International Road Tunnel Fire Detection Research Project – Phase II

Task 2: Full-Scale Fire Tests in a Laboratory Tunnel for Study of Tunnel Fire Detection Technologies

Prepared by:

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TASK 2: FULL-SCALE FIRE TESTS IN A LABORATORY TUNNEL FOR STUDY OF TUNNEL FIRE DETECTION TECHNOLOGIES

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International Road Tunnel Fire Detection Research Project – Phase II

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EXECUTIVE SUMMARY

This report presents the results of Task 2 of the International Road Tunnel Fire Detection Research Project – Phase II. The capabilities and limitations of nine fire detectors/detection systems were investigated using various tunnel fire scenarios in a laboratory research tunnel with dimensions of 10 m wide by 37 m long and 5.5 m high.

Nine fire detectors/detection systems that were selected from five types of fire detection technologies provided a good representation of current fire detection technologies available for use in tunnel fire detection. They included: two linear heat detection systems, one optical flame detector, three CCTV fire detectors, one smoke detection system and two spot heat detectors.

The simulated tunnel fire scenarios used in the test series were pool fires placed in an open space, underneath a simulated vehicle and behind a large simulated vehicle; stationary vehicle fires in the simulated engine and passenger compartments; as well as moving fires with two different speeds and driving directions relative to the detectors. The fuel types included gasoline, propane, wood crib and plastic foam. The fire sizes varied from approximately 125 kW to 3,400 kW. The flammable fuel fires grew quickly, reaching the maximum heat release rates in less than one minute. The stationary vehicle fires presented in the test series grew slowly, taking more than 8 minutes to reach their maximum heat release rates.

The performances of the fire detectors/detection systems, including their response times, and their ability to locate and monitor a fire in the tunnel, were evaluated using the same fire scenarios. The fire characteristics produced in the various fire scenarios, including the fire growth rate, temperatures and smoke spread in the tunnel, were measured. Test results showed that the detection capability of the fire detectors/detection systems was affected by fuel type, fire size, location and growth rate of the fire as well as the detection method.

For a small gasoline pool fire (125 kW) located in the open space of the tunnel, the optical flame detector and CCTV fire detectors responded quickly to the fire. The linear fiber optic heat detection system also detected the fire quickly based on the rate of rise of the temperature. The smoke detection system detected the fire but its response was relatively slow. The two spot heat detectors and the other linear heat detection system did not respond to this small fire.

The pool fire located underneath a vehicle was a challenge for the detectors/detection systems, as the flame and heat produced by the fire were confined by the vehicle body. For a small fire (125 kW) located underneath a vehicle, only a CCTV flame/smoke detector and a smoke detection system responded to the fire. With an increase in fire size, more detectors/detection systems responded to the fire located underneath the vehicle, and the detection times also reduced. However, the fire detectors/detection systems evaluated in the test series showed substantial difference in response times to the fires located underneath a vehicle. For example, their response

times to a 2 m^2 gasoline pool fire varied from 4 s to 183 s, depending on the type of fire detector/detection system.

The pool fire located behind a large vehicle was a freely burning fire. The large vehicle body in front of the fire did not affect the burning process of the fire as well as temperature development and smoke spread in the tunnel. However, the view of the flames from front of the vehicle was obstructed by the large vehicle body and by the smoke that quickly formed beneath the tunnel ceiling. It was difficult for the CCTV flame detector to detect the fire in this scenario, because the flames behind the vehicle were hardly identified. For the other fire detectors/detection systems, their response times and their difference in response time decreased with an increase in fire size. Except for a CCTV flame detector, all the detectors/detection systems responded to a large 2 m^2 gasoline pool fire (3,400 kW) located behind the vehicle in less than 35 seconds in the test. Generally, the fire detectors/detection systems responded to the fire located behind a vehicle more quickly than to a fire located underneath the vehicle.

The stationary vehicle fires in the engine and passenger compartments developed slowly, because of their fuel type and fire location. The flame, heat and smoke produced by the fires at a few minutes after the ignition were limited. They resulted in slow response times for the fire detectors/detection systems. Except for the response time of the optical flame detector to the engine compartment fire, the detection times for other fire detectors/detection systems in the test series varied from 76 s to 391 s for the engine compartment fire, and from 171 s to 271 s for the passenger compartment fire. The two spot heat detectors did not respond to the passenger compartment fire in the test.

The small moving vehicle fires were difficult to detect. These fires did not produce any changes in the temperature and smoke density in the tunnel when they traveled through the tunnel. Only the optical flame detector detected the moving fire at the speed of 27 km/h, but not at the speed of 50 km/h in the test series. No other fire detector/detection system responded to the moving fire in the test series.

Propane fires were used to simulate some tunnel fire incidents in the test series. These fires did not produce visible smoke. They presented a challenge for those fire detectors/detection systems that responded to the fire based on the characteristics of smoke produced by the fire.

The linear fiber optic heat detection system was able to identify the fire location within a 2-meter range in the test series. Other fire detector/detection systems were able to identify the fire location within their detection zone. The size of the detection zone was dependent on the system design and their detection method.

The visual CCTV fire detectors were able to provide video images to monitor fire conditions in the tunnel. The period of time available for monitoring fire conditions using the cameras changed with the fire size, location and growth rate of the fire, and fuel types. For the large fires with a quick growth rate, the available monitoring time was very short (less than 1 minute) as the visibility was obscured by smoke that quickly developed in the tunnel.

ACKNOWLEDGEMENTS

The project is conducted under the auspices of the Fire Protection Research Foundation (FPRF). The authors would like to acknowledge the support of the Technical Panel, Sponsors as well as many NRCC staff to this project. A special acknowledgement is noted to Kathleen Almand of the FPRF for her contribution in managing the project.

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1. INTRODUCTION

A number of technical issues related to the use of current fire detection technologies for road tunnel protection were identified in Phase I of the International Road Tunnel Fire Detection Research Project [1]. One concern was that relatively few test programs have been conducted to study the performance of tunnel fire detection technologies. The programs that were conducted mainly focused on the performance of either linear heat detection systems or optical flame detectors [2-8]. Many existing and newly developed fire detection technologies, such as spot heat detectors, smoke detection systems and visual CCTV flame and smoke detectors were not studied systematically. The other concern was that the performances of detectors/detection systems in these programs were evaluated mostly with pool fires that had a constant heat release rate of up to 3 MW. Impact of other fire scenarios, such as stationary and moving vehicle fires, on detection performance was not investigated.

The present work is Task 2 of the International Road Tunnel Fire Detection Research Project (Phase II). It investigates some concerns on the use of current fire detection technologies for road tunnel protection. A series of fire tests were conducted in a laboratory tunnel facility with dimensions of 10 m wide by 37 m long and 5.5 m high. The performance of nine fire detectors/detection systems that were selected from five different types of fire detection technologies was evaluated with a number of tunnel fire scenarios. These fire detectors/detection systems were: two linear heat detection systems, one optical flame detector, three CCTV fire detectors, one smoke detection system and two spot heat detectors. They provided a good representation of current fire detection technologies that could be used for fire detection in tunnel applications.

All the detectors/detection systems were evaluated using the same fire scenarios. The simulated tunnel fire scenarios included pool fires with a fast growing rate and a constant heat release rate, stationary vehicle fires with a slow growth rate, and moving vehicle fires. The fire sizes in the test series were varied from 125 kW to 3,400 kW and fuel types were gasoline, propane, wood crib and plastic foam. The fires were located, respectively, in an open space, underneath the simulated vehicle, behind a large simulated vehicle, inside the simulated engine and passenger compartments with or without the obstacles around the fire source. These fire scenarios were considered representative of tunnel fire incidents, and challenges for fire detection [9].

This report presents the results of Task 2 of the International Road Tunnel Fire Detection Research Project (Phase II). Information on the test tunnel, fire scenarios, fire detectors/detection systems and test instrumentation is provided. The fire characteristics produced by the various fire scenarios, such as the fire growth rate, heat flux, temperature and smoke spread in the tunnel, are presented. The performances of the fire detectors/detection systems to the tunnel fire scenarios, including their response times, and their ability to locate and monitor a fire, are reported.

2. TEST TUNNEL

The full-scale fire tests were carried out in a new Carleton University laboratory research tunnel that was located at the site of the National Research Council (NRC) full-scale fire test facilities. The tunnel facility is 37.5 m long, 10 m wide and 5.5 m high. The tunnel has two end doors, one large side door to an adjacent burn hall at the West end of the tunnel, two side louvers at the East end of the tunnel and five ceiling openings to the ducts and the fan system. The schematic of the test tunnel is shown in Figure 2.1.

The two end doors of the tunnel were closed during the tests. The two side louvers at the East end of the tunnel that were located close to the fire source, however, were partially opened, to provide an air supply for the fire. The opening of two side louvers was 1.5 m wide by 4.9 m high for the North louver, and 2.75 m wide by 4.9 m high for the South louver. The large side door that was located far from the fire source was also partially opened with an opening of 0.6 m wide for observing and approaching the tunnel during the tests. A photograph showing the East end of the tunnel during the tests is provided in Figure 2.2.

Smoke produced in the tests can be collected and exhausted through a fan system that was mounted in the tunnel facility. For the present work, however, the mechanical ventilation system was not operated. Only natural ventilation under ambient conditions was maintained in the tunnel during the tests. The smoke produced in the tests was naturally vented through ceiling openings and ducts to outside the tunnel. These ceiling openings were located at the West end of the tunnel and their total opening size was 32.25 m^2.

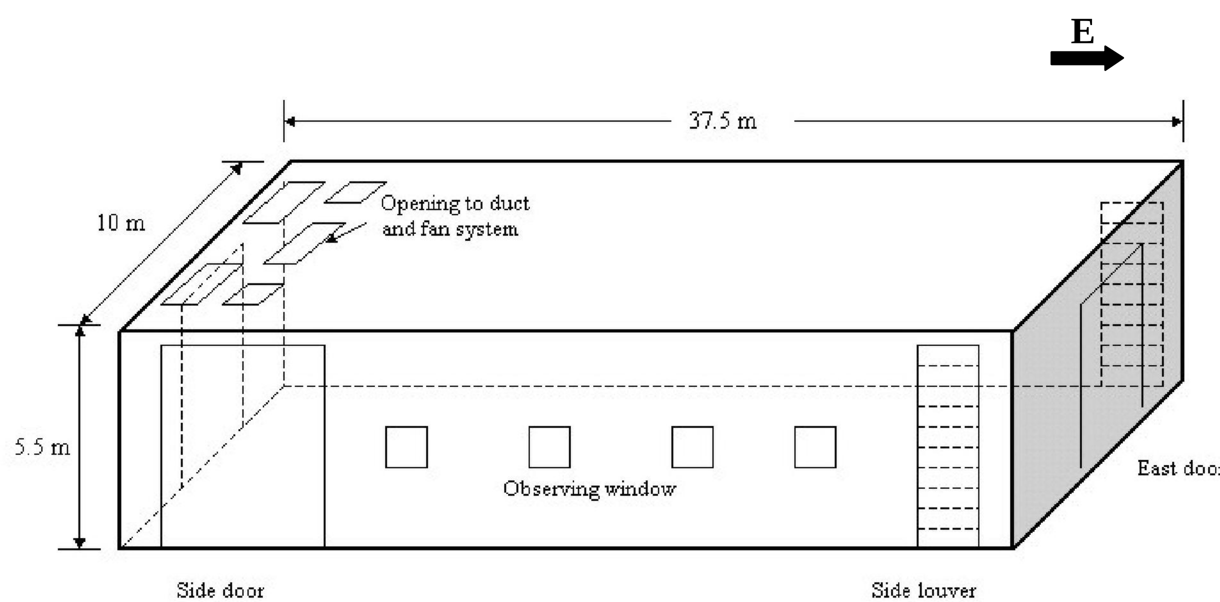

Figure 2.1. Schematic of the laboratory tunnel

Figure 2.2. View of the East end of the tunnel facility

3. FIRE DETECTORS/DETECTION SYSTEMS AND SETUPS

Nine fire detectors/detection systems were used in the test series. These detectors and systems were selected by the Technical Panel in Task 1 of the project [9] and covered five types of currently available technologies. They were: two linear heat detection systems, one optical flame detector, three CCTV fire detectors, one smoke detection system and two spot heat detectors. General information on these detectors and systems in the test series is summarized in Table 3.1. A detailed description on these detectors and systems was provided in the report of Task 1 of the project [9].

Table 3.1. Fire Detection Systems in Test Program

Technology	System no.	System information	Alarming threshold	Detecting location
Linear heat	D-1L1	Fiber optic linear heat detection	Level 1: 50^{o}C, 10^{o}C/min; Level 2: 100^{o}C, 15^{o}C/min;	Two parallel cables in the tunnel, 2.5 m from the wall
	D-2L2	Analogue (co-axial cable) linear heat detection system	Fixed Temp: 70^{o}C, Rate of rise: 10^{o}C/min;	Two parallel cables in the tunnel, 2.5 m from the wall
Flame	D-3F1	IR3 flame detector	Sensitivity: very high (0.3 m x 0.3 m n-heptane fire at 65 m on-axis and 45.7 m off-axis.	30 m from the fire source and 4.3 m from ground
CCTV	D-4C1	Visual flame and smoke detector	Flame: low (25%); Offsite: 50% Smoke: normal	30 m from the fire source and 4.8 m from ground
	D-5C2	Visual flame detector	See Table 3.3	30 m from the fire source and 4.6 m from ground
	D-6C3	Visual flame detector	Sensitivity: 10 kW fire at 30m.	30 m from the fire source and 4.2 m from ground
Spot heat	D-7H1	Heat detector with a fixed temperature	79.5^{o}C fast response bulbs	3 m spacing at the center of tunnel ceiling
	D-8H2	Rate-anticipation heat detector	Fixed Temp: 57.2^{o}C	15.2 m spacing at the center of tunnel ceiling
Smoke	D-9S1	Air sampling system	Fire threshold: 0.203%/m	Air sampling line at the center of tunnel ceiling

It was required that the configuration and installation of the fire detectors/detection systems in the test tunnel be based on the design of a system for protecting a road tunnel with dimensions of 10 m wide by 5.5 m high by 2,000 m long [9]. Their installation configuration could not be changed during the tests. The sensitivity levels or alarm thresholds of the fire detectors/detection systems also could not be 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 operating environment tests in the Lincoln tunnel undertaken in Tasks 5 and 6 of the project.

All the fire detectors/detection systems were installed in the test tunnel facility by the system suppliers. The locations of the nine detectors/detection systems in the test tunnel are shown in Figure 3.1. The outputs of the detectors/detection systems were connected to a data acquisition system.

System D-1L1 was a fiber optic linear heat detection system based on Raman scattering. The entire optical fiber was used as the sensing medium. Fire warning signals could be triggered when the temperature field exceeds a certain rate of rise of the temperature and/or a fixed temperature. Two alarm threshold levels were set up and used in the test series. The alarm temperature and the rate of rise of the temperature were 50^{o}C and 10^{o}C/min and 100^{o}C and 15^{o}C/min fore Levels 1 and 2, respectively. The fire location in the tunnel could be identified using the temperature distribution along the fiber cable. The spatial resolution of the system for fire location was 1.2 m.

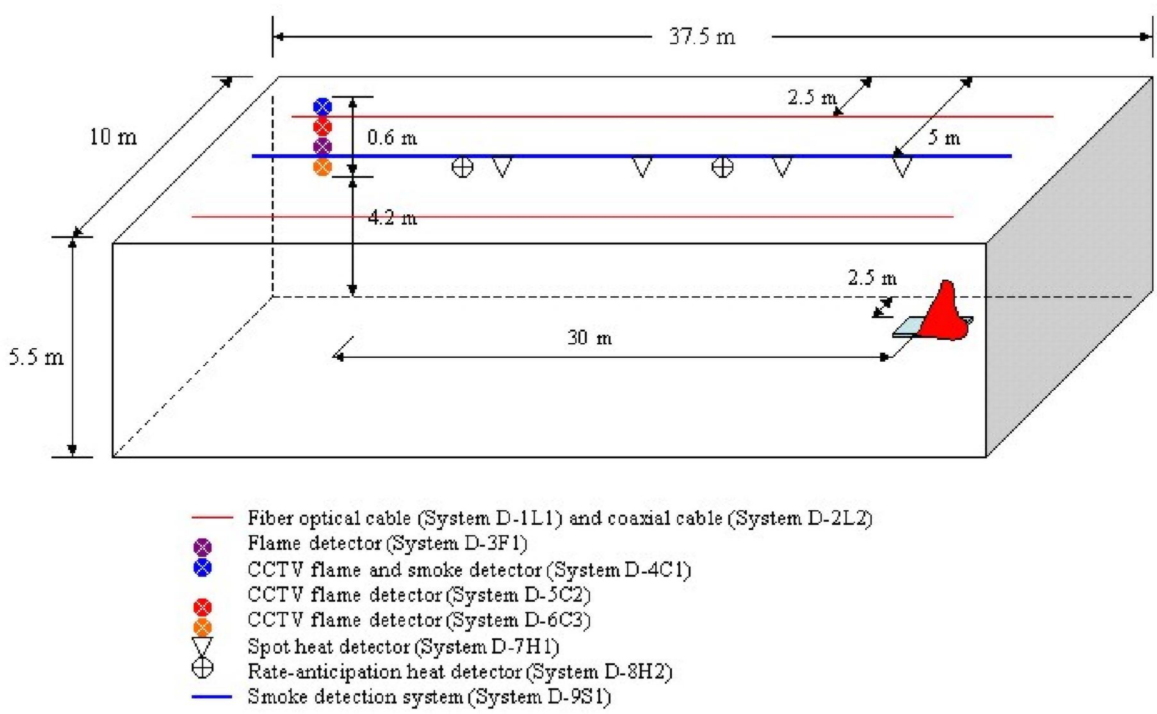

Figure 3.1. Schematic of detector/detection system setup in the test tunnel

Two parallel sensing cables of System D-1L1 were installed below the ceiling of the tunnel facility (see Figure 3.1). Each cable was located at approximately 80 mm from the ceiling, 2.5 m from the wall and 5 m from the other cable. A 2,198 m length of the cable was used in the test series. The cable section installed at the ceiling of the tunnel was from 2,000 m to 2,198 m, which is the maximum sensing length of the system recommended by the supplier. The remaining cable length was stored on the floor of the test facility. The fiber optic cable in the tunnel was protected with a 2 mm diameter stainless tube. The detailed configuration of the sensing cable in the test series is shown in Figure 3.2.

System D-2L2 was an analogue (coaxial cable) linear heat detection system. The sensor cable consisted of a conductor, an insulating layer, and a metal-weaving screen layer. Fire warning signals could be given based on rate of temperature rise and/or exceeding a fixed temperature. During tests, the alarm temperature and the rate of temperature rise of the system were 70°C and 10°C/min.

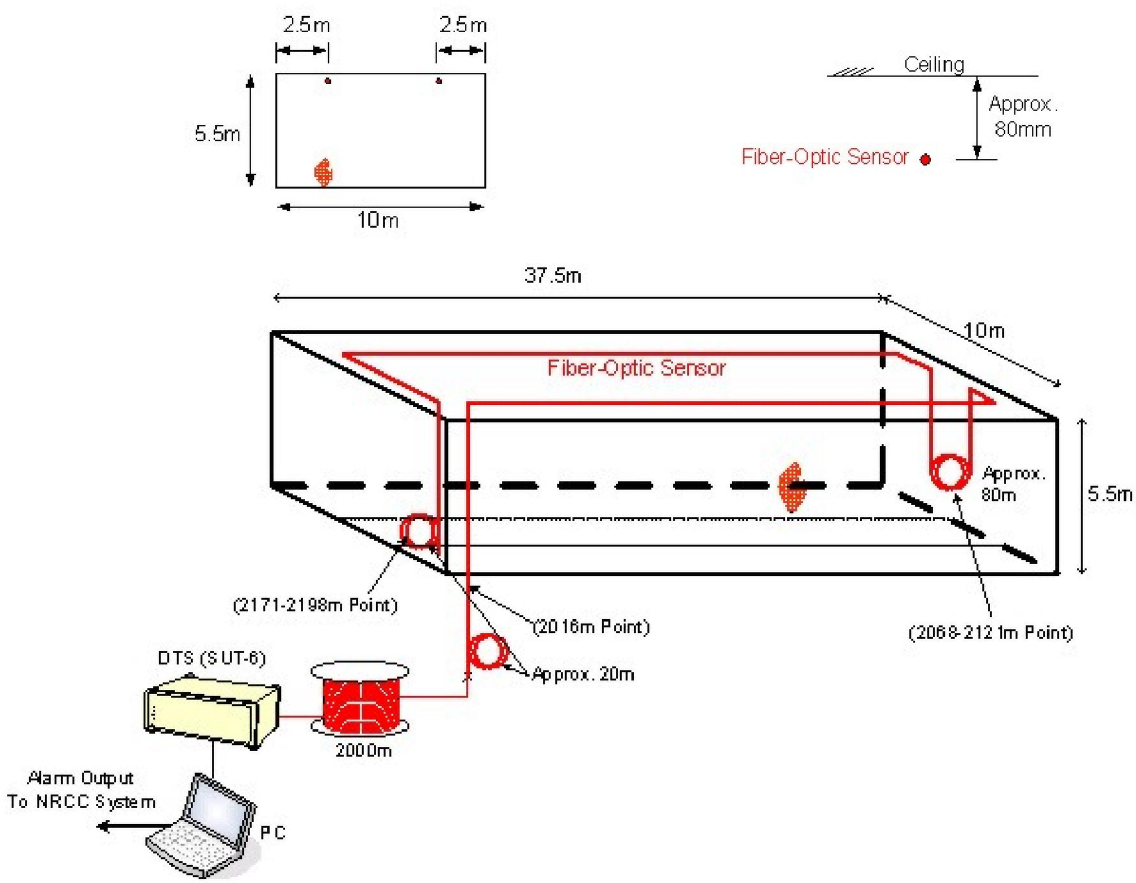

Figure 3.2. Configuration of System D-1L1 in the test tunnel

The configuration of the cables for System D-2L2 in the test tunnel was similar to that used for System D-1L1. Two parallel cables were installed below the ceiling of the tunnel (see Figure 3.1). Each cable was located at approximately 80 mm from the ceiling, 2.5 m from the wall and 5 m from the other cable. A 90 m length of cable, as one detection section for the system, was installed in the test tunnel. Figure 3.3 shows the cables of both System D-1L1 and System D-2L2 below the ceiling of the tunnel.

