A STUDY OF THE FACTORS AFFECTING FATALITIES OF AIR BAG AND BELT-RESTRAINED OCCUPANTS IN FRONTAL CRASHES

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ABSTRACT

The combination of seat belt use and frontal air bags is highly effective in frontal impacts, reducing front-seat occupants' fatality risk by an average of 61 percent compared to an unbelted occupant in a vehicle without air bags. Nevertheless, a number of fatalities are still occurring. Whereas the safety community is generally aware of factors that make specific crashes fatal – e.g., extreme crash severity, compartment intrusion, occupant fragility – there is a need for quantitative information on the relative frequency of these factors, and how often they occur in combination.

This study began with in-depth reviews of NASS-CDS fatality cases. Case selection was limited to belted occupants in frontal impacts of late-model vehicles equipped with air bags. The reviews focused on coded and non-coded data, and resulted in the identification of factors contributing to the occupant's fatal injuries. The factors were compiled and analyzed by a team of NHTSA researchers including crash investigation specialists, crashworthiness and biomechanical engineers.

Factors were assigned based on their relevance, and emphasized those that have the potential of being addressed through vehicle design improvements. Many of the fatal crashes occurred under conditions that were considered more severe than what can be reasonably addressed with crashworthiness and restraint technologies. While the physical characteristics of some occupants were found to play a role in their demise, it was more common that the loading conditions from the crash were simply too injurious owing to a reduction in the occupant's survival space. Impact configurations with insufficient structural engagement or with oblique directions of force frequently result in degradation of structural integrity and occupant trajectories that reduce the effectiveness of restraint systems even in moderate-severity crashes. The findings of this study indicate that corner impacts and oblique frontal crashes should be a priority area for future research.

INTRODUCTION

The total number of passenger vehicle occupant fatalities occurring in the United States decreased from 30,686 in 2006 to 28,933 in 2007. Based on the vehicle miles traveled, this reduction in total fatalities corresponds to a decrease in the fatality rate per 100 million vehicle miles traveled from 1.42 in 2006 to 1.36 in 2007 [NHTSA, 2009]. This decrease in fatalities was accompanied by a one percentage-point increase in seat belt use over the same time period.

Frontal crashes are the most common type of fatal crash, with over 43% of occupant fatalities occurring in cases where the frontal crash is the most harmful event. In 2007, 11,659 fatalities occurred in frontal crashes. Fatality Analysis Reporting System (FARS) data indicate there were 4,835 fatalities of belted occupants with air bags in frontal crashes in 2007.

Seat belt use and air bags are each quite effective in reducing fatality risk in frontal impacts, and the combination of both is even more effective. Kahane (2000) estimates that when drivers and right-front (RF) passengers buckle up with three-point belts, they reduce their fatality risk in frontal impacts by 40 to 64 percent (Table 1). Similarly, in 1991, Evans reported that safety belts were 42 percent effective in preventing fatalities for drivers and 39 percent effective for right-front passengers.

The extent to which air bags are effective at reducing fatality risk has been shown to be dependent on seating position, belt use, and impact direction. Viano [1995] estimated that the addition of a driver-side air bag provided a twelve percent increase in

effectiveness over a seat belt alone. A more recent study by Cummings *et al.* [2002] suggested air bags were eight percent effective in reducing fatality risk. Air bags are slightly more effective for adult passengers than for drivers, and for unbelted than for belted occupants (Table 2). The combined effect of seat belt use and air bags is quite large. Relative to an unrestrained occupant in a seat position not equipped with an air bag, the estimated combined fatality reduction for seat belts and air bags is at least 48 percent for light truck and van (LTV) drivers in 11:00 and 1:00 impacts with other vehicles and ranges as high as 74 percent for LTV passengers in single-vehicle 12:00 impacts (Kahane, 2004). Assuming the 2005 calendar year mix of occupants, vehicles and crashes, the average combined fatality reduction of seat belts and air bags in all frontal crashes is 61 percent relative to an unrestrained occupant without an air bag. In other words, for every 100 frontal fatalities that would have occurred to unbelted occupants in vehicles without air bags, 39 would still be expected to happen even if these occupants had buckled up and the vehicles had been equipped with air bags.

