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INVESTIGATION OF A FATAL FIRE IN A MOVING VEHICLE

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ABSTRACT

This paper summarizes the essentials of an investigation conducted by the authors to test conflicting scenarios regarding the cause and origin of an accidental fire. Fire investigators proposed that an underbody fuel-leak ignited while the vehicle was in motion and transferred sufficient heat through the steel floor to cause rapid, but undetectable, ignition and fire growth in the interior of the vehicle. To assess the feasibility of the proposed scenario, a series of experiments were designed together with the development of *a priori* modeling studies. The transient heating across the vehicle floor was modeled, which allowed determining the characteristics for fire ignition inside the vehicle depending on the scenario studied. The post-ignition regime was studied using computational fire modeling to obtain an approximate time for smoke detection by the passengers. Results from these models provided input to the design of experimental tests with a real-scale vehicle under a forced flow imitating driving conditions. The tests showed that the only situation for which the scenario was feasible was for the condition where unexpected perforations existed in the floor pan. In the case where the floor pan did not contain perforations (as in the subject accident vehicle), heat transfer from the under-floor flame was insufficient to cause ignition of interior materials.

INTRODUCTION

The role of a fire investigator is to interpret the evidence at the fire scene to identify the probable situations and conditions under which the fire might have occurred. In general terms, the identification of the origin, the ignition source, and the spread rate can ultimately lead to the development of several plausible time-lines of the fire development. Maybe, some more probable than others. By correlating the available witness accounts to the timelines and the application of models and experimental testing, it is often possible to converge on a smaller set of scenarios, or maybe a sole scenario, agreeing well with the evidence. Reports of investigations of accidental fires are rarely available compared to the high volume of them conducted yearly on a global scale. This fact is unfortunate because much of this work could be used to feed new knowledge back into the scientific community for the benefit of all. Accident investigation is an essential part of the development of the Fire Safety Engineering discipline and provides a means of improving our understanding of the subject [1]. Information extracted from accidents, failures and past events leads to greater understanding, improved engineering designs and enhanced safety.

This paper presents the investigation conducted by the authors to test conflicting scenarios regarding the cause and origin of an accidental fire. This tragic fire (Fig. 1) occurred in a moving mini van, after 5 to 6 min of driving, and resulted in the death of three passengers, injuries to the surviving passenger and the driver and the complete loss of the vehicle. The initial fire investigators proposed that the fuel source was a fuel spray released from a degraded supply or return line next to exhaust components under the vehicle. Supposedly, the resultant flame exposed the rear floor pan of the vehicle to intense heat transfer resulting in the ignition of interior materials, and the subsequent fire burned out the vehicle interior. Allegedly, interior materials were ignited while the vehicle was traveling at moderate city

speed and without enough warning to the occupants. However, this assumed scenario is not supported by the accounts of the main witness, who report no pre-fire indicators such as odors, smoke, irritating gasses or buildup of heat by any of the occupants. The driver describes the event as being a sudden conical plume of white smoke at the rear of the van, followed shortly thereafter by rapid fire growth. She was immediately alerted of the plume because she heard a “pop”, and one of the passengers said “what’s that?”. The driver immediately stopped, ran around the back and opened the right side-sliding door and was able to remove one child from the middle row of seats. The driver attempted to re-enter, but could not because the interior of the van was filled with flames and smoke. Three passengers were unable to exit and perished in the fire. The driver’s description of the fire spread suggests dramatically fast time-line.



Figure 1. Vehicle testing site (right) and the post fire remains of the real case (left).

Our investigation aims at deciding which of the following two hypothetical scenarios is the most probable cause of the fire:

- Hypothesis of an external source: Underbody fuel-spray fire while the vehicle was moving at moderate speed.
- Hypothesis of an internal source: Rapid ignition of flammable gas cloud.

To assess which hypothetical scenario best matches the evidence and witness accounts, the investigation uses modeling and a series of experiments. The majority of work reported in this paper pertains to the analysis of the external ignition hypothesis and its feasibility.

MOTOR VEHICLE FIRES

Automobile fires belong to the more general class of fires in transportation systems, which include trucks, buses, trains, subways and airplanes and has been reviewed in [2]. Tewarson [3] examined the flammability of plastic vehicle components and parts, by subjecting them to ignition and burn tests. Santrock and Kononen [4] examined the ignition properties of typical automobile fluids other than the engine fuel (motor oil, lubricants, transmission fluid).