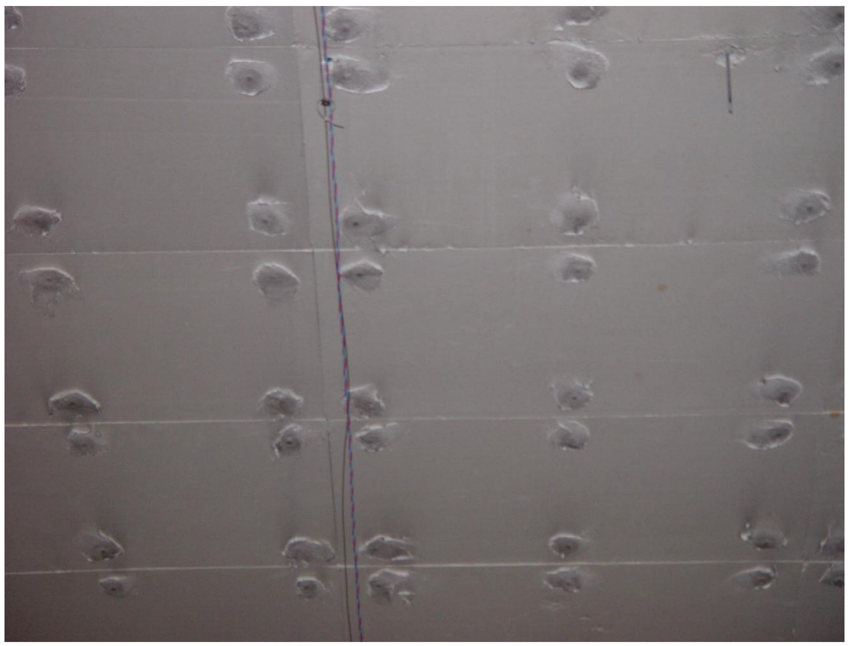

Figure 3.3. Sensing cables of Systems D-1L1 and D-2L2 on the ceiling of the tunnel

System D-3F1 was a multi-spectrum infrared (IR) flame detector. It consisted of three IR sensors. One sensor detected the typical CO_2 spectral band and was used to detect flame radiation. The other two sensors covered different, adjacent, and specially selected spectral bands, where black body emitters and background radiation were produced. They were used to minimize false alarms. The detector was installed at the North sidewall of the test tunnel, and at 4.3 m from the ground (see Figures 3.1 and 3.4). The detector sensitivity was set to be "very high" for a 0.3 m x 0.3 m gasoline pool fire located at a distance of 65 m on-axis and 45.7 m off-axis.

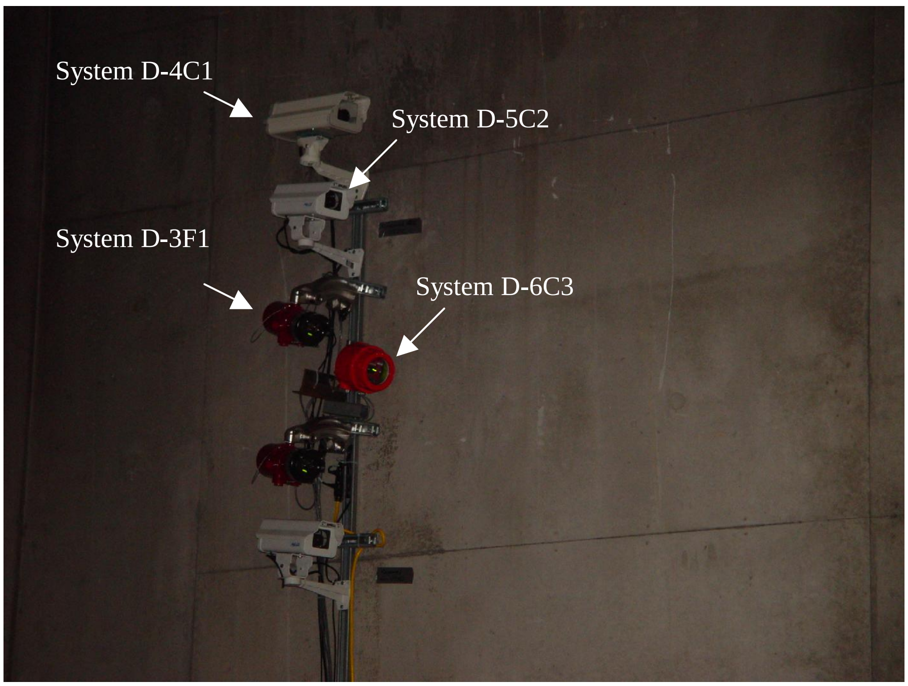

Figure 3.4. Configuration of flame and visual detectors in the test tunnel

System D-4C1 was a Closed Circuit Television (CCTV) flame and smoke detection system. Fire alarms were produced, once the characteristics of flame and smoke produced in a fire incident were identified. For the current test series, the detector was installed at the North sidewall of the test tunnel, and at 4.8 m from the ground (see Figures 3.1 and 3.4). One side of the view for the camera ran parallel with the North wall of the tunnel. The entire tunnel was covered starting at 18.0 m from the camera. In a tunnel detection application, a second camera located behind this camera would cover the blind spot of the camera. The view of the tunnel covered by the camera is shown in Figure 3.5.

The detector had two flame algorithms and one smoke alarm algorithm. The first flame algorithm was used to detect the fire in the field of view of the camera and the second one "Offsite" was used to detect the presence of a flaming fire by the reflected light produced by the fire. The camera sensitivity settings during the test program are listed in Table 3.2.

Table 3.2. Sensitivity settings in System D-4C1

Setting	FSM8
Flame	Low (25)
Offsite	50%
Smoke	Normal
Outdoor	Checked

Figure 3.5. View of the test tunnel provided by System D-4C1

System D-5C2 was the second CCTV detection system. It detected a fire based on the characteristics of the flame produced by the fire. During the test series, the detector was located at the North sidewall of the test tunnel, and at 4.6 m from the ground (see Figures 3.1 and 3.4). The view of the tunnel covered by the camera is shown in Figure 3.6. It can see more of the tunnel than System D-4C1. In a tunnel detection application, a second camera located behind this camera would cover the blind spot of the camera. The sensitivity settings of the detector during the tests are listed in Table 3.3.

Table 3.3. Sensitivity settings in System D-5C2

Intensity	Mean Crossing	Intensity Standard Deviation	Flicker Mask Counter Bit Mask	Flicker Mask Counter	Color
64	4	16	127	16	Yes

Figure 3.6. View of the test tunnel provided by System D-5C2

System D-6C3 was the third CCTV detection system. It detected a fire based on the characteristics of the flame produced by the fire. Unlike Systems D-4C1 and D-5C2, its image sensing and processing were combined into one detector, and fire information and videos were directly sent to the monitoring computer through a controller, once a fire incident was identified. During the test series, one detector was located at the North sidewall of the test tunnel, and at 4.2 m from the ground (see Figures 3.1 and 3.4). No image of the test tunnel and experimental setup was shown on the screen of the monitoring computer. The flame image was shown only after the fire was detected. The sensitivity of the detector during the test program was set to detect a 10 kW fire at approximately 30 m.

System D-7H1 was a pneumatic, spot type heat detection system based on frangible bulb technology. The device was fitted on a sensing line pressurized using air. A fire signal was given when the frangible bulb was broken during a fire incident, and the air in the line was released. For the present test series, two 15 m long zones of 12.7 mm steel pipe were installed along the center of the test tunnel (see Figure 3.1). Five 79.5^{o}C fast response sprinkler heads were installed per zone at 3 m spacing and 200 mm below the ceiling. A photograph of the system installed in the tunnel is shown in Figure 3.7. Prior to the test, the pipe was pressurized with approximately 20 psi of compressed air using a compressor. The compressor was run continuously during the test to compensate for any small leaks in the installation.

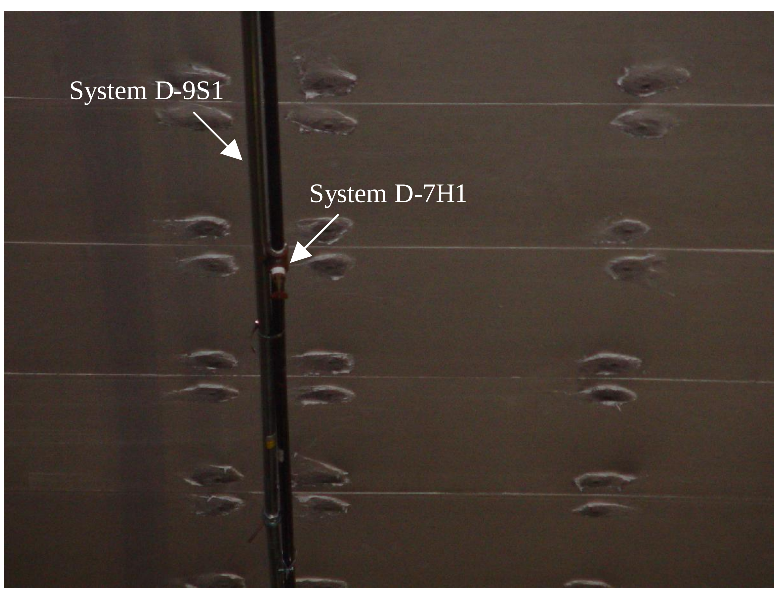

Figure 3.7. Photograph of System D-7H1 and System D-9S1 in the test tunnel

System D-8H2 was a rate-anticipation spot heat detector. It activated when the temperature reached the preset temperature in a fire incident. Its protection area was 15.24 m by 15.24 m. For the current test series, two 57.2^{o}C heat detectors were installed along the center of the tunnel ceiling (see Figure 3.1) at 15 m spacing and 110 mm below the ceiling.

System D-9S1 was an air sampling-type smoke detection system. Air was continuously drawn into a pipe network through holes in the piping to a centrally-located smoke detector using an air pump or aspirator. Alarms were issued, if the amount of smoke in the sampled air exceeded threshold levels. For the current test series, a 34 m long sampling pipe with 6 sampling holes at a 5.6 m spacing was installed along the center of the tunnel ceiling (see Figure 3.1). The pipe installed in the test tunnel represents 28% of the total coverage area of one smoke detector in a real tunnel as well as in the operating environment tests in the Lincoln tunnel undertaken in Tasks 5 and 6 of the project. In order to match the air-flow sampled in a full coverage area, 28% of the airflow through the detector was from the pipe installed in the test tunnel. Photographs of the pipe in the test tunnel are shown in Figures 3.7 and 3.8.

A number of additional fire detectors, including spot heat detectors, flame and CCTV detectors, were also installed in the test tunnel for collecting extra test data (see Figures 3.4 and 3.8). These additional detectors were not connected to the central data collection system, but to the individual data collection system of the system suppliers. This report does not include the performance of these extra detectors/detection systems in the tests.

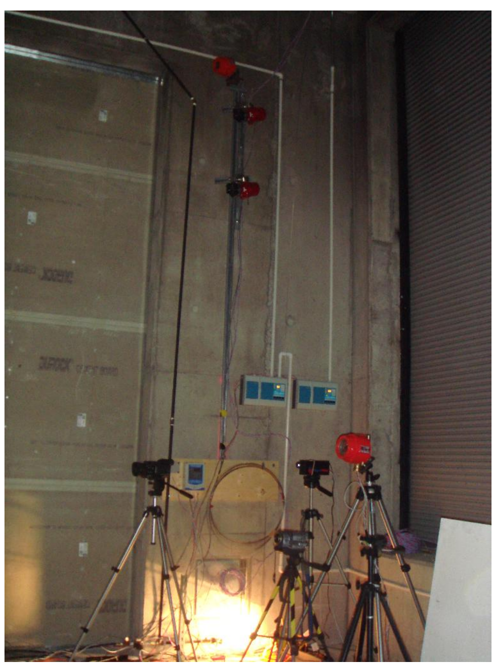

Figure 3.8. Photograph of detectors on the South wall of the tunnel

4. INSTRUMENTATION

Various instruments were used to monitor fire tests. These included thermocouples, heat flux meters, smoke meters, velocity meters and video cameras, as shown in Figure 4.1. The location of each instrument in the tunnel is shown in Figure 4.2.

Fifty-five thermocouples (Type K, 18 gauge, Figure 4.1f) were installed at the ceiling of the tunnel facility for temperature measurements. As shown in Figure 4.2, the transverse and longitudinal distances between thermocouples on the ceiling of the tunnel were 1.67 m and 3.125 m, respectively, and each thermocouple was 150 mm below the ceiling. Two thermocouple trees were dropped from the ceiling of the tunnel. One was located above the fire to measure the gas/flame temperatures of the fire source and to monitor the fire development. The second tree was located at the middle of the tunnel (18.7 m from the end of the tunnel and 5 m from the wall of the tunnel) to monitor fire development in the tunnel. There were five thermocouples on each tree spaced at 1.1 m intervals starting 0.6 m above the tunnel floor.

Three smoke meters were used for measuring smoke optical density in the tunnel (Figure 4.1d). They were located at the middle of the tunnel and approximately 12 m from the fire source. One sampling-obscuration smoke system was used to measure the smoke from the hot layer. The inlet was located at 150 mm below the tunnel ceiling. Two straight-line obscuration smoke systems were used to measure the smoke density 1.53 m and 2.5 m above the tunnel floor. The measuring methods of these two types of smoke meters are described in Reference [10].

Hand held Dwyer VT140 Thermo-anemometers with remote vane sensors mounted on 4 m long aluminum poles were used to measure the air velocity in the tunnel (Figure 4.1a). The measurements were taken at the middle of the tunnel at 3 heights: 150 mm below the ceiling, 2.75 m above the ground and 0.7 m above the ground.

Five heat flux meters and radiometers were used to measure the heat and radiant flux of the fire, and to monitor the fire development (Figure 4.1b). They were located 1 m, 2 m, 5 m, 10 m and 29 m from the fire source and at 1.45 m above the ground, as shown in Figure 4.2. The radiometer that was located at 29 m from the fire source was placed near the end of the tunnel close to the flame detectors. It was used to measure flame radiant that could reach the detectors.

Two regular Sony Hi8 digital video cameras were used to provide a video record for the tests (Figure 4.1e). One video camera was located near the fire source to monitor the fires. The second one was located 29 m from the fire source to monitor the fire and smoke development in the tunnel.

The location of the instrumentation remained unchangeable in the test series. The test data together with outputs of the detectors/detection systems were collected at one second intervals by a data acquisition system (Figure 4.1c).

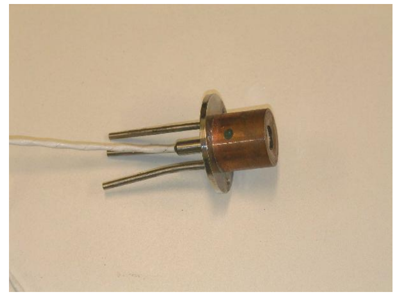

Figure 4.1a). Velocity meter

Figure 4.1b). Heat flux

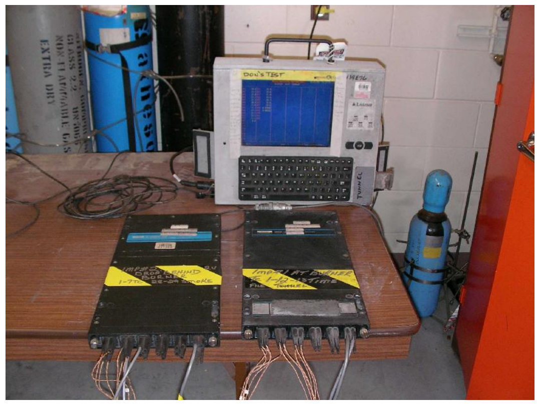

Figure 4.1c). Data Collection system

Figure 4.1d). Smoke meters

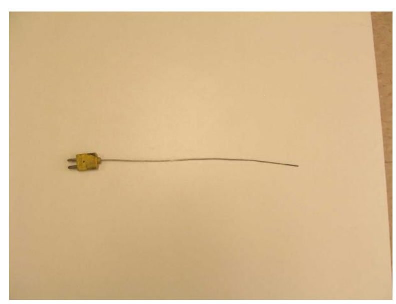

Figure 4.1e). Video Camera

Figure 4.1f). Thermocouple

Figure 4.1. Instrumentation used in the test program

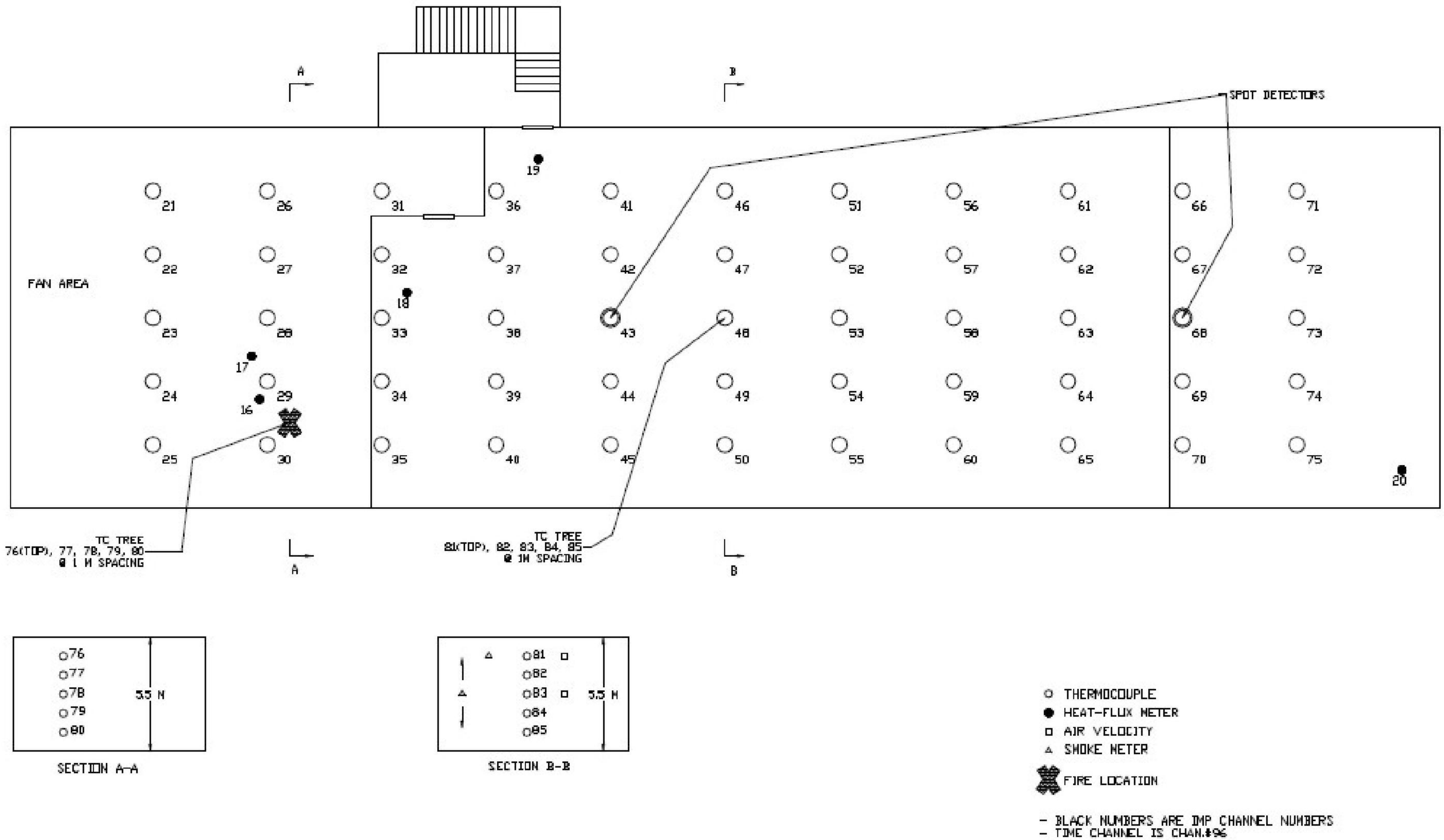

Figure 4.2. Schematic of instrumentation in the test tunnel

5. TEST PROCEDURE

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

- Prepared fire scenarios;
- Checked instrumentation and each detection system prior to each test, to assure normal operation;
- Activated fan systems and measured air velocities around the mock-up.
- Started the data acquisition system and video recorders for 60 s, and then manually ignited the fire;
- Terminated the test when:
  - All the detectors activated;
  - Or 4 minutes after the fire reached its maximum heat release rate;
  - Or a maximum safe operating temperature of 200^{o}C at the ceiling that was 3 m from the fire source was reached. This was used to ensure that the detection systems mounted in the tunnel were not damaged.
- Checked each detection system to determine if they still functioned properly after the fire test.

6. FIRE TESTS AND RESULTS

Twenty-one full-scale fire tests were conducted in the test tunnel. The fire scenarios included gasoline pool fires located in an open space, underneath a simulated vehicle and behind a simulated vehicle, simulated stationary vehicle fires located in an engine compartment and in a passenger compartment and a moving vehicle fire with two driving directions and speeds. The fire sizes varied from approximately 125 kW to 3,400 kW and fuel types included gasoline, propane, wood crib and plastic foam. These fire scenarios were considered representative of the majority of tunnel fire incidents [9]. The fire scenarios and the measurement of heat release rates of fires are discussed in the report of Task 1 of the project [9].

For the tests involving liquid pool fires and stationary passenger vehicle fires, the fire source was placed at the same location in the test tunnel: 6.5 m from the East end of the tunnel and 2.5 m from the North wall of the tunnel. This simulated a fire in the side lane of a tunnel. At this location, the fire source was located below the cables of Systems D-1L1 and D-2L2, 30 m from the optical flame and CCTV detectors (Systems D-3F1 to D-6C3), approximately 3 m from the nearest sprinkler of System D-7H1, approximately 7.5 m from the nearest spot heat detector of System D-8H2 and approximately 4 m from the nearest sampling hole of System D-9S1.

The fire characteristics produced by the fire scenarios, such as the fire growth rates, temperatures and smoke spread in the tunnel, were investigated. The activation time of each detector/detection system was recorded. The ability of the detection systems to locate and monitor the fire incident was also evaluated.

6.1. Pool Fires

Pool fire scenarios used in the test series included an open gasoline pool fire, gasoline pool fires located underneath a simulated vehicle, and gasoline pool fires located behind a large simulated vehicle. A propane burner with a controlled heat release rate was also used for simulating pool fires located underneath a vehicle. The test conditions and results of the tests using pool fire scenarios are listed in Table 6.1.

6.1.1. Pool Fire in Open Space

A 0.3 m by 0.3 m pan with gasoline was placed in the North lane of the test tunnel. There was no obstacle around the fire source. Ambient temperature in the tunnel was 6^{o}C and air velocity in the tunnel was measured to be zero. The test evaluated the response of the detectors/detection systems to a small open pool fire. The results provided a reference for the tests using shielded fire scenarios.

