CRASHES THAT RESULT IN FIRES

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ABSRTACT

NASS and FARS data were analyzed to determine the crash environments that produced major fires. Case reviews were conducted for NASS cases with a major fire. Annually, there are about 400 fatalities in FARS with fire as the most harmful vehicle event. There are about 60 cases annually in NASS with a fire recorded. FARS years since 1978 and NASS years since 1997 were studied. NASS and FARS fire statistics for different crash modes with documented fires are presented. Also included are plots of deformation profiles for NASS vehicles with fires. These plots show damage profiles at the 10%, 25% and 50% frequency of occurrence levels. The frontal crash mode accounts for about half of the fires in FARS and NASS. Rollovers account for about 25% of the major fires in NASS and carry the highest risk of fatality in FARS fires. In NASS, the vast majority fires that occur in frontal and rollover crashes originate under the hood. Incapacitation and entrapment of occupants are important survival factors when underhood fires occur.

INTRODUCTION

The Motor Vehicle Fire Research Institute (MVFRI) was formed to conduct this research to improve the fire safety of present and future motor vehicles. Research to better understand the nature of motor vehicle fires was initiated in 2001 and completed in 2009. The purpose of this paper is to document the major results of the research to identify the crash characteristics associated with crash initiated fires in passenger vehicles. Since the research was conducted at different times, the periods during which the data was analyzed may vary. The detailed reports are listed in the Reference section of the paper and are available on the MVFRI website, mvfri.org.

Investigations of fire occurrence have been undertaken with a focus on identifying the conditions that produce crash induced fires. The examination of crash modes, fire origins and vehicle attributes were included. NASS and FARS data were researched under contracts with George Washington University, Pacific Institute or Research and Evaluation and Dr. George Bahouth. Friedman Research and Associates examined state data and FARS data in conjunction with the other databases. Some of the highlights from these studies are included in this paper.

FARS DATA ON FIRES

FARS is a census of fatal crashes that occur on public roads. FARS assigns the Most Harmful Event (MHE) to vehicles involved in crashes with a fatality. The MHE applies to the vehicle not the persons in the vehicle. Consequently, there is no certainty that the fatalities were associated with the fire rather than the crash forces.

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 (ie. 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. In the analysis to follow, all rollovers are grouped together, regardless of the area of damage. No crashes with rollover are included in the groupings of front, side or rear damage areas.

Table 1 shows the damage distribution for the subset of cases with fire as the most harmful event. The data is separated into cases with and without rollovers. The damage in rollover may be caused by the rollover or by objects impacted before or during the rollover. Table 2 shows data for fatal fires with entrapment. In the 1994 to 2003 FARS years of data, the entrapment rate for the fatalities with fire as MHE was 23%. [Bahouth, 2007, Digges, SAE 2005].

Table 1. Distribution of Average Annual Fatalities when Fire was Most Harmful Event by Crash Type and Damage Location – FARS 2000 to 2005

Damage Location	No Roll	Rollover	Total
Non-Collision	2.1%	3.3%	5.4%
Front	45.8%	14.5%	60.3%
Right	5.8%	2.5%	8.3%
Rear	9.4%	2.0%	11.4%
Left	5.6%	2.1%	7.8%
Top	0.4%	1.4%	1.9%
Undercarriage	1.0%	0.6%	1.6%
Unknown	1.7%	1.7%	3.4%
Total	71.8%	28.2%	100.0%

Table 2. Distribution of Average Annual Fatalities with Entrapment when Fire was Most Harmful Event by Crash Type and Damage Location – FARS 2000 to 2005

Damage Location	No Roll	Rollover	Total
Non-Collision	18%	23%	21%
Front	23%	25%	23%
Right	21%	22%	21%
Rear	28%	28%	28%
Left	27%	20%	25%
Top	22%	19%	20%
Undercarriage	21%	18%	20%
Unknown	15%	15%	15%
Total	23%	23%	23%

NASS/CDS DATA ON FIRES

Research performed at the GW University used the National Automotive Sampling System - Crashworthiness Data System (NASS/CDS) data to examine the crash factors that are associated with crash induced motor vehicle fires [Kildare, 2006].

NASS/CDS is a sample of tow away crashes that occur on US roads each year. The sample is stratified 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 and the data is referred to as "weighted."

