HYDROGEN VEHICLE FUEL SYSTEMS – LOCALIZED FIRE PROTECTION CONSIDERATIONS

Milestone 2

VEHICLE FIRE CONDITION REPORT

Submitted To:

Transport Canada
Road Safety

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1.0 Background

1.1 Overview

The experience with compressed natural gas (CNG) vehicles provides a window into a future of fuel cell vehicles using compressed hydrogen fuel systems. There are now over 5,500,000 CNG vehicles in the world – some OEM and most aftermarket conversions. Since the year 2000, there have been over 20 failures of CNG tanks onboard vehicles. The single largest cause of these failures (over 50%) was fire.

Some of the fire failures could be attributed to slow reacting thermally-activated pressure relief device (TPRD) designs, but the majority of the failures was caused by localized fire effects where the flame exposure was at a location on the tank remote from the TPRD location. These CNG cylinder failures have occurred on OEM passenger vehicles (Ford Crown Victoria, Honda Civic), as well as on OEM transit buses (Heuliez, Man Bus).

TPRDs do not tend to activate unless they are exposed directly to a high heat source, or direct flame impingement. There is no requirement in the ANSI/CSA PRD1 standard for TPRDs to exhibit any minimum activation time in the chimney test (exposure to hot gases).

1.2 Current Fire Testing Requirements

All CNG or draft compressed hydrogen tank standards worldwide only specify a bonfire test of a tank where the fire source is a standard 1.65 m length. This fire length is derived from a US DOT fire test developed in the 1970s for application to composite air-breathing cylinders of relatively small size.

The history of CNG tank failures has shown that this standard 1.65 m fire test is inadequate for the larger pressure vessels used as fuel tanks onboard passenger vehicles, trucks and especially transit buses.

1.3 The Need for a Literature Review

While it would seem obvious that the industry should reduce the size of the fire used in bonfire tests, there is a reluctance to do so because (a) industry would have to agree on the dimensions and temperature profile of the smaller fire source, and (b) it would make current designs inadequate for fire protection purposes, i.e. they would only work if they are placed in (or in very close proximity to) the fire. The industry has not yet explored alternative fire protection methods that could be used in installations (e.g. protective coatings, heat shields, and remote sensing devices).

The overall objective of this study is to improve the level of safety of hydrogen-fueled vehicles. One way of improving safety is to develop a localized fire test procedure for the purpose of testing various fire protection strategies for hydrogen vehicle fuel systems. In addition, fire safety would be enhanced through modifications to hydrogen fuel system installation codes..

In order to develop a localized fire test, there is a need for a review of vehicle fire literature to identify the localized fire conditions that can exist, including fire dimensions, flame intensity and temperature and fire propagation behaviour. The literature review must include an analysis of research from testing and case studies from actual incidents for both gasoline and alternative fuel vehicles.

2.0 Existing Research - Gasoline Vehicles

2.1 Causes/Ignition Sources of Motor Vehicle Fires[1] [2]

There is some discrepancy or lack of clarity about what the most common cause of motor vehicle fire is. According to The National Fire Protection Association's Guide for Fire and Explosion Investigations, 1998, the most common cause of motor vehicle fire is collision with another vehicle or a stationary object such as a tree or a barrier, and a subsequent fuel leak, although there have been cases reported of "spontaneous" fire in a stationary vehicle (see Section 4: Case Studies). However, statistics compiled by the NFPA indicate fires classified as a direct result of collision as being only 3%, with the most common "cause" as being "unclassified" or "unknown" at 24% (see Table 8 below).

In most instances, the sources of ignition energy in motor vehicle fires are the same as those associated with structural fires like arcs, overloaded wiring, open flames, etc, but there are some unique sources: such as the hot surfaces of the catalytic converter, turbocharger, and manifold.

Open Flames. In older vehicles, the most common open flame is caused by a backfire through the carburetor. Lighted matches in ashtrays may ignite debris in the ash tray, resulting in a fire that exposes combustible plastic dashboard or seat materials. In recreational vehicles, appliance pilot flames or operating burners and ovens are open flame ignition sources.

Electrical Sources. The primary source of electrical power in a vehicle is the battery. With no battery, there can be no other electrical source of energy. With a battery, however, consistent energy can be produced by the generator or alternator, which is more than sufficient to cause a fire. Overcurrent protection devices, such as fuses, circuit breakers, or fusible links, are used on motor vehicles to provide safety. However, in some cases, breakdown of parts, improper use, or installation of additional equipment can defeat these safeguards.

Overloaded Wiring. Unintended high-resistance faults in wiring can raise the conductor temperature to the ignition point of the insulation, particularly in bundled cables such as the wiring harnesses or the accessory wiring under the dash where the heat generated is not readily dissipated. This can occur without activating the circuit protection. Faults and mechanical failures of high-current devices such as power seat or window motors can also result in ignition of insulation, carpet materials, or combustible debris that may accumulate under seats. Pre-fire history of electrical malfunction provides clues as to whether a vehicle may be susceptible.

Electrical Arcing. In post-crash situations, arcs can be generated through the crushing or cutting of wires, particularly battery and starter cables, which are not electrically protected and are

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[1] http://www.interfire.org/res_file/92115-1.asp Excerpt from NFPA 921*Guide for Fire and Explosion Investigations 1998 Edition*, copyright © National Fire Protection Association, 1998.

[2] See Also: Severy et al., Automobile Collision Fires, and API PUBL 2216, Ignition Risk of Hydrocarbon Vapors by Hot Surfaces in the Open Air.

designed to carry high currents. The large amount of energy available in a battery can be enough to ignite materials such as engine grease, some plastic materials, and electric insulation. Significant arcing can also occur along with the crushing of the battery or batteries.

Lamp Filaments of Broken Bulbs. Lamp filaments of broken bulbs are also a source of ignition energy especially for gases, vapours, or liquid fuels in a spray or mist form. Normally operating headlamp filaments have temperatures on the order of 1400°C.

External Electrical Sources Used in Vehicles. While most electrical sources in vehicles are self-contained, in some situations electrical power is provided from commercial facilities. Examples of these sources are electrical hook-ups used in recreational vehicles and trailers and electric heaters for engines and vehicle interiors. Inspection for electrical power cords should be made when applicable, since an overload of the cord or failure of the appliance could be the cause of the fire. Where recreational vehicles are connected to commercial power, the branch circuit wiring should be inspected for indications that it was a possible ignition source.

Hot Surfaces. Exhaust manifolds and components can generate sufficient temperatures to ignite diesel spray and to vaporize gasoline. Automatic transmission fluid, particularly if heated due to an overloaded transmission, can ignite on a hot manifold. Engine oil and certain brake fluids dropping on a hot manifold can also ignite. The internal components of a catalytic converter have operating temperatures in the range of 700°C under normal operation and can be much higher if unburned fuel is introduced due to a fuel or ignition system malfunction. External temperatures of these converters can reach temperatures of 315°C under normal operation and higher where ventilation or air circulation is restricted.

Mechanical Sparks. Metal (e.g., steel and magnesium) to pavement sparking can generate enough energy to ignite liquid fuel vapours or gaseous fuels. Sparks generated at speeds as low as 8 km/h have been determined to have temperatures of 800°C (orange sparks). Higher speeds have produced temperatures of 1200°C (white sparks). Sparks can also be caused by moving parts such as pulleys rubbing against other metallic objects. Sparks from tools striking metals seldom cause ignition. Aluminum pavement sparks are not an ignition source, according to the NFPA *921 Guide for Fire and Explosion Investigations*.

Smoking Materials. Modern upholstery fabrics and materials are treated with flame retardant and are generally difficult to ignite with a cigarette. Ignition may occur if a lit cigarette becomes buried in a crevice between seat cushions, paper, or other debris or if the seat material comes in contact with open flame.

2.2 Forensic Study - Burn Patterns in Vehicle Fire

The burn or damage patterns remaining on the body panels and in the interior of the vehicle are often used to locate the point(s) of origin and for cause determination.

It was once felt that rapid fire growth and extensive damage was indicative of an incendiary fire. However, the type and quantity of combustible materials found in automobiles today, when burned, can produce this degree of damage without the intentional addition of another fuel such as gasoline. In the case of a total burnout, one cannot normally conclude whether the fire was incendiary on the basis of observations of the vehicle alone. The use of fire patterns or degree of fire damage to determine a point of origin or cause should be used with caution. The interpretations drawn from these patterns should be verified by witness evidence, laboratory analysis, service records indicating mechanical or electrical faults, or factory recall notices. The investigator should also be familiar with the composition of the vehicle and its normal operation.

The relatively small compartment sizes of vehicles may result in more rapid fire growth given the same fuel and ignition source scenario, when compared to the larger compartments normally found in a structure fire. However, the principles of fire dynamics are the same in a vehicle as in a structure and, therefore, the investigative methodology should be the same.

A forensic study by the New Hampshire Materials Laboratory (NHML)[3] found that the hottest spot in a vehicle fire is often different from the point of origin. Determining the point of origin requires the interpretation of burn patterns, often progressing backwards from the hottest spot to the point of origin. This paper discussed analysis of materials and their degradation in a fire: steels, copper, plastics, insulation, thermosets, and thermoplastics.

The author recommends vehicles should be stored under cover until the investigators have finished their examinations. Oxidation patterns are important in identifying the point of origin, but they are temporal. Exposure to the elements rapidly degrades the information they have to offer. Covered storage is available at "self-storage" areas for about half the cost of the open air storage at most commercial insurance storage lots. Conditions at the time of the fire, or just prior, are often very important to investigators. Was the vehicle running smoothly or not? Were there any prior problems? Was the vehicle running when the fire started? How recently had the vehicle been run if it was off? Had it received any recent repair work? What color was the smoke, if any? The answers to these and other relevant questions can make the difference as to whether or not the fire initiation can be reconstructed.

In 2001, Indrek Wichman at Michigan State conducted a literature review of flammability and combustion as related to the transportation industry[4]. If fire in a transportation vehicle is an unacceptable risk, then it is fire initiation, as opposed to fire growth and chemistry, that is key. However, if initiation cannot be prevented, then growth and chemistry have to be examined. Wichman's paper provides an exhaustive analysis of the parameters of all three stages of fire – initiation, growth (fire spread), and chemistry and how to test them, but concludes that fire behaviour is complex, "multi-faceted, and contains many areas of overlap" and expresses

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[3] NHML Resources**,** Burn Pattern in Vehicle Fires: Forensic Analysis, Frederick Hochgraf, Wade D. Bartlett, 3/91.

[4] A Review of the Literature of Material Flammability, Combustion and Toxicity Related to Transportation, Indrek S. Wichman, Progress in Energy and Combustion Science 29, 2003, pp 247-299.

preference of the cone calorimeter test to measure flame spread rates. Wichman's paper illustrates the challenges of quantitatively studying fire propagation behaviour.

Many studies are of a qualitative nature, such as the GM tests (see below) in 1997-1998, which observed fire behaviour and measured temperatures in simulated motor vehicle fires in crashed-tested passenger vehicles. Some reported on specific case studies, and others are statistical in nature, collecting data from actual accident reports that involved a motor vehicle fire.

Almost all the tests and data collection found in the literature is dedicated to passenger safety, i.e. tests designed around rate of temperature climb and fire ingress to the passenger compartment, along with other hazards such as toxic gases emitted as plastic components burn. However, this data can be useful in determining how a pressurized tank may be affected in a vehicle fire as tanks are usually located in the back or the trunk of the car, located just behind/below the passenger compartment.

A forensic approach was taken by P. Maynard in a presentation on Motor Vehicle Fires[5] when presenting a paper to fire and explosion investigators. According to Maynard, most vehicle fires are deliberately lit and that it is uncommon for *moving* vehicles to burst into flames because, aside from human factors, the car is air-cooled by movement and flammable vapours are unable to accumulate in a moving car. However, a fire may start shortly after the vehicle stops if there is a fuel and / or electrical fault, but a fire initiating in the passenger compartment is unlikely to be explained in this way. Maynard goes on to say accidental fires originating in the passenger compartment are rare. Accidents which breach the fuel tank of a vehicle or leave it upside down / sideways are more likely to cause a fire. Forensically finding the fire's origin (or "seat") is challenging because fires usually burn vigorously and to completion if ventilation is adequate. If the vehicle is secured (doors and windows closed) when a fire ignites in the passenger compartment, ventilation is very limited, the fire will extinguish or smoulder, and the compartment will be filled with smoke. But if the fire smoulders for long (and hot) enough, a window will eventually fail and the fire will immediately develop to engulf the vehicle.

Fires in the engine compartment of a vehicle tend to be less intense than fires in the passenger compartment. Apart from leaking fuel, there is only limited combustible material in an engine compartment. Accidental fires in particular will most likely not burn the entire engine compartment, and will not spread to the passenger compartment of a vehicle (one of the scenarios studied in several of the GM tests, see below). The point of origin for an engine compartment fire can often be deduced from burn patterns on the paint. Many electrical sources exist in the engine compartment and if the fire seat is at an electrical system, the investigator should check for arcing or signs of resistance heating. The fuel line should be checked for leaks. The supply line should be made from high grade metal and should not melt in the temperatures reached in an engine compartment fire. Signs of shearing or corrosion in the fuel line can indicate an accidental fire.

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[5] Fire and Explosion Investigation, Section 8: Motor Vehicle Fires. Philip Maynard, University of Technology Sidney, Australia. www.forensics.edu.au/downloads/Section8mvprinter.pdf

In 1990, the National Highway Traffic Safety Administration (NHTSA) conducted an analysis of motor vehicle fires up to 1990, in order to assess the efficacy of Federal Motor Vehicle Safety Standard (FMVSS) 301, which applies to passenger cars, light trucks, school buses, prescribes impact test requirements aimed at reducing the chances of fuel-fed fires caused by fuel system breaching in vehicle crashes[6].

2.3 Findings of the NHTSA Report DOT HS 807 675

Motor vehicle fires in all police-reported traffic crashes are relatively rare, occurring at the rate of approximately 3 fires for every 1,000 vehicles involved in crashes. For all vehicles involved in fatal crashes, fires are considerably more frequent, with about 26 fires per 1,000 vehicles in crashes, nearly 9 times the rate for all crashes. For each of the 3 classes of vehicles of primary interest in this study - passenger cars, light trucks, and school buses, the fire rate and estimated number of fire crashes annually are:

	Fires per 1,000 Vehicle Crashes	Total Number of Fires Annually
Passenger cars	2.9	23,600
Light trucks	2.9	5,200
School buses	2.4	60

For injury crashes involving passenger cars or light trucks, the fire rate is higher at 7 to 8 fires per 1,000 crashes.

Fire in fatal collisions of passenger cars has increased significantly over the last several years, from 20 per 1,000 crashes in 1975 to 28 per 1,000 crashes in 1988. A primary reason for this increase is believed to be an increasing proportion of older vehicles in the car population. Older vehicles are more likely to experience fire, given a crash. The fire rate was not found to be related to car size, as defined by vehicle curb weight. Therefore, the trend to smaller cars over the last several years does not appear to be a factor in the increased rate of fires in fatal passenger car crashes. The “Age Factor”, Parsons reported, is believed to result from the general degradation (corrosion, weakening of metal structures; hardening, cracking of flexible hoses, etc.) of vehicles over time. Another possible factor that could contribute to the age effect is the probable under-reporting of accidents involving older vehicles, owing to their decreased worth.

Fire is also associated with more severe accidents in terms of injuries/fatalities of vehicle occupants. In fatal crashes, vehicles with fire experience anywhere from 70 to 80 percent more

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[6] NHTSA Report # DOT HS 807 675, http://www.nhtsa.dot.gov/cars/rules/regrev/evaluate/807675.html, **Motor Vehicle Fires in Traffic Crashes and the Effects of the Fuel System Integrity Standard,** Glenn G. Parsons, November, 1990.

occupant fatalities than do vehicles in all fatal crashes. For nonfatal crashes, occupants of vehicles with fire sustain 3 to 4 times the chance of serious injuries as occupants of vehicles in all crashes. For moderate injuries, the risk is about 2 times greater for occupants of vehicles in a fire crash.

Crashes with fire are also more severe in terms of crash impact forces exerted on the vehicle and its occupants, and in terms of the extent of damage sustained by the vehicle:

- Among all crashes resulting in fatal injury, those that involved fire are 30% more likely to occur on roadways with the highest speed limits. Higher speed limits indicate higher traveling speed and hence, higher impact speeds and crash forces.
- Among all fatal crashes, those that involve fire are 70 to 90% more likely to be single vehicle collisions with fixed objects; this indicates more severe impacts for crashes with fire.
- For all police reported crashes, vehicles with fires are 2½ to 5 times more likely to have sustained the highest levels of damage due to the crash, as recorded by vehicle damage indices.

Impacts to the front of the vehicle account for 60 to 70% of the crash fires, for both passenger cars and light trucks. This applies to fatal, as well as non-fatal crashes. Rear impacts are over-represented (3 times as likely) in fatal fire crashes involving passenger cars, but not for light trucks. This may be a reflection of *the more vulnerable location of fuel tanks* in cars than in light trucks. For less severe, non-fatal collisions, this over-representation of fire in rear impacts does not appear.

2.4 General Motors – Fire Initiation & Propagation Tests

In the periods 1997 to 1998, Jeffrey Santrock et al. of General Motors conducted an exhaustive series of tests on vehicle fire propagation (VFP), conducting crash tests on various designs of cars and light trucks[7]. In all the simulated crashes and rollovers, none of the test vehicles caught fire, so after the crash, the damaged vehicle was subjected to a simulated fire, either an engine fire or a gas pool fire under the vehicle. Thermocouples and infrared cameras tracked the temperature rise and fire behaviour, using a threshold temperature of 600°C to indicate the presence of flame.

Engine compartment fires and gas pool fires were studied because there are several ways these fires can initiate in a passenger vehicle damaged in a crash.

Engine Compartment Fires due to:

- Ignition of combustible solids in the engine compartment by heat generated from an electrical short, which could include an internal short in the battery;
- Ignition of a combustible liquid sprayed onto a hot surface; or
- Ignition of gasoline leaking from a ruptured fuel line by an electrical arc.

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[7] Evaluation of Motor Vehicle Fire Initiation and Propagation, Parts 3 - 13, Jeffrey Santrock et al, GM Corporation, 1998.

Ignition of a Gasoline Spill

A gasoline spill ignition is possible for vehicles struck in the rear due to ignition of gasoline leaking from a ruptured fuel system. There are two possible outcomes of the crash test with regards to fuel system integrity:

- The fuel system ruptures and leaking fluid is detected during the crash test or the vehicle roll, or
- The fuel system does not rupture and leaking fluid is not detected during the crash test or the vehicle roll.

The National Institute of Standards and Technology issued a 1998 report in conjunction with the post-crash fire test General Motors conducted, describing the significant fire hazard due to spills of flammable liquids, particularly gasoline[8]. While only a small fraction of motor vehicle crashes result in fire, crashes forceful enough to cause fuel spills are more likely to result in fire. A NHTSA analysis (An Analysis Of Fires In Passenger Cars, Light Trucks, Vans, DOT-HS-808-208, December 1994) of police crash reports from Michigan, which includes data on fuel leaks, indicated that the probability of fire, given a fuel leak, is >50 times higher than the probability of fire with no fuel leak, and an analysis by the NFPA found that fuel is the most frequent form of material first ignited. This is why the GM tests focused on the fire effects of liquid spills. Note that gasoline is the only automotive fluid above its ignition point at normal operating conditions, thus any gasoline release can readily be ignited by any pilot source.

