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Findings of the International Road Tunnel Fire Detection Research Project

Z. G. Liu, CAFS Unit Inc., Ottawa, ON, Canada

A. Kashef, G. Crampton and G. Lougheed, National Research Council of Canada, Ottawa, Canada*

Y. Ko and G. Hadjisophocleous, Carleton University, Ottawa, Canada

Kathleen H. Almand, The Fire Protection Research Foundation, Quincy, MA, USA

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Abstract. Fire detection systems play a crucial role in ensuring safe evacuation and firefighting operations in road tunnels, but information on the performance of these systems in tunnels has been limited and guidelines for their application in tunnel environments are not fully developed. Recently, the National Research Council of Canada (NRC) and the Fire Protection Research Foundation completed a 2-year international research project, with the support of private- and public-sector organizations, to determine some of the strengths and weaknesses of the various types of fire detection systems and the factors that can affect their performance in tunnel environments. The project included both laboratory and field fire tests combined with computer modeling studies. Although this research was conducted on road tunnels, the findings should apply to other tunnels, such as those used in subway systems. As part of the project, the NRC conducted two series of tests in the Carleton University-NRC tunnel facility to investigate the performance of detection systems under minimal and longitudinal airflow conditions. In addition, NRC conducted tests in the Carré-Viger Tunnel in Montréal, as well as a computer modeling study. The project studied nine fire detection systems that covered five types of currently available technologies. The performance of the detection systems, including response times and ability to locate and monitor a fire in the tunnel and the effect of the tunnel environment, were evaluated under the same conditions. This article 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 full-scale fire tests conducted in a laboratory tunnel facility and in an operating road tunnel as well as of the computer modeling activities is reported.

Keywords: fire detection systems, road tunnels, fire scenarios, field fire tests, laboratory fire tests, computer modeling, computational fluid dynamics, fire dynamic simulator

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

* Correspondence should be addressed to: A. Kashef, E-mail: ahmed.kashef@nrc-cnrc.gc.ca

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 2-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 provide input to 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.

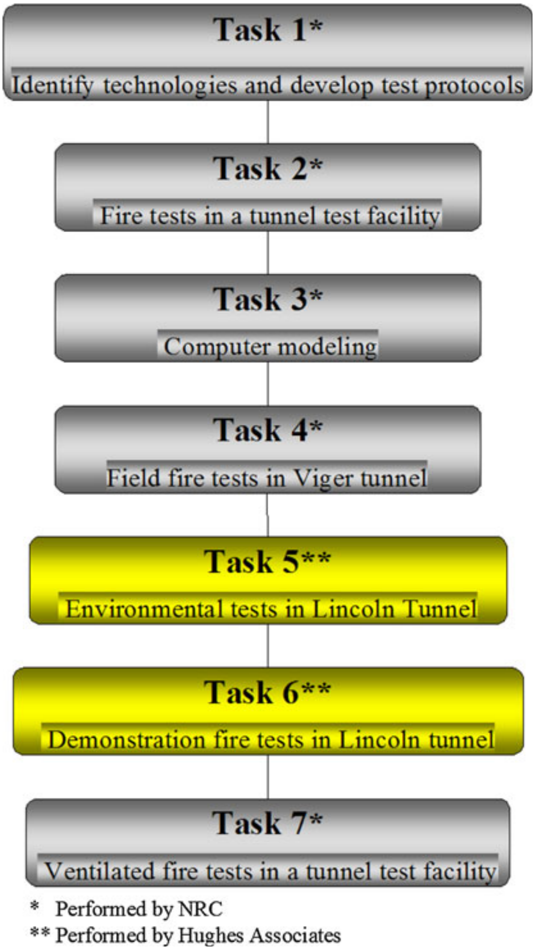

Figure 1. Project tasks.

This article provides an overview of the project as well as findings from the tasks carried out by NRC (Tasks 1, 2, 3, 4, and 7). Full details of the project and its findings and recommendations will be the subject of future publications.

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 video image detection (VID) systems, 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 Ref. [11].

Table 1
Fire Detectors/Detection Systems in the Project

Technology	System	System information	Detecting location
Linear heat	D-1L1	Fiber optic linear heat detection	Two parallel cables 2.5 m from the wall
	D-2L2	Analogue (co-axial cable) linear heat detection system	Two parallel cables 2.5 m from the wall
Flame	D-3F1	IR3 flame detector	30 m from fire source and 4.3 m from ground
CCTV	D-4C1	Visual flame and smoke detector	30 m from fire source and 4.8 m from ground
	D-5C2	Visual flame and smoke detector	30 m from fire source and 4.6 m from ground
	D-6C3	Visual flame detector	30 m from fire source and 4.2 m from ground
Spot heat	D-7H1	Heat detector with a fixed temperature	3 m spacing at the center of tunnel ceiling
	D-8H2	Rate-anticipation heat detector	15.2 m spacing at centerline of tunnel ceiling
Smoke	D-9S1	Air sampling system	Line at centerline of tunnel ceiling

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. Investigations on the performances of the fire detection systems in the project were focused on both their detection capability in fire incidents, including response times to a fire and ability to locate and monitor a fire in the tunnel as well as their reliability in harsh tunnel environments, including their nuisance alarm immunity and requirements for maintenance.

