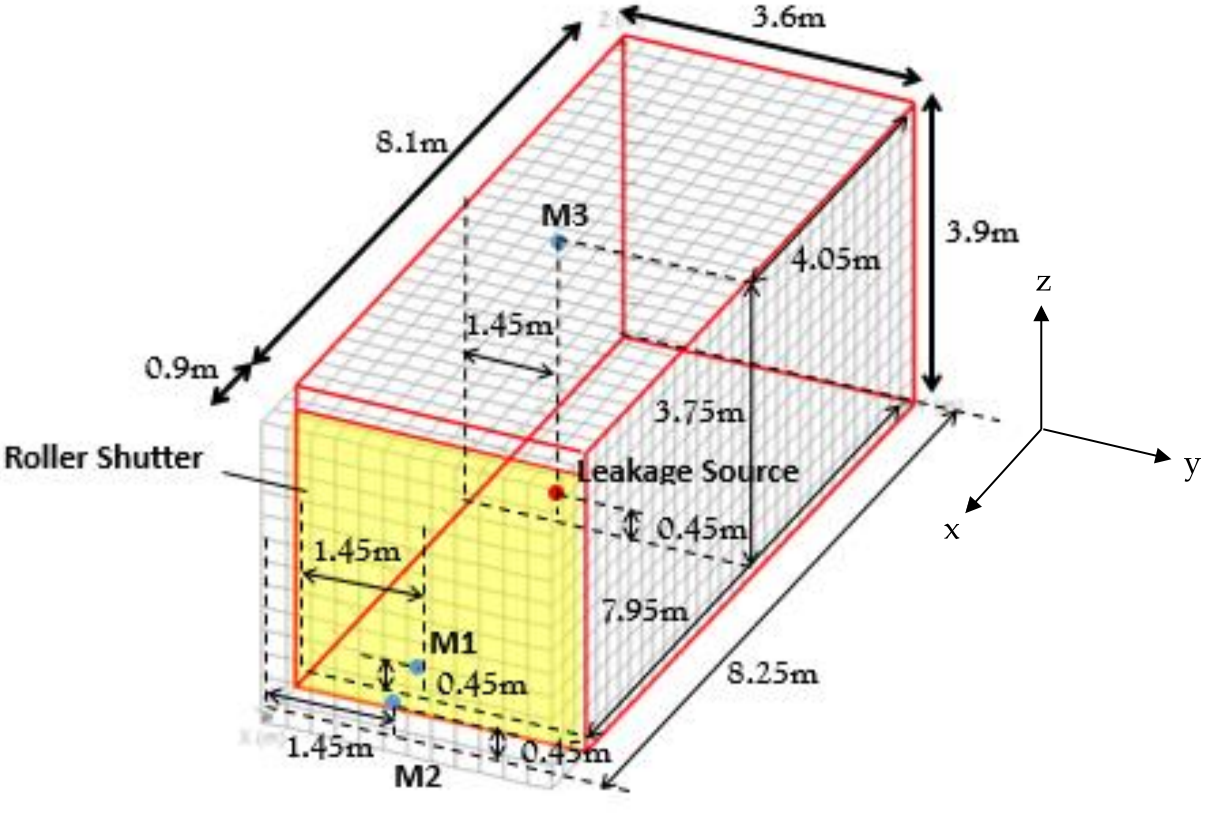
(c) FFFS activated

(d) Fire extinguished at 10 s after activating FFFS

Figure 3.13: Fire Suppression Process in Scenario D2

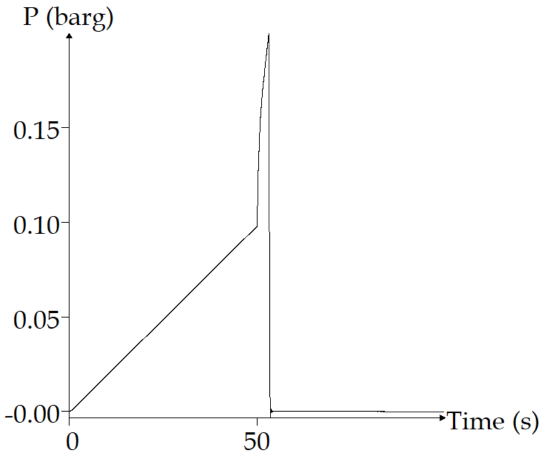
Figure 4.1: Garage Explosion in Wong Tai Sin, Hong Kong

(a) Outlook

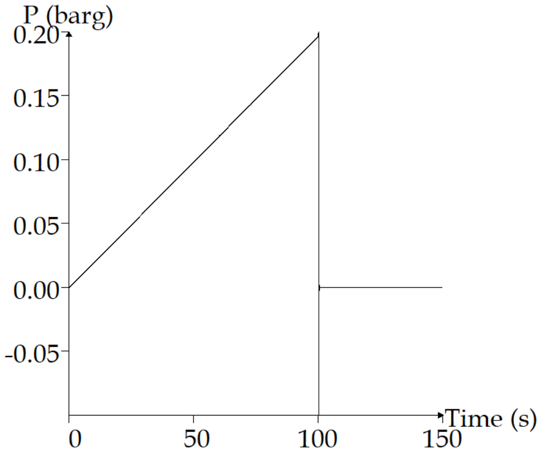


(b) Monitor Points in 3D views

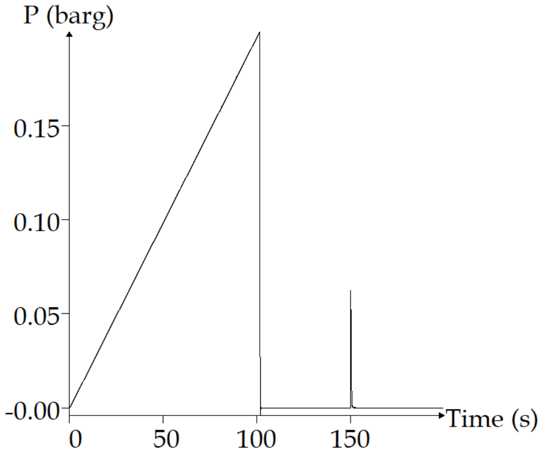
Figure 4.2: The Garage for Simulation in the Present Study