The section below summarizes the data/results from this series of tests. For all the thermal contours and thermocouple data, refer to the actual report, available on the US Department of Transport's Docket Management system: http://www.regulations.gov/search/index.jsp or on the Motor Vehicle Fire Research Institute's website: http://www.mvfri.org/Library/b-03.html.

2.4.1 Fire Test F961115: 1996 Dodge Caravan – Front End Crash & Engine Fire[9]

A 1996 Dodge Caravan Sport was crash tested and then an electrical igniter was used to artificially ignite the battery and power distribution center housing. The fire was allowed to burn until flames spread into the passenger compartment and along the headliner toward the rear of the passenger compartment. Flames spread from the engine compartment into the passenger compartment through the broken windshield. Flames penetrated the dash through the A/C evaporator- and condenser-line pass-through, where the pass-through closures had been dislodged in the crash test. Flames also penetrated the dash through the HVAC air intake, where the recirculation door had been dislodged in the crash test. The rate of flame spread through the openings in the dash was slower than through the windshield. Flames in the passenger

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[8] Aspects of Motor Vehicle Fire Threat from Flammable Liquid Spills on a Road Surface, T.J. Ohlemiller and T.G. Cleary, Building and Fire Research Laboratory, National Institute of Standards and Technology, NISTIR 6147, 1998.

[9] Evaluation of Motor Vehicle Fire and Propagation, Part 3: Propagation of an Engine Compartment Fire in a 1996 Passenger Van, J. Santrock et al, GM Corp

compartment were extinguished approximately 11 minutes after flames were first noted above the igniter.

Thermocouples located on the top of the battery and PDC housing (adjacent to the igniter) and at the rear of the PDC housing recorded temperatures of 809, 453, and 689°C respectively at 60 seconds post-ignition. Thermocouples located toward the right edge of the battery recorded temperatures of only 130 and 51°C at this time, and thermocouples located above the battery and under the HVAC air intake cowl recorded temperatures < 100°C (battery tray was polypropylene) with 30% inorganic filler. The air intake resonator and air cleaner housing were polypropylene with 20% inorganic filler. The air intake boot was EPDM elastomer with 40% carbon black).

Flame-spread along the hood liner toward the front of the engine compartment required that the flame-front move downward along the slope of the crumpled hood. This type of flame movement is called opposed-flow spread because flame movement is against the buoyancy-induced airflow. Flame-spread on the hood liner toward the windshield was in the direction of the buoyancy-induced airflow, and would be expected to have been faster because of the coincident flow of gaseous fuel and heat. It was impossible to estimate directional flame-spread rates accurately because the exact point of flame attachment to the hood liner could not be determined from the videotapes. The video stills indicate that by one minute post-ignition, the hood liner was burning from the rear-edge of the hood to approximately 15 cm forward of the battery and PDC. The maximum width of the burning area of the hood liner was approximately 30 cm, estimated from the width of the fire plume emerging from the rear edge of the hood: As noted above, the flaming hood liner would have been a source of radiant heating to objects below it in the engine compartment, which would have been a factor in the spread of flames to other objects beyond the site of ignition.

The hood liner started to separate from the hood at about 2 minutes post-ignition, allowing the previously unexposed cotton shoddy to ignite. When held in place to the underside of the hood by thermoplastic clips, the cotton felt backing of the hood liner was shielded from exposure to open flames. As the thermoplastic clips melted, the hood liner pulled away from the hood on the left side of the vehicle, exposing the cotton felt backing to flames. Once ignited, the cotton felt burned more vigorously than the polyester mat. The additional heat released by the burning cotton felt enhanced flame-spread along the HVAC air intake cowl and, secondarily, also ignited the paint on the exterior surface of the hood.

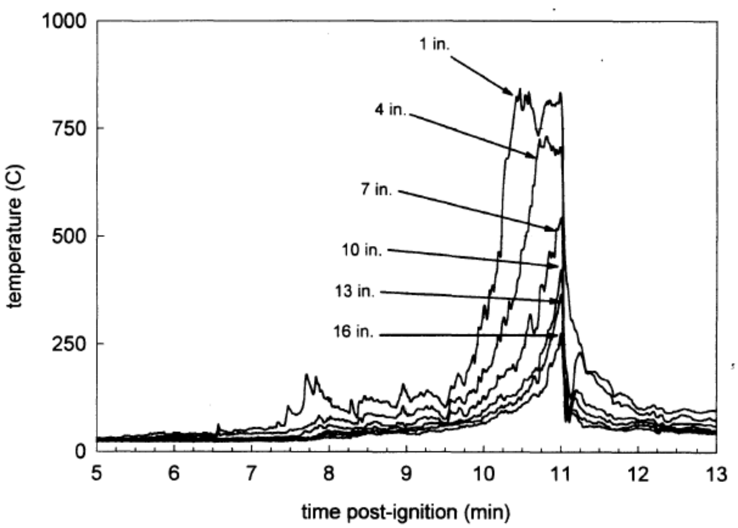

Figure 1: Fire Test F96115 - Plot of Air Temperature in Passenger Compartment Below Headlining.

Most of the battery, the PDC, and the forward edge of the HVAC air intake cowl in the left side of the engine compartment were burning 3 minutes post-ignition. Flames entered the passenger compartment via the windshield at about 4 minutes post-ignition. Flames did not spread rapidly from the instrument panel to other components in the passenger compartment. One factor that slowed fire growth in the passenger compartment was the direction of airflow during this stage of the fire, and although components in the front of the passenger compartment were heated by radiation from the fire on the instrument panel, this was insufficient to cause them to ignite until later.

A layer of heated combustible gasses produced by thermal decomposition of materials in the instrument panel, the deployed air bags, the interior trim panels, the front seats, and the carpet accumulated below the headliner of the test vehicle, and ignited between 9 and 10 % minutes post-ignition. The temperature recorded from the thermocouple closest to the headliner increased from approximately 150 to > 800°C between 9 and 10% minutes post-ignition.

The dash panel in the test vehicle contained a number of openings that could provide a path for flames to spread from the engine compartment into the passenger compartment. These potential fire paths included the HVAC air intake, the heater pass-through, A/C pass-through, the HVAC condensate drain pass-through, the brake linkage pass-through, and the steering column pass-through. These openings and fire propagation pathways can be significantly affected by a front end crash (as they were in this case) in ways that are difficult to predict. In this test, the pattern of fire damage to components in the instrument panel suggested that flames and hot gas entered the passenger compartment through three openings in the dash panel: the heater pass-through, the A/C pass-through, and the HVAC air intake.

The temperature at the exterior surface of the engine compartment dash panel silencer pad above the heater pass-through started to increase about 4 minutes post-ignition, but remained less than 600°C until approximately 6 minutes post-ignition.

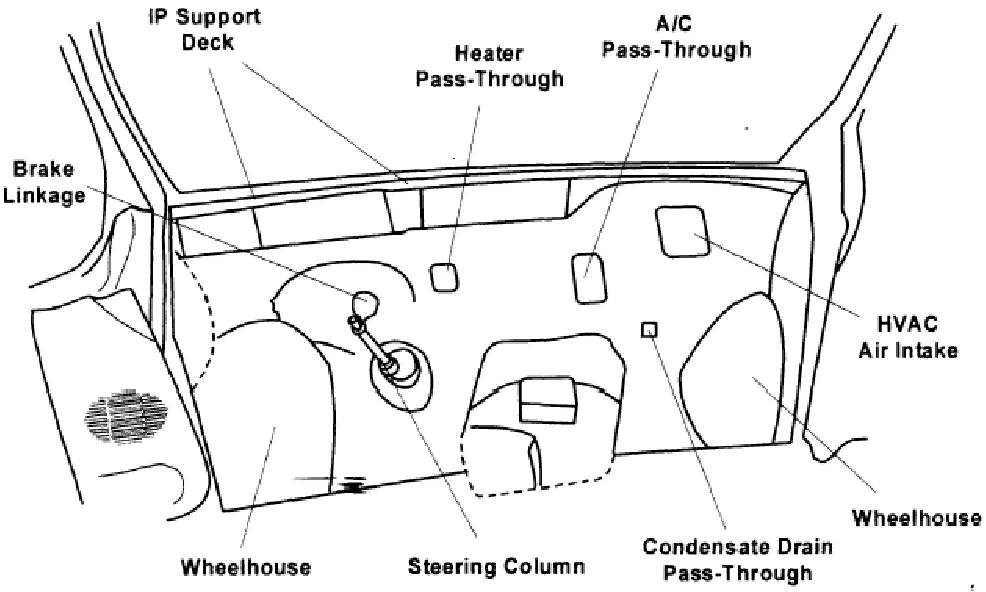

Figure 2 Diagram of Dash Panel in 1996 Passenger Van

2.4.2 Fire Test F961116: 1996 Dodge Caravan – Rear End Crash & Gasoline Pool Fire[10]

A 1996 Plymouth Voyager was struck in the rear by a moving barrier, neither leaks in the fuel system nor fire were observed during or after the crash test, nor the rollover test. A gasoline pool fire was simulated by drilling a hole in the fuel tank and allowing ~243 ml/min of gasoline to flow a tray beneath the van, which was ignited by a propane torch. Flames entered the passenger compartment via left rear vent window and the open-spot weld seam at the rear of the left rear wheelhouse.

Table 1: Test Summary – '96 Caravan, Rear End Collision, Gasoline Pool Fire

Time from Ignition, Seconds	Event	Max. Temp, °C rear left wheel house, near lift gate	Max. Temperatures °C, floor panel
-32	Plug removed from filler neck and gasoline begins to accumulate beneath test vehicle.		
0	Gasoline ignited using a propane torch		

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[10] Evaluation of Motor Vehicle Fire and Propagation, Part 4: Propagation of of an Underbody Gasoline Pool Fire in a 1999 Passenger Van, J. Santrock et al, GM Corp.

Time from Ignition, Seconds	**Event**	**Max. Temp, °C rear left wheel house, near lift gate**	**Max. Temperatures °C, floor panel**
5 - 10	Flames from burning gasoline pool entered left rear wheel house.	50	450
10 - 15	Heated gases start to enter vehicle through a split spot weld seam between left rear wheelhouse and floor pan.	75	500
60 - 90	The filler shield sagged onto he left rear tire.	350	675
90 – 110	Flames entered the passenger compartment through the split spot weld seam and ignite the left rear quarter trim panel.	650	700
100 - 105	Flames from the wheel house sporadically reached the bottom of the left rear vent window.	650	700
110 – 115	Flames emerging from the left rear wheelhouse sporadically reached the top of the left rear vent window.	700	~700
120 – 130	The lower surface of the foam pad in the second bench seat cushion started to burn.	840	675
135	Flames began to enter the passenger compartment through the left rear vent window.	850	675
150	Flames in the left rear corner of the passenger compartment sporadically reached the headlining panel.	800	700
170	The headlining panel ignited and flames spread laterally across the rear of the passenger compartment and forward toward the middle bench seat.	800	650
183	The upper surfaces of the middle bench seat back ignited	900	625
215	Fire suppression began.	675	500

Max temperatures read by thermocouple data plots,± 10°C.

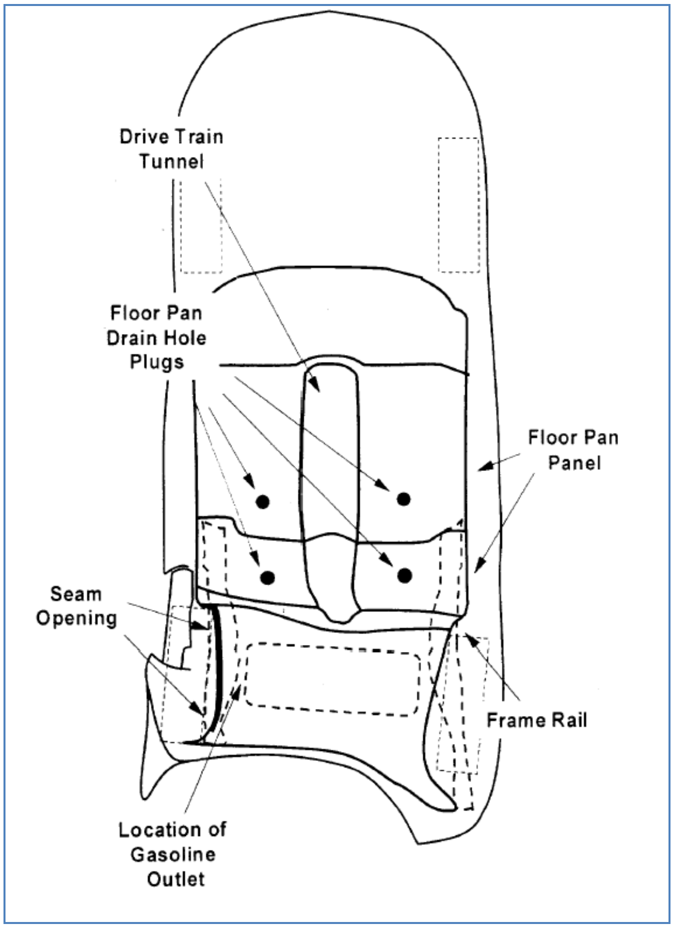

Figure 3: Overhead view of test vehicle

2.4.3 Fire Test F971001: 1997 Chevrolet Camaro – Rear End Crash, Roll & Gasoline Pool Fire[11]

The test vehicle was a 1997 Chevrolet Camaro, subjected to a crash test, a roll test, and then a gasoline fire pool test. In the crash test, the test vehicle was stationary and struck in the rear by a moving barrier. No leaks were detected in the fuel system of the test vehicle during the crash test or the subsequent roll test performed after the crash test, and no fire evidence was observed during or after the crash test. For the fire test, a gasoline pool was created under the test vehicle, where a gasoline delivery system consisting of a gasoline reservoir, compressed nitrogen reservoir, a pressure regulator, and a flow regulator was used to deliver liquid gasoline under the test vehicle during this test, at a flow rate of 515 ± 20 cm^3/s. A hand-held propane torch was used to ignite the gasoline.

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[11] Evaluation of Motor Vehicle Fire and Propagation, Part 6: Propagation of of an Underbody Gasoline Pool Fire in a 1997 Rear Wheel Drive Passenger Car, J. Santrock et al, GM Corp.

The fire was allowed to burn until flames spread into the passenger compartment and along the headlining panel to the front of the passenger compartment. Flames appear to have entered the passenger compartment through seam openings around the left rear wheelhouse, a gap under the driver's door, and through a floor pan drain hole. Heating of the carpet by conduction through the floor pan also appears to have played a role in flame-spread into the passenger compartment. The carpet, the interior left quarter trim finishing panel, and the left rear seat cushion were burning 170 seconds after the gasoline pool was ignited. Flames started to spread forward along the lower surface of the headlining panel between 180 and 190 seconds after ignition. Fire suppression started approximately 210 after ignition.

Table 2: Test Summary – '97 Camaro, Rear End Collision, Gasoline Pool Fire

Time from Ignition, Seconds	Event	Max. Temperatures, °C rear left corner	Max. Temperatures °C, floor panel
-30	Start of gasoline flow		
0	Gasoline vapour under the test vehicle was ignited using a propane torch		
5	The temperature recorded by the thermocouple on top of the floor pan drain hole plug under the left rear seat cushion started to increase	~300	650
7	Flames from the burning gasoline pool entered the passenger compartment through the seam opening around the left rear wheel house.	~400	650
12	Flames from the burning gasoline were visible in the left rear corner of the test vehicle	475	600
40 to 45	The fire plume disappeared from the left rear corner of the test vehicle.	400	750
100 to 110	Flames from the burning gasoline pool ignited the rear bumper energy absorber	500	~850
150 to 170	Ignition of the left quarter interior trim finishing panel.	525	~900
160	Flames burned through the floor pan drain hole plug located under the rear left seat cushion.	520	900
175	Flames began to reach the left rear corner of the headlining panel.	530	900

Time from Ignition, Seconds	Event	Max. Temperatures, °C rear left corner	Max. Temperatures °C, floor panel
188	Flames burned through the carpet in the area between the rear seat cushions.	550	~970
199	Signal to begin fire suppression.	550	950

Max temperatures read by thermocouple data plots,± 10°C.

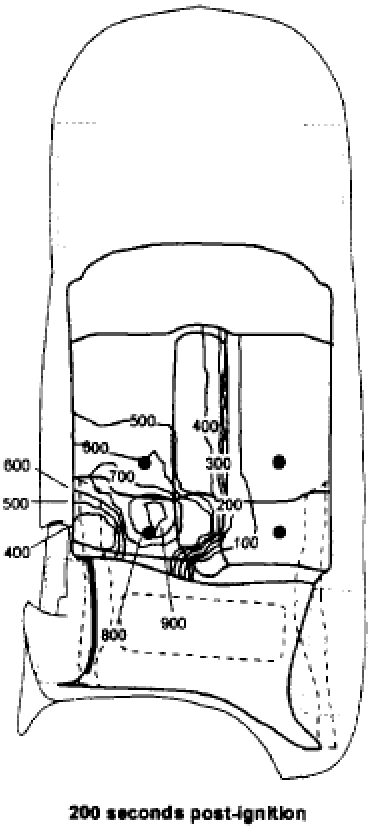

Figure 4: Fire Test F971001 - Isothermal contour plots, est. temperatures below floor @ 200 s post-ignition.

A threshold of 600°C was used as an indicator of the presence of flame. Thus the test data indicates that flame-spread into the passenger compartment progressed simultaneously along three pathways. These pathways included crash-induced seam openings between the rear floor pan panel and left rear inner quarter panel, a gap between the back of the driver's door and door frame that was created by damage to the test vehicle sustained during the crash test, and a drain hole in the floor panel. Flame-spread along these pathways appeared to be a consequence of the elongated shape and location of the gasoline pool under the test vehicle, which resulted in these three areas being exposed to flames during this test.

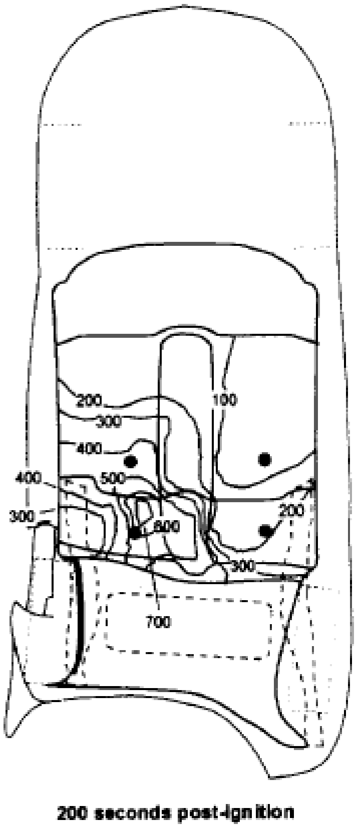

Figure 5: Fire Test F971001 - Isothermal contours plots of est. temperatures below floor panel at 200 s post-ignition

2.4.4 Fire Test F971003: 1997 Chevrolet Camaro – Front End Collision & Engine Fire[12]

Another 1997 Chevrolet Camaro was crash-tested by being towed into a fixed steel pole. No fire evidence was observed during or after this crash test. An artificial means of starting a fire in the engine compartment of the test vehicle was used in the fire test - a propane torch was installed in the engine compartment of the test vehicle so that flames from the torch impinged on the upper and lower cases of the HVAC module just forward of the dash panel. Flames spread laterally and forward in the engine compartment, and appear to have entered the passenger compartment through the HVAC module and through the windshield. There was flame-spread observed to fluids beneath the vehicle. Flame temperatures were recorded in the HVAC module rearward of the dash panel by 11 minutes post-ignition. A section of the forward edge on the right side of the instrument panel upper trim panel was burning by 5 minutes post-ignition. A section of the

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[12] Evaluation of a Motor Vehicle Fire Initiation and Propagation Part 7: Propagation of an Engine Compartment Fire in a 1997 Rear Wheel Drive Passenger Car, J. Santrock et al for GM Corp.

windshield fell inward about 11 minutes post-ignition. Flames were observed under the right side of the instrument panel at 13 minutes post-ignition. Fire suppression started approximately 16 minutes after ignition.

