Opportunities for Safety Innovations Based on Real World Crash Data

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Abstract –An analysis of NASS and FARS was conducted to determine crash conditions that involved injuries that are not currently being directly addressed by vehicle safety standards or by consumer information test protocols. Analysis of both field data and US NCAP tests were conducted to determine the relative safety provided by seating position and by vehicle model year. Opportunities for improvements were determined by crash categories with large populations of injuries that were not addressed by safety tests or smaller numbers that were increasing in frequency. Areas of opportunities include improved occupant restrain in rollovers, improved frontal protection for rear seat occupants and improved fire prevention in frontal and rollover crashes.

INTRODUCTION

Recent safety initiatives in the US have addressed some of the major safety issues. Federal Motor Vehicles Safety Standards have upgraded the test conditions for front seat occupants in frontal crashes, and front and rear occupants in near-side crashes. In addition, the rear crash fuel integrity standard has been strengthened and the roof crush resistance has been doubled. This paper examines the US field data to search for additional opportunities for safety improvements.

Areas of opportunities were based on analysis of NASS/CDC data on FARS data. The NASS/CDS is a sample of crashes in the US with a severity determined by a requirement for at least one vehicle to be towed from the scene. The FARS is a census of crashes on the US pubic roads in which at least one person was fatally injured.

TRENDS IN US FATALITIES BY CRASH TYPE

FARS does not directly 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 caused by the non-roll impacts. If the damage comes from ground contact, the crash is classified as a non-collision. When rollovers occur, they are classified according to whether or not they occurred during the 1st harmful event (ie. non-rollover, rollover during the 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.

The average annual fatalities by crash type are shown in Figure 1. The data in Figure 1 was smoothed by using a 5 year moving average beginning in 1979 and ending in 2007. The data point for any given 5 year group is shown at the mid year of that group.

It is evident from Figure 1 that the numbers of fatalities in frontal and side crashes have been decreasing in recent years. The number in rollovers has been increasing and is nearly equal to the number of fatalities in vehicles with frontal damage. This result suggests opportunities for reducing rollover casualties. A further analysis of rollover casualties is merited and is presented in the section to follow.

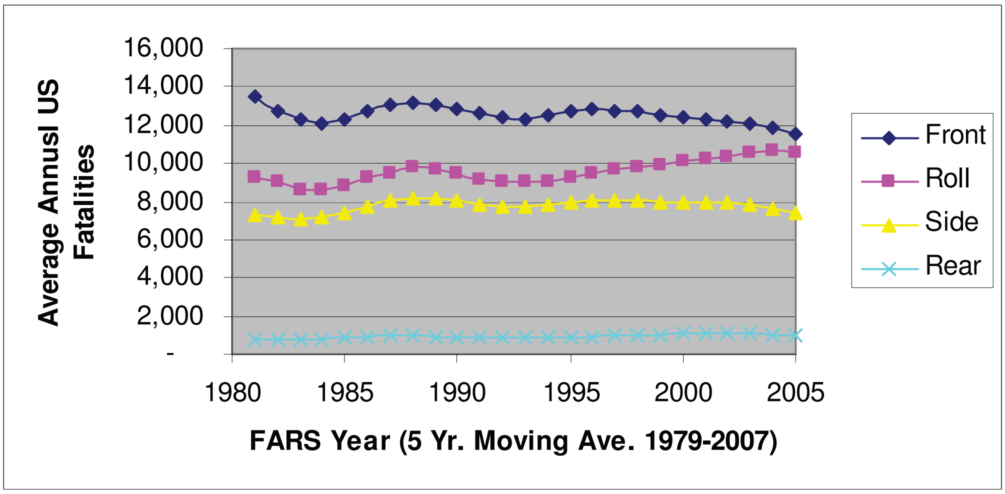

Figure 1. Annual Fatalities by Crash Damage Location – FARS 1979 to 2007 (5Yr Moving Average)

TRENDS IN ROLLOVER CASUALTIES

Table 1 shows the distribution of driver and right front passenger fatalities by belt use and ejection status. The data is averaged over the FARS years of 2003 to 2007. The table shows that ejection of unbelted occupants is associated with about half of the fatalities in rollovers. The ejection issue has recently been addressed by a proposed Federal Motor Vehicle Safety Standard No. 226 Ejection Mitigation [1]. Another recent change was a doubling the roof loading requirement in FMVSS 216 Roof Crush Resistance [2]. When fully implemented in the vehicle fleet, new Ejection Mitigation Standard will save 402 lives annually and the Roof Crush Resistance Standard will save 135 lives annually These two changes should improve the protection for both belted and unbelted occupants in rollover crashes. However, there has been no Government requirement to improve the safety belt performance in rollover crash.