The fire was allowed to burn freely for approximately 12 minutes until the gasoline in the pan was burnt out (Figure 6.1). The fire developed very quickly reaching a maximum heat release rate of 100~125 kW. The rate of rise of the ceiling temperature above the fire source was approximately 15^{o}C/min. The maximum ceiling temperature above the fire source was approximately 22^{o}C. A small amount of dark smoke was generated and accumulated below the ceiling. The smoke did not obstruct the view of the CCTV detectors during the test.

Figure 6.1. An open space gasoline pool fire in the test tunnel

As shown in Table 6.1, all the optical flame and CCTV detectors responded quickly to the small open gasoline pool fire. Their response times were within 14 s. The linear fiber optic heat detection system D-1L1 also detected the fire at 24 s as the ceiling temperature quickly increased. The smoke detection system detected the fire at approximately 103 s. There was no response from the linear heat detection system D-2L2 and the two spot heat detectors since the ceiling temperature was below their alarm temperature thresholds.

6.1.2 Pool Fires underneath a Simulated Vehicle

A series of tests were conducted to simulate a fire incident in which two vehicles crashed and fuel leaked from one of the vehicles, resulting in a gasoline pool fire underneath the vehicle. As shown in Figure 6.2, a pan was placed underneath a simulated vehicle. The simulated vehicle had the same footprint (1.5 m wide by 2.4 m long) as the bottom area of a standard passenger vehicle. The gap between the bottom of the simulated vehicle and the ground was 0.3 m. A plate with a size of 1.5 m wide by 1.2 m high, simulating a crashed car located between the fire source and the wall-mounted detectors, was placed 1.5 m in front of the fire source and 0.3 m above the ground.

During the tests, the fire source was located at the same place as the open pool fire in Test T-1. Six fire tests with various fire sizes and two fuel types were conducted to evaluate performances of detectors/detection systems to fires located underneath the vehicle. The test conditions and results are listed in Table 6.1. The heat release rates of four gasoline pool fires underneath the vehicle listed in the table are values measured in the open space with the same size of pool fuels [9]. Actual heat release rates of fires generated in tests could be lower than those in the open space, because of the vehicle body above the fuel pool.

Figure 6.2. Schematic of the setup for a fire underneath a vehicle

Table 6.1. Test Conditions and Results in Pool Fire Scenarios

FIRE SCENARIO	TEST NO	FIRE SOURCE	FUEL TYPE	HEAT RELEASE RATE (KW)	T_{ROOM} (^OC)	D-1L1 (S)	D-2L2 (S)	D-3F1 (S)	D-4C1 (S)	D-5C2* (S)	D-6C3 (S)	D-7H1 (S)	D-8H2 (S)	D-9S1 (S)
Open fire	T-1	0.3 x 0.3	Gasoline	100 ~ 125	6	24	N/R	4	14	10	9	N/R	N/R	103
Fire under the vehicle	T-2	0.3 x 0.3	Gasoline	100 ~ 125	6	N/R	N/R	N/R	125	N/R	N/R	N/R	N/R	133
	T-3	0.6 x 0.6	Gasoline	550 ~ 650	6	37	75	26	29	44	N/R	N/R	N/R	50
	T-7	1.0 x 1.0	Gasoline	1500 ~ 1700	1	26	51	6	10	17	28	231	125	47
	T-15	1.0 x 2.0	Gasoline	3000 ~ 3400	13	17	26	4	156	13	38	183	101	86
	T-16	Burner	Propane	1500 ~ 1700	13	22	35	12	15	N/R	195	152	72	N/R
	T-18	Burner	Propane	3000 ~ 3400	9	25	27	3	8	14	N/R	31	36	N/R
Fire behind the vehicle	T-8	0.3 x 0.3	Gasoline	100 ~ 125	5	43	N/R	22	19	24	N/R	N/R	N/R	125
	T-9	0.6 x 0.6	Gasoline	550 ~ 650	5	30	58	12	127	16	N/R	N/R	N/R	52
	T-10	1.0 x 1.0	Gasoline	1500 ~ 1700	10	11	21	8	32	N/R	N/R	62	37	38
	T-11	1.0 x 2.0	Gasoline	3300 ~ 3400	12	20	14	8	26	16	N/R	20	19	33

Note:

- N/R: no response
- No test data from Detection System D-5C2 was collected by the project data acquisition system, because of technical problems with System D-5C2. The test data of System D-5C2 that are listed in Table 6.1 were provided by the manufacturer after the tests and were not verified using data from the data acquisition system used for the other detectors.
- The systems listed in the table are:
    1) D-1L1: Linear fiber optic heat detection system
    2) D-2L2: Linear analogue heat detection system
    3) D-3F1: Optical flame detector
    4) D-4C1: CCTV flame/smoke detector
    5) D-5C2: CCTV flame detector
    6) D-6C3: CCTV flame detector
    7) D-7H1: Spot heat detector
    8) D-8H2: Spot heat detector
    9) D-9S1: Smoke detection system

6.1.2.1 Flames, Smokes and Temperatures Produced by Fires

Four flammable fire tests were conducted using four pan sizes of 0.09 m^2, 0.36 m^2, 1.0 m^2 and 2.0 m^2 located underneath the simulated vehicle. In Test T-2, a 0.09 m^2 pan with gasoline was allowed to burn freely for approximately 8 minutes. The fire size was small, and the flame was confined underneath the vehicle but smoke escaped from the vehicle, as shown in Figure 6.3. The maximum ceiling temperature above the fire source was approximately 13^{o}C. The rate of rise of the ceiling temperature above the fire source was approximately 5^{o}C/min. Both the maximum ceiling temperature and rate of rise were lower than those generated using the open gasoline pool fire in Test T-1 with the same pan size.

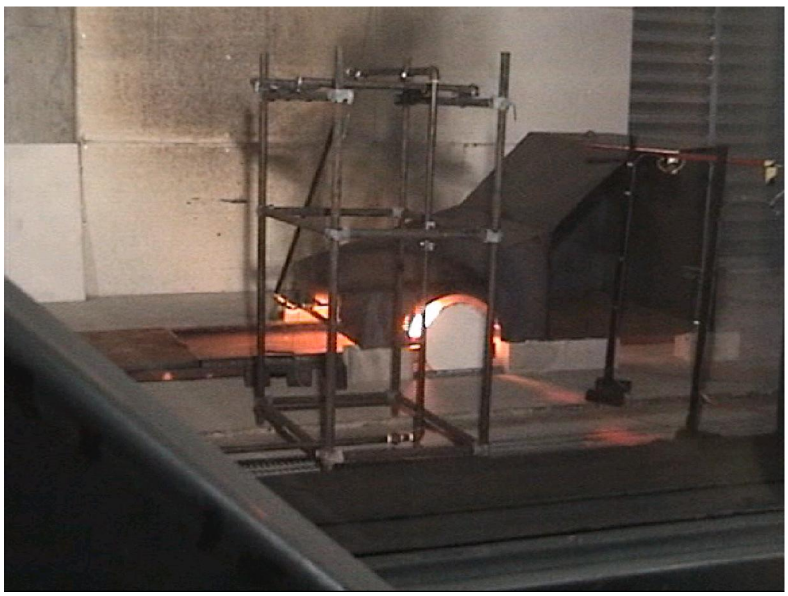

Figure 6.3. A 0.3 m x 0.3 m gasoline pool fire located underneath the simulated vehicle in Test T-2

Only the visual flame-smoke CCTV detector D-4C1 and the smoke detection system D-9S1 detected the fire at 125 s and 133 s, respectively, since they responded to the smoke produced by the fire. The response times were longer than those for the open pan fire. All other fire detectors/detection systems did not respond to the fire in Test T-2.

With the larger pans, the fire size increased and more flames and smoke were produced outside the simulated vehicle, as shown in Figure 6.4 for Test T-7 with a 1.0 m^2 pan size. The heat flux measured in Test T-7 are shown in Figure 6.5. Once ignited, the gasoline pool fire developed quickly. The heat flux continuously increased with time until the fire was extinguished at 5:50 minutes after ignition. The maximum heat flux measured at 1 m from the fire source was approximately 19 kW/m^2.

Figure 6.4. Tunnel conditions with a gasoline pool fire (1.0 m x 1.0 m) located underneath the simulated vehicle in Test T-7

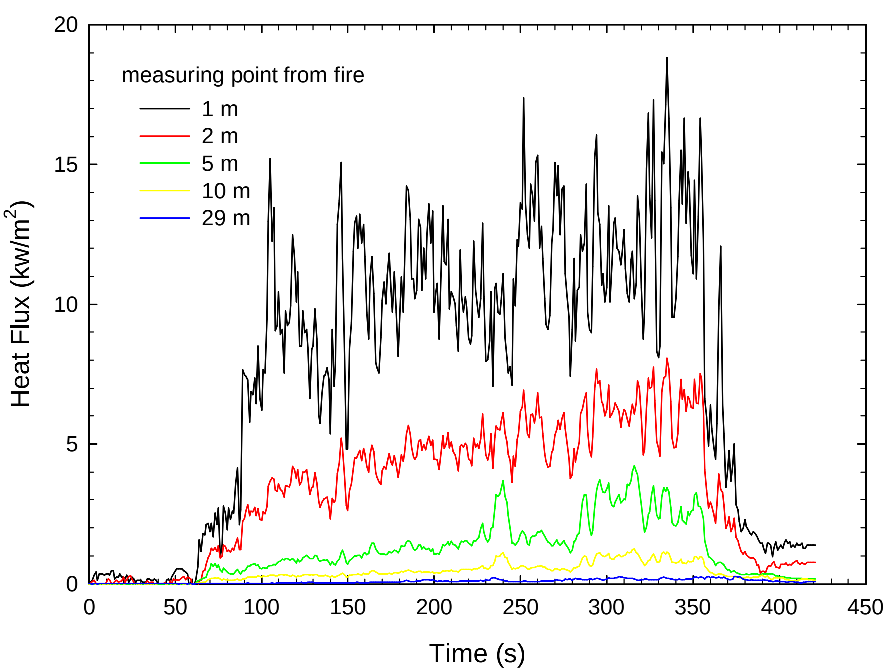

Figure 6.5. Variations of heat flux with distance from the fire source in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire located underneath the simulated vehicle

Figure 6.6 shows the temperatures measured above the fire source in Test T-7. The maximum temperature measured at 0.6 m above the ground was approximately 900°C and it declined with an increase in distance from the fire source. The temperatures measured 2.8 m above the ground did not show substantial decrease with an increase in distance from the fire source.

The temperature measured at the mid point of the tunnel (Figure 6.7) showed different trend from those measured above the fire source. A hot smoke layer was quickly formed beneath the ceiling after ignition. The temperatures increased with time and with an increase in the elevation above the ground. The maximum temperature measured at 5 m above the ground was approximately 95°C.

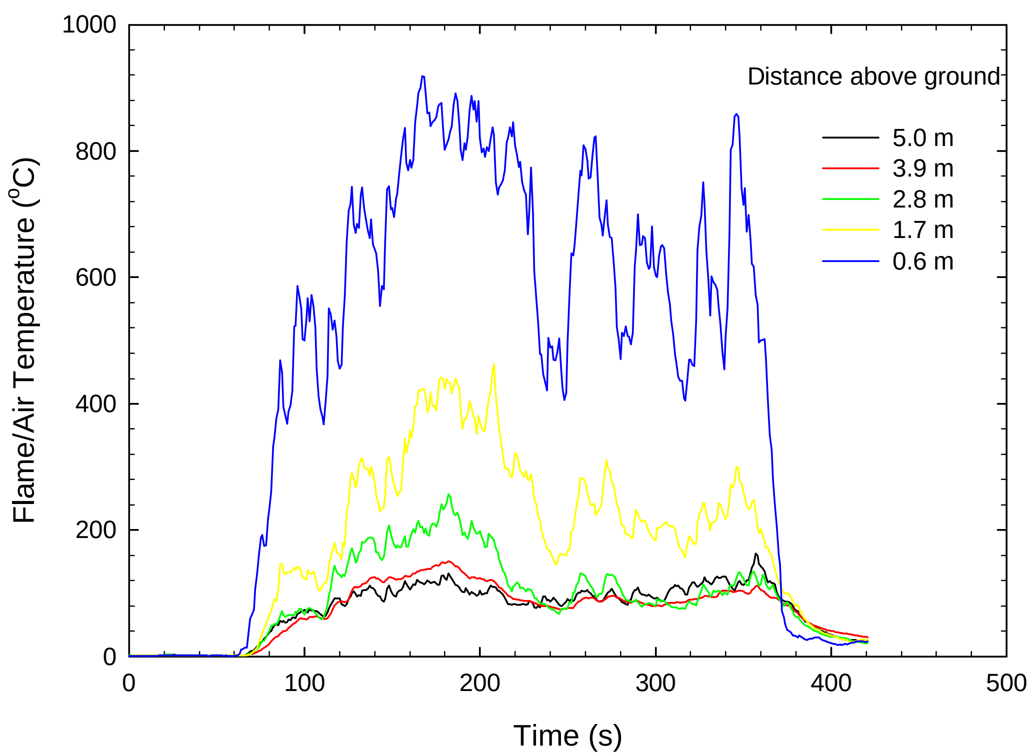

Figure 6.6. Flame and air temperatures above the fire source in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire located underneath the vehicle

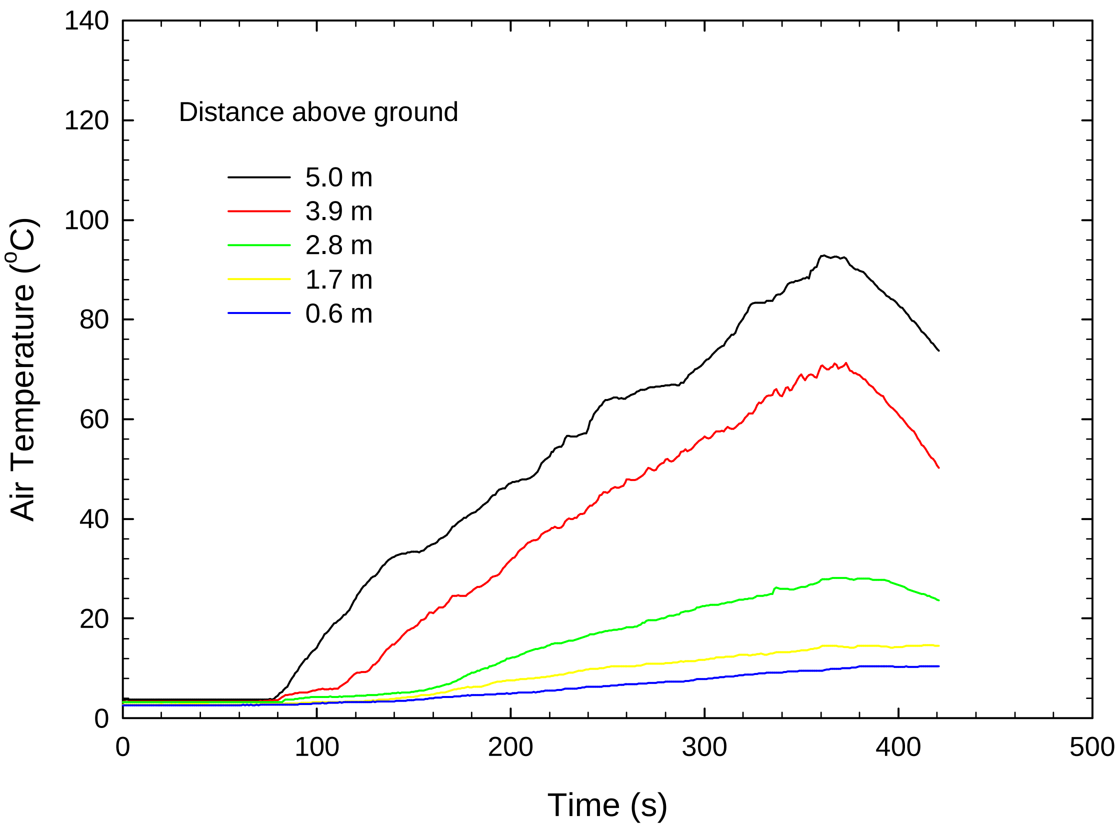

Figure 6.7. Variation of air temperatures with elevation at the middle of the tunnel in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire located underneath the simulated vehicle

Figure 6.8 shows the variation in ceiling temperatures along the center of the tunnel in Test T-7. The temperature increased quickly with time and decreased with an increase in distance from the fire source. The maximum temperature measured at the center of the tunnel was approximately 125°C near the fire source.

Figure 6.9 shows changes in the ceiling temperature across the tunnel measured near the fire source (6.2 m from East end of the tunnel). The temperature decreased with an increase in distance from the fire source. The maximum ceiling temperature near the fire source was approximately 170°C.

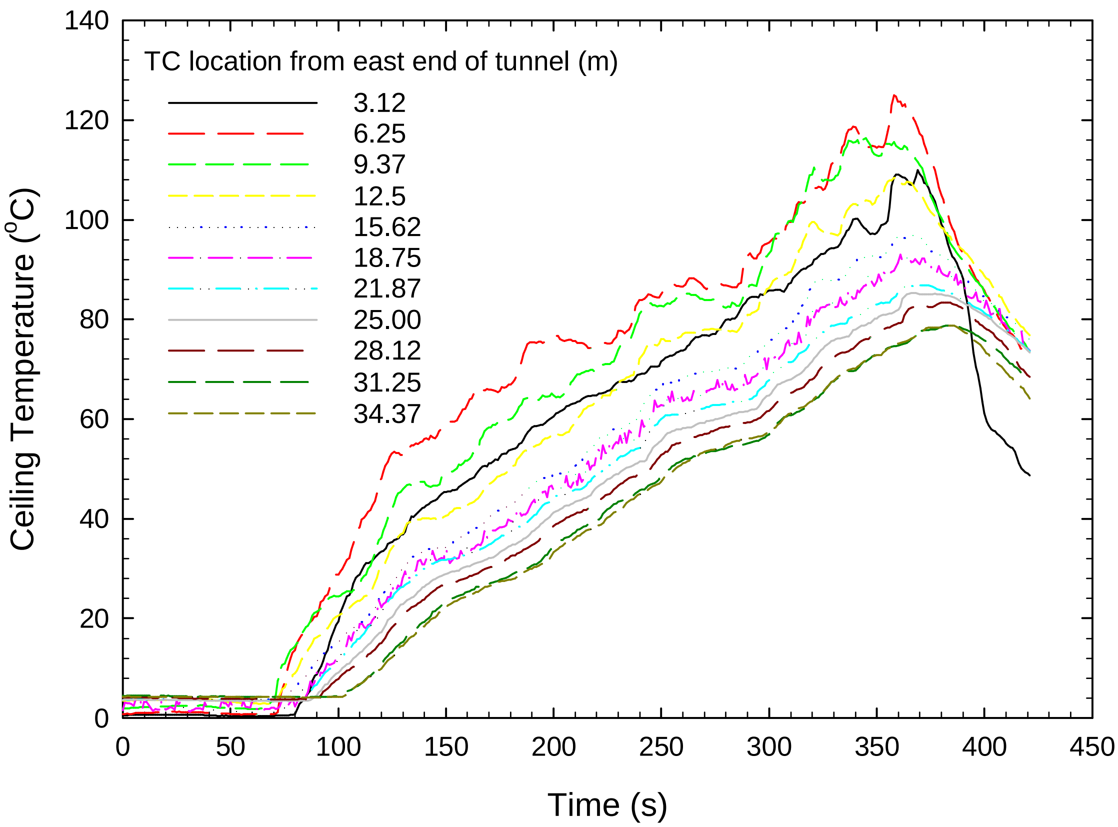

Figure 6.8. Ceiling temperatures along center of the tunnel in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire located underneath the simulated vehicle

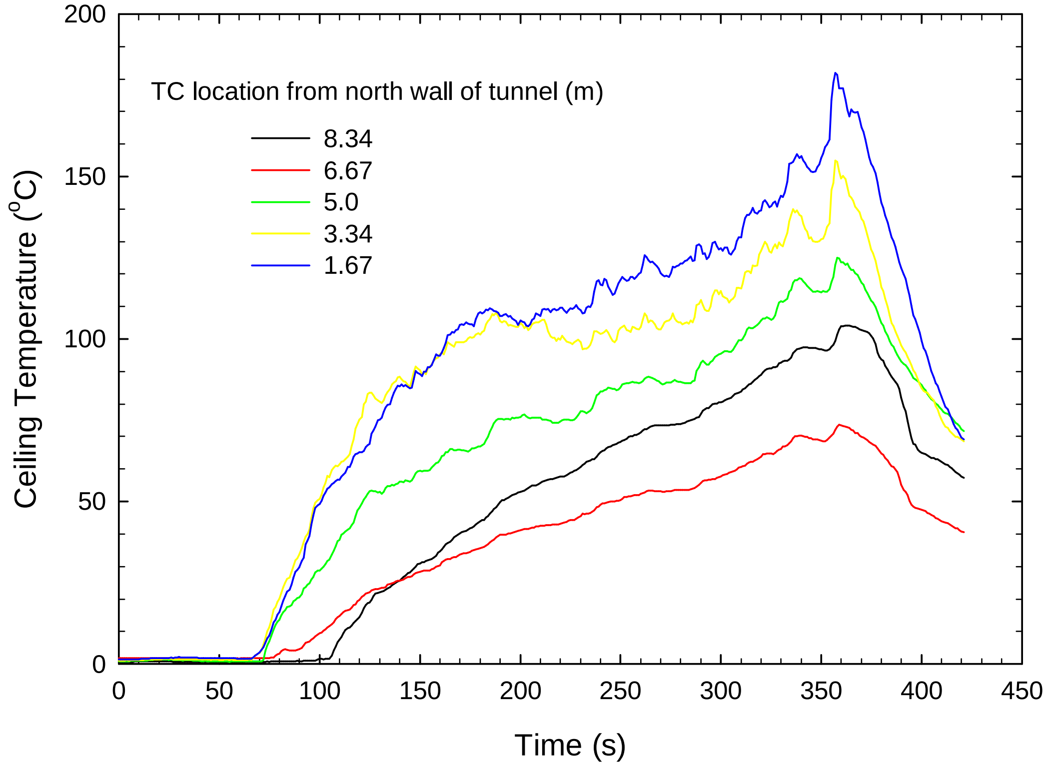

Figure 6.9. Ceiling temperatures across the tunnel near the fire source in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire underneath the vehicle

The ceiling temperature distribution in the tunnel at 2 minutes after ignition is shown in Figure 6.10. It suggests that the fire had substantial impact on the ceiling temperature in an area within a 5 m radius from the fire source. The differences in ceiling temperature across the tunnel tended to become small as the distance from the fire source increased. Figure 6.10 also shows that the ceiling temperature near the partially open side louver at the East end of the tunnel and near the partially open side door at the West end of the tunnel substantially dropped, in comparison with temperatures located in other areas, showing the effect of airflow in these areas.

