

Findings of the International Road Tunnel Fire Detection Research Project

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1. INTRODUCTION

Fire detection systems are an essential element of fire protection for road tunnels. Fire detectors should provide early warning of a fire incident, identify its location and monitor fire development in tunnels. Their role can make the difference between a manageable fire and one that gets out-of-control. As such, fire detection systems play a crucial role in ensuring safe evacuation and firefighting operations [1-3].

Recent studies, however, indicated that information on the performance of current fire detection technologies and guidelines for their use in road tunnel protection are limited [4]. A few test programs that mainly focused on the performance of linear heat detection systems and optical flame detectors were conducted in Europe and Japan [5-9]. Many other types of fire detection technologies, such as spot heat detectors, smoke detection systems and newly developed visual flame and smoke detectors have not been studied systematically. In addition, there are no generally accepted test protocols and performance criteria for use in the evaluation of various fire detection technologies for tunnel protection. The test conditions and fire scenarios were changed from one test program to another. The performances of detectors in these programs were evaluated mostly with pool fires of a constant heat release rate of up to 3 MW. Other types of fire scenarios, such as stationary and moving vehicle fires, were not considered. Another concern on the use of current fire detection systems is that their reliability, including false alarm rates and maintenance requirements in smoky, dirty and humid tunnel environments, have not been systematically investigated.

The Fire Protection Research Foundation (FPRF) and the National Research Council (NRC) of Canada have conducted a two-year international research project, with support of government organizations, industries and private sector organizations, to investigate currently available fire-detection technologies suitable for tunnel applications. The main objective of the study was to look at some of the strengths and weaknesses of the various types of detection systems and what can affect their performance in tunnel environments [10]. The results of the study will provide information for use in the development of performance criteria, guidelines and specifications for tunnel fire-detection systems and will be used to update NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways. The results will also help optimize technical specifications and installation requirements of fire detection systems for tunnel applications. Although this research is being conducted on road tunnels, the findings should apply to other tunnels as well, such as subway systems.

Seven tasks were carried out as part of the project. These included full-scale fire tests in a new laboratory tunnel facility and in an operating road tunnel in Montreal, Canada, environmental and fire tests in the Lincoln Tunnel located in New York City, as well as a

computer modeling study. Figure 1 shows the different tasks of the project. NRC conducted five tasks and two tasks were performed by Hughes Associates.

Nine fire detection systems that covered five types of currently available technologies were studied in the project. The fire scenarios that were used were representative of the majority of tunnel fire incidents. The scenarios included small open pool fires, pool fires located underneath a simulated vehicle, pool fires located behind a large vehicle, engine and passenger compartment fires in a stationary vehicle, and moving vehicle fires. The fire size and airflow speed in the tunnel were also varied.

This paper provides an overview of the project as well as research findings from the tasks carried out by NRC.

2. SELECTED FIRE DETECTION SYSTEMS

The nine fire detection systems evaluated in the project were: two linear heat detection systems, one optical flame detector, three visual CCTV fire detectors, one smoke detection system and two spot heat detectors. These detectors are representative of current fire detection technologies for use in tunnel fire detection. Information on these systems is listed in Table 1. A detailed description of these technologies is provided in Reference [11].

Table 1. Fire Detectors/Detection Systems in the Project

Technology	System no.	System information
Linear heat	D-1L1	Fiber optic linear heat detection system
	D-2L2	Analogue (co-axial cable) linear heat detection system
Flame	D-3F1	IR3 optical flame detector
CCTV	D-4C1	Visual based fire and smoke detection system
	D-5C2	Visual flame detector
	D-6C3	Visual fire detection system
Spot heat	D-7H1	Heat detector with a fixed temperature
	D-8H2	Rate-anticipation heat detector
Smoke	D-9S1	Air sampling- system

The configuration and installation of the fire detection systems in the test tunnel was based on the design of a system to protect a road tunnel with dimensions of 10 m wide by 5.5 m high by 2,000 m long. The installation configuration was not changed during the tests. The sensitivity levels or alarm thresholds of the fire detection systems were also not changed during the test series. The alarm levels were required to be the same as those used in operating tunnels and with those used in the environment tests in the Lincoln tunnel.

The system suppliers installed all the fire detection systems in the tunnel facility. The performance of the fire detection systems, including response times, and ability to locate and monitor a fire in the tunnel, were evaluated under the same fire conditions.

