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Publisher’s version / Version de l'éditeur:
https://doi.org/10.1007/s10694-008-0076-2
Fire technology - the special issue on smoke control in buildings and tunnels, 45, 2, pp. 221-237, 2008-12-30

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NRCC-51159

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December 30, 2008

A version of this document is published in / Une version de ce document se trouve dans:
Fire technology - the special issue on smoke control in buildings and tunnels, Dec. 30, 2008, pp. 1-17, DOI: 10.1007/s10694-008-0076-2

Findings of The International Road Tunnel Fire Detection Research Project

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ABSTRACT

Fire detection systems are essential fire protection elements for road tunnels to detect fires, activate safety systems and direct evacuation and firefighting. However, information on the performance of these systems is limited and guidelines for application of tunnel fire detection systems are not fully developed. The National Research Council of Canada and the Fire Protection Research Foundation, with support of government organizations, industries and private sector organizations, have completed a research project to investigate current fire detection technologies for road tunnel protection. The project included studies on the detection performance of current fire detection technologies with both laboratory and field fire tests combined with computer modelling studies.

This paper provides an overview of the findings of the project. Fire detectors, fire scenarios and test protocols used in the test program are described. A summary of the research results of the series of full-scale fire tests conducted in a laboratory tunnel facility and in an operating road tunnel as well as of the computer modelling activities will be reported.

1 INTRODUCTION

Fire detection systems are an essential element of fire protection for road tunnels. The function of fire detectors is to detect fire incidents in their early stage, identify their location and monitor fire development in the tunnel. As such, their role can make the difference between a manageable fire and one that gets out-of-control and plays 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 have provided information that can be used in the development of performance criteria, guidelines and specifications for tunnel fire detection systems. The results will also help optimize technical specifications and installation requirements of fire detection systems for tunnel applications. Although this research was being conducted in 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 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 modelling study. NRC conducted five tasks and Hughes Associates performed two tasks. This paper provides an overview of the project as well as findings from the tasks carried out by NRC (Tasks 1, 2, 3, 4, and 7).

2 SELECTED FIRE DETECTION SYSTEMS

Nine fire detection systems that covered five types of currently available technologies for use in tunnel fire detection were studied in the project. These detectors were: two linear heat detection systems, one optical flame detector, three video image detection (VID) systems, one smoke detection system and two spot heat detectors. Information on these systems is listed in Table 1 [11].

Technology	System	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
VID	D-4C1	Flame/smoke VID system
	D-5C2	Flame/smoke VID system
	D-6C3	Flame VID system
Spot heat	D-7H1	Heat detector with a fixed temperature
	D-8H2	Rate-anticipation heat detector
Smoke	D-9S1	Air sampling- system

Table 1. Fire Detectors/Detection Systems in the Project.

3 FIRE TEST PROTOCOLS AND SCENARIOS – TASK 1

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

Flammable pool fires may be caused by fuel leakage or in collisions. The fire can develop very quickly and reach 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 1 shows a pool fire located underneath a simulated vehicle.

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 can develop slowly and reach its maximum HRR in 8~12 min [12,13]. Two scenarios were used: an engine compartment and a passenger compartment fire. An 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 2 shows a 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 directions relative to the detectors.

Fig. 1. Pool fire underneath a vehicle

Fig. 2. Simulated passenger compartment fire.

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

Two series of full-scale fire tests were conducted in the Carleton University laboratory research tunnel that is located at the site of the NRC full-scale fire test facilities. The dimensions of the laboratory tunnel are 10 m wide x 5.5 m high x 37.5 m long [14]. Twenty-one full-scale fire tests were conducted under minimum airflow speed conditions in the first test series (Task 2). As shown in Figure 3, 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 second fire test series (Task 7) involved fifteen full-scale fire tests and were conducted under longitudinal airflow conditions in which the East end door was open. Airflow conditions were simulated by operating the facility fan system in exhaust mode at different speeds. The airflow speeds were 0, 1.5 and 3 m/s in the tunnel.