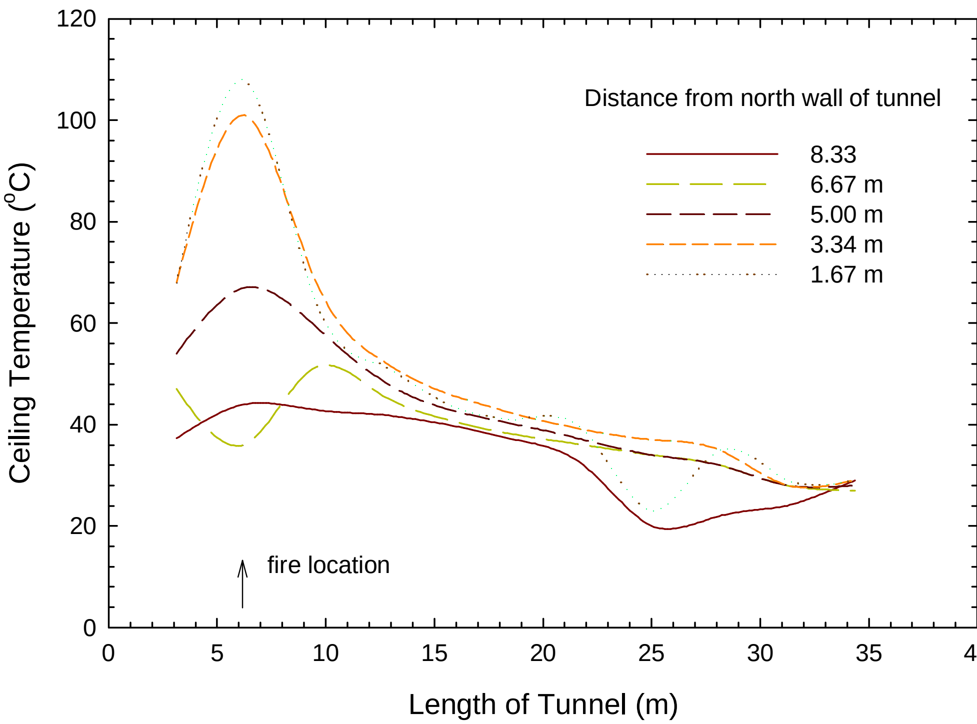

Figure 6.10. Ceiling temperature distribution in the tunnel at 2 minutes after ignition in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire underneath the vehicle

Figure 6.11 shows the variation in smoke density measured at the middle of the tunnel with time in Test T-7. The smoke density at 150 mm below the ceiling initially increased slowly, and then quickly increased from 170 s after ignition. The smoke densities measured at 2.5 m and 3.97 m below the ceiling were not very high, and increased slowly with time. There was no airflow in the tunnel.

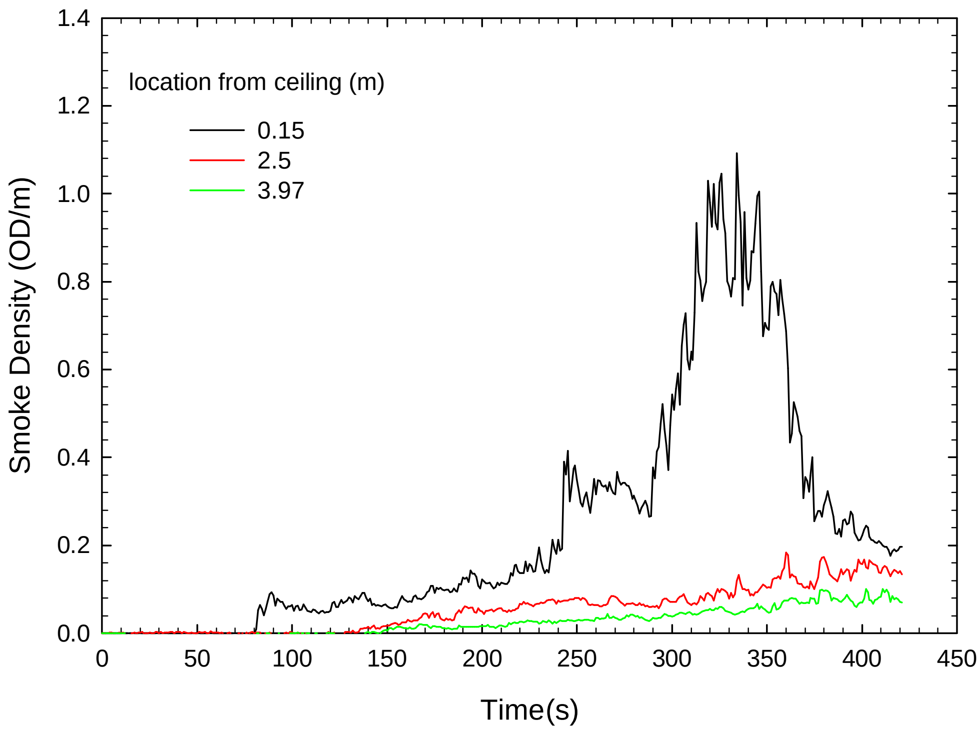

Figure 6.11. Variations of smoke density below the ceiling at center of the tunnel in Test T-7 with a 1.0 m by 1.0 m gasoline pool fire located underneath the simulated vehicle

Figures 6.12 through 6.15 compare the changes in the heat flux measured at 1 m from the fire source, the smoke density measured 150 mm below the tunnel ceiling, the maximum ceiling temperatures along the center of the tunnel and across the tunnel near the fire source for the tests with four gasoline pool pan sizes located under the simulated vehicle. The heat flux, smoke density and ceiling temperatures increased with an increase in pan size from 0.09 m^2 to 1.0 m^2. However, when the pan size increased to 2.0 m^2, the heat flux, smoke density and maximum ceiling temperatures in the tunnel were lower than those measured with the 1.0 m^2 pan. The test results suggested that the large 2.0 m^2 pool fire located underneath the simulated vehicle did not fully combust, because the air supply required for combustion and the radiative heat transfer from the flame to the fuel surface were restricted by the vehicle body that was positioned above the fuel pool.

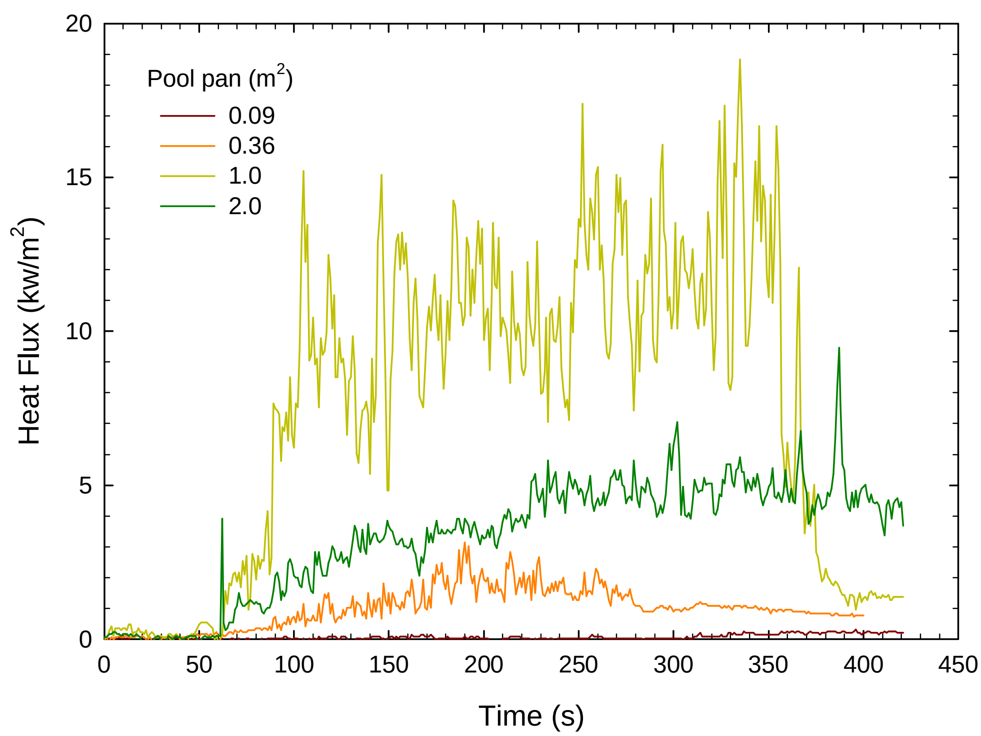

Figure 6.12. Heat flux measured at 1 m from the fire with four gasoline pool pans located underneath the simulated vehicle

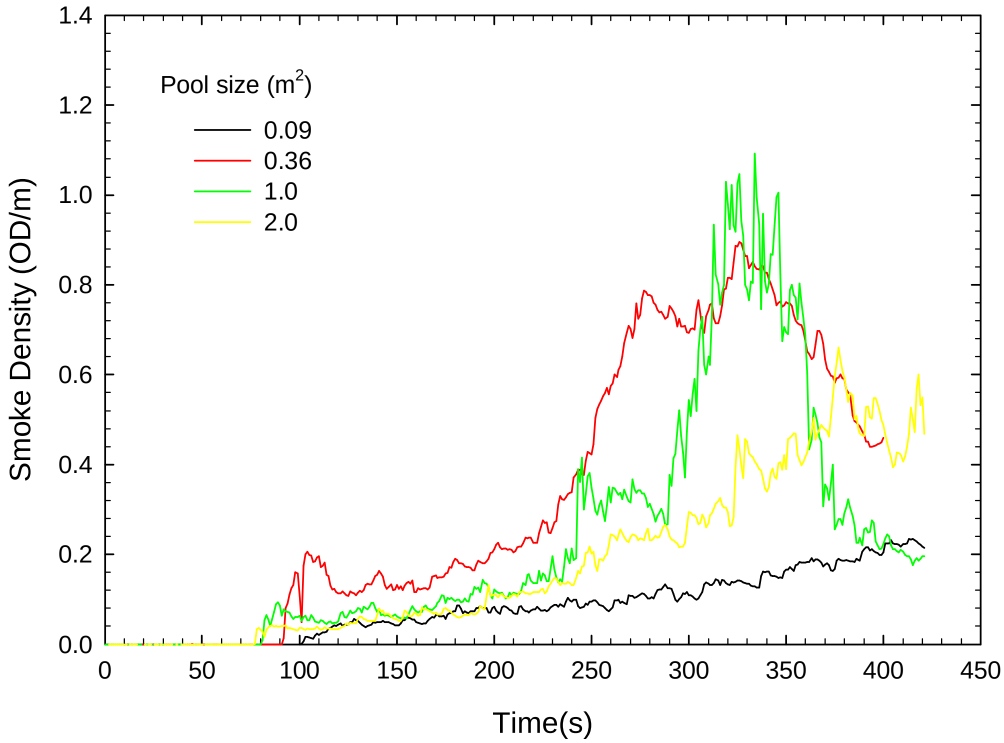

Figure 6.13. Smoke densities measured at 15 cm below the ceiling with four gasoline pool pans located underneath the simulated vehicle

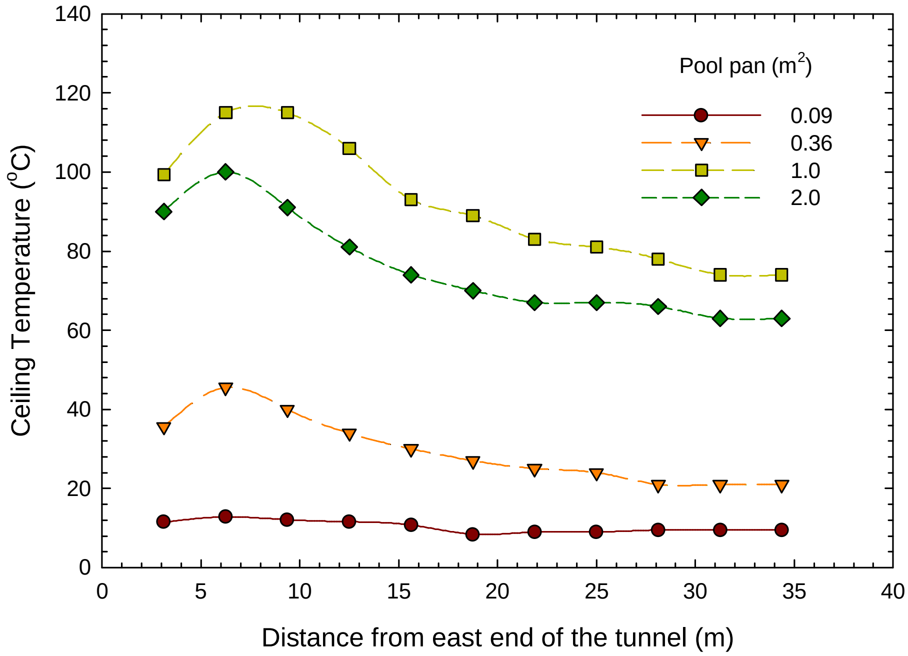

Figure 6.14. Maximum ceiling temperatures along center of the tunnel with four gasoline pool pans located underneath the simulated vehicle

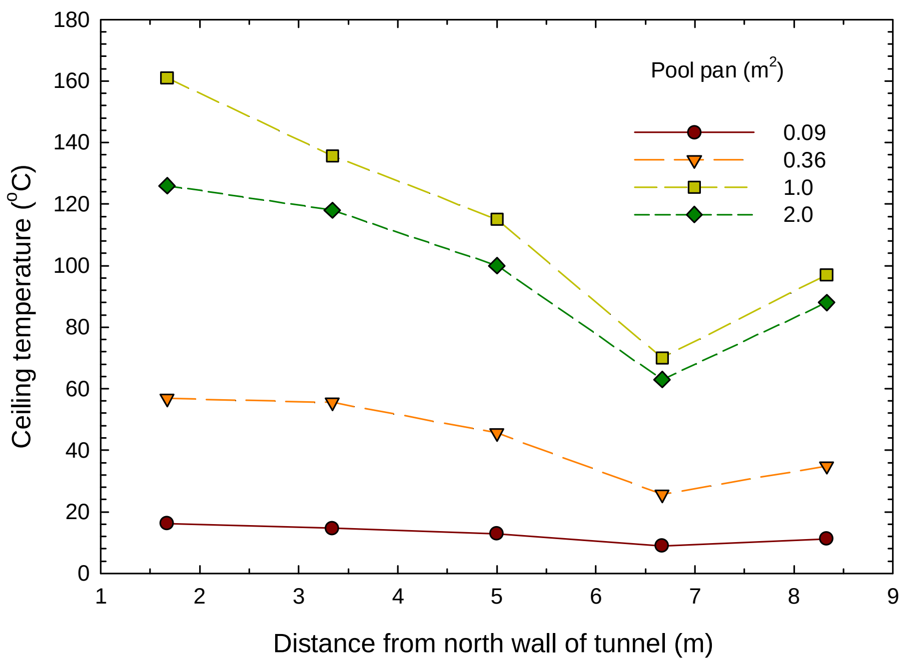

Figure 6.15. Maximum ceiling temperatures across the tunnel near fire with four gasoline pool pans located underneath the simulated vehicle

Two propane fire tests (Tests T-16 and T-18) were conducted using a propane burner to simulate large pool fires underneath the vehicle. The structure of the propane burner was described in the report of Task 1 [9]. The setup of the fire scenarios with the propane burner was the same as those with the gasoline pool fires. During the tests, the heat release rate produced by the propane burner fire was controlled manually to simulate the heat output produced by the gasoline pool fires determined in calibration tests [9].

As shown in Figure 6.16, the propane fires are clean fires and no visible smoke is produced by the propane fires in the tests. The flames generated from the propane burner were similar to the fire produced by the gasoline pool fire, when viewed from the front of the simulated vehicle.

Figure 6.17 shows the ceiling temperatures measured in Tests T-7 and T-16 with gasoline and propane fires. The temperatures were measured at thermocouple #28 located at the center of the tunnel ceiling. The temperature measured in the two tests had a similar trend and the maximum temperatures were comparable.

a). Side view of a propane burner fire

b). Front view of a underneath propane fire

Figure 6.16. The propane fire (1,700 kW) in Test T-16

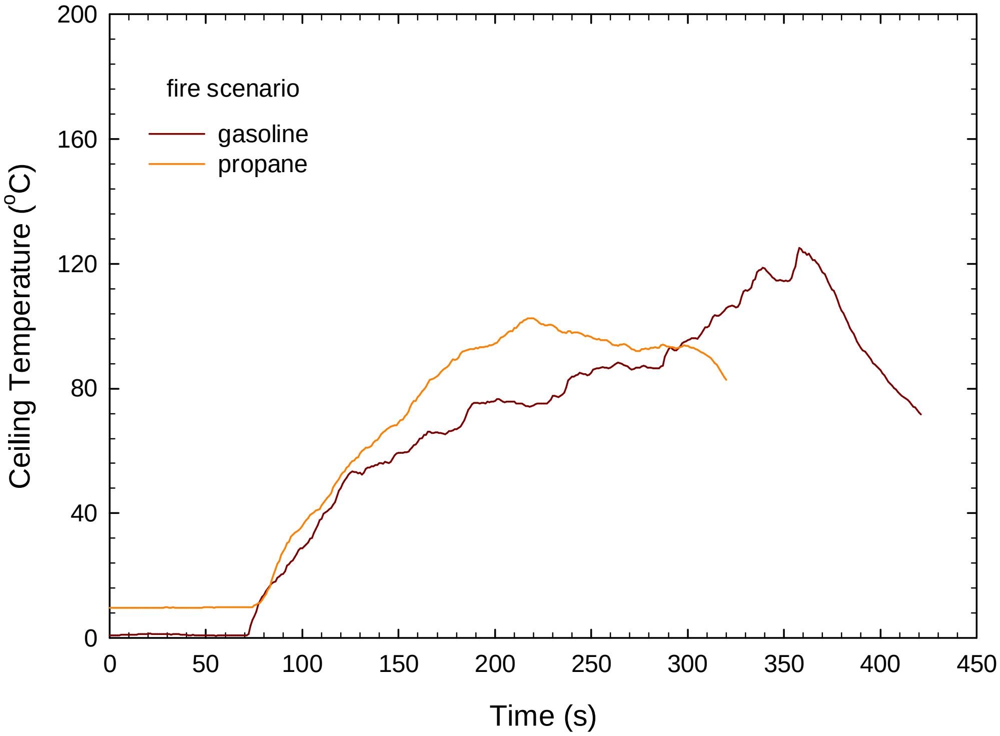

Figure 6.17. Ceiling temperatures measured at Thermocouple #28 at center of the tunnel ceiling in Test T-7 with gasoline pan fire and in Test T-16 with propane

6.1.2.2 Response of Fire Detectors/Detection Systems

The linear heat detection system D-1L1 did not detect the fire located underneath the vehicle with a 0.09 m^2 gasoline pool fire, but it detected the other three gasoline fires within 37 s, as shown in Table 6.1. The response time decreased with an increase in fire size. The detection time was 37 s for the 0.36 m^2 gasoline pool fire, and then decreased to 17 s for the 2.0 m^2 gasoline pool fire. System D-1L1 was also able to provide information on the temperature along the cable with time, as shown in Figure 6.18 for Test T-3 with a 0.36 m^2 gasoline pool fire. The system responded to the change in temperature, and the position with the highest temperature is the location closest to the fire source.

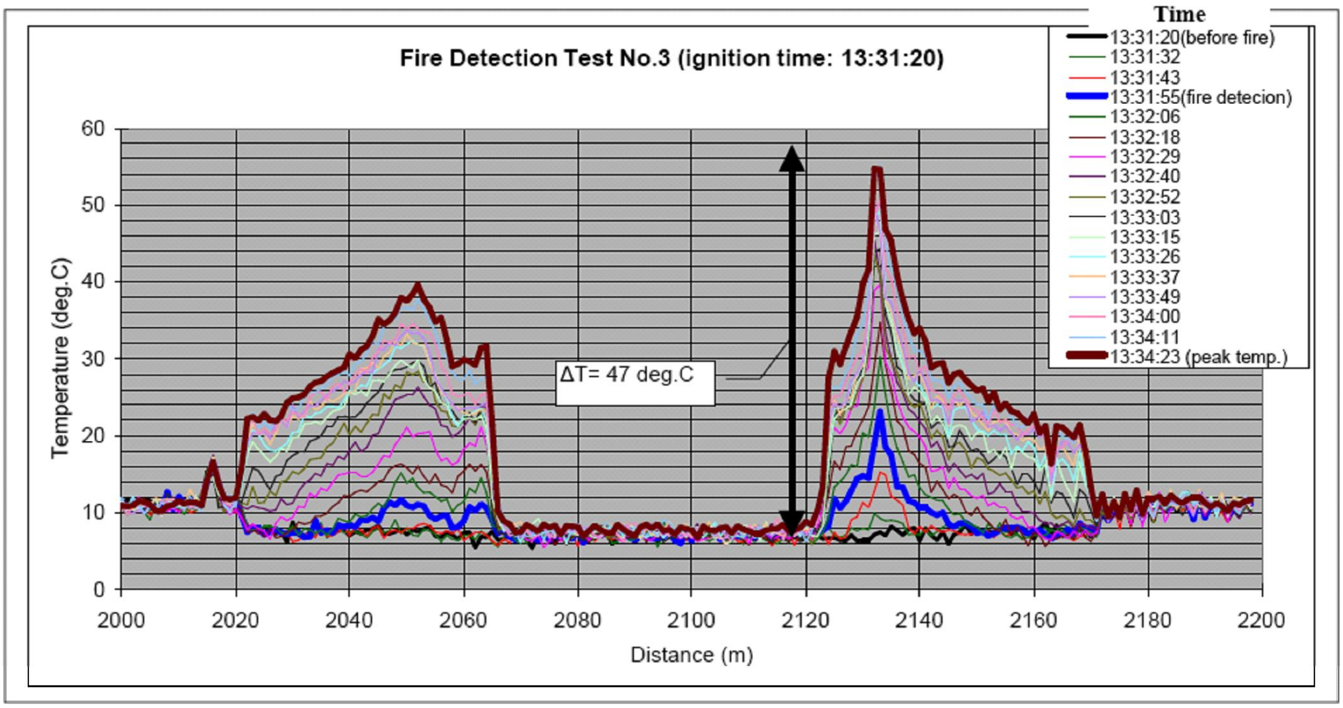

Figure 6.18. Variations of temperature along the cable of System D-1L1 with time in Test T-3 with a 0.36 m^2 gasoline pool pan located underneath the simulated vehicle

The linear heat detection system D-2L2 did not detect a 0.09 m^2 gasoline pool fire (T-2). It detected the other three gasoline fires with the response time ranging from 75 s (T-3) to 26 s (T-15). The response time decreased with an increase in fire size.