NASS/CDS classifies fires as either Major or Minor. 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)

Table 3 shows the summary of the complete data set of NASS major and minor fires. In total over the 11 year period from 1994-2004, 631 fires in vehicles were recorded in NASS/CDS, representing 79,354 weighted cases. The cases were approximately evenly distributed between minor and major fire occurrences unweighted (46% / 54%) and weighted (52% / 48%). During the same period there were 71,101 cases of vehicles without fires.

Table 3. Distribution of Vehicle Fire Cases in NASS/CDS 1994/2004 – Unweighted and Weighted

	Fire Severity				
Type	Minor	Major	Unk.	All Fires	No Fire
Unwg.	290	335	6	631	71,101
Wht.	40,994	38,173	187	79,354	35,955,359

The data in Table 3 is the basis for the tables to follow in this section. Subsequent tables will show distributions of this data by extent of vehicle damage, extent of injuries, and crash direction. For convenience, percentages are used in the tables rather than the actual numbers.

NASS data provides several methods to characterize the severity of crashes. One involves coding the

extent of damage caused by the crash using the Collision Damage Classification (CDC) as specified by SAE standard J224. The CDC describes the vehicle damage including the degree to which the damage extends inward toward the vehicle. This code partitions the vehicle into nine segments. For side crashes, the nine segments are parallel to the side of the vehicle and extend across the vehicle. A CDC extent of damage 6 would penetrate the vehicle centerline. For front and rear damage, a CDC extent of damage 6 would penetrate the occupant compartment.

Tables 4 and 5 show the distribution of the CDC extent of damage for all vehicles, vehicles in crashes with fires and vehicles with both fire and entrapment. The last row in the table shows the percentage of vehicles in each category that have a CDC extent of damage of 4 or greater. Tables for both weighted and unweighted data are shown.

Table 4. Extent of Damage (CDC) All Vehicles and Fire Cases in NASS/CDS 1994/2004 – Unweighted

Damage Ext	All Vehicles	Fire Vehicles	Fire + Entrapment
1	22%	8%	0%
2	33%	22%	5%
3	25%	25%	13%
4	9%	15%	21%
5	4%	11%	21%
6	3%	9%	19%
7	1%	6%	12%
8	1%	1%	3%
9	2%	3%	5%
4+	20%	46%	82%

Table 5. Extent of Damage (CDC) All Vehicles and Fire Cases in NASS/CDS 1994/2004 – Weighted

Damage Ext.	All Vehicles	Fire Vehicles	Fire + Entrapment
1	35%	7%	0%
2	35%	36%	2%
3	18%	21%	17%
4	5%	9%	23%
5	2%	7%	20%
6	2%	6%	25%
7	1%	11%	8%
8	0%	1%	3%
9	1%	2%	2%
4+	12%	35%	81%

A more detailed investigation of the damage patterns of vehicles with crash induced fires was conduced by the Pacific Institute for Research and Evaluation, PIRE [Bahouth 2006]. The percentile damage patterns for vehicles with crash induced major fires are shown in Figure 1. The vehicle front is to the left and the rear toward the right. The 5th, 10th, 25th and 50th percentiles of damage profiles are plotted. The contours in Figure 1 show how frequently each area of the vehicle is damaged. Left and right side damage has been combined. The contours are based on all crashes with major fires and recorded damage in NASS 1995-2004.

Figure 1 shows the distribution of damage outcome but it does not reflect the relative frequency of the crashes with fires for the various crash directions. The corresponding crash frequencies are 68% frontal, 25% side and 7% rear.

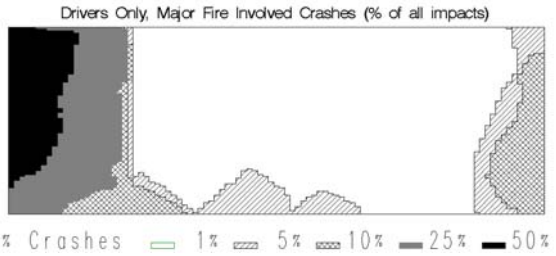

Figure 1. Vehicle Damage Patterns for Major Fires Based on NASS 1995-2004 Weighted (Bahouth, 2006)

Tables 6 and 7 show the distributions of MAIS injuries for the same categories of vehicles as in Tables 4 and 5. MAIS is a person level injury severity rating based on the most severe AIS injury suffered by an individual. AIS stands for the "Abbreviated Injury Scale", an injury severity rating developed by the Association for the Advancement of Automotive Medicine.