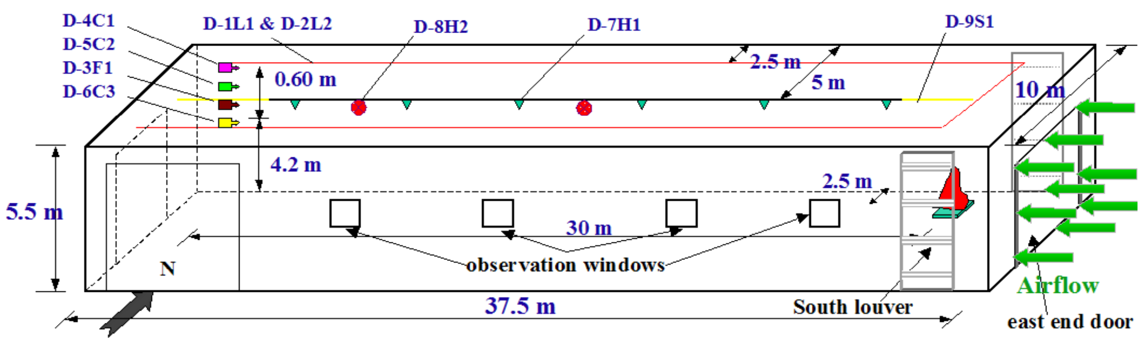

Fig. 3. Schematic of the detection system setup in the laboratory tunnel.

The nine fire detection systems (Table 1) were evaluated in these test series. Figure 3 shows a schematic of the tunnel facility with the location of the fire detection systems. 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.

5 COMPUTER MODELLING – TASK 3

The use of Computational Fluid Dynamics (CFD) models to simulate the dynamics of fire behaviour in tunnel applications has been increasing quickly with the rapid development of computer technology. 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. CFD simulations were conducted to help understand and optimize the technical specifications and installation requirements for application of fire detection technologies in road tunnels.

The current study employed 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, predictorcorrector scheme.

The work of Task 3 included CFD modelling activities to support pre and post full-scale test phases. CFD simulations were initially used to assist in the preparation of the full-scale experiments with regards to instrumentation type and locations as well as to determine important parameters involved in the experiments. After conducting the full-scale tests, numerical predictions were compared against selected experimental data. Further simulations were used to investigate the impact of different parameters on fire behaviour and detection system performance.

Twenty CFD simulations were conducted to compare numerical predictions against selected full-scale fire tests 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 (OD) were made at different locations corresponding to lab and field measurement points.

After establishing the validity of the numerical model, CFD simulations were further used to determine the effect of the 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 lengths were simulated: 37.5 m (similar to the length of the laboratory tunnel) and 500 m. The two tunnels were three lanes with 10 m and 12 m widths, respectively, and had a height of 5.5 m.

6 FIELD FIRE TESTS IN AN OPERATING TUNNEL – TASK 4

A series of full-scale fire tests were conducted in an operating road tunnel (Figure 4). The test section was 600 m long, 5 m high and 16.8 m wide (4 lanes). 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.

Six detection systems were installed in the tunnel, including one optical flame detector, three visual VID fire detectors and two linear heat detection systems (Figure 5). The detection systems were the same ones used in the laboratory tunnel facility tests. Nine full-scale fire tests were conducted using three fire scenarios: a small open pool fire (~125 kW), a pool fire (~625 kW) underneath a simulated vehicle and a pool fire 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 5. Four longitudinal airflow speeds were used in the tests by operating the jet fan system: 0 m/s, 1.3 m/s, 2 m/s and 2.4 m/s. Instrumentation that included thermocouples, smoke meters, velocity meters and video cameras.