(a) Simulation C1

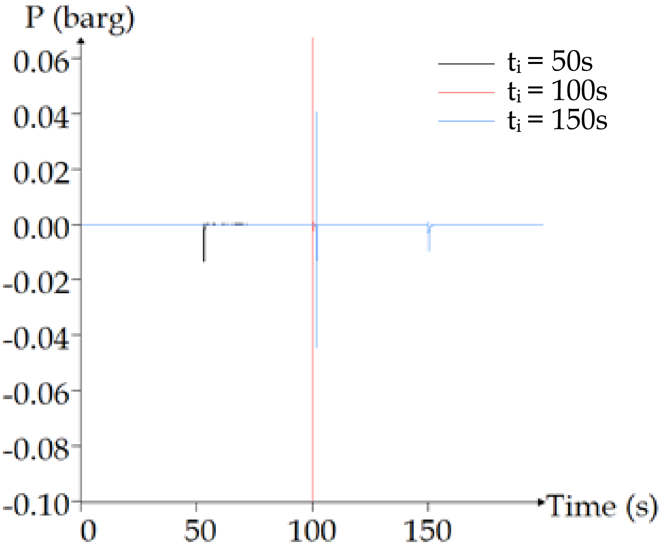


(b) Simulation C2

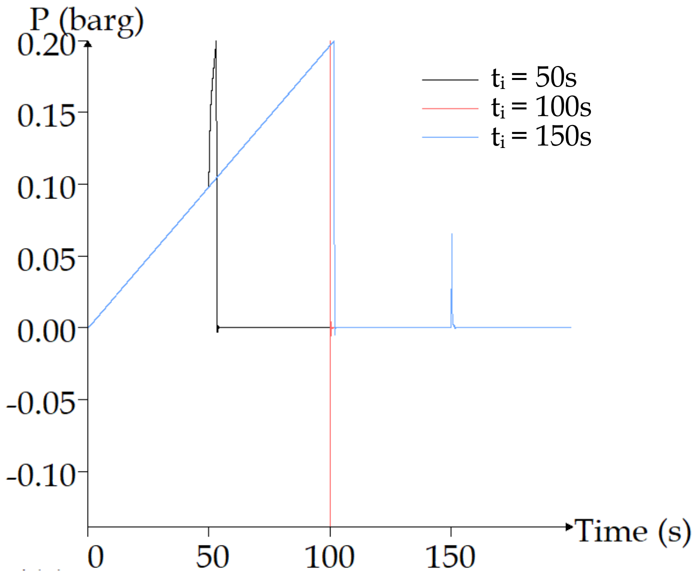


(c) Simulation C3

Figure 4.3: Pressure Variations at Monitor Point M1

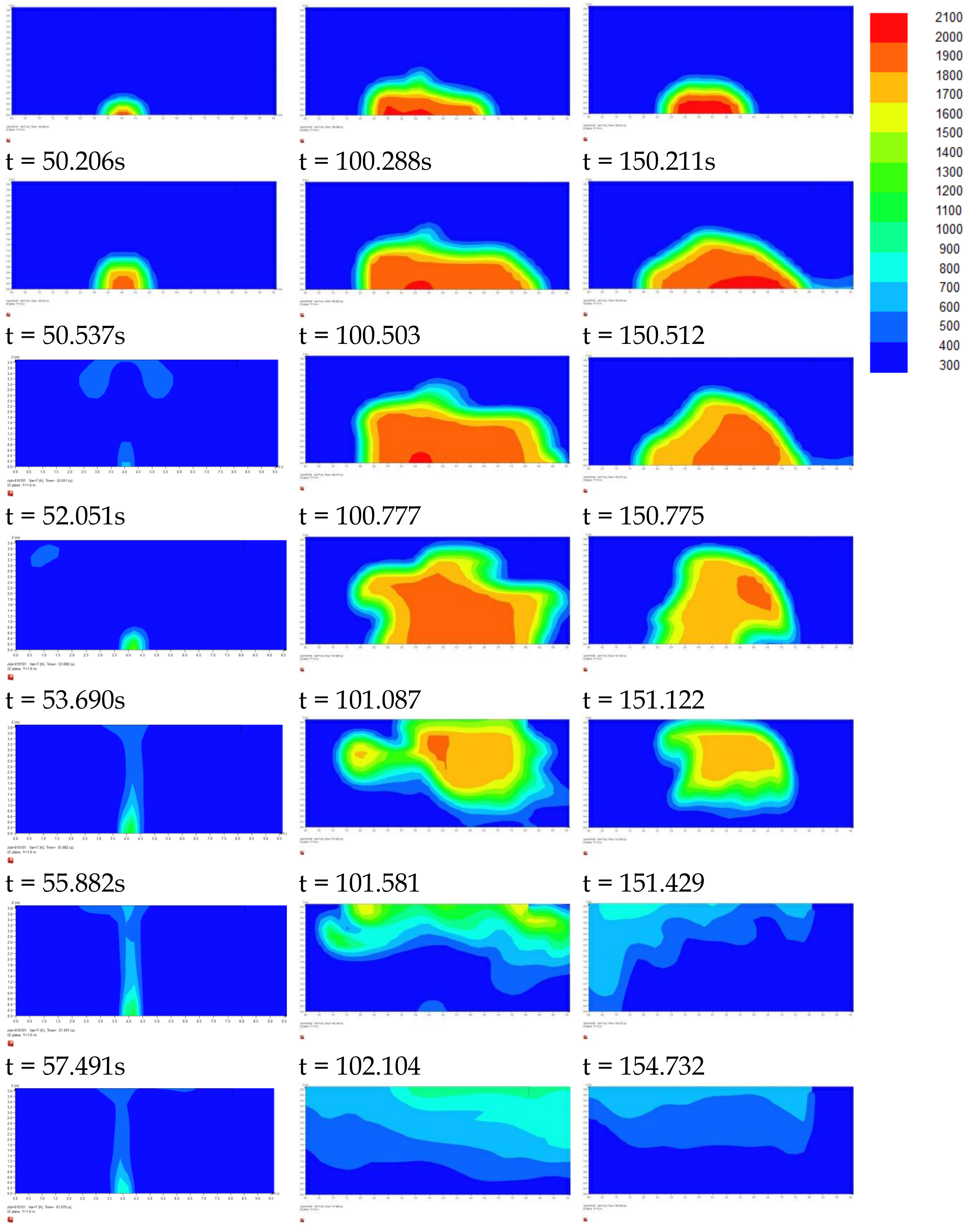


(a) At Monitor Point M2



(b) At Monitor Point M3

Figure 4.4: Pressure Variations



t = 50.206s t = 100.288s t = 150.211s

t = 50.537s t = 100.503 t = 150.512

t = 52.051s t = 100.777 t = 150.775

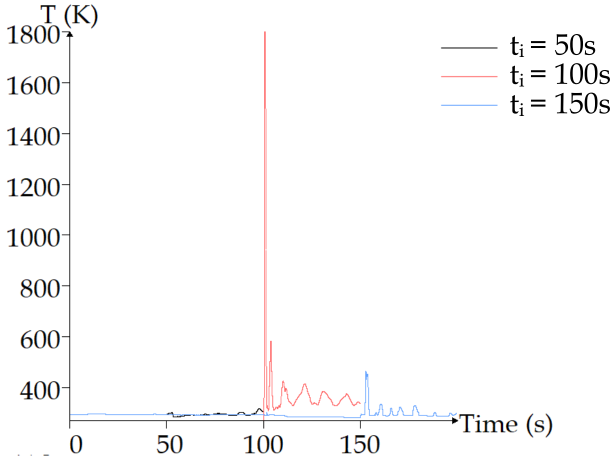
t = 53.690s t = 101.087 t = 151.122

t = 55.882s t = 101.581 t = 151.429

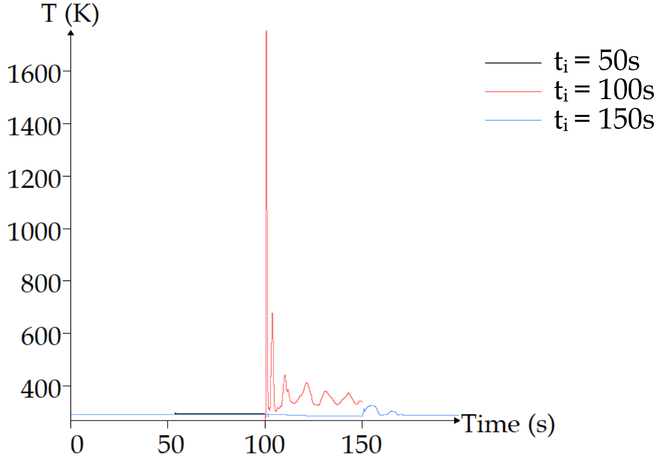
t = 57.491s t = 102.104 t = 154.732

t = 61.079s t = 111.980 t = 160.978

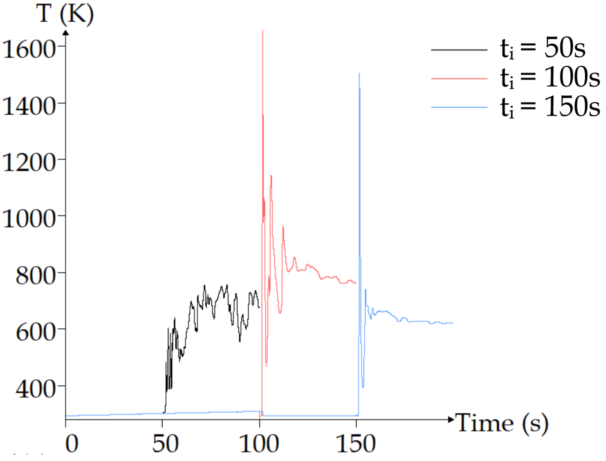
Figure 4.5: Transient Temperature Distributions



(a) At Monitor Point M1

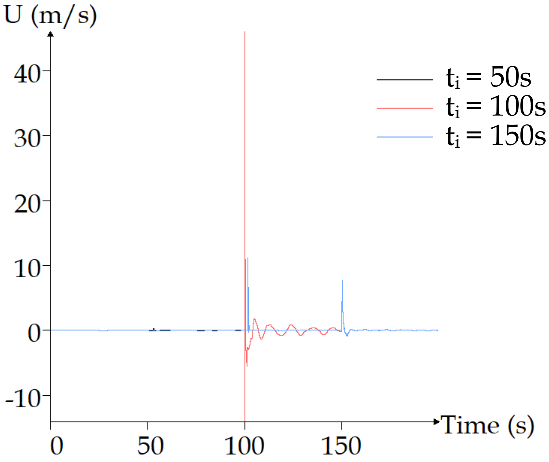


(b) At Monitor Point M2

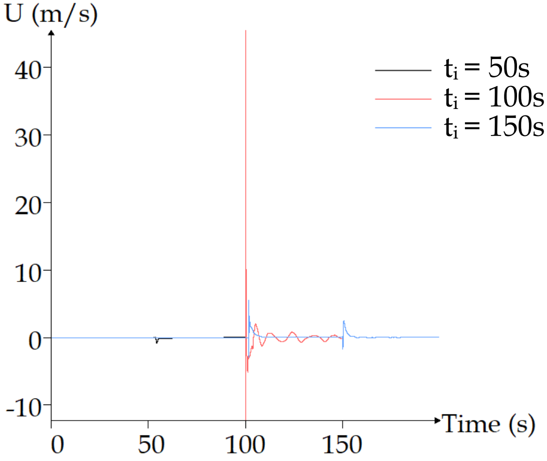


(c) At Monitor Point M3

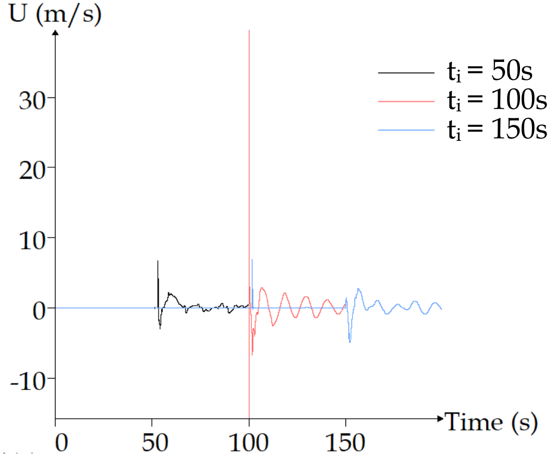
Figure 4.6: Temperature Profiles



(a) At Monitor Point M1

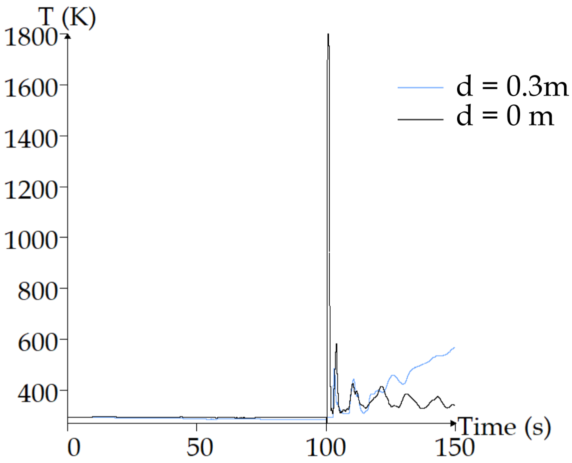


(b) At Monitor Point M2

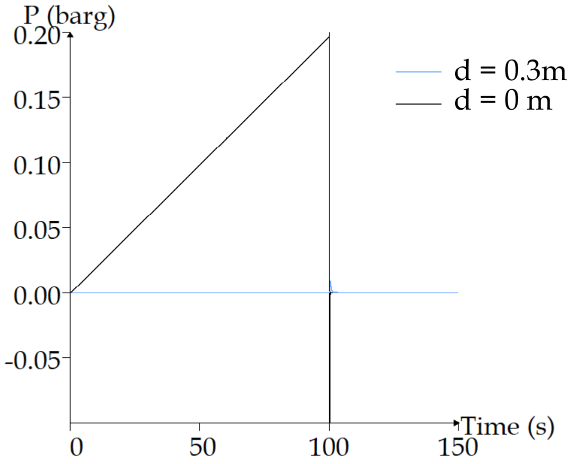


(c) At Monitor Point M3

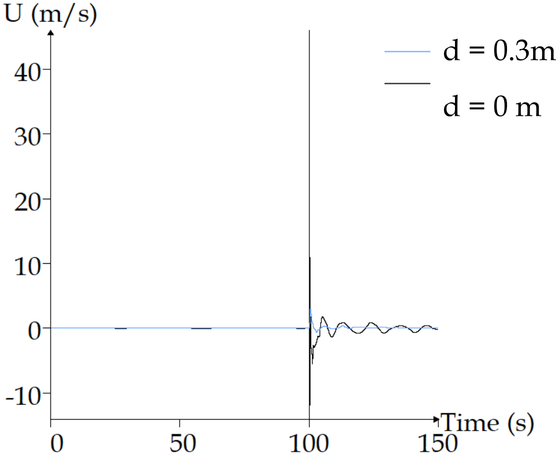
Figure 4.7: Transient Horizontal Velocity



