TECHNOLOGIES TO IMPROVE IMPACT RELATED FIRE SAFETY

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ABSTRACT

The research reported in this paper is a follow-on to a five year research program conducted by General Motors in accordance with an administrative Settlement Agreement reached with the US Department of Transportation. In a subsequent Judicial Settlement, GM agreed fund more than $4.1 million in fire-related research over the period 2001-2004. The purpose of this paper is to provide a public update report on the projects that have been funded under this latter research program, along with results to date. This paper is the sixth in a series of technical papers intended to disseminate the results of the ongoing research.

The projects and research results reported in this paper include statistical analyses of vehicle fires based on FARS and NASS and summaries of technologies to reduce crash induced fires

INTRODUCTION

The GM/DoT Settlement research program has been documented elsewhere [NHTSA 2001]. The research reported in this paper is a follow-on to that project.

The Fatality Analysis Reporting System (FARS) is a database maintained by the US Department of Transportation. It contains records of all fatal crashes that occur on public roads in the United States. The FARS database has been used to document the variations in fatal injuries annually since 1975.

The FARS database documents all fatalities that occurred as a result of the crash including those where a fire resulted. In this paper, the term "FARS Fatalities" designates the fatalities in which a fire occurred in the vehicle, regardless of whether or not the fire caused the fatality. Since 1979, FARS also coded the "most harmful event" (MHE). If the fire event has been coded as the most harmful event, burn or inhalation injuries are the most likely cause of the fatality. In many crashes, it may be difficult to discern the cause of the fatality (biomechanical trauma vs. fire trauma). This distinction was not investigated and the coding was taken directly from FARS. Previous studies have attempted to investigate the uncertainty and difficulty in coding fire as the most harmful event [Davies 2002].

Earlier papers reported that between 1979 and 2000, when fire was coded as the most harmful event (MHE), the fatality rates for vehicles less than 5 years old had declined by 72.4% [Friedman 2003 and 2005; Digges 2003]. The MHE fire rates for pickups less than 5 years old had reduced by 82.4%, but their rates were still higher than the rate for passenger cars.

A follow-on analysis grouped years of FARS data to examine changes in the fatal crashes with fires [Bahouth, 2007]. The figures presented in the earlier papers showed that the fire rates of vehicles generally decreased during the decade of the 1980's but have remained relatively constant since 1990. To examine these trends, the FARS years were aggregated into three groups – 1979-1989; 1990-1999; and 2000-2005. Figure 1 shows the FARS fire rate and FARS MHE fire rate using billions of annual vehicle miles traveled (VMT) as the denominator.

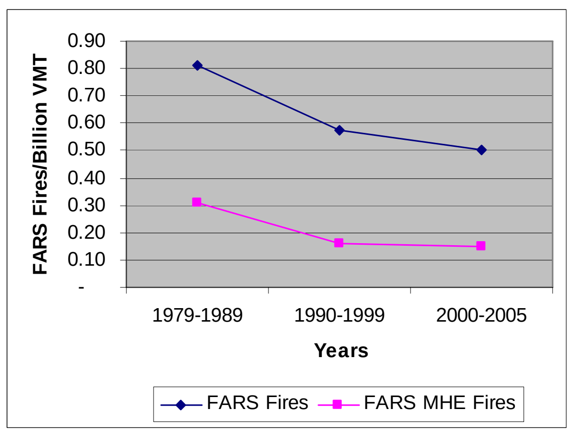

Figure 1. Fatalities in Vehicles with Fires and in Vehicles with Fire as the Most Harmful Event per Billion Vehicle Miles Traveled Annually - FARS

FARS does not record the direction of force in the crash. However, the location of principal damage is coded. In this coding, rollovers with damage from impacts with fixed objects or with other vehicles are coded according to the location of the damage. If the damage comes from ground contact, the crash is classified as a non-collision. Rollovers are classified according to the event during which it occurred (i.e. Non-rollover, rollover during 1st harmful event, or rollover during subsequent events). Most of the rollovers have damage to the front or sides of the vehicle. This damage may have been caused by impacts with fixed or non-fixed objects before or during the rollover. In some cases, these impacts may have been the cause of the fatality. The FARS can be examined by damage area only and without identifying the rollovers. However, in the analysis to follow, all rollovers are grouped together, regardless of the area of damage. No crashes with rollover are included in the front, side or rear damage areas. When FARS is analyzed in this way, the average annual fatalities are shown in Figure 2.

