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Liu, Z.G.; Kashef, A.; Loughheed, G.D.;
Crampton, G.P.

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INVESTIGATION ON THE PERFORMANCE OF FIRE DETECTION SYSTEMS FOR TUNNEL APPLICATIONS – PART 2: FULL-SCALE EXPERIMENTS UNDER LONGITUDINAL AIRFLOW CONDITIONS

Z. G. Liu¹, A. Kashef, G. Loughheed*, G. Crampton
Fire Research Program, Institute for Research in Construction
National Research Council of Canada, Ottawa, Canada, K1A 0R6,

ABSTRACT

This paper presents the results of the full-scale experiments conducted in a laboratory tunnel facility under longitudinal airflow conditions and in the Carré-Viger Tunnel. The performance of nine fire detection systems representing five types of the fire detection technologies for road tunnel applications was investigated using representative tunnel fire scenarios. The changes in fire characteristics caused by longitudinal airflow, such as fuel burning time, fire growth rate, temperatures and smoke spread in the tunnel, were measured and analyzed. The experimental results showed that the detection time of the fire detection systems under longitudinal airflow conditions could be increased or decreased, depending on the fuel type, fire size and location, airflow velocity and detection method.

Key words: road tunnel, longitudinal airflow, fire detection, pool and vehicle fires

1. INTRODUCTION

Longitudinal airflow is common in road tunnels. It can be produced by natural airflow due to air temperature and meteorological conditions, by traffic flow in the tunnel, or by the operation of tunnel mechanical ventilation system to maintain air quality in the tunnel [1]. Although there are many studies on the use of emergency ventilation systems for fire and smoke control [2-5], there have been few investigations on the effect of ventilation conditions on the performance of fire detection systems in tunnel environment.

One study conducted by Ministry of Transport of the Netherlands has investigated the effect of longitudinal airflow on the performance of linear heat detection systems in an operating road tunnel in 2002 [6]. The air speed in the tests ranged from 1 m/s to 5 m/s. Pool fires and simulated vehicle fires were used in the tests. The test results showed that the detection time was delayed with longitudinal airflow or there was no response with high airflow speed. Also, the fire location identified by the detection systems was not the real fire position as the fire plume was tilted.

A second study was conducted by the Japan Highway Public Corporation to evaluate the effect of longitudinal airflow on the performance of optical flame detectors in an operating road tunnel [7]. The air speeds in the tests were 5 m/s and 8 m/s. Three pool fire sizes ranging from 0.5 MW to 2.1 MW were used. The study demonstrated that optical flame detectors were able to detect all the fires presented under longitudinal airflow conditions. However, the detection time increased with an increase in wind speed.

¹Now with CAFS UNIT Inc., Ottawa, ON

*Correspondence should be addressed to: Gary Loughheed, E-mail: gary.loughheed@nrc.ca

These two studies provide useful information regarding the performance of linear heat detection systems and optical flame detectors under longitudinal airflow conditions. However, their performances were only evaluated using open pool fires. Their performances for other representative tunnel fire scenarios, such as stationary vehicle fires and obstructed pool fires, were not considered. In addition, the impact of longitudinal airflow on the performance of other types of fire detection technologies, such as spot heat detectors, smoke detection systems and video image detectors (VID) were not studied. As a result, the effect of ventilation on the performance of fire detection systems in tunnel environment was identified as an important issue to be investigated [8].

A two-year international research project, with support of government organizations, industries and private sector organizations, was recently conducted to investigate currently available fire detection technologies for tunnel applications [9]. As part of the project, the effect of longitudinal airflow on the performance of fire detection systems was investigated. A series of fire tests were conducted in both a laboratory tunnel facility and the Carré-Viger tunnel in Montreal under longitudinal airflow conditions. In addition, the performance of the fire detectors in an operating tunnel environment and at their maximum detection range was also investigated in the Carré-Viger tunnel.

Nine fire detectors/detection systems representative of five types of fire detection technologies were evaluated in the test series. They included linear heat detection systems, an optical flame detector, VID fire detectors, an air-sampling smoke detection system and spot heat detectors. The tunnel fire scenarios used in the test series were non-obstructed and obstructed pool fires, and stationary vehicle fires. The fuels used in the tests included gasoline, wood crib and plastic foam. The fire sizes varied from approximately 650 kW to 3,400 kW as measured using an open calorimeter under natural ventilation conditions. The longitudinal airflow speed was varied from 0 m/s to 3 m/s in the tests conducted in the laboratory tunnel facility, and from 0 m/s to 2.4 m/s in the Carré-Viger tunnel. The airflow in the tunnel was toward the fire detectors that were mounted on the tunnel wall. This was the most challenging scenario to the detectors.

The test results in the laboratory tunnel facility with minimal airflow conditions are provided in the part 1 of this paper [10]. The Part 2 of this paper presents the results of the full-scale experiments conducted in the laboratory tunnel and in the Carré-Viger tunnel under longitudinal airflow conditions.

2. TEST TUNNELS

A detailed description of the laboratory tunnel facility is provided in the reference [11]. The door at the East end of the tunnel was open during the ventilation tests. The door at the West end of the tunnel and two side louvers at the East end of the tunnel were closed. The mechanical fan system mounted on the tunnel was operated. An airflow entered the tunnel through the open door at the East end, and then vented out through the five ceiling openings near the West end of the tunnel. This provided a longitudinal airflow in the tunnel.