Table 3: Test Summary – '97 Camaro, Front End Collision, Engine Fire

Time after Ignition, Minutes	Event	Max. Temperatures, °C, engine compartment	Max. Temperatures °C, instrument panel
0	Ignition of propane torch	620	
2	Propane torch turned off	500	60
2.25	Flames visible on the right air inlet screen.	575	50
4 - 6	Flames spread laterally in the engine compartment.	230	850
11.1	Sections of the windshield fall onto the instrument panel upper trim panel.	800	765
8 – 9	A measurable pressure difference develops across dash panel.	775	875
13 – 15	Deployed passenger airbag ignites and burns.	810	850
14.92	Flames emerge through defroster outlet in instrument panel upper trim panel.	875	850
15.83	Test ended.	~950	950

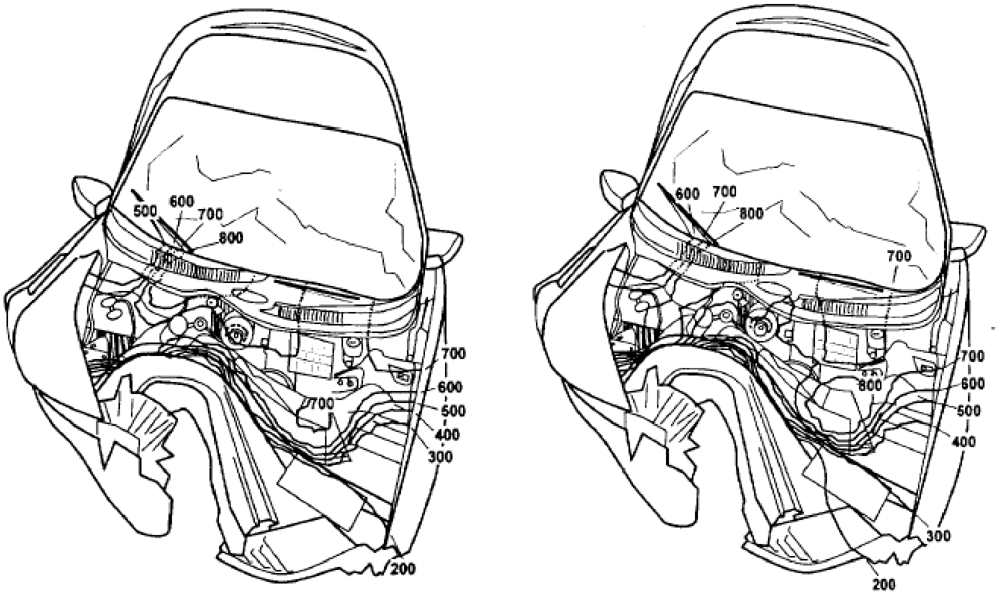
The estimated isothermal contour plots suggest that flames spread laterally at the rear of the engine compartment along the air inlet screen and forward from the area where the propane torch was located between 4 and 8 minutes post-ignition. The video record showed that flames emerged from the forward edge of the left upper dash extension panel under the dislodged battery top ~ 8 minutes post-ignition. The isothermal contour plots show temperatures were greater than 600°C in this area at 10 minutes post-ignition, suggesting that flames spread to the left air inlet screen above the dislodged battery top, between 9 and 10 minutes post-ignition.

Flames spread laterally and forward in the right and left sides of the engine compartment between 10 and 16 minutes post-ignition, laterally to the right upper side panel and to the left upper side panel in the rear of the engine compartment, and forward on the right side of the compartment to the upper radiator support cross-member and to the engine air cleaner housing in the right side of the engine compartment.

The inner edge of the right front fender, which was broken during the crash test, ignited between 6 and 8 minutes post-ignition. The right front wheelhouse panel liner' ignited between 10 and 11 minutes post-ignition. Burning pieces of the right front fender fell off of the test vehicle and onto the test surface beginning at about 13 minutes post-ignition**.** The estimated isothermal contour plots and the video records indicate that flames did not spread forward of the deformed hood when the test was ended at about 16 minutes post-ignition.

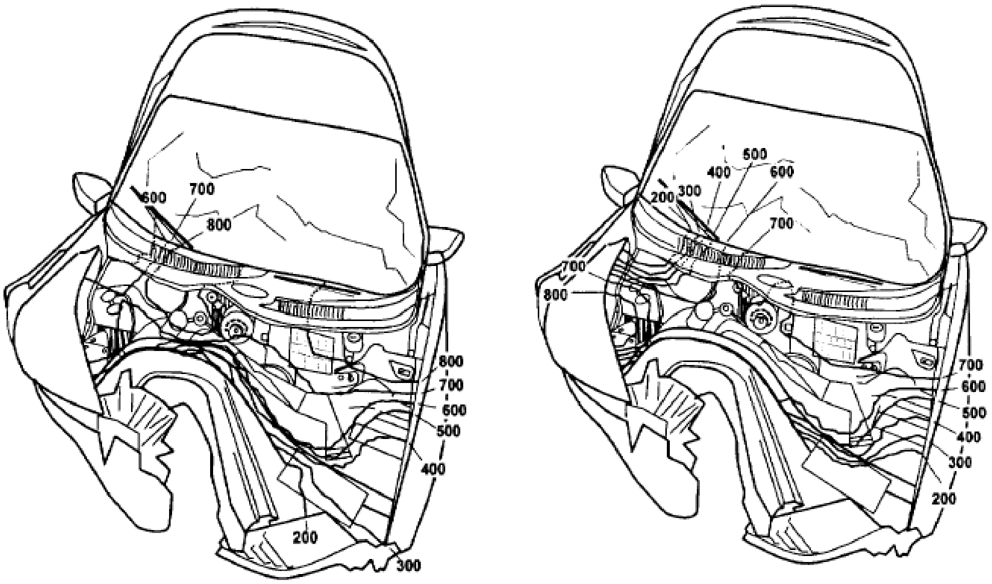
Pieces of burning material started to fall into the mixture of petroleum oils, brake fluid, and engine coolant pooled under the engine compartment at about 8 minutes post-ignition. Some of this burning material self-extinguished shortly after falling into this fluid pool under the engine compartment. Other pieces continued to burn until the test was ended and the fire was extinguished. It could not be determined whether the fluid mixture ignited in the area around the pieces of plastic that continued to burn. At the time this test was ended, flames had not spread across the surface of the pooled fluids away from the burning material that fell from the vehicle.

The pattern of fire damage observed during inspection of the test vehicle after this test suggested that flame-spread into the passenger compartment progressed along two pathways simultaneously. These pathways include the windshield and the HVAC module in the dash panel, both of which were broken in the crash test.



13 minutes post-ignition

14 minutes post-ignition



15 minutes post-ignition

16 minutes post-ignition

Figure 6: Fire Test F971003 - Isothermal contour plots of est. temps in upper engine compartment.

2.4.5 Fire Test 980609: 1998 Ford Explorer – Crash Test Rear & Gasoline Pool Fire[13]

This fire test was conducted on June 9, 1998 with a 1998 Ford Explorer. In the crash test, this vehicle was stationary and was struck in the left rear (driver‘s side) by a moving barrier. The fuel system of the test vehicle did not leak at any time during the crash, but fluid was observed leaking from the filler tube of the test vehicle during a static roll test performed after the crash test. No evidence of fire was observed during or after this crash test. An artificial method of creating an underbody gasoline pool was used with gasoline pumped continuously from an external reservoir onto the ground under the rear of the test vehicle. The outlet of the artificial gasoline supply tube was near the rear inboard corner of the fuel tank in the test vehicle. The gasoline was ignited with a propane torch and allowed to burn until flames were observed spreading across the headlining panel in the test vehicle. Flames entered the passenger compartment through the window-opening in the left quarter panel, a seam opening between the rear compartment floor panel and the quarter panel behind the left rear wheelhouse, a seam opening between the rear compartment floor panel and the quarter panel in the right rear corner of the test vehicle, and a gap between the bottom of the rear lift gate and lift gate sill on the right side of the test vehicle. Fire suppression began at approximately 170 seconds after the gasoline was ignited.

Table 4: Test Summary – ’98 Ford Explorer, Rear End Collision, Gasoline Pool Fire

Time after Ignition, Seconds	Event	Max. Temps, °C, crash-induced opening*	Max. Temps, °C, left quarter trim panel
-29	Start of gasoline flow		
0	Ignition	Amb.	Amb.
10 – 15	Flames entered left wheel house	560	50
10 - 20	Flames entered right wheel house.	610	~75
30 - 60	Right rear tire started to burn	450	100
90 - 100	Edge of left interior quarter trim panel started to burn.	500	150
120	Spare tire blew out.	550	250
120 – 125	Flames enter rear compartment through seam opening in rear left corner of the test vehicle. Temperature at the carpet surface at the rear of the vehicle spike at ~200 °C, then drop back to <100 °C..	560	650
150 – 160	Fire plume started to spread along rear section of headlining panel.	700	660
157	Rear left tire blew out.	700	620

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[13] Evaluation of Motor Vehicle Fire and Propagation, Part 9: Propagation of a Rear-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle, J. Santrock et al, GM Corp.

Time after Ignition, Seconds	Event	Max. Temps, °C, crash-induced opening*	Max. Temps, °C, left quarter trim panel
170	Fire suppression began.	660	660

*** Crash-induced seam opening between the rear compartment floor panel and the left rear wheelhouse panel.**

The distribution of flames on the test vehicle underbody was affected by the shape, dimensions, and location of the gasoline pool on the cement board relative to the test vehicle, the distance from the cement board (a layer of fiberglass-reinforced cement construction board was placed on bottom of the fluid containment pan) to the vehicle underbody, and the shape of the test vehicle underbody.

Flames extended upward during the first few seconds after ignition, contacting the rear axle, spare tire, exhaust pipe and floor pan to the right and left of the spare tire, and vapour recovery canister and floor pan to the left of the spare tire. Flames spread laterally outward as they encountered these objects on the underbody of the test vehicle. Flame height increased uniformly over the next 120 seconds. Flames entered the left rear wheelhouse between 5 and 10 seconds post-ignition, and started to emerge sporadically from the top of the wheelhouse between 10 and 15 seconds post-ignition. Flames entered the right rear wheelhouse between 10 and 15 seconds post-ignition, and started to emerge sporadically from the top of the wheelhouse between 20 and 25 seconds post-ignition. Flames started to emerge sporadically behind the rear bumper by 5 seconds post-ignition.

The height of the fire plume emerging from the rear left wheelhouse was about 190 cm at 119 seconds post-ignition, and the spare tire blew out at about 120 seconds post-ignition, causing a transient increase in flame volume under, to the sides, and to the rear of the test vehicle, at which point the height of the fire plume emerging from the rear left wheelhouse decreased to ~ 165 cm. Inspection of the test vehicle after this fire test revealed that the side-wall of the spare tire facing downward was charred and contained a hole where it was pushed against the rear axle differential housing. The location and orientation of the hole indicated that air venting from the tire was directed downward onto the fluid containment pan and outward radially from under the rear of the test vehicle. The resulting transient increase in airflow over the surface of the gasoline pool had two effects: it increased ventilation under the test vehicle and it distributed a mixture of gasoline aerosol and vapour outward in the direction of airflow. These combined effects resulted in the transient increase in flame volume at 120 seconds post-ignition. The height of the fire plume emerging from the rear left wheelhouse decreased to about 140 cm at 125 seconds post-ignition and remained approximately constant until 157 seconds post-ignition. The rear right tire blew out at approximately 157 seconds post-ignition and a video still from one of the cameras shows that the inner side-wall and sections of the tread of the rear right tire burning at 50 seconds post ignition.

The approximate distribution of flames under the test vehicle was indicated by isothermal contours with $t \geq 600°C$. This analysis indicates that flames were present below an area of the floor pan in the drive train tunnel just forward of the differential housing starting at about at about 50 seconds post-ignition. The area where estimated temperatures were greater than 600°C did not change substantially for the next 100 seconds. Estimated temperatures below the floor pan increased between 167 and 170 seconds post-ignition, which was coincident with the timing of the rear right tire blowing out. Temperatures > 600°C were recorded in the rear left wheelhouse sporadically starting at about 25 seconds post-ignition, and continuously from about 75 seconds post-ignition until the end of this test. Isothermal contours were not estimated for the rear right wheelhouse because no thermocouples were located in the rear right wheelhouse.

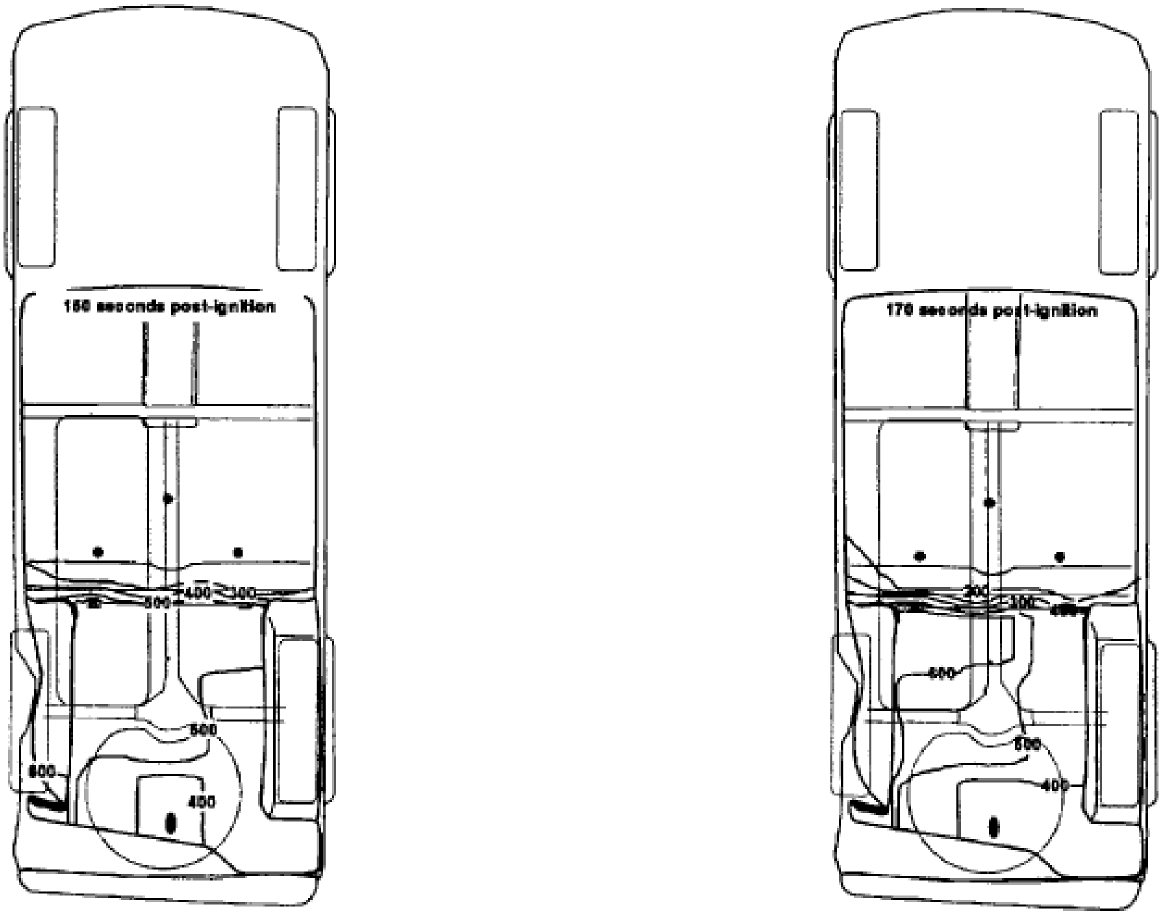

Figure 7: Fire Test F980609 - Isothermal contour plots, est temps below floor at 150, 170 s post-ignition

Flame spread into the passenger compartment was characterized by the data as progressing along a number of pathways simultaneously. The forward vertical and lower horizontal edges of the left quarter trim panel around the left quarter glass opening were ignited by the fire plume rising along the exterior of the left quarter panel. Flames spread into the rear compartment through a crash-induced seam opening at the rear of the left rear wheelhouse. Flames spread into the area behind the right quarter trim panel through a crash-induced seam opening at the rear right comer of the floor pan. Conduction through the floor pan resulted in ignition of the lower edge of the right rear quarter trim panel at the base of the rear right wheelhouse. Flames spread into the rear compartment under the bottom right edge of the lift gate.

2.4.6 Fire Test 980611: 1998 Ford Explorer – Front End Crash & Gasoline Pool Fire[14]

A 1998 Ford Explorer, stationary, was struck in the left front (driver's side) by a moving barrier. The fuel tank in the test vehicle was punctured by the drive shaft (specifically by the universal joint connecting the rear propulsion shaft to the transfer case) during the crash test. Fluid was observed leaking from the fuel tank onto the ground under the test vehicle after impact, but no evidence of fire was observed during or after the crash. An artificial method of creating an underbody gasoline pool was used in this test. Gasoline was pumped continuously during this test from an external reservoir onto the ground under the test vehicle to simulate the leaking fluid that was observed after the crash test. The gasoline was ignited with a propane torch and allowed to burn until flames were observed spreading across the headlining panel of the vehicle. Flames entered the passenger compartment through drain holes and electrical pass-through openings in the floor panel. Fire suppression began at approximately 250 seconds after the gasoline was ignited.

Table 5: Test Summary – '98 Ford Explorer, Front End Collision, Gasoline Pool Fire

Time after Ignition, Seconds	Event	Max. Temp, °C, electrical pass-through.	Max. Temps °C, driver's side seat cushion.
-28	Start of gasoline flow		
0	Gasoline under vehicle ignited.	Amb.	Amb.
10	Flames enter passenger compartment through electrical pass-through opening in floor panel under left front seat.	600	Amb.
75	Flames burn through grommet in second electrical pass-through opening in floor panel under left front seat.	790	175
130	Flames burn through floor carpet above second electrical pass-through opening in floor panel under left front seat.	775	400
205	Flames burn through floor carpet above second electrical pass-through opening in floor panel under left front seat.	760	525
235 - 250	Temperature recorded by thermocouples below left front seat cushion rapidly increase to > 800°C	775	820

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[14] Evaluation of Motor Vehicle Fire and Propagation, Part 10: Propagation of a Mid-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle, J. Santrock et al, GM Corp.