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 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 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 to 3,400 kW. Figure 2 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 develops slowly reaching its maximum HRR in 8–12 min [12, 13]. Two stationary

Figure 2. Pool fire underneath a vehicle.

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 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 and 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 National Research Council (NRC) full-scale fire test facilities. The dimensions of the test facility were 10 m wide $\times$ 5.5 m high $\times$ 37.5 m long (Fig. 4). The first series (Task 2) were conducted under minimum airflow speed conditions. 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 fire test series (Task 7) 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 to draw air through the east-end door. The airflow speeds in the test series were 0, 1.5 and 3 m/s.

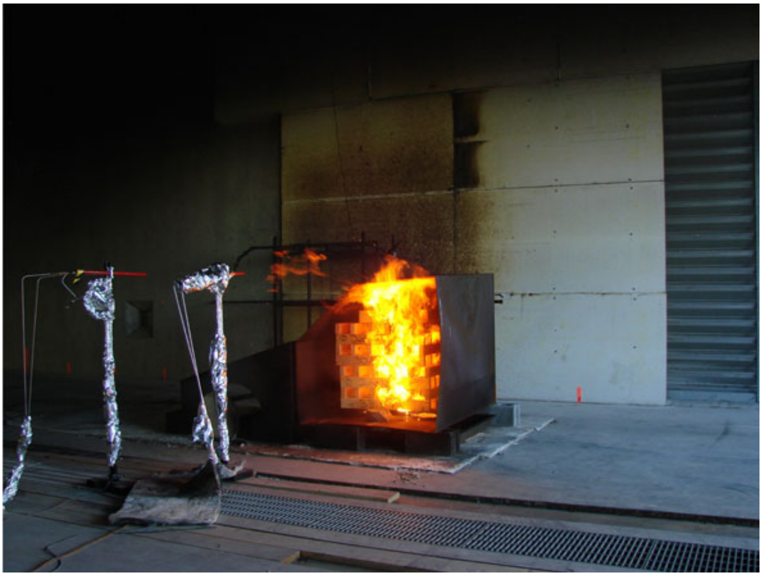

Figure 3. Simulated passenger compartment fire.

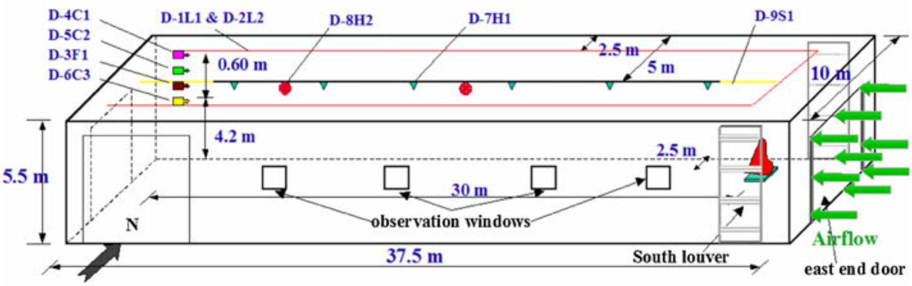

Figure 4. Schematic of the detection system setup in the laboratory tunnel.

The 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. 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. Detailed information on the tunnel facility, the location of fire detection systems and instrumentation in the test tunnel is provided in Ref. [14].

4.1. Tests under Minimum Airflow Conditions (Task 2)

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 Fig. 5. 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 (Fig. 6). One VID detector could not detect the fire located behind

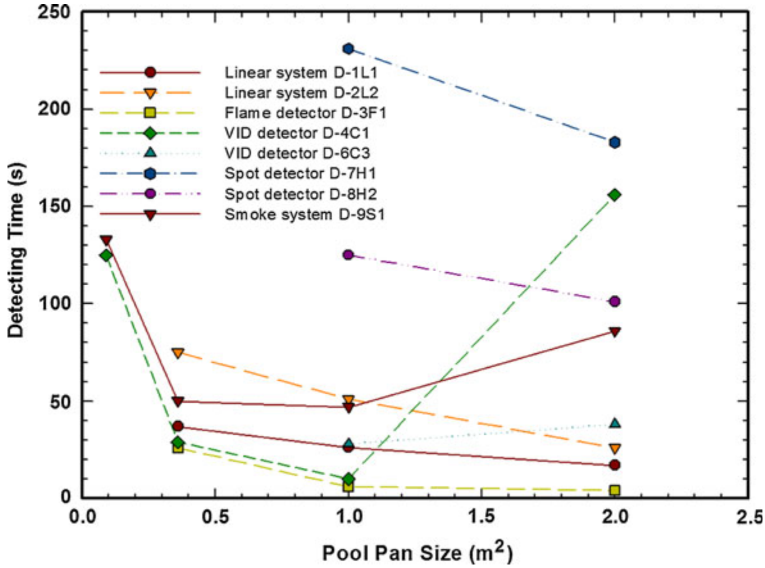

Figure 5. Detecting times—pool fires underneath vehicle.