The distribution of the air velocity in the tunnel was measured by placing an air velocity measuring tree at the thirty-nine predetermined points in a series of non-fire tests [12]. There were seven meters on the tree spaced at 0.6 m intervals starting 0.8 m above the ground. Each air velocity meter was calibrated prior to the tests. The data was collected at a one-second interval using a portable handheld data logger. In order to ensure that the target air velocity was achieved, the air velocity around the fire was measured prior to each fire test.

The Carré-Viger Tunnel is a road tunnel in Montreal (Figure 1). The section used for the tests was 400 m long, 5 m high and 16.8 m wide (representing 4 lanes). The tunnel is equipped with four jet fans for longitudinal ventilation [13]. The capacity of each jet fan is 23.6 and 14.2 m³/s in the supply and exhaust modes, respectively. Each jet fan can operate on its own or in combination with other fans. The ventilation flows can be adjusted as needed.

Air velocity measurements in the Carré-Viger Tunnel were conducted at a number of cross sections of the tunnel, including the section where the fire was located using a velocity meter. The measurement locations were 60 m, 90 m, 150 m and 210 m from the fans. The velocities were measured at 9 points at each location. Measurements were taken prior to and during the tests.

3. FIRE DETECTION SYSTEMS

Nine fire detection systems were evaluated in the test series in the laboratory tunnel facility. These detection systems were the same ones used in the previous minimum airflow tests [10]. The setup and locations in the tunnel were also the same as in the previous tests. A detailed description of the detectors and systems was provided in the reference [10].

The sensitivity levels of five of the fire detectors/detection systems in the test series were the same as in the previous minimum airflow tests [10]. However, the sensitivity levels of the linear heat detection system D-2L2, the optical flame detector D-3F1, the flame/smoke VID detector D-4C1 and the VID fire detector D-5C2 were modified by the system suppliers, based on their performances in environmental tests in the Lincoln Tunnel [14] and in the minimum airflow tests [10].

The fixed fire alarm temperature of the linear heat detection system D-2L2 remained at 70°C. Its rate of rise of temperature criteria was lowered to 7°C/min from the previous 10°C/min. The sensitivity level of the optical flame detector D-3F1 was decreased to the medium level from the previous very high level. The sensitivity level of the flame/smoke VID detector D-4C1 was not changed during the tests, but a 30 s pre-alarm period was added, once a fire signal was received by the system. The pre-alarm period was used to validate if the signal was a real fire alarm or a nuisance alarm. System D-5C2 was converted to be a flame/smoke VID detection system from the flame detection system used in minimum airflow tests. It responded to a fire incident, once the characteristics of flame and smoke produced in a fire incident were identified. General information on the detectors

and systems used in the tests is summarized in Table 1. A schematic showing the locations of the detection systems is provided in Reference [10].

Table 1. Fire Detection Systems in Test Series.

Technology	System no.	System information	Alarming threshold
Linear heat	D-1L1	Optical fiber linear heat detection	Level 1: 60°C, 10°C/min; Level 2: 100°C, 15°C/min;
	D-2L2	Analogue (co-axial cable) linear heat detection system	Fixed Temp: 70°C, Rate of rise: 7°C/min;
Flame	D-3F1	IR3 flame detector	Sensitivity: medium (0.3 m x 0.3 m n-heptane fire at 30.5 m on-axis).
Video image detector	D-4C1	Flame/ smoke video image detector	Flame: low (25%); Offsite: 50% Smoke: normal Pre-alarm period: 30 s
	D-5C2	Flame/smoke video image detector	Intensity: 60 Mean crossing: 4 Inten. standard deviation: 16 Flicker mask counter: 16
	D-6C3	Flame video image detector	Sensitivity: 10 kW fire at 30m.
Spot heat	D-7H1	Heat detector with a fixed temperature	79.5°C fast response bulbs
	D-8H2	Rate-anticipation heat detector	Fixed Temp: 57.2°C
Smoke	D-9S1	Air sampling system	Fire threshold: 0.203%/m

Six fire detectors/detection systems were used in the test series in the Carré-Viger Tunnel in Montreal. They were: two linear heat detection systems D-1L1 and D-2L2, one optical flame detector D-3F1, and three video image detection (VID) systems D-4C1, D-5C2 and D-6C3. The sensitivity levels of these fire detectors/detection systems were the same as in the laboratory tunnel facility under longitudinal airflow conditions.

A schematic showing the set-up of the detectors/detection systems in the Carré-Viger Tunnel is shown in Figure 1. The sensing cables of the two linear heat detection systems D-1L1 and D-2L2 were installed on the ceiling of the tunnel in a loop with a dimension of 8.4 m wide and 50 m long. The sensing cables were 80 mm below the ceiling and 4.2 m from the wall of the tunnel. The total length of the two linear heat detection systems D-1L1 and D-2L2 were approximately 2,230 m and 140 m, respectively.

The optical flame detector and three VID fire detectors were fastened to a lift vehicle and located near the North wall of the tunnel to simulate wall-mounted detectors. The height of the optical flame detector D-3F1, the VID flame/smoke detector D-4C1, the VID flame/smoke detector D-5C2 and the VID flame detector D-6C3 above the ground were approximately 4 m, 4.5 m, 4.3 m and 3.9 m, respectively.

The distance between the wall-mounted detectors and the nearest section of the linear heat detectors was approximately 25 m. The distance between the jet fans and the linear heat detectors and the wall mounted detectors were 55 m and 90 m, respectively.

Figure 1. Schematic of detection systems and fire setup in the Viger Tunnel.

4. INSTRUMENTATION

The instrumentation for the longitudinal airflow tests conducted in the laboratory tunnel facility was the same as used in the minimum airflow test series. The instrumentation included thermocouples, heat flux meters, smoke meters, velocity meters and video cameras. A detailed description of the instrumentation is provided in reference [10].