Time after Ignition, Seconds	Event	Max. Temp, °C, electrical pass-through.	Max. Temps °C, driver's side seat cushion.
	as flames burn through it.		
250 -260	End of test, beginning of fire suppression	750	750

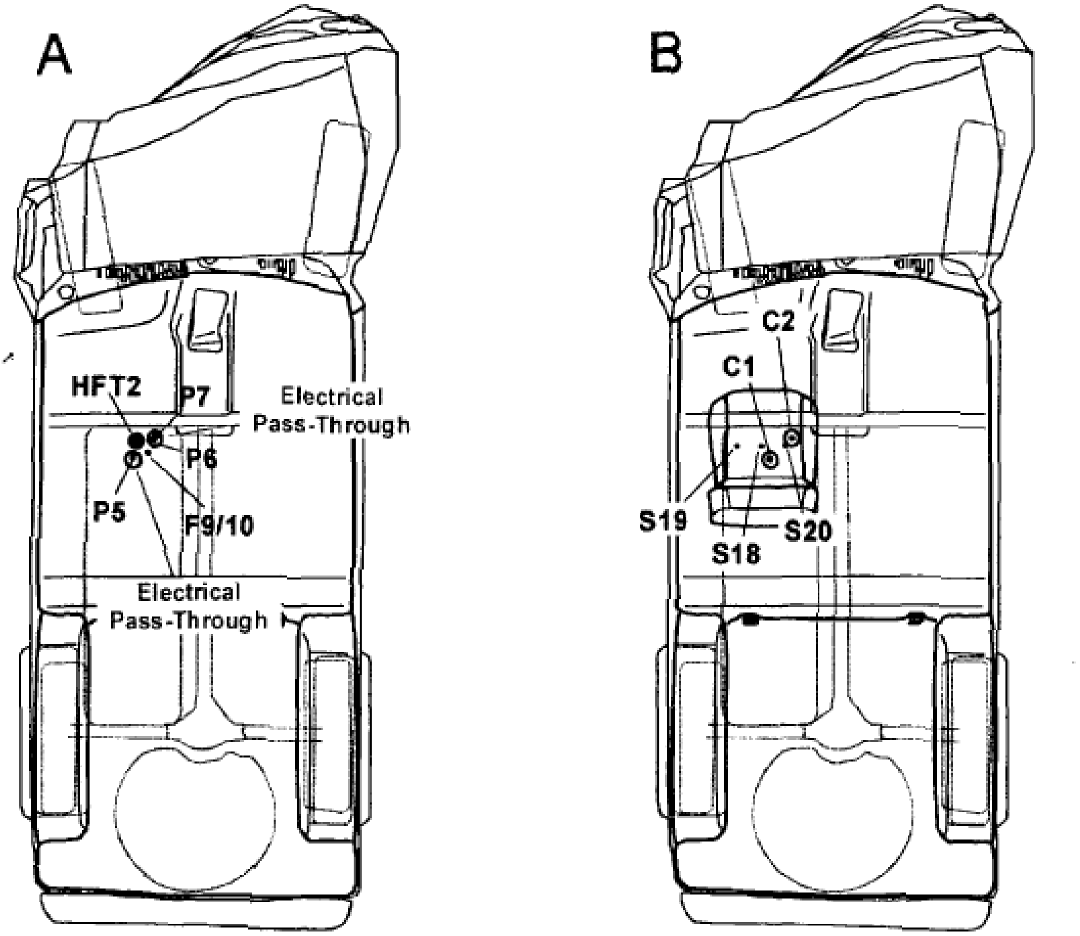

Figure 8: Diagrams of locations of thermocouples and electrical pass-through.

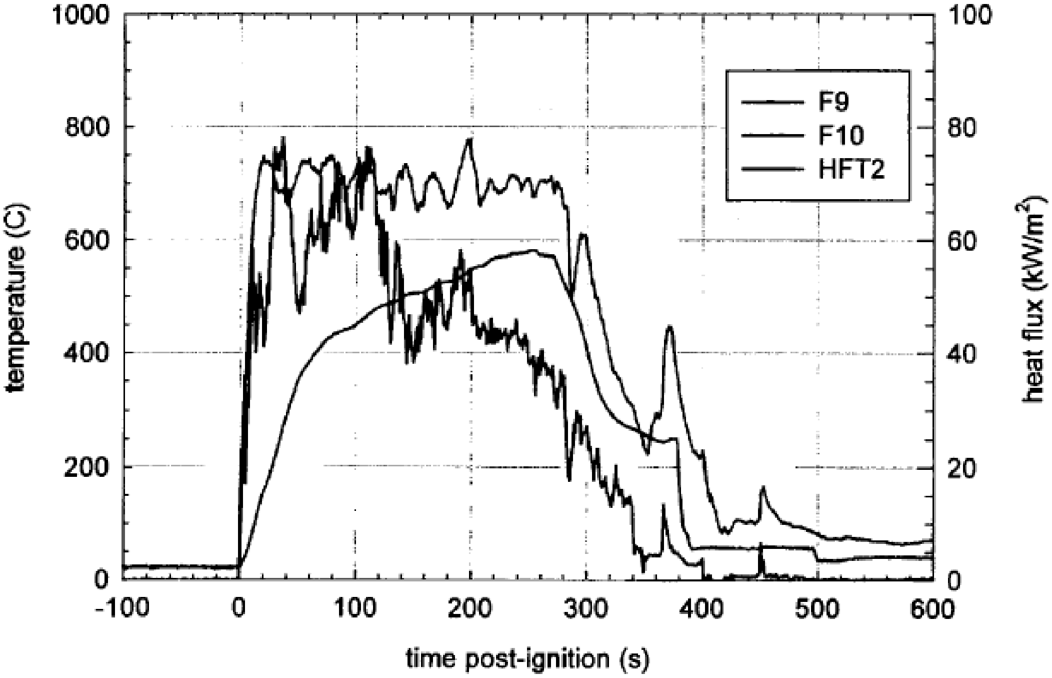

Figure 9: Fire Test F980611 - Temperature Plots for thermocouples on floor pan under driver's seat.

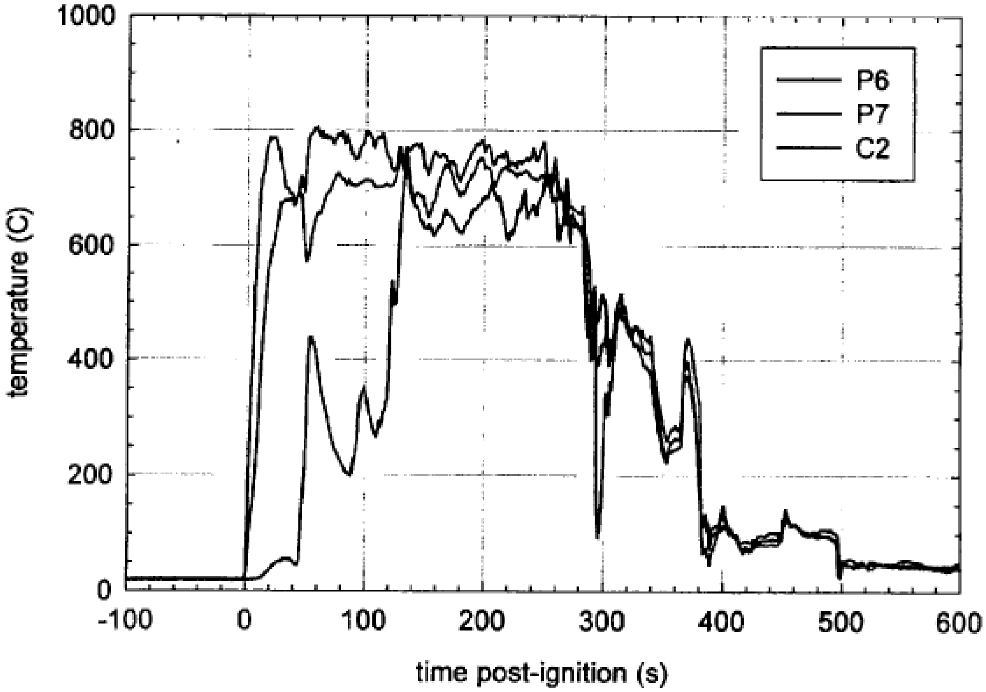

Figure 10: Fire Test F980611 - Temperature Plots for thermocouples in the electrical pass-through (P6, P7) and floor carpet (C2).

Temperature data from thermocouples located below the left front seat cushion suggests that brackets for the power seat mechanism and support structure under the seat affected the distribution of flames on the pad in the seat cushion. Maximum temperatures recorded at this location were just over 800°C at about 240 seconds post-ignition.

Flame spread into the passenger compartment through drain holes in the floor panel and by conduction through the floor panel. The floor carpet over the drive train tunnel under the rear of the center console was burned and charred, consumed by fire. A drain hole opening is visible in the exposed section of floor panel. An area of the floor carpet that was under the rear bench seat was burned and charred, also consumed by fire, and a drain hole opening is visible at the edge of the carpet. When the floor carpet was removed after this test, a number of other drain hole openings were observed in the floor panel. Grommets were in place in all of these drain hole openings before this fire test, and appeared to have been partially or completely consumed by fire. The maximum temperature of the floor panel was between 530 and 535°C recorded between 280 and 310 seconds post-ignition, and the maximum temperature at the roof trim was greater than 600°C by 253 seconds post-ignition.

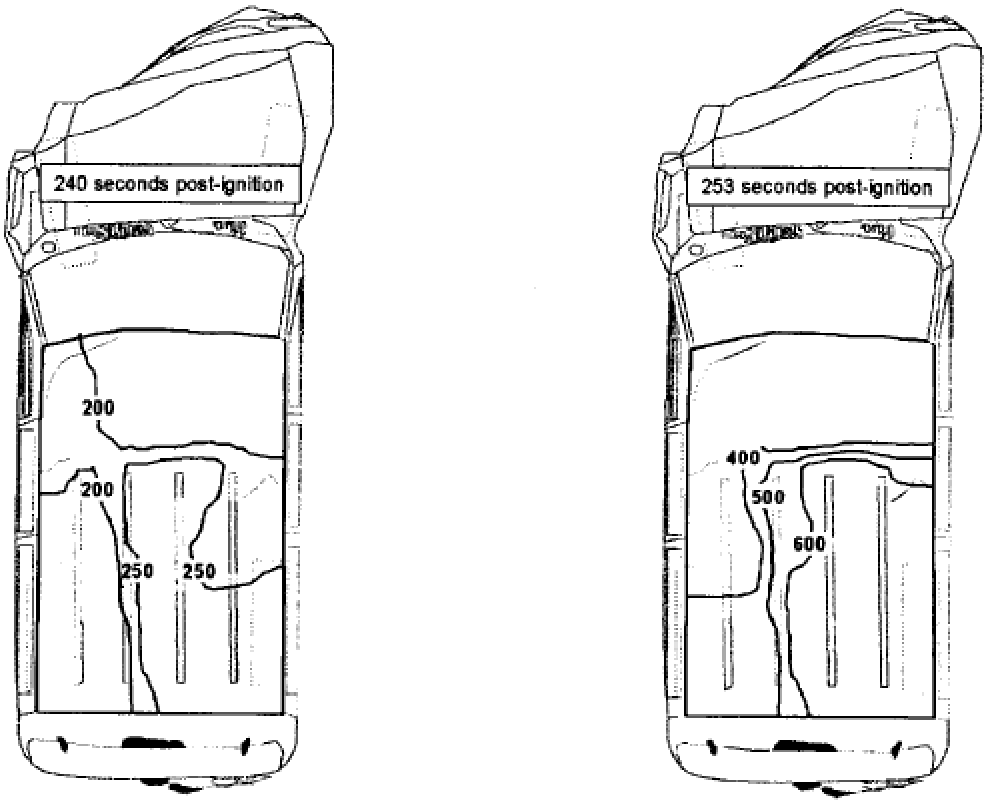

Figure 11: Fire Test F980611 - Isolthermal contour plots of est. temps along lower surface of roof trim panel of rear compartment at 240, 253 s post-ignition.

2.4.7 Fire Test F99030A: 1998 Honda Accord – Rear End Crash, Gasoline Pool Fire[15]

A stationary 1998 Honda Accord was struck in the left rear (driver's side) by a moving barrier. The fuel tank in the test vehicle was compromised during this crash test and fluid was observed leaking from the fuel tank after the crash test, but no evidence of fire was observed during or after the crash test. An artificial method of creating an underbody gasoline pool was used in which gasoline was pumped continuously from an external reservoir onto the top of the fuel tank. The outlet of the artificial gasoline supply tube was in the area of the fuel pump assembly and the tear in the fuel tank. Liquid gasoline was fed at ~400 cm^3/min throughout the test, flowing from several points on the rear cross-member of the rear suspension sub-frame onto the floor under the rear of the test vehicle, and ignited with a propane torch. Flames entered the passenger compartment through crash-induced seam openings around the left and right wheelhouses. The test was stopped when flames were observed on the headlining panel in the test vehicle. Fire suppression began at approximately 155 seconds after the gasoline was ignited.

Table 6: Test Summary – '98 Honda Accord, Rear End Crash, Gasoline Pool Fire

Time after Ignition, Seconds	Event	Max. Temps, °C, crash-induced seam opening, left rear, in passenger compartment.	Max. Temps, °C, crash-induced seam opening, left rear, in trunk.	Behind rear seat back, inside trunk, °C.
-35	Start of gasoline flow ~400 cm^3/min maintained until ~140 second post-ignition.			
0	Gasoline beneath vehicle ignited.	Amb.	Amb.	Amb.
15	Flames in the area between the left side of the floor panel in the trunk and the left rear tire.	240	450	Amb.
75	Flames started to vent from the right rear wheelhouse.	760	850	40
75 – 90	Flames began to contact the rear surface of the left side of the rear seat back and ignite the foam pads in the rear seat back and rear seat bolsters.	815	845	~50
120	Temperature measured at the headliner panel increases rapidly to >800°C as flames	860	830	~60

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[15] Evaluation of Motor Vehicle Fire Initiation and Propagation Part 12: Propagation of an Underbody Gasoline Pool Fire in a 1998 Front-Wheel Drive Passenger Vehicle, J. Santrock et al, GM Corp.

Time after Ignition, Seconds	Event	Max. Temps, °C, crash-induced seam opening, left rear, in passenger compartment.	Max. Temps, °C, crash-induced seam opening, left rear, in trunk.	Behind rear seat back, inside trunk, °C.
	observed on the lower surface of the roof trim panel in the rear left quadrant of the passenger compartment.			
140 – 145	Gasoline flow stopped.	860	875	100
155	End of test, beginning of fire suppression.	660	575	350

Using infrared camera footage, flame diameter at the cement board surface was estimated at ~82 cm at 1 seconds post-ignition, decreasing to about 35 cm by 60 seconds post-ignition. The distribution of flames on the underbody was affected by the location of the gasoline pool on the cement board relative to the test vehicle, the distance from the cement board to the vehicle underbody, and the shape of the test vehicle underbody. At the time of ignition, flames extended laterally from about the center of the test vehicle to the right rear wheel and longitudinally from about the rear cross-member of the rear suspension sub-frame rearward to the spare tire well in trunk. Gasoline vapour, accumulated under the rear of the test vehicle, was consumed within a few seconds after ignition.

The shape and distance between the vehicle underbody and the cement-board surface affected flame distribution. Liquid gasoline flowing off of the rear cross-member pooled under the rear section of the rear suspension sub-frame and the spare tire well in the trunk. Before ignition, the gasoline pool appeared to be radially symmetrical with a diameter of 18 - 22 cm, and the gasoline pool appeared to be was centered on the longitudinal centerline of the test vehicle. Approximate vertical distances between the cement-board surface to the underbody were as follows: 9 - 13 cm at the rear cross-member of the rear suspension sub-frame and 10 - 12 cm at the spare tire well in the trunk.

By 10 seconds post-ignition, flame diameter just above the cement board surface was ~ 60 cm, and defined by the diameter of the gasoline pool. Flames spread laterally outward as they encountered objects on the underbody of the test vehicle, but did not contact either wheel at this time. By 15 seconds post-ignition, flames on the underbody of the test vehicle had started to extend beyond the perimeter of the gasoline pool, and started to emerge sporadically from crash-induced seam openings around the left rear wheelhouse between 10 and 15 seconds post-ignition just inboard of the top of the left rear tire. The volume of flames in this area increased throughout this test. Flames had emerged from the right rear wheelhouse by 75 seconds post-ignition and from the left rear wheelhouse by 90 seconds post-ignition. The volume of flames extending rearward along the spare tire well increased from the time of ignition through about 138 seconds post-ignition.

The diameter of flames at the cement board surface and the volume of flames impinging on the underbody of the test vehicle decreased after the flow of gasoline from the tubing at the top of the fuel tank was discontinued.

The decrease in the estimated flame diameter at the surface of the cement board from ~ 82 to 36 cm between the time of ignition and 60 seconds post-ignition was attributed to an increase in the burning rate of liquid gasoline flowing downward on underbody components in the test vehicle. After ignition, liquid gasoline in contact with the fuel tank and rear suspension sub-frame would have been heated by the fire, increasing the vaporization rate from liquid gasoline on underbody components in the test vehicle. An increased vaporization rate would have resulted in a decrease in the volume flow rate of liquid gasoline onto the cement board surface and, consistent with the decrease in the diameter of flames on the cement board surface observed, a decrease in the size of the gasoline pool under the test vehicle as this test progressed. Video stills indicated an increased vaporization rate from liquid gasoline in contact with underbody components also would have resulted in an increase in the volume of flames in spaces along the test vehicle underbody as this test progressed.

From 60 to 140 seconds post-ignition, the flame diameter at the cement board surface decreased from ~ 36 to 31 cm. The distribution of flames on the test vehicle underbody did not appear to increase appreciably during this time. These observations suggest that the vaporization rate from liquid gasoline in contact with components on the vehicle underbody and flow rate of liquid gasoline onto the cement board surface were approximately constant during this time interval.

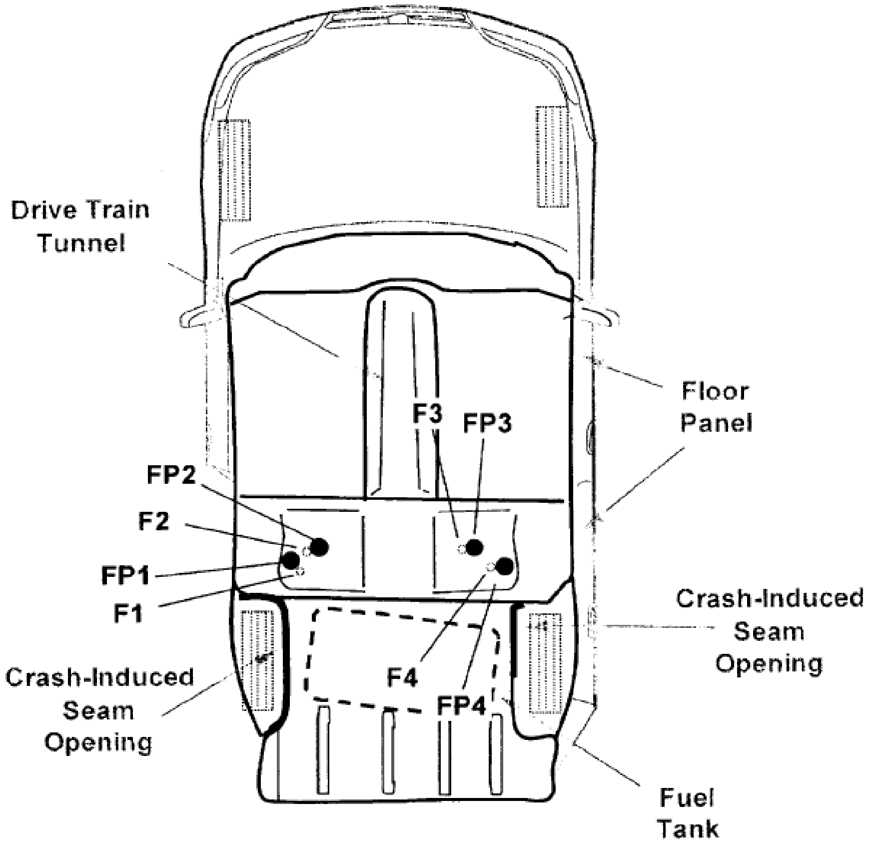

Figure 12: Fire Test F99030A - Location of crash induced seam openings.