7 RESULTS

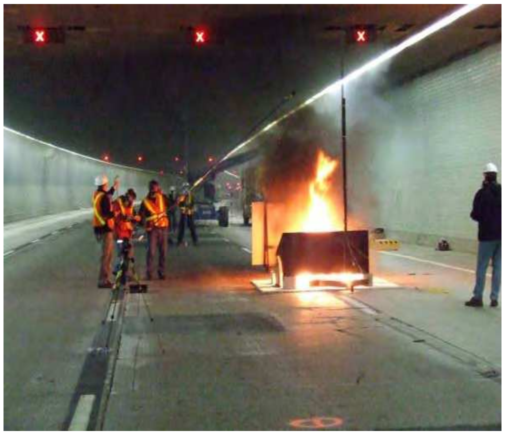

Fig. 4. Tested tunnel

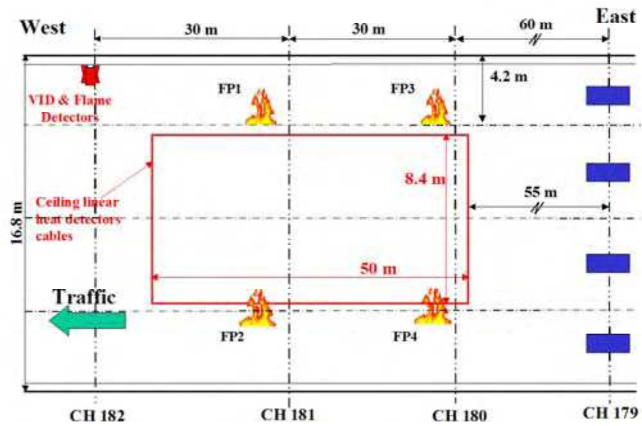

Fig. 5. Schematic of installed fire detection systems.

7.1 Task 2: Tests under Minimum Airflow Conditions

The response of the detection systems 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 underneath the vehicle as shown in Figure 6. With an increase in fire size, more detectors responded at reduced times. 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 7). One VID detector could not detect the fire located behind the vehicle, as the flames were not visible. For the other fire detection systems, the response times decreased with an increase in fire size.

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. The D-3F1 system was the only detection system that was able to detect the moving fire at only one speed (27 km/h).

7.2 Task 7: Tests under Longitudinal Airflow Conditions

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. For a large pool fires underneath a vehicle under longitudinal airflow conditions, the burning rate increased and consequently the ceiling temperatures and smoke density were higher. For this scenario, the response times of heat and smoke detection systems were generally shorter than those under minimum airflow conditions, as shown in Figure 8. For the optical flame and VID detectors, there was no systematic change in response time.

The ceiling temperature produced by the pool fires located behind a large vehicle decreased with an increase in airflow speed as a result of the deflection of the fire plume and increased dilution of the smoke. As a result, the response times of heat detection systems to these fire scenarios generally increased (Figure 9). With the increase in airflow speed, the smoke layer lost its buoyancy and descended filling the height of the tunnel facility. Figure 9 shows a slight decrease in the response time of the smoke detection system. The response time for the optical flame detector and VID fire detectors, generally, increased with an increase in airflow speed. In this case, the plume structure was disrupted and smoke filled the space between the fire source and the detectors making it difficult to detect the fire. In Figures 8 and 9 "no response" phrase meant that the test was terminated before the detection systems detected the fire.

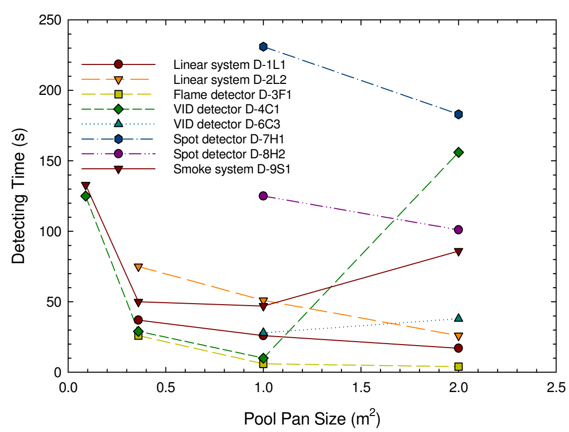

Fig. 6. Detecting times – pool fires underneath vehicle.

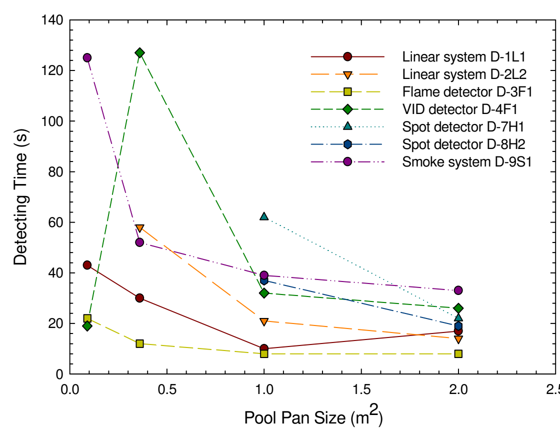

Fig. 7. Detecting times – pool fires behind vehicle.