Table 1. Distribution of Average Annual Fatalities by Belt Use and Ejection– FARS 2003 to 2007

Belt Use	No Ejection	Total Ejection	Partial Ejection	All
Not Belted	17%	44%	9%	70%
Shoulder Belt Only	0.3%	0.3%	0.1%	0.6%
Lap Belt Only	0.3%	0.1%	0.1%	0.5%
Lap and Shoulder Belt	25%	1.3%	2.3%	29%
Total	43%	46%	11%	100%

Another distribution of the fatalities for the 2003 to 2005 period is shown in Table 2. This table shows groupings according whether the crash involved planar forces, rollover or both. Table 2 shows that rollovers are involved in 33% of the fatalities, but only 12% do not involve planar impacts. An equal number (12%) are involved in frontal impacts in addition to the rollover. This table indicates the need to consider most fatal rollovers as multiple impacts, involving frontal or side crashes in addition to the rollover.

Table 2. Distribution of Average Annual Fatalities by Crash Type and Damage Location – FARS 2003 to 2007

Direction	Planar	Rollover	Total
Front	37%	12%	49%
Side	24%	6%	30%
Rear	3%	1%	4%
Other	2%	2%	4%
Roll		12%	12%
Total	67%	33%	100%

It is difficult from FARS to determine the significance of the planar impacts in rollover crashes. However, it is evident that a large fraction of rollovers involve impacts other than ground contact either before or during the rollover. The NASS/CDS provides additional insight into rollovers with multiple impacts. An earlier paper examined front seat occupants with serious (MAIS 3+) injuries and classified the planar impacts according to severity [3]. Table 3 from that paper provides a separation of the NASS data according to the damage severity and the classification of rollover. The damage severity of the vehicle involved in the rollover is categorized according to the three severity levels. The approximate crash severities were: minor (less 24 kilometers per hour), moderate (24 to 55 kilometers per hour), and severe (greater than 55 kilometers per hour). The columns in the table classify serious injuries according to the rollover characteristics. The Roll Only column refers to single vehicle rollovers that do not involve subsequent harmful events other than contacts with the ground. The R 1st/Multiple column refers to crashes where rollover is the first harmful event, but one or more harmful events occur after the rollover. The harmful events could be impacts with fixed or non-fixed objects and vehicles. The third and fourth columns contain the data for crashes that involve a harmful event before the rollover occurs. For the "NF Object" column, the first harmful event is with a non-fixed object such as a guardrail or another vehicle. For the "Fixed Object" column, the first harmful event is an impact with a fixed object like a tree or pole that does not break.

Table 3. Distribution Seriously Injured Belted Front Seat Occupants in Rollovers by Vehicle Damage Severity and Characteristics of the Crash

Damage Severity	All Belted with Serious Injuries				
	Roll Only	R 1st/Multiple	NF Object	Fixed Object	Total
MINOR	0.8%	0.1%	6.7%	2.8%	10.4%
MODERATE	21.6%	3.7%	7.4%	19.1%	51.9%
SEVERE	8.5%	1.6%	4.9%	15.8%	30.9%
OTHER/UNK	0.1%	0.1%	0.9%	5.8%	6.9%
Total	31.1%	5.5%	19.8%	43.7%	100.0%

Table 3 indicates that about 69% of the seriously injured are in rollovers that involve impacts other than the rollover to ground impact. The largest fraction involves impacts with fixed objects such as poles, trees and guardrails. About 20% involve impacts with non-fixed objects, primarily other vehicles.

Figure 3 shows the upward trend of belted fatalities in rollover. During the same period the number of unbelted fatalities has decreased. With increases in belt use due more aggressive education, belt reminders and law enforcement the increase in the percentage of belted occupants fatalities is expected to continue. Additional countermeasures may be required to reverse the increasing trend in belted fatalities.