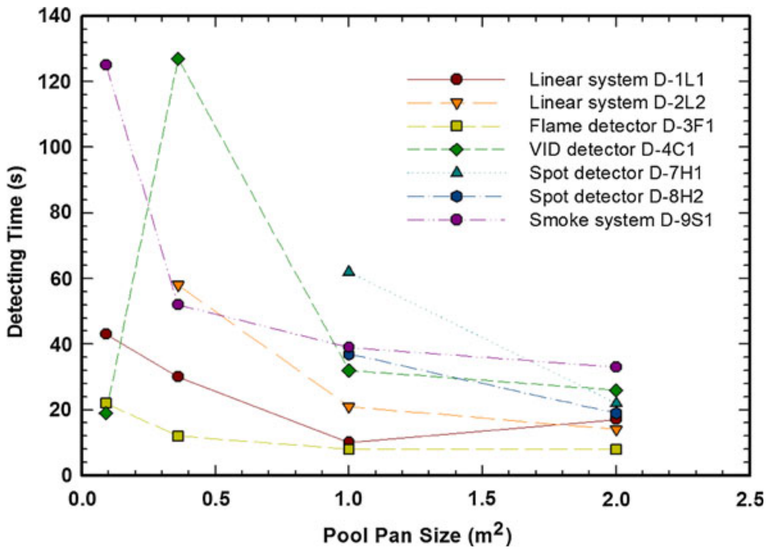

Figure 6. Detecting times—pool fires behind vehicle.

the vehicle, as the flames were not visible. For 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-1L1 system was the only detection system that was able to detect the moving fire at only one speed (27 km/h).

4.2. Tests under Longitudinal Airflow Conditions (Task 7)

For large pool fire underneath a vehicle scenario 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 Fig. 7. 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 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

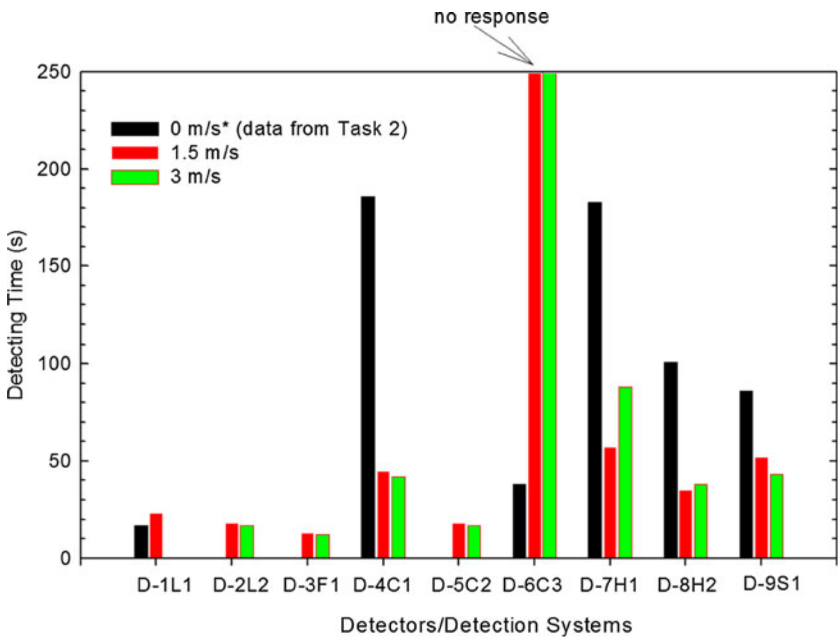

Figure 7. Detecting times—2 m^2 gasoline pool fire underneath vehicle.

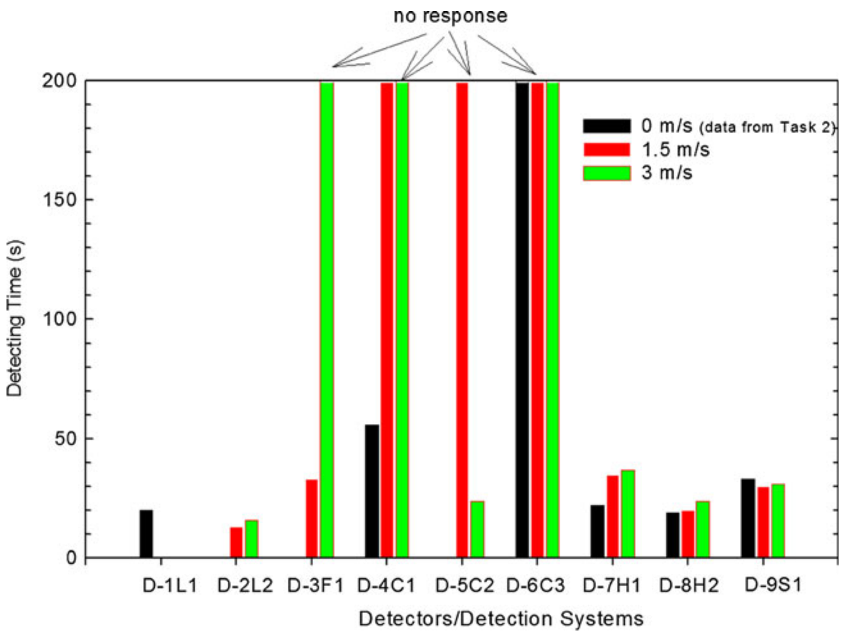

Figure 8. Detecting times—2 m^2 gasoline pool fire behind vehicle.