Instrumentation used in the Carré-Viger Tunnel included thermocouples, smoke meters, velocity meters and video cameras. Three thermocouple trees were distributed in the tunnel to monitor temperatures produced by the fires. Thermocouple tree #1 was located near the fire source in each test to measure the flame/plume temperature of the fire and to monitor the fire development. The locations of the other thermocouple trees (#2 and #3) were fixed in the tunnel. They were placed at the middle of the tunnel 15 m and 30 m downstream of the fire, respectively, when the fire was located 30 m from the detectors mounted on the wall of the tunnel. The thermocouple trees were 45 m and 60 m downstream of the fire, when the fire was located at 60 m from the detectors. There were five thermocouples on each tree spaced at 1.0 m intervals starting 1 m above the tunnel floor.

Two smoke meters were attached to thermocouple trees #2 and #3 to measure the smoke optical density and monitor the smoke spread in the tunnel. There was a 0.6 m vertical light path between the transmitter and the receiver for each smoke meter. The first smoke meter on the thermocouple trees was located near the ceiling with its mid-point approximately 0.3 m below the ceiling. The second smoke meter had its mid-point 2.3 m below the ceiling.

A vane anemometer mounted on a 4 m long aluminum pole was used to measure the air velocity in the tunnel. The air velocity was manually recorded during the tests.

Two video cameras were used to record and monitor fire conditions in the tests. One video camera was located near the wall-mounted detectors. It was used to monitor conditions in the tunnel between the fire and the detectors. The second video camera was placed near the fire source. It was used to monitor the fire conditions from behind the fire towards the detectors.

Four data acquisition systems were used. There was one system for each thermocouple tree used to collect temperature and smoke data. One system was located near the fire detectors/detection systems and was used to monitor the response of the detectors/detection systems to the fires. The test data was collected at a 1 s time interval.

5. TEST PROCEDURE

The general test procedure used in the test series was as follows:

- Activated fan systems;
- Measured air velocities around the fuel pan;
- Started the data acquisition system and video recorders for 60 s, and then manually ignited the fire;
- The test was terminated once the fuel in the pan was burnt out and the fire was self extinguished;
- Checked each detection system to determine if it still functioned properly after the fire test.

6. FIRE SCENARIOS

Three representative tunnel fire scenarios were selected and used in the laboratory tunnel test series, based on the previous minimum airflow tests [10]. They were gasoline pool fires located underneath a simulated vehicle, gasoline pool fires located behind a simulated large vehicle, and a solid material fire located inside the passenger compartment of a simulated stationary vehicle. The setups of the fire scenarios and location of the fire were remained the same as in the previous minimum airflow tests [10].

Three pans with a size of 0.6 m x 0.6 m, 1.0 m x 1.0 m and 1.0 m x 2.0 m were used for scenarios with a pool fire located underneath the vehicle. Two pans with a size of 1.0 m x 1.0 m and 1.0 m x 2.0 m were used for scenarios with a pool fire located behind a large vehicle. The passenger compartment fire was set up with a wood crib and a large piece of polyurethane foam.

Nine full-scale fire tests were conducted in the Carré-Viger Tunnel using three fire scenarios. The scenarios included unobstructed gasoline pool fires, gasoline pool fires located underneath a simulated vehicle, and gasoline pool fires located behind a simulated large vehicle. The fire sizes in the tests varied from approximately 125 kW to 650 kW. The fire size was limited to minimize possible damage to equipment and the tunnel. The scenarios were similar to ones used in the laboratory tunnel tests [10].

For tests conducted in the Carré-Viger Tunnel, the fires were placed at different locations to evaluate the detection capability of the fire detectors/detection systems at the maximum detection distance and coverage areas. Figure 1 shows the locations of the fires in the tunnel. Detailed information on the fire locations is as follows:

- Fire Position 1 (FP 1) was located in Lane 1 of the tunnel and approximately 33 m from the detectors mounted at the North wall of the tunnel, 4.8 m from the North wall of the tunnel and 0.6 m from the nearest section of the linear heat detector cables.
- Fire Position 2 (FP 2) was located in Lane 4 approximately 35 m from the detectors mounted at the North wall of the tunnel, 12.8 m from the North wall of the tunnel and 0.2 m from the nearest section of the linear heat detector cables.
- Fire Position 3 (FP 3) was located in Lane 1 approximately 60 m from the detectors mounted at the North wall of the tunnel, 4.8 m from the North wall of the tunnel and 0.6 m from the nearest section of the linear heat detector cables.
- Fire Position 4 (FP 4) was located in lane 4 approximately at 61.5 m from the detectors mounted at the North wall of the tunnel, 12.8 m from the North wall of the tunnel and 0.2 m from the nearest section of the linear heat detector cables.

The distance of the fire at positions FP 1 and FP 3 to the North wall of the tunnel (4.8m) was greater than used in the laboratory tunnel tests (2.5 m). This gave a wider view for the detectors mounted on the wall to monitor the fire.

7. RESULTS

7.1 Fire Tests in the Laboratory Tunnel Facility

Fifteen full-scale fire tests were conducted in the laboratory tunnel. The targeted air velocities in the tunnel were: 0 m/s, 1.5 m/s and 3 m/s. The airflow in the tunnel was toward the fire detectors that were mounted on the tunnel wall. The effect of airflow on the response time of detection systems and their ability to locate and monitor the fire incident was investigated. The changes in fire behaviour, such as the fire growth rate, temperature and smoke spread in the tunnel under longitudinal airflow conditions, were measured.