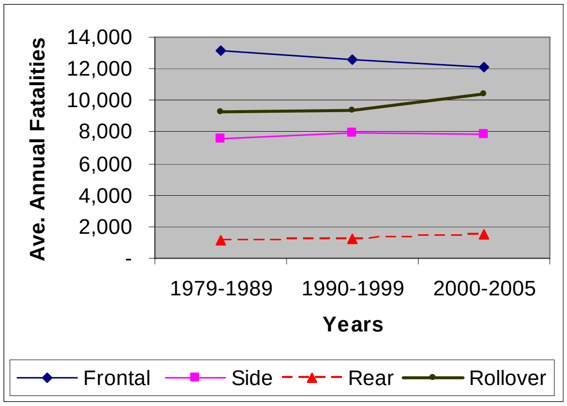

Figure 2. Average Annual Fatalities in Vehicles by Damage Area, with Rollover Separated - FARS

Using the same separation of rollovers as in Figure 2, the changes in fatalities when fire was the most harmful event can be examined. The results are plotted in Figure 3.

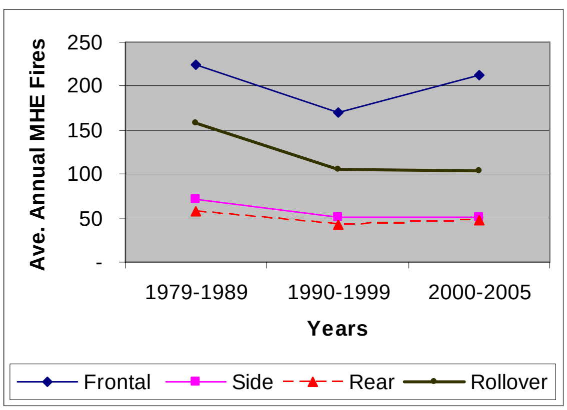

Figure 3. Average Annual Fatalities with Fire as the Most Harmful Event by Damage Area, with Rollovers Separated – FARS

Figure 4 shows the distribution of damage for the rollover fatalities in FARS years 2000 to 2005. The figure compares all rollover fatalities and rollover fatalities with fires. In the figure, non-collision and top damage were combined under "Roll". Left and right side damage were combined. "UCarr" is an abbreviation for undercarriage damage.

FARS does not provide data on fire origin and the designation of crash direction is by damage area. NASS provides better information on these variables and can be used in conjunction with FARS to gain a better understanding of collision related fires.

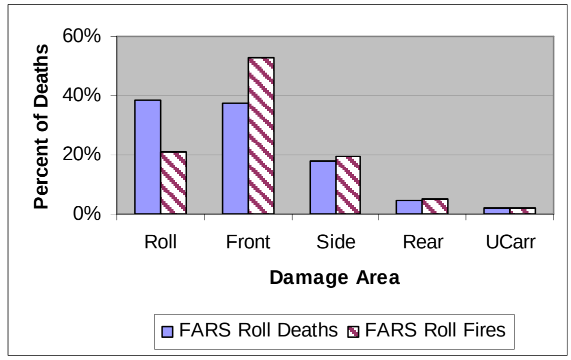

Figure 4. Damage Areas in Rollovers with Fatalities and Rollovers with Fires and Fatalities – FARS 2000-2005

NASS/CDS is a sample of tow away crashes that occur on US roads each year. The sample scheme stratifies cases by the severity of the crash. The sample rate for minor crashes is much lower than for severe crashes. In order to expand the stratified sample to the entire population it represents, an inflation factor is assigned to each case in the NASS/CDS sample. When the data is processed using the actual number of cases investigated, the data is referred to as "unweighted" or "raw." When the data is processed using the total of the inflation factors, the results should represent the total population of vehicles involved in tow-away crashes and the data is referred to as "weighted." In the analysis to follow weighted data estimates are reported. The figures to follow are based on a more detailed analysis of fires in NASS from George Washington University [Kildare, 2006]. This report contains both weighted and unweighted estimates.

One of the most significant variables in the analysis of fire occurrence is crash direction (mode). This variable specifies whether a crash is frontal, near side, far side, rear or rollover. Crash direction was defined using a combination of documented variables - principal direction of force (PDOF), general area of damage (GAD1) and rollover (ROLLOVER). The following criteria were used to establish crash direction.