(a) Temperature



(b) Pressure



(c) Horizontal velocity

Figure 4.8: At Monitor Point M1

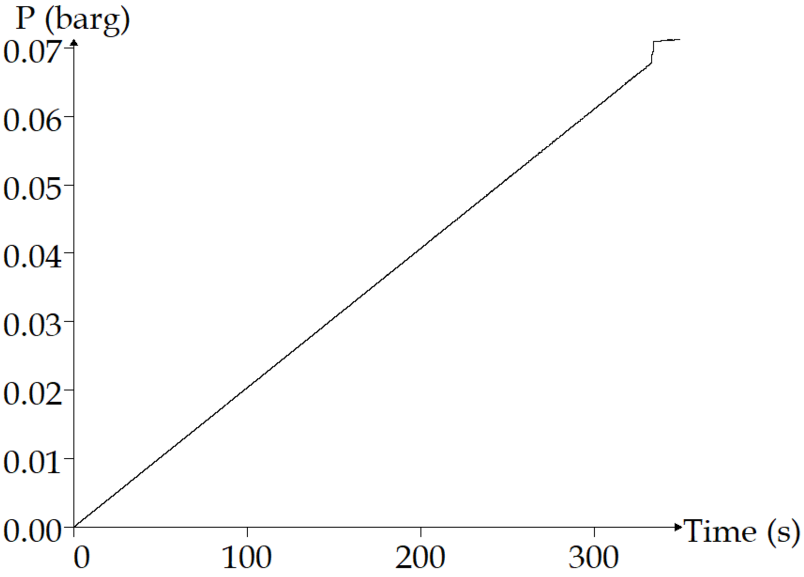


Figure 4.9: Simulation H1

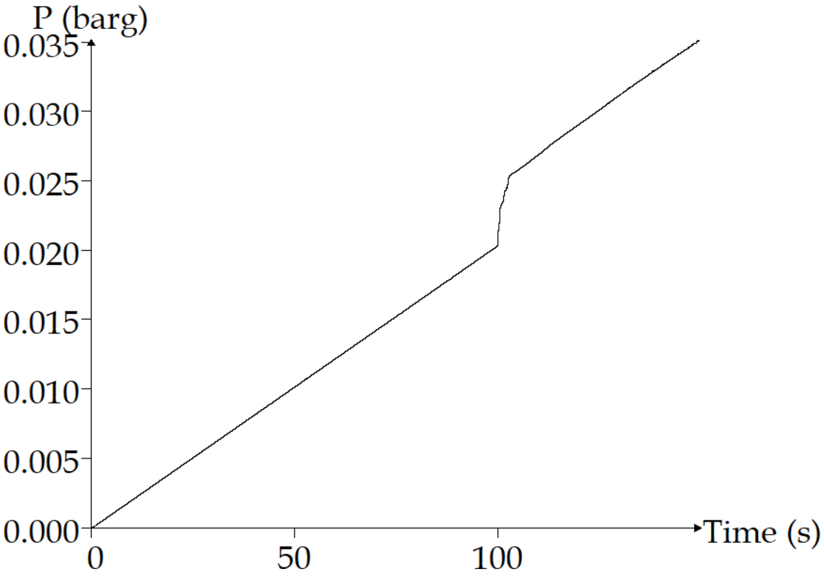
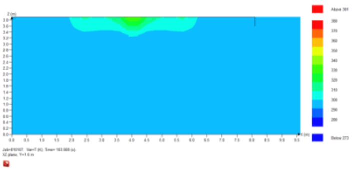
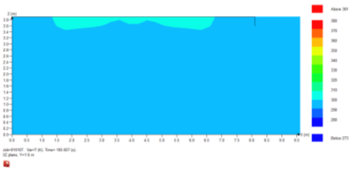