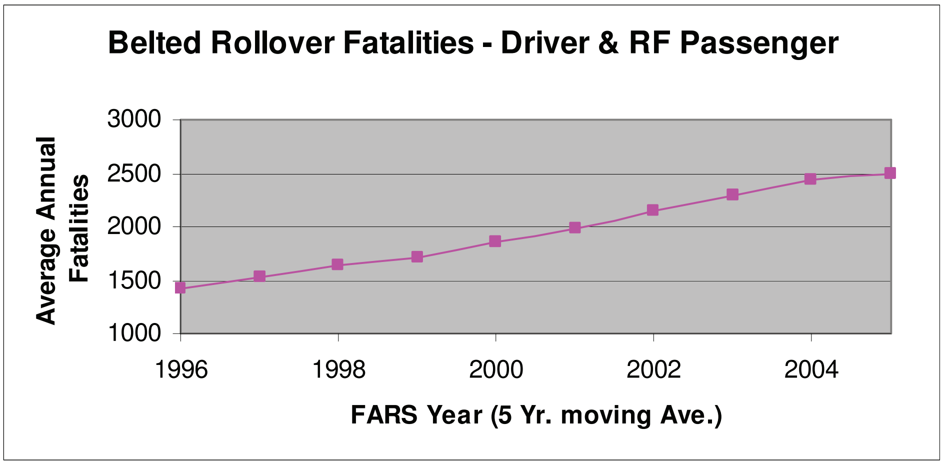

Figure 2. Annual Driver and RF Passenger Fatalities in Rollovers – FARS 1994 to 2007 (5Yr Moving Average)

Tables 1 and 3 suggest the need for rollover protection for occupants exposed to multiple impacts that involve frontal and side impacts prior to the rollover. Figure 2 shows the increasing number of belted fatalities in rollovers. Improvements in restraint systems to keep the occupant in place during multiple impacts provide an opportunity for improved occupant rollover protection. Recent initiatives by NHTSA to improve the roof strength and prevent ejections address critical opportunities, but fall short of testing the protection provided by restraint system in complex rollover events.

TRENDS IN REAR SEAT CASUALTIES

As in rollovers, the belt us among rear seat occupants has increased in recent years. This change is reflected by an increasing percentage of belted occupants being fatally injured. Figure 3 shows the increasing trend in belt use among fatally injured children and adults. Of particular interest is the increase for adults that began at 15% and is now close to 60%. The average number of rear seat occupant fatalities in the US during the recent 5 year period was around 2,200 per year. The number of children age 15 and under was 780 per year.

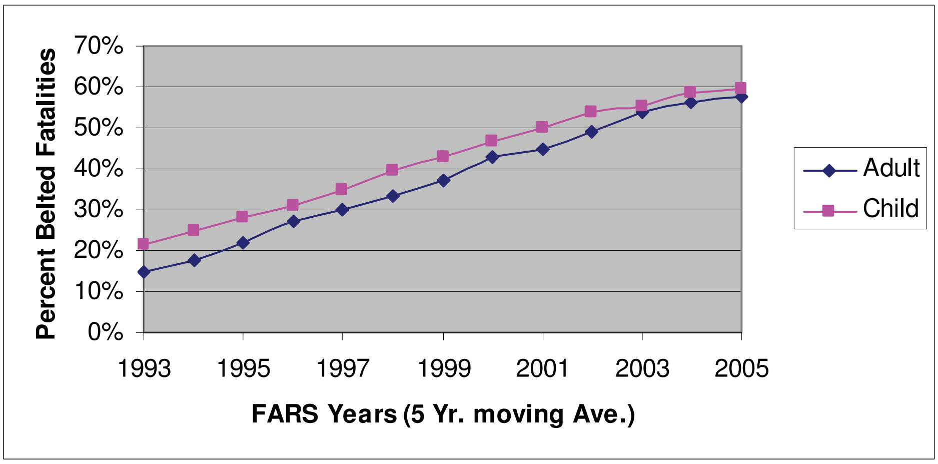

Figure 3. Average Annual Rear Seat Adult Occupant Fatalities by Belt Use – FARS 1991 to 2007 (5Yr Moving Average)

Figure 4 shows the distribution of fatally injured belted adult rear seat occupants by crash direction. This figure indicates a priority for protection in both frontal and side crashes. The distribution of crashes has not changed much over the years. However, other studies to follow suggest that frontal protection for rear seat occupants may have degraded relative to the front seat in recent model vehicles [5]. Consequently, there are opportunities for improvements in rear seat safety.