Table 1.
Estimated fatality reduction by seat belt use in frontal impacts

	In passenger cars	In LTVs
Impacts with fixed object	60%	64%
Impacts with another vehicle	42%	40%

Table 2.
Estimated fatality reduction by air bags in frontal impacts

	Belted	Unbelted
12:00 impacts		
Drivers	25%	33%
RF Passengers 13+	28%	36%
11:00 and 1:00 impacts		
Drivers	13%	17%
RF Passengers 13+	15%	19%

Great effort has been focused on improved occupant protection in frontal crashes over the past decade. Federal Motor Vehicle Safety Standard (FMVSS) No. 208 "Occupant Crash Protection" and the New Car Assessment Program (NCAP) tests have influenced restraint system designs, and the Insurance Institute for Highway Safety (IIHS) offset frontal program has led to frontal structure enhancements. Continued consumer interest in high test scores has prompted manufacturers to focus heavily on achieving top ratings in the NCAP and IIHS tests. For the 2006 model year, 95 percent of the new vehicles tested received a four- or five-star NCAP rating [NHTSA, 2007b]. Similarly, a large majority of new vehicles are receiving Good ratings in the IIHS offset frontal test.

While those efforts have resulted in improvements in test scores, it takes time for the newer vehicles to replace the existing fleet. The median age of cars in operation in the U.S. was 9.2 years in 2007 [R.L. Polk, 2008]. Furthermore, vehicle design cycles typically last four to five years, and the result is that many of the occupants involved in crashes do not benefit from the safety enhancements of newer models. Nevertheless, in 2007, it was calculated that 77.6 percent of the on-road fleet was equipped with frontal air bags.

The objective of this study is to examine, in detail, characteristics of fatal frontal crashes to gain an understanding of why, despite the use of seat belts and availability of air bags in modern vehicles, fatalities continue to occur. It is desired to look at the relative importance of the various elements that distinguish a fatal crash from one that may have been survivable. The outcome of this study can serve as a guide for determining future research priorities to promote further reductions in the occupant fatality rate.

METHOD

The fatal crashes analyzed in this study were collected by the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS). The fatally injured occupants must have been riding in the front row of a passenger vehicle whose General Area of Damage for the most significant event was coded as the front (GAD1=F). In order to eliminate vehicles whose safety technology is no longer current, the model year was required to be 2000 or newer. Vehicles were also required to have been fitted with a frontal air bag at the fatal occupant's seating location at the time of production – though there was no requirement that the air bag deployed upon impact. Fatally injured occupants were only included if their appropriate manual restraint was coded as in-use at the time of crash, even if improperly used. The restraint criteria allowed for inclusion of cases in which the air bag was switched off, the air bag was not replaced after a previous deployment or did not deploy for some other reason,

the seat belt was incorrectly used, or cases of a child in a booster seat. Case years 2000 through 2007 were selected from CDS for this study.

The collection of fatality cases was analyzed by a team composed of crashworthiness and biomechanical engineers, crash investigators and a statistician. Since the objective of the study required more detailed information than what could be extracted from the CDS coded variables alone, the team developed a case analysis strategy that could be employed for each individual case review. The strategy relied on information available in the scene diagram, scene and vehicle photographs, crash summary, injury patterns, vehicle crash performance, and overall crash outcome (i.e. other occupants in fatality vehicle or crash partner occupants). In an attempt to minimize subjectivity, a case review template was developed and a number of factors and classifications were specified to capture the essential information of the cases.

Each team member individually reviewed a subset of the cases and prepared summary documents for later discussion with the entire group. The group then met and reviewed each case using the summary documents as a guide. Following the discussion, the team reached a consensus on the various factors that led to the crash being fatal for the occupant of interest. A factor, in this context, is an event or condition present at or after the time of impact that probably and logically increased the likelihood that this specific impact would be fatal to the occupant. For example, the condition that the occupant is obese is likely to be a factor in an impact where the occupant bottomed out the air bag and sustained major thoracic injuries, while it is unlikely to be a factor in a crash where an exterior object penetrated the vehicle and struck the occupant in the head.

Factors related to the fatality were deemed primary or secondary, depending on the nature of their causative effects. The ability to relegate a factor to secondary status allowed the team to capture the entire essentials of the case without diluting the importance of the factor(s) deemed most significant for the fatality. A primary factor can be considered a necessary condition for a fatality, in the sense that removing it from the set of circumstances would likely lead to the crash not being fatal. A secondary factor increases risk, and could possibly make the difference between life and death, however its removal would probably not change the significance of the primary factors. A listing of the factors with brief descriptions is provided in the Appendix. Although case reviews did consider pre-crash events and their influence on the severity of the crash, the objectives of this study were to look at crashworthiness, restraint, and occupant-related factors.