Most vehicle fires occur immediately after a crash. However, statistics show that the vehicles burned in fires of parking structures is a significant figure. This is due to the high density of parked vehicle resulting in a high number of them being exposed to the flames in any single event. Fire safety in vehicles puts attention on leakages from the fuel tank, filler pipes, and connections during and after crashes, as well as the flammability of the materials used in the vehicle, especially for the passenger’s compartment.

After a crash, the usual first fuel to burn is the flammable liquid released accidentally. Typical ignition sources include hot manifolds in the engine compartment; electrical arcs and

short circuits in the electrical system; and friction sparks. Gaps and opened seams produced in a crash allow for the penetration inside the vehicle by the flames from an external fire (typically flames in the underbody). However, in the absence of a crash, the only manufacturing openings connecting the underbody fire with the inside of the compartment are drain holes in the floor board and similar features. An exemplar timeline for the fire development in a staged post-crash vehicle can be found in [5], which reports results from exposing a passenger car to a 16-liter underbody spill fire. The test showed the following sequence of events: fire penetration to the passenger compartment in about 10 s; compartment full of smoke in 45 s; gasoline pool burn-out in 60 s; substantial flame spread inside the vehicle in 150 s; smoke incapacitation of the passengers in 200 s.

PRELIMINARY INVESTIGATIONS

The case investigated in this work corresponds to a rare event in that the compartment fire occurred in a moving vehicle, driving normally and not involved in any crash. Thus, both internal and external ignition-sources were considered as hypothetical scenarios. For the hypothesis of an external source, the primary element of analysis is to study the process of fire propagation to the interior of the vehicle. Once a fire is initiated in the interior, the abundance of combustible material in the confined space of a passenger's compartment (carpet, head liners, seat, etc) promotes rapid flame spread. In events where the fire is initially located outside of the vehicle's enclosure, there are two situations that can lead to the ignition of the interior:

- Piloted ignition: the enclosure has some openings, which allow the external fire to ignite interior materials.
- Auto ignition: heat transfer through the enclosure boundary surface (traditionally steel structure) is sufficient to ignite the interior material.

The case investigation was conducted in three major phases:

1. Review and correlation of accident data including official accident site photographs, witness accounts, collection and documentation of evidence and survey of pertinent literature. A summary of these data is collected in Table 1, which details parameters of the vehicle, the situation of the accident, description of the event and a summary of essential evidence.
2. Modeling to assess the heat transfer of a flame in the underside of a steel surface with a 50 km/h air flow and potential ignition of the floor-covering materials. Enclosure fire modeling to predict smoke and fire growth characteristics inside of the vehicle passenger compartment and to help in the placement of sensors during the full-scale tests.
3. Physical testing of three scenarios to assess their validity to explain the evidence, and to compare the results with the prediction of the modeling.

FIRE MODELING

Two modeling studies were performed before the experimental series was initiated. First, an analysis of the heat transfer from an underbody flame through the floor structure to the interior flooring materials, and then a model of the fire development inside the passenger's compartment. Modeling and theoretical analysis should be used *a priori* to design the experiments and *a posteriori* to help in the interpretation of the results.

Thermal Modeling

The transient heating of the floor from the exterior (Fig. 2, left) by a flame on the bottom was modeled to allow calculating the approximate ignition times of the floor-covering materials inside the vehicle. The goal was to assess both the auto ignition and the piloted ignition.

The heat to the floor is conducted along the slab and lost to the surrounding air. Mathematically, this was modeled as transient heat transfer by conduction in an infinite slab heated from both sides, assuming radial symmetry (Eq. 1). The heat exchange from the flame and that lost to ambient is modeled as volumetric heat (Eq. 2).

$$\frac{1}{r} \frac{\partial}{\partial r} \left(rk \frac{\partial T}{\partial r} \right) + \dot{q}''' = \rho c \frac{\partial T}{\partial t} \quad (1)$$

$$\dot{q}''' = \begin{cases} \sigma \varepsilon \frac{1}{\delta} (T_f^4 - T^4) - h_i \frac{1}{\delta} (T - T_0) - h_o \frac{1}{\delta} (T - T_0) & \text{at } r < r_f \\ -h_i \frac{1}{\delta} (T - T_0) - h_o \frac{1}{\delta} (T - T_0) & \text{at } r \geq r_f \end{cases} \quad (2)$$