7.1.1 Pool Fires Located underneath Vehicle

Fire tests were conducted with longitudinal airflow in the tunnel with three sizes of gasoline pool fires located under the simulated vehicle: 0.6 m x 0.6 m, 1.0 m x 1.0 m and 1.0 m x 2.0 m. One test was conducted with airflow of 0 m/s for 0.6 m x 0.6 m pan size duplicating a test conducted with minimum airflow conditions [10]. Tests with airflow velocities of 1.5 and 3.0 m/s were conducted with all the fire sizes.

The air velocities around the simulated vehicle were measured prior to each test. For the targeted air velocity of 1.5 m/s in the tunnel, the air velocity varied from 1.4 m/s to 1.7 m/s upstream of the vehicle and 0.9 m/s to 1.1 m/s downstream of the simulated vehicle due to blockage by the vehicle body. For the targeted air velocity of 3 m/s in the tunnel, the air velocity varied from 2.8 m/s to 3.3 m/s upstream of the vehicle and 1.9 m/s to 2.1 m/s downstream of the simulated vehicle.

Tests showed that the airflow in the tunnel affected the flame size and geometry (Figures 2 and 3). With minimal airflow, the flame that extended from the front and sides of the simulate vehicle became vertical near the vehicle. With airflow, the flame was tilted towards the ground. At an airflow speed of 3 m/s, the flame produced by the small 0.6 m x 0.6 m pool fire became unstable and short (Figure 2c).

It was difficult to identify the flame from the front of the vehicle (Figure 2d), as the fire plume was shielded by the vehicle. The impact of airflow on the fire plume was reduced with an increase in fire size. As shown in Figures 2b and 3a at the same wind speed of 1.5 m/s, the angle of the fire plume with respect to the ground was increased with an increase in the fire size. In addition, more flames and smoke were produced by large pool fires and they were clearly identified from the front of the vehicle (Figures 3c).

Figure 2. A 0.6 m x 0.6 m gasoline pool fire located underneath the vehicle with longitudinal airflow.

Figure 3. A 1.0 m x 2.0 m gasoline pool fire located underneath the vehicle with longitudinal airflow.

The smoke produced by the fire under longitudinal airflow conditions was directly blown toward the fire detectors mounted on the sidewall of the tunnel. The available time for VID detectors to respond to and to monitor the fires in the tunnel was affected, depending on fire size and airflow velocity. The smoke produced by the small 0.6 m x 0.6 m fire was limited and was quickly vented from the tunnel. The visibility in the tunnel was not affected much and the detectors were able to monitor the fires in whole test period. However, the visibility time decreased to 98 s from 122 s with an increase in fire size from a 1.0 m x 1.0 m pan to a 1.0 m x 2.0 m pan with an airflow speed of 1.5 m/s. When the wind speed increased to 3 m/s, the visibility time was reduced to 70 s for both large fires. The rapid decrease in visibility under airflow conditions presented a challenge to the detectors that responded to the fire based on visual flame and smoke images.

Test results also showed that the airflow had a significant impact on the ceiling temperature and its distribution, depending on the fire size and airflow velocities. The ceiling temperature produced by the small 0.6 m x 0.6 m pool fire decreased with an increase in airflow velocity in the tunnel (Figure 4). However for the two larger pool fires, the temperature at the ceiling varied with airflow in the tunnel (Figures 5 and 6). The highest temperature at the center of the tunnel was measured in the tests with an airflow velocity of 1.5 m/s.

With airflow in the tunnel, the hot spot at the ceiling was shifted downstream of the fire source. The shift distance increased with an increase in airflow velocity, as shown in Figure 7, but decreased with an increase in fire size.

Figure 4. Ceiling temperature at the center of the tunnel with a 0.6 m x 0.6 m pan fire at three airflow velocities

Figure 5. Ceiling temperature at the center of the tunnel with a 1.0 m x 1.0 m pan fire at three airflow velocities.

Figure 6. Ceiling temperature at the center of the tunnel with a 1.0 m x 2.0 m pan fire at three airflow velocities

Figure 7. Maximum ceiling temperature along the center of the tunnel with a 1.0 m x 2.0 m pan fire at three airflow velocities

Similar trends were noted for the smoke optical density measured near the ceiling at the center of the tunnel facility. As shown in Figure 8, the smoke optical density produced by the 0.6 m x 0.6 m pool fire significantly decreased with an increase in airflow speed, as the fire plume was difficult to reach the ceiling. However, with the larger pool fires, there was an increase in the peak smoke optical density with airflow. As shown in Figure 9, more smoke was produced by the 1.0 m x 2.0 m fire with airflow in the tunnel. The peak smoke optical density at an airflow velocity of 1.5 m/s was similar to that at airflow velocity of 3 m/s.

Figure 8. Smoke density near the tunnel ceiling for a 0.6 m x 0.6 m fire at three airflow velocities.

Figure 9. Smoke optical density near the tunnel ceiling for a 1.0 m x 2.0 m fire with three airflow velocities.

The temperature and smoke optical density measurements and the flame dynamics suggest that there were likely two factors that affected the conditions in the tunnel for a gasoline pool fire located under a simulated vehicle:

- The airflow in the tunnel cooled the fire plume and the smoke layer in the tunnel.
- The airflow in the tunnel resulted in an increased burning of the fuel exterior to the simulated vehicle, especially for large pool fires, because of more air supply available for the combustion of the fuel. However, the external flame was unstable with higher airflow velocities.

The detector response times for the pool fires located underneath the vehicle with longitudinal airflow in the tunnel are shown in Figures 10 - 12.