3. FIRE TEST PROTOCOLS AND SCENARIOS – TASK 1

Three types of fire scenarios, involving various fire sizes, types, locations and growth rates, were selected. The fire scenarios were: flammable pool fires, stationary passenger vehicle

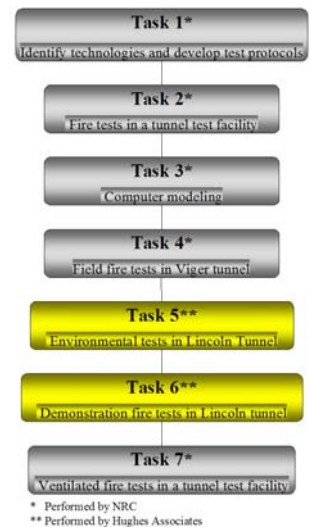


Figure 1. Project tasks

fires and moving vehicle fires. These fire scenarios were considered representative of the majority of tunnel fire incidents and presented a challenge to the fire detection systems. A detailed description on these scenarios is provided in reference [11].

Flammable pool fires may be caused by fuel leakage or in collisions. The fire develops very quickly reaching its maximum heat release rate (HRR) in a short time. Small open pool fires, pool fires located underneath a vehicle, and pool fires located behind a large vehicle were used in the fire tests with gasoline as the fuel. A propane burner was also used to simulate pool fires in tunnels. The fire sizes in the tests ranged from 125 kW to 3,400 kW. Figure 2 shows a pool fire located underneath a simulated vehicle



Figure 2. Pool fire underneath

Stationary passenger vehicle fires may be caused by collisions, an electrical failure or by a defective fuel delivery system and exhaust system failures. The fire develops slowly reaching its maximum HRR in 8~12 min [12, 13]. Two stationary vehicle fire scenarios were used in the tests: an engine compartment and a passenger compartment fires. A vehicle engine compartment fire was simulated by controlling the growth rate of a pool fire that was placed inside a simulated engine compartment. A passenger compartment fire was simulated using wood cribs and plastic foam inside a vehicle mock-up. Figure 3 shows a simulated passenger compartment.



Figure 3. Simulated passenger compartment fire

Moving vehicle fires in road tunnels could be caused by an electrical failure or by a defective fuel delivery system and exhaust system failures. A moving vehicle fire was simulated by dragging a fire source using a high-speed winch apparatus. Fire tests were conducted with different driving speeds and driving directions relative to the detectors.

4. FIRE TESTS IN THE TUNNEL TEST FACILITY – TASKS 2 & 7

Two series of full-scale fire tests were conducted in the tunnel test facility. The dimensions of the test facility were 10 m wide x 5.5 m high x 37 m long (Figure 4). The first series (Task 2) were conducted under no-ventilation conditions (airflow speed was kept as close as possible to zero). The door at the East end of the tunnel was closed and air was provided through the louvers in the North and South walls at the East end of the tunnel. The other series (Task 7) were conducted under longitudinal airflow conditions. For the second series of tests, the door at the East end of the tunnel was open and airflow conditions were simulated by operating the facility fan system in exhaust mode to draw air through the tunnel in the East-West direction. The airflow speeds in the test series were 0, 1.5 and 3 m/s.

Nine fire detection systems (Table 1) were evaluated in these tests. Figure 4 shows a schematic of the tunnel facility with the location of the fire detection systems. Detailed information on the tunnel facility and the location of fire detection systems in the test tunnel is provided in reference [14].

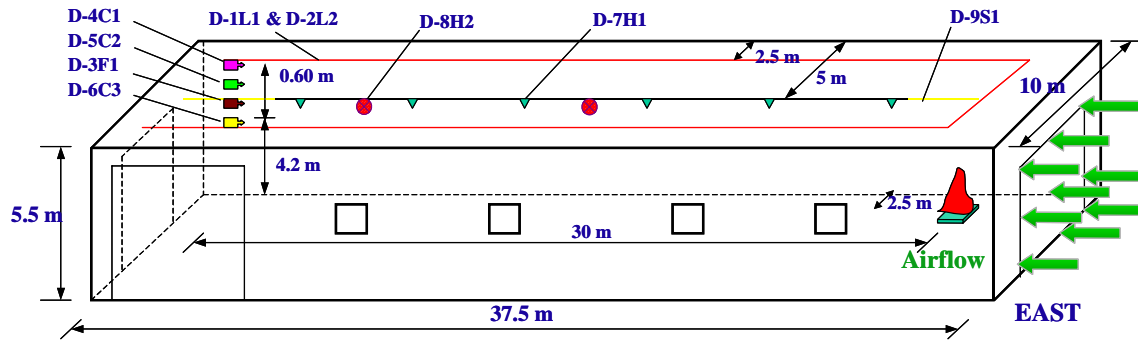


Figure 4. Schematic of the detection system setup in the laboratory tunnel

The fire conditions and smoke spread in the tunnel were monitored using 55 thermocouples on the ceiling, two thermocouple trees, three smoke meters, five heat flux meters, one velocity meter and two video cameras. A detailed description of the instrumentation is provided in reference [14].

The response of the fire detection systems to the fires used in the tests was dependent on fuel type, fire size, location and growth rate as well as detection method. The fire scenario with a pool fire located underneath a vehicle presented a challenge for the detection systems, as the vehicle body confined the flame and heat produced by the fire.