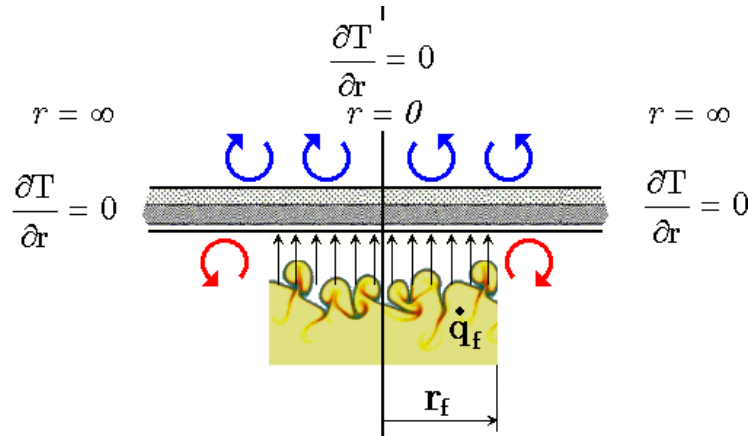


Figure 2. Schematic of the floor heated from below in the thermal model

The layered floor (carpet, acrylic and steel) was treated as one layer 2.5-cm thick (according to the manufacturer notes) and with weighted properties taken from [6]. The carpet is modeled a 10 mm thick layer of PP+PE. The polyacrylic layer is 12 mm thick and the steel plate of 2 mm. The flame temperature T_f was assumed to be 900 °C, the emissivity ε to 0.9, the flame radius r_f to 10 cm, the convective heat transfer inside the van h_i to 7 W/mK, and the convective heat transfer outside h_o (air velocity of 50 km/h) was set to 55 W/mK.

The results (Fig. 2, right) show that the center of hot spot heats up at an initial rate of about 130 °C/min. The heating slows down significantly after reaching 300 °C and reaches steady state temperature (450 °C) after about 600 s. A typical auto-ignition temperature for carpet material is about 600 °C [1], so the calculations predict that auto ignition of the floor-covering will not take place. If a pilot source is present in the vicinity (holes in the floor) and assuming a piloted ignition temperature of carpet of 400 °C [1], ignition would occur 380 s after flame exposure started. These results are later compared to experimentally measured temperature profiles (Figs. 5 and 6).

<p>The vehicle</p> <ul style="list-style-type: none"> • An approx. 8-year old luxury mini-van outfitted for comfort and utility which had traveled 170,000 km. Aftermarket interior. AC and heating system for front and rear passenger areas. • Gasoline engine. Deteriorated exhaust system: tail pipe missing, muffler riddled with holes, episodes of engine misfire. Catalytic converter OK. 	
Event Line (local time)	Events or Description
Evening before the fire	<ul style="list-style-type: none"> • Van traveled recently over 240 km and driver stated that vehicle performed excellently. • Vehicle was parked overnight in the driveway outside. • Weather: light rain and cool, air temperature ~13 °C.
from 13:30 to 13:36 (approx.)	<ul style="list-style-type: none"> • Loaded children in car and left house at about 13:30. • Traveling on city roadways; several stop signs and stop lights. • Vehicle performance got progressively poorer and decided to return home. • At about 13:36, the driver hears a report (“pop” or hissing sound). • Child in back seat says “what’s that?!”. • Driver observes a conical plume of “dense white smoke” from behind the middle of the back seat.
13:36 (approx.) and afterwards	<ul style="list-style-type: none"> • Driver immediately pulls off road to right side. • Van appears to be full of smoke; then fire. • Exits by driver door, runs around back of van. • Opens right side sliding door and removes child from the right seat of the middle row. • Passenger compartment full of smoke and hot gas during this procedure; head liner melting and dripping. • Rapid fire spread from rear along headliner. • Unable to re-enter van to extract the other children, hair singed, hands burned.
After the fire	<ul style="list-style-type: none"> • No fire or spilled fuel under van while witnesses assisting driver or when first responders arrive. • Van interior totally involved in fire. • No fire suppression for 15 min
<p>Fire damage to van</p> <ul style="list-style-type: none"> • Interior complete burn-out. All windows broken. Buckling of steel roof. • Engine compartment damage is lower than in passenger compartment. • Rear tires severely burned. Front tires burned noticeably less than rear tires • Spare tire mounted to underside rear floor pan degraded at interface to floor pan • Fuel-tank shield made of polymer is partially melted from top down. • Underbody polymeric materials that were not close to floor pan exhibit minimal heat effect (except for those close to the burning rear tires) • Survey of debris in the rear of the van compartment include: melted aluminum, jack and jack handle, charred remains of various carpet samples, and other unidentified materials and objects. • No open penetrations in the passenger compartment floor pan. 	