Table 6. Extent of Injuries - Vehicles and Fire Cases in NASS/CDS 1994/2004 Unweighted

Unweighted			
MAIS	All Vehicles	Fire Vehicles	Fire + Entrap
0	24%	9%	1%
1	44%	22%	9%
2	14%	14%	13%
3	10%	18%	20%
4	4%	9%	11%
5	3%	10%	10%
6	1%	18%	36%
3+	19%	55%	77%

Table 7. Extent of Injuries - Vehicles and Fire Cases in NASS/CDS 1994/2004 - Weighted

Weighted			
MAIS	All Vehicles	Fire Vehicles	Fire + Entrap
0	49%	27%	0%
1	42%	37%	15%
2	6%	9%	14%
3	2%	9%	14%
4	1%	4%	7%
5	0.4%	4%	7%
6	0.1%	9%	42%
3+	3%	27%	71%

The AIS system assigns an injury severity rating to each injury suffered by a person. This rating scale ranges from 1 to 6. The risk of death increases with each AIS level. AIS 6 is nearly certain death. AIS 1 and 2 are classified as minor and moderate injuries with very low risk of death. AIS 3 and above are serious and severe injuries. A person may suffer more than one injury. MAIS (M = Maximum) designates the most severe AIS that a person suffers and MAIS 3+ indicates people who suffer one or more injuries of severity AIS 3 or greater. In NASS cases, about 20% of the vehicle occupants with MAIS 3+ injuries ultimately die from the injury or from complications including those associated with advanced age and preexisting medical conditions. Deaths from injuries less severe than MAIS 6 have not been segregated in the table. The last row in the table shows the percentage of vehicles whose occupants have injuries of MAIS 3 or greater.

Tables 8 and 9 show the distribution of crash involved vehicles using the 'Crash Direction' variable to classify the mode of the crash. The definition of each crash mode is discussed in the paragraphs to follow.

Frontal crashes were determined to be any crash where the Principal Direction of Force, (PDOF) was 1, 11, or 12 o'clock or at 10 and 2 o'clock when the highest CDC deformation location was coded as front (F). This definition is used by NHTSA in their analysis of frontal crashes.

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

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; hence multiple impacts with any other planar impact occurring first would also be included as a rollover crash. A classification of rollover indicates that a rollover event was involved in the crash at some point.

All crashes not meeting the criteria of the other aforementioned crash directions was labeled as 'Other.' About 25% of NASS cases exhibit complexities of the crash mode so that they do not fit the defined categories for frontal, side, rear and rollover.

Tables 8 and 9 show the distribution by crash mode of all fire crashes and the major and minor fires for each crash mode. Tables of both weighted and unweighted data are shown.

Table 8. Distribution of No Fire and Fire Cases in NASS/CDS by the Fire Severity and Crash Mode - Unweighted

Unwgt	Fire Severity		All Fire and Crashes	
Type	Minor	Major	All Fire	All Crashes
Frontal	50%	50%	55%	45%
Side	49%	51%	10%	13%
Rear	23%	77%	7%	5%
Rollover	49%	51%	22%	11%
Other	23%	77%	6%	26%
Total	46%	54%	100%	100%

Table 9. Distribution of No Fire and Fire Cases in NASS/CDS by the Fire Severity and Crash Mode Weighted

Weighted	Fire Severity		All Fire and Crashes	
Type	Minor	Major	All Fire	All Crashes
Frontal	57%	43%	50%	42%
Side	55%	45%	6%	12%
Rear	23%	77%	5%	6%
Rollover	49%	51%	27%	8%
Other	48%	52%	12%	32%
Total	52%	48%	100%	100%

Table 10 shows the distribution vehicle fires in NASS by crash direction and fire severity for weighted and unweighted data.

Table 10. Distribution of Fire Cases in NASS/CDS by the Fire Severity and Crash Direction – NASS/CDS 1994-2004 – Unweighted and Weighted Data

	Unweighted		Weighted	
Type	Minor	Major	Minor	Major
Frontal	59%	51%	55%	45%
Side	11%	10%	6%	6%
Rear	4%	10%	2%	8%
Rollover	23%	21%	25%	29%
Other	3%	9%	11%	13%
Total	100%	100%	100%	100%

Figure 2 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.