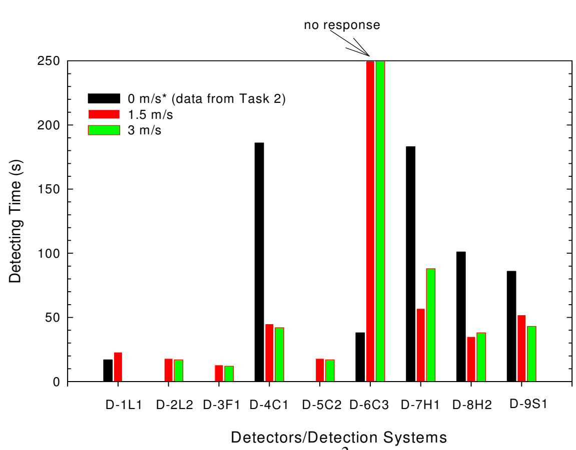

Fig. 8. Detecting times – 2 m² gasoline pool fire underneath vehicle.

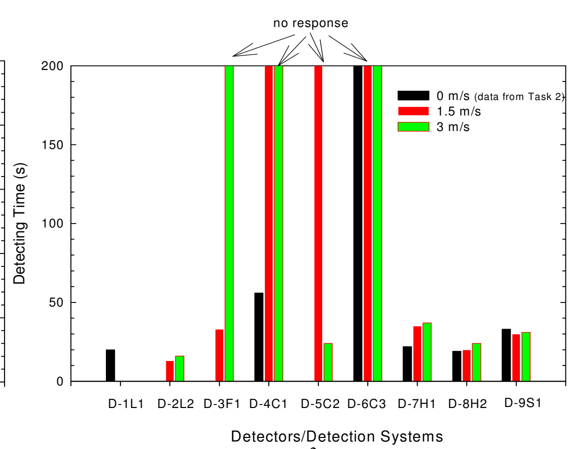

Fig. 9. Detecting times – 2 m² gasoline pool fire behind vehicle.

7.3 Task 4: Field Fire Tests in an Operating 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 D-1L1 system 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 the fire location (Figure 10). The D-2L2 system 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 VID detectors were able to detect the small fires at their maximum detection range (~60 m).

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

The detector response times to a 0.36 m^2 fire behind a vehicle are summarized in Figure 11 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 D-3F1 detector and the three VID systems were affected by the change in fire locations. The D-3F1 detector and the D-4C1 and D-5C2 detectors did not respond to the fire located at 60 m from the detectors. The D-6C3 detector responded to the fires at both locations.

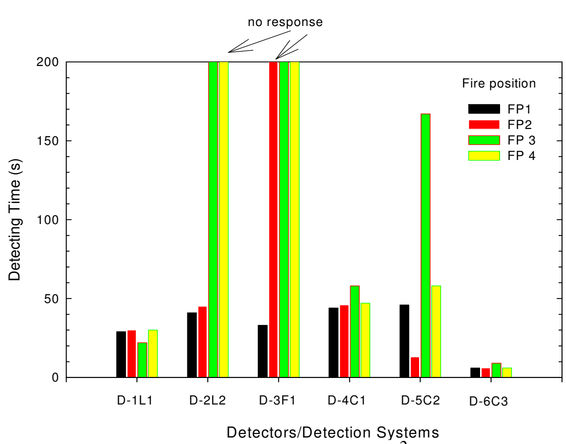

Fig. 10. Detecting times – 0.02 m^2 open fire.