Some detection systems were able to detect a small pool fire located underneath the vehicle with minimal airflow in the tunnel, as shown in Figure 5. With an increase in fire size, more detectors responded at reduced times.

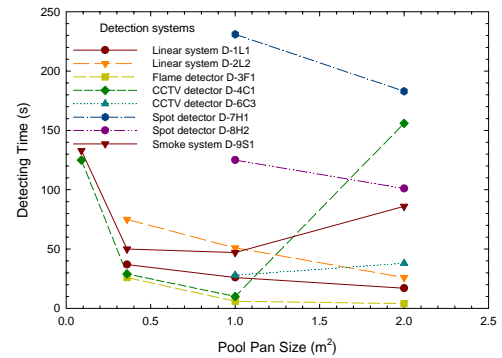


Figure 5. Detecting times – pool fires underneath vehicle

A large vehicle body in front of the pool fire did not affect the performance of heat and smoke detection systems, but presented a challenge for the visual-based fire detectors (Figure 6). One CCTV flame detector could not detect the fire located behind the vehicle, as the flames were not visible. For other fire detection systems, the response times decreased with an increase in fire size.

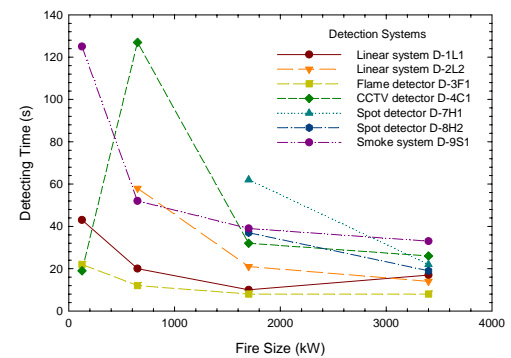


Figure 6. Detecting times – pool fires behind vehicle

The response of fire detection systems to the stationary vehicle fires in the engine and passenger compartments was slow, because these fires developed very slowly. The flame, heat and smoke produced by the fires were limited during the initial few minutes after ignition.

It was difficult for fire detection systems to detect a small moving fire, since there was no change in the temperature or smoke density in the tunnel. Only the optical flame detector detected the moving fire at the speed of 27 km/h (but not at the speed of 50 km/h). No other fire

detector/detection system responded to the moving fires.

The results for tests under longitudinal airflow conditions showed that the response times of fire detection systems could be increased or decreased, depending on the fire scenario, airflow speeds and detection method. A scenario in which the detection time could decrease for some detectors was for large pool fires located underneath a vehicle. In this scenario, the burning rate increased under longitudinal airflow conditions. The temperatures and smoke density near the ceiling were higher and the response times of heat and smoke detection systems were generally shorter than those under low airflow conditions, as shown in Figure 7. For the optical flame and CCTV detectors, there was no systematic change in response time.

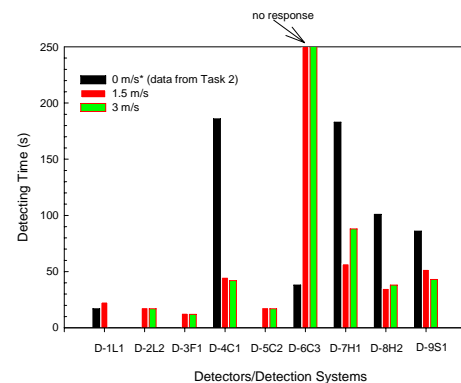


Figure 7. Detecting times – 2 m² gasoline pool fire underneath vehicle

The ceiling temperature produced by the pool fires located behind a large vehicle decreased with an increase in airflow speed as a result of fire plume deflection and increased dilution of the smoke. As a result, response times of heat detection systems to pool fires behind large vehicle generally increased (Figure 8). With the increase in airflow speed, the smoke layer lost its buoyancy and descended filling the height of the tunnel facility. Figure 8 shows a slight decrease in the response time of smoke detection system. The response time for optical flame detector and CCTV fire detectors, generally, increased with an increase in airflow speed. In this case, the plume structure was significantly disrupted and smoke filled the space between the fire source and the detectors making it difficult to detect the fire. In Figure 7 and Figure 8 “no response” phrase meant that the test was terminated before the detection systems detected the fire.

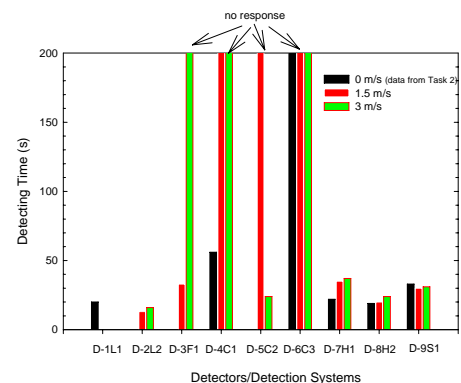


Figure 8. Detecting times – 2 m² gasoline pool fire behind vehicle

5. FIELD FIRE TESTS IN AN OPERATING TUNNEL – TASK 4

A series of full-scale fire tests were conducted in an operating road tunnel in Montreal (Carré-Viger Tunnel) in collaboration with the Ministry of Transportation of Quebec (Figure 9). The test section was a 4-lane section 600 m long, 5 m high and 16.8 m wide. The tunnel was equipped with four jet fans. The performance of fire detection systems in a real tunnel environment and at their maximum detection distance was investigated in these tests.