The optical flame detector D-3F1 could not detect the 0.09 m^2 gasoline pool fire (T-2), but it detected the three other gasoline fires with the response time ranging from 26s to 4 s. The response time decreased with an increase in fire size.

The visual flame-smoke CCTV detector D-4C1 detected the four gasoline pool fires located underneath the vehicle with the response time ranging from 156 s to 10 s. The response time generally decreased with an increase in fire size. However, the response time for the 2.0 m^2 gasoline pool fire was 156 s and even longer than that with the 0.09 m^2 gasoline pool fire.

The video camera was able to provide images on fire conditions in the tunnel during the entire test with the 0.09 m^2 gasoline pool fire. The view of the camera was, however, obstructed during the tests with smoke produced from larger fires, as the smoke density in the hot layer increased. The time at which the view of the camera was completely obstructed by the smoke was approximately 3:30 minutes for the 0.36 m^2 gasoline pool fire, 3:45 minutes for the 1.0 m^2 gasoline pool fire, and 4:40 minutes for the 2.0 m^2 gasoline pool fire. The obstructed time increased with an increase in fire size. This was consistent with smoke density measured in the tests. As shown in Figure 6.13, the smoke density produced by the 0.36 m^2 gasoline pool fire was higher than those measured in the two large gasoline pool fires during the initial 5 minutes of the fire.

The visual CCTV flame detector D-6C3 did not detect two small pan fires located underneath the simulated vehicle (T-2&3), but it responded to the two larger fires in less than 40 s (T-7 and T-15).

Both spot heat detectors D-7H1 and D-8H2 only responded to the two larger pan fires located underneath the simulated vehicle (T-7 and T-15). The detection time decreased with an increase in pan size. For the 2.0 m^2 gasoline pool fire located underneath the vehicle, the response times of the two detectors were 183 s and 101 s.

The smoke detection system D-9S1 detected all four gasoline pan fires located under the simulated vehicle with the response time ranging from 133 s to 47 s. The detection time decreased with an increase in the fire size. However, the response time for the test with the 2.0 m^2 pan was longer than the test with 0.36 m^2 pan. This was consistent with smoke density measured in the tests. As shown in Figure 6.13, the smoke density measured in the fire with 2.0 m^2 pan was lower than that measured in the fire with the 0.36 m^2 pan.

For propane fire in Tests T-16 and T-18, the smoke detection system D-9S1 did not respond to the fires since no visible smoke was produced in the tunnel. The visual CCTV flame detector D-6C3 also had difficulty in detecting the propane fires. It detected the 1,700 kW fire at 195 s in Test T-16 and could not detect the large fire with 3,400 kW in Test T-18.

All other detectors/detection systems were able to detect the propane fires with response times ranging from 3 s to 152 s. The response time decreased with the increase in propane fire size. Compared to the same setup with a 1.0 m^2 gasoline pool fire in Test T-7, the detection time for the 1,700 kW propane fire in Test T-16 was reduced for the linear heat detection systems D-1L1 and D-2L2, and for the two spot heat detectors (D-7H1 and D-8H2), but slightly increased for the optical flame detector D-3F1 and the visual CCTV flame and smoke detector D-4C1. The cable of the linear heat detection system D-2L2 was damaged in Test T-18 with the 3,400 kW propane fire. The maximum ceiling temperature was higher than 240°C.

6.1.3. Pool Fires behind a Large Vehicle

A series of tests were conducted using a fire scenario that was set up with an open pan fire located behind a large steel plate, which simulated the front portion of a large truck. The fire scenario was simulated for a tunnel fire incident in which an open gasoline pool fire was formed behind a large vehicle due to the crash or mechanical failure of the vehicle. The plate was 2.5 m wide by 3.5 m high. It was placed 0.3 m above the tunnel floor, and 6 m in front of the pool fire, simulating the front portion of a crashed truck located between the pool fire and the detectors. The distance between the edge of the plate and the wall of the tunnel was 1.2 m. A schematic of the open pool fire located behind a large simulated vehicle is shown in Figure 6.19 and a photograph of its setup in the test tunnel is shown in Figure 6.20.

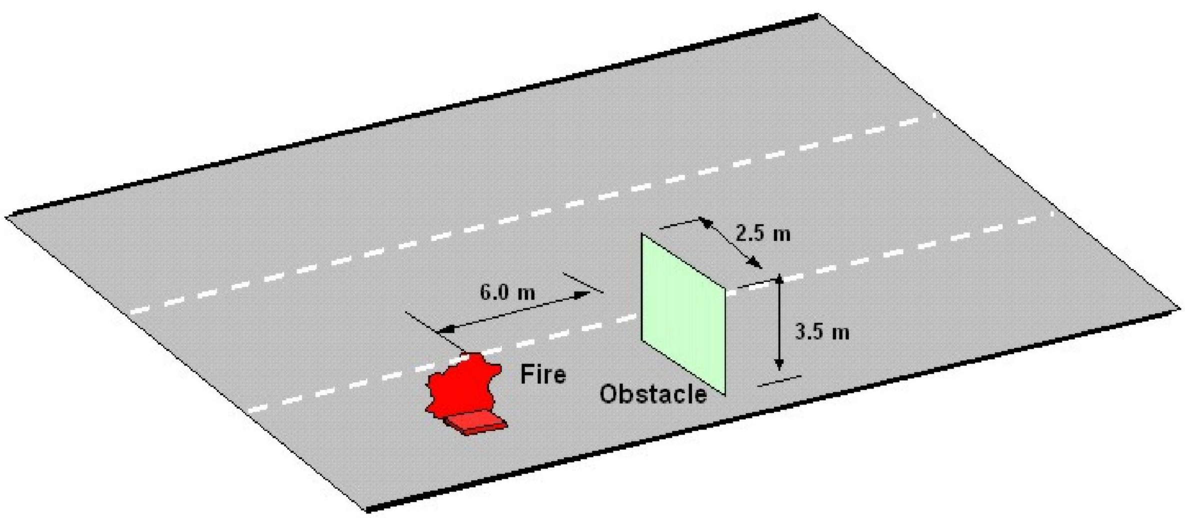

Figure 6.19. Schematic of the setup of a pool fire located behind a large simulated vehicle

Figure 6.20. Photograph of the setup of a pool fire located behind a large simulated vehicle in the test tunnel

6.1.3.1 Flames, Smokes and Temperatures Produced by Fires

Four tests with gasoline pool fires ranging from 125 kW to 3,400 kW were conducted. The pan sizes located behind the simulated vehicle were 0.09 m^2, 0.36 m^2, 1.0 m^2 and 2.0 m^2. The gasoline pool fire located behind the vehicle was a freely burning fire with sufficient air supply. Figure 6.21 shows a 1.0 m^2 gasoline pool fire in Test T-10. It developed very quickly and generated a hot smoke layer below the tunnel ceiling.

Figure 6.21. A 1.0 m^2 gasoline pool fire located behind a large vehicle

It was difficult to view the flames from the front of the large simulated vehicle. When the fire was small, the flame could only be observed in the gap between the bottom of the vehicle and the ground (Figure 6.22). With an increase in fire size, the flame became bigger and higher, and the tip of the flame flickered out from behind the large simulated vehicle at the initial stage of the fire, as shown in Figure 6.23a with a 2.0 m^2 gasoline pool fire in Test T-11. However, as shown in Figure 6.23b, a smoke layer quickly formed beneath the ceiling with the growth of the fire, which obstructed the view of the flames from the front of the large vehicle.

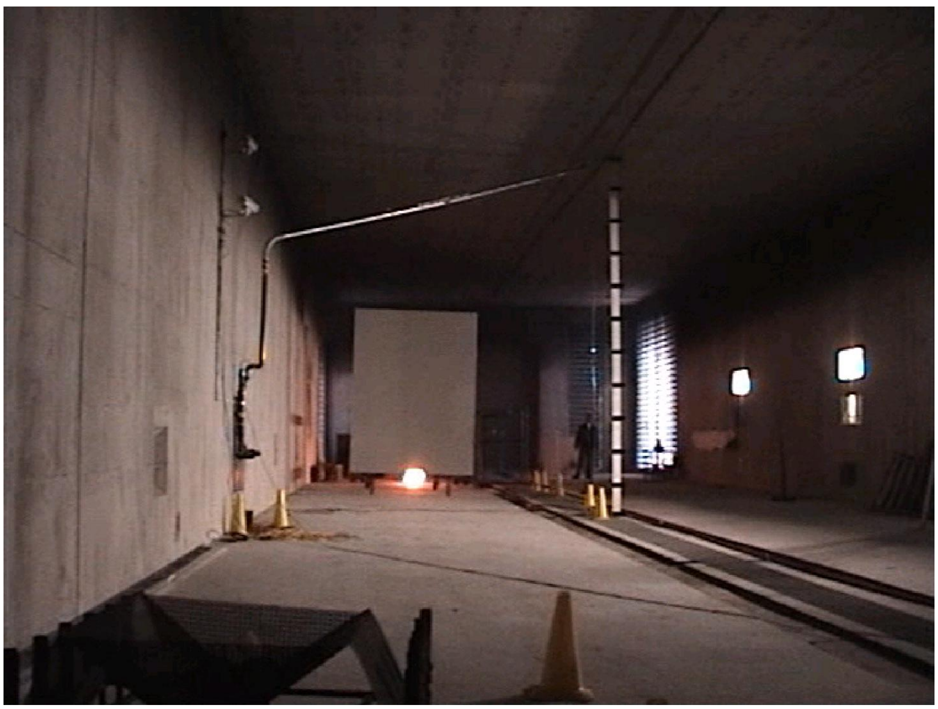

Figure 6.22. Front view of a 0.09 m^2 gasoline pool fire located behind a large simulated vehicle (T-8)

a). A 2.0 m^2 gasoline pool fire behind a large vehicle at 10 s after ignition

b). A 2.0 m^2 gasoline pool fire behind a large vehicle at 25 s after ignition

6.23. Front view of a 2.0 m^2 gasoline pool fire located behind a large simulated vehicle in Test T-11

In order to terminate the test, the fires located behind the vehicle were suppressed using a compressed air foam (CAF) system at the end of the test. There was an initial increase in fire size and heat release rate as the discharge of the foam agitated the fire.

Figures 6.24 to 6.26 compare the heat flux measured at 1 m from the fire source, the ceiling temperatures measured at 3 m from the fire source, and the smoke density measured 150 mm below the ceiling with the same gasoline pool pan (1.0 m^2) for fires located underneath and behind the vehicle in Tests T-7 and T-10. The results indicate that fires located behind the vehicle developed much faster than fires located underneath the vehicle, and generated hotter ceiling temperatures. Also, the hot smoke layer developed more quickly beneath the tunnel ceiling.

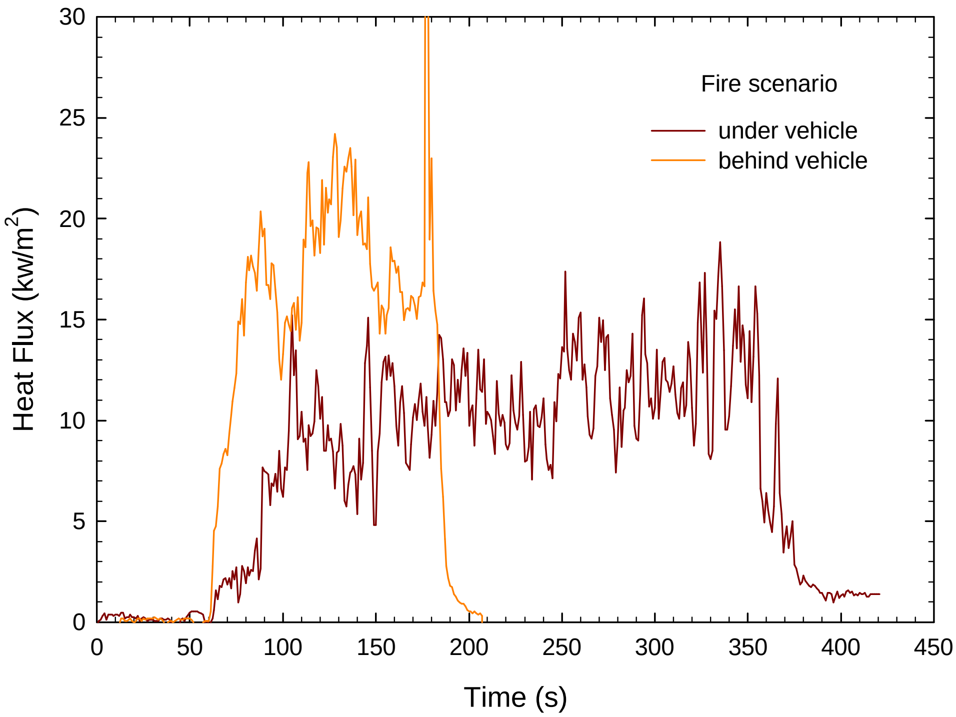

Figure 6.24. Heat flux measured at 1 m from the fire source with a 1.0 m^2 gasoline pool pan at two fire scenarios (Tests T-7 and T-10)

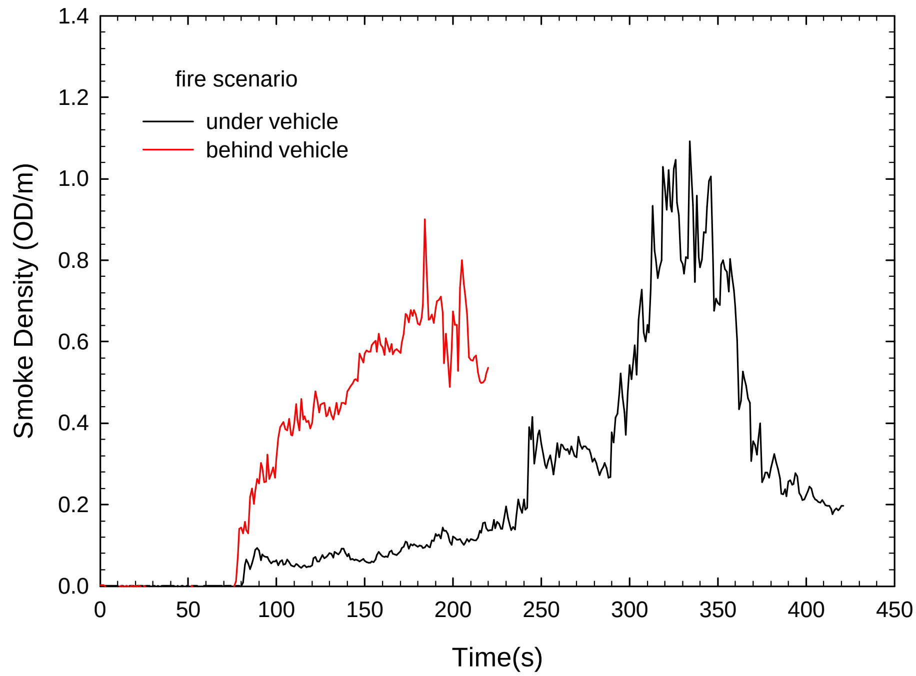

Figure 6.25. Smoke Density measured at 0.15 m below the ceiling at the center of the tunnel with a 1.0 m^2 gasoline pool pan at two fire scenarios (Tests T-7 and T-10)

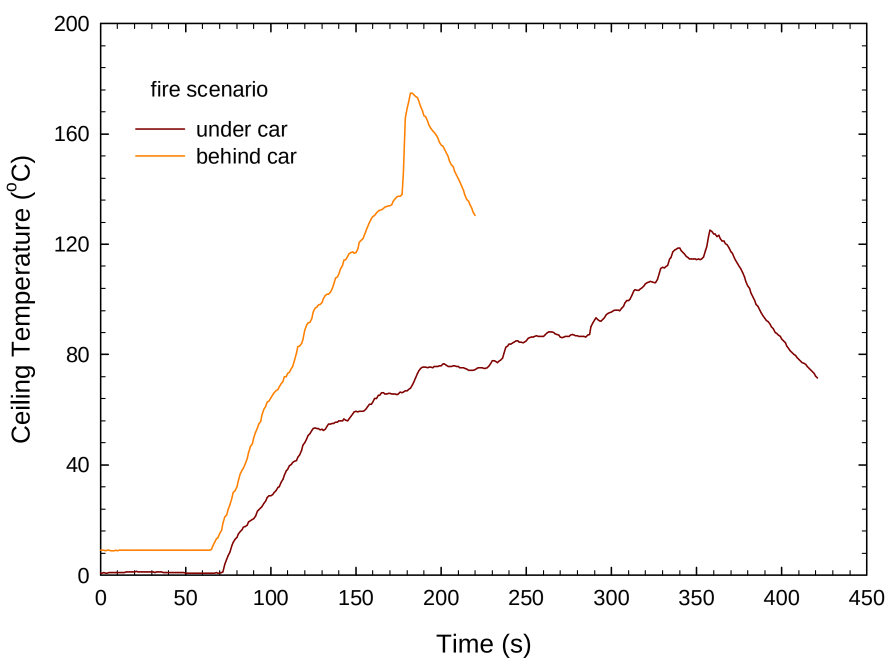

Figure 6.26. Ceiling temperatures measured at 3 m from the fire source with a 1.0 m^2 gasoline pool pan at two fire scenarios (Tests T-7 and T-10)

The fire characteristics produced in the fire scenario were also changed with the pool size located behind the vehicle. Figure 6.27 compares the changes in heat flux produced by the four different fires located behind the vehicle. The larger fires produced higher heat fluxes and had a faster growing rate. Their growths were also different from those observed in pool fires located underneath the vehicle, as shown in Figure 6.12.

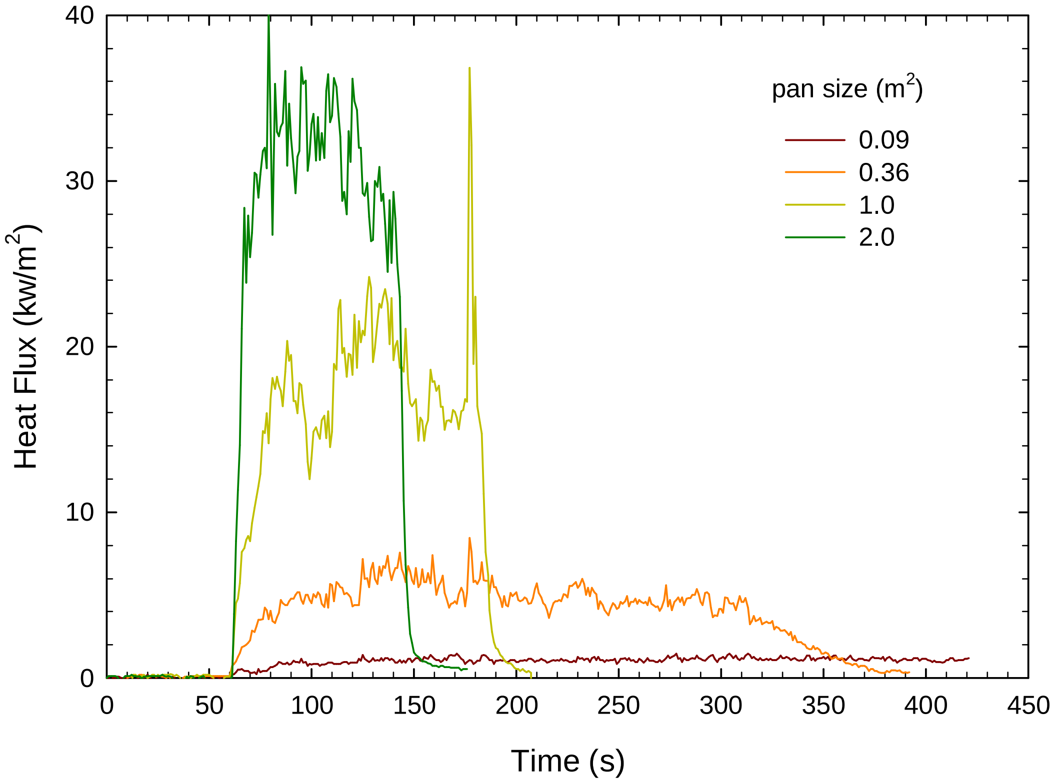

Figure 6.27. Heat flux measured for four pool fires located behind the large simulated vehicle

Figures 6.28 and 6.29 show the maximum ceiling temperatures across the tunnel near the fire source and along the center of the tunnel with four pool fires located behind a vehicle. The ceiling temperatures increased with fire size. The maximum ceiling temperature near the fire source produced by the 3,400 kW fire was 419°C that was almost two times higher than that produced by the 1,700 kW fire (Figure 6.28). The ceiling temperatures across the tunnel and along the center of the tunnel decreased with an increase in distance from the fire source. The impact of the fire on the ceiling temperature increased with an increase in fire size. For the 3,400 kW fire, its significant impact area was within a 10 m radius from the fire source (Figure 6.29), which was much larger than that with the same size of the pan located underneath the vehicle.