detection systems to these fire scenarios generally increased (Fig. 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 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 Figs. 7 and 8 "no response" phrase meant that the test was terminated before the detection systems detected the fire.

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 (Fig. 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.

Six detection systems were installed in the Viger tunnel, including one optical flame detector, three visual VID 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

Figure 9. Carré-Viger tunnel.

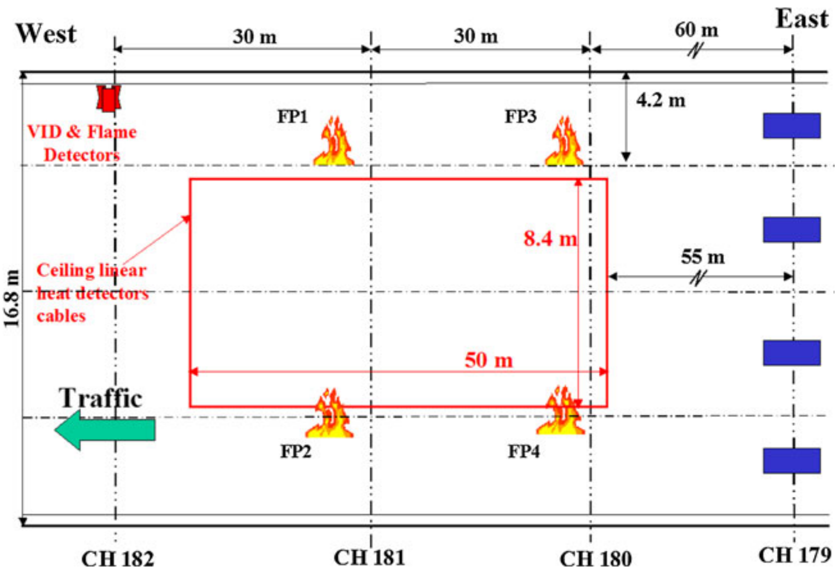

Figure 10. Field fire tests in Viger tunnel.

tests. Three types of fire scenarios were used in the test series: 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 Fig. 10. Four longitudinal airflow speeds were used in the tests by operating the jet fan system mounted in the tunnel: 0, 1.3, 2 and 2.4 m/s. Instrumentation that was used in the test series included thermocouples, smoke meters, velocity meters and video cameras.

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 fire location (Fig. 11). 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 and 2.0 m/s (Fig. 12). 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 with depending on the airflow conditions. The shape of the temporal fluctuations of the visual flame caused both increased and decreased response times.

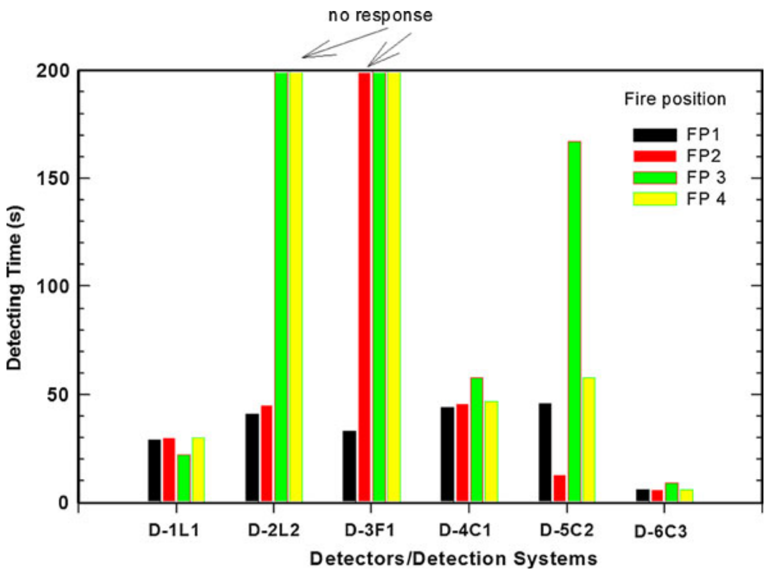

Figure 11. Detecting times—0.02 m^2 open fire.