Flames spread into the passenger compartment through the crash-induced seam openings around the left and right wheelhouses simultaneously. Flames entering the passenger compartment through a crash-induced seam opening between the left rear wheelhouse panel and left rear inner quarter panel ignited the left side of the rear seat back, the left rear seat belt, and the left side of the rear shelf trim panel. Flames entering the trunk through a crash-induced seam opening between the left rear wheelhouse and floor panel ignited the trunk floor panel, the interior trim panel on the left side of the trunk, the left speaker in the rear shelf, and the grille over the speaker. Flames entering the passenger compartment through crash-induced seam openings between the right wheelhouse and the right inner quarter panel ignited the right rear seat back bolster and the interior trim panel on the right rear pillar.

Flames were visible in the area between the left side of the floor panel in the trunk and the inboard side of the left rear tire by 15 seconds post-ignition. The height of this fire plume increased between 15 and 60 seconds post-ignition. Infrared thermograms show that, although this fire plume did not contact the trunk lid directly during this time, it did heat the left rear area of the deformed trunk lid. Flames had begun to vent from the right rear wheelhouse by 75 seconds post-ignition and from the left rear wheelhouse by 90 seconds post-ignition (Fig. 30).

The height of the fire plumes venting from the rear wheelhouses increased until the fire was extinguished starting at about 155 seconds post- ignition.

Flames also began to contact the rear surface of the left side of the rear seat back between 75 and 90 seconds post-ignition. Flames were visible on the lower surface of the roof trim panel through the upper left corner of the rear window opening by 120 seconds post-ignition and venting from the passenger compartment along the rear edge of the roof by153 seconds post-ignition.

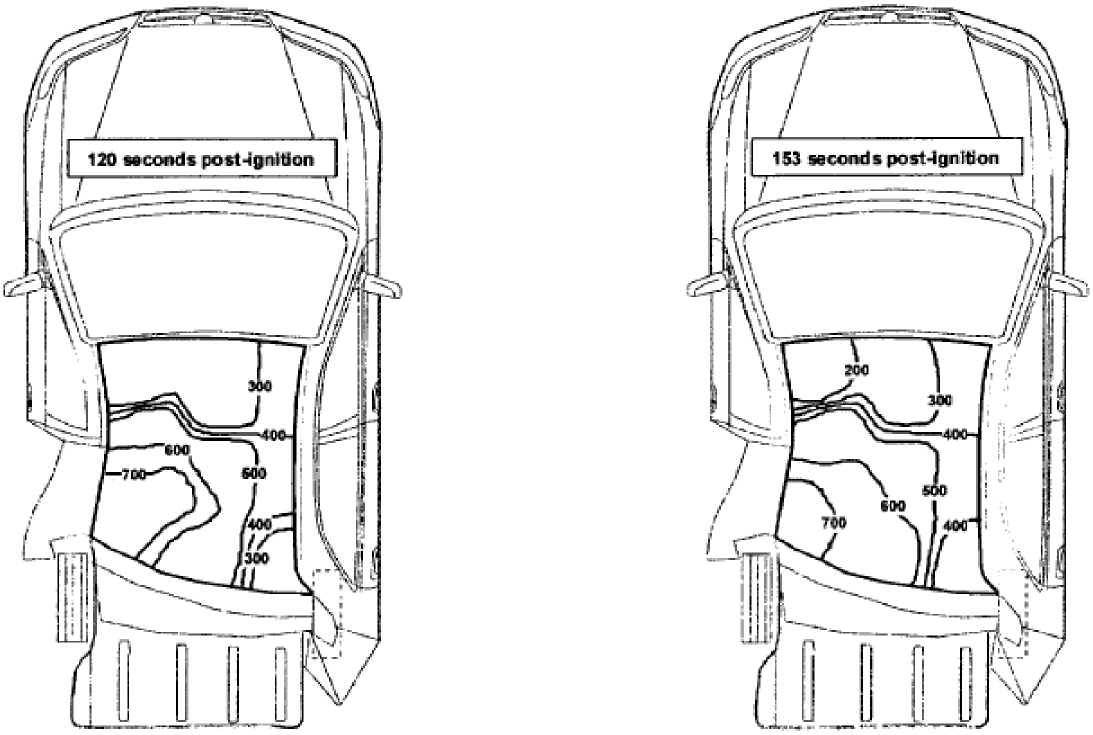

Figure 13: FIre Test F99030A - Isothermal contour plots of est. temps along lower surface of roof trim panel at 120, 153 s post-ignition.

2.4.8 Fire Test 99030B: 1998 Honda Accord – Front End Crash, Engine Fire[16]

A stationary 1998 Honda Accord was struck in the left front corner (driver's side) by a moving barrier. A fire was observed in the windshield fluid reservoir of the test vehicle after this crash test. This fire was caused by:

1) Auto-ignition of power steering fluid on the exhaust manifold and,
2) Ignition of methanol vapour in the windshield washer fluid reservoir after burning power steering fluid aerosol entered the reservoir.

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[16] Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 13: Propagation of an Engine Compartment Fire in a 1998 Front-Wheel Drive Passenger Vehicle, Jeffrey Santrock et al, General Motors Corporation

The fire test ignition protocol simulated this ignition scenario, where holes were cut in the front and left side of the replacement windshield washer fluid reservoir to simulate damage to the original reservoir that occurred in the crash test, a power steering fluid aerosol was sprayed from a hand-held oil mister through a flame of a propane torch toward openings in the windshield washer fluid, and ignited methanol vapour in the windshield washer fluid reservoir. The windshield washer fluid reservoir started to bum between 4 and 6 minutes after ignition of the methanol vapour. Flames spread to the left front wheelhouse panel, the left front headlamp assembly, and the left front tire between 10 and 20 minutes post-ignition, and into the engine compartment of the test vehicle between 21 and 22 minutes post-ignition. Flames spread into the passenger compartment through the windshield and through pass-through openings in the dash panel between 22 and 27 minutes post-ignition. This test was ended at ~27 minutes post-ignition.

Table 7: Test Summary – '98 Honda Accord, Front End Crash, Engine Fire

Time after Ignition, Minutes*	Event	Max. Temp, °C, windshield washer reservoir	Max. Temperatures °C, windshield
-0.25	Burning power steering fluid aerosol was sprayed toward the windshield washer fluid reservoir in the test vehicle.		
0	Ignition of methanol vapour in the windshield fluid reservoir was confirmed by observing temperature increase recorded from thermocouples in the windshield fluid reservoir.	Amb.	Amb.
4 - 6	The windshield washer fluid reservoir started to burn.	375	Amb.
11 – 12	Flames spread from the windshield washer fluid reservoir to the left front inner fender panel.	225	~50
15 – 16	Flames spread from the windshield washer fluid reservoir and the left front inner fender panel to the left front tire.	130	~65
21 - 22	Flames spread across the hood insulator into the engine compartment.	550	650
22 – 24	Flames started to vent from the engine compartment along the rear edge of the hood and impinge onto the windshield.	775	800

Time after Ignition, Minutes*	Event	Max. Temp, °C, windshield washer reservoir	Max. Temperatures °C, windshield
25 - 26	Pieces of burning windshield started to fall inward into the passenger compartment.	~820	900
26 - 27	The left front seat cushion, center console, and steering wheel were ignited by pieces of burning windshield.	750	675
27	Beginning of fire suppression.	480	~550

* Time after ignition of methanol vapour in the windshield washer fluid reservoir by a burning power steering fluid aerosol.

As flames were observed spreading through the engine compartment, temperatures were slightly lower than the 600°C threshold used to indicate the presence of flames in previous tests, despite visual evidence of flame.

Flames spread into the passenger compartment through the windshield and through pass-through openings in the left side of the dash panel. Flames entering the passenger compartment through pass-through openings in the dash panel ignited components in the left side of the instrument panel. Flame-spread through the windshield progressed by (1) flame-spread rearward along the top of the instrument panel and (2) ignition of interior components by pieces of windshield with the inner layer burning and falling into the passenger compartment.

The lower left corner of the windshield in the test vehicle was exposed to heated gases from the fire starting at about 7 minutes post-ignition. A section of the windshield in front of the left front seat was exposed to flames from the burning HVAC air intake cowl starting at about 22 minutes post-ignition. A hole developed in the lower left side of the windshield in front of the steering wheel between 22 and 24 minutes post-ignition. Flames from the engine compartment entered the passenger compartment through this hole and spread upward along the interior surface of the windshield, igniting the windshield inner-layer around this hole and in an area where pieces of glass were dislodged from the windshield and the inner-layer was exposed. Pieces of windshield with the inner-layer burning started to fall into the passenger compartment between 23 and 23 minutes post-ignition, and a section of the windshield sagged onto the left side of the instrument panel between 24 and 25 minutes post-ignition.

Temperature plots indicate a section of the forward edge of the left side of the instrument panel ignited between 23 and 23½ minutes post-ignition, where holes developed along the lower edge of the windshield. This suggests that flames venting from the engine compartment along the rear edge *of* the left side of the deformed hood ignited the top of the instrument panel as sections of the windshield fell onto the instrument panel. Flames spread to the right across the front of the instrument panel between 23½ and 25 minutes post-ignition and, coincident with the timing of holes developing in the center of the windshield, rearward on the center of the instrument panel between 25 and 27 minutes post-ignition. Flames spread to the right on the forward section of the instrument panel between 25½ and 26 minutes post-ignition and ignited the deployed passenger side air bag.

Inspection of the test vehicle after this test showed that fire damage to the top of the instrument panel extended from the left A-pillar to the deployed passenger airbag. The areas around the side window defroster vents were not burned. The area that showed evidence of fire damage after this test was greater that the area of the instrument panel where estimated temperatures were > 600°C.

Pieces of windshield in which the windshield inner-layer had ignited and was burning fell into the passenger compartment and ignited the deployed passenger side air bag, the floor carpet in front of the right front seat, the front seat cushions, the steering wheel cover, and the center console.

The dash panel and hinge pillar panels contained a number of pass-through and other openings with elastomer and polymer closures. Some of these openings were in an area of the test vehicle that was inside the rear of the left front fender, and would have been exposed to a portion of the fire plume from the burning windshield washer fluid reservoir, left front tire, and left front inner fender panel that was channelled rearward by the deformed left outer fender panel. Two of the pass-through closures in the upper part of the left hinge pillar had burned through during this test. An electrical pass-through closure in the upper left of the dash panel was charred, but did not appear to have burned through.

Consistent with the visual inspection of the test vehicle after this test, temperature data recorded from thermocouples on the interior surfaces of these pass-through closures indicate that flames burned through the upper closure in the left hinge pillar at about 25 minutes post-ignition and through the lower closure in the left hinge pillar at about 25½ minutes post-ignition. These temperature data indicated that flames did not burn through the electrical pass-through closure in the upper left part of the dash panel.

The pattern of heat and fire damage to the roof trim panel, estimated temperature profiles along the lower surface of the headlining panel, and data recorded from the aspirated thermocouple assembly located in the passenger compartment indicate that a burning upper layer did not develop in the passenger compartment during this test. Except for a section of the fabric covering on the roof trim panel and a section of the fabric covering on the left sun visor, the roof trim panel showed no evidence of being exposed to heat and flames during this test.

Temperature data recorded by thermocouples on the lower surface of the roof trim panel indicate that heated gases started to accumulate along the roof of the test vehicle between 22½ and 23 minutes post-ignition. Sample estimated temperature isothermal contours are provided in the figure below.

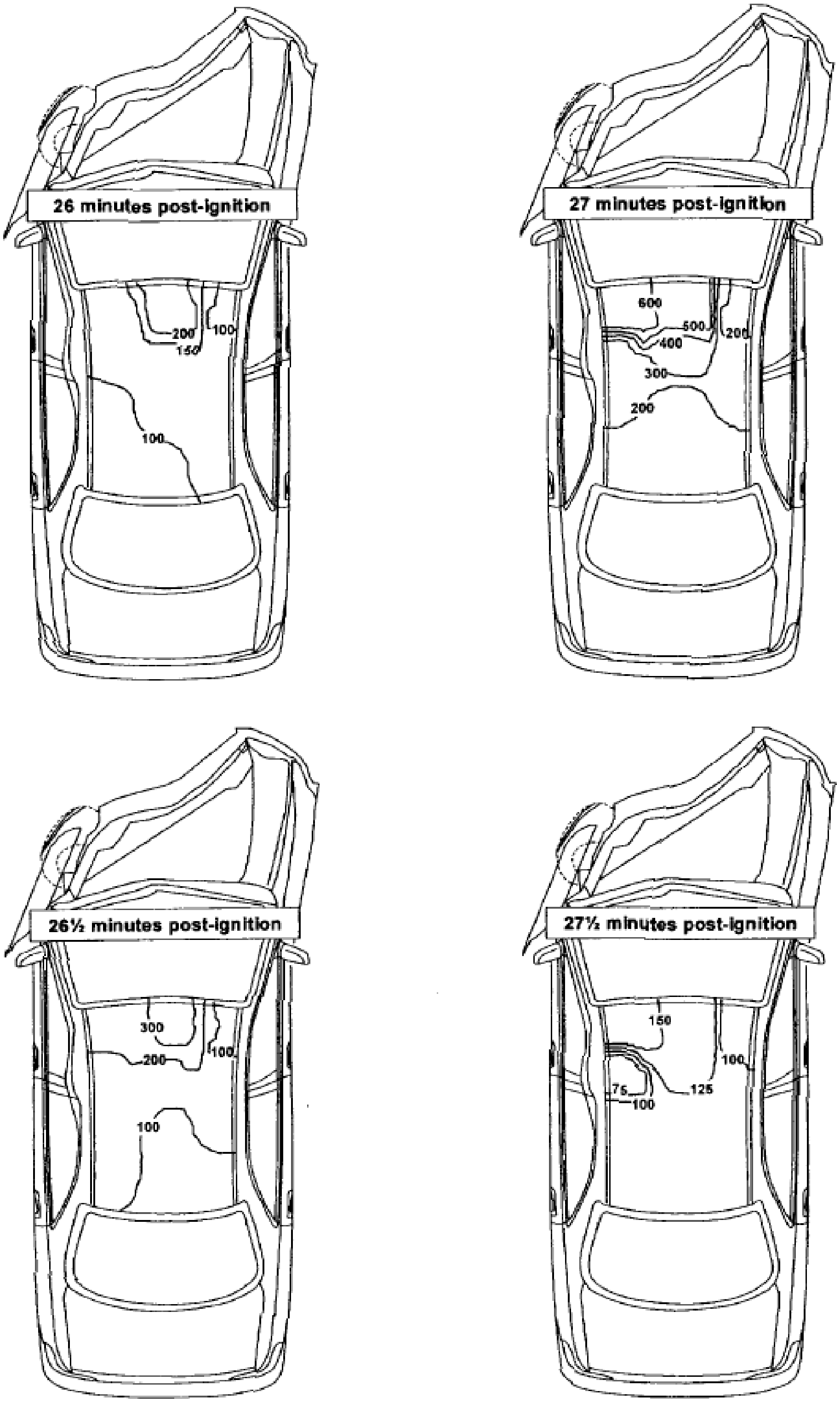

Figure 14: Fire Test F99030B - Isothermal contour plots of test. temps on the roof trim panel at 26-27 minutes post-ignition.

2.4.9 Conclusions to be Drawn from the GM Tests

Propagation pathways depended on several factors:

- Damage done to the vehicle during a crash.
- Design of the vehicle.
- Location of the initial fire.
- Nature of the fire.
- Whether and how the flames contact plastic components inside and outside the vehicle.

In these tests, fire propagation seemed most dependent on where the fire starts. In the gasoline pool fire tests, temperatures exceeded 600°C within the passenger compartment from <1 to 3 minutes. When the fire was started in the engine compartment, it took ~5 to 10 times as long for flames to spread into the passenger compartment, and to reach those temperatures.

Plastic components of the vehicle often contributed fuel to the fire, and in some tests increased intensity of the flame. In the engine fire tests, flames spread to the passenger compartment via the windshield and electrical pass-through's. Flames from gasoline pool fires tended to enter passenger compartment via seams around the wheel house. Fire Test F99030A showed how quickly temperatures can rise in crash-induced seam openings, while Fire Test F99903B showed very little temperature rise in a crash induced seam opening, indicating how sensitive to the particulars of the damage the fire's behaviour can be.

3.0 Statistics, Trends, and Patterns Reported – Gasoline Vehicles

The Fire Analysis and Research Division of the National Fire Protection Association compiled trends and patterns on vehicle accidents, civilian deaths, and property damage in the US, providing statistical data on the cause and effect of motor vehicle fires[17].

Table 8: Highway Vehicle Fires, by Factor Contributing to Ignition. 1999-2002 Fires Reported to U.S. Fire Departments in NFIRS Version 5.0

Factor Contributing to Ignition	Fires	Civilian Deaths	Civilian Injuries	Property Damage
Unclassified or unknown-type mechanical failure, malfunction	24%	2%	10%	21%
Leak or break	13%	6%	15%	11%
Unclassified or unknown-type electrical failure or malfunction	9%	1%	3%	9%
Unspecified short-circuit arc	7%	0%	4%	6%
Backfire	6%	1%	7%	3%
Unclassified factor contributed to ignition	6%	12%	7%	10%
Exposure fire	6%	3%	3%	11%
Short circuit arc from defective or worn insulation	4%	0%	2%	3%
Worn out	4%	0%	2%	2%
Collision, knock down, run over or rollover	3%	57%	13%	8%
Flammable liquid or gas spilled	2%	4%	5%	2%
Heat source too close to combustibles	2%	2%	5%	3%
Abandoned or discarded material	2%	2%	2%	2%

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[17] U.S. VEHICLE FIRE TRENDS AND PATTERNS, Marty Ahrens, Fire Analysis and Research Division, National Fire Protection Association, August 2005, www.nfpa.org.

Factor Contributing to Ignition	Fires	Civilian Deaths	Civilian Injuries	Property Damage
Unclassified or unknown-type misuse of material or product	2%	4%	6%	2%
Unclassified or unknown-type operational deficiency	2%	1%	3%	1%
Short circuit arc from mechanical damage	2%	1%	2%	1%
Arc or spark from operating equipment	1%	1%	1%	1%
Equipment not being operated properly	1%	2%	3%	1%
Installation deficiency	1%	0%	1%	0%
Flammable liquid used to kindle fire	1%	2%	1%	1%

Note: These are national estimates of fires reported to U.S. municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. National estimates are projections. Casualty and loss projections can be heavily influenced by the inclusion or exclusion of one unusually serious fire. More than one factor contributing to ignition could be entered. Property damage figures are not adjusted for inflation. Fires, in which the factor contributing to ignition was undetermined, not reported, or coded as "none" were allocated proportionally among fires with known factor contributing to ignition. Although this field is not required for fires that were coded as intentionally set or attributed to a cause of "other", the share of incidents with unreported data (fires - 17%, deaths - 22%, injuries – 10%, property damage – 27%) or fires with "none" (fires - 28%, deaths - 16%, injuries – 19%, property damage – 27%) generally exceeded those for undetermined (fires - 11%, deaths - 11%, injuries – 10%, property damage – 13%) suggesting that this type of allocation would be most appropriate. Source: NFIRS and NFPA survey.