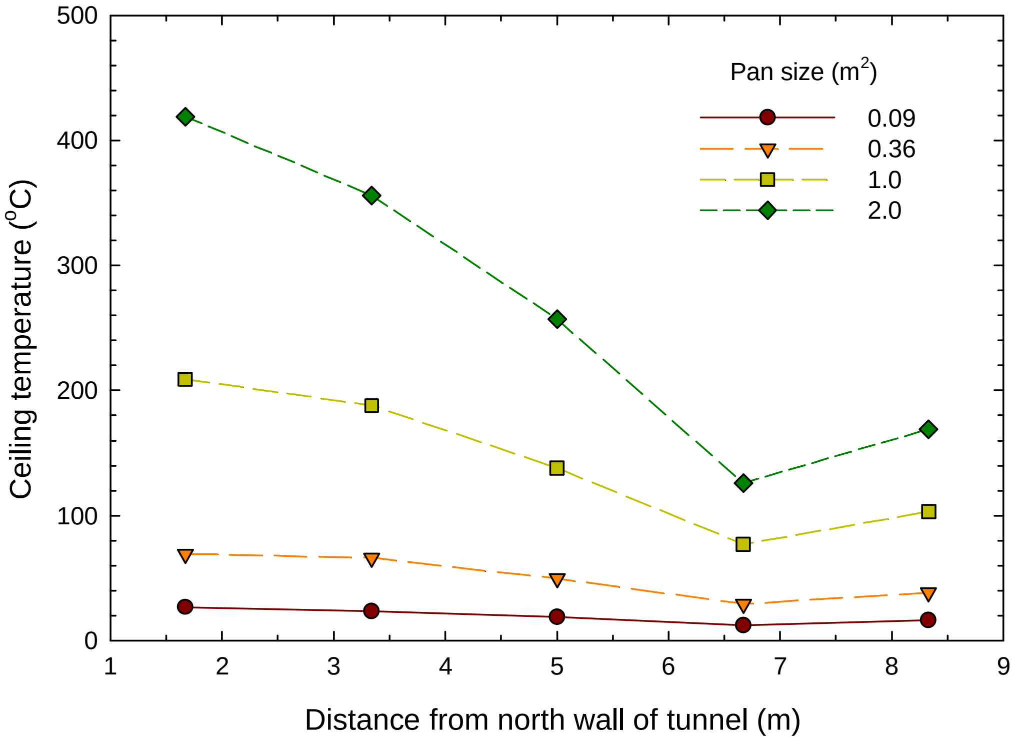

Figure 6.28. Maximum ceiling temperatures across the tunnel measured near the fire source in four pool fires located behind the large simulated vehicle

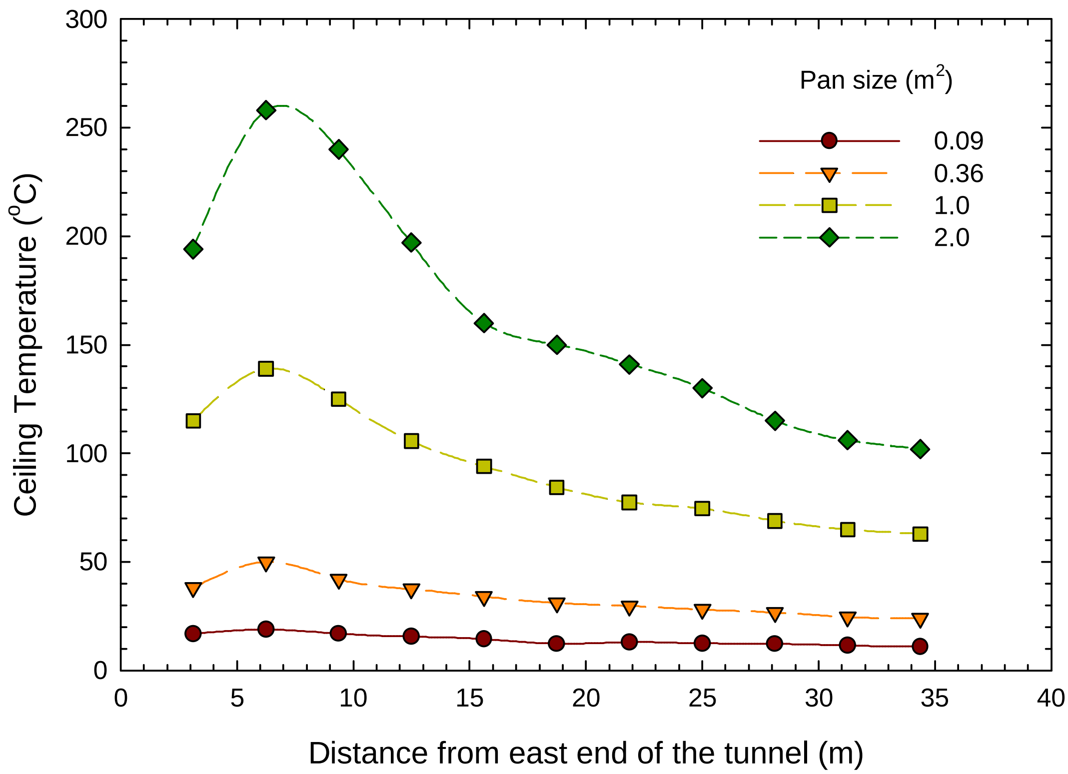

Figure 6.29. Maximum ceiling temperatures along center of the tunnel measured in tests with pool fires located behind the large simulated vehicle

Figure 6.30 shows the smoke density measured 150 mm below the tunnel ceiling in the tests with four pool fires located behind the simulated vehicle. With an increase in fire size, the smoke density substantially increased, but also the smoke spread in the tunnel was faster. As indicated in Figure 6.30, it took approximately 40 s after ignition for the smoke produced by the 125 kW fire to reach the center of the tunnel, but only approximately 15 s for the smoke produced by the 3,400 kW fire to reach the same location.

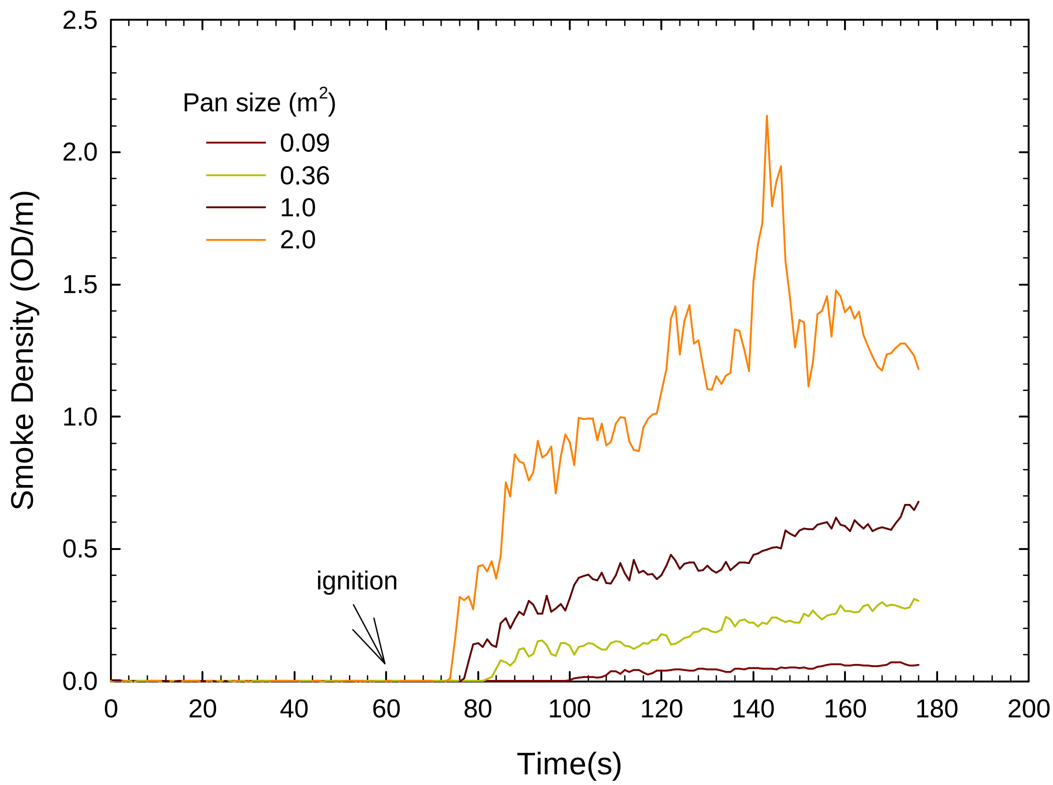

Figure 6.30. Smoke density produced by the pool fires located behind a large simulated vehicle

6.1.3.2 Response of Fire Detectors/Detection Systems

The linear heat detection system D-1L1 detected all four fires located behind the vehicle with the response times ranging from 43 s to 11 s. The detection time decreased with an increase in fire size, but its detection time to a 2.0 m^2 gasoline pool fire was longer than a 1.0 m^2 gasoline pool fire.

The linear heat detection system D-2L2 did not detect the 0.09 m^2 gasoline pool fire, but it detected the other three fires with the response times ranging from 58 s to 14 s. The detection time decreased with an increase in fire size.

As shown in Table 6.1, the response times of both linear heat systems for fires located behind the vehicle were shorter than the detection times for fires located underneath a vehicle. The cable for the linear heat detection system D-2L2 was damaged in Test T-11 with a 2.0 m^2 gasoline pool fire, as the maximum ceiling temperature was higher than 400^{o}C.

Optical flame detector D-3F1 detected all four fires located behind the simulated vehicle with the response times ranging from 22 s to 8 s. The detection time decreased with an increase in fire size.

Visual CCTV flame and smoke detector D-4C1 also detected all the four fires located behind the simulated vehicle. The detection time was 19 s for the 0.09 m^2 gasoline pool fire, but increased to 127 s for the 0.36 m^2 gasoline pool fire, and then reduced to 26 s for the 2.0 m^2 gasoline pool fire.

The video camera provided video images on fire conditions in the tunnel for the initial 6 minutes of the test with a 0.09 m^2 gasoline pool fire located behind the simulated vehicle. When the fire size increased, the period of time available for monitoring the tunnel conditions decreased, as the development of the smoke layer and the smoke density increased. The time for completely obstructing the camera view by the smoke was approximately 3 minutes for 0.36 m^2 gasoline pool fire, 1:28 minutes for the 1.0 m^2 gasoline pool fire, and 34 seconds for the 2.0 m^2 gasoline pool fire. These times were consistent with smoke density measured in the tests (Figure 6.30) and much shorter than those for the tests with the fire located underneath the vehicle.

Visual CCTV flame detector D-6C3 did not respond to the four gasoline pool fires located behind the vehicle.

Both spot heat detectors D-7H1 and D-8H2 only responded to the two larger fires using the 1.0 m^2 and 2.0 m^2 gasoline pans. These detectors also only responded to the larger fires located underneath the vehicle. The detector response was consistent with temperatures measured in the tests. As shown in Figure 6.29, the maximum ceiling temperatures at the center of the tunnel measured in the tests with 0.09 m^2 and 0.36 m^2 gasoline pans were lower than activation levels of the two spot heat detectors. For the tests with the larger size pans, the detection times were shorter than those for the fires located underneath the vehicle. The detection time of both spot heat detectors for a 2.0m^2 gasoline pool fire was approximately 20 s.

Smoke detection system D-9S1 detected all four gasoline fires located behind the vehicle with the detection times ranging from 125 s to 33 s. The detection time decreased with an increase in the fire size and was slightly shorter than those measured in the tests with fires underneath the vehicle, particularly for the 2.0 m^2 gasoline pool fire. The fire located behind the vehicle developed quickly, resulting in a short detection time.

6.2 Stationary Vehicle Fires

Two types of stationary vehicle fire scenarios were used in the test series: an engine compartment fire and a passenger compartment fire. The fire scenarios were designed to simulate fire incidents in which the fire ignited in either the engine compartment or the passenger compartment of the vehicle due to the crash or mechanical failure of the vehicle. Compared to the flammable pool fires, fires in the engine and passenger compartments of a vehicle developed much slower due to the fuel type and location [11, 12].

During the tests, no obstacle was located between the fire source and the detectors. Fuels used in the tests included gasoline, propane, plastic foam, and wood cribs. The fire scenarios, the measurement of heat release rates of fires and dimensions of the mock-ups used in the tests are discussed in the report of Task 1 [9]. The performance of fire detectors/detection systems to detect slowly growing fires was investigated in these tests. Test conditions and results for stationary vehicle fire tests are provided in Table 6.2.

6.2.1 Engine Compartment Fires

A simulated vehicle engine compartment with dimensions of 1.5 m wide by 1.2 m long by 0.67 m high was built, as shown in Figure 6.31. Two simulated engine compartment fire tests involving gasoline and propane fuels (Tests T-5 and T-17) were conducted.

A gasoline fuel pan with a movable lid was placed inside the engine compartment in Test T-5. The dimension of the fuel pan was 1.0 m wide by 2.0 m long by 0.2 m high. During the test, the size of the opening of the pan gradually increased to simulate the fire growth rate produced by a real vehicle engine compartment fire [9, 11, 12]. The maximum heat release rate produced in the test was approximately 2,000 kW.

A propane burner that had a controlled heat release rate was used to simulate a vehicle engine compartment fire in Test T-17. The burner was placed inside the engine compartment. The growth rate and heat release rate during the test were controlled manually and were similar to those produced by a real vehicle engine compartment fire [11, 12].

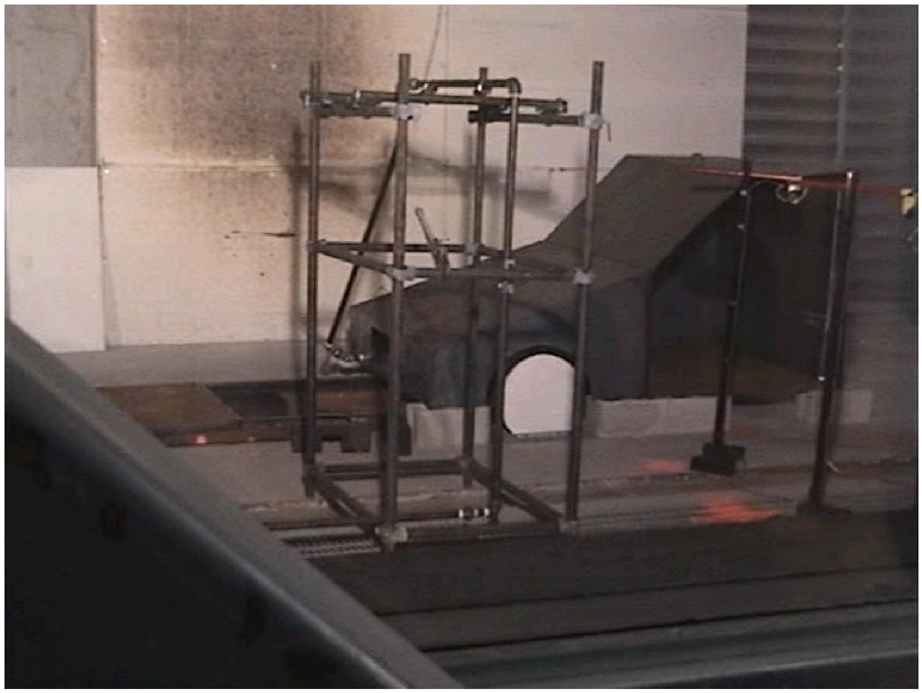

Figure 6.31. Photograph of the setup for the engine compartment

Table 6.2. Test Conditions and Results in Stationary Vehicle Fire Scenarios

FIRE SCENARIO	TEST NO	FIRE SOURCE	FUEL TYPE	HEAT RELEASE RATE (KW)	T_{ROOM} (^{O}C)	D-1L1 (S)	D-2L2 (S)	D-3F1 (S)	D-4C1 (S)	D-5C2* (S)	D-6C3 (S)	D-7H1 (S)	D-8H2 (S)	D-9S1 (S)
Stationary vehicle fire	T-5	Engine compartment	Gasoline	~2,000	1	107	175	5	76	96	149	391	295	177
	T-17	Engine compartment	Propane	~2,000	9	33	71	5	7	N/R	N/R	338	252	N/R
	T-14	Passenger compartment	Wood crib	1100~1500	13	171	291	173	188	178	271	N/R	N/R	230
	T-19	Passenger compartment	Foam	100	10	105	N/R	76	12	61	N/R	N/R	N/R	115

Note:

- N/R: no response
- No test data from Detection System D-5C2 was collected by the project data acquisition system, because of technical problems with System D-5C2. The test data of System D-5C2 that are listed in Table 6.1 were provided by the manufacturer after the tests and were not verified using data from the data acquisition system used for the other detectors.
- The systems listed in the table are:
    1). D-1L1: Linear fiber optic heat detection system
    2). D-2L2: Linear analogue heat detection system
    3). D-3F1: Optical flame detector
    4). D-4C1: CCTV flame/smoke detector
    5). D-5C2: CCTV flame detector
    6). D-6C3: CCTV flame detector
    7). D-7H1: Spot heat detector
    8). D-8H2: Spot heat detector
    9). D-9S1: Smoke detection system

6.2.1.1 Flames, Smokes and Temperatures Produced by Fires

The fire in the engine compartment grew slowly in Test T-5. The flames were confined inside the engine compartment at the initial stage of the fire (Figure 6.32a) and then gradually developed outside the compartment to become a big fire (Figure 6.32b). The fire development and smoke spread in the tunnel could be observed clearly, since there was no obstacle around the simulated vehicle. The test was terminated using a compressed air foam (CAF) system when the fire reached its maximum heat release rate of approximately 2,000 kW at 8:30 minutes after ignition. An initial increase in fire size and heat release rate was produced with the discharge of foam, which agitated the fire.

a). A simulated engine compartment fire at its initial stage in Test T-5

b). A simulated engine compartment fire at its full development stage in Test T-5

Figure 6.32. Tunnel conditions during a simulated engine compartment vehicle fire in Test T-5

Figure 6.33 shows the heat flux measured at different locations in the tunnel in Test T-5. The fire developed slowly but continuously increased, showing a difference in the trend from those observed in pool fires located underneath and behind the vehicle. It took more than 8 minutes for the fire to reach its maximum heat release rate. The maximum heat flux measured at 1 m from the fire source was close to 30 kW/m^2 before the fire was extinguished by the foam. The heat flux decreased with an increase in distance to the fire source.

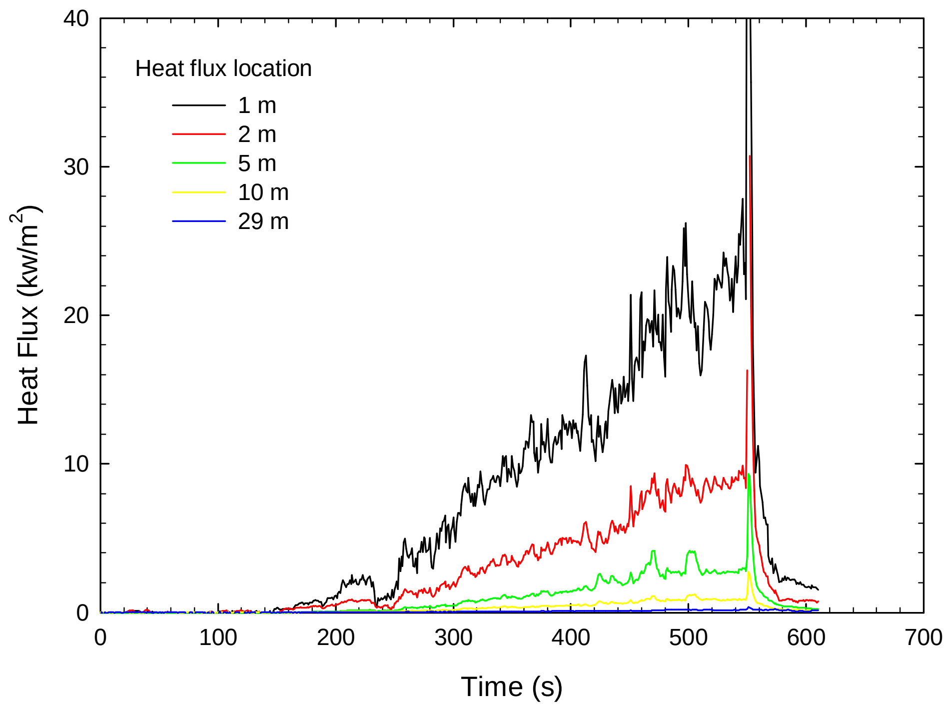

Figure 6.33. Variations of heat flux measured in Test T-5 with a simulated engine compartment fire

The variation of ceiling temperatures along the center of the tunnel and across the tunnel near the fire source in Test T-5 is shown in Figures 6.34 and 6.35, respectively. The ceiling temperatures increased slowly with time and reached their maximum temperatures of 150°C at the center of the tunnel and 230°C near the fire source after approximately 8 minutes. The ceiling temperatures further increased as the CAF foam was applied to terminate the test.

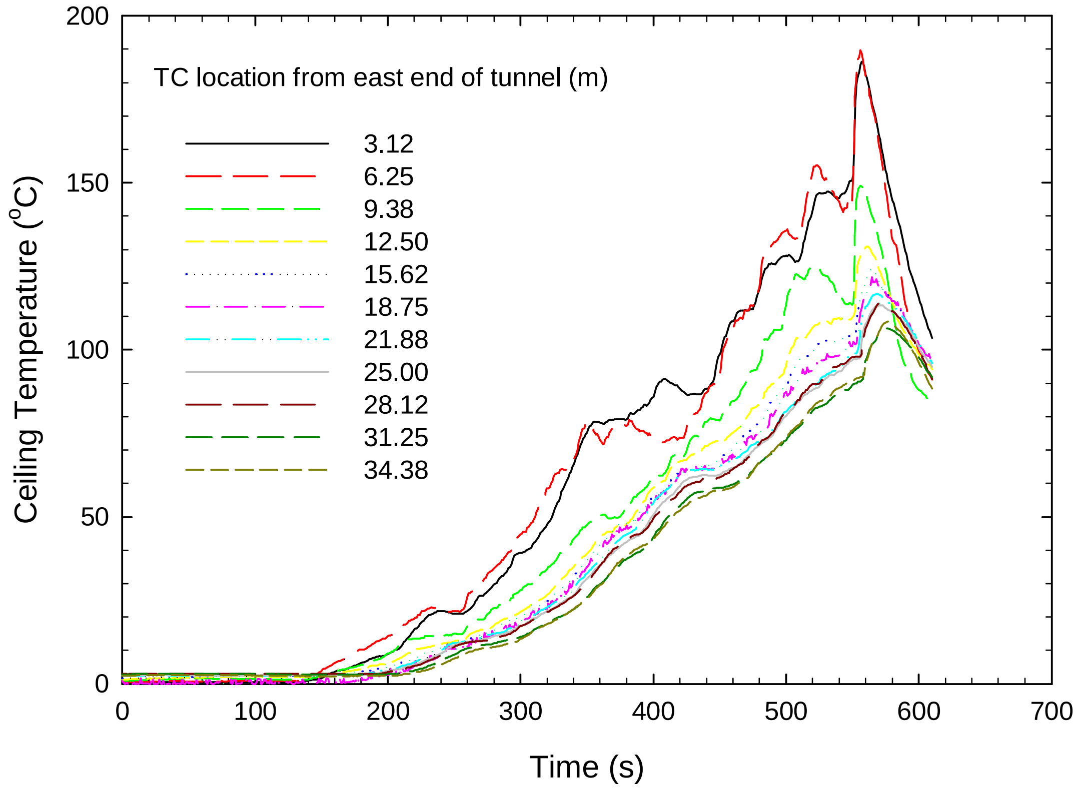

Figure 6.34. Ceiling temperatures along center of the tunnel in Test T-5 with a simulated engine compartment fire

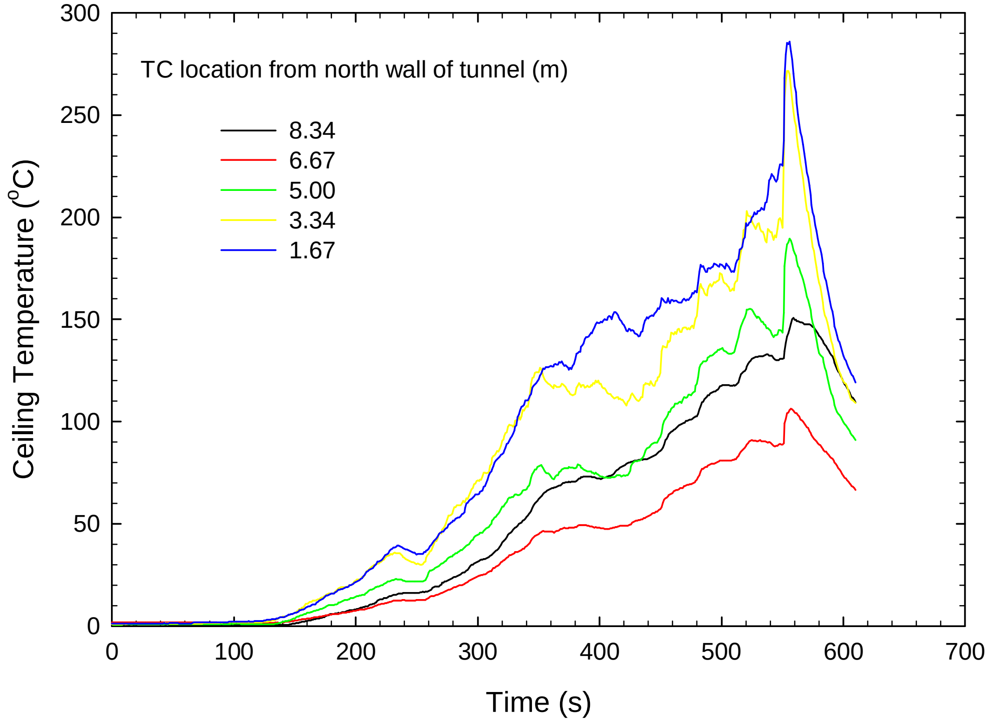

Figure 6.35. Ceiling temperatures across the tunnel near the fire source in Test T-5 with a simulated engine compartment fire

Figure 6.36 shows the smoke density measured at the middle of the tunnel in Test T-5. Smoke density in the tunnel also slowly increased. The smoke density at 150 mm below the ceiling was very low at the beginning of 2 minutes of the fire development, and then gradually increased. The smoke densities measured at 1.53 m and 2.5 m above the tunnel floor started to increase approximately 4 minutes after ignition.