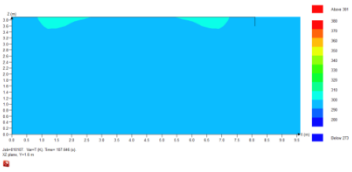
Figure 4.10: Simulation H2



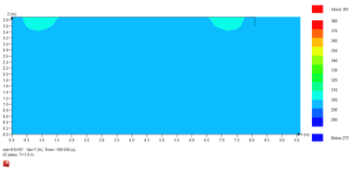
t=103.669 s



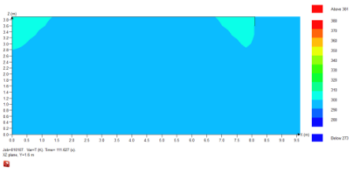
t=105.657 s



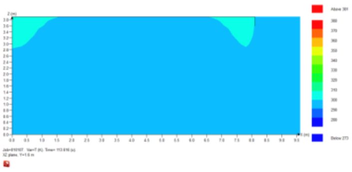
t=107.646 s



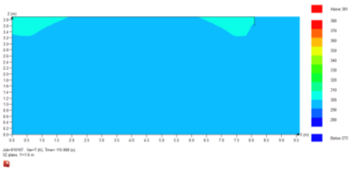
t=109.639 s



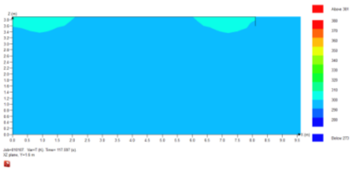
t=111.627 s



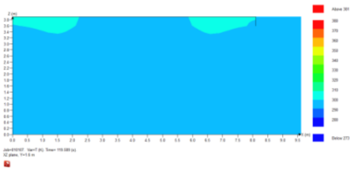
t=113.616 s



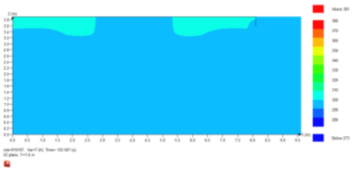
t=115.608 s



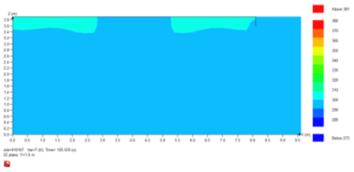
t=117.597 s



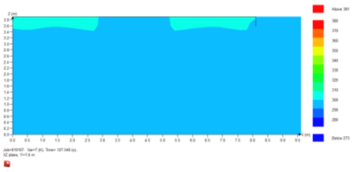
t=119.589 s



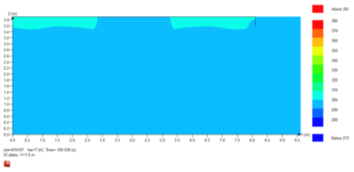
t=121.578 s



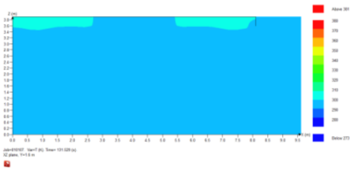
t=123.567 s



t=125.559 s



t=127.548 s



t=129.536 s

Figure 4.11: Transient Temperature Distributions of Simulation H2