Table 1. Summary of background information

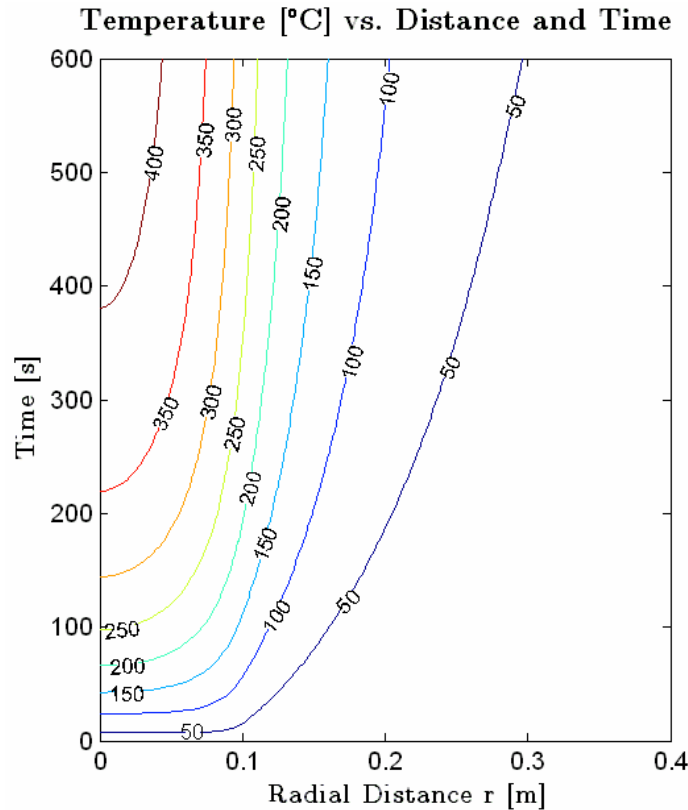


Figure 3. Analytical results of temperature in the space vs. time domain in the thermal model

Post ignition and early fire growth

The post ignition regime was studied using FDS [7] to provide estimations of the early fire environment. The objective is to have rough estimates of the time-line of the thermal and smoke environment in the passenger's compartment. In the small space of the passenger's compartment of a vehicle, the first indicators of ignition are smoke (smell, sight) and heat. Both are readably perceived by occupants and warn in early times of the impending danger. When these pre-fire indicators are perceived, passengers will have a much greater chance of escaping on time before flames spread inside of vehicle. For the following results, both the external and internal ignition hypotheses are studied by the same scenario since the assumptions are essentially the same.

A very simple and approximate study of heat and mass propagation in the interior on the vehicle was conducted with FDS [7]. The domain is set roughly to the interior of the vehicle following Fig. 4. The fuel is assumed to be PS using the 2004 FDS database values. The time line is initiated at the instant of flaming ignition, regardless of how, and the fire growth is assumed to be a slow t^2 -fire [8]. The simulation results are used to estimate approximately the time to fire detection by the driver due to smoke and irritant combustion gases (less than 25 s) or heat. (less than 30 s). The thresholds for detection were set at high values to ensure that the calculated times are an overestimation. For smoke irritation the threshold is 500 mg/m^3 , and for a 5 °C for the gas temperature increase. The pyrolyzates produced by materials decomposition during the pre-ignition heating regime is not accounted for in the FDS model. Adding this into the analysis is expected to lead to faster detection times. The

simulations estimate that the passengers' compartment is filled with smoke at about 80 s after flame ignition in the interior.

Both modeling results indicate that an approximated time line in the case of an external source will be of 380 s for ignition of the interior carpet and less than 25 s after ignition for detection of the fire by the passengers. This time line is far from matching the time line described by the witnesses.