RESULTS

A total of 138 fatalities, from 133 vehicles in 132 total crashes, were selected from the 2000-2007 CDS files for inclusion in this study. Of those fatalities, 63% (87) were in passenger cars with the remaining cases in light trucks, SUVs or vans. Eighty-three percent (115) were drivers and the rest were right-front passengers. Occupant ages ranged between ten and 87 years and 61% (84) of the occupants were male. Average occupant height was 171 cm (67 inches) and average occupant weight was 83.9 kg (185 lb).

During the case reviews, it became apparent that some of the cases did not fit the study criteria and were thus excluded from the study. Examples include cases in which it was determined, after careful review, that the fatality-inducing event was not a frontal impact or that the occupant was not wearing the manual belt restraint. Cases in which the occupant died immediately prior to the crash due to illness or was apparently committing suicide were also deleted. Seventeen cases were deleted from the original set leaving 121 for analysis. A histogram of occupant age among the 121 cases is shown in Figure 1. The distributions of vehicle model year and type are shown in Figure 2 and 3.

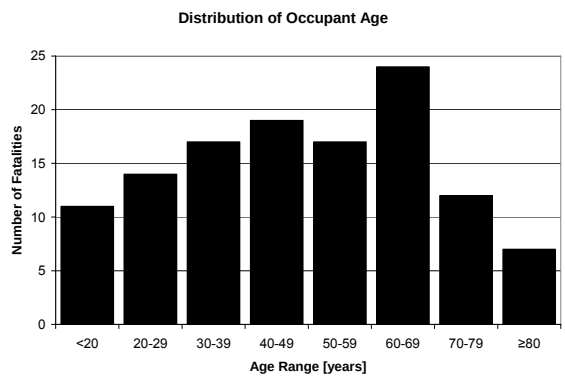

Figure 1. Histogram of fatal occupant age.

The frontal air bag deployed for all but six of the fatalities, and in one of the non-deploy cases, the passenger-side air bag switch was set to the off position. Manual belt use was deemed as proper in all cases.

Table 3 shows the factors and their frequency of occurrence as either primary or secondary among the

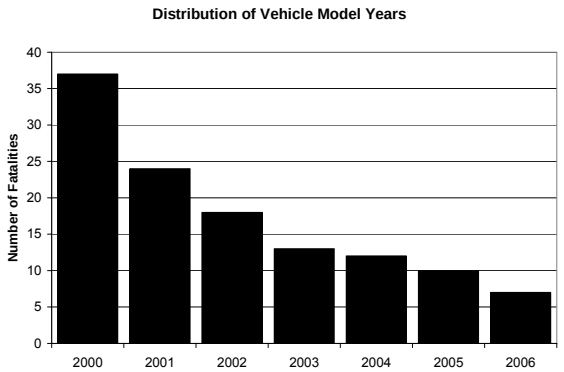

Figure 2. Histogram of vehicle model year.

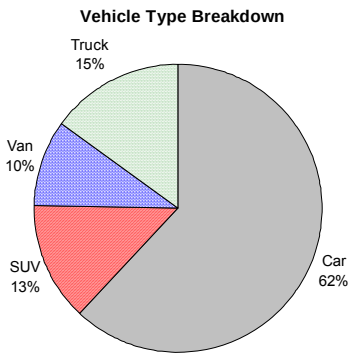

Figure 3. Breakdown of vehicle type.

121 cases. Note that the cases could have multiple primary and secondary factors.

References to specific cases are in the form 200X-YY-ZZZ, where 200X represents the CDS year, YY the primary sampling unit (PSU) and ZZZ the case number. Cases can be viewed using the on-line CDS case viewer accessible via the NCSA page available at http://www.nhtsa.dot.gov.

DISCUSSION

Careful review of the 121 fatalities yielded a list of factors to gain a better understanding of why restrained occupants die in frontal crashes. A consistent team-based approach was used to determine which factors were relevant in each crash, and the resultant breakdown of factors pointed to a handful of key areas that may warrant further study. Some of the factors have a greater potential to be addressed by improvements in restraint systems and vehicle crashworthiness, but many of the crashes were simply so severe that crash avoidance becomes the first line of defense. The discussion covers some of the most common primary factors and provides examples and explanation on how they were selected.