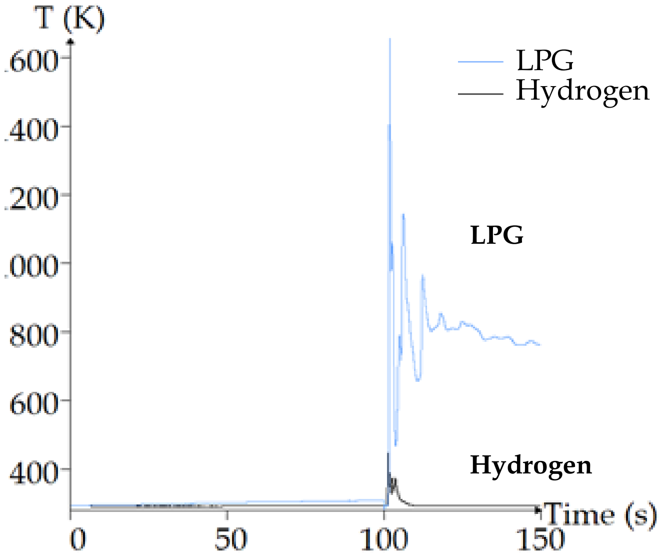
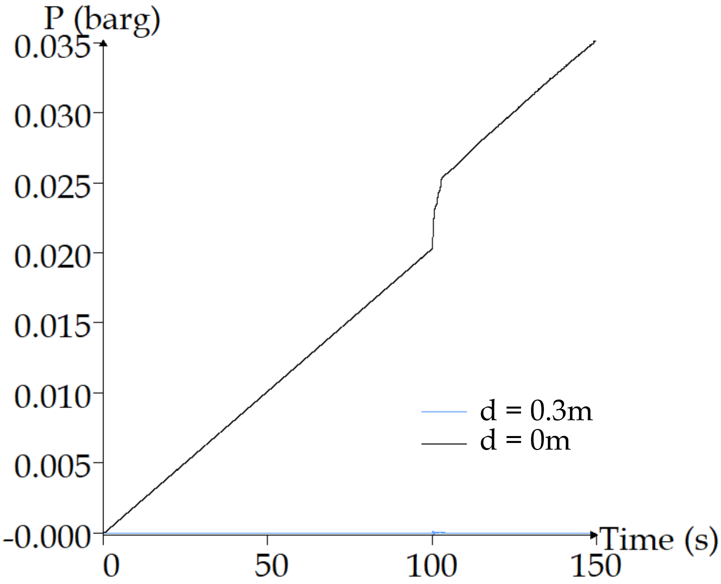
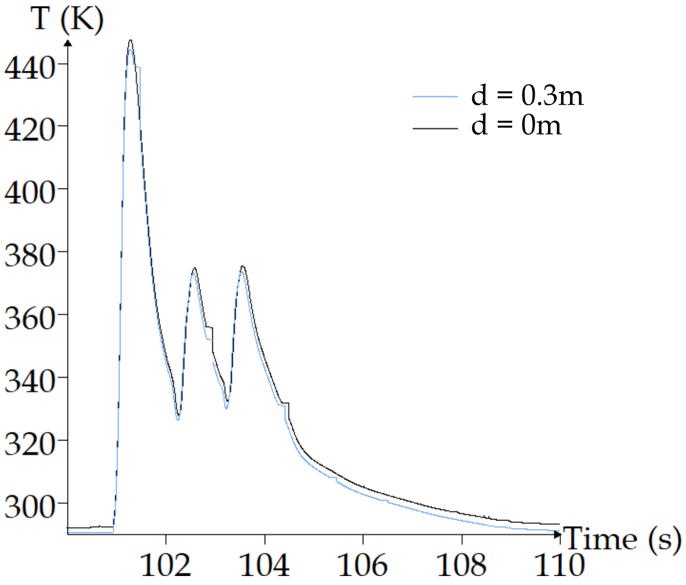


Figure 4.12: Comparing LPG and Hydrogen at Monitor Point M3



(a) Pressure variations

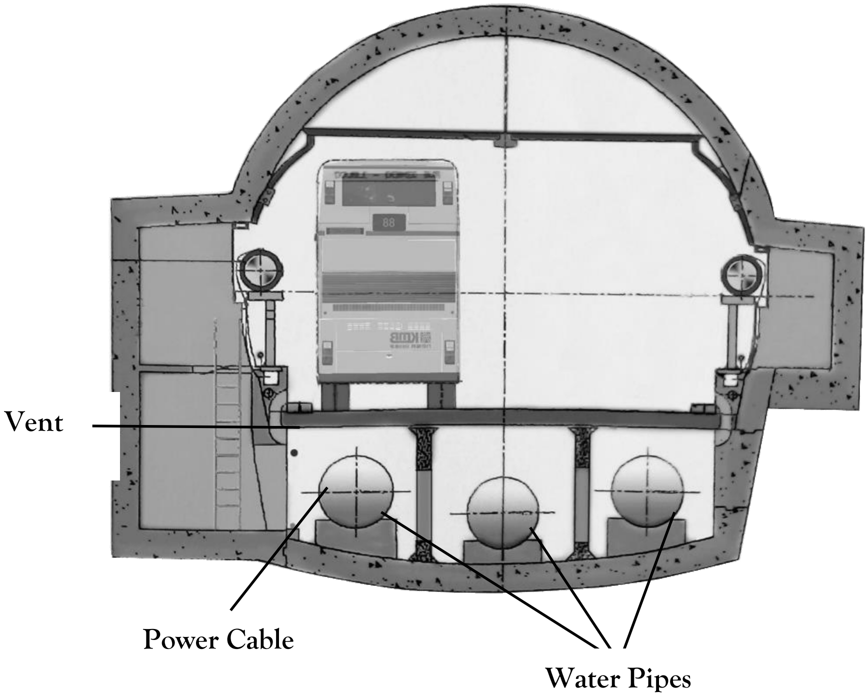


(b) Temperature variations

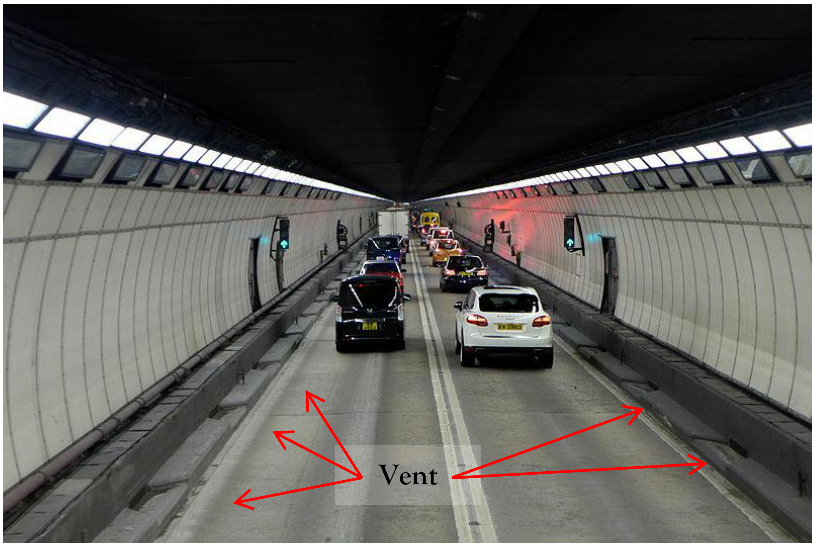
Figure 4.13: Results at Monitor Point M3 of Simulations H2-1 and H2-2

Figure 5.1(a): Connaught Road Central Underpass with AADT of 131,220

Figure 5.1(b): Fire involving a Double-deck Bus close to a Footbridge



(a) Cross-section



(b) Photo of the tunnel

Figure 5.2: Sample SVT in the Simulation Study

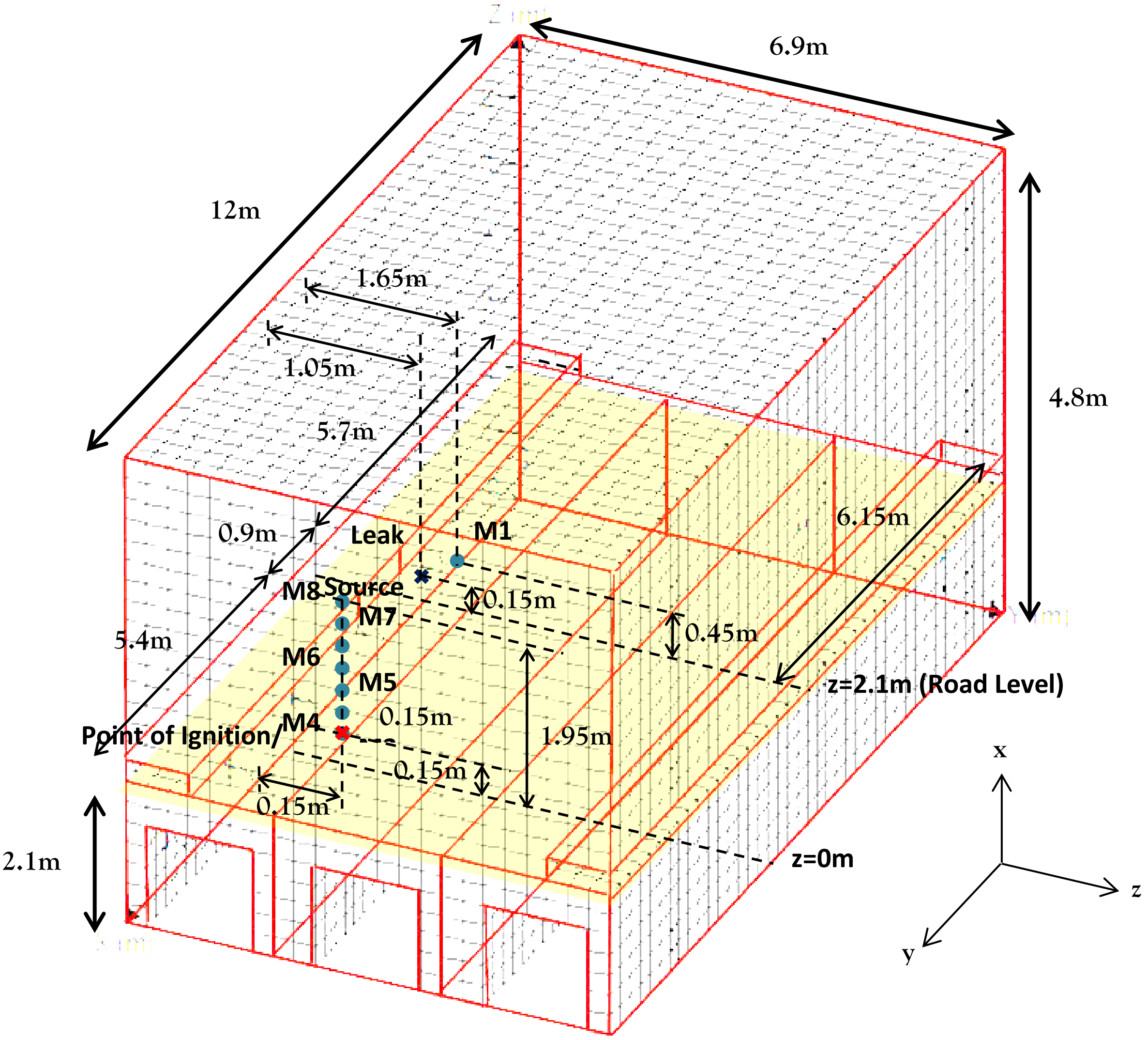
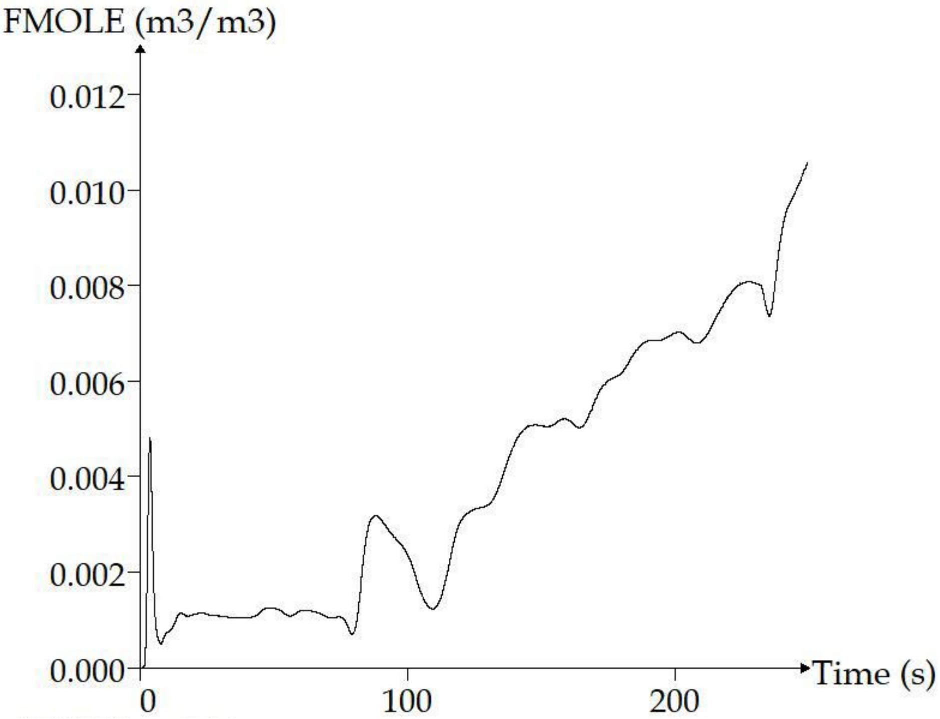
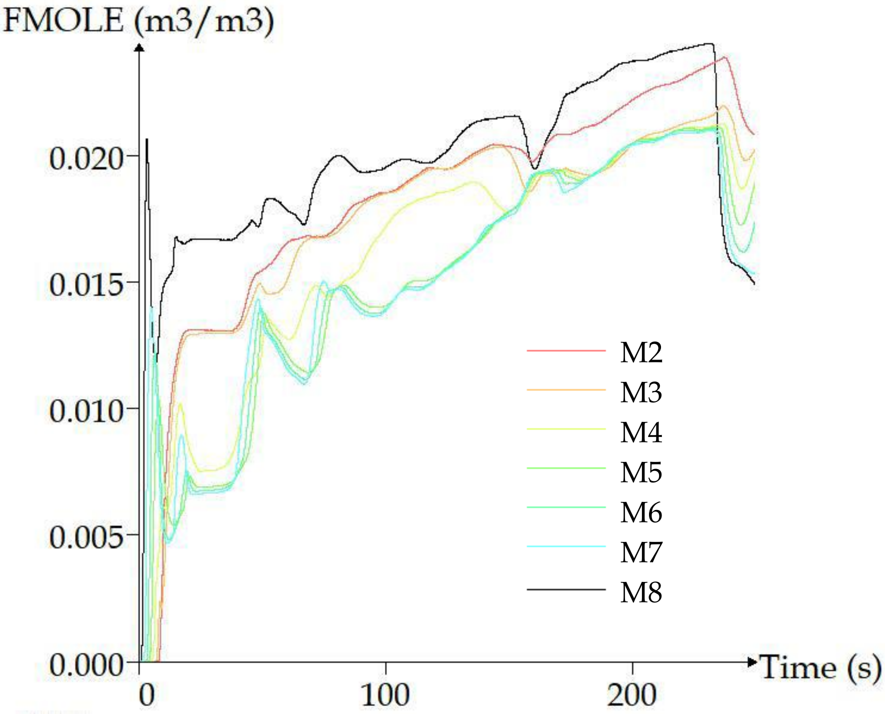