Table 9: Vehicle Fires, by Factor Contributing to Ignition Grouping. 1999-2002 Fires Reported to U.S. Fire Departments in NFIRS Version 5.0

Factor Contributing to Ignition	Fires	Civilian Deaths	Civilian Injuries	Property Damage
Mechanical failure or malfunction	**48%**	**9%**	**34%**	**37%**
Leak or break	13%	6%	15%	11%
Backfire	6%	1%	7%	3%
Worn out	4%	0%	2%	2%
Unclassified or unknown-type mechanical failure or malfunction	24%	2%	10%	21%
Electrical failure or malfunction	**23%**	**2%**	**12%**	**22%**
Unspecified short-circuit arc	7%	0%	4%	6%

Factor Contributing to Ignition	Fires	Civilian Deaths	Civilian Injuries	Property Damage
Short circuit arc from defective or worn insulation	4%	0%	2%	3%
Short circuit arc from mechanical damage	2%	1%	2%	1%
Arc or spark from operating equipment	1%	1%	1%	1%
Unclassified or unknown-type electrical failure or malfunction	9%	1%	3%	9%
Misuse of material or product	**11%**	**16%**	**25%**	**11%**
Flammable liquid or gas spilled	2%	4%	5%	2%
Heat source too close to combustibles	2%	2%	5%	3%
Abandoned or discarded material	2%	2%	2%	2%
Unclassified or unknown-type misuse of material or product	2%	4%	6%	2%
Flammable liquid used to kindle fire	1%	2%	1%	1%
Cutting or welding too close to combustibles	1%	0%	1%	0%
Improper fuelling technique	1%	1%	3%	0%
Operational deficiency	**7%**	**61%**	**20%**	**13%**
Collision, knock down, run over or roll over	3%	57%	13%	8%
Equipment not being operated properly	1%	2%	3%	1%
Failure to clean	1%	0%	0%	0%
Unclassified or unknown-type operational deficiency	2%	1%	3%	1%
Fire spread or control	**6%**	**5%**	**4%**	**11%**
Exposure fire	6%	3%	3%	11%
Design, manufacturing or	**1%**	**0%**	**1%**	**2%**

Factor Contributing to Ignition	Fires	Civilian Deaths	Civilian Injuries	Property Damage
installation deficiency				
Installation deficiency	1%	0%	1%	0%
Natural condition	**0%**	**1%**	**1%**	**1%**
Unclassified factor contributed	**6%**	**12%**	**7%**	**10%**

Table 10: U.S. Highway Vehicle Fires, by Heat Source 1999-2002 Annual Averages

Heat Source	Fires	Civilian Deaths	Civilian Injuries	Property Damage(in Millions)
Arcing	59,700 (22%)	10 (3%)	160 (12%)	$204 (20%)
Radiated or conducted heat from operating equipment	47,800 (18%)	90 (23%)	230 (18%)	$164 (16%)
Heat from equipment with unclassified or unknown-type power	33,700 (12%)	40 (9%)	160 (12%)	$100 (10%)
Backfire from internal combustion engine	19,300 (7%)	10 (2%)	100 (8%)	$54 (5%)
Spark, ember or flame from operating equipment	17,900 (7%)	50 (14%)	170 (13%)	$59 (6%)
Unclassified or unknown-type hot or smouldering object	17,200 (6%)	30 (8%)	90 (7%)	$49 (5%)
Unclassified heat source	15,900 (6%)	30 (8%)	70 (5%)	$79 (8%)
Heat or spark from friction	10,100 (4%)	40 (11%)	60 (4%)	$51 (5%)
Match	9,900 (4%)	10 (2%)	40 (3%)	$52 (5%)
Heat from other unclassified or unknown-type open flame or smoking material	8,700 (3%)	20 (5%)	30 (3%)	$59 (6%)
Radiated heat from another fire	4,600 (2%)	0 (0%)	0 (0%)	$14 (1%)
Heat from direct flame or convection	3,800 (1%)	10 (1%)	0 (0%)	$27 (3%)

Heat Source	Fires	Civilian Deaths	Civilian Injuries	Property Damage(in Millions)
current				
Cigarette	3,600 (1%)	10 (2%)	50 (3%)	$9 (1%)
Multiple heat sources, including multiple ignitions	3,600 (1%)	30 (7%)	20 (1%)	$23 (2%)
Unclassified heat spread from another fire	2,700 (1%)	0 (1%)	10 (1%)	$13 (1%)
Incendiary device	2,400 (1%)	0 (1%)	10 (1%)	$12 (1%)
Cigarette lighter	1,600 (1%)	10 (2%)	60 (4%)	$6 (1%)
Other known heat source	7,300 (3%)	10 (1.6%)	70 (5%)	$30 (3%)
Total	269,900 (100%)	380 (100%)	1,310 (100%)	$1,005 (100%)

Table 11: U.S. Highway Vehicle Fires, by Area of Fire Origin, 1999-2002 Annual Averages

Area of Fire Origin	Fires	Civilian Deaths	Civilian Injuries	Property Damage (in Millions)
Engine area, running gear, wheel area	176,900 (66%)	150 (40%)	640 (49%)	$543 (54%)
Operator or passenger area	45,100 (17%)	80 (20%)	240 (18%)	$235 (23%)
Unclassified vehicle area	10,800 (4%)	40 (11%)	50 (4%)	$43 (4%)
Exterior, exposed vehicle surface	8,500 (3%)	10 (1%)	40 (3%)	$28 (3%)
Cargo or trunk area of vehicle	8,000 (3%)	10 (3%)	90 (7%)	$37 (4%)
Fuel tank or fuel line	4,400 (2%)	60 (17%)	130 (10%)	$28 (3%)
On or near highway, parking lot or street	3,500 (1%)	10 (2%)	10 (1%)	$15 (2%)
Unclassified area of origin	3,300 (1%)	10 (3%)	10 (1%)	$19 (2%)
Separate operator or control area	3,000 (1%)	0 (1%)	10 (1%)	$18 (2%)
Other known area	6,600 (2%)	10 (3%)	80 (6%)	$40 (4%)
Total	269,900 (100%)	380 (100%)	1,310 (100%)	$1,005 (100%)

Table 12: U.S. Highway Vehicle Fires, by Item First Ignited, 1999-2002 Annual Averages

Item First Ignited	Fires
Electrical wire or cable insulation	73,200 (27%)
Flammable or combustible liquid or gas, including accelerants, aerosols, and atomized vapour	70,600 (26%)
Unclassified item first ignited	41,800 (15%)
Multiple items first ignited	29,100 (11%)
Vehicle seats or upholstered furniture	19,600 (7%)
Tire	5,400 (2%)
Unclassified or unknown-type liquid, piping or filter	3,900 (1%)
Rubbish, trash, or waste	3,200 (1%)
Light vegetation, including grass and leaves	2,200 (1%)
Unclassified or unknown-type structural component or finish	1,600 (1%)
Drive belt, V-belt or conveyor belt	1,500 (1%)
Other known item	17,900 (7%)
Total	269,900 (100%)

Table 13: U.S. Highway Vehicle Fires in which a Flammable or Combustible Liquid or Gas was the Item First Ignited by Type of Material First Ignited 1999-2002 Annual Averages

Type of Material	Fires
Gasoline	53,200 (75%)
Unclassified or unknown-type flammable or combustible liquid	5,500 (8%)
Unclassified or unknown-type flammable gas	3,400 (5%)
Class IIIB combustible liquid, including transformer, cooking and lubricating oil	2,900 (4%)
Class IA flammable liquid, including ether and pentane	1,700 (2%)
Class II combustible liquid, including kerosene, numbers 1 and 2 fuel oil and diesel fuel	1,000 (1%)
Plastic	700 (1%)
Multiple types of material	400 (1%)
Other known type	1,900 (3%)
Total	**70,600 (100%)**

4.0 Case Studies - Gasoline Vehicles

4.1 WTRAC (Washington State Transportation Center) – Case Studies of Motor Vehicle Reports

In January 2001, Washington State University compiled a report on case studies of motor vehicle fires examining the methodologies used in data collection and presenting summaries of results.[18] The goal was to provide sufficient detail of collision-fire incidents to further understanding of the cause(s) of fire, fire propagation rates and paths, and the mechanism and extent of resultant injuries. While fires resulting from collisions are rare and occur due to the confluence of improbable events, case studies show that fires can occur in a wide range of crash circumstances and severity. Photographs, inspection results, witness statements and investigator experience were the bases for the data presented in this report, which illustrates a wide variety of post-collision ignition times, fluid system breaches, ignition source availability, impact types and impact severity.

Data was collected from several forms:

- Case Summary Worksheet
- General Vehicle Form
- Interview Form
- Exterior Vehicle Form
- Interior Vehicle Form
- Field Fire Investigation Form
- Incident Site Form
- Incident Reconstruction Form
- Occupant Injury Assessment Form (Engineers and Medical)

There were 35 vehicles, ranging from 1988 to 1999 model year, involved in the study, 40 deformations, and 42 collision types. The majority of incidents were two vehicle incidents at 45.2%, followed by rollovers at 11.9% and collision with trees at 11.4%. Some incidents of post-collision fire occurred in unexpected ways and after relatively low energy impacts. One report described a fire initiating while the vehicle was being towed, presumably a significant period of time after impact and rest. The low energy events included an impact with a deer.

The makes included 7 Ford vehicles, 4 from Chevrolet, 3 Mitsubishi, 3 Plymouth, 3 Toyota, 2 Dodge, 2 Jeep, and a variety of others (see Table below).

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[18] Case Studies Of Motor Vehicle Fires, by Leland E. Shields Leland E. Shields, Inc., Robert R. Scheibe GT Engineering, Timothy E. Angelos Roberta Mann Design Research Engineering, LLC TOKUIW Memorial Burn Center, for WTRAC, January 2001

Table 14: Vehicle Makes in the Study

Vehicle Type	% of Total
Passenger Cars	62.9
Sport Utility	14.3
Vans	14.3
Light Pickup Truck	8.6

Deformation was most commonly in the front of the vehicle (front end collision) at 52.5%, and the majority of fires started in the engine compartment.

The Table below summarizes the case studies included in the WTRAC report. In some cases, one or more fuels or ignition sources are believed to be more likely than others present. Times are estimated from witness descriptions of events and responder logs. High estimates of propagation times were used, and the times are with respect to rest after impact. Entries that refer to "electrical" as an ignition source may include the possibility of electrical arc, spark, or resistance heating. In cases marked with *, the engine was reported on fire after impact.

Table 15: Case Studies in the WTRAC Report

Fire Vehicle	Impact Description	Est Delta V kph	Likely Fuel/ Ignition Source	Est Time to Ignition/Time to Interior	Initial Fire Location
1992 Mitsubishi Eclipse	Frontal w front of pickup	47-53	Engine oil, coolant/Exhaust manifold, electrical or mechanical spark	<3 / 5-8	Engine compartment
1992 Ford Explorer	Right side w front of car	31-40	Coolant/Electrical	Immediate/2-4	Engine compartment
1995 BMW 525i	Front w barrier, narrow	48-64	Gasoline, coolant, polymerics/ Electrical, exhaust manifold	2-5 / 4-6	Engine compartment
1996 Chrysler Sebring	Side w side of tractor trailer	8-21	Most fluids except gasoline, polymerics/Electrical spark, exhaust manifold	3-5* / 4-6	Engine compartment
1991 Plymouth Acclaim	Front w side of pickup	3-16	Coolant/Electric motor	8-10* extinguished 9-11 w no spread to interior	Engine compartment

Fire Vehicle	Impact Description	Est Delta V kph	Likely Fuel/ Ignition Source	Est Time to Ignition/Time to Interior	Initial Fire Location
1997 Plymouth Voyager	Front w side of van, underride	19-27	Gasoline, other fluids/Electrical or mechanical spark, exhaust manifold	Immediate/4-6	Engine compartment
1991 Mitsubishi Eclipse	Override of culvert, rollover	Minor	Engine oil/Exhaust pipe, mechanical spark	~Immediate/ extinguished without spread to interior	Exhaust system, car inverted
1990 Lincoln Town Car	Rear-end by front of ¾ ton van	80-97	Gasoline from tank/ Electrical, mechanical spark	Immediate/fully engulfed in 9	Rear end and/or interior
1994 Mazda 323	Rear-end by front of passenger car	64-71	Gasoline from tank/Electrical, mechanical spark, exhaust manifold	Immediate/<2	Rear end and/or interior
1995 Ford Escort	Front w rear of pickup	10-16	Engine oil, and coolant/Exhaust manifold, and electrical	<2/extinguished in 5-10 w no spread to interior	Engine compartment
1991 Toyota Previa	Override of tow dolly	Minor	Gasoline from tank/Mechanical spark	Immediate/ Immediate to exit paths	Pool fire under driver door
1990 Dodge Caravan	Frontal impact w tree	64-80	All fluids/Electrical, mechanical spark, exhaust manifold	Immediate/1-3	Engine compartment
1988 Plymouth Sundance	Undercarriage impact and rollover	Minor	Unknown fluids/Unknown	<5*/ fully engulfed within 10	Between front wheels on inverted car
1993 Honda Prelude	Front w utility pole	37-45	Coolant, power steering fluid, polymerics/Electrical	5 / <10	Engine compartment
1994 Toyota Camry	Front w narrow object	50-63	Coolant, brake fluid, polymerics/Electrical, mechanical spark, exhaust manifold	1-2 / <5	Engine compartment
1994 Saturn	Rear by front of passenger car	68-77	Gasoline from tank/ Electrical, mechanical spark	Immediate / 1-3	Passenger compartment
1992	Rear by front	23-35	Gasoline from tank/	Immediate/	Rear end

Fire Vehicle	**Impact Description**	**Est Delta V kph**	**Likely Fuel/ Ignition Source**	**Est Time to Ignition/Time to Interior**	**Initial Fire Location**
Chevrolet Sportvan	of under-riding pickup		Electrical, mechanical spark	fully engulfed with 11	
1993 Chevrolet Silverado	With vehicle above, front w rear of van	35-55	Power distribution box, coolant, brake fluid/Electrical, mechanical spark	Unknown/ extinguished w no spread to interior	Engine compartment
1995 Chevrolet K-15 Pickup	Frontal w tree	35-42	Coolant, brake fluid polymerics/Electrical, mech. spark, exhaust manifold.	Unknown / 3-7	Engine compartment
1995 Toyota Camry	Front w guard rail	34-42	Coolant, transmission fluid, polymerics/ Electrical, mechanical spark, exhaust manifold	1-4 / fully engulfed within 9	Engine compartment
1994 Dodge Caravan	Override of steel road plate	Minor	Gasoline from tank/Mechanical spark	Immediate/ Immediate to exit paths	Pool fire under passenger compartment
1991 Ford Escort	Front w rear of car and tree	43-48	All fluids/Exhaust manifold, electrical, mechanical spark	<3 / 6-10	Engine compartment
1988 Mercury Sable	Frontal w Deer	8-13	Coolant, power steering, transmission fluid/Exhuast manifold, electrical spark.	5 / Unknown	Engine compartment
1991 Ford Ranger	Frontal w rear of minivan, rollover	45-56	Coolant, transmission fluid, polymerics/Exhaust manifold, electrical, mech spark.	1-2 / 2-3	Engine compartment
1993 Jeep Grand Cherokee	Front w barrier after side impact w car	16 - 23	Coolant, gasoline/ Exhaust manifold, electrical, mech spark	Immediate/ Unknown	Engine compartment
1992 Oldsmobile 98	Frontal w side of pickup	27-34	Coolant, transmission fluid, brake fluid, polymerics/Exhaust manifold, electrical,	Unknown/ Unknown	Engine compartment

Fire Vehicle	Impact Description	Est Delta V kph	Likely Fuel/ Ignition Source	Est Time to Ignition/Time to Interior	Initial Fire Location
			mech spark		
1995 Nissan Pathfinder	Sideswipe of truck and rollover	Minor	Gasoline from filler neck/ Electrical, mech spark	Immediate/ Immediate	Right rear
1990 Ford Tempo	Front w rear of minivan	42-52	Most fluids, polymerics/ Electrical, mech spark	Immediate / estinguished <2 min with no spread to interior	Engine compartment
1998 Subaru Legacy	Override of culvert and rollover	Minor	Engine oil, brake fluid, coolant, polymerics/ Exhaust components, electrical, mech spark	Unknown/ Unknown	Lower engine compartment
1995 Ford Taurus	Front w barrier after side contact w truck	16-27	Power steering and tansmission fluid, collant, polymerics/ Exhaust manifold, electrical	5-15/ Unknown	Engine compartment
1999 Pontiac Grand Am	Non-collision	N/A	Power sterring fluid, coolant, gasoline/ Exhaust manifold	N/A / extinguished without spread to interior	Engine compartment
1990 Ford Bronco II	Front w rear of tractor trailer	16 - 32	Most fluids/ Exhaust manifold, electrical, mech spark	Immediate / 3-5	Engine compartment
1993 Chevrolet Cavalier	Frontal w tree	13-19	Coolant, brake fluid, polymerics/ Electrical, mech spark, exhaust manifold	Immediate/ 10-15	Engine compartment
1993 Mitsubishi Minivan	Non-collision	N/A	Gasoline/ Electrical spark	Spread to interior	?
1997 Jeep Cherokee	Non-collision	N/A	Gasoline, power steering fluid, transmission fluid, polymerics/ Electrical, exhaust manifold	N/A / extinguished before spread to interior	Engine compartment

Based on the data compiled the investigators concluded that the causes and severity of collision-related fires can vary widely and depend on numerous and complex factors. This concurs with evidence from the GM tests (see above). Fuels available for ignition, ignition sources, post-collision ignition times, and fire propagation depend on crash configurations, collision environment, and subtle or transient events such as fuel/air mixtures, surface temperatures, arcs, or sparks. The investigators also concluded that in certain cases, even detailed field investigations may not provide conclusive evidence of post-collision fire causation.

Other investigators found data that agreed with the WTRAC report that showed that frontal crashes are the most prevalent type of crash with fire occurrence, producing about half of all fire cases. Rollover crashes were the second most prevalent type of crash with fire occurrence, with about 25% of the vehicle fires examined.[19] Of the fires studied, 74% originated in the engine compartment. The fuel tank is second at 13%, with the remaining fire sources widely scattered. Fires that originate in the passenger compartment were found to be infrequent. The engine compartment fire frequency is heavily influenced by the high percentage of fires in frontal crashes (50%, and the high frequency that these fires originate under the hood (92%). For rear impacts, the fuel tank is the predominant fire origin at 95%, but 22% of all fires in rear crashes still originate in the engine compartment.

4.2 Case Studies by the Fire Protection Research Foundation

The Fire Protection Research Foundation produced a report on fire safety in April 2007 that included case studies of motor vehicle fires[20], to analyze previous vehicle fire hazards in the current vehicle fleet and to use this knowledge to identify hazards in the Emerging Fuel Vehicle (EFV) fleet. The results of this project are intended to provide vital fire safety information to the traveling public as well as to emergency response personnel to increase the prevention of and safety when reacting to EFV fire hazard situations.

Statistical analysis found that the characteristics of the incidents that cause the most fires and deaths in vehicle fires were:

- Collision incidents - 20% of fires and 69% of fire deaths
- Incidents where fire originated under the hood and wheel well - 67% of fires and 42% of fire deaths, and
- Incidents involving cars - 80% of fires and 67% of fire deaths.