The ceiling temperatures produced by small fires located underneath a vehicle were lower than those produced under non-ventilated conditions. These temperatures were further decreased with the increase in airflow velocity. The response times of heat detection systems to these fires, generally, increased with the increase in airflow speed (Figure 10).

Ceiling temperatures produced by large pool fires located underneath a vehicle with an airflow velocity of 1.5 m/s were higher than those produced under non-ventilated conditions. The increased temperature was due to the increased burning rate of the fire compared with tests with minimal airflow in the tunnel. However, the ceiling temperatures were lower in the tests with airflow velocity of 3 m/s. Therefore, the response times of linear heat detection systems to large pool fires located under a vehicle were shorter for tests with an airflow velocity of 1.5 m/s than those in tests with minimal airflow velocity as well as for the higher airflow velocity tests.

Under airflow conditions, smoke production was increased and its spread in the tunnel was more rapid. As a result, the period of time available for VID systems to detect and monitor the fire decreased with the increase in airflow speed as well as fire size.

Both flame and smoke VID D-4C1 and D-5C2 were, generally, able to detect fires located underneath the vehicle. VID D-5C2 detected small fires located underneath a vehicle at the three airflow velocities. The response time decreased with an increase in fire size but was not affected by a change in airflow velocity (for small fires, smoke was the main parameter that controlled the response time). On the other hand, the response times of detector D-4C1 decreased with an increase in airflow velocity.

Figure 10. Response times of fire detection systems to a 0.6 m x 0.6 m fire located underneath the vehicle at three airflow velocities.

Figure 11. Response times of fire detection systems to a 1.0 m x 1.0 m fire located underneath the vehicle at three airflow velocities

It was difficult for flame VID D-6C3 to detect fires located underneath a vehicle under longitudinal airflow conditions, as the fire plume was tilted and shielded behind the obstacle. The detector did not respond to a 1.0 m x 1.0 m gasoline pool fire located underneath the vehicle at an airflow speed of 1.5 m/s but did respond with the other two airflow velocities.

The sensitivity of the primary optical flame detector was reduced to medium sensitivity for the tests with longitudinal airflow as a result of the environmental tests conducted in the Lincoln tunnel [13]. The shielding of the flame by the obstruction in front of the simulated vehicle made it difficult for the flame detector with a medium sensitivity to detect the pool fires located under the simulated vehicle. It did not respond to a small fire located underneath a vehicle at an airflow speed of 1.5 m/s (Figure 10). However, it detected the same fire at an airflow speed of 3 m/s. The response time of the medium sensitivity flame detector increased with an increase in airflow speed for the experiments with the 1.0 m² pool fire (Figure 11). However, the airflow did not affect the response time for the 1.0 m x 2.0 m pool fire (Figure 12).

With airflow, the smoke in the tunnel was diluted reducing the smoke optical density for small pool fires located underneath a vehicle. As a result, the response times of the smoke detection system increased with the increase in airflow speed (Figure 10). For large pool fires located underneath a vehicle, more smoke was produced due to the increased burning rate of the fire. Generally, the response times of the smoke detection system were shorter than those under non-ventilated conditions. For the 2 m² pool fire, its detection time decreased with an increase in air velocity (Figure 12).

Both spot heat detectors D-7H1 and D-8H2 were not able to detect a small fire located underneath the vehicle. They responded to large fires at the three airflow velocities. The response times under longitudinal airflow conditions were shorter than those under non-ventilated conditions, as the fire size was increased by the airflow. However, the response times also increased with an increase in airflow velocity from 1.5 m/s to 3 m/s. This was consistent with the change in ceiling temperature produced by the fire in the tests.

Figure 12. Response times of fire detection systems to a 1.0 m x 2.0 m fire located underneath the vehicle at three airflow velocities.

7.1.2. Pool Fires Located behind a Large Vehicle

Two large pans (1.0 m x 1.0 m and 1.0 m x 2.0 m) were used for the tests with 25 L and 40 L of gasoline, respectively. Tests with average airflow speeds of 1.5 m/s and 3 m/s in the tunnel were conducted for each fire size. The airflow velocities on four sides of the pan were measured prior to each test. The results showed that the airflow velocities around the pan were similar. The tests were terminated when the fuel in the pan was burnt out and the fire self-extinguished.

The pool fire located behind a large vehicle was a free burning fire. The door at the East end of the tunnel was open during the tests with longitudinal airflow and the airflow was towards the fire. The impact of the airflow on the characteristics of the open pool fire was studied and the response of the fire detection systems was evaluated.

Test results showed that for the same amount of fuel in the pan, the test duration decreased with an increase in the airflow speed in the tunnel (Table 2). These results indicate that the airflow in the tunnel increased the burning rate of the pool fire.

Table 2. Burn times for tests with fire located behind a large vehicle.

Test No	Pan Size (m)	Fuel in Pan (L)	Airflow Speed (m/s)	Burn Time (s)
V-6	1.0 x 1.0	25	~ 1.5	365
V-7	1.0 x 1.0	25	~ 3.0	355
V-8	1.0 x 2.0	40	~ 1.5	315
V-9	1.0 x 2.0	40	~ 3.0	260

With airflow, the fire plume was tilted toward the downstream side of the fire source (Figure 13). The angle of the fire plume to the ground decreased with an increase in airflow speed. The fire plume decreased in length and became unstable at high airflow speeds (3 m/s). The effect of the airflow on the fire plume decreased with an increase in fire size.

a. 1.5 m/s

b. 3.0 m/s

Figure 13. A 1.0 m² gasoline pool fire located behind the vehicle.