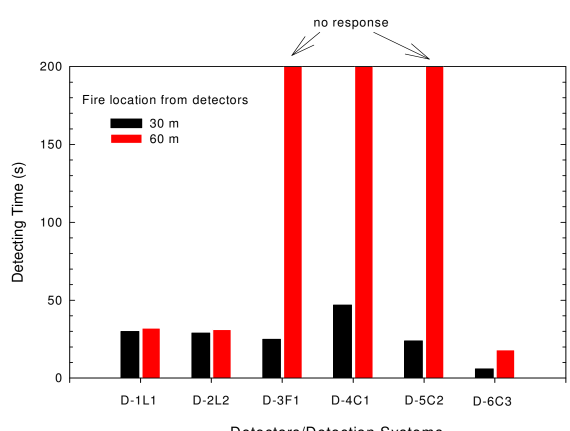

Fig. 11. Detecting times – 0.36 m^2 fire behind vehicle (wind speed 1.3 m/s).

7.4 Task 3: Computer Modelling

Three series of CFD simulations were conducted to compare numerical predictions against selected full-scale fire tests (Tasks 2, 4, and 7 of the project). The comparisons were conducted for non-ventilated and longitudinal ventilation conditions. Two types of fire scenarios were simulated: pool fires (under and behind vehicles) and stationary vehicle fires (engine or passenger compartment), using the same dimensions and initial and boundary conditions as used in the full-scale tests. Fire sizes varied from approximately 100 kW to

3,400 kW with various growth rates (1 min to 12 min to reach the maximum heat release rate). The CFD simulations involved various fire locations (underneath a vehicle and behind a large vehicle) and various fuel types (gasoline, propane, wood crib and polyurethane foam).

Comparisons were made of temperature and smoke optical density (OD) measurements. Figure 12 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.

The comparisons of ceiling temperatures were, in general, favourable. The numerical predications 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.

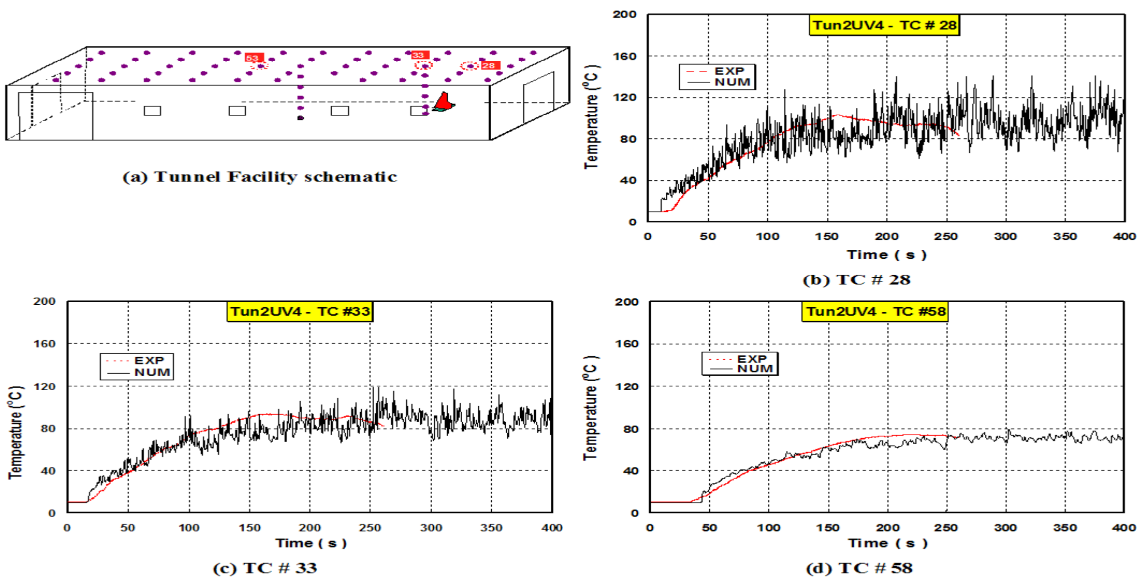

Fig. 12. Temperature comparisons – 1.0x2.0 m gasoline pool fire under vehicle.

Figure 13 shows the comparison of the numerical predictions of smoke 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 favourable for the OD values near the tunnel ceiling.