Figure 5.3: Grid system of FLACS and Monitor Points in 3D view

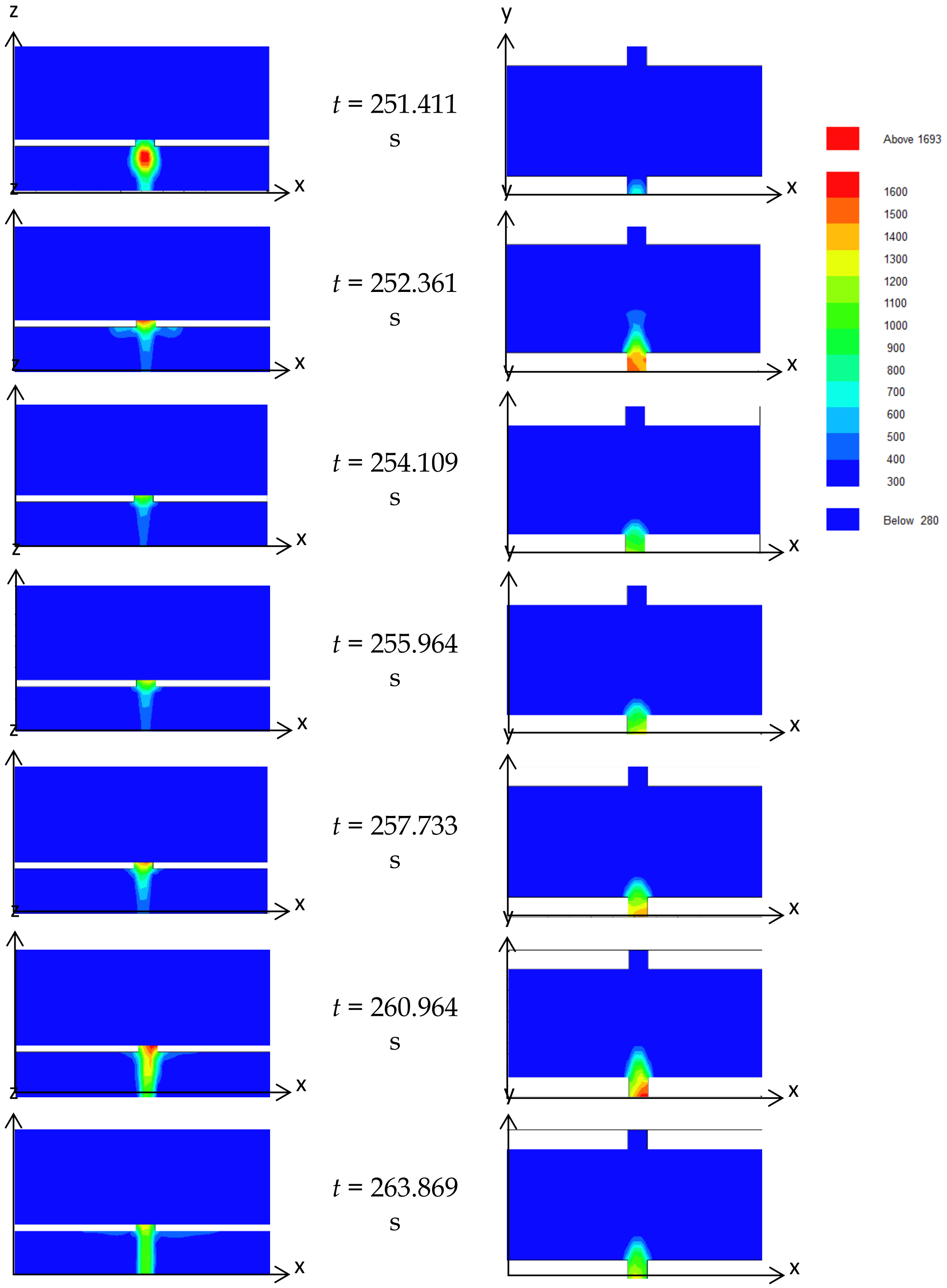


(a) At monitor point M1



(b) At monitor points M2 to M8

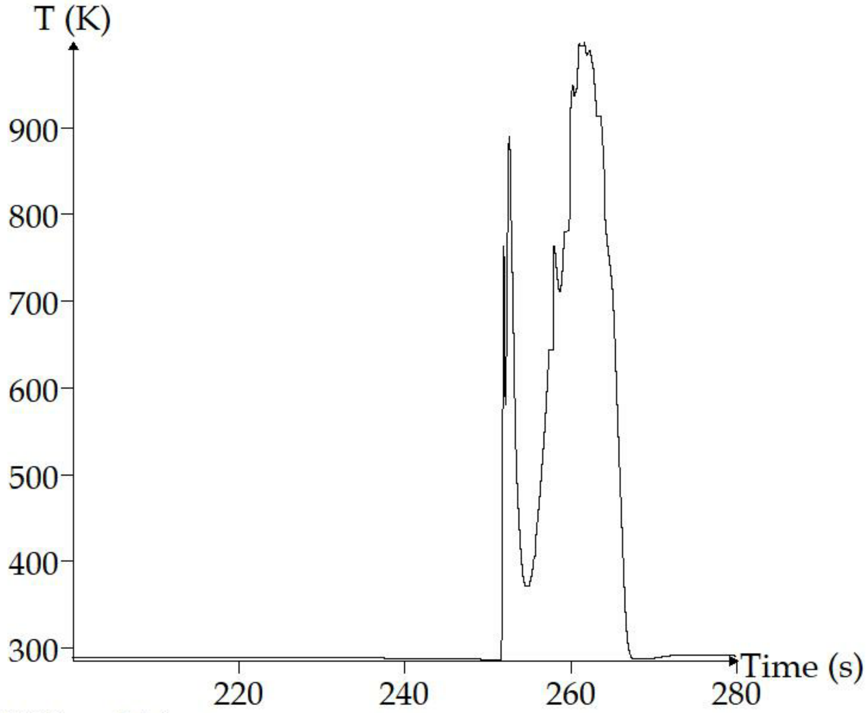
Figure 5.4: Transient LPG Concentration



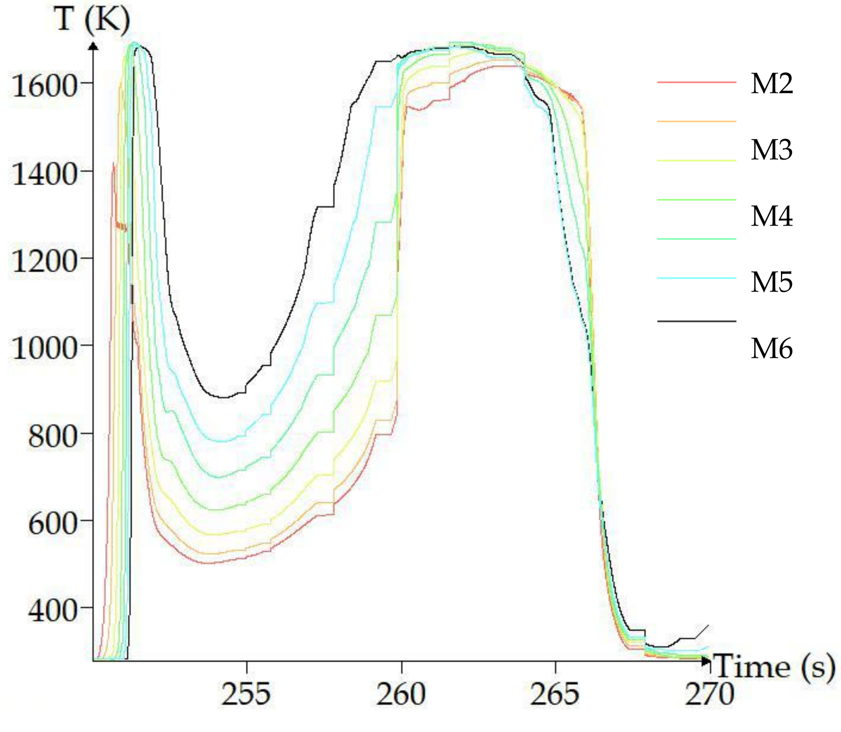
(a) x-z plane at y = 0.2 m

(b) x-y plane at z = 2.3 m

Figure 5.5: Transient Temperature Distributions



(a) Transient Temperature Profile at Monitor Point M1



(b) At Monitor Points M2 to M8

Figure 5.6: Transient Temperature Profiles at Monitor Points

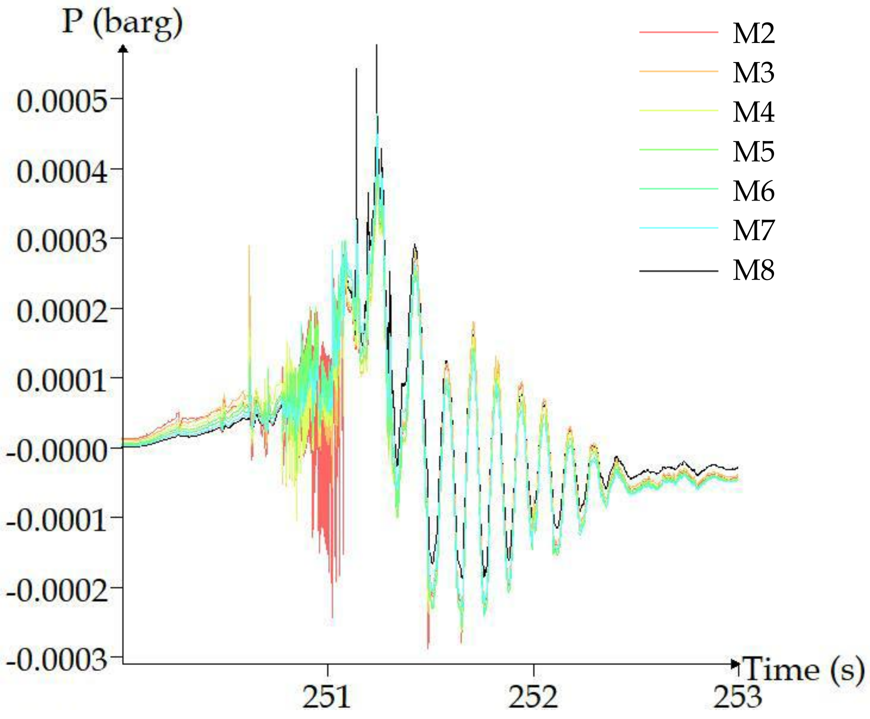
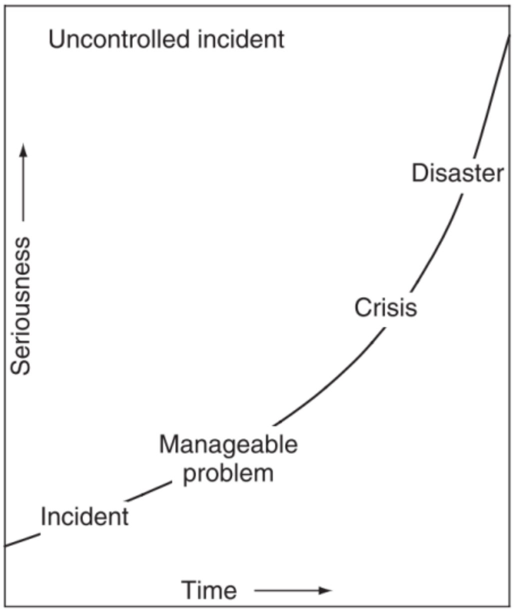
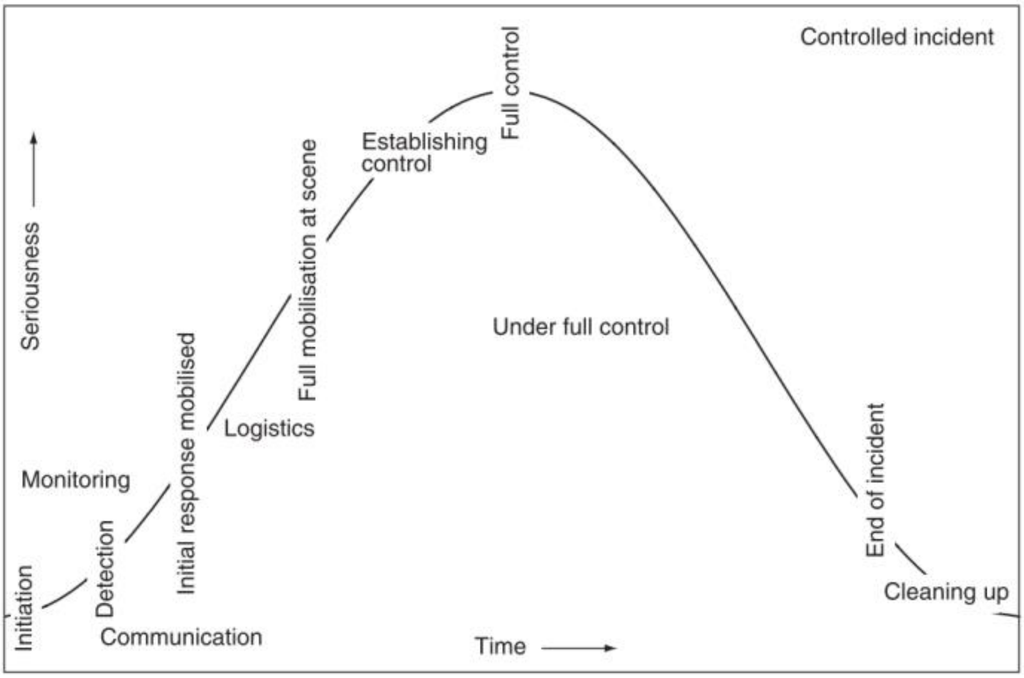