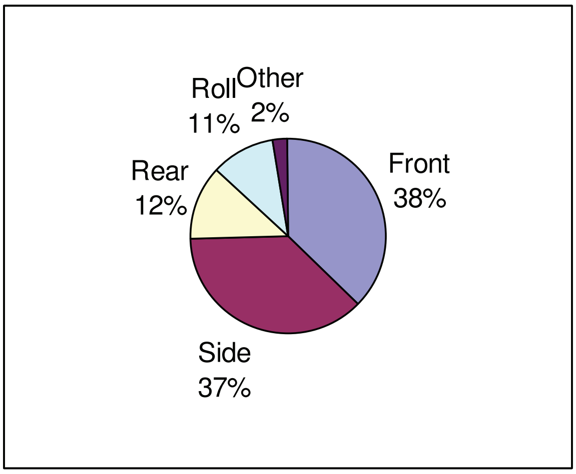

Figure 4. Distribution of Rear Seat Adult Occupant Belted Fatalities by Crash Direction – FARS 2003 to 2007

To better understand the safety opportunities for improving the crash protection for rear seat occupants, selected crash tests were examined.

Insight into the differences in crash protection in the front and rear seats can be determined from a series of tests conducted by The National Highway Traffic Administration (NHTSA). Using the NCAP protocol impact into a rigid frontal barrier at 56 km/h, NHTSA crash tested 5 different Model Year 2004 vehicles with 5th percentile female dummies in both the front and rear outboard position. The 5th percentile female dummy is 157.5 cm tall and weighs 44.5 kg. By having the same dummy at both seating positions, it is possible to compare the relative crash protection at the two locations. The results are shown in Figures 5 and 6.

Figure 5 shows that the average chest deflection is twice as high for the rear dummy compared to the front dummy.

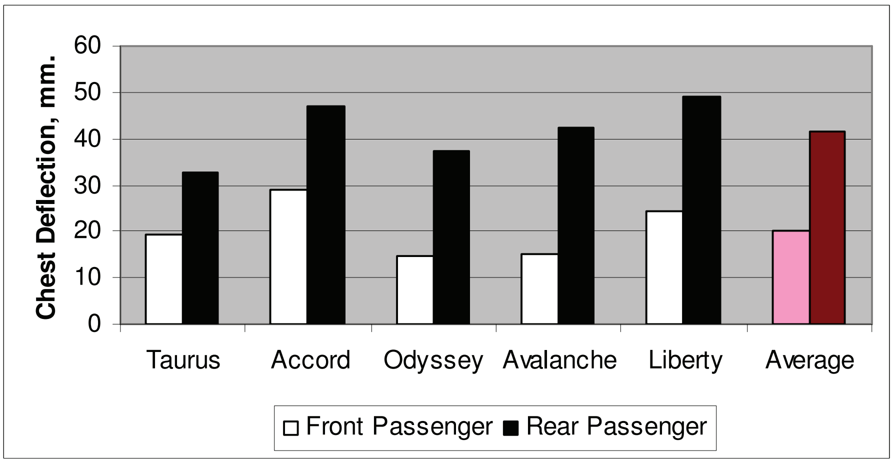

Figure 5. Chest Deflection for Small Female Dummy in Front and Rear Outboard Positions in Tests with Frontal NCAP Protocol, 2004 MY Vehicles

Figure 6 shows that the average head injury measurements for the rear dummy were twice that of the frontal dummy. In fact, the average HIC for the rear dummies exceeds the 700 allowable by the FMVSS 208, the US Federal Standard for frontal occupant protection.

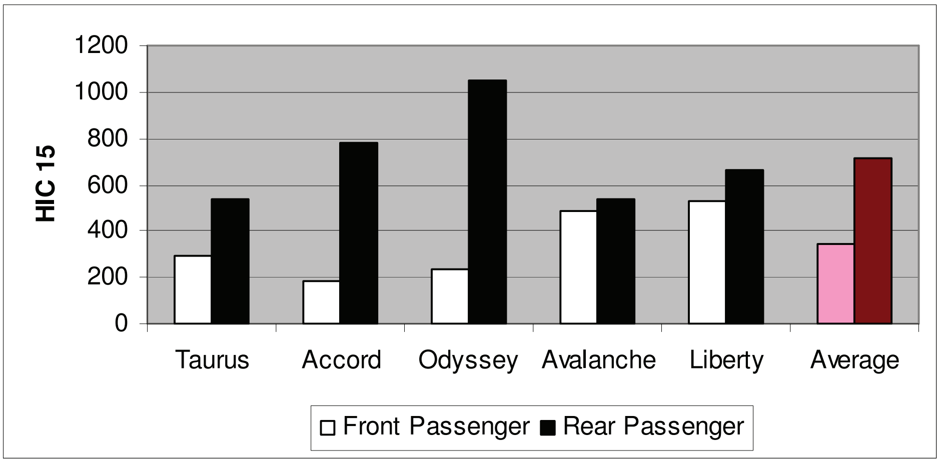

Figure 6. Head Injury Criteria (HIC 15) for Small Dummy in Front and Rear Outboard Positions in Tests with Frontal NCAP Protocol, 2004 MY Vehicles