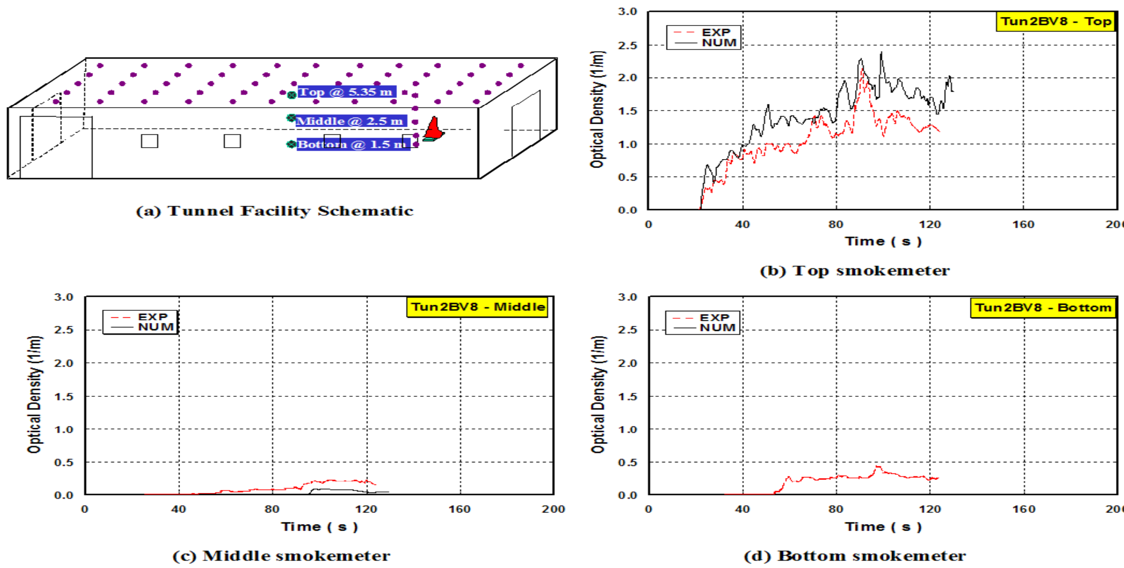

Fig. 13. Smoke OD comparisons – 1.0x2.0 m gasoline pool fire behind vehicle.

Four ventilation conditions were simulated: no ventilation, longitudinal, fully-, and semi-transverse ventilation for the two tunnels described in Section 5. The longitudinal ventilation (Tun2LT1) condition was created by introducing 3.0 m/s airflow at portal opposite to the fire with airflow towards the fire. 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 the floor level and exhausting airflow at the ceiling was used to simulate the fully-transverse (Tun2FT1) ventilation condition.

Figure 14 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 a 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 system. 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^{o}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 15 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 near the fire.

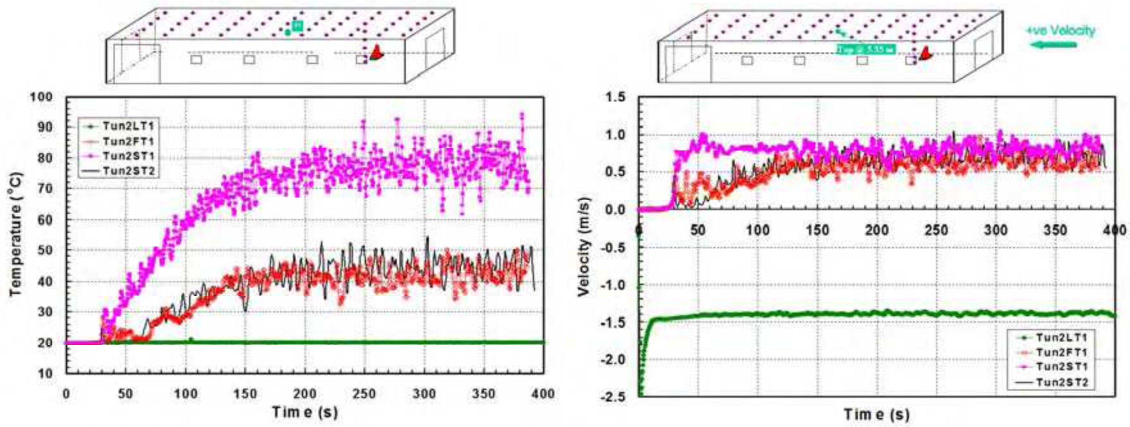

Fig. 14. Temporal airflow speed and temperature at mid-tunnel section.