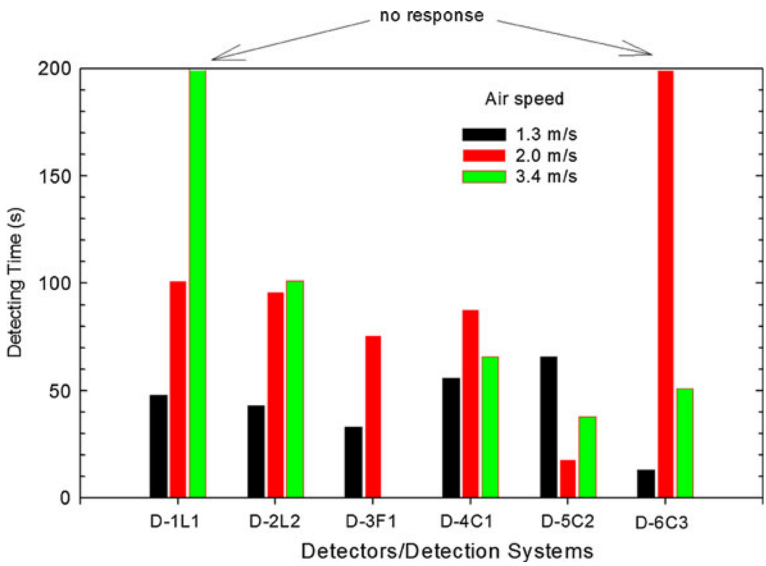

Figure 12. Detecting times—0.36 m^2 fire under vehicle.

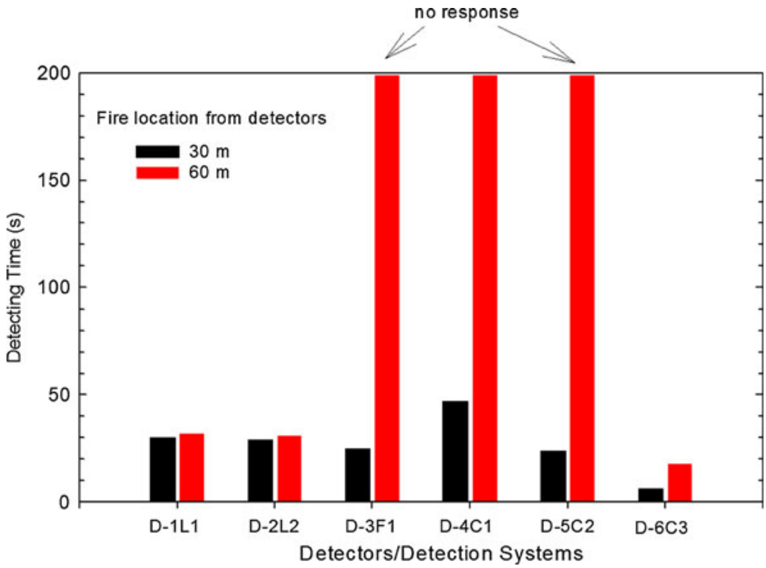

Figure 13. Detecting times—0.36 m^2 fire behind vehicle (wind speed 1.3 m/s).

The detector response times to a 0.36 m^2 fire behind a vehicle are summarized in Fig. 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 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.

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 behavior 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.

Twenty CFD simulations were conducted to replicate laboratory and field full-scale experiments. 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 measurements points.

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 to 3,400 kW with various growth rates (1–12 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 OD measurements. Figure 14 shows the comparisons of ceiling temperatures for the simulation of a 1.0×2.0 m pool fire under a vehicle for a test in the laboratory tunnel without longitudinal airflow.

The comparisons of ceiling temperatures were, in general, favorable. 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.