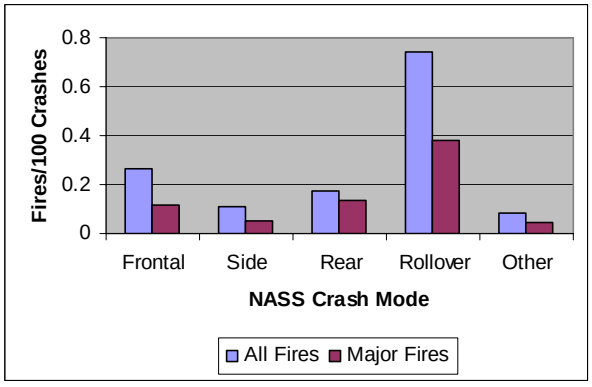

Figure 2. Rates of Crashes with Fires and Crashes with Major Fires, by Crash Direction – NASS 1995-2004

Tables 11 and 12 display the distribution of fire origin by crash direction. Fires of all severity are included in the data. The abbreviations are for occupant compartment and engine compartment. Fires originating in the cargo/trunk and other areas are included in the Ext. category. Tables for both unweighted and weighted data are shown.

Table 11. Fire Origin in Crashes by Crash Direction, Fires of All Severity; NASS/CDS 1994-2004 –Unweighted Data

Unwgt	Eng. Comp.	Fuel Tank	Occ. Comp.	Exter.	Unk
Frontal	86%	2%	3%	5%	3%
Side	54%	26%	4%	7%	9%
Rear	18%	54%	4%	14%	11%
Roll	63%	20%	3%	5%	9%
Other	59%	12%	0%	6%	24%
All	72%	13%	3%	6%	6%

Table 12. Fire Origin in Crashes by Crash Direction, Fires of All Severity; NASS/CDS 1994-2004 –Weighted Data

Weight	Eng. Comp.	Fuel Tank	Occ. Comp.	Exter.	Unk
Frontal	93%	1%	1%	4%	1%
Side	59%	30%	3%	2%	5%
Rear	26%	58%	1%	12%	4%
Roll	66%	28%	1%	2%	3%
Other	80%	15%	0%	0%	5%
All	78%	15%	1%	4%	2%

Table 13 displays the distribution of fire origin recorded in NASS for fires of all severity and crashes in all directions. The 'Exterior' cell includes fires from the trunk, wheels and other areas outside the passenger compartment.

Table 13. Fire Origin in Crashes by Crash Direction, Fires of All Severity and All Crash Directions; NASS/CDS 1995-2004 – Weighted and Unweighted Data (Bahouth, 2006)

	Unweighted		Weighted	
Type	Minor	Major	Minor	Major
Eng. Com.	87%	51%	84%	61%
Fuel Tank	2%	22%	1%	29%
Occ. Com.	3%	21%	10%	2%
Exterior	7%	6%	5%	8%

ENGINE COMPARTMENT FIRES

The previous tables have shown the prevalence of engine compartment fires that occur in NASS crashes. A further examination of these fires is merited. A study by PIRE investigated the damage patterns that are associated with engine compartment fires [Bahouth, 2006]. Some of the results are summarized in the tables and figures to follow.

Table 14 shows the distribution of crashes with engine compartment fires by crash direction. Other locations not shown in the figure include the trunk area, passenger compartment, instrument panel and wheels/brakes.

Table 14. Vehicle Populations where Fire Origin was Engine Compartment - NASS CDS 1995-2004 - Unweighted and Weighted

Damage Area	Unweighted	Weighted
Front	84%	89%
Rear	1%	0%
Left	9%	7%
Right	6%	4%

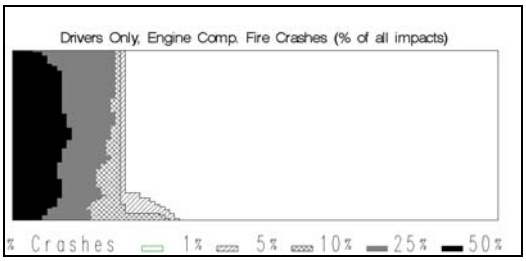

Figure 3. Damage Patterns where Fire Origin is Engine Compartment - NASS CDS 1995-2004 Weighted

Figure 3 shows the 5th, 25th and 50th percentile damage patterns for crashes where a fire originated in the engine compartment. As shown in Table 13, these are largely frontal crashes. However a small population of side crashes and rollover events results in engine compartment fires as well. This analysis did not include the rollover crashes with engine compartment fires.