Table 3. Fatality factors in 121 cases

Factor	Pri	Sec	Grp*
Exceedingly severe crash	37	10	C
Underride, limited vertical structural engagement	23	13	C
Limited horizontal structural engagement	20	8	C
Oblique impact	17	11	C
Anomaly (unusual crash circumstance)	17	0	C
Elevated occupant age	16	14	O
Trailer's guard did not prevent underride	13	2	C
Tall, narrow object	9	1	C
Roof, A-pillar, or other upper-compartment intrusion	6	43	V
Excessive IP or toe pan intrusion, or buckling of floor pan	4	27	V
Obese occupant (BMI ≥ 30)	3	21	O
Poor occupant-air bag interaction	3	18	R
Vehicle not manufactured to current design practices	2	23	V
Front-to-front incompatibility between two passenger vehicles (cars or LTVs)	2	10	C
Multiple event crash	2	1	C
Post-crash fire resulting in fatal burns	2	0	C
Belt system did not adequately restrain	1	10	R
Out-of-position occupant	1	3	C
Seat or seat back did not adequately restrain	1	3	V
Air bag injured out-of-position occupant (e.g., SCI case)	1	2	R
"Back-seat bullet" – rear-seat occupant increased the load on the front seat and contributed to seat failure	1	2	B
Pre-existing medical condition	1	1	O
Air bag did not deploy	1	0	R
Post-crash injury complications	1	0	O
Air bag bottomed out	0	26	R
Short-stature occupant	0	7	O
Steering assembly moved upward	0	3	V
Air bag switched off	0	1	B
Belt-induced injury	0	1	R
Tall or large occupant (not obese)	0	1	O

* Factors are divided among five different groups: C - crash configuration or partners; R - restraint performance; V - vehicle structure performance; O - occupant vulnerability; B - occupant behavior. The factors are described in the Appendix.

Exceedingly Severe Crash

Thirty-seven of the fatalities were attributed primarily to the crash being exceedingly severe. While there was no quantitative criteria (delta-V, crush, etc.) used to determine whether a crash was exceedingly severe, this factor was typically selected when it was apparent that the amount of crash energy absorbed was much higher than that at typical crash test speeds. In these cases, it was understood that the vehicle structure and restraint systems were overwhelmed relative to their design targets.

Crashes between two vehicles traveling in opposite directions on a high-speed roadway would be considered exceedingly severe, given ample evidence that both vehicles were traveling at or above posted speeds. "Exceedingly severe" was applied as a primary factor more than any other factor, and it was frequently the only primary factor coded. In an exceedingly severe crash, it is expected that secondary effects may include large occupant compartment intrusions and air bags that bottom-out when loaded by the occupant. There were some cases in which exceedingly severe was considered a secondary factor. In these cases, the high level of crash energy was felt to play a role in the occupant's demise, but other factors such as structural engagement or crash direction were deemed more directly responsible.

One example of a case considered exceedingly severe was 2007-74-107, in which a 2000 Ford Taurus impacted a 2000 Buick Park Avenue in a full-frontal configuration, resulting in fatality to the three front-seat occupants of the two cars. This crash of two similarly-sized passenger vehicles occurred on a highway where one vehicle was traveling in the wrong direction, so both vehicles were traveling at a high rate of speed immediately prior to the impact. The distributed impact resulted in a delta-V of 59 mph for the Taurus (Figure 4), which had received a five-star NCAP rating and a Good IIHS frontal rating. The high level of crash energy led to instrument panel intrusion and there was evidence that the occupant loading caused the air bag to bottom-out.

While not irrelevant to the study of the fatal frontal crash problem, the exceedingly severe crashes can be separated from the rest of the fatalities based on the difficulty associated with addressing crashes of such severity. These high-energy crashes require vehicle structure and restraint design trade-offs that may not be technically viable. Rather, the team believes the exceedingly severe crashes identified could benefit from crash avoidance technologies that could either prevent or mitigate the severity of the event, and were thus segregated from the other cases.

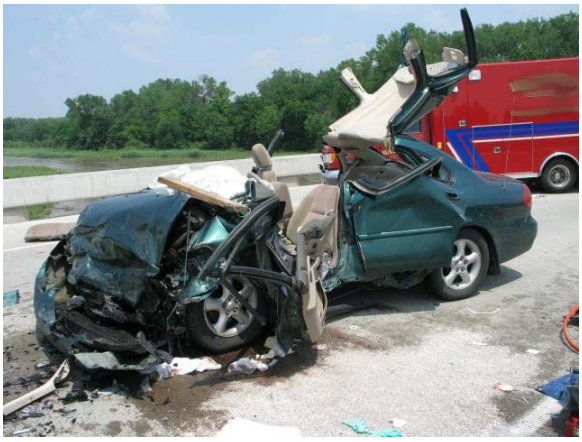

Figure 4. Example of exceedingly severe as primary factor – case 2004-74-107

Limited Structural Engagement

The second most commonly coded primary factors were those related to less-than-optimal engagement of front structural components. Limited structural engagement was coded when the front of the vehicle was loaded in a way that failed to engage one or both of the two primary longitudinal members (frame rails) in an effective manner. Limited vertical engagement and limited horizontal engagement both shift part of the energy absorption responsibility to the occupant compartment, and typically result in large intrusions that shrink the occupant ride-down space.