Figure 9. Field fire test in Viger Tunnel in Montreal

Six detection systems were installed in the Viger tunnel, including one optical flame detector, three visual CCTV fire detectors and two linear heat detection systems. Figure 10 shows a schematic of installed fire

detection systems in the tunnel. The detection systems were the same ones used in the laboratory tunnel facility tests. Three types of fire scenarios were used in the test series: a small open pool fire (~125 kW), a pool fire (~625 kW) located underneath a simulated vehicle and a pool fire located behind a simulated vehicle. The fire setups were similar to those in Task 7. The fire source was placed at different locations in the tunnel (FP#1 through FP#4), as shown in Figure 10. Four longitudinal airflow speeds were used in the tests by operating the jet fan system mounted in the tunnel: 0 m/s, 1.3 m/s, 2 m/s and 2.4 m/s. Instrumentation that was used in the test series included thermocouples, smoke meters, velocity meters and video cameras.

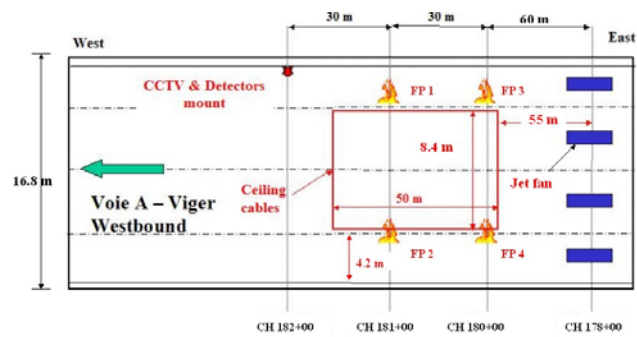


Figure 10. Field fire tests in Viger Tunnel

General observations on the performance of the fire detection systems in the Montreal tunnel tests indicated that fire detection systems worked well in an operating tunnel environment. Their performances were consistent with those determined in the laboratory tunnel tests under the same test conditions.

The fiber optic linear heat detection system, D-1L1, was able to respond to small fires, based on the rate of rise of temperature, even if the ceiling temperature produced by the fire was not high. Its performance was not affected by fire location (Figure 11). The linear heat detection system D-2L2 detected only fires located at positions FP #1 and FP #2. The optical flame detector D-3F1 was able to detect small fires only when they were located in its detecting range (~30 m). The three CCTV fire detectors were able to detect the small fires at their maximum detection range (~60 m).

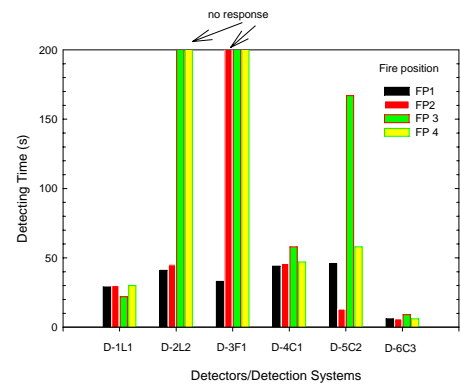


Figure 11. Detecting times – 0.02 m² open fire

The response times to a fire located underneath a vehicle was delayed or reduced under airflow conditions. The linear heat detection system D-1L1 only detected fires in tests with airflow speeds of 1.3 m/s and 2.0 m/s (Figure 12). The linear heat detection system D-2L2 responded to fires at the three airflow speeds. The response time of the optical flame detector D-3F1 was delayed with the increase in airflow speed. The response times of the three CCTV fire detectors were varied with depending on the airflow conditions. The shape or the temporal fluctuations of the visual flame caused both increased and decreased response times.

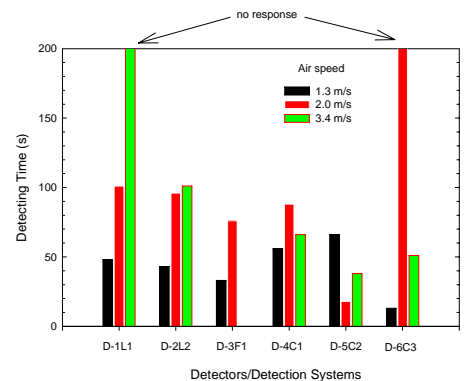


Figure 12. Detecting times – 0.36 m² fire under vehicle

The detector response times to a 0.36 m² fire behind a vehicle are summarized in Figure 13 for tests with an airflow velocity of 1.3 m/s. The response times of the two linear heat

detection systems were not affected by the change in fire location. A section of the detection cable was always near the fire source.