SMALL- AND FULL-SCALE EXPERIMENTS

Small-Scale Tests

Preliminary tests were conducted to decide on the spray apparatus and flow rate that will be used in the experiments to represent the external and the internal fire sources.

For the external fire, it was decided to have the fire source imitating a leak in a pressurized fuel-line. Thus, a gasoline spray-nozzle connected to a reservoir containing a standard fuel pump was ignited and tested at several flow rates, from 100 ml/min to 300 ml/min. In order to obtain a flame size big enough and to avoid spray rates forming a pool fire on the ground below the vehicle, it was determined that 215 ml/min flow rate would be used in the full-scale tests. This value is in agreement with the spray fire of 200 ml/min used in under-hood tests conducted by NIST and GM [9]. Gasoline sprayed at this rate produces approximately a 100 kW fire.

For the internal fire source, tests were conducted to evaluate a fire initiated from a pressurized small can of WD-40 (hydrocarbon-based oil, 74 ml capacity), which is a USA commercial product for automobile maintenance. In order to test the system to recreate the proposed internal fire scenario, the WD-40 aerosol was released inside a drum (imitating a small close space). Prior to ignition, the released aerosol produced a distinct white plume. The spray was calibrated and it was determined that the best released was to empty the can in 7 s. This results in a flow of 10 ml/s and an approximated heat released rate of 2.5 kW (using the heat of combustion of light petroleum base oil).

Full-Scale Testing

Two full-scale tests were conducted to evaluate the hypothesis of an external source, using an underbody spray-fire during replicated driving conditions (see right of Fig.1). The first test had the floor pan of the vehicle with penetrations (piloted ignition scenario) and the second had no penetrations (auto-ignition scenario). A third test was conducted to evaluate the hypothesis of an internal source and fire growth in the passenger compartment was studied after ignition of an aerosol plume from a pressurized container located behind the back seats.

In preparation for these tests a platform was constructed, where the vehicle was situated approximately 60 cm above the ground. A photograph of the vehicle on the test platform is shown in right side image of Fig. 1. The front of the platform was ramped down to the ground at an approximate 30° angle to help direct airflow under the van. A large fan designed for wind tunnel applications was used to simulate the air flow that would develop around and under the van when it was being driven. The fan was located at a distance of 1.2 m in front of the van and adjusted to develop winds consistent with the real scenario. Due to

the complex geometry under the van (axles, fuel tank, exhaust, suspension) the slip-stream wind speed under the van varied between 20 and 70 km/h.