In the NCAP tests, crash pulse (compartment acceleration vs. time history) is similar for the front and rear occupants. However, the front occupants have the benefit of advanced technology belts and air bags that ameliorate their exposure to the crash. The advanced restraint technology has not been introduced into the rear seats. There is evidence that the advanced restraint technology has permitted manufacturers to increase the severity of the NCAP crash pulse while maintaining relatively low injury readings for front seat occupants. The benefit of increasing the crash pulse severity is a reduced vehicle cost because the front of the vehicle becomes shorter and stiffer.

Analysis of the NCAP tests provides an opportunity to examine how the stiffness of vehicles has changed over the years. Figures 7 and 8 show how the average stiffness of cars and SUVs' tested in the NCAP program has increased over the years. In the plots, the max and minimum stiffness values for each year were ignored. The static stiffness (K) was calculated using the equation 1.

$$K = \frac{MV^2}{X^2} \qquad \text{Eq. (1)}$$

Where: M= Vehicle Mass
V = Test Speed
X = Maximum Vehicle Crush

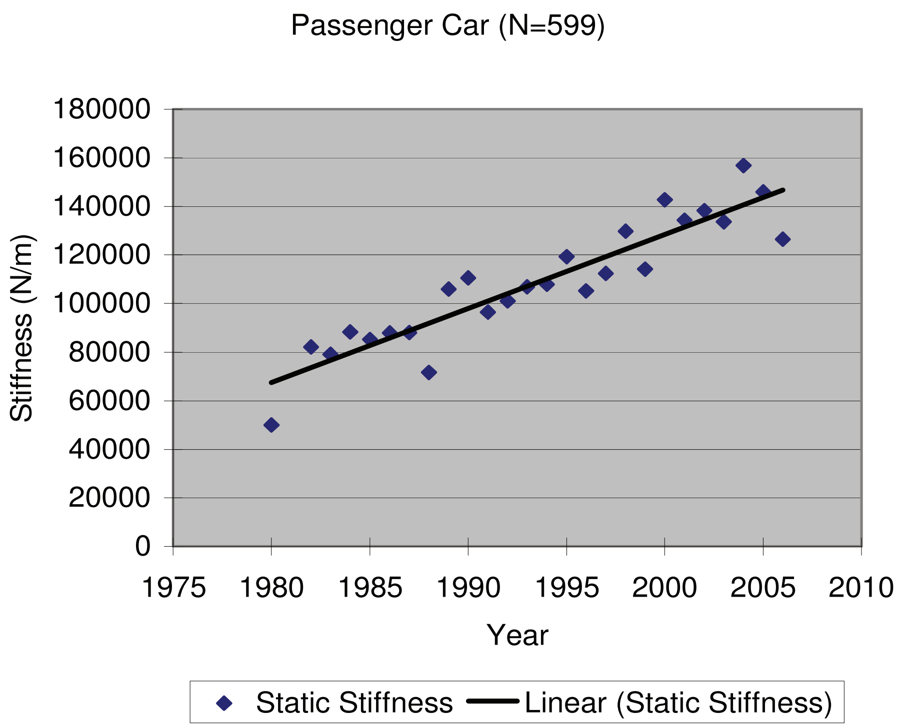