The photo in Figure 14 shows that although the pool fire located behind the vehicle was large, the flames were difficult to see from the front of the large simulated vehicle, since the large vehicle body obstructed the view to the fire. The flame could only be observed at the two sides of the vehicle and in the gap between the bottom of the vehicle and the ground, as the fire plume was tilted and shielded behind the vehicle.

a. Side view

b. Front view

Figure 14. A 1.0 m x 2.0 m gasoline pool fire located behind the vehicle at wind speed of 1.5 m/s.

Test results showed that the airflow changed the fire growth and smoke production and spread in the tunnel for the fires located behind the vehicle. The visibility of the detectors that were located downstream of the fire was also affected. The video images provided from detector D-5C2 showed that the smoke produced by the 1.0 m x 1.0 m fire descended gradually from the ceiling for the tests with an airflow speed of 1.5 m/s. The available time with visibility for the Detector D-5C2 in the test was 93 s. When the airflow speed increased to 3 m/s, the smoke was blown towards the detector, instead of descending from the ceiling. Visibility was lost at 61 s after ignition. The considerable smoke produced by the 1.0 m x 2.0 m fire was also directly blown toward the detector. The visibility time available for detector D-5C2 were 33 s at an airflow speed of 1.5 m/s and 31 s at an airflow speed of 3 m/s. The detectors had a very short period of time to respond to and monitor the fire.

Figures 15 and 16 show the smoke optical densities near the tunnel ceiling produced by two large pool fires at three airflow velocities. For the 1.0 m x 1.0 m pool fire located behind the vehicle, the smoke density slightly decreased with an increase in airflow speed, as the fire plume was tilted toward the ground and the smoke had difficulty reaching the ceiling under high airflow conditions. For the 1.0 m x 2.0 m pool fire, more smoke was produced and smoke optical densities near the ceiling was higher than that under non-ventilated condition and slightly increased with an increase in airflow velocity.

Figure 15. Smoke optical density near the ceiling at the middle of the tunnel for a 1.0 m x 1.0 m fire.

Figure 16. Smoke optical density near the ceiling at the middle of the tunnel for a 1.0 m x 2.0 m fire.

Figures 17 and 18 show the variation in ceiling temperature with time along the center of the tunnel produced by two large pool fires located behind the vehicle at three airflow velocities. The results show that the ceiling temperatures decreased with an increase in airflow speed, and the hot spot at the ceiling was shifted downstream of the fire. The shift distance depended on the fire size and airflow speed. The maximum distance observed in the tests was approximately 6-8 m. As a result, the hot spot identified by heat detection systems (linear and spot) under longitudinal airflow conditions would not indicate the real fire location.

Figure 17. Ceiling temperatures along the center of the tunnel with a 1.0 m x 1.0 m gasoline pan fire at 115 s after ignition.

Figure 18. Ceiling temperatures along the center of the tunnel with a 1.0 m x 2.0 m gasoline pan fire at 80 s after ignition.

Figure 19. Response times of fire detection systems to a 1.0 m x 1.0 m fire located behind the vehicle.

Figure 20. Response times of fire detection systems to a 1.0 m x 2.0 m fire located behind the vehicle.

The impact of longitudinal air flow on the performance of fire detection systems to two fire sizes located behind a vehicle is summarized in Figures 19 and 20. The response times of the linear heat detection system D-1L1, the flame detector D-3F1, the VID flame/smoke system D-4C1, two spot heat detectors D-7H1 and D-8H2 to the fire increased with an increase in airflow velocity in the tunnel, as the ceiling temperature decreased and the fire plume was tilted towards the ground.

The flame/smoke VID detector was able to detect two fires at an airflow velocity of 3 m/s, but had no response to the fires at an airflow velocity of 1.5 m/s.

The VID flame system D-6C3 did not respond to the fire located behind the vehicle under any airflow conditions, as the fire plume was tilted and shielded behind the vehicle.

The airflow had a limited impact on the response of the smoke detection system to the fire located behind a vehicle, as the change in the smoke optical density near the ceiling was limited under airflow conditions.

7.1.3. Stationary Vehicle Fires

One test involving a passenger compartment fire was conducted using an airflow speed of 3 m/s. During the test, no obstacle was placed between the fire source and the detectors. The airflow velocities on four sides of the mock-up were measured prior to the test.

The simulated passenger compartment fire used a wood crib and a polyurethane foam as fuel. It developed slowly, in comparison to the flammable liquid fires. No visible flame was observed outside the compartment and the amount of smoke produced was also limited in the initial stage of the fire. However, compared to the fire under a minimum airflow condition, the airflow in the tunnel increased the burning rate of the fire in the passenger compartment.

The heat fluxes produced by the simulated vehicle fire are shown in Figure 21. The heat flux was measured 1 m from the fire source. It indicates that the fire inside the passenger compartment developed slowly after ignition. It took more than 120 s for sufficient heat flux to be produced by the fire to be measured by the heat flux meter. The airflow had a limited influence on the development of the fire in the initial stage. However, once the flames were fully formed, the fire developed much faster than in the test with minimal airflow in the tunnel. The fire reached the maximum heat release rate approximately 240 s after ignition.

Figure 21. Variations of heat flux produced by a simulated passenger compartment fire.

Figure 22. The side view of the simulated passenger compartment fire with wood cribs and foam with an airflow speed of 3 m/s.

Figure 22 is a photograph showing the simulated passenger compartment fires with longitudinal airflow. The fire plume outside the compartment was blown toward the downstream end of the vehicle. Compared to the flammable liquid fire, the flame produced by the solid material fuels was short and the tip was not tilted towards the ground.