The performance of the flame detector D-3F1 and three CCTV fire detectors were affected by the change in fire locations. The optical flame detector D-3F1 and the flame/smoke CCTV detector D-4C1 and D-5C2 did not respond to the fire located at 60 m from the detectors. The flame CCTV detector D-6C3 responded to the fires at both locations.

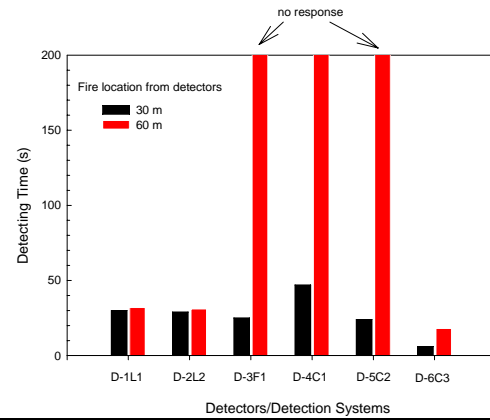


Figure 13. Detecting times – 0.36 m² fire behind vehicle (wind speed 1.3 m/s)

6. COMPUTER MODELING – TASK 3

Due to the rapid development of computer technology and high costs of test programmes, the use of Computational Fluid Dynamics (CFD) models to simulate the dynamics of fire behaviour in tunnels is increasing quickly. The details of fluid flow and heat transfer provided by CFD models can prove vital in analyzing problems involving far-field smoke flow, complex geometries, and impact of fixed ventilation flows.

The current research study employs the Fire Dynamic Simulator (FDS) CFD model [15] to study the fire growth and smoke movement in road tunnels. FDS is based on the Large Eddy Simulation (LES) approach and solves a form of high-speed filtered Navier-Stokes equations valid for low-speed buoyancy driven flow. These equations are discretized in space using second order central differences and in time using an explicit, second order, predictor-corrector scheme.

For the tunnel detection project, the following CFD modeling activities were conducted:

- CFD simulations were carried out to compare numerical predictions against the data from a demonstration test in the laboratory tunnel facility [16]. Further simulations were conducted to assist in the preparation of the full-scale experiments.
- CFD simulations were conducted to replicate laboratory and field experiments of Tasks 2, 4, and 7. The simulations covered different fire sizes, location, ventilation scenarios, and fuel type. Comparisons of temperature and smoke optical density values were made at different locations corresponding to lab and field measurement points.
- Further simulations were conducted to investigate the impact of various fire scenarios, ventilation mode, and tunnel length on fire behaviour and detection system performance. Information from the model can be used in developing appropriate test protocols and for understanding and optimizing the performance of fire detection systems for road tunnel protection.

CFD simulations were carried out to compare numerical predictions against selected experimental data from the laboratory and field experiments. The initial and boundary conditions of each simulation were set to mimic the conditions of the corresponding test. Comparisons were made of temperature and smoke optical densities measurements. Figure 14 shows the comparisons of ceiling temperatures for the simulation of a 1.0 x 2.0 m pool fire under a vehicle for a test in the laboratory tunnel without longitudinal airflow.