Vertical (underride) – Vertical engagement problems typically arose in impacts to semi-trailers or when passenger cars struck higher-riding light trucks. In many of these cases, the crush at the level of the bumper was minor while the upper portion of the vehicle's front was crushed all the way back to the occupant compartment. The upper structures typically lack sufficient energy-absorbing capability, even in moderate severity crashes, to withstand the deformation into the occupant compartment. This factor was not mutually exclusive with "Trailer's guard did not prevent underride." All cases where the trailer guard was a factor were also assigned the vertical (underride) factor to demonstrate the role played by the case vehicle's structure in addition to capturing the importance of the trailer's structure.

An example of a crash with limited vertical structural engagement as a primary factor is 2007-9-63, in which a 2006 Toyota Avalon struck a semi-trailer. In

this case, the vehicle sustained minor crush at the bumper level, but the hood and windshield header were severely deformed (Figure 5). Due to the excessive occupant compartment deformation, the restraint performance was irrelevant since the greenhouse structures could not withstand the impact. This occupant was believed to have contacted the intruding windshield header, which was reinforced by the semi-trailer, with his head and the intruding steering assembly with his thorax.

Figure 5. Example of limited vertical structural engagement as primary factor – case 2007-9-63. The front bumper beam sustained minor damage, yet the hood was pushed back beyond the windshield.

Horizontal – Horizontal offset problems typically arose in extreme offset or corner impacts with other vehicles or narrow objects. As in the limited vertical engagement cases, the limited horizontal engagement cases did not demonstrate good engagement with the longitudinal energy-absorbing structures of the vehicle and the result is usually severe occupant compartment deformation. The struck object often peels away the front fender and then contacts the firewall area resulting in large instrument panel intrusions. Crashes with limited horizontal engagement can be identified frequently as having a Collision Deformation Classification (CDC) designation of "FLEE" or "FREE." For these crashes, the maximum width of deformation measured from the side surface of the subject vehicle is 410 mm (16 inches) or less.

Case 2004-50-32 involves a 2001 Subaru Forester in which the right front passenger was killed as a result of an extreme right offset pole impact (Figure 6). The pole contacted the right front of the vehicle, outboard of the longitudinal member, and caused the instrument panel, toe pan, and windshield header to intrude into the occupant's seating position. Instrument panel intrusion was measured as 81 cm for the right front seating position.

Figure 6. Example of limited horizontal structural engagement as a primary factor – case 2004-50-32. Note the minimal induced damage to the front structure on the vehicle's left side. The direct damage was limited to the area behind the right headlight.

Oblique Crash

Oblique impacts were also common among these fatal crashes, and were coded as primary factors in seventeen cases. Oblique crashes could involve a small overlap or a full overlap, but the key was that the principal direction of force was at enough of an angle from twelve o'clock to affect occupant trajectories and the subsequent restraint interaction. It was found that occupants sometimes missed the air bag as they moved forward and laterally in response to the impact. Depending on the seating position and the direction of the obliquity, the occupant would move towards the A-pillar or center instrument panel. Large A-pillar intrusions were common in oblique cases because of the less-than-optimal structural engagement, and this would exacerbate the severity for the occupant by even further reducing ride-down space.

An example of a crash with an oblique impact as the primary factor is 2004-49-168, which involved a 2004 Mercedes S430 (Figure 7). This vehicle was struck with a 40 degree PDOF, and the total delta-V was 30 km/h. The right front passenger moved forward and to the right in response to the impact, and her head most likely did not fully engage the deployed frontal air bag, striking the A-pillar instead and causing serious head injuries. Because of the oblique angle, she did not benefit from the frontal air bag or the side curtain air bag that also deployed in this crash.