Frontal - Frontal crashes were determined to be any crash where the PDOF was 1, 11, or 12 o'clock or was at either 10 or 2 o'clock with the highest deformation location coded as front (F).

Side - Side crashes were determined to be any crash where the PDOF was 3 or 4 o'clock or was at 2 o'clock with the highest deformation location not coded as front (F) or where the PDOF was 8 or 9 o'clock or was at 10 o'clock with the highest deformation location not coded as front (F).

Rear - Rear crashes were determined to be any crash where the PDOF was 5, 6 or 7 o'clock.

Rollover - Rollover crashes were determined to be any crash where a rollover was indicated by the variable ROLLOVER. It is important to note that crashes with any involvement of rollover were included as a rollover crash. Multiple impacts with any other planar impact occurring first would be included as a rollover crash.

Other - All Crashes not meeting the criteria of the other aforementioned crash directions was labeled as 'Other.' Some of the vehicles in NASS do not have a PDOF assigned. These vehicles with unknown PDOF were included in the 'Other" category.

NASS/CDS classifies fires as either Minor or Major. These fire severities are defined as the following:
A Minor Fire is a general term used to describe the degree of fire involvement and is used in the following situations:

- Engine compartment only fire
- Trunk compartment only fire
- Partial passenger compartment only fire
- Undercarriage only fire
- Tire(s) only fire.

A Major Fire is defined as those situations where the vehicle experienced a greater fire involvement than defined under "minor" above, and is used in the following situations:

- Total passenger compartment fire
- Combined engine and passenger compartment fire (either partial or total passenger compartment involvement)
- Combined trunk and passenger compartment fire (either partial or total passenger compartment involvement)
- Combined undercarriage and passenger compartment (either partial or total passenger compartment involvement)
- Combined tire(s) and passenger compartment (either partial or total passenger compartment involvement)

About 50% of the fires in NASS/CDS are classified as "Major". This is true for both weighted and unweighted data [Kildare 2006].

Figure 5 shows the distribution of all crashes (with and without fires) and crashes with major fires by crash direction. The distribution of minor fires is generally similar to major fire distribution [Kildare 2006].

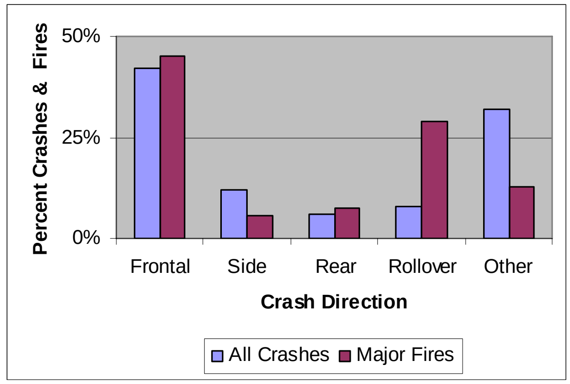

Figure 5. Distribution of Crashes and Crashes with Major Fires, by Crash Direction – NASS 1995-2004

Figure 6 shows the frequency of fires per 100 crashes for each crash mode. The denominator for the rate calculation is the total number of crashes in the crash mode under consideration.

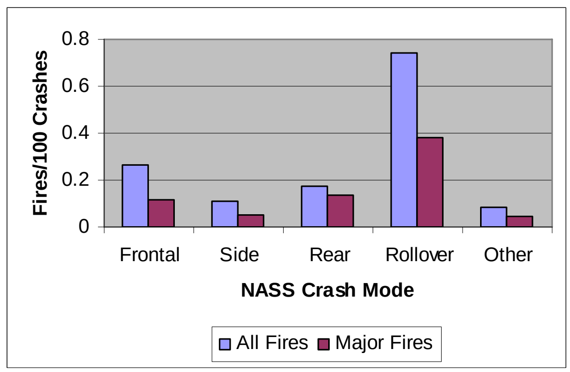

Figure 6. Rates of Crashes with Fires and Crashes with Major Fires, by Crash Direction – NASS 1995-2004

NASS also codes the fire origin. The distribution of the origins for major fires is shown in Figure 7. Over 60% of major fires originate in the engine compartment.

A further breakdown of major fire origins by frontal and rollover crash mode is shown in Figure 8. The engine compartment was the most frequent major fire origin for both the frontal and rollover crash modes. For the rollover crash mode, the fuel tank origin was a close second in major fire frequency.