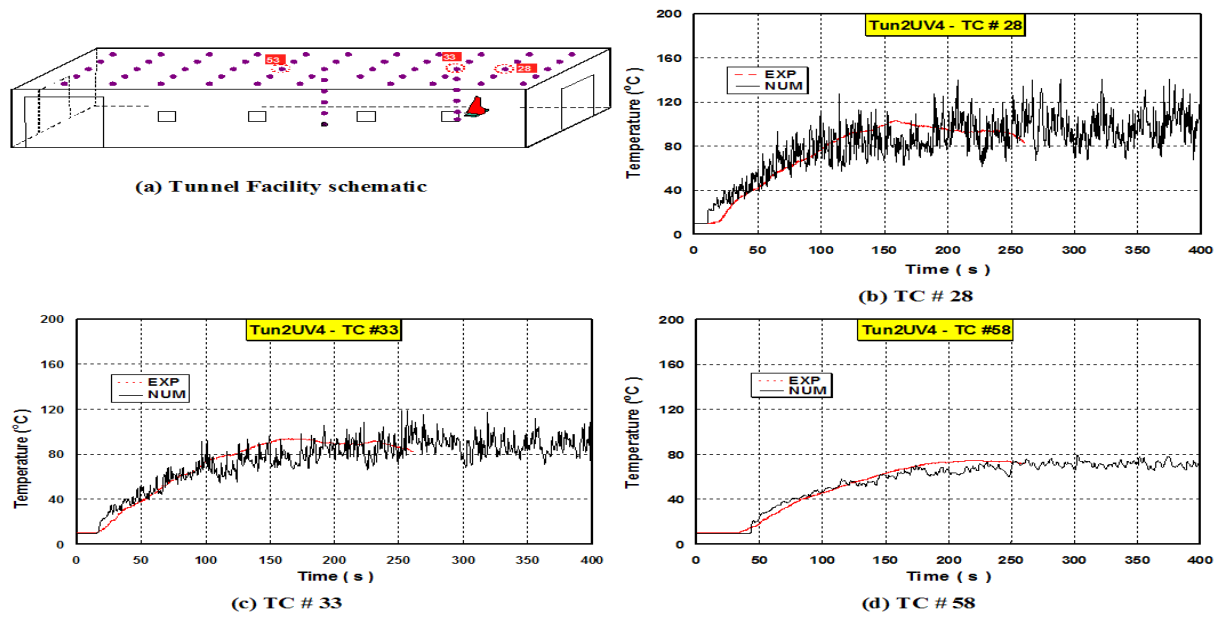


Figure 14. Temperature comparisons – 1.0x2.0 gasoline pool fire under vehicle

The comparisons of ceiling temperatures were, in general, favourable. The numerical predictions were featured by fluctuations with rather large amplitudes especially at locations close to the fire. The experimental results did not exhibit the same fluctuations. This can be attributed to two reasons; the frequency of data collection was courser (1 Hz) than that for the numerical predictions (< 0.01 Hz), and the plume shape was not perfectly replicated by the numerical procedure.

Figure 15 shows the comparison of the numerical predictions of smoke optical density (OD) against the experimental data for the 1.0 x 2.0 m pool fire behind a large vehicle for a test in the laboratory tunnel without longitudinal airflow. The OD values were compared at three heights at the center of the tunnel; namely, 1.5 m, 2.5 m, and 5.35 m. The figure indicates a smoke layer that travelled close to the ceiling. At the mid and lower heights, the OD values were much smaller. The comparisons were quite favourable for the OD values near the tunnel ceiling.

CFD simulations were also conducted to investigate the impact of various parameters, such as fire scenario, ventilation mode, and tunnel length, on fire behaviour and detection system performance. Four ventilation conditions were studied: no ventilation, longitudinal, fully-, and semi-transverse ventilation. Two tunnels were simulated with lengths of 37.5 m (similar to the length of the laboratory facility) and 500 m and the height of 5.5 m. The two tunnels were three lanes with 10 m and 12 m widths, respectively. The longitudinal ventilation (Tun2LT1) condition was created by introducing a 3.0 m/s airflow at one tunnel portal. The semi-transverse ventilation condition was simulated by injecting airflow at the floor level (Tun2ST1) or by exhausting smoke and hot gases through the tunnel ceiling (Tun2ST2). Injecting airflow at floor level and exhausting airflow at ceiling was used to simulate the fully-transverse (Tun2FT1) ventilation condition.