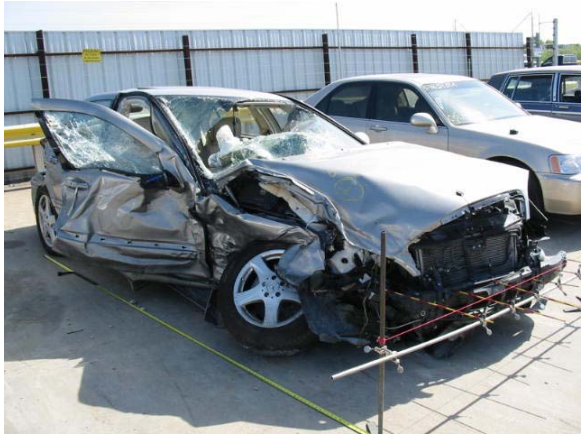

Figure 7. Example of oblique impact as a primary factor – case 2004-49-168

Roof, A-Pillar or Other Upper-Compartment Intrusion and Excessive IP or Toe Pan Intrusion

Large intrusions of the roof, A-pillar, windshield header, and instrument panel were the most frequently coded secondary factor in this study. In most cases, these large intrusions were the result of poor structural engagement or extreme crash severity. The intrusions were considered as a result of the nature of the impact, and were thus only secondary factors, even though they were frequently directly responsible for the severity of the injuries.

Elevated Occupant Age

There were some crashes that, at first glance, did not appear to be overly severe and the vehicles had not sustained the extent of damage that would be expected in a fatal crash. In some of these cases, a review of the occupant and the injuries revealed that occupant-related factors were responsible for the fatality.

Occupant fragility due to elevated age was frequently cited as a primary factor (sixteen cases) owing to the general decrease in injury tolerance among the elderly population. Elevated occupant age was coded when the team felt strongly that a younger and more robust individual would have survived based on the perceived severity of the impact. These cases generally had relatively little occupant compartment intrusion and were not oblique in nature. Figure 8, case 2005-79-139, shows one such example. There were also fourteen cases where elevated age was coded as a secondary factor. These were crashes where severity or loading direction would have presented any occupant with a demanding loading condition, but the occupant's tolerance was considered to affect their outcome.

Figure 8. Example of crash with elevated occupant age as primary factor – case 2005-79-139

CONCLUSION

The detailed review of fatality cases conducted in this study yielded a tally of important factors that may help to explain why restrained vehicle occupants continue to die as a result of frontal crashes. The team analyzed evidence from each case to develop an explanation of why the fatality occurred and to enhance the already-coded crash investigation data with an objective assessment of critical factors. While 37 of the 121 fatalities were attributed to the crash being overly severe, the following factors arose as those most prevalent in the fatal crashes:

- Underride or limited vertical structural engagement
- Limited horizontal structural engagement
- Oblique impact direction
- Elevated occupant age
- Semi-trailer underride guard did not prevent underride

The above-listed factors provide a list of issues that need to be addressed further reduce fatalities of restrained occupants in frontal crashes. Despite an increase in occupant seat belt usage and improvements to vehicle crashworthiness, the factors listed above provide an explanation of why occupants continue to sustain fatal injuries in frontal crashes. The factors also point to areas for potential improvements in crash performance through advanced restraint technologies and structural enhancements that may help further reduce occupant fatality risk.

REFERENCES

Cummings, P., McNight, B., Rivara, F.P., Grossman, D.C. (2002) "Association of Driver Air Bags with Driver Fatality: A Matched Cohort Study." *British Medical Journal*, vol. 324, pp. 1119-1122.

Evans, L. (1991) "Traffic Safety and the Driver." Van Nostrand Reinhold, New York.

Kahane, C.J. (2000) "Fatality Reduction by Safety Belts for Front-Seat Occupants of Cars and Light Trucks." DOT HS 809 199.

Kahane, C.J. (2004) "Lives Saved by the Federal Motor Vehicle Safety Standards and Other Vehicle Safety Technologies." DOT HS 809 833.

NHTSA (2007a) "Traffic Safety Facts 2006 Data – Occupant Protection." DOT HS 810 807.

NHTSA (2007b) "The New Car Assessment Program Suggested Approaches for Future Program Enhancements." DOT HS 810 698.

NHTSA (2008a) "Traffic Safety Facts 2007 Data – Occupant Protection." DOT HS 810 991.

NHTSA (2008b) "Traffic Safety Facts CrashStats – 2007 Traffic Safety Annual Assessment Highlights." DOT HS 811 017.

NHTSA (2009) "Traffic Safety Facts 2007." DOT HS 811 002.

R.L. Polk & Co. (2008) "R.L. Polk & Co. Reports Vehicle Age in U.S. On The Rise." http://usa.polk.com/News/LatestNews/News_20080215_scrappage.htm

Viano, D.C. (1995) "Restraint Effectiveness, Availability and Use in Fatal Crashes: Implications to Injury Control." *Journal of Trauma – Injury, Infection, and Critical Care*, vol. 38, no. 4, pp. 538-546.