The most common registered vehicles were cars, 60%, running on traditional gasoline systems, 96%, and were therefore considered to be the type of vehicle with the largest sample for fire to occur. While fires originating in fuel lines only accounted for 1% of vehicle fires, they

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[19] Recent MVFRI Research in Cash-Induced Vehicle Fire Safety, K.K. Digges and R.R. Stephenson, SAE Technical Paper 2007-01-0880, from the 2007 World Congress, April, 2007.

[20] Fire Safety of the Traveling Public and Firefighters for Today's and Tomorrow's Vehicle Fleet, for the Fire Protection Research Foundation, by James A. Milke, Peter B. Sunderland, Kevin M. Levy, Victor L. Ontiveros, and Allison C. Carey Department of Fire Protection Engineering, University of Maryland, April, 2007

accounted for 13% of the deaths. This observation indicates that the ratio of deaths per fire was significantly higher for fuel line fires than for any other type, making them the most fatal type of fire.

Statistical reviews identified the scenarios examined. Further information about important fire scenarios was obtained by consulting experts in the field of vehicle fires who gave insight into the most encountered and fatal scenarios. For example, Assistant Chief Kerber of the College Park Fire Department identified that while underhood fires preceded by a collision are statistically the most important, in his experience the common vehicle fire incidents originate under the hood and are not preceded by collision.

The six scenarios are:

1. Underhood fire after collision
2. Refuelling fire
3. Interior fire
4. Large vehicle fire
5. Pool fire after rear end collision
6. Underhood fire without collision

In examining these scenarios, the following categories were considered:

- Cause of the fire
- Area of fire origin
- Vehicle type, and
- Fuel system

In the causes category were four possible attributes: collision, intentional, component failure, and static discharge. In the origin category there were six possible attributes: underhood, wheel well fuel line or tank, passenger area, trunk, and pooling. In the vehicle type category there were five attributes: car, pick-up/SUV/van, motorcycle, truck/trailer, and bus. Finally, in the fuel type category there were four attributes: gasoline, diesel, gasoline hybrid, and compressed natural gas (CNG).

The NPRF report selected six case studies to illustrate the above:

4.2.1 Case Study I - Underhood Fire after Collision

Incident Description: A 1992 Ford Explorer was struck by a 1991 Toyota Corolla, impact occurred between the front of the car and the right sight of the SUV adjacent and forward of the front wheel. It was observed that within one minute of impact flames of 6- 15 inches high were observed in the SUV. Impact damage was limited through the vehicle was eventually totally consumed by the fire.

Ignition Circumstances: The ignition occurred during post-crash events.

Ignition Heat Source: The most likely ignition source was concluded to be electrical sparks in the area of the power distribution box on the right-front fender or resistance heating due to an electrical short. Items that burned and fire timeline The fire most likely was started by the ignition of coolant from a "ruptured cooling host connection near the bulkhead" by electrical sparks from caused by the shorting of wires and subsequent resistance heating or arcing in the power distribution box. Soon after fire consumed the entire engine compartment and then spread to the passenger compartment through the windshield.

Time to first detection of fire: The SUV driver observed fire from his vehicle within the 30 seconds of the collision.

Fire extinguishment method: None. The fire extinguished only after all available fuel was burned. The SUV was completely consumed by the fire.

Extent of damage and injuries: Collision damage to the SUV was minimal and was confined to the right front fender, wheel and suspension area. Crush damage to both vehicles was limited in part by impact to stiff structures supporting the wheels of each vehicle. There was negligible static crush intrusion into the engine compartment. Damage to the car was to the left front bumper, engine, and left wheel area. The left front wheel itself was deformed and pushed rearward.

Scenario Type and Importance: This case involves a fire scenario where the fire originates under the hood and the precipitating event causing the fire is a collision. This case importantly represents how many vehicle collision fires are fed by fuels other than gasoline. During the examination of this fire many engine fluids other than gasoline were suspected to have started the fire. This proves that despite gasoline naturally dangerous properties, other fluids can also present fire hazards following a collision. This case also represents how many vehicle fires originate under the hood of a car due to the close proximity of fuels (e.g. gasoline, oil, grease, etc.), heat, and electrical components. Additionally this case represents two of the primary types of registered highway vehicles: SUV's and cars.

Underhood Collision Fires are very common; they account for the largest fraction of vehicle fires and deaths. The large number of deaths is most likely due to events of the collision increasing the chance that a person is trapped or disabled inside a vehicle and therefore made vulnerable more often than in other scenarios. It is known that collisions are involved in the majority of vehicle fires. Combined with the fact that underhood/wheel well originating fires are also the most common origin of vehicle fires, the Underhood Fire after Collision scenario is proven statistically to be the most common and fatal scenario[21].

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[21] An Overview of the US Highway Vehicle Fire Problem, M. Ahrens, 2005a, National Fire Protection Association, Quincy MA.

4.2.2 Case Study II - Refuelling Fire

Incident Description: A man was pumping gas into a pickup truck at a station when he grabbed the nozzle and felt a shock. The spark ignited nearby gasoline vapours and caused his truck to become involved. The truck and a portion of the gas station were destroyed.

Ignition Circumstances: The ignition occurred during refuelling.

Ignition Heat Source: The heat of the ignition came from the electrical arcing of static electricity between the operator and the pump nozzle handle.

Items that burned and fire timeline: The gasoline vapours around the nozzle were ignited first, and almost immediately following that the entire vehicle was consumed by the fire spreading to that point. From the meter on the pump it has been determined that after the fire ignited 17 additional gallons of gasoline were pumped into the vehicle.

Time to first detection of fire: Immediate.

Fire extinguishment method: The fire was extinguished by the fire department by unspecified means after the fire chief activated the pump shutoff switch near the gas station register.

Extent of damage and injuries: The occupants of the vehicle were uninjured. The entire truck was consumed by the fire as was part of the gasoline pump.

Scenario Type and Importance: A refuelling fire, considered to be avoidable with proper operator education.

4.2.3 Case Study III - Interior Fire

Incident Description: The owner was driving his SUV and began smelling smoke. He then noticed some flaming items/debris coming from under the dashboard just above his legs and feet.

Ignition Circumstances: The ignition began while the vehicle was being driven, but without any direct event starting it such as a collision.

Ignition Heat Source: It is probable that the source was a short or arcing from an exposed electrical conductor that had been damaged when the stereo was installed.

Items that burned and fire timeline: Arcing from electrical wiring likely ignited insulation behind the dashboard.

Time to first detection of fire: The driver first noticed a burning smell presumably this was very shortly after ignition.

Fire extinguishment method: The fire was extinguished by pre-connected hose lines from a fire apparatus using water tanks.

Extent of damage and injuries: The driver was uninjured, however the vehicle was a total loss as it was mostly consumed by fire before being extinguished.

Scenario Type and Importance: This case represents fire scenarios where the fire originated in the passenger compartment while the vehicle was moving, which some have reported as quite rare (Maynard). This is an important case because it represents a major area of fire origin often directly affected by the operator of the vehicle. In this case the user had an improperly installed stereo which most likely caused the fire.

4.2.4 Case Study IV - Large Vehicle Fire

Incident Description: A tour bus was carrying 47 passengers, many of them older adults in West Virginia when a fire occurred.

Vehicle Type: The vehicle involved was a large tour bus.

Ignition Circumstances: The ignition occurred while the vehicle was in operation on the road, likely starting during braking.

Ignition Heat Source: The rear brake began dragging causing a large amount of frictional heat which ignited the fire.

Items that burned and fire timeline: The dragging brake ignited the rear tire first from where the fire spread from the wheel well up into the passenger compartment.

Time to first detection of fire: The fire is believed to have burned for nearly seven minutes before a passerby detected it.

Fire extinguishment method: Two engine companies applied two hose lines to attack the blaze. A HAZMAT team contained oil and fuel runoff.

Extent of damage and injuries: The rear of the bus was the most heavily damaged and several passengers were taken to hospital.

Scenario Type and importance: This case exemplifies most large vehicle fires, where the major problems occur during extrication of passengers since the ratio of passengers to exits is lower for most large personnel transport vehicles than for smaller vehicles.

4.2.5 Case Study V - Pool Fire after Rear End Collision

Incident Description: A collision between a pickup truck and a rented limousine. The back end of the limo was enveloped in flames so intense that the limo driver could not get close enough to attempt to open to passenger doors.

Vehicle Type: The vehicle involved in the fire was a limousine with a car's base structure.

Ignition Circumstances: The ignition occurred post crash.

Ignition Heat Source: The most likely ignition source was sparks from metal components in the crash.

Items that burned and fire timeline: The fuel tank located behind the rear axel was punctured so that "gas spewed out of the cracks when it was impacted by the truck. Gasoline in the tank was the most prolific source of fuel, but eventually the fire spread to the interior of the vehicle.

Time to first detection of fire: Immediate.

Fire extinguishment method: Unspecified.

Extent of damage and injuries: The limo driver escaped the vehicle uninjured, however the three other passengers perished. They were reported in autopsy to have burned to death with minor injuries from the collision. The vehicle was entirely consumed by the fire.

Scenario Type and importance: This case shows the devastating effects of an under-vehicle pool fire. Federal Motor Vehicle Safety Standard (FMVSS) 301, "Fuel System Integrity," was issued to reduce the risk of just such crash fires occurring in survivable crashes (see above). The fire proved to be the most lethal factor due to the short time in which the vehicle became involved and the lack of a viable escape route in such a large and fast-developing fire.

4.2.6 Case Study VI - Underhood Fire without Collision

Incident Description : The involved vehicle was being sold by a salvage company. It had no prior damage from a collision and had been stored by the owner but was never claimed when the salvage company was moved to the location and claimed the title. They attempted to start the vehicle but the battery was dead. They jump started the vehicle and then the mechanic walked away to allow the vehicle to warm up. About 10 minutes after starting the vehicle smoke was observed coming from the vehicle.

Vehicle Type: The vehicle involved was an SUV.

Ignition Circumstances: The vehicle had never been involved in a collision to the knowledge of the mechanic and was simply idling after a jump start.

Ignition Heat Source: Unknown underhood source, possibly a spark or hot surface.

Items that burned and fire timeline: It is suspected that gasoline from a broken fuel line due to a mechanical malfunction or other unintentional cause started the fire.

Time to first detection of fire: Within ten minutes of ignition.

Fire extinguishment method: Pre-connected hose lines from a tank of water on a fire vehicle.

Extent of damage and injuries: The SUV was totally lost and caused damage to the two vehicles parked on either side.

Scenario Type and importance: This fire occurred under the hood, which is a very common source, by unintentional and non-collision circumstances. The cause of this fire is most likely from improper maintenance by the operator. After remaining dormant while in storage, it's possible one or more components degraded or malfunctioned, leading to the fire.

5.0 Existing Research - Alternative Fuel Vehicles

5.1 Overview

The Fire Protection Research Foundation conducted a study assessing the fire risk factors of emerging (alternative) automotive fuels, including CNG and Hydrogen. Vehicles fuelled by emerging fuels are appearing in greater numbers on North American highways. The registration of 392,000 new hybrids in the U. S. between 2000 and 2006 (according to Milke et al. for the NPRF report[22]) points to alternative fuel vehicles becoming increasingly prevalent on the roads, while relatively little is known about the fire risks of emerging vehicle fuels. Emerging Fuel Vehicles are defined in this study to be vehicles fuelled by alternative fuels (alcohol fuels and alcohol-gasoline blends, CNG, hydrogen, biodiesel, LPG, electricity, coal-derived fuels) and gasoline-electric hybrid vehicles.

As part of the Milke et al. study, a failure modes and effects analysis (FMEA) was performed on three Emerging Vehicle Fuel (EVF) fuel systems:

- Compressed Natural Gas (CNG)
- Compressed Hydrogen Gas Fuel Cell
- Gasoline-Electric Hybrid

These systems have many components in common with traditional fuel systems. The CNG and Hybrid EFVs in particular have the same principal components as traditional fuel systems. These three components include:

- Fuel storage
- Piping from storage to engine
- Combustion at engine

For the FMEA - failure modes are any method in which a component can act to cause a release of fuel or exposure to high voltage. A few examples of failure modes are an electrical short, deformation of a component resulting in fuel leakage, and corrosion of a component resulting in an electrical path and/or fuel leakage. Virtually all fuel system components have multiple failure modes.

One of the most catastrophic failure modes is fuel tank rupture caused by fire, due to the tremendous amount of mechanical energy stored in a compressed gas tank. Federal Motor Vehicle Safety Standard (FMVSS) No. 304, *Compressed natural gas fuel container integrity* requires a bonfire test. Draft International Standard ISO 15869-1, *Gaseous hydrogen and*

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[22] Fire Safety of the Traveling Public and Firefighters for Today's and Tomorrow's Vehicle Fleet, for the Fire Protection Research Foundation, by James A. Milke, Peter B. Sunderland, Kevin M. Levy, Victor L. Ontiveros, and Allison C. Carey Department of Fire Protection Engineering, University of Maryland, April, 2007.

hydrogen blends – Land vehicle fuel tanks – Part 1: General requirements also specifies a bonfire test. Both procedures expose a compressed gas cylinder at its working pressure to a 165cm long bonfire. But, as described earlier, passing this test does not mean the tank will survive a localized fire, which can result in a rapid increase in the gases' potential energy, enough to rupture the tank before the TPRD activates.

5.2 Compressed Natural Gas

One major difference between the use of natural gas and gasoline is that CNG is stored in an array of high pressure storage tanks at pressures up to 25 MPa (3600 psi). While a CNG vehicle is not in use and the engine is shut down, high pressure normally closed solenoid valves prevent fuel from moving from the high pressure storage tank into the fuel lines. During operation, the solenoid valves open and CNG is directed into the fuel line. Once in the fuel line, the CNG is passed though a regulator which decreases the pressure, providing gas to the fuel injection system at the proper pressure. After the regulator, fuel is passed though a heater and a low pressure filter before entering the engine. The air to fuel ratio at the engine is monitored by sensors to provide an efficient combustion process.

Multiple safety components are used in a CNG fuel system to minimize the risk. During refuelling operations, a magnetic fuel door interlock switch shuts off the engine whenever the fuel door is open. Manual shutoff valves isolate each storage tank to facilitate replacement or repair of individual tanks. Thermally-activated pressure relief devices protect the storage tank from rupture in a fire situation. During refuelling, check valves allow incoming fuel to bypass the high pressure solenoid valves and enter the storage tanks. The check valves close once refuelling is completed.

The failure modes with the greatest risk factors were over-pressure of the storage tank, freezing of the check valve, deformation and seal embrittlement of the fill receptacle, deformation of the TPRD, and having the storage tank exposed to a localized flame. Two major fire hazards can result from rupture and rapid leakage of CNG. Ignition of the gas release could result in a large flame. Alternatively the gas could accumulate and detonate upon ignition.

While TPRDs are designed to melt and release the gas before the tank wall loses strength, they can deform and fail to activate, or operate prematurely. Deformation could cause the relief line leading to the TPRD to be too constricted to relieve the pressure adequately to prevent an over pressure state in the cylinder, which would raise the severity of this scenario to the same level as for the overpressure state of the storage tank. Then there is the problem of localized flame (discussed above) weakening the tank wall and increasing internal gas pressure while failing to melt the TPRD[23].

The failure of TPRDs to release in vehicle fires is a recognized source of rupture, according to

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[23] Fire Safety of the Traveling Public and Firefighters for Today's and Tomorrow's Vehicle Fleet, for the Fire Protection Research Foundation, by James A. Milke, Peter B. Sunderland, Kevin M. Levy, Victor L. Ontiveros, and Allison C. Carey Department of Fire Protection Engineering, University of Maryland, April, 2007.

global records compiled by Powertech[24]: 30% of CNG tank failures were a result of motor vehicle fire accounting for the single most significant cause of failure of CNG tanks, and 36% of ruptures of high pressure storage tanks in the period of 1976 to 2007 were due to TPRDs not operating properly. Of the CNG tank failures caused by vehicle fire, just over 30% were related to a lack of heat directed at the TPRD due to a localized fire.

R.R. Stephenson reports that in the FMVSS 304 standard in the US, a bonfire test is required whereby a bare tank and associated TPRD is subjected to a propane flame for 20 minutes, and the tank must either not rupture or vent within 20 minutes. Because tanks are not usually expected to withstand 20 minutes of flame, the test is really evaluating the performance of the TPRD. Shielding of the TPRD is critical, because if the TPRD is shielded too well from the flame it will not activate and the tank will burst[25].

5.3 Case Studies - CNG Vehicles

There are few (if any) case studies on hydrogen-fuelled vehicles, simple because most hydrogen vehicles are at the development or prototype stage. However, there are case studies of motor vehicle fires involving CNG vehicles, either in fire tests or operational vehicles, and this information can shed light on fire behaviour and propagation if the fuel system was replaced with a hydrogen one.

The following incidents illustrate localized fire impingement failures of CNG tanks onboard light duty vehicles and buses.

5.3.1 Ford Crown Victoria (Madison, WI)

A Type 2 (steel lined, glass fibre hoop wrapped) cylinder manufactured by Pressed Steel Tank ruptured in a fire. The CNG vehicle was a 1996 Ford Crown Victoria. The incident investigation focused on the TPRD. The TPRD was removed from the failed tank and subjected to a yield temperature determination test.

It was concluded that a directed flame from inside the vehicle onto the cylinder compromised the cylinder's hoop strength, which allowed the cylinder to fail before the TPRD's fuse could melt to release the gas. As a result of these tests, Ford developed an insulator to insulate the natural gas fuel tank from a locally directed flame projecting from the interior of the vehicle. Insulations installed behind the back seat on subject vehicles were designed to prevent future failures of this type.

5.3.2 Honda Civic (Seattle, WA)

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[24] Root Cause Analysis and Report for CNG Cylinder Field Failures, Final Report for the Society of Automotive Engineers, Fuel Cell Safety Committee, Powertech Labs, L. Gambone, 2007.

[25] Fire Safety of Hydrogen-Fueled Vehicles: System-Level Bonfire Test, R.R. Stephenson, www.mvfri.org

A Lincoln Composites Type 4 cylinder, with a Superior TPRD installed in a Honda Civic CNG vehicle, exploded as a result of a vandalism fire set in the vehicle. The CNG cylinder exploded as firefighter crew approached to a distance of 50-75 feet. There were no injuries, but 12 vehicles were damaged or destroyed in the explosion and subsequent fires. Debris from the explosion was thrown up to 100' in all directions including on the overpasses above the incident.

The Investigation determined that the cylinder ruptured before the TPRD activated to release the gas due to localized fire. It has been surmised that a plastic/rubber vent box covering the valve/TPRD may have shielded the TPRD during the fire.

As a result of the above incident, Honda conducted tests on Honda Civic CNG models, in recognition that in the event of arson, CNG tanks may experience a sudden and unexpected rupture of the tank that could present an unfamiliar condition to emergency responders.[26].

In one test, a Honda Civic CNG vehicle was set on fire to re-create a potential explosion resulting from an arson fire. A gasoline soaked rag was ignited and thrown into the rear seat of the passenger compartment. Although the TPRD activated and began venting the CNG tank contents after an elapsed time of 19 minutes, 49 seconds, the tank ruptured after 21 minutes, 34 seconds.
In another test, Honda researchers used a fire resistant heat insulation fabric installed behind the rear seat, in front of the CNG tank (installed behind the rear seat). The above test was repeated. The TPRD activated after an elapsed time of 17 minutes, 43 seconds. The tank did not rupture.