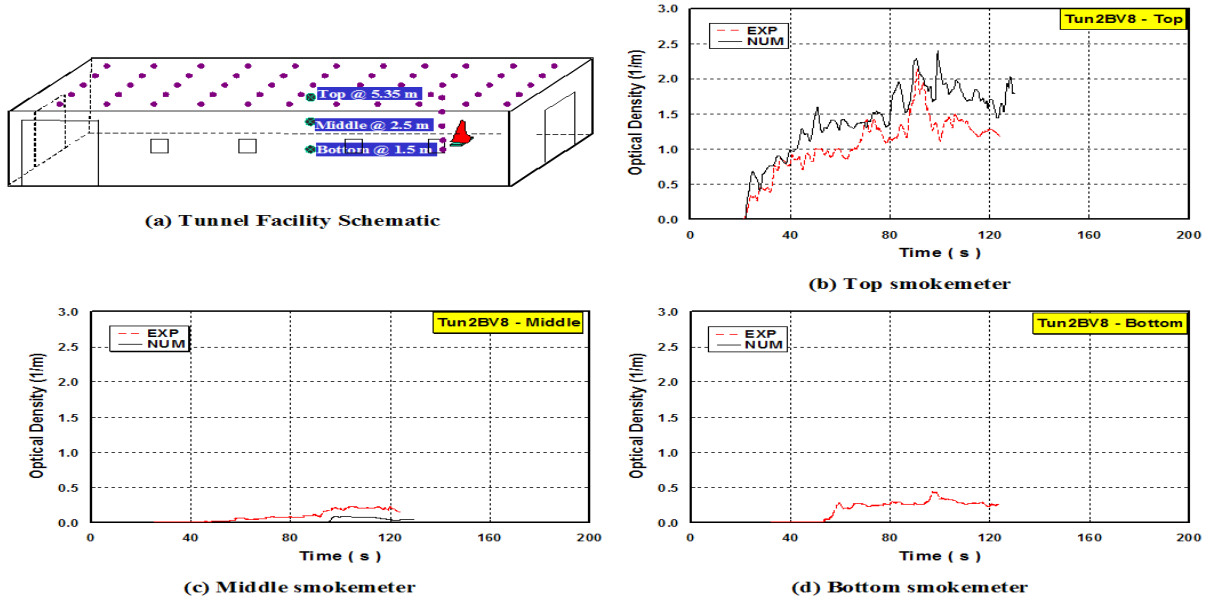


Figure 15. Smoke OD comparisons – 1.0x2.0 gasoline pool fire behind vehicle

Figure 16 shows the temporal plots of the airflow speeds and temperature at a point close to the ceiling at mid-tunnel for different ventilation schemes. Among all the simulations, Tun2LT1 with longitudinal ventilation scheme produced a quasi-steady state velocity profile at the middle of the tunnel. The airflow speed achieved its steady state in less than 20 s. For all other ventilation schemes, the airflow speed attained its steady-state value at approximately 100 s. The time at which the velocity field arrives at its steady-state condition affects the rate of temperature rise and hence the performance of the detection process. The rate of ceiling temperature rise up to the steady-state conditions at mid-tunnel for Tun2FT1, Tun2ST1, and Tun2ST2 was 0.13, 0.30, 0.10°C/s, respectively. As such, Tun2ST1 resulted in the fastest rate of rise of ceiling temperature and Tun2ST2 resulted in the slowest rate of rise of ceiling temperature. In Tun2LT1, the temperature remained at ambient conditions.

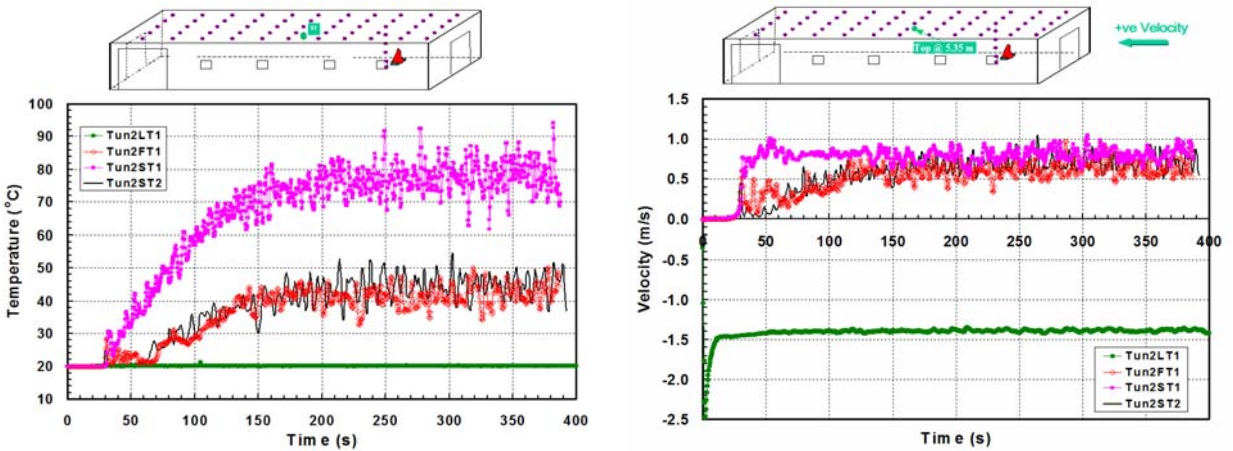


Figure 16. Temporal airflow speed and temperature at mid-tunnel section

Figure 17 shows the comparisons of the ceiling temperatures and soot volume fractions for the two tunnel lengths. Both temperature and soot profiles were similar for the two lengths. As such, the length of the tunnel has no significant effect on the ceiling temperature and smoke accumulation.