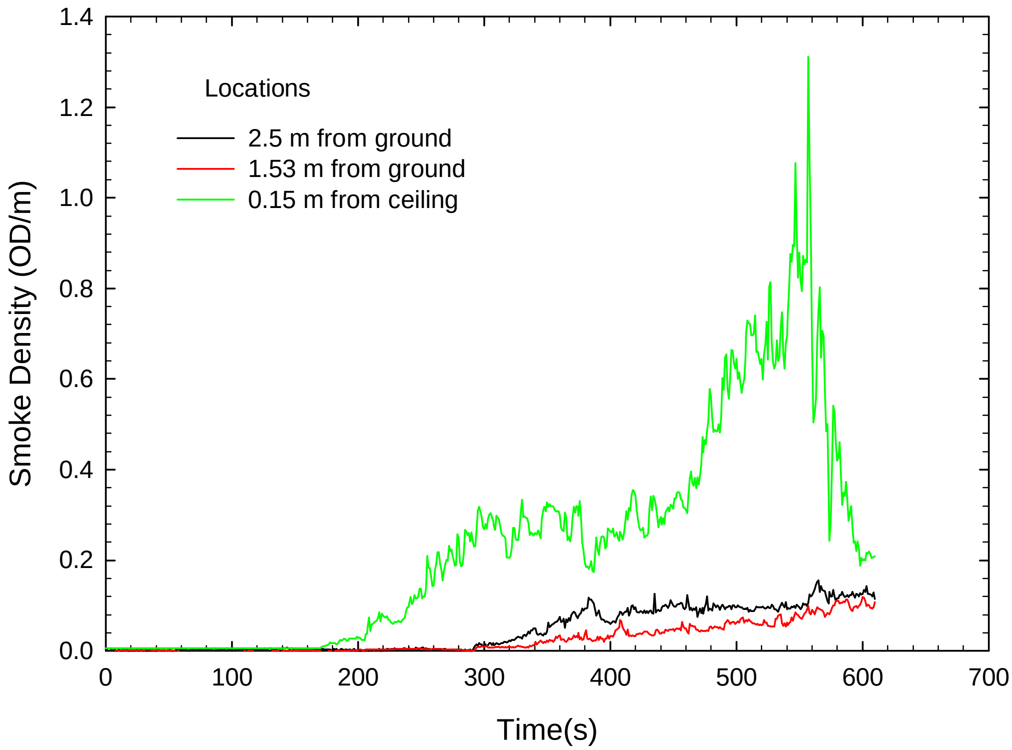

Figure 6.36. Variations of smoke density below the ceiling at center of the tunnel in Test T-5 with a simulated engine compartment fire

6.2.1.2 Response of Fire Detectors/Detection Systems

The fire detectors/detection systems generally had slow response to the simulated engine compartment fire in Test T-5, as the fire grew slowly. The linear heat detection systems D-1L1 and D-2L2 detected the fire at 107 s and 175 s, respectively. The two spot heat detectors D-7H1 and D-8H2 detected the fire at 391 s and 295 s. The smoke detection system D-9S1 also responded slowly to the engine compartment fire at 177 s. The two visual CCTV detectors D-4C1 and D-6C3 detected the fire at 76 s and 149 s, respectively. The optical flame detector D-3F1 detected the flames from the engine compartment at 5 s after ignition.

The fire in Test T-17 with propane fuel also grew slowly. Flames developed out from the two sides of the engine compartment but no visible smoke was generated. The response times of the linear heat detection systems, spot heat detectors and the visual CCTV detector D-4C1 to the propane fire varied from 5 s to 338 s. They were shorter than the times for the simulated engine compartment fire with gasoline, as shown in Table 6.2. The response time of the optical flame detector D-3F1 did not change for the two fire tests. However, both visual CCTV detector D-6C3 and the smoke detection system D-9S1 did not respond to the propane fire.

6.2.2. Passenger Compartment Fires

A mock-up simulating the front portion of a vehicle passenger compartment with a dimension of 1.5 m wide by 1.2 m long by 1.2 m high was built. It was assumed that during the fire incident, the door on the driver side of the vehicle was left open, as the driver escaped from the burning vehicle. The flames and smoke escaped from the passenger compartment through the opening door. Two simulated passenger compartment fire tests involving wood and polyurethane foam (T-14 and T-19) were conducted.

The fire produced in the passenger compartment is mainly involved with solid fuels and plastic foam. For the present test series, a wood crib with a dimension of 0.8 m by 0.8 m by 0.7 m and a weight of 62.5 kg was placed inside the compartment in Test T-14. Three small pans with 100 ml of methyl hydrate per pan were placed underneath the wood crib in a triangular arrangement. They were used as ignition sources for the wood crib fire. The setup of the passenger compartment fire scenario is shown in Figure 6.37.

The wood crib fire was repeatable and easily controlled in the tests. It could produce a fire that had a similar heat release rate and growth rate as those produced in a real vehicle passenger compartment fire [11, 12], when an appropriate wood crib size and ignition source were used. The heat release rate of the simulated passenger compartment fire produced by the wood crib fire was measured in Task 1 of the project [9]. The maximum heat release rate produced in the test was approximately 1,200 kW.

In Test T-19, polyurethane foam was used to simulate the smoke and fire produced in a vehicle passenger compartment in the initial stage of the fire. The dimensions of the foam was 0.6 m by 0.6 m by 0.1 m thick and it weighed 1.0 kg. The heat release rate from the foam was 100 kW. The combustion characteristics of the polyurethane foam, including its heat release and smoke production rate is provided in Reference [13].

Figure 6.37. Photograph of the setup for a simulated passenger compartment vehicle fire

6.2.2.1. Flames, Smokes and Temperatures Produced by Fires

The simulated passenger compartment fire with the wood crib developed very slowly in Test T-14. In the initial stage of the fire, no visible flame was observed outside the compartment and the amount of smoke produced was also limited. After 3 to 4 minutes, initial flames were observed outside the compartment through the opening, as shown in Figure 6.38.

Figure 6.38. Simulated passenger compartment fire with wood cribs in Test T-14

The development of the passenger compartment fire is illustrated by the change in heat flux measured in the test, as shown in Figure 6.39. Approximately 2 minutes after ignition, the heat flux produced by the fire could not be measured. The fire size started to increase and it took approximately 6 minutes for the fire to reach its maximum heat output. The fire size remained unchangeable for another 9 minute period until the fuel gradually burnt out. The test lasted approximately 18 minutes before the fire was extinguished. Compared to the engine compartment fire in Test T-5, the simulated passenger compartment fire in Test T-14 was smaller and showed a different growth rate.

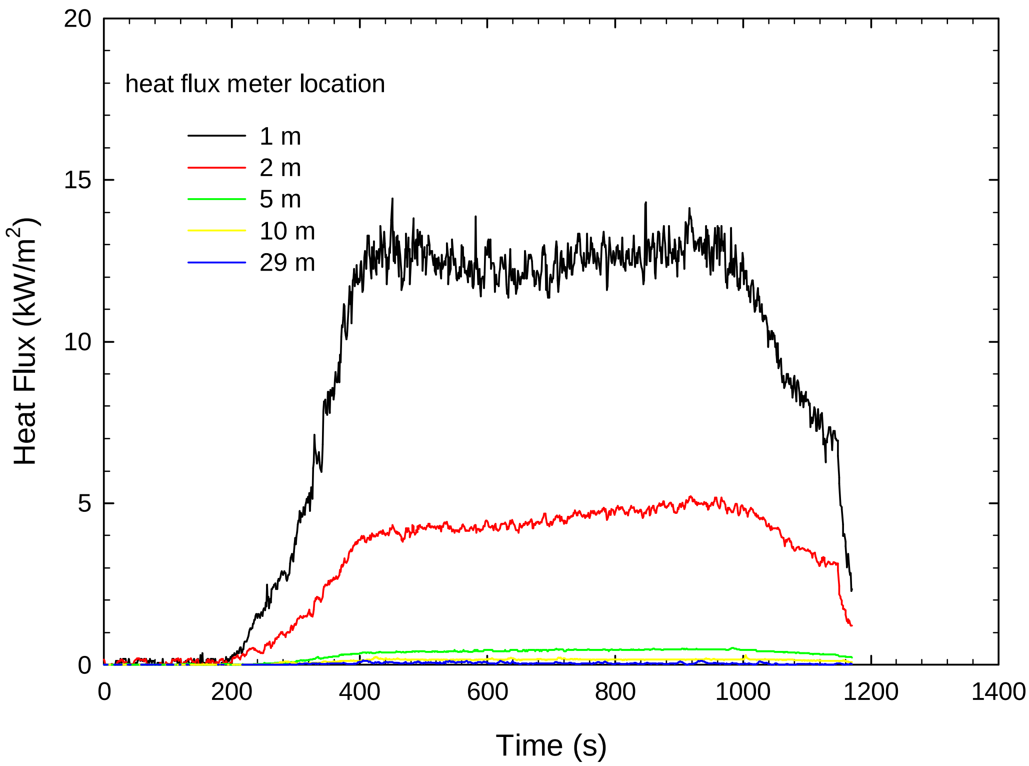

Figure 6.39. Variations of heat flux generated in Test T-14 with a simulated passenger compartment fire

Ceiling temperatures in the tunnel had the same trend as observed in the heat flux measured for the fire. As indicated in Figure 6.40, the ceiling temperatures across the tunnel near the fire source started to increase a few minutes after ignition. The ceiling temperatures gradually increased to a maximum of 100°C near the fire source and subsequently remained constant. The development of ceiling temperatures along the center of the tunnel had the same trend as those measured across the tunnel near the fire source, as shown in Figure 6.41. Its maximum ceiling temperature at the center of the tunnel was lower than 100°C during the test.

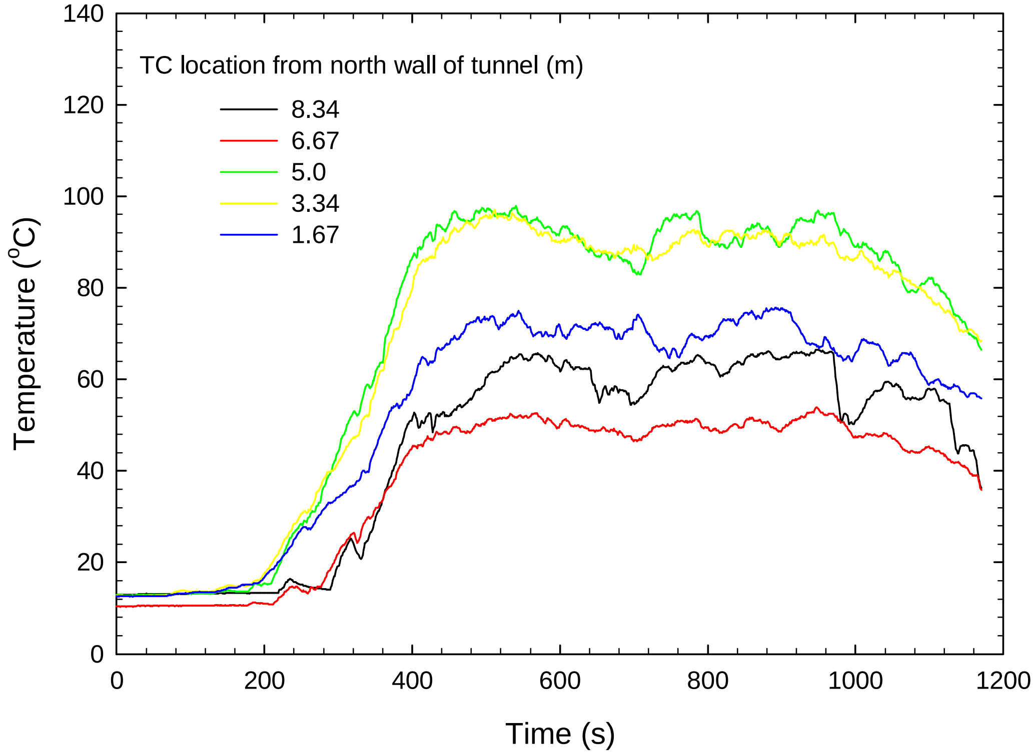

Figure 6.40. Ceiling temperatures across the tunnel near fire source in Test T-14

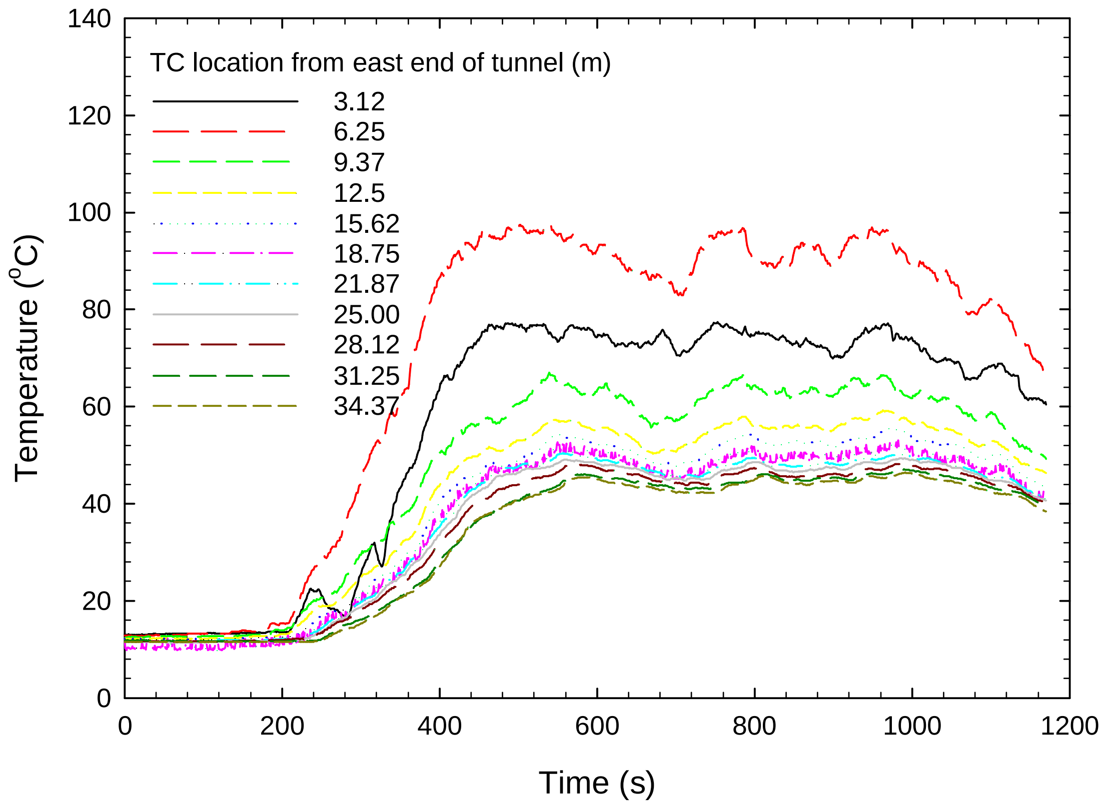

Figure 6.41. Ceiling temperatures along center of the tunnel in Test T-14 with a simulated passenger compartment fire

Figure 6.42 shows the smoke density measured in Test T-14. The smoke density produced in the test was not very high, compared to the simulated engine compartment fire involving gasoline. In addition, the difference in smoke density measured at locations near the tunnel ceiling and in the lower portion of the tunnel was not significant in the later stage of the test. This was consistent with the observation during the test in which low density smoke filled the entire tunnel and there was no distinct hot smoke layer in the tunnel, as observed in the other fire scenarios.

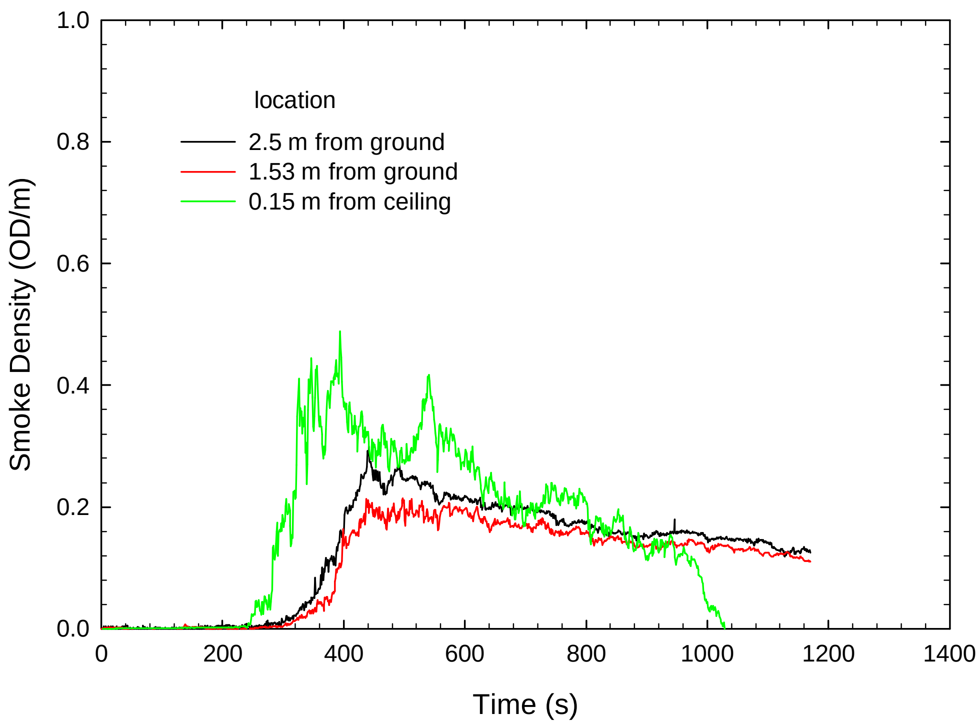

Figure 6.42. Variations of smoke density below the ceiling at center of the tunnel in Test T-14 with a simulated passenger compartment fire

For Test T-19 using polyurethane foam, the foam was sprayed with 100 ml of methyl hydrate and placed behind the simulated passenger compartment. After ignition, the fire grew quickly. Although the fire size was small, the visible flame and dark smoke produced by the fire could be observed from the front of the passenger compartment, as shown in Figure 6.43. The fire self-extinguished in 18 minutes after the fuel was burnt out.

Smoke densities produced in the three stationary vehicle fires measured at 150 mm below the ceiling are compared in Figure 6.44. The smoke density produced by the passenger compartment fire with polyurethane foam developed the earliest. The smoke density produced by the engine compartment fire with gasoline fuel was the highest.

Figure 6.43. Polyurethane foam fire in Test T-19

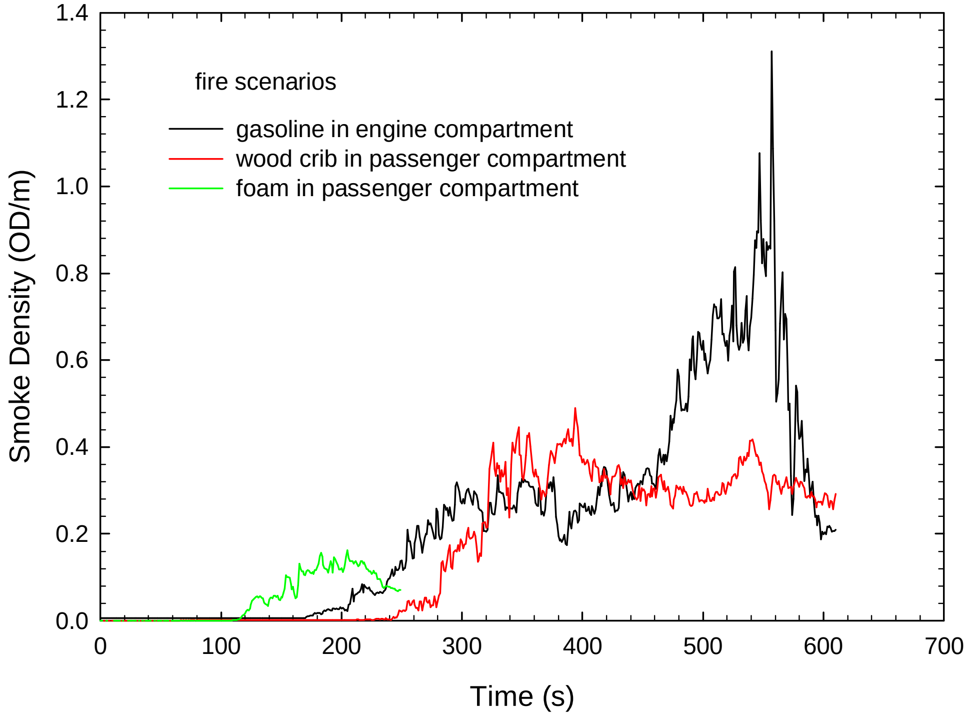

Figure 6.44. Smoke density generated in the three simulated stationary vehicle fires measured 150 mm below the ceiling

6.2.2.2 Responses of Fire Detectors/Detection Systems

The response of fire detectors/detection systems to the simulated passenger compartment fire in Test T-14 was slow. The two linear heat detection systems D-1L1 and D-2L2 detected the fire at 171 s and 291 s, respectively. The optical flame detector D-3F1 also had a slow response to the fire at 173 s. The two visual CCTV detectors D-4C1 and D-6C3 detected the fire at 188 s and 271 s, respectively. The smoke detection system D-9S1 responded to the fire at 230 s. The two spot heat detectors D-7H1 and D-8H2 did not respond to the fire.