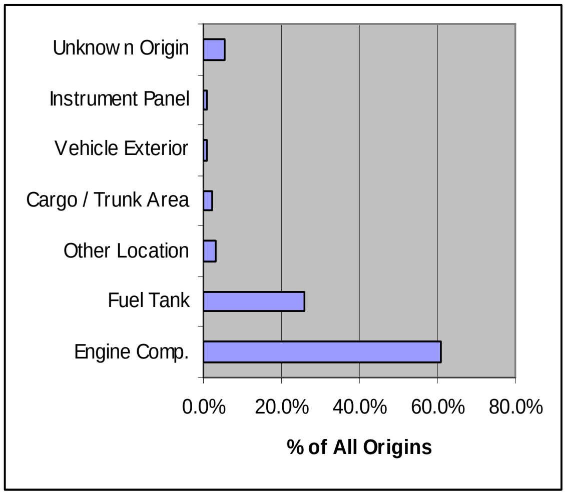

Figure 7. Distribution of Origins for Major Fires, All Crash Modes– NASS 1995-2004

Examination of individual cases of major fires in NASS 1997-2004 rollovers found that impacts prior to the rollover occurred in all cases with fuel tank fire origins for model year 1997 and later vehicles (Digges & Kildare, 2007). The study also found that seventy percent of the cases had engine compartment fire origins. About half of the cases with major engine compartment fires in rollovers did not involve significant impacts prior to the rollover.

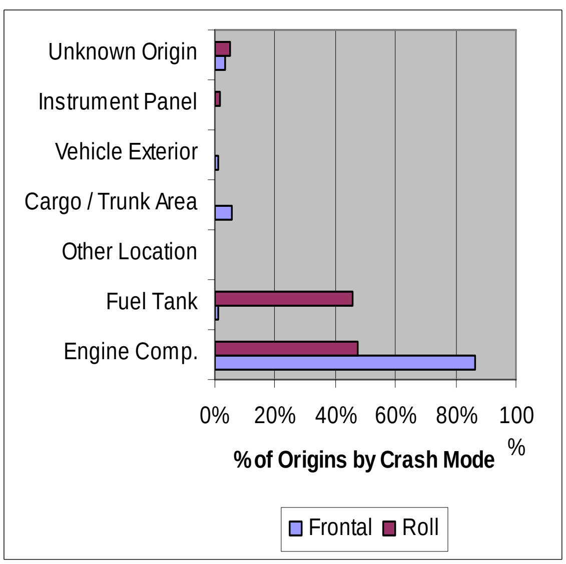

Figure 8. Distribution of Origins for Major Fires, Frontal and Rollover Crashes– NASS 1995-2004

The vehicle damage patterns exhibited by vehicles with fires in NASS have been analyzed and the results reported in a recent paper [Bahouth, 2006].

DISCUSSION OF FIRE DATA

As with other highway crash types, the rate of fires in fatal crashes per billion annual vehicle miles traveled has decreased significantly during the past twenty-five years. The decline is displayed in Figure 1.

During the same period, the annual average number of fatalities in vehicles with frontal damage has decreased, while fatalities in rollovers have increased. These trends are shown in Figure 2.

Except for frontal crashes, there is a downward trend in the annual number of fatalities where fire was the most harmful event (MHE). This trend is shown in Figure 3. However, for frontal damage crashes, the trend for fatalities with fire as the most harmful event has been upward during the past five years. During this same period, Figure 2 shows that the overall trend in fatalities in vehicles with frontal damage has been downward.

Figure 4 presents data on the location of vehicle damage in fatal rollover crashes. An examination of the vehicle damage areas in rollovers shows that the majority of FARS rollovers with fires also have frontal damage. These rollovers with frontal damage also have the highest fire rates. The lowest fire rates are in rollovers that have top damage or damage from the ground (non- collision). These latter two classes contribute about 20% of the rollovers with fires and fatalities.

The NASS data for major fires generally confirms the FARS data with regard to frequency of fires by crash direction or vehicle damage area. Figure 5 shows that nearly half of major fires are in frontal crashes. Rollovers contribute about 30% of the major fires and have the highest fire rate. The high fire rates for rollovers relative to the other crash modes are displayed in Figure 6.

Figures 7 and 8 provide information on the origins for major fires. Figure 7 shows that over 60% of major fires in NASS have their origins in the engine compartment. Figure 8 shows that for frontal crashes, over 80% of the major fires originate in the engine compartment. For rollovers, 47% originate in the engine compartment. This data indicates an opportunity to further improve fire safety by controlling engine compartment fires.