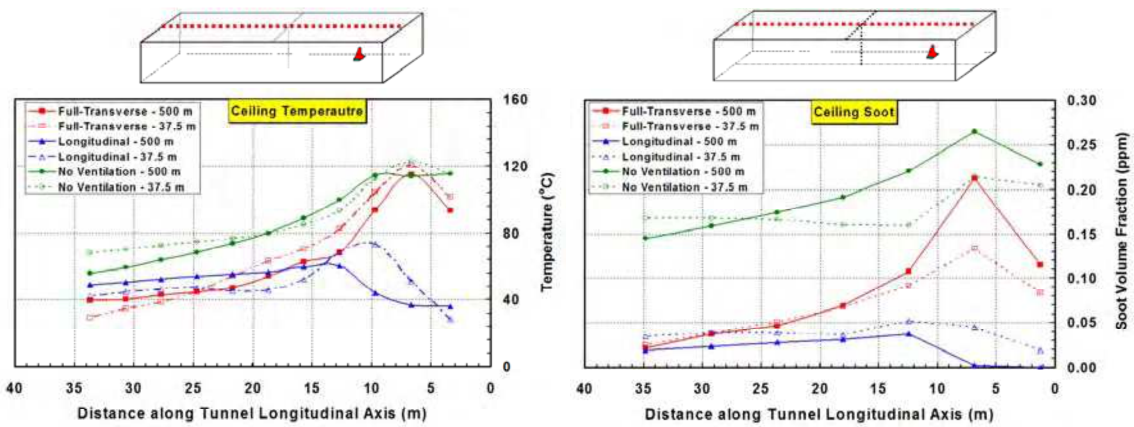

Fig. 15. Average ceiling airflow temperature and soot volume fraction along the tunnel.

8 SUMMARY AND CONCLUSIONS

In general, roadway tunnels are challenging environments for fire detection systems, both in terms of the detection challenge and the environmental conditions under which these systems must operate. Nine fire detection systems, representing five currently available detection technologies for tunnel applications, were investigated in the project. 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 modelling was used to investigate the impact of various fire scenarios, ventilation modes, tunnel operating conditions and tunnel geometries on fire behaviour 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. Based on overall performance, the air sampling detection system performed well; it was able to detect the fire for most scenarios including those with longitudinal airflow. The linear heat detection systems were also able to detect the fires for most scenarios. The systems that rely on field-of-view had problems detecting fires that were concealed by obstructions. Multiple detectors could be used to address this issue. The VID systems that included detection based on both flame and smoke characteristics had better performance in terms of detecting a fire but had problems in the environmental tests. The spot heat detection systems were not able to detect small fires (< 1,500 kW).

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

Responses of detection systems to stationary vehicle fires were slow because of the slow fire growth rate. The fastest response time of evaluated detection systems was approximately 3 min. The response time was further delayed under airflow conditions.

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 VID detectors to detect obstructed fires under airflow conditions due to the tilt of the flames towards the obstruction and the disruption of the flame structure. Moreover, for large fires with quick growth rates, the available monitoring time for visual-based VID was greatly reduced (< 1 min) as a dense smoke layer quickly formed in the tunnel. Under airflow conditions, the response time of the VID system was further delayed by smoke filling the tunnel.

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 detectors, linear heat detection systems, and smoke aspiration detection systems. However, more effort is required to relate CFD results to the VID 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.

ACKNOWLEDGMENTS

Contributions of the following organizations to the project are acknowledged:
Ministry of Transportation of British Columbia, Ministry of Transportation of Ontario, Ministry of Transportation of Quebec, The City of Edmonton, Transportation Department, Transit Projects Branch, Port Authority of New York and New Jersey, Carleton University, AxonX LLC/Johnson Control, Siemens Building Technologies, Tyco Fire Products, VisionUSA, Sureland Industrial Fire Safety, United Technologies Research Corporation, J-Power Systems/Sumitomo Electric USA, Inc., A & G Consultants, PB Foundation, Micropack, Inc., Honeywell Inc. The authors would also like to acknowledge the contributions of the Technical Panel members and other NRC staff to this project.

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