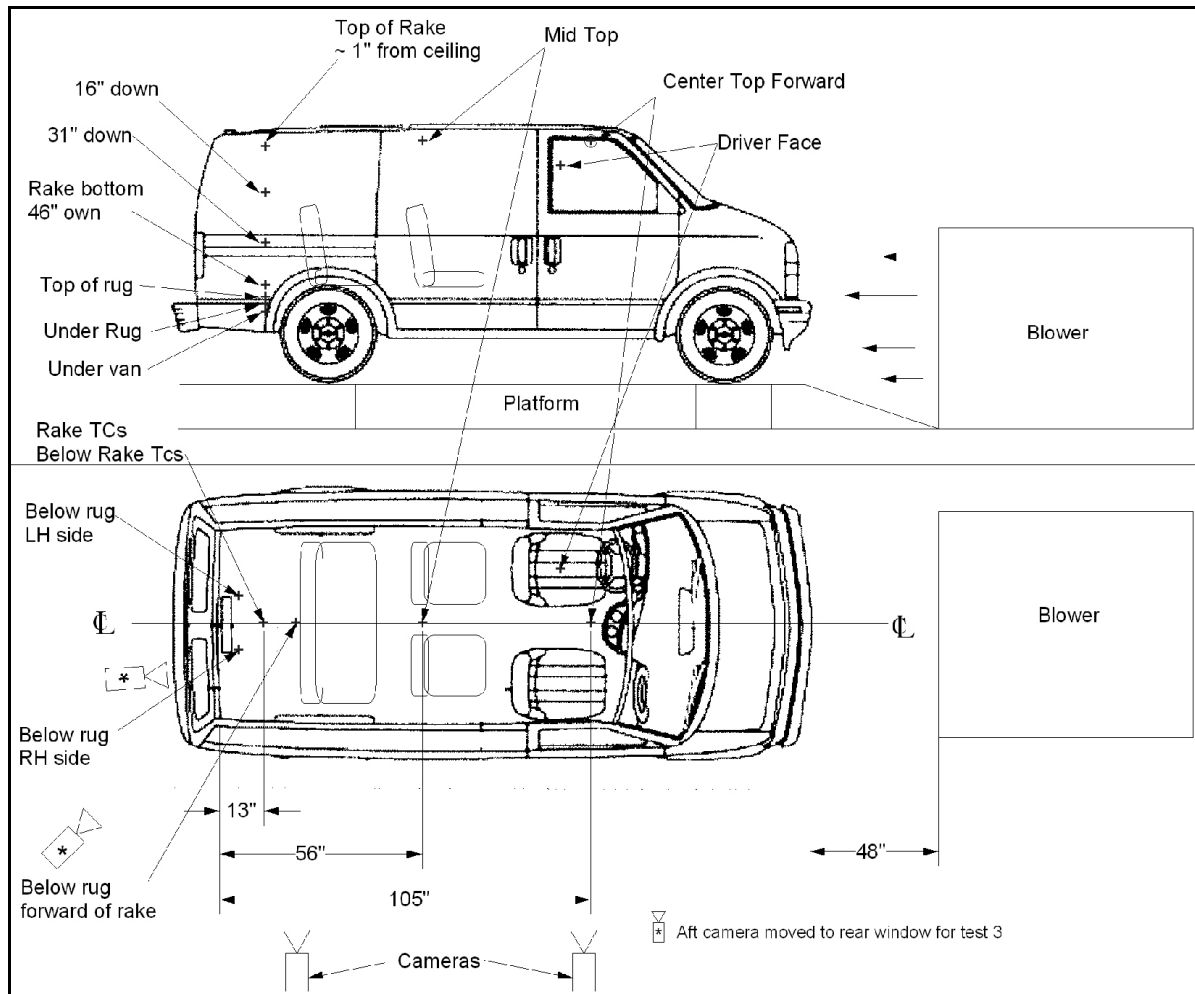


Figure 4. Location of thermocouples inside the vehicle for the full scale tests.

Each test was instrumented using thermocouples and video cameras. Fig. 4 is a schematic of the test set-up showing location of the measurement locations. The instruments were placed at selected locations throughout the inside and outside of the vehicle, with more measurement points right above the area of fire impingement (note vertical rake with thermocouple at the rear). Results from the FDS model were used to help determine the best location of the thermocouples and the video cameras. A thermocouple in front of the nozzle recorded flame duration and ambient conditions were also recorded. Gas measurements of the interior atmosphere at the driver position were taken during each test using acetaldehyde and acrolein sensitive Dreager tubes. The threshold detection level of these tubes was 10 ppm. These measurements were made to see if these common irritant gasses, produced during degradation of plastic materials, could alerting the passengers to the impending fire. The spray nozzle was located under the van next to the alleged degraded fuel line. The nozzle was pointed so that the center of the spray pattern contacted the under floor pan aft of the rear axle. There was only one exemplar van of this vintage available for the tests. Consequently, we needed to be frugal with the floor covering materials, the head liner and the seats so that we had enough virgin materials to conduct three tests. Thus the termination requirement for all but the last test was to stop the experiment when flames spread to the

headliner. Termination of the test was accomplished by use of a high capacity CO₂ extinguisher piped directly into the passenger compartment.

External Fire - Piloted ignition scenario: Fig. 5 shows the temperature measurements in the passenger compartment for the test where penetrations were present in the floor pan. At $t=0$, the spray-fire was initiated under the van and the temperature of the floor-covering material started to increase after 40 s. Piloted ignition occurred approximately after 210 s, and it is seen in Fig. 5 as the temperature of the rake location reached 400 °C. Temperature rise at the ceiling thermocouples ('rake top') is first sensed at about 170 s after spray-fire initiation, and flames reached the height of the head liner at about 230 s when the fire was manually extinguished. Video records showed visual evidence of smoke at the back of the van approximately 120 s after spray-fire initiation and 80 s before fire reached the headliner in the test with floor pan penetrations. Both acetaldehyde and acrolein were detected inside the compartment before the tests was terminated. Comparison with the results from the ignition model of Eqs. (1) and (2) shows good agreement. Translating the time zero of the heat transfer model results to the first measured temperature increase ($t=40$ s). When flames penetrate the compartment at 210 s, the model predicted temperatures of 350°C, which compares well with the 400°C measured below the rake. The affected carpet material was replaced after this experiment to allow the next large-scale experiment.