Figure 23 shows the variation of the maximum ceiling temperature along the center of the tunnel. The ceiling temperature decreased with airflow in the tunnel. The hot spot at the ceiling did not shift towards the downstream of the tunnel under airflow conditions. This is consistent with the fire plume observed in the two tests.

The impact of airflow on the smoke spread near the ceiling is shown in Figure 24. The smoke optical density had a significant decrease under airflow conditions.

Figure 23. Maximum ceiling temperature along the center of the tunnel at two airflow velocities.

Figure 24. Ceiling smoke density at center of the tunnel at two airflow velocities.

The visibility in the tunnel was reduced under airflow conditions. However, the smoke produced by the fire was limited and quickly vented from the tunnel through the openings in the tunnel ceiling. The VID detectors were able to view and monitor the passenger compartment fire during the entire test.

The impact of airflow on the response of fire detectors/detection systems to the simulated passenger compartment fire is shown in Figure 25. Generally, the response times of the fire detection systems were long and increased under longitudinal airflow conditions, as the temperature and smoke optical density near the ceiling decreased.

The VID D-C1 detector did not respond to the fire. Two spot heat detectors D-7H1 and D-8H2 did not respond to the fire in the test with airflow in the tunnel but they did respond in the tests with minimum airflow conditions.

Figure 25. Response times of fire detection systems to a passenger compartment fire.

7.2 Fire Tests in the Carré-Viger Tunnel

The performance of the fire detection systems was investigated in a series of fire tests conducted in the Carré-Viger Tunnel in Montreal, Canada. Four airflow velocities were used in the tests: 0 m/s, 1.3 m/s, 2 m/s and 2.4 m/s. The fire size varied from 125 kW to 650 kW.

7.2.1 Open Pool Fires

Four tests were conducted with a 0.3 m by 0.3 m gasoline pool fire. The fire was placed at four locations in the tunnel. There was no obstacle around the fire source. Ambient temperature in the tunnel was 18°C with no prevailing wind. All tests were conducted with minimal airflow velocity in the tunnel (approximately 0 m/s). As a result, a vertical flame was produced (Figure 26).

Figure 26. Small pool fire in Carré-Viger Tunnel.

The fire was allowed to burn for approximately 9 minutes until the gasoline in the pan was consumed. The fire developed very quickly. The maximum heat release rate produced by the fire was approximately 125 kW. The maximum ceiling temperature near the fire source was approximately 35°C.

The substantial smoke was produced by the fire and accumulated below the ceiling. The smoke density decreased with an increase in distance from the fire location. The smoke did not obstruct the view of the detectors during the tests.

The response of the detection systems to the small non-obstructed fire are shown in Figure 27. The performance of the detection systems was similar to those in laboratory tunnel tests.

The linear heat detection systems were able to respond to small fires based on the rate of rise of temperature, even though there was limited increase in the ceiling temperature. The response times of the linear heat detection systems were less likely to be affected by fire location in the tunnel, as the fires were always near a section of the cable. Detection system D-1L1 detected all four of the small fires where as detection system D-2L2 did not detect the fires located at positions FP3 and FP4. Both of these fires were located at the East end of the cable loops (Figure 1).

The optical flame detector, D-F3F1, had a maximum detection range of 30 m. It only detected the small fires within this range (location FP1).

The three VID systems were able to detect the small open fires at their maximum detection range (~60 m). The change in location of the small open fire in the tunnel had a limited impact on the performance of Detectors D-4C1 and D-6C3, but had an impact on the performance of D-5C2 with the longest response time for the fire located at position FP 3, which was in the lane closest to the tunnel wall on which the detectors were located.

Figure 17. Response times of detection systems to open pool fires.

7.2.2 Pool Fires Located underneath a Vehicle

Three tests with a 0.6 m x 0.6 m gasoline pool fire located underneath a simulated vehicle were conducted in the Carré-Viger Tunnel. The setup of the fire scenario was the same as used in the laboratory tunnel tests of the project [10]. A 1.5 m wide by 1.2 m high plate, simulating a crashed car, was located between the fire source and the wall-mounted detectors. It was placed 1.5 m in front of the fire source and 0.3 m above the ground. The heat release rate of the fire was approximately 650 kW when measured using a calorimeter.

The fire source was at location FP #1 in the three tests (Figure 1): 32 m from the detectors mounted on the wall and 4.8 m from the North wall of the tunnel. The tests were used to study the impact of airflow on the response of the detectors/detection systems to a small fire located underneath a vehicle. The jet fans used for the tunnel emergency ventilation system were used to produce average airflow velocities of 1.3 m/s, 2.0 m/s and 2.4 m/s at the fire location.

The fire was allowed to burn freely until the gasoline in the pan was consumed. The fire plume was tilted under longitudinal airflow conditions and its angle to the ground was reduced with an increase in airflow speed. At high airflow speeds, the fire plume became short and unsteady, and the view of the detectors mounted on the wall to the flames was obstructed by the plate placed in front of the fire.

Both ceiling temperature and smoke density decreased with an increase in airflow velocities.

The detector response times are shown in Figure 28. Generally, the challenge for the detectors increased under the longitudinal airflow conditions.

The response time of the linear heat detection systems increased with an increase in airflow speed, as the ceiling temperature decreased. The linear heat detection system D-2L2 detected the fires in all the tests, but the system D-1L1 failed to respond to the fire when the airflow speed was 2.4 m/s.

The response time of the optical flame detector D-3F1 was delayed with an increase in airflow speed. It did not respond to the fire in the test with an airflow velocity of 2.4 m/s.

The response times of the three VID systems to the fire could be delayed or shortened under airflow conditions, as the flames behind the obstacle were unsteady.