The lethality of engine compartment fires depends on the time available between the ignition of the fire and the time required for it to penetrate the occupant compartment. In the event occupants are trapped or immobile due to injuries, the rescue time also becomes a critical factor. Data on rescue times has been published earlier [Digges 2005]. The 75% percentile rescue time for FARS rural cases was 24 minutes.

Data on the fire penetration time for selected tests conducted by General Motors has also been published [Tewarson, SAE 2005-01-1555]. In three tests of crashed vehicles with fires ignited in the engine compartment, the time to occupant compartment fire penetration varied from 10 to 23.5 minutes. The tests showed that once flames from the engine compartment penetrated the occupant compartment, the time to untenability was extremely short – a maximum of 3 minutes. This short tenability time of the occupant compartment when exposed to intense flames further amplifies the need to prevent or control engine compartment fires and delay their penetration of the occupant compartment.

The challenge of controlling engine compartment fires has increased with time due to the increasing amount of plastics used in motor vehicles. The amount of combustible materials has increased from 20 lbs per vehicle in 1960 [NAS 1979] to 200 lbs in 1996 [Twearson, 1997, Abu, 1998,]. Combustible plastics now constitute the major fire load (twice the weight and heat content of the gasoline) in a typical vehicle and these combustible materials are often ignited and contribute to the intensity of an automobile fire [Aherns, 2005; Friedman, 2005].

SUMMARY OF ENGINE COMPARTMENT FIRE TESTS AND MATERIALS FIRE PROPERTIES

Under a contract with MVFRI, the GM/DOT Settlement research program in motor vehicle fire safety has been summarized by a team of fire experts led by FM Global [Tewerson, Vols I, II and III, 2005]. Of particular interest has been the analysis of eleven, highly instrumented burn tests using crashed vehicles. These tests included underhood ignition scenarios and spilled fuel fires of an intensity that could be possible after a crash. The test results were summarized in an earlier ESV paper [Digges 2005].

Three of the vehicles that had undergone frontal crashes were then subjected to underhood fires with ignition sources either at the battery location or by the ignition of sprays and pools of mixtures of hot engine compartment fluids from a propane flame located in and below the engine compartment.

For the three crashed vehicle burn tests with ignition in and under the engine compartment, flame penetration time into the passenger compartment varied between 10 to 23.5 minutes. Once the flame penetrated the passenger compartment, the environment rapidly became untenable. The time between flame penetration and untenability of the passenger compartment varied from 48 seconds to 3 minutes.

The windshield and the bulkhead were the principal ports of entry for the flame spread into the occupant compartment. If the hood remained relatively intact, the fire tended to enter through openings in the bulkhead. The windshield was the principal flame entry port when it was directly exposed to flame as a consequence of openings in the hood near the base of the windshield. Whether the windshield is intact or broken as a result of the crash will also influence the rate of flame spread into the passenger compartment.

Additional research summarized test procedures to determine fire behavior of materials [Tewerson Vol 2 2005] and thermophysical properties of automotive plastics and engine compartment fluids [Tewerson Vol 3, 2005 and SAE 2005-01-1560, 2005]. Data on the toxicity and thermophysical properties of automotive plastics was reported by Southwest Research under a related research project funded by NHTSA and MVFRI [Battipaglia, 2003; Griffith, 2005]. A comparison of the fire properties of plastics used in aircraft with those used in automotive applications was reported by Lyon and Walters [Lyon 2005].

ENGINE COMPARTMENT FIRE SAFETY FEATURES

Possible countermeasures for engine compartment fires fall into three categories: (1) fire prevention, (2) delay in fire penetration of the occupant compartment and (3) fire suppression. The three areas will be discussed separately.

Fire Prevention

Considerable fire prevention technology is present in vehicles on the road. To assess this technology, a database of 2003 model year vehicles was assembled and the technologies were documented in a database [Fournier 2001]. Lists of available fire prevention technologies were summarized in subsequent papers [Fournier, SAE 2005-01-1423 and Report R06-20, 2006]. The design considerations discussed included:

- Structural crashworthiness of the vehicle frame
- Tank placement
- Fuel line routing/compliance
- Tank materials selection
- Fuel filler connections
- Electrical grounding
- Battery placement

The technologies that were reviewed included:

- Check valves for the tank filler tube
- Roll-over valves
- Shut-off mechanisms for electronic fuel pumps
- Returnless fuel systems that reduce the exposure to damage
- Crash sensing battery disconnects or cut-offs
- Collapsible drive shafts

Research was initiated to explore possible ignition sources for engine compartment fires. Tests were conduced by Biokinetics to measure engine compartment and exhaust component surface temperatures of four different classes of vehicles during driving conditions and when the vehicle was stopped after driving [Fournier, R04-13, 2004 and R06-23, 2006]. While driving uphill, the maximum temperature measured on the surface of the exhaust manifold varied from a low of 241 ^{o}C for a minivan to a high of 550 ^{o}C for a passenger car. Tests of underhood fluids showed that the minimum temperature of a hot surface to cause ignition was in the order of 310 ^{o}C for lubricants and 518 ^{o}C for coolants [Tewarson, SAE 2005-01-1650].

The Friedman Research Corporation used state police reported accident data to examine the frequency of fires in pickup trucks of the same model but with different engines. The state data showed that the eight cylinder (V-8) engines had a higher fire rate than the inline six cylinder engines. An obvious difference is the increased exposure of the exhaust manifold in the V-8 [Friedman, 2006].

A considerable difference was noted in the maximum temperature of exhaust components for different vehicles under similar operating conditions. Control of the maximum underhood temperature, as exhibited by the vehicle with the lowest exhaust temperature, could provide an opportunity for improved fire safety, by reducing the intensity of a possible ignition source.

The prevention of fluid leakage offers another opportunity for improved fire safety. A research program by Biokinetics investigated and documented the technology in present day vehicles to prevent fuel leakage when lines from the fuel tank are severed [Fournier, R0-6-20, 2006].

Biokinetics conducted leakage tests on 20 fuel tanks to study the fuel containment technologies employed and their performance. The tests simulated a vehicle rollover by rotating a tank, filled to capacity, about an axis that when installed in a vehicle would be parallel to the vehicle's longitudinal axis. The tanks were rotated to seven discreet positions during the rollover simulation. None of the tanks leaked when all hoses were intact. In each position, the fuel system hoses were disconnected one at a time to represent a damaged or severed line and the resulting leaks were observed. The results of the testing showed that six of the tanks leaked in every orientation and ten leaked in some orientations. However, four did not leak with each of the lines severed and when subjected to all orientations. The results of these tests are discussed in more detail in earlier papers [Fournier, R04-06c, 2004; Digges, 2005].

Another recent paper by Biokinetics has documented in detail the technology that prevents leakage when lines are severed [Fournier R06-20, 2006]. This report also evaluates the technology available to prevent siphoning of the fuel from the tank after a fuel line is severed.

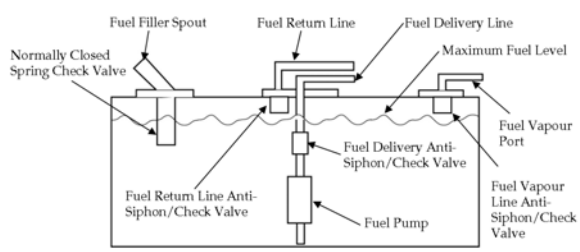

Figure 9 - Fuel Tank Leakage Prevention Components Found in Service (after Fournier, July 2006)

Some leakage prevention technologies currently incorporated in vehicles are illustrated in Figure 9. They include a check valve in the fuel filler spout, and check and anti-siphon valves in the fuel delivery line, the fuel vapor port and the fuel return line. Other leakage prevention technologies include inertia shut-off switches, logic built into engine computer controls and other monitoring devices that automatically shut down the fuel pump when a concern is detected. Some vehicles have eliminated the fuel return line, thereby reducing the opportunity for fuel to escape.

Delay of Fire Penetration

Test data and inspection of crashed vehicles with engine compartment fires indicates that there are two principal areas for fire entry into the occupant compartment – the firewall and the windshield. Once the flames breach the hood and impinge on the windshield, there is a large vulnerability to rapid occupant compartment penetration via a broken and collapsed windshield. If the flames are contained under the hood, the firewall becomes a vulnerable fire penetration area.

An opportunity for reducing the firewall vulnerability is by minimizing the area of openings through which the fire can penetrate. One approach to reduce openings studied during the GM/DoT research program was the use of intumescent materials that would expand with heat and close openings [Hamins, 2007]. The research was not successful with the intumescent materials that were used. Another suggested approach was to apply mechanical devices to close the largest openings. This approach was not investigated.