A case by case study of major fires in rollovers found that in 17 of 24 NASS cases, the fire origin was in the engine compartment [Digges 2007]. About half of these fires were in rollovers that were induced by tripping mechanisms with the wheels coded as the impact location. It was observed that these engine compartment fires could occur without severe damage to the vehicle except for the roof. This type of vehicle damage is illustrated in Figures 4 and 5.

Figure 4. Major Fire after Rollover with Engine Compartment Origin – NASS Case 1997-41-126

Figure 5. Major Fire after Rollover with Engine Compartment Origin – NASS Case 2001-18-58

A case-by-case study of major fires in frontal crashes found that run-off-the road and pole impacts were the most frequent characteristics of engine compartment fires in the NASS cases studied [Digges 2008].

STATE DATA ANALYSIS

Analysis of state data was performed under contract with Friedman Research Corporation (Friedman 2003 and 2005). Four states were found to record fire data along with crash direction and severity. The analysis found that the highest fire rates for both passenger cars and LTV's was in rollover crashes.

In the 2005 report, Friedman examined attributes of pickup trucks that may have been associated with large reduction in fire rates observed in FARS during the period 1979-2001 [Friedman 2005 and 2006]. Fuel injection appears to have reduced the fire rates. There was no consistent difference regarding engine size, but for one pickup model, the I6 had a lower fire rate than the V8. Check valves appeared to reduce the fire rate in rear impacts. Fuel cut-off switches appeared to be beneficial in rollovers.

DISCUSSION

In recent model year passenger vehicles, the fire threat has increased in frontal crashes and rollovers. The most frequent fire origin is the engine compartment. About half of the engine compartment fires spread to the occupant compartment. There is generally more time to escape from these fires as

compared to fires with a fuel tank origin. However, entrapment occurs in about 23% of FARS cases with fire as the MHE. Continued improvement in egress and rescue offer promise of further reductions of fire related casualties. Control of engine compartment fluid leakage and of electrical isolation in all crashes, including rollovers, are other promising fire safety countermeasures.

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REFERENCES

Bahouth , G., "Analysis of Fire Related Crash Fatalities and Crashed Vehicle Rescue Times", Report prepared for MVFRI, March 30, 2007. www.mvfri.org

Bahouth, G., "Post Crash Exterior Crush Patterns and Motor Vehicle Fire Occurrence" SAE Paper 2006-01-0789, April, 2006.

Bahouth, J., and Kuzentsov, A., "Automotive and Fire Safety Research", prepared for MVFRI by The George Washington University, January, 2005. www.mvfri.org

Digges, K., "Fire Occurrence in Frontal Crashes Based on NASS/CDS", SAE Paper 2008-01-0256, April, 2008.

Digges, K., and Kildare, S., "Fire Occurrence in Rollover Crashes Based on NASS/CDS", SAE Paper 2007-01-0875, April, 2007.

Fell, J., Tippets, S., and Bahouth, J., "An Analysis of Vehicle Fire Rates in Fatal Crashes: Is there an Indication of Underreporting?" SAE Paper 2007-01-0876, April, 2007.

Fell, J., "Interim Report to MVFRI on FARS Missing Data", Pacific Institute for Research and Evaluation, prepared for MVFRI, November 2004. www.mvfri.org.

Friedman, K., Holloway, E., and Kenny, T., "Impact Induced Fires: Pickup Feature Design Analysis", SAE 2006-01-0550, April, 2006.

Friedman, K., Holloway, E., and Kenny, T., "Impact Induced Fires: Statistical Analysis of FARS and State Data Files (1978-2001)", SAE Paper 2005-01-1421, April, 2005.

Friedman, K., Holloway, E., and Kenny, T.., "Impact Induced Fires: Pickup Design Feature Analysis", prepared for MVFRI by Friedman Research Corporation, October 2005. www.mvfri.org

Friedman, K., Holloway, E., and Kenny, T., "Final Report, Impact Induced Fires & Fuel Leakage: Statistical Analysis of FARS and State Data Files (1978-2001)", prepared for MVFRI by Friedman Research Corporation, July 2003. www.mvfri.org

Kildare, S, and Digges, K., "Analysis of Fire Occurrence in Automotive crashes Using NASS CDS Data (1994-2004), prepared for MVFRI by The George Washington University, November, 2006. www.mvfri.org,