APPENDIX

Description of factors related to crash configuration or partners

Anomaly – Unusual crash configuration or circumstances, such as being struck by an airborne or rolling vehicle; hitting an unusually-shaped vehicle or object; or experiencing multiple frontal impacts, with the air bag deploying on an earlier impact than the most severe one.

Exceedingly severe crash – The velocity change and acceleration are so great that it is not very likely the occupant could ride down and survive in the time and space available, even if structural engagement had been excellent, the vehicle had been manufactured to current design standards, the occupant was young, and the restraint system functioned well. Fundamentally, if this had been a full-frontal impact, it would likely have been fatal to the driver and RF passenger; if it had been an offset with 50 percent overlap, it would likely have been fatal to the occupants of the impacted half. Typically, the time and space available for the restraint system, already limited because of the high speed, is further reduced because the instrument panel intrudes and the floor pan buckles at these force levels, even in vehicles manufactured to current design standards. In short, the restraint system is overwhelmed. This is usually a primary factor, but it can be a secondary factor if a crash was just below that severity level, and there were other risk-increasing factors.

Front-to-front incompatibility – When the case vehicle hits a car or LTV head-on, and that other vehicle is much stiffer and/or heavier, or has the frame rails located substantially higher, the case vehicle may experience a disproportionate share of the damage and experience compartment intrusion above and beyond what might be expected from the speed and degree of offset.

Limited horizontal structural engagement – The primary frontal longitudinal members of the case vehicle did not engage with the structure of the other vehicle or object because the impact was (1) on the corner of the case vehicle, (2) strongly offset to the point where the direct damage on the case vehicle was outside the longitudinal member, and/or (3) with a narrow object that fits between the longitudinal members. Intrusion of various components may increase and occupant trajectory can be affected. Air bags may deploy late or not at all. This becomes a primary factor if an impact at the same velocity with good structural engagement would have had a low fatality risk.

Multiple-event crash – Impact(s) prior to the main impact cause the air bag to deploy before it is most needed, or displace the occupant out of position, or cause the occupant to load the belt system and/or air bag from an angle for which it is not optimally designed.

Oblique crash – The direction of impact is sufficiently far away from longitudinal so as to affect occupant trajectories (away from the air bag and not straight ahead into the seat belt). Components may be displaced laterally and longitudinally.

Out-of-position occupant – Includes people displaced out of position by small impacts or off-road excursion prior to the main impact and, less frequently, people who were already out of position before the crash (e.g. asleep). This can result in belted occupants being too close to the deploying air bag or to static components such as the side structure or steering assembly.

Post-crash fire resulting in fatal burns – A fire that develops as a result of the crash is responsible for the occupant's demise.

Tall, narrow object – In addition to the risk-increasing factors associated with the narrow object's limited horizontal engagement, the height of the object, typically a tree or pole tends to push components in front of it such as the instrument panel and steering assembly upwards and into the compartment. The occupant's head may contact the tree or pole.

Trailer's guard did not prevent underride – The case vehicle hit the rear of a semi-trailer or single-unit truck equipped with an underride guard. Nevertheless, there was severe underride, presumably because the vehicle missed the guard or pushed the guard out of the way, upward or sideways.

Underride, limited vertical structural engagement – The primary frontal longitudinal members of the case vehicle did not engage with the structure of the other vehicle due to a height mismatch. This results in excessive damage depth and compromise of the occupant compartment on the case vehicle. Underride becomes a primary factor if an impact at the same velocity with good structural engagement would have had a low fatality risk.

Description of factors related to restraint system performance

Air bag bottomed out – This was quite common, but it was always a secondary factor. It was a consequence of the impact's severity and/or the occupant's weight. There were no cases where the air bag bottomed out for no particular reason. There were also no cases where it was evident that a more capacious air bag would have prevented the fatality, because most of these crashes were quite severe.

Air bag did not deploy – This would be coded in a crash where a deployment would have typically been expected and would likely have benefited the occupant. In other words, where this was the primary factor (one case), the team believes a deployment would likely have prevented the fatality.

Air bag injured out-of-position occupant – Poor belt fit or multiple impacts can allow occupants to approach the air bag before it deploys. If an occupant has the characteristic injuries, such as atlanto-occipital cervical spine dislocation plus brain injury plus abrasions of the neck and face, there was a possibility they were too close to the deploying air bag. These instances were rare in our study of belted occupants in vehicles with redesigned air bags (MY 1998+).