Figure 7. Average Static Stiffness of Passenger Cars Tested Annually by NCAP

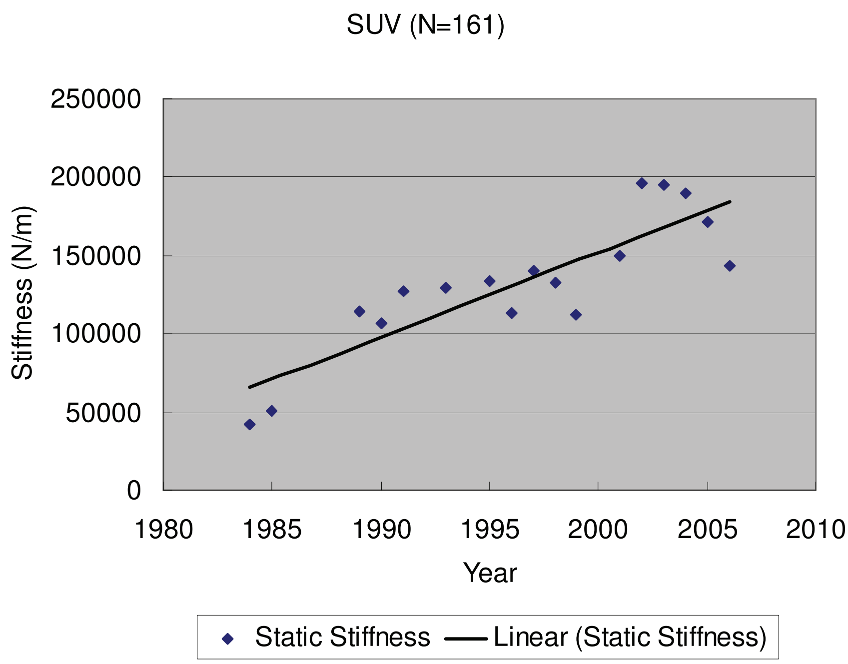

Figure 8. Average Static Stiffness of Passenger Cars Tested Annually by NCAP

An earlier study compared the effectiveness of the rear seat position compared to the right front seat in preventing fatal injuries in fatal crashes [4]. One result is shown in Figure 9. The result indicates that the rear seat position is still safer than the front seat, but the difference is reduced in recent model year vehicles.

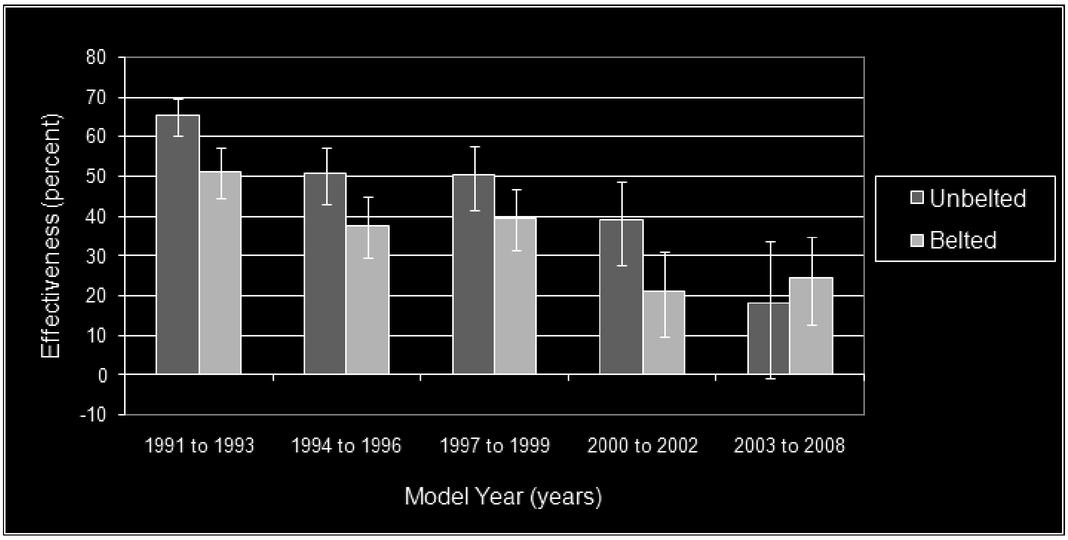

Figure 9. Effectiveness of Rear Seat Relative to Front Seat In Preventing Fatal Injuries in Frontal Crashes, All Passenger Ages Aggregated [4]

TRENDS IN FIRE CASUALTIES

Another increasing trend is the frequency of fires in frontal crashes with fire as the most harmful event. Although the numbers are small the increasing trends justify further investigation. Figure 10 shows the average annual fatalities but restricted to crashes in which fire was the most harmful event. Although the absolute numbers are small, the results show a 60% increase in the group with frontal damage during the averaging periods 2000 to 2005. A similar rate of growth has been experienced in rollover crashes.