Figure 28. Response times for pool fires located underneath a simulated vehicle.

7.2.3 Open Pool Fires behind a Large Vehicle

Two full-scale tests with a gasoline pool fire located behind a simulated vehicle were conducted in the Carré-Viger Tunnel. The fire scenario was setup using a 0.6 m x 0.6 m gasoline pan fire located behind a large plate. The plate, simulating the front portion of a large van, was 1.2 m wide by 2.4 m high. It was placed 0.3 m above the tunnel floor and 3.5 m in front of the pool fire and between the pool fire and the detectors mounted at the wall of the tunnel. The heat release rate of the fire was approximately 650 kW.

The fire was placed at positions FP 1 and FP 3 (Figure 1). The airflow velocity in the tunnel was 1.3 m/s. The tests were designed to study the response of the detectors/detection systems to a fire located behind a vehicle under airflow conditions.

The fire developed very quickly. A large fire plume and significant smoke were produced. The fire plume and smoke were pushed downstream of the fire by the airflow. The fire plume and smoke production were much larger than those produced by the fire underneath the vehicle with the same size of pool fire. However, it was difficult to view the flames from the front of the fire, as the flames were shielded by the obstruction plate.

Figure 29 shows the ceiling temperature measured at three distances from the fire source. The temperatures measured 15 m and 30 m downstream of the fire were higher than that measured at the fire location. The rate of temperature rise was faster than that at the fire location. The ceiling temperature produced by the fire located behind the vehicle was higher than that produced by the fire located underneath the vehicle under the same airflow conditions.

Figure 30 shows the smoke optical density measured 15 m and 30 m from the fire source. The smoke optical density measured at the two locations was comparable. It was higher than that produced by the fire located underneath the vehicle under the same test conditions. The view of the VID fire detectors to the tunnel was affected by the smoke accumulated in the tunnel within a few minutes after the fire was ignited.

Figure 29. Ceiling temperatures at three locations.

Figure 30. Smoke optical density near the tunnel ceiling measured at two locations.

The detector response times to the fire located behind a simulated vehicle are shown in Figure 31.

The linear heat detection systems were able to detect the fires, and their detection times were not affected by the change in fire locations. At both locations, the fire was close to the detection cables.

The optical flame detector D-3F1 detected the fire at 25 s when the fire was located 32 m from the detector. It did not respond to the fire when it was located 60 m from the detector, since the distance was greater than its maximum detection distance.

Both the flame/smoke VID systems (D-4C1 and D-5C2) detected the fire when it was located 32 m from the fire (location FP 1). However, they were unable to detect the fire at position FP 3 which was 60 m from the fire. The flame VID system D-6C3 detected the fires at both locations.

Figure 31. Response times for pool fires located behind a simulated vehicle.

SUMMARY

Full-scale fire tests in a laboratory research tunnel facility and in the Carré-Viger tunnel in Montreal suggested that longitudinal airflow in the tunnel had a significant impact on the performance of the fire detectors/detection systems. The detection time of the fire detection systems could be increased or decreased, depending on the fuel type, fire size and location, airflow velocity and detection method. The fire detection systems evaluated in the project worked well in an operating tunnel environment. Their performances in operating tunnel environments were generally consistent with those measured in the laboratory tunnel tests.

The general performance of each type of technology in the tests is summarized as follows:

- 1. Linear heat detection systems.** 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 and smoke layer by the airflow. 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 under airflow conditions resulting in faster response times.

The linear heat detection systems were able to detect small fires based on the rate of the rise of temperature, and their performance was not affected by the change in fire location in the tunnel, as the fires were always near a section of the cable. However, under longitudinal airflow, the hot spot at the ceiling was shifted downstream and the actual fire location was up to 10 m from the location indicated by the detection system.

- 2. Flame detector.** The response times of the flame detector to fires located under a vehicle, behind a vehicle or inside a vehicle were generally increased under longitudinal airflow conditions as the flames were tilted and there was an increased concealment of

the flames by obstacles. However, its response time to a large shielded fire under a simulated vehicle was not affected much by longitudinal airflows, as the size of the fire increased.

The detector was able to quickly detect small unobstructed fires (125 kW) at its maximum detection range (30 m). Its detection capability was substantially decreased with a change in the sensitivity from high level to medium level.

3. **Video imaging detection (VID) systems.** The flame VID detector 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). Its response time to concealed fires increased under longitudinal airflow conditions as the fire was more likely to be concealed by obstructions.

The flame/smoke VID detectors that utilized both flame and smoke characteristics had better response for the concealed fire scenarios than the flame VID detector. The effect of the longitudinal airflow on their performance was limited, in comparison with other types of fire detection technologies. Their response times were changed case by case, and with the detectors provided by different manufacturers.

The longitudinal airflow in the tunnel affected the buildup of smoke in the tunnel downstream of the fire. This increased build-up of smoke in the tunnel and decreased the time available for VID detectors to detect and monitor a fire. The VID fire detectors were able to quickly detect small unobstructed fires (125 kW) at their maximum detection ranges (60 m).

4. **Spot heat detectors.** Spot heat detectors 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. 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.** Its response time to the small fire under a simulated vehicle increased with an increase in airflow velocity, as the smoke optical density was decreased by the airflow in the tunnel. For the scenarios with large pool fires behind a simulated vehicle and located under a simulated vehicle, the effect of longitudinal airflow on its response time was limited as the amount of smoke produced and its spread increased with airflow in the tunnel.

No spot heat detector and no smoke detection system were tested in the Carré-Viger tunnel. The impact of a change in fire location on their detection performance was not investigated.

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