External Fire - Auto ignition scenario: Fig. 6 shows the temperature measurements in the compartment for the test where there were no penetrations in the floor pan. Significant heating of the steel floor is starts at 70 s and the subsequent rise is very similar to that in the previous test since the outside spray-fire and air flow conditions were the same. However, there is no fire ignition in the compartment in more than 500 s. Smoke was visible at 230 s at the back of the van for the test where there were no floor pan penetrations – filling the van and becoming progressively denser until the test was terminated. Thermocouples inside the compartment show essentially no temperature rise. The heating of the floor caused extensive thermal degradation of the floor-covering materials in a radius of about 0.5 m around the flame impingement point but were not high enough to cause spontaneous ignition. This time line correlates well with camera recordings of the experiment. Both acetaldehyde and acrolein were detected inside the compartment before the tests was terminated. In order to test the effect of the external airflow, at 300 s the air fan was shut down. Thus, external convective heat-losses were substantially reduced and the effect in the steel floor is immediate, showing at sudden rise of 40°C at 300 s (see thermocouple 'below rake forward' in Fig. 6). For this experiment both acetaldehyde and acrolein were also detected inside the compartment before the tests was terminated.

Comparison with the results from the ignition model of Eqs. (1) and (2) shows very good agreement. It is seen the heating curves are the same and predictions are within the expected experimental error range (± 5 %). The comparison in this test is even better than for the previous one because the model assumptions do not contemplate the effect of the penetrations in the floor-pan.

Sudden Internal Fire: Test results from a rapid cloud fire located behind the rear seat of the van are nearly identical to the gas temperature measured in Fig. 5 at $t=240$ s when flaming ignition took place. Flame propagation took place rapidly and acetaldehyde and acrolein were not detected inside the compartment in the short time of the experiment.