For the polyurethane foam fire in Test T-19, the linear heat detection system D-1L1 detected the fire at 105 s. The optical flame detector D-3F1 responded to the fire at 76 s. The visual CCTV detector D-4C1 detected the fire at 12 s. The smoke detection system D-9S1 responded to the fire at 115 s. The other four detectors and detection systems did not respond to the polyurethane foam fire due to the fire size.

6.3 Moving Fires

A moving vehicle fire can be caused by many factors, including a fuel delivery failure with ignition by hot exhaust components. The fire is not only a realistic scenario that occurred on many occasions in tunnels, but it is also a challenge for a fire detection system [1].

A moving fire source was constructed for the test series. The fire source consisted of a fibrefrax pad with dimension of 0.3 m by 0.3 m. 50 ml of gasoline was sprayed on the blanket. The heat release rate was approximately 100 ~ 150 kW, when the fire source was at rest, as shown in Figure 6.45.

During the tests, the pad was ignited inside a box, preventing the fire from being detected before moving. After ignition, the fire source was dragged by a cable using a high speed winch apparatus in the lane closest to the South wall of the tunnel. The total distance traversed by the fire source was 30 m. There was no obstacle around the fire source when the fire traveled.

Six fire tests with two different driving speeds (approximately 27 km/h and 50 km/h) and two driving directions relative to the detectors (facing to and driving away from the detectors) were conducted. Tests T-4B and T-13B were two repeated tests for driving speeds of 27 km/h and 50 km/h, respectively. The test conditions and results are listed in Table 6.3.

Figure 6.45. A still fire before it moved in the tunnel

Figure 6.46 shows a moving fire at a speed of 27 km/h travelling towards the detectors from the East end the tunnel. The moving fire size was smaller than a still fire and no visible smoke was observed.

Figure 6.47 shows the ceiling temperature along the center of the tunnel in Test T-12 with a moving fire at the speed of 27 km/h. There was no change in temperature when the fire traveled through the tunnel, and also no smoke production was observed in the tunnel.

Only the optical flame detector D-3F1 detected the moving fire at a speed of 27 km/h with the detection time ranging from 2 s to 4 s. The response time was shorter when the detector faced the moving fire than that when the fire moved away from the detector. The optical flame detector did not respond to the fire when it moved at the speed of 50 km/h. All other detectors/detection systems did not respond to the moving fires in the test series.

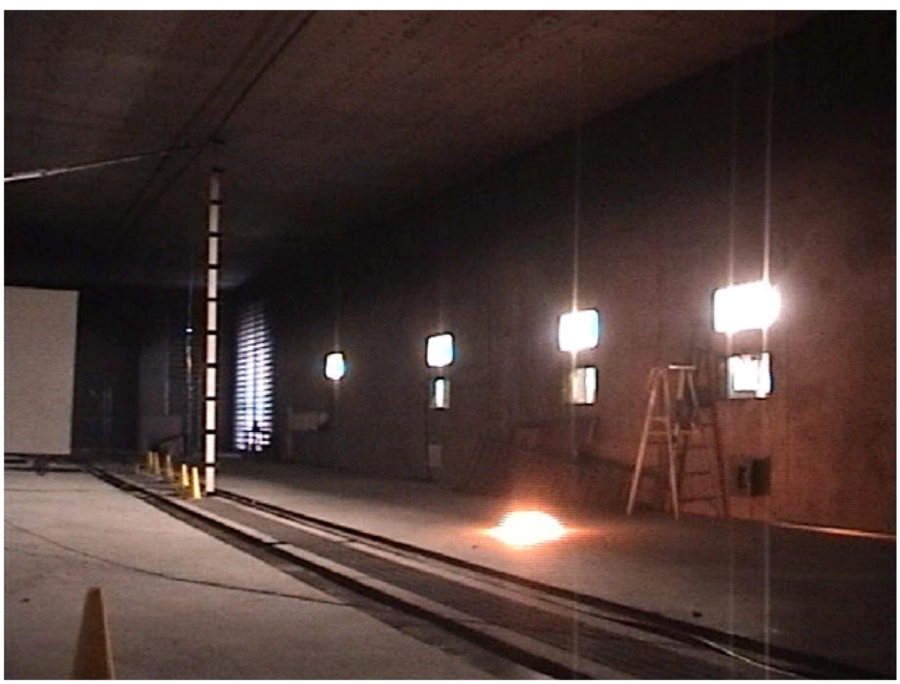

Figure 6.46. A moving fire at the speed of 27 km/h from East end to West end of the tunnel

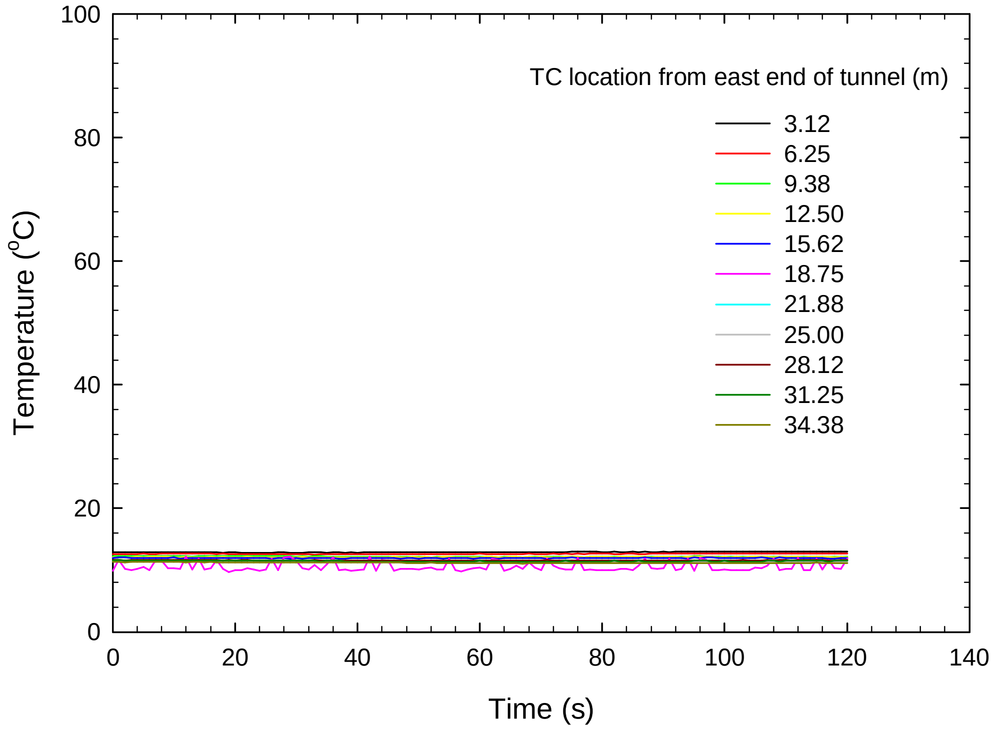

Figure 6.47. Ceiling temperatures along center of the tunnel in Test T-12 with a moving fire at speed of 27 km/h

Table 6.3. Test Conditions and Results in Moving Fire Scenarios

FIRE SCENARIO	TEST NO	FIRE SOURCE	FUEL TYPE	HEAT RELEASE RATE (KW)	T_{ROOM} (^{O}C)	D-1L1 (S)	D-2L2 (S)	D-3F1 (S)	D-4C1 (S)	D-5C2* (S)	D-6C3 (S)	D-7H1 (S)	D-8H2 (S)	D-9S1 (S)
Moving vehicle fire	T-4A	50 km/h, facing	Gasoline	100~150	1	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
	T-4B	50 km/h, facing	Gasoline	100~150	1	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
	T-6	50 km/h, away	Gasoline	100~150	1	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
	T-12	27 km/h, facing	Gasoline	100~150	10	N/R	N/R	2	N/R	N/R	N/R	N/R	N/R	N/R
	T-13A	27 km/h, away	Gasoline	100~150	10	N/R	N/R	4	N/R	N/R	N/R	N/R	N/R	N/R
	T-13B	27 km/h, away	Gasoline	100~150	10	N/R	N/R	4	N/R	N/R	N/R	N/R	N/R	N/R

Note:

- N/R: no response
- No test data from Detection System D-5C2 was collected by the project data acquisition system, because of technical problems with System D-5C2. The test data of System D-5C2 that are listed in Table 6.1 were provided by the manufacturer after the tests and were not verified using data from the data acquisition system used for the other detectors.
- The systems listed in the table are:
    1). D-1L1: Linear fiber optic heat detection system
    2). D-2L2: Linear analogue heat detection system
    3). D-3F1: Optical flame detector
    4). D-4C1: CCTV flame/smoke detector
    5). D-5C2: CCTV flame detector
    6). D-6C3: CCTV flame detector
    7). D-7H1: Spot heat detector
    8). D-8H2: Spot heat detector
    9). D-9S1: Smoke detection system

7. SUMMARY

The performance of nine fire detectors/detection systems, including their response times, and their ability to locate and monitor a fire in the tunnel, was investigated in a laboratory research tunnel facility using a number of tunnel fire scenarios. The fire characteristics produced in the various tunnel fire scenarios, including their fire growth rates, temperatures and smoke spread in the tunnel, were measured. Test results showed that the response of fire detectors/detection systems to a tunnel fire incident was dependent on the fire size, location and growth rate of the fire, fuel types as well as the detection principles.

Flammable pool fires located in the open space, underneath a vehicle and behind a large vehicle developed quickly and reached their maximum heat release rates within a short period of time. The fire size in the test series varied from 125 kW (0.3 m x 0.3 m) to 3,400 kW (1.0 m x 2.0 m), producing a maximum ceiling temperature near the fire source ranging from 13^{o}C to 429^{o}C and the maximum smoke density at 15 cm beneath the ceiling at the center of the tunnel from 0.28 OD/m to 2.2 OD/m.

For a small gasoline pool fire (125 kW) located in the open space, the optical flame and CCTV fire detectors responded quickly to the fire within 15 s. The linear fiber optic heat detection system also detected the fire quickly based on the rate of rise of the temperature. The smoke detection system detected the fire but its response was relatively slow. The two spot heat detectors and the other linear heat detection system did not respond to this small fire.

The combustion of the pool fire located underneath the vehicle was affected by the vehicle body above the fire source. The flames and heat produced by the fire were confined by the vehicle body. The view of the flames from the front of the vehicle was also partially obstructed by a simulating vehicle that was placed between the detectors and fire source. The pool fire located underneath the vehicle was a challenging fire for the detectors/detection systems in the test series.

Figure 7.1 summarizes the detection times of the fire detectors/detection systems to the gasoline pool fires located underneath the vehicle in the tests. For the small fire (125 kW), only a CCTV flame and smoke detector and a smoke detection system responded to the fire. With an increase in fire size, more detectors/detection systems responded to the fire, and the detection times also reduced. However, the fire detectors/detection systems evaluated in the test series showed substantial difference in response times to the fires located underneath a vehicle. For example, the response times to a 2 m^2 gasoline pool fire varied from 4 s to 183 s, depending on the type of fire detector/detection system.

The pool fire located behind a large vehicle was a freely burning fire. The large vehicle body in front of the fire did not affect the burning process of the fire as well as temperature development and smoke spread in the tunnel. However, the view of the flames was obstructed by the vehicle. In addition, the hot smoke layer produced by the fire quickly formed, which also obstructed the view of the flames. This was a challenging fire scenario for those detectors that detected fires based on the characteristics of the flames produced by the fire. For example, one CCTV flame detector did not respond to the fires behind the vehicle presented in the tests, since its view of the flames was obstructed.

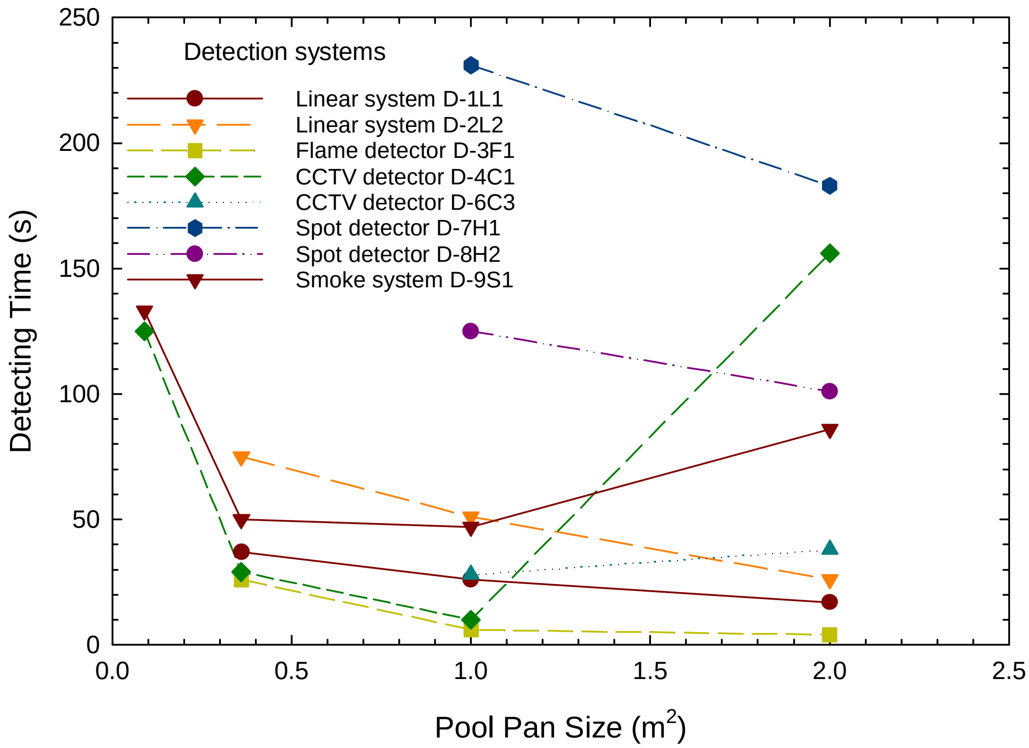

Figure 7.1. Detection times of fire detectors/detection systems to gasoline pool fires underneath a vehicle

Figure 7.2 summarizes the detection times of the fire detectors/detection systems to gasoline pool fires located behind a simulated large vehicle. In comparison to the fires located underneath the vehicle, more detectors/detection systems were able to detect small fires located behind a vehicle. With an increase in fire size, their response times decreased and the difference in the detection time also decreased. The response time of all the fire detectors/detection systems to a 2 m^2 gasoline pool fire located behind the simulated large vehicle was less than 35 s. Generally, the fire detectors/detection systems responded to the fire located behind a vehicle more quickly than to a fire located underneath the vehicle.

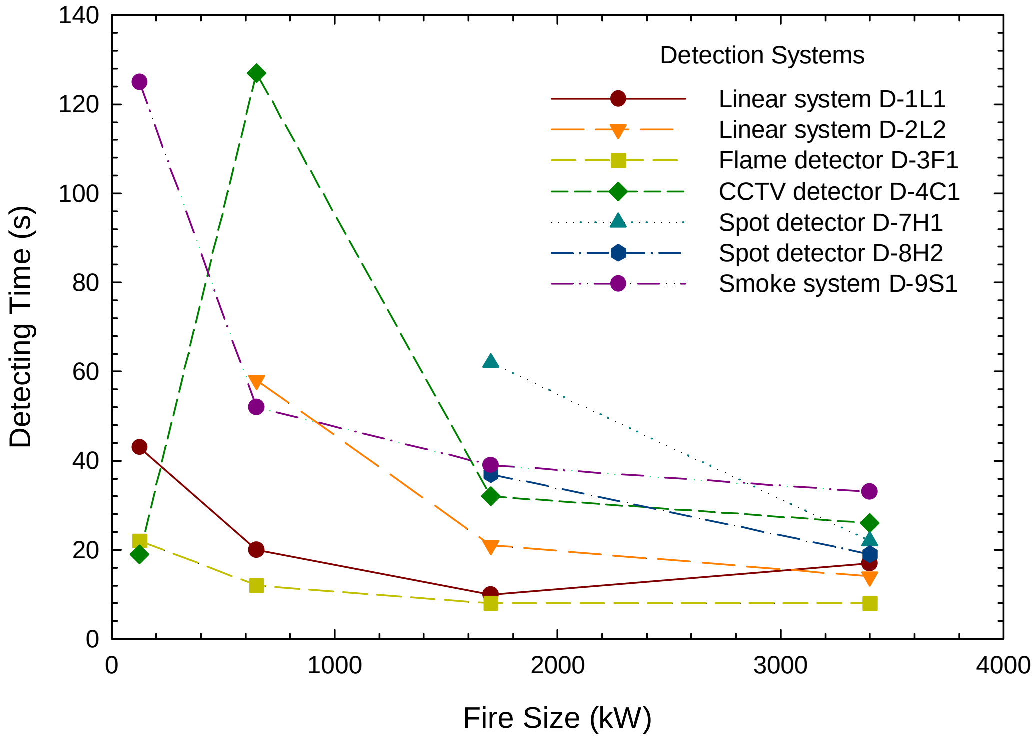

Figure 7.2. Detection times of fire detectors/detection systems to gasoline pool fires behind a vehicle

Stationary vehicle fires, including both engine and passenger compartment fires, developed slowly, because of their fuel type and fire location. The flame, heat and smoke produced by the fires at a few minutes after the ignition were limited. In the present test series, it took more than 8 minutes for the simulated engine compartment fire involving gasoline fuel, and approximately 6 minutes for the simulated passenger compartment fire involving wood cribs to reach their maximum heat release rates. The fire sizes ranged from approximately 1,200 kW to 2,000 kW with the maximum ceiling temperatures near the fire source ranging from 95°C to 200°C and with the maximum smoke density 150 mm below the tunnel ceiling at the center of the tunnel ranging from 0.5 OD/m to 1.0 OD/m. Generally, fire detectors/detection systems had slow responses to the stationary vehicle fires, because of the slow growth rate of the fires.

Figure 7.3 summarizes the detection times of fire detectors/detection systems to the fires in the engine and passenger compartments of the stationary vehicle in the test series. Except for the response time of the optical flame detector to the simulated engine compartment fire, the detection times of the fire detectors/detection systems to the simulated stationary vehicle fires were much longer than those to the pool fires. The detection times for the passenger compartment fire were longer than those for the engine compartment fire, due to a difference in fuel type, fire size, growth rate and location. The detection times of the fire detectors/detection systems ranged from 76 s to 391 s for the engine compartment fire, and from 171 to 271 s for the passenger compartment fire. Two spot heat detectors did not respond to the simulated passenger compartment fire.

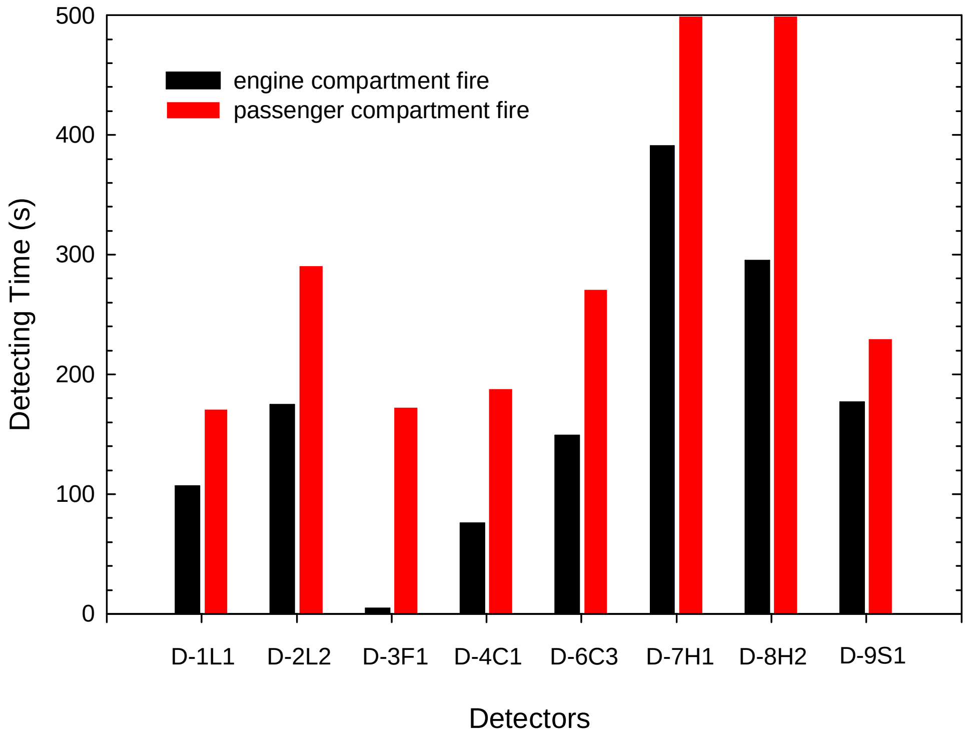

Figure 7.3. Detection times of fire detectors/detection systems to the simulated stationary vehicle fires

The small moving vehicle fires were difficult to detect. These fires did not produce any changes in the temperature and smoke density in the tunnel when they traveled through the tunnel. Only the optical flame detector detected the moving fire at a low speed of 27 km/h but had no response to the fire at a speed of 50 km/h. No other detector/detection system responded to the moving fire in the present test series.

Propane fires were used to evaluate the performance of fire detectors/detection systems in the test series. They produced similar heat release rates as the gasoline pool fires, but no visible smoke was generated from the propane fires. The propane fires presented a challenge for those detectors/detection systems that responded to the fire, based on smoke generated from the fire.

The linear fiber optic heat detection system was able to identify the fire location within a 2-meter range in the tests. Other detector/detection systems were able to identify the fire location within their detection zone. The size of the detection zone was dependent on the system design and the detection method.

The visual CCTV fire detectors were able to provide video images to monitor fire conditions in the tunnel. The period of time available for monitoring fire conditions using the cameras changed with the fire size, location and growth rate of the fire, and fuel types. For the large fires with a quick growth rate, the available monitoring time was very short (less than 1 minute) as the visibility was obscured by smoke that quickly formed beneath the tunnel ceiling.

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