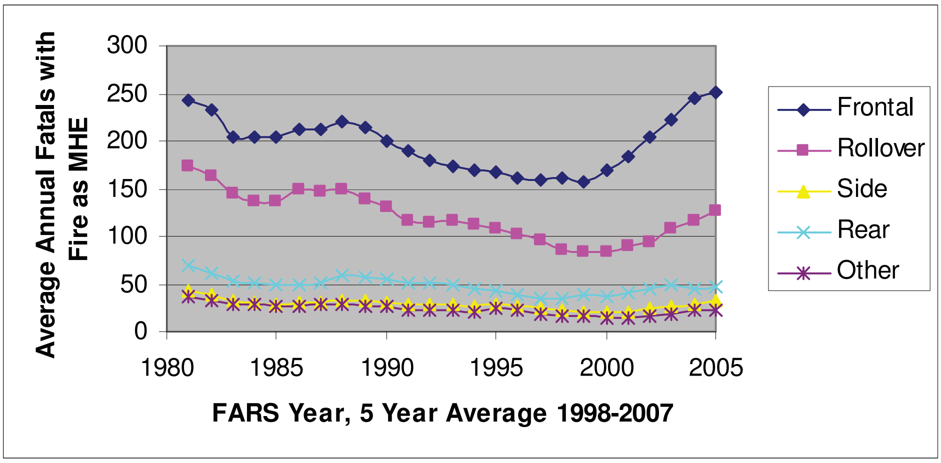

Figure 10. Average Annual Fatalities by Crash Damage Location – FARS 1979 to 2007 (5Yr Moving Average)

Table 4 shows the distribution of fatalities in FARS years 2000 to 2007 where fire was the most harmful event. The distribution is broken down by the most severe damage direction and rollover is also identified if it occurred during the sequence of crash events. This table shows that moat of the rollovers have damage caused by impacts other than the rollover. Rollovers with frontal damage constitute about 1/3 of all rollovers. In fact, about half of the crashes with fire as the MHE have frontal damage. These results suggest that opportunities may exist for improving fire safety in frontal crashes, rollovers and rollovers following frontal crashes.

Table 4. Distribution of Average Annual Fatalities when Fire was Most Harmful Event by Crash Type and Damage Location – FARS 2000 to 2007

Damage Location	No Roll	Rollover	Total
Non-Collision	0.6%	8.9%	9.5%
Front	37.6%	11.9%	49.5%
Right	11.2%	2.9%	14.1%
Rear	3.2%	1.4%	4.6%
Left	12.8%	2.8%	15.6%
Top	0.5%	3.1%	3.6%
Undercarriage	0.2%	0.7%	0.9%
Unknown	0.7%	1.5%	2.3%
Total	66.8%	33.2%	100.0%

NASS/CDS characterizes fires as either major or minor. A minor fire is an external fire that does spread to the occupant compartment or an occupant compartment fire that does not spread to the entire compartment or to other vehicle compartments.
NASS/CDS defines a major fire as the following situations:

- Total passenger compartment fire
- Combined engine and passenger compartment fire
- Combined trunk and passenger compartment fire
- Combined undercarriage and passenger compartment
- Combined tire(s) and passenger compartment

About half of the fires in NASS/CDS are major fires [5]. Major fires are more likely to produce serious burn injuries and are the subject of the analysis to follow [6].

Entrapment was recorded in 15% of NASS major fires where entrapment status was known [7]. An examination of the crash severity at which entrapment occurs was investigated for all NASS cases, including those with no fire. For frontal, side and rear crashes with no fires, 50% of entrapments occurred at crash severities less than 17 mph. For far-side crashes the delta-V for 50% entrapment was 20 mph [8]. These results suggest that occupant entrapments can occur in relatively low severity crashes. For NASS entrapped occupants, 58% had AIS 3+ injuries [9] These findings suggest that opportunities exist for reducing entrapment.

Table 5 shows the distribution of NASS major fires by crash mode. As in FARS, the frontal and rollover crash modes comprise the largest percentages. Table 6 shows a further examination of the fire origin documented for these most frequent crash modes.

Table 5. Distribution of Major Fires by Crash Mode, Weighted and Unweighted Data NASS 1995/2005 [9]

Crash Mode	UNW	WGT
Front	51%	45%
Side	10%	6%
Rear	10%	8%
Rollover	21%	29%
Other/Unk	9%	13%

The engine compartment is the most frequent fire source in both of these crash modes. Earlier studies reported that no fuel leakage was noted for most engine compartment fires [9]. This result suggests the benefit of controlling electrical faults and leakage of all flammable fluids in frontal and rollover crashes.

Table 6. Origin of Major Fires, Weighted and Unweighted Data NASS 1995/2005 [9]

Fire Origin	Front UNW	Front WGT
Engine Compartment	83%	90%
Fuel Tank	4%	1%
Other	13%	9%
Unk	4%	1%
	Roll UNW	Roll WGT
Engine Compartment	53%	50%
Fuel Tank	34%	46%
Other	13%	4%
Unk	9%	3%

FAR-SIDE CRASHES

The opportunities for casualty reduction in far-side crashes has been previously treated [10,11]. These studies showed that far-side belted occupants sustain about 2,166 MAIS 3+ injuries annually. This compares with 7,360 MAIS 3+ for near-side belted occupants. At present there is no crash test to evaluate far-side protection. The case for such a test was outlined in an earlier paper [11].