Belt system did not adequately restrain – This occurs when something has allowed excessive occupant excursion in the belt. Shoulder belts integrated into the seat back may permit excessive excursion when, for example, a large occupant exerts sufficient force to bend the seatback and pull it forward. There was one case where the belt anchorage tore loose. Excursion could also be increased by poor belt fit (very short occupant), or by a series of impacts.

Belt-induced injury – Although CDS attributed injuries to the belt system in several cases, the team only considered it a factor if these injuries were fatal, and of higher severity than would be expected for this type of impact.

Poor occupant-air bag interaction – The occupant's thorax does not hit the center of the air bag, and as a result engages at best a limited portion of the energy-absorbing capability of the air bag. This happens often as a direct consequence of oblique force or a vehicle rotation introduced by a corner impact or strongly offset impact; as a result this factor is often secondary (because a consequence) to "oblique crash" or "limited horizontal engagement." It may also result from delayed deployment, an occupant with unusual stature or out-of-position, or upward displacement of the steering assembly.

Description of factors related to vehicle structure or component performance

Excessive IP or toe pan intrusion, or buckling of the floor pan – Instrument panel (IP) intrusion and floor-pan buckling both reduce the space available between the occupant and the front interior for ride-down by the restraint system. Severe IP intrusion can result in direct contact with the belted occupant leading to fatal thoracic injuries. Gross reduction of the occupant's survival space can reduce the effectiveness of the restraint systems and can entrap the occupant.

Roof, A-pillar or other upper-compartment intrusion – The roof, A-pillar, windshield header, roof side rail, and/or striking vehicle/object entered the space of the occupant compartment from the front, side, and/or top, resulting in fatal head injuries to the occupant. This is usually a secondary factor, because it is a direct consequence of what happened in the crash (underride; corner impact; tall, narrow object).

Seat or seat back did not adequately restrain – The seat tore loose from its track, or moved forward along the track during impact, or moved up or down in response to intrusion. The occupant space available for ride-down was reduced or the occupant was allowed to contact the front interior with a more vulnerable body region (neck or abdomen rather than thorax).

Steering assembly moved upward – The upward motion of the steering assembly, in response to the vehicle's structural deformation, concentrated the impact of the steering wheel into the driver's chest. The phenomenon was a consequence of exceedingly severe impacts or tree impacts, and not a primary, first-cause factor.

Vehicle not manufactured to current design practices – This usually refers to MY 2000+ vehicles that were carryovers from somewhat earlier designs, with poor or marginal performance on the IIHS offset test, especially with regard to structural performance. These vehicles tend to allow more IP, toe pan or floor pan intrusion/deformation than the latest designs.

Description of factors related to intrinsic occupant vulnerability

Elevated occupant age – This occurs when an impact that resulted in fatal injuries would probably not have been fatal to a 30-year-old occupant. The younger occupant would have sustained a less severe type of injury than this occupant, or even if they had sustained the same injury, they would probably have survived it. There is no specific minimum age for this factor; typically these occupants are over 70, but in some of the more severe crashes, as young as 65-70 years old.

Obese occupant – The occupant had a body mass index (BMI) of 30 or more, and that increased fatality risk because the occupant bottomed out the air bag, overtaxed the belt system or the seat, increased impact force on the ribcage, or reduced the space between the occupant's torso and the steering assembly or instrument panel.

Pre-existing medical condition – The occupant was more vulnerable to impact trauma than the average for his or her age due to an illness (which was not, itself, the cause of the fatality).

Post-crash injury complications – An injury or combination of injuries that is rarely fatal became fatal as a result of complications during the convalescence. Typically, the victim would be an older person.

Short-stature occupant – Because of short stature, the occupant contacts the air bag with a different body region than the one for which the air bag is designed (e.g. the neck instead of the center of the chest). Because of short stature, a driver sits closer to the air bag and reduces the space available for ride-down by the restraint system or even becomes exposed to injury by the deploying air bag. The occupants in this study who were granted this factor were 160 cm or shorter.

Tall or large occupant (not obese) – Usually advantageous, this could increase risk if the occupant contacts upper-interior components despite being belted or overtaxes the belt or seat system. The only occupant in this study with this factor was 193 cm tall and weighed 106 kilograms.

Description of factors related to occupant behavior that increased injury risk

Air bag switched off – The case vehicle is a pickup truck factory-equipped with an on-off switch for the passenger air bag, and the switch is off – with or without the occupants being aware of it.

Back-seat bullet – An unrestrained back-seat occupant was seated behind the victim and contacted the back of the front seat during the impact. This "back-seat bullet" increased the load on the victim and/or reduced the space between the front seat and the instrument panel.