Even if technology is not applied to the firewall fire penetration problem, there are designs that may be beneficial. Competitive vehicles display large differences in the area of openings in the metal firewall. Typical examples are shown in Figures 10 and 11. Figure 10 shows a large opening on the left side for the heating and air conditioning system. The ducting for the system is flammable and could burn away in an engine compartment fire, providing an entry to the occupant compartment. The firewall in Figure 11 has a much smaller opening and, therefore, should be beneficial in resisting the penetration of flames into the occupant compartment.

Another path for flames to enter the occupant compartment is through the windshield. The fire shield offered by the firewall, hood and cowl can delay the spread of fire in the direction of the windshield. However, in recent vehicles, the metal in the cowl area has been replaced with combustible plastics. As a consequence, the opportunity for fire to burn through the cowl area and impinge on the windshield is increased.

Figure 12 illustrates that the plastic cowl between the hood and firewall burns away during an engine compartment fire. For crashes in which the hood remains intact, cowl designs to resist fire penetration could extend the time until flames impinge on the windshield and expose the occupant compartment to the fire.

Figure 10 – Vehicle Firewall with Large Openings

Figure 11 – Vehicle Firewall with Small Openings

Figure 12 –Vehicle with Plastic Cowl Consumed

During the MVFRI survey of fire safety technologies in new vehicles, several car sales personnel indicated that the underhood liners on their vehicles could serve as fire blankets and act to smother engine compartment fires. These claims prompted a research project to evaluate the fire resistant properties on underhood insulation materials. During this project, Biokinetics measured the heat release rate of twenty different underhood liners to examine the extent that these materials might mitigate or aggravate the containment of an underhood fire [Fournier R06-23, 2005; Digges, 2006]. The results showed that the differences in heat release rate ranged over two orders of magnitude. The materials with the lowest heat release rate resisted combustion and could have aided in reducing the fire intensity. Those with the highest heat release rate contributed fuel to the engine compartment fire. There appeared to be no correlation between the cost of the vehicle and the heat release rate of the underhood liner. Additional specifications to improve the fire resistance of underhood liners could reduce the fuel load in the engine compartment and might contribute to reducing the fire growth rate.

Fire Suppression

Fire suppression of underhood fires is in the early stages and offers considerable promise. Several technologies have been researched and there are fire suppression products for a variety of applications on the market [Hamins, 2007]. In an earlier research project, University of Maryland demonstrated a foam based underhood fire suppression system [Gunderson 2005]. The system demonstrated the ability to extinguish an 80kW fire fed by a pool of fuel located near the battery.

One of the impediments to the deployment of an underhood fire suppression system is the lack of specifications to determine its efficacy. To assist in understanding the requirements for suppression systems specifications, a research project was undertaken by NIST. A summary report outlined the requirements and considerations for motor vehicle fire suppression, including suppression of underhood fires [Hamins, 2007]. Some of the considerations are as follows:

- Post-crash vehicle fires differ from fires in intact vehicles, as the geometric configuration may be modified by the collision in ways that cannot be precisely defined beforehand.
- The final orientation of the crashed vehicle may influence the fire ignition and growth rate, and the suppression system requirements.
- Underhood fires occur in a compartment that is partially open to the environment, which can lead to suppressant loss.
- The time of initiation of a fire after a collision can vary.
- Re-ignition of the fire may occur if the fire sources remain after the suppressant has been expended.
- Ambient factors such as temperature, wind, and incline of the road may influence suppression system performance.

CONCLUSIONS

Frontal and rollover crashes account for most major fires in NASS. The engine compartment is the most frequent origin of major fires in frontal and rollover crashes. The fuel tank is also a frequent origin of major fires in rollovers, but impacts prior to the rollover may be a major cause of fuel tank spillage in these events.

When examining 2000-2005 FARS fatalities with fire as the most harmful event, frontal damage crashes account for more that half of the population. Rollovers account for another twenty-five percent.

Controlling fires in frontal and rollover crashes offers the largest opportunity for fire safety improvements. A number of present-day vehicles incorporate technologies to prevent fuel leakage in rollovers. There are other technologies to delay the fire penetration into the occupant compartment. However, these technologies are not universally employed. Additional attention to the fire safety in frontal and rollover crashes is needed to offset the increased fuel load from combustible plastics that is present in today's motor vehicles.

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Further details of research and progress associated with this work may be obtained at: www.mvfri.org

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