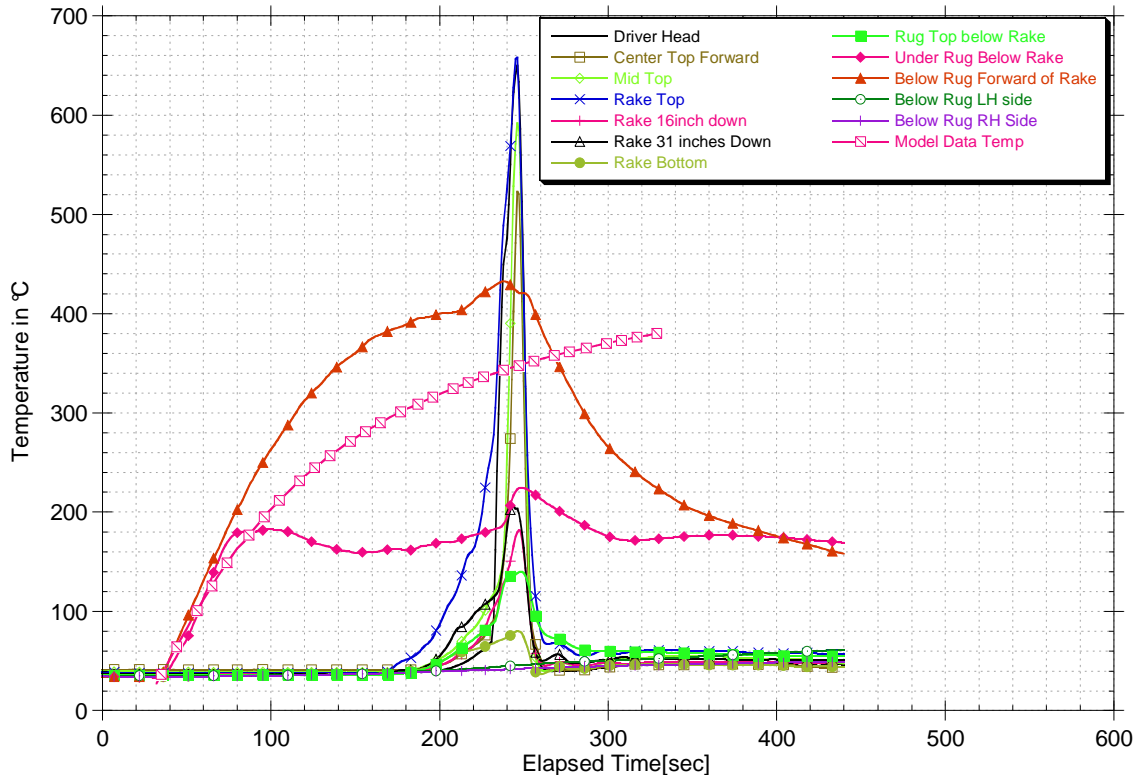


Figure 5. Under-floor spray test: penetrations at flame impingement site. Temperature measurements and heat transfer modeling results.

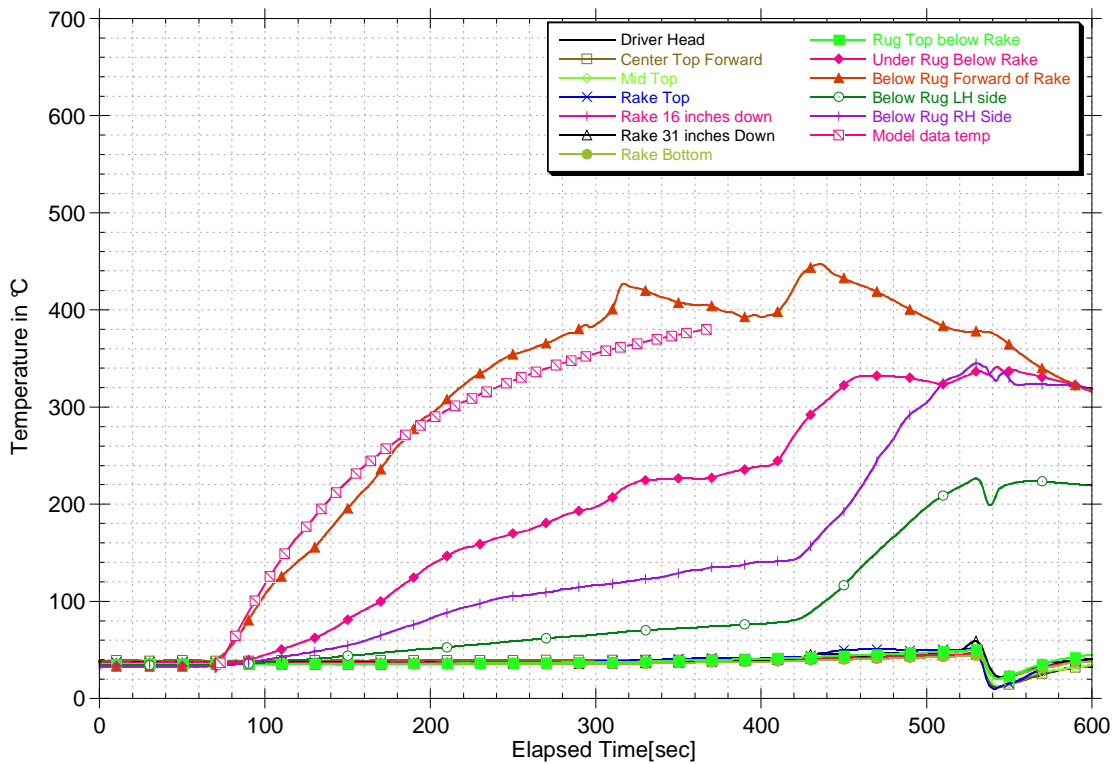


Figure 6. Under floor spray test: no penetration at flame impingement site. Temperature records and heat transfer modeling results.

CONCLUSIONS

Experimental and modeling investigations of an accidental fire have been conducted. The fire scenario proposed by the initial fire investigators - a spray fire under the moving vehicle igniting interior materials - posed an unusual case for study. Results from both the heat transfer model and the test, where there were no penetrations in the floor pan at the spray fire impingement site, prove that the scenario proposed by the investigators was flawed because it would not match the evidence and the time line described by the witnesses. If in fact, a spray fire occurred below the van, there would have been more than enough time for the driver to have stopped and evacuate all of the passengers before fire could spread to the interior space. Even the condition where penetrations existed in the floor pan would, according to both the heat transfer model and the test, allow substantial time for alarm and evacuation.

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