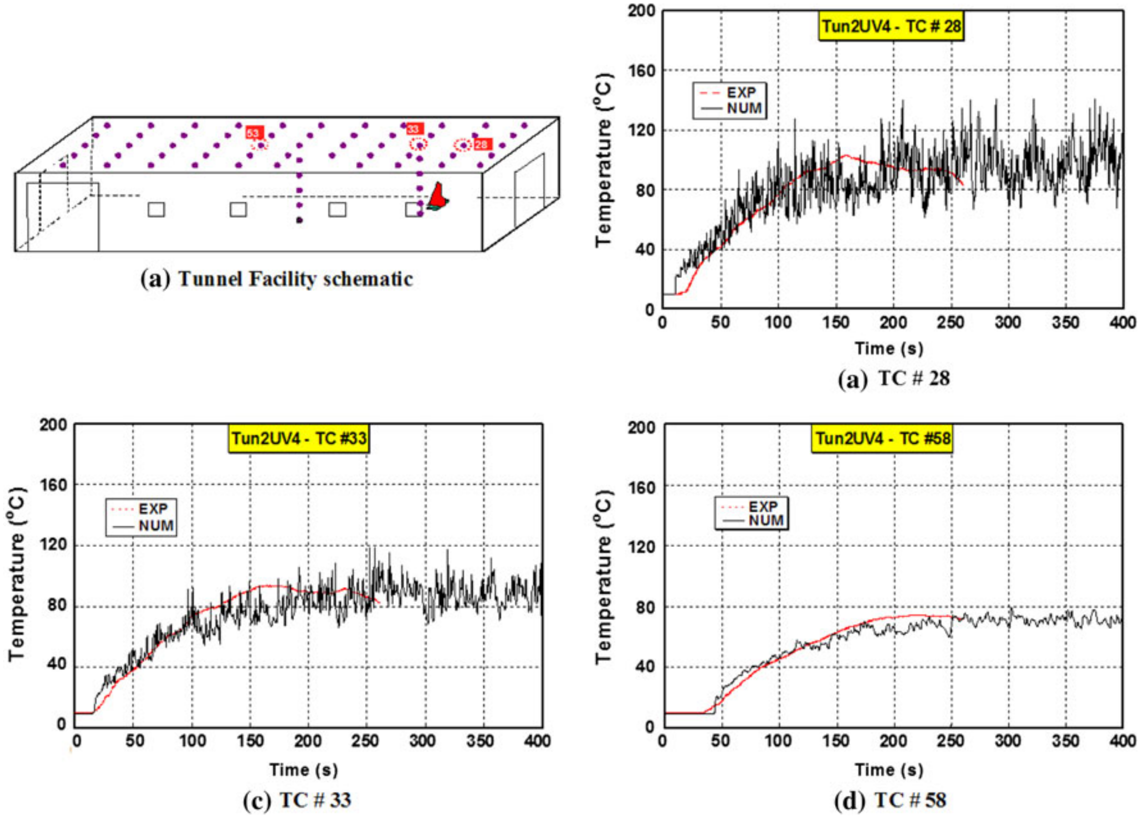

Figure 14. Temperature comparisons—1.0 × 2.0 gasoline pool fire under vehicle.

Figure 15 shows the comparison of the numerical predictions of smoke OD against the experimental data for the 1.0 × 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, 2.5, 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 favorable 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 behavior 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 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 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 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°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 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.

7. 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

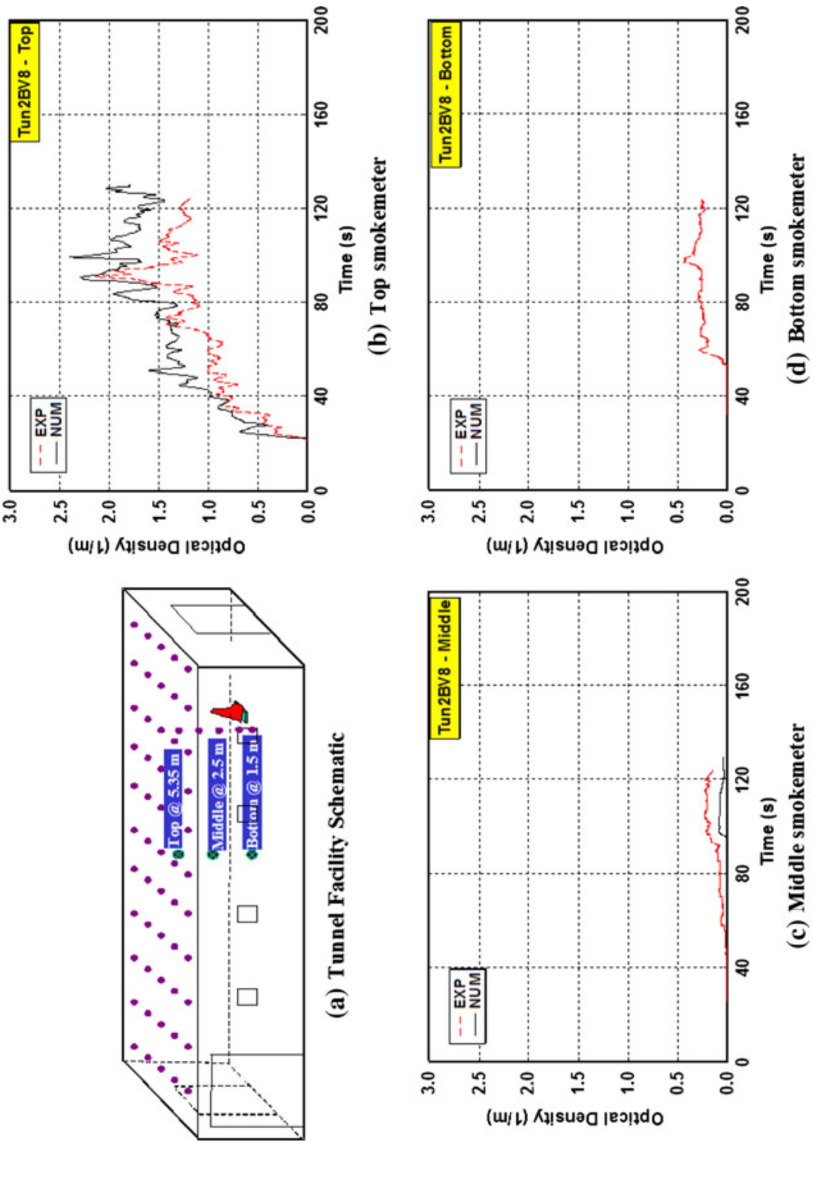

Figure 15. Smoke OD comparisons—1.0 × 2.0 gasoline pool fire behind vehicle.