Figure 5.7: Pressure Profile in the Concealed Space



(a) Development of an Uncontrolled Event



(b) Development of a Controlled Event

Figure 6.1: Importance of Fire Safety Management

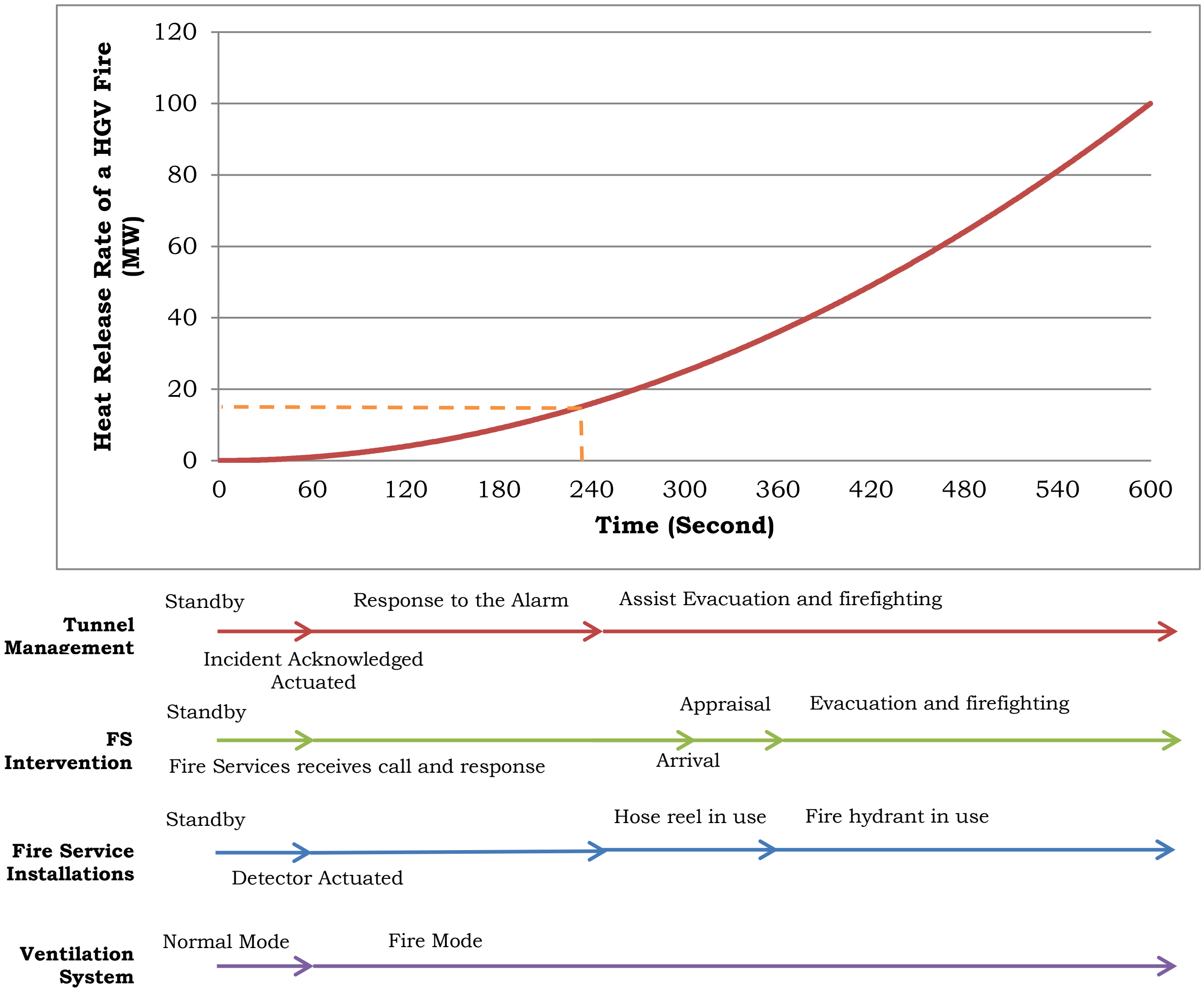


Figure 6.2: Timeline Analysis

Figure 6.3: Systematic Risk Management

TABLES

Date	Location		Name of Tunnel	Length	Fatalities	Economic Loss (Euro)
10.4.1995	Austria	Bregenz	Pfander Tunnel	7 km	3	N/A
13.1.1997	Italy	Susa	Prapontin Tunnel	4.9 km	0	N/A
24.3.1999	France	Chamonix	Mont Blanc Tunnel	11.6 km	39	>200M
29.5.1999	Austria	Salzburg	Tauern Tunnel	6.4 km	12	>7M
30.8.1999	Germany	Munich	Candid Tunnel	252 m	0	>40,000
14.7.2000	Norway	Odda	Selijestad Tunnel	1.2 km	0	>250,000

Table 1: Tragic Fire Incidents in Road Tunnels (Colombo, 2001)

No.	**Fire Load**	**Calorific Energy**
1	32 Wood pallets and 6 PE Pallets	240 GJ
2	20 Wood pallets and 20 PUR Mattresses	129 GJ
3	Upholstered Sofa	152 GJ
4	4 Wood Pallets and 40 Cartons with 1800 PS Cup	67 GJ

Table 2: Test Designs in the Runehamar Tunnel Fire Tests (UPTUN, 2008d)

<table>
<tr><th colspan="2"></th><th>2004</th><th>2008</th><th>2011</th><th>2014</th><th>2017</th></tr>
<tr><td rowspan="4">Passenger Car</td><td>Experimental Peak HRR (MW)</td><td>5</td><td colspan="4">5 – 10</td></tr>
<tr><td>Time to Experimental Peak HRR (min)</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td>0 – 30</td><td colspan="2">0 – 54</td></tr>
<tr><td>Representative Peak HRR (MW)</td><td rowspan="2">N/A</td><td colspan="2">5</td></tr>
<tr><td>Time to Peak Representative HRR (min)</td><td colspan="2">10</td></tr>
<tr><td rowspan="4">Multiple Passenger Cars</td><td>Experimental Peak HRR (MW)</td><td rowspan="4">N/A</td><td colspan="4">10 – 20</td></tr>
<tr><td>Time to Experimental Peak HRR (min)</td><td rowspan="3">N/A</td><td>13 – 55</td><td colspan="2">10 – 55</td></tr>
<tr><td>Representative Peak HRR (MW)</td><td rowspan="2">N/A</td><td colspan="2">15</td></tr>
<tr><td>Time to Peak Representative HRR (min)</td><td colspan="2">20</td></tr>
<tr><td rowspan="4">Bus</td><td>Experimental Peak HRR (MW)</td><td>20</td><td colspan="2">20 – 30</td><td colspan="2">25 – 34</td></tr>
<tr><td>Time to Experimental Peak HRR (min)</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td>7 – 10</td><td colspan="2">7 – 14</td></tr>
<tr><td>Representative Peak HRR (MW)</td><td rowspan="2">N/A</td><td colspan="2">30</td></tr>
<tr><td>Time to Peak Representative HRR (min)</td><td colspan="2">15</td></tr>
<tr><td rowspan="4">Heavy Goods Truck</td><td>Experimental Peak HRR (MW)</td><td>20 - 30</td><td colspan="2">70 – 200</td><td colspan="2">20 – 200</td></tr>
<tr><td>Time to Experimental Peak HRR (min)</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td>10 –18</td><td colspan="2">7 – 48</td></tr>
<tr><td>Representative Peak HRR (MW)</td><td rowspan="2">N/A</td><td colspan="2">150</td></tr>
<tr><td>Time to Peak Representative HRR (min)</td><td colspan="2">15</td></tr>
<tr><td rowspan="4">Tanker</td><td>Experimental Peak HRR (MW)</td><td>100</td><td colspan="2">200 – 300</td><td colspan="2">200 – 300</td></tr>
<tr><td>Time to Experimental Peak HRR (min)</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td>–</td><td colspan="2">–</td></tr>
<tr><td>Representative Peak HRR (MW)</td><td rowspan="2">N/A</td><td colspan="2">300</td></tr>
<tr><td>Time to Peak Representative HRR (min)</td><td colspan="2">–</td></tr>
</table>

Table 3: HRR of Vehicle Fires in Road Tunnels as proposed by NFPA 502

NFPA 502 2017	***Peak Experimental HRR in Road Tunnels with Fixed Water-based Firefighting System***	***Time to Peak HRR***
Passenger Car	-	-
Multiple Passenger Cars	*10 - 15*	*35*
Bus	*20*	-
Heavy Goods Truck	*15 - 90*	*10 - 30*
Tanker	*10 - 200*	-

Table 4: The experimental HRR of Vehicle Fires in Tunnels with Fixed Water-based Firefighting System as proposed by NFPA 502

Table 5: Minimum Coverage of Engineering Analysis Recommended by NFPA 502

2011 & 2014 Edition	2017 Edition
• Users of the facility • Restricted vehicle access and egress • Fire emergencies ranging from minor incidents to major catastrophes • Fire emergencies occurring at one or more locations inside or in close proximity to the facility • Fire emergencies occurring in remote locations at a long distance from emergency response facilities • Exposure of emergency systems and structures to elevated temperatures • Traffic congestion and control during emergencies • Built-in fire protection features, such as the following systems: (a) Fire alarm and detection (b) Standpipe (c) Water-based fire-fighting (d) Ventilation (e) Emergency communications • Facility components, including emergency systems • Evacuation and rescue requirements • Emergency response time • Emergency vehicle access points • Emergency communications to appropriate agencies • Vehicles and property being transported • Facility location, such as urban or rural (risk level and response capacity) • Physical dimensions, including roadway profile • Natural factors, including prevailing wind • Anticipated cargo • Impact to buildings or landmarks near the facility	• New facility or alteration of a facility • Transportation modes using the facility • Anticipated traffic mix and volume • Restricted vehicle access and egress • Fire emergencies ranging from minor incidents to major catastrophes • Potential fire emergencies including but not limited to the following: (a) At one or more locations inside or on the facility (b) In close proximity to the facility (c) At facilities a long distance from emergency response facilities • Exposure of emergency systems and structures to elevated temperatures • Traffic congestion and control requirements during emergencies • Fire protection features, including but not limited to the following system: (a) Fire alarm and detection (b) Standpipe (c) Water-based fire-fighting (d) Ventilation (e) Emergency communications (f) Protection of structural elements • Facility components, including emergency systems • Evacuation and rescue requirements • Emergency response time • Emergency vehicle access points • Emergency communications to appropriate agencies • Facility location such as urban or rural (risk level and response capacity) • Physical dimensions, number of traffic lanes, and roadway geometry • Natural factors, including prevailing wind and pressure conditions • Anticipated cargo • Impact to buildings or landmarks near the facility • Impacts to facility from external conditions and/or incidents • Traffic operating mode (unidirectional, bidirectional, switchable, or reversible)

Year Fire Safety Provision	1987	1990	1994	2005	2012
Automatic Fixed Installation other than Water	✓	✓	✓	✓	✓
Closed Circuit Television System	✓	✓	✓	✓	✓
Dynamic Smoke Extraction System	Required for tunnels over 230 m				
Emergency Generator	✓	✓	✓	✓	✓
Emergency Lighting		✓	✓	✓	✓
Emergency Power Points				✓	✓
Exit Sign				✓	✓
Fire Alarm System	✓	✓	✓	✓	✓
Fire Control Centre	✓	✓	✓	✓	✓
Fire Hydrant / Hose Reel	✓	✓	✓	✓	✓
Fire's Communication System	✓	✓	✓	✓	✓
Fixed Foam System				✓	✓
Gas Detection System	✓	✓	✓	✓	✓
Pedestrian Crossover Facilities	For twin tube tunnels where practicable			Shall be provided at 100 m intervals	
Portable Hand-operated Approved Appliance	✓	✓	✓	✓	✓
Traffic Control Sign	✓	✓	✓		

Table 6: Evolution of Fire Safety Provisions for Road Tunnels

	Government Department	**Area of Concerns**
1.	Fire Services Department (FSD)	Fire service installations and fire safety provisions
2.	Electrical and Mechanical Services Department (EMSD)	Tunnel electrical system and equipment
3.	Architectural Services Department (ASD)	Building structures design
4.	Highways Department (HyD)	Designs on tunnel building and immersed tubes structure works
5.	Civil Engineering Department (CED)	