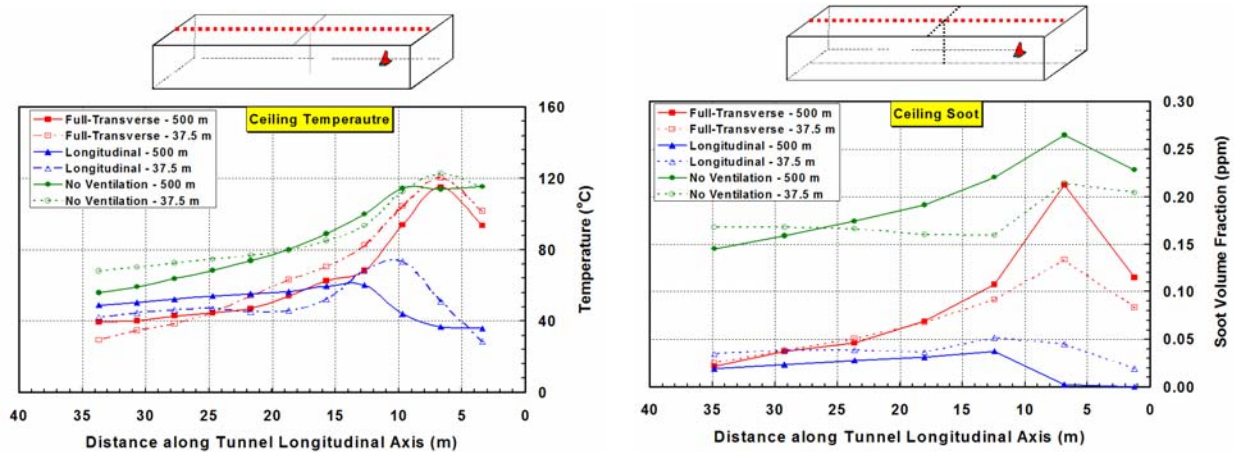


Figure 17. Average ceiling airflow temperature and soot volume fraction along the tunnel

7. SUMMARY AND CONCLUSIONS

Nine fire detection systems were evaluated in the project. These systems were representative of current fire detection technologies for use in tunnel fire detection. A test protocol for evaluating various fire detection technologies for road tunnel protection was developed. The performance of selected fire detection systems for various tunnel fire scenarios was investigated in a laboratory tunnel and in an operating road tunnel under different longitudinal airflow conditions. Computer modeling was used to investigate the impact of various fire scenarios, ventilation modes, tunnel operating conditions and tunnel geometries on fire behavior and detection system performance.

In general, the performance of fire detection systems was dependent on fuel type, fire size, location and growth rate as well as detection method. Moreover, the performance was affected (delayed or shortened) under longitudinal airflow conditions. The linear optical heat detection systems, the optical flame detector, visual-based CCTV fire detectors, and smoke detection system were able to detect a small-unobstructed fire. The spot heat detectors did not detect fires sizes smaller than 1,500 kW. The performance of the linear heat detection system and visual-based CCTV fire detectors were, generally, not affected by fire location.

It was difficult for most detection systems to respond to small fires located underneath a vehicle. In this case, the confining of flame and heat produced by the fire by the vehicle body made it difficult for the detectors to detect the fire. With an increase in fire size, more detectors responded to the fire and their detection times also decreased.

Pool fires located behind a large vehicle presented a challenge for optical-based detectors since the view of the flames were obstructed by the vehicle. However, other detection systems were able to quickly detect small fires located behind a vehicle.

Responses of detection systems to stationary vehicle fires were slow because of their slow growth rate. The fastest response time of evaluated detection systems was approximately 180 s. The response time was further delayed under airflow conditions.

The small moving vehicle fires were difficult to detect, as they did not result in significant change in the tunnel environment (temperature or smoke density). Only the optical

flame detector, set at high sensitivity level, was able to detect the moving fire at a speed of 27 km/h.

Under airflow conditions, the response time of heat and smoke detection system was shortened for fires under vehicle, as the fire size was increased and higher temperatures and smoke densities were produced.

For fires located behind a large vehicle, the response time of heat detection systems increased as the airflow speed increased. It was a challenge for the optical flame and visual-based CCTV detectors to detect obstructed fires under airflow conditions due to the tilt of the flames towards the obstruction and the disruption of flame structure. Moreover, for large fires with quick growth rates, the available monitoring time for visual-based CCTV was greatly reduced (< 1 min) as a dense smoke layer quickly formed in the tunnel. Under airflow conditions, the response time of CCTV was further delayed.

The performance of detection systems in an operating tunnel environment was generally consistent with those evaluated in the tunnel test facility under corresponding conditions.

In general, good agreement in temperatures was observed between numerical predictions and experimental data. Some discrepancies were noted in the comparisons of numerical prediction against experimental data for tests with longitudinal airflow especially at the test facility entrance. These discrepancies may be attributed to turbulence conditions and plume shape that were not fully reproduced by the model.

Among the numerically investigated ventilation schemes, the semi-transverse supply ventilation system resulted in the highest ceiling temperature and soot volume fraction. Both the full- and semi-transverse exhaust ventilation systems produced similar average ceiling temperature and soot profiles. The longitudinal ventilation system resulted in the lowest average ceiling temperature. The semi-transverse supply ventilation system resulted in the fastest rate of rise of ceiling temperature and the semi-transverse exhaust ventilation system resulted in the slowest rate of rise of ceiling temperature. These changes in conditions in the smoke layer would affect the ability of ceiling mounted detectors to detect a fire.

In general, the data predicted from the CFD simulations can be related to the performance of spot heat detector, linear heat detection systems, and smoke aspiration detection systems. However, more effort is required to relate CFD data to the CCTV and flame detection systems. CFD can provide temporal and spatial information on the expected shape of the plume, heat flux and wall temperatures, which could possibly be related to the performance of the optical-based detectors.

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