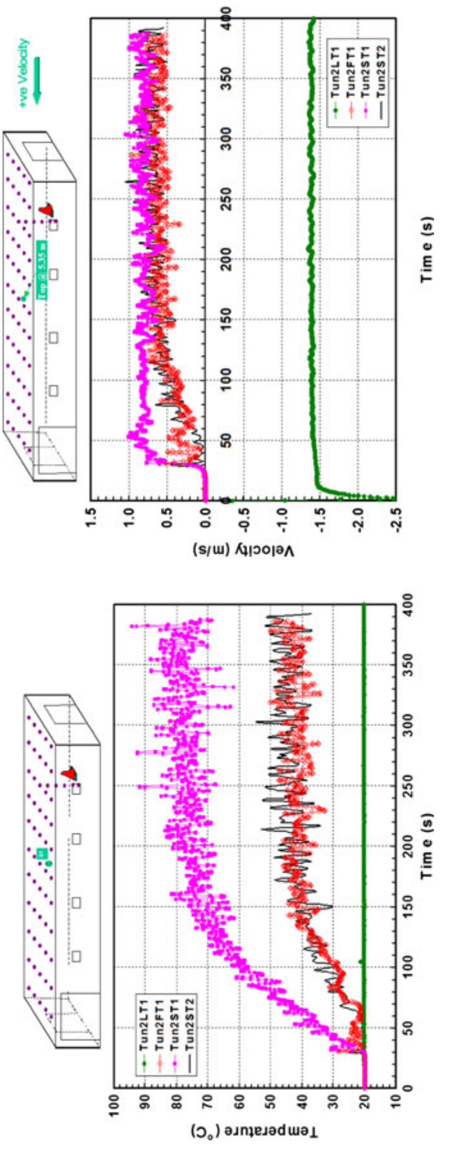

Figure 16. Temporal temperature and airflow speed at mid-tunnel section.

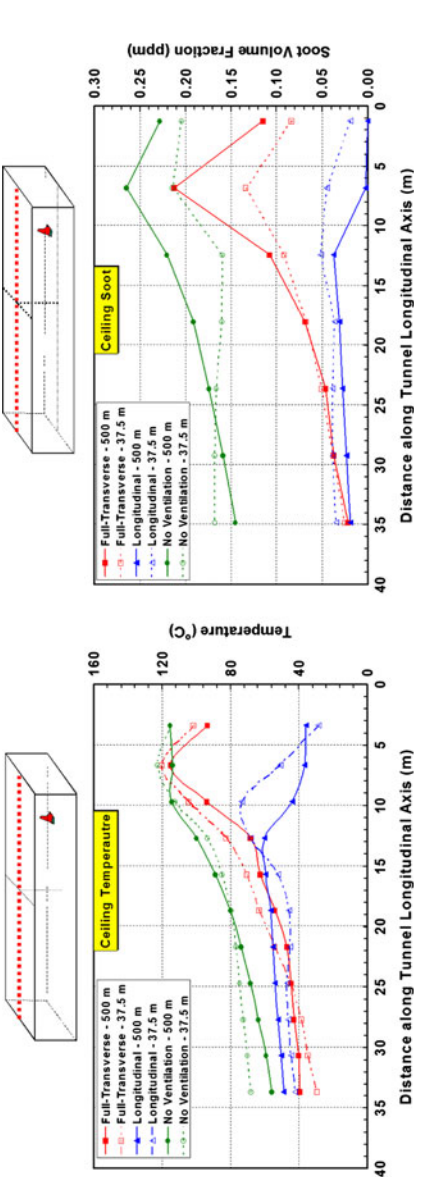

Figure 17. Average ceiling airflow temperature and soot volume fraction along the tunnel.

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. The general performance of each type of technology can be summarized as follows:

1. *Linear heat detection systems* The linear heat detection systems had good response to the fire scenarios, based on rate of temperature rise. Longitudinal airflow in the tunnel delayed the response time for these systems for most scenarios as the temperature at the ceiling decreased with the tilting of the flame and cooling of the fire plume by the airflow. The one scenario in which there was a faster response with a longitudinal airflow was a large shielded fire under a simulated vehicle. In this case, the size of the fire increased resulting in faster response times.

   The fiber-optic based linear heat detection system could also determine the fire location. However, under longitudinal airflow, the hot spot at the ceiling could be shifted downstream and the actual fire location could be up to 10 m from the location indicated by the detection system.
2. *Flame detector* The flame detector as with other systems that relied on field-of-view (FOV) had difficulty detecting fires located under a vehicle, behind a vehicle or inside a vehicle. The response time to these scenarios were increased under longitudinal airflow conditions as the flames were tilted and, as a result, there was an increased concealment of the flames by obstacles. To deal with obstructions, most manufacturers of FOV detectors recommend two detectors covering the same area from different angles, such as from both directions within a tunnel.
3. *Video imaging detection (VID) systems* Three types of VID systems were investigated in the project. There was a variation in the performance of the system depending on the method used to determine the presence of a fire. All the systems were able to detect small open fires within their detection range (60 m). Those systems that relied on flame characteristics and thus field-of-view had difficulty detecting concealed fires (under a vehicle, behind a vehicle or inside a vehicle). The detectors that utilized both flame and smoke characteristics had better response for the concealed fire scenarios. The two detectors that used both flame and smoke characteristics were not affected or the response time improved with airflow in the tunnel as detector response was primarily dependent on the detection of smoke.