Table 7: Area of Concerns of Different Government Departments

Experimental site	**Fire source**	**Type of water-based fire-fighting systems**	**Fire suppression effects**
Japanese road tunnel (Setoyama et al., 2004)	Gasoline pool fires	Water spray system	• Air temperature in tunnel decreased quickly to ambient temperature
Benelux Tunnel, Netherland (Ministry of Transport, 2002)	Wood cribs	Sprinkler system	• Sprinkler system could not extinguish the fire occurring inside vehicles. • Air temperature upstream and downstream of the fire decreased from approximately 250-350°C to 20-30°C in a very short period of time. • The smoke layer was disturbed upon the activation of sprinklers, and visibility was almost entirely obstructed. • No significant steam formation and no deflagration were observed in the test program.
Memorial Tunnel, USA (Arvidson, 2003)	Diesel pool fires	Foam-water sprinkler systems, water density with foam additives (3% AFFF) ranging from 2.4 L/min.m^2 to 3.8 L/min.m^2	• Fires were extinguished in less than 30 s. • The effectiveness of the deluge foam-water sprinkler system was not affected by a longitudinal ventilation velocity of 4.2 m/s.
UPTUN Project, Europe (Opstad and Brandt, 2005)	Diesel pool fires, sheltered diesel pool fires, partly sheltered and fully developed wood pallet fires	Low and high-pressure water mist system	• Effectiveness of the water mist system in controlling a fire was strongly dependent on the fire size, nozzle type, location and water discharge rate. • Heat release rates were reduced by up to 50 % upon activation of the systems

Table 8: Fire Test Results of Water-based Fire-fighting Systems

No.	Name	Brand	Model	Technical parameter	Quantity
1	Calorimeter（Portable）	Tianyue	MR-3A	Measurement range：0-10kW/m^2 Accuracy：±5%RH	2
2	Type-K Thermocouple	Nanpu	WRNK-221 3*10m	Measurement range：0 --1100℃ Accuracy：±2.5℃ Max. temperature：1300℃	12
			WRNK-221 3*3m		120
			WRNK-221 3*15m		25
			WRNK-121 3*3m		40
			WRNK-121 3*5m		10
			WRNK-121 3*15m		12
3	Air Flow Sensors / Transmitters	Jiekong	JK－V203	Measurement range：0 –20m/s Accuracy：±4％FS Output：4－20mA	12
4	Dual Channel Ultra-low Drift DC Preamplifier	HB	HB－812A	Working frequency：DC－3KHz Gain：10－10K Low pass filtering cut-off frequency：1Hz Input resistance：5MΩ Common-mode rejection ratio：>80db	4
5	Differential Pressure Transducer	ALPHA	168P0025BA2YB	Range：±25Pa Output： 4－20mA Accuracy：±0.25％FS	4
			168P0050BA7YB	Range：±50Pa Output：4－20mA Accuracy：±0.25％FS	4
6	Ultra-thin Radiation Heat Flux Metre	Captec	HS－30	Dimension： 30×30mm, Thickness：0.4 mm, Working Temperature： -180°C～ 200°C, Thermal resistance： 0.006°C/W/m^2, Input range： ±200 kW/m^2（Max ±500 kW/m^2）, Sensitivity： 2.18 μV/（W/m^2）, Response time： 0.3s Impedance： about 100Ω/dm^2	4

No.	Name	Brand	Model	Technical parameter	Quantity
7	Radiation Heat Flux Metre	Captec	TS－30	Dimension： 30×30mm, Thickness： 0.4 mm, Working Temperature： -180°C -200°C, Thermal resistance： 0.006°C/W/m^2, Input range： ±200 kW/m^2 (Max. ±500 kW/m^2）， Sensitivity： 1.64 μV/（W/m^2）， Response time： 0.05s Impedance： about 100Ω/dm^2, Spectral response： 0.3μm～50μm	5
8	Gas Analyzer（Portable）	Encel	M900	Range：O_2：0～25.0%, CO：0～10000ppm Temperature：0～600℃	4
9	Electronic Balance	Suzhan	TCS－3000	Range：0－3000kg, Accuracy：1kg, Dimension：2.5m×5.5m, 4－20mA	1
			TCS－1000	Range：0－1000kg, Accuracy：0.2kg, Dimension：1.6m×1.6m, 4－20mA	1
10	Camera		Video Camera		2
			Infra-red Camera		1
			CCTV Monitor		1
Total					264

Table 9: Instrumentation in Full-Scale Burning Tests

Experimental scenarios	Fire source	Ventilation condition	Activation of the ventilation system	Suppression agent
W1	Wood pallet stack fire	No ventilation	-	Foam-water spray
W2	Wood pallet stack fire	3 m/s	Fan activated after fire ignition	Water spray
W3	Wood pallet stack fire with a top shield plate	3 m/s	Fan activated after fire ignition	Water spray
W4	Wood pallet stack fire with a top shield plate	3 m/s	Fan started 90 s later than the WFFFS	Water spray
D1	Diesel pool fire	No ventilation	-	Foam-water spray
D2	Diesel pool fire	3 m/s	Fan activated after fire ignition	Foam-water spray
D3	Diesel pool fire with a top shield plate	3 m/s	Fan activated after fire ignition	Foam-water spray
D4	Diesel pool fire with a side shield plate	3 m/s	Fan activated after fire ignition	Foam-water spray

Table 10: Testing Scenarios

	Time of Introduction	% of LPG Vehicles	Major Types of LPG Vehicles
Netherlands	1950s	8.6 (1995)	Passenger Cars
US	1912	0.3 (1994)	Light Duty and Medium Duty Trucks
Australia	1950s	6.0 (1996)	Taxis
Japan	1924 (1962 for taxis)	0.5 (1995)	Taxis
Canada	1970s	1.0 (1996)	Taxis
Austria	Not available	Not available	Buses
Greece	Not available	Not available	Taxis
Spain	Not available	Not available	Taxis and Buses
South Korea	Not available	Not available	Taxis, Buses and Trucks

Table 11: Number and Major Types of LPG Vehicles in Different Countries (Lau et al. 1997)

Release Scenario	Initial pressure (barg)	Initial temperature (^oC)	Mass flow rate (kgs^{-1})
Overfilling and subsequent opening of Pressure Relief Valve (PRV)	27	27	0.59
PRV opens spuriously	9	27	0.21
Leakage from a hole in the fuel tank	9	27	0.21
Vehicle fire and subsequent opening of PRV	27	74	0.55

Table 12: Vapour Mass Flow Rate

Monitor point	x/m	y/m	z/m	Remarks
M1	7.95	1.45	0.45	Near the roller shutter in the garage
M2	8.25	1.45	0.45	Near the roller shutter out of garage
M3	4.05	1.45	3.75	Near the ceiling above the point of ignition

Table 13: Monitor Points

Monitor Point	x / m	y / m	z / m
M1	6.15	1.65	2.55
M2	6.15	0.15	0.15
M3	6.15	0.15	0.45
M4	6.15	0.15	0.75
M5	6.15	0.15	1.05
M6	6.15	0.15	1.35
M7	6.15	0.15	1.65
M8	6.15	0.15	1.95

Table 14: Monitor Points

Monitor Point	M2	M3	M4	M5	M6	M7	M8
Height z / m	0.15	0.45	0.75	1.05	1.35	1.65	1.95
Concentration / %	2.082	2.031	2.003	1.913	1.765	1.541	1.486

Table 15: Concentrations of LPG at Monitor Points

Time	Time Elapsed (Min)	Event of Incident
1324	0	A fire call received
1325	1	Heavy smoke is detected via CCTV at Alcove 10 in the Kowloon bound tube by management staff in the tunnel control room. The fire emergency procedures activated immediately:- ● informing the FSD via direct telephone line; ● dispatching first rescue team to the incident scene; ● stopping the entrance of vehicles to both tunnel tubes; ● switching the ventilation system to fire mode; and ● opening the west emergency gate to facilitate the access of fire engines.
1328	4	The tunnel rescue team arrived at the incident scene and attempted to control the fire and to evacuate people. FSD arrived at the tunnel portal.
1330	6	The fire engines arrived at the fire scene to tackle the fire.
1337	13	Summoning for additional manpower to assist in evacuation process, the fire was upgraded to No. 3 Alarm.
1344	20	The fire was under control.

Table 16: A Brief Event of Incident (Transport Department, 2000)

Table 17: Fire Safety Provision of the Lion Rock Tunnel

Fire Safety Provision	Details
Closed Circuit Television System	
Ventilation / Dynamic Smoke Extraction System	
Fire Hydrant / Hose Reel System	
Fire Control Centre	The fire control centre is located in 1/F of Administration Building at the northern portal of tunnel tube at Sha Tin Side. A minor control kiosk is provided near the southern portal of the tunnel tube at Kowloon side.
Fire Detection System	
Fire Communication Facilities	
Gas Detection System	
Emergency Telephone	
Drencher System	A drencher system with water supply from the water town main of WSD provided at about 100m intervals. To avoid unnecessary panic induced by accidental discharge, the drencher is operated by remote control inside the Tunnel Control Room

Table 18: Description of Frequency (Government of the HKSAR, 2006)

		Consequence				
		Insignificant	Minor	Moderate	Major	Catastrophic
Probability (Likelihood)	Rare	Low	Low	Low	Medium	Medium
	Unlikely	Low	Low	Medium	Medium	High
	Possible	Low	Medium	Medium	High	High
	Likely	Medium	Medium	High	High	Very High
	Frequents	Medium	High	High	Very High	Extreme

Table 19: Risk Matrix (The Government of HKSAR, 2006)

Descriptor	**Description of Frequency**
Rare	May occur only in exceptional circumstances - can be assumed not to occur during period of the project (or life of the facility)
Unlikely	Event is unlikely to occur, but it is possible during period of the project (or life of the facility)
Possible	Event could occur during period of the project (or life of the facility)
Likely	Event likely to occur once or more during period of the project (or life of the facility)
Frequents / Almost Certain	Event occurs many times during period of the project (or life of the facility)