DISCUSSION

Analysis of US fatal crashes indicates that the number of fatalities in frontal and side crashes is decreasing while the number in rollovers is increasing (Figure 1). The fatalities in rollovers now nearly equal the fatalities in frontal crashes. A further analysis of fatal rollovers shows that the number of belted fatalities has increased while the number of unbelted has decreased. Recent US crashworthiness regulatory initiatives have been introduced to reduce ejections and improve roof strength. However, there are still no initiatives to evaluate the safety performance of safety belts and other occupant restraints in the rollover crash environment. Both NASS and FARS data indicate that a large fraction of serious injuries and fatalities occur in rollover crashes that are preceded by frontal and side impacts. These results suggest an opportunity for improving the crash safety in rollovers involving multiple impacts. Improved test procedures to evaluate the safety systems under the dynamic conditions of a rollover crash offer a safety improvement opportunity.

A second area of opportunity is the improved protection of rear seat occupants. Although US NCAP tests indicate that the rear seat dummies experience higher injury measures than front seat dummies, the accident data shows that the rear seat is still safer than the front seat. However, in recent model passenger vehicles, the difference is decreasing. As the frontal stiffness of the newer vehicles has increased, the front seat protection has been improved by less intrusion, and more sophisticated restraint systems. However, the increased frontal stiffness may increase the severity acceleration pulse for a given change in velocity. This change, in turn, would increase the injury risk of rear seat occupants who do not have the benefit of advanced restraint technology. Clearly, a safety improvement opportunity exists for belted rear seat occupants.

Although the numbers of fatalities with fire as the most harmful event is small, there is a counter trend in frontal crashes. Overall, fatalities in frontal crashes are decreasing while fire related fatalities in frontal crashes are increasing. Fires in rollovers are also increasing in frequency. Analysis of NASS data suggests that motor fuel is rarely documented as the source of these fires. Other possible fire origins are electrical faults and contacts between flammable fluids and hot engine surfaces. Once the fire originates the combustible plastic materials in the vicinity of the engine compartment can support fire growth and eventual penetration into the occupant compartment. Test procedures to evaluate electrical isolation and containment of all flammable fluids after a frontal crash or rollover offer an opportunity for improved fire safety.

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REFERENCES

1 - FMVSS 226 Ejection Mitigation, Federal Register December 2, 2009, (Vol. 74, No. 230) [Rules and Regulations] Page 63180

2- FMVSS 216 Roof Crush Resistance Federal Register: April 7, 2010 (Vol. 75, No. 66)][Rules and Regulations] Page 17605

3-Digges, K., and Eigen, A., "Classification of Rollover According to Crash Severity," *50th Proceedings of the Association for the Advancement of Automotive Medicine"*, p141-154, October 2006.

4- Sahraei, E., Soudbakhsh, K., Digges, K., **"**Protection of Rear-seat Occupants in Frontal Crashes, Controlling for Occupant and Crash Characteristics", *Stapp Car Crash Journa*l, Vol. 53, p.75-92, 2009.

5- Digges, K., "Technologies to Improve Impact Related Fire Safety," 20*th International Technical Conference on the Enhanced Safety of Vehicles*, paper 07-0480, June 2007a.

6 - Kildare, S., and Digges, K., "Analysis of Fire Occurrence in Automotive Crashes Using NASS CDS Data (1994-2004)," GW University Report prepared for MVFRI, October 2006, www.mvfri.org

7 -Digges, K., and Stephenson, R., "Recent MVFRI Research in Crash-Induced Vehicle Fire Safety," SAE paper 2007-01-0880, April, 2007b.

8- Digges, K., and Stephenson, R. "A Research Program to Study Impact Related Fire Safety," *19th International Technical Conference on the Enhanced Safety of Vehicles*, Washington DC, May, 2005a.

9- Digges, K., Stephenson, R., and Bedewi, P., "Research Programs in Crash-Induced Fire Safety," SAE paper 2005-01-1425, April, 2005b.

10- Digges, K., Gabler, H., "Opportunities for Reducing Casualties in Far-side Crashes", SAE 2006-01-0450, April 2006.

11- Digges, K., Echemendia, C., Fildes, B., and Pintar, F., "A Safety Rating for Far-Side Crashes", Paper Number 09-0217, *Proceedings of the 21st ESV Conference,* June 2009.