   The longitudinal airflow in the tunnel affected the build-up of smoke in the tunnel downstream of the fire. This increased build-up of smoke decreased the time available for detectors dependent on field-of-view to detect a fire and thus detection did not occur in several instances. As noted under flame detectors, the use of multiple detectors would be required to provide effective coverage.
4. *Spot heat detectors* Spot heat detectors were used only in the laboratory tunnel tests under minimal airflow and with longitudinal airflow. Under minimal airflow conditions, the detectors were not able to detect small fires. They only

responded to fires of 1,500 kW or larger. Longitudinal airflow in the tunnel delayed the response time for these systems for most scenarios as the temperature at the ceiling decreased with the tilting of the flame and cooling of the fire plume by the airflow. The one scenario in which there was a faster response with a longitudinal airflow was a large shielded fire under a simulated vehicle. In this case, the size of the fire increased resulting in faster response times.
5. *Smoke detection system* An air sampling smoke detection system was included in both laboratory tunnel test series. The system was able to detect all the fires in the laboratory tunnel except those using in propane burner, which produced a limited amount of smoke. The longitudinal airflow affected the response of the smoke detection system. For the scenarios with pool fires behind a simulated vehicle and large pool fires located under a simulated vehicle, the response time decreased as the amount of smoke produced increased with airflow in the tunnel. There was an increase from approximately 50 s to approximately 150 s in response time for the scenario with the small fire under a simulated vehicle. In this case, smoke optical density was decreased by the airflow in 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 detector, linear heat detection systems, and smoke aspiration detection systems. However, more effort is required to relate CFD data 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.

The research program has provided valuable information to detection system manufacturers, which will lead to further improvements in technology. In the meantime, tunnel specialists can use the information from this study in determining the most appropriate technology for their application. The NFPA Technical

Committee responsible for Standard 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, will be considering this information in the further development of the standard.

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References

1. PIARC (1999) Fire and smoke control in road tunnels. World Road Association, Chongqing
2. NFPA 502 (2004) Standard for road tunnels, bridges, and other limited access highways. National Fire Protection Association, Quincy
3. U.S. Department of Transportation Federal Highway Administration (1984) Prevention and control of highway tunnel fires. FHWA-RD-83-032
4. Zalosh R, Chantranuwat P (2003) International road tunnel fire detection research project, phase 1: review of prior test programs and tunnel fires. The Fire Protection Research Foundation (November)
5. Ishii H, Kawamura K, Ono T, Megumi H, Kikkawa A (1997) A fire detection system using optical fibres for utility tunnels. Fire Safety J 29:87–98
6. Mashimo H (2002) State of the road tunnel safety technology in Japan. Tunn Undergr Space Technol 17:145–152
7. Magerle R (2001) Fire protection systems for traffic tunnels under test. In: Proceedings AUBE 01 conference, NIST
8. Azuma T, Gunki S, Ichikawa A and Yokota M (2004) Effectiveness of a flame sensing type fire detector in a large tunnel. In: 6th international conference on safety in road and rail tunnels, Marseilles, France, October
9. Brugger S (2004) Rapid fire detection concept for road tunnels. In: 5th international conference on safety in road and rail tunnels, Marseilles, France, October
10. Liu ZG, Kashef A, Lougheed GD, Su JZ, Bénichou N, Almand KH (2006) An overview of the international road tunnel fire detection research project. In: 10th fire suppression and detection research application symposium, Orlando, FL., U.S.A. February 01
11. Liu ZG, Crampton GP, Kashef AH, Lougheed GD, Gibbs E, Su JZ, Benichou N (2006) International road tunnel fire detection research project—phase II: task 1, fire detectors, fire scenarios and test protocols. NRCC Client Report (B-4179.1), July

12. Mangs J, Keski-Rahkonen O (1994) Characterization of the fire behaviour of a burning passenger car, part I: car fire experiments. Fire Safety J 23:17–35
13. Mangs J, Keski-Rahkonen O (1994) Characterization of the fire behaviour of a burning passenger car, part II: parametrization of measured rate of heat release curves. Fire Safety J 23:37–49
14. Liu ZG, Crampton GP, Kashef AH, Lougheed GD, Gibbs E, Muradori S (2007) International road tunnel fire detection research project—phase II: task 2, full-scale fire tests in a laboratory tunnel. NRCC Client Report (B-4179.2), November
15. McGrattan KB (2005) Fire dynamics simulator (version 4)—technical reference guide. NIST Special Publication 1018, National Institute of Standards and Technology, Gaithersburg, MD