5.3.3 CNG Bus Fire – Bordeaux, France

A Type 4 cylinder manufactured by Ullit (Superior valve & spiral TPRD), installed in an OEM Bus, ruptured when vandals set fire to the bus (Molotov cocktail thrown into the passenger compartment). One of the roof mounted cylinders burst within 10 minutes after the fire broke out. Horizontal jet flames were witnessed, indicating the remaining TPRDs released the fuel in the other cylinders.
The CNG fuel system was not compliant with ECE R110 (the bus was placed into service prior to the existence of this regulation).

5.3.4 CNG Bus Fire – Monbeliard, France

An Ullit Type 4 (Superior valve with spiral-type TPRD) cylinder, installed in an OEM Bus, ruptured after a small fire started in the engine compartment due to a short circuit. The TPRD activated but system design restricted the vent rate, causing the tank closest to the fire to burst. The TPRDs were fitted with 1.5 mm flow limiters in order to comply with a French regulation that mandates a CNG release time of 25-35 minutes. The fire broke through a roof opening located 20 cm ahead of the ruptured cylinder, creating a localized thermal stress in the cylinder

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[26] Communications between Honda and NHTSA, October 31, 2007.

mid-section. In addition, it was postulated that the ignited CNG release from the adjacent cylinder's TPRD impinged on the ruptured cylinder.
The CNG fuel system was not compliant with ECE R110 (the bus was placed into service prior to the existence of this regulation).

5.3.5 CNG Bus Fire – Saarbrucken, Germany

A Dynetek Type 3 (aluminum lined, fully-wrapped carbon fibre) cylinder installed in an OEM Bus ruptured approximately 9 minutes after a fire broke out in the bus' engine compartment, which started because of an oil deposit close to the hot gearbox. Two buses were burnt out in the resulting fire. Nineteen out of twenty CNG cylinders exposed to fire behaved as expected, with the two TPRDs per cylinder activating for a controlled release of the stored gas. After the fire was thought to be "in control" and 15 minutes after fire initially broke out, one of the cylinders burst.
After investigation it was determined that one of the 38 TPRDs did NOT activate because the eutectic fuse did not have time to melt completely (TPRD "freezing"), leading to tank overpressure and rupture. A fire-induced short circuit triggered the opening of a roof-mounted door which directed the flames to the cylinder sidewall. This localized fire resulted in the weakening of the cylinder in an area away from the TPRD.

5.4 Hydrogen – Risk Assessment Studies

Hydrogen fuel systems have many similar components to CNG fuel systems. As in the CNG system, the hydrogen system uses high pressure storage tanks, TPRDs and check valves. Storage tanks in the hydrogen system are also outfitted with thermally-actuated pressure relief devices that will vent the tank should the temperature increase creating an unsafe operating condition, e.g. from fire exposure. High pressure solenoid valves are also used to control the flow of fuel out of the storage tanks as in CNG vehicles. Some of the other safety components include an engine control unit to monitor system pressures and temperatures. An electronic control unit (ECU) monitors hydrogen sensors that detect hydrogen accumulation throughout the vehicle. The ECU also monitors temperature sensors and pressure sensors "at the hydrogen storage tanks and along the distribution lines and components (according to Toyota, 2006). The temperature and pressure sensor measurements are both applied to preventing overpressure in any of the components. Additionally, the ECU monitors crash sensors mounted on the vehicle. Lastly, because of the high voltage electricity used, ground fault interrupters (GFI) or other methods are used to limit the exposure to high voltage to occupants and emergency responders. In all cases, if conditions are detected by the ECU that are outside of the nominal range of operating conditions, the ECU will shut down the system (Toyota, 2006).

The failure modes for hydrogen powered vehicles with the greatest risk factors are over-pressurization of the storage tanks, direct and alternating current shorting without ground fault interruption (GFI) in the fuel cell vehicles, normal activation of the TPRD via direct flame, crack of the high pressure tank inlet lines, and lastly localized flame exposure to the low pressure tank outlet lines.

While the cause and effects of these failures are the same as for CNG described above, hydrogen is easier to ignite than CNG, so the risk rating is higher. And because a hydrogen flame is invisible, detection is more difficult than for ignited flames from CNG and other petroleum based fuels.

For the case of hydrogen fuel cell vehicles, breach of the electrical cables is a deadly hazard due to high voltages, which are high enough to allow for arcing through air.

The TPRD is also at risk of failure in the event of localized flame, but even if it operates properly, there is a chance that the gas will not ignite when initially released and will accumulate and form an explosive mixture.

When exposed to a localized flame, breaching of the low pressure lines could occur without activating the temperature sensors designed to isolate the lines from the tank and other components. A localized hydrogen flame leaking from a component has an adiabatic flame temperature of 2,348 K in air. Stainless steel's melting temperature is 1,693 K, so the flame is hot enough to melt and cause the failure of the fuel line. Toyota measures pressures as well, so other leak preventative measures may respond to the hazard, but other factors raise the hydrogen vehicle's risk factor – such as the likelihood of component (fuel line?) failure in a collision, and the close proximity of this component to other components which are easily affected by the failure and able to cause a localized flame in the engine compartment[27].

Studies have shown that 85% of crash-related fires are electrical in origin and electrical ignition sources may have higher potential in electric or hydrogen fuel cell vehicles. If hydrogen is released, there is a good chance it will ignite. In some cases it may be preferable for the hydrogen to ignite quickly rather than accumulate and give rise to a deflagration[28].

Electrical fire countermeasures can include the location and protection of the batteries. Gasoline vehicles frequently have the battery in the front of the engine compartment, vulnerable to crushing and shorting in a frontal crash. There are up to 7 flammable fluids (not counting gasoline, but including coolant and windshield washer fluid which can splash on the battery and other wiring) under the hood of current vehicles. It is possible that hydrogen fuel cell vehicles will have fewer flammable fluids to be exposed to such an ignition source. Some gasoline vehicleslocate the battery in the trunk (e.g. BMW). They also have a battery disconnect (circuit breaker) which is activated by the crash sensors on the car. Certainly hydrogen fuel cell vehicles

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[27] Fire Safety of the Traveling Public and Firefighters for Today's and Tomorrow's Vehicle Fleet, for the Fire Protection Research Foundation, by James A. Milke, Peter B. Sunderland, Kevin M. Levy, Victor L. Ontiveros, and Allison C. Carey Department of Fire Protection Engineering, University of Maryland, April, 2007.

[28] Crash-Induced Fire Safety Issues with Hydrogen-Fueled Vehicles, R. R. Stephenson, www.mvfri.com.

will have that feature on at least the high voltage sources, and perhaps also on the lower voltage sources (14 or 42 V) for the other loads.

5.5 Hydrogen Vehicle Fire Safety Research

As discussed earlier, the design of compressed hydrogen fuel systems for hydrogen vehicles has been largely based on the CNG vehicle experience. As a result, the test procedures used to qualify on-board hydrogen fuel systems for service use the test protocol developed for the CNG industry. For example, evaluation of fire performance of the fuel system is limited to fire testing of individual components, i.e. the hydrogen fuel tank itself. Similarly, vehicle OEMs perform fire tests of gasoline tanks according to a standard procedure, but they are not required by regulation to perform fire tests of complete vehicles.

Vehicle OEMs do not consider hydrogen-fuelled vehicles any differently than petroleum-fuelled vehicles. Since fire tests of complete vehicles are not required by regulation for vehicles fuelled by petroleum products, CNG, LPG, etc., then such a test is not necessary as a regulatory requirement for hydrogen vehicles. As stated by the Japan Automobile Manufacturers Association, "…in vehicle fire testing, all fuel cell vehicles, gasoline vehicles and natural gas vehicles ought to be tested and evaluated under identical conditions"[29], meaning that if hydrogen vehicles are subjected to some special fire test condition, then it should be applied to all vehicle types.

While vehicle OEMs resist any regulatory imposition of fire testing involving vehicles, they do perform a certain amount of in-house fire testing. Essentially all major OEMs involved in the development of fuel cell vehicles have performed fire testing involving complete hydrogen vehicles. This testing has remained confidential to each OEM and is not available to the public.

In the public domain, the fire testing of hydrogen vehicles has apparently only been conducted by the University of Miami, the Japan Automobile Research Institute (JARI), and by the Motor Vehicle Fire Research Institute (MVFRI).

5.5.1 The University of Miami

The first public investigation of hydrogen vehicle fire effects was conducted by Michael Swain of the University of Miami in 2001[30]. The purpose of the study was to produce a "…video

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[29] Japan Automobile Manufacturers Association ("JAMA") response to Docket No. NHTSA-2004-18039: NHTSA's Four-Year Plan for Hydrogen Fuel Cell, Fuel Cell and Alternative Fuel Vehicle Safety Research, (www.jama.org/library/technical_comment_2004-10-08.html), dated October 8, 2004

[30] EV World, "Hydrogen Car Fire Surprise" (http://evworld.com/article.cfm?storyid=482), January 18, 2003.

comparing the severity of a hydrogen and gasoline fuel leak and ignition"[31]. Swain ignited hydrogen leaking from a fuelling receptacle on a vehicle, and compared it to the ignition of gasoline leaking from a fuel line. The hydrogen burned away after about 100 seconds, with no heat damage to the vehicle.

5.5.2 Japan Automobile Research Institute

JARI conducted a series of fire tests at Powertech Labs to evaluate the fire safety of vehicles that use compressed hydrogen as fuel[32] [33]. The fire tests were conducted on vehicles that used compressed hydrogen and on vehicles that used compressed natural gas and gasoline and compared temperatures around the vehicle and cylinder, internal pressure of the cylinder, irradiant heat around the vehicle, sound pressure levels when the pressure relief device was activated, and damage to the vehicle and surrounding flammable objects.

For the hydrogen vehicle fires, 2 tanks of 24.8 MPa working pressure (and about 65 L water volume each) were installed separately in the trunk compartment of each vehicle, along with high pressure stainless steel lines running to the engine compartment of the vehicle, to simulate the tubing that might exist to supply fuel cell engines. The tanks were protected using TPRDs of VTI glass bulb design, intended for use on CNG tanks. The TPRDs were either provided with vent tubes out of the vehicle, or without any vent tubes to allow the escaping hydrogen to vent into the vehicle. The fires were initiated in the passenger compartment, or a pool fire under the vehicle, and burned until the TPRDs activated.

One purpose of the tests was to identify whether the bonfire test to be required for land vehicle fuel tanks (ISO/CD 15869) applies to vehicle fires. It was found that the internal pressure and the cylinder surface temperature were different before the TPRDs were activated, compared to the bonfire test. Furthermore, a fireball was formed if the hydrogen gas was vented in the trunk in a gasoline pool fire situation. As a result, JARI concluded that it would be necessary to identify the strength of tanks after the fire test, and to determine a safe way of venting the hydrogen from a vehicle[15].

Another conclusion by JARI was that vehicles equipped with compressed hydrogen gas cylinders were no more dangerous than CNG or gasoline vehicles in the event of a vehicle fire[14].

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[31] M. Swain, University of Miami, EV World, "Fuel Leak Simulation" (2003), http://evworld.com/library/swainh2vgasvideo.pdf), March 25, 2003

[32] J. Suzuki, et al, "Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles", SAE 2006 World Congress & Exhibition, April 2006, Detroit, MI, USA, Session: Fire Safety (Part 1 of 6): Hydrogen Vehicle Safety (Part 1)

[33] Y. Tamura et al, "Evaulation of the High-Pressure Hydrogen Gas Cylinders in Simulated FCEV Fires", JARI Research Journal, Vol. 24, No. 10.

JARI has also conducted in-house studies to understand the impact of a hydrogen-jet flame when the TPRD is activated, on fire-fighting and rescue activities[34]. They investigated a vehicle-fire situation with an upward hydrogen-jet flame from a high-pressure cylinder (70 MPa) and the resulting skin-burn injuries on a thermal mannequin dressed in fireproof clothing. The results indicated that in the event of a vehicle fire, the upward hydrogen-jet flame was no more dangerous than gasoline.

5.5.3 Motor Vehicle Fire Research Institute

The Motor Vehicle Fire Research Institute has sponsored one fire test of a vehicle equipped with a Type 3 hydrogen tank of 34.5 MPa service pressure, but without a pressure relief device[35]. The purpose of the test was to determine "how far away is safe for rescue and bystanders if the TPRD valve does not release".

The vehicle's gasoline fuel tank was removed and replaced with the hydrogen tank, and the vehicle exposed to a propane bonfire in order to simulate the occurrence of a gasoline pool fire on the underside of the vehicle. Measurements included temperature and carbon monoxide concentration inside the passenger compartment of the vehicle to evaluate tenability. Measurements on the exterior of the vehicle included blast wave pressures. Documentation included standard, infrared, and high-speed video. The interior of the vehicle became untenable due to high temperature and carbon monoxide concentration just after 4 minutes into the test. However, this was a result of the bonfire source, not the hydrogen cylinder. Catastrophic failure occurred in approximately 12 minutes, severely damaging the remains of the burnt vehicle well after its interior had become untenable[36].

To examine the safety of hydrogen-fuelled vehicles, K.H. Digges[37] asked the following questions:

(1) What are the surface temperature and internal pressure responses of hydrogen tanks when exposed to bonfire tests and how do these responses influence the design of the pressure relief device?
(2) What are the failure characteristics of different hydrogen tank designs?
(3) What is an appropriate burn test for hydrogen fuel tanks?

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[34] Y. Tamura, et al, "Evaluating the Thermal Hazard of Hydrogen-Jet Flames in Vehicle Fires Using a Thermal Manikin", JARI Research Journal, Vol 28, No. 7

[35] K. Digges & R. Stephenson, "Recent MVFRI Research in Crash-Induced Vehicle Fire Safety, SAE 2007-01-0880, April, 2007.

[36] N. Weyandt, "Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices" SAE Document No. 2007-01-0431.

[37] MVFRI Research Summary, Kennerly H. Digges, Research In Fire Safety For Hydrogen-Fueled Vehicles Based On Contracts With: Southwest Research Institute and FIREXPLO.

(4) What is the extent of the risk of major vehicle fires (occupant compartment entry) from the hydrogen leakage permitted by a broken fuel line?
(5) What is the influence on the location of the leakage on the risk of a major fire or explosion?
(6) What are the characteristics of the most significant threats associated with hydrogen leakage?
(7) What is an appropriate test to assure the safety of hydrogen fuel lines?
(8) What is the nature of the most significant threats associated with hydrogen fuel tanks and fuel lines subjected to crash induced fires?

Figure 15: Hydrogen Tank Bonfire Test Apparatus

In a bonfire test Digges conducted without a TPRD, the composite material on the surface of the tank ignited after approximately 45 seconds. After 6 minutes and 27 seconds, the cylinder failed catastrophically through the bottom, launching the 14.0 kg main portion 82 m from the test location. Blast pressures were 300 KPa at 190 cm. The internal temperature and pressure of the hydrogen at the time of failure was 39°C and 35.7 MPa, respectively. The pressure inside the cylinder did not rise sufficiently so that a pressure-activated pressure relief device would have activated to prevent rupture. The temperature inside the cylinder also did not climb sufficiently to activate a thermally-activated pressure relief device if it used the *internal* temperature as the temperature source. Digges concluded it is necessary to place TPRDs such that they see the same, or worse, fire as the tank.

In a second test in 2006, Digges et al. conducted a bonfire test of a Type 3 (aluminum liner, composite shell) hydrogen fuel tank installed in a “popular” SUV. Again, the test was performed on a tank without a TPRD, so it is only relevant as far as measuring fire temperatures and tank temperature and pressure prior to rupture are concerned, as opposed to testing how an actual system would react to a motor vehicle fire.

The initializing fire was a propane burner (265 kW) which burned until the hydrogen tank burst. The burner pan size was approximately one inch larger that the tank in each dimension.

The fire was initiated and portions of the vehicle became involved (plastic body panels, tires, and then the interior). The temperatures on the underside of the cylinder quickly rose in excess of

650°C. Measurements inside the vehicle showed that the driver's position space became untenable (CO > 1% and temperature > 200°C) in about 4 minutes. The internal tank pressure remained fairly constant during the first 9 minutes, at which time the pressure transducer failed. The fire continued and grew and the hydrogen tank burst after 12 minutes. Digges concluded, based on analysis of the video and thermocouple data, that is was "very likely" that a TPRD mounted at either end of the tank in this test could have been thermally actuated and prevented the tank from bursting.

Next, Digges examined the effects of hydrogen leaking from broken fuel lines. These tests showed that while there is a high risk associated with tank rupture, a hydrogen fire is a lot less damaging than a gasoline fire.

Similar to the GM tests on gasoline pool and engine compartment fire tests, Digges simulated hydrogen leaks and ignition in passenger vehicles, measuring temperature and heat flux. Underside and engine compartment tests were done, some allowing the hydrogen to accumulate prior to ignition.

Figure 16: Damage done to Vehicle During H2 Fire Test

In other tests, hydrogen jet-fires impinged directly on the underside of the hood of the engine compartment. The thermocouple in the direct path of the jet-fire recorded a temperature above 1204°C in each test, but temperatures on the underside of the vehicle did not increase appreciably.

Figure 17: Fuel Line Leakage w Hood Open

Figure 18: Fuel Line Leakage w Hood Closed

Digges[38] observed that only minor overpressures (less than 0.25 psig) were measured from releases on the underbody of the vehicle, and for the low flow rate (24-g/min) releases in the engine compartment. These pressures are not typically considered high enough to cause bodily harm or window breakage. Overpressures nearest the underbody release remained relatively constant with increased duration due to the lack of confinement areas for hydrogen accumulation. At longer durations, the overpressure on the interior of the engine compartment did increase for the underbody releases, although not enough to cause any apparent damage to the vehicle.

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[38] MVFRI Research Summary, Kennerly H. Digges, Research In Fire Safety For Hydrogen-Fueled Vehicles Based On Contracts With: Southwest Research Institute and FIREXPLO.

In fact, in Digges's test damage to the vehicle was minimal for the majority of tests and consisted mainly of burnt plastic components. Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment. Temperatures for longer duration delayed-ignition tests, however, were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend as temperature data.

High temperatures were evident in the areas of the hydrogen release, and in areas such as the engine compartment, in which the hydrogen could collect. However, these temperatures were brief in the delayed ignition tests, insufficient to ignite surrounding exterior components. In the jet-fire tests, temperatures and heat fluxes were obviously of a magnitude and duration that could cause severe burns or ignite most plastic components. The extent of a jet-fire hazard would ultimately depend on the size, location, and direction of leak. At no time, however, was there a significant rise of temperature in the passenger compartment of the test vehicle.

This is in contrast to what GM discovered when it conducted similar tests with gasoline as the fire's fuel. It is possible that once the problem of tank rupture is solved (or at least the risk factor significantly reduced), a hydrogen fuelled vehicle may be considered safer than one fuelled with gasoline.

5.6 Hydrogen OEM Vehicle Fire Research

OEM fire testing of hydrogen vehicles has focused on using a point source of fire, i.e. either initiating a fire within the passenger compartment, or using a pool fire beneath the vehicle. One OEM has investigated the effects of a tire fire on an installed hydrogen tank.

The consensus of the OEMs appears to support the idea that the fire testing of a complete vehicle is an expensive proposition, and the results may be highly dependent on how a fire is initiated in or around the vehicle (cargo?, pooled fire?, passenger compartment?, engine compartment?). It is thus more cost effective to test fuel systems mounted in a simulated installation package.

Many tests have been concerned with the ignition of hydrogen mixtures either leaking into the vehicle, or leaking out of the tailpipe. These tests are not concerned directly with the fire safety of the fuel system, but the consequences of fuel leakage.