CHARACTERISTICS OF CRASHES WITH MULTIPLE FRONTAL IMPACTS

Shaun Kildare
Kennerly Digges
The George Washington University, National Crash Analysis Center
USA

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ABSTRACT

Data from the National Automotive Sampling System – Crashworthiness Data System (NASS CDS)[1] were analyzed to determine the characteristics of multiple-frontal impact crashes with the objective of identifying opportunities for employing safety systems. Multiple impacts initiated by a frontal impact accounted for about 24% of the population of seriously injured (MAIS 3+) drivers in recent model passenger vehicles. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. Lane departure and roadway departure were the most frequent pre-crash events. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts.

INTRODUCTION

Multiple impact crashes are those in which a vehicle sustains two or more collisions in the course of a single crash sequence. According to National Automotive Sampling System (NASS) Crashworthiness Data System (CDS), between 1997 and 2006, nearly 16 million occupants were involved in multiple impact collisions. The data further indicates that while only 30 percent of all occupants are involved in multiple impacts, this population accounts for nearly half of all seriously injured occupants (defined as occupant Maximum Abbreviated Injury Score of 3 or greater (MAIS 3+)). Occupants in multiple impacts are almost twice as likely to be seriously injured when compared with their counterparts in single impacts.

This work expands upon previous research on multiple impacts by focusing on the study of multiple impacts in which a vehicle sustained at least two separate impacts to the front of the vehicle in the course of a single crash sequence, referred to herein as multiple-frontal impacts. An analysis of available crash data and subsequent individual case reviews is presented. Multiple frontal impacts were examined to identify possible collision avoidance / mitigation and crashworthiness countermeasures. The analysis and results presented here are excerpted from a larger work by the authors on the topic. [1]

PRIOR WORK

Limited prior work has been completed on the study of multiple impacts in general, and no prior work has focused specifically on multiple frontal impacts. However, the findings of this work relating to multiple impacts overall appear to correlate well with results from the earlier works.[2]

The distribution of vehicles by collision type in the NASS CDS correlates well with the distributions presented by Fay and Sferco in 2001 [2], however NASS CDS exhibits an elevated contribution from multiple impacts. Fay and Sferco found multiple impacts to constitute 26.5% to 29% of the vehicle population in crash data from the United Kingdom and Germany (GIDAS)[3] while NASS CDS, over equivalent time periods, found this percentage to be 37.2% to 39%. In line with Fay and Sferco's conclusion that the proportion of vehicles in multiple impacts would increase as time progressed, a study of NASS CDS for more recent years has found the proportion of multiple impacts to have increased to 39.8%. The finding that the majority of multiple impacts involved only two impacts was also confirmed, with two impact multiple impacts constituting over half of all multiple impacts. Fay and Sferco also identified that multiple impacts accounted for a significant proportion, 30% to 43% of seriously injured occupants (depending on data source, UK or

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[1] NASS CDS is a database of a representative sample of two-away crashes on U.S. roads.

[2] A brief summary of the comparison of current data and previous works is presented here; the complete analysis with full tables may be found in reference [1].

[3] German In-Depth Accident Study; accident analysis study conducted in Germany collecting data on approximately 2000 case per year in a manner similar to the NASS CDS system, more info available at www.gidas.org,

Germany). NASS CDS data indicates that multiple impacts accounted for a larger proportion of the injured population over the same time period, and that this proportion has increased in recent years. (Table 1)

Table 1.
Distribution of MAIS 3+ Population
By Impact Type,
Comparison of GIDAS & NASS CDS data [4]

MAIS 3+ Rate			
Impact Type	**GIDAS 1996 - 2000**	**NASS CDS 1996 - 2000**	**NASS CDS 2001 - 2006**
Single Frontal	33%	31%	28%
Single Side	21%	14%	12%
Single Rear	2%	1%	1%
Single Rollover	1%	4%	4%
Multiple Impact	43%	50%	55%

In 2003, Leonard and Frampton [3] presented a follow on paper to Fay and Sferco which examined data from the United Kingdom and focused on the seriously injured. Again, the data from NASS CDS over an equivalent time period found similar distributions of this population, with multiple impacts constituting a larger proportion of the seriously injured population than rollovers.

In 2004, Digges and Bahouth [4] performed an analysis updating earlier work by Fay at al. with NASS CDS data from 1998-2000. Their work confirmed that multiple impacts continued to contribute significantly to the seriously injured population. Digges and Bahouth also identified that the frontal-frontal, side-side, and frontal – side type multiple impacts constituted the majority of seriously injured occupants in multiple impacts. This work found similar results.

J. Bahouth's 2004 dissertation under the direction of Digges [5] further examined general multiple impacts to identify characteristics of injurious multiple impacts. Using NASS CDS data from 1998-2002, J. Bahouth classified multiple impacts where both delta-v's [5] were greater than 15 mph or where the second impact was of a greater severity than the first impact (secondary / primary)[6] as "consequential multiple impact crashes" which were linked with serious injury. As presented here, the current analysis has identified a similar link between the secondary / primary type multiple impacts, specifically multiple frontal impacts, and injury.

Also in 2004, Logan, Scully and Fildes [6] used ANCIS (Australia) crash data and found similar conclusions to that of earlier work. Notably, Logan et al. found multiple impacts constituted 32% of the data they examined and that these collisions were linked with elevated occurrences of serious injury.

Most recently in 2009, Raj and Digges [7] examined fatal frontal collisions with airbag non-deployments and found that 90% of this population included multiple impacts. The most common sequence of impacts in this population was impacts with curbs / guardrails followed by impacts with narrow objects. Impacts with roadside and narrow objects were also found in this work to be associated with higher instances of occurrence of multiple frontal impacts in general and injurious multiple frontal impacts specifically.

METHODOLOGY

The data source for this analysis was the NASS CDS for calendar years 1988 – 2006.[7] The data were analyzed in three ways. First, the data elements currently existing in the entire database were examined to determine the frequency of multiple impact and their characteristics. Second, it was found that some useful variables were available after certain calendar years and in those analyses the data was limited accordingly. Finally, the case by case analysis was limited to calendar years 1997 – 2006

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[4] Calculated using data in Table A-1. Values for GIDAS calculated from results published in Fay and Sferco 2001 [2]. Data presented is extracted from complete work which is the basis for this paper [1].

[5] Delta-v is the change in speed of a vehicle in the course of a single impact. For example, a vehicle which decelerates from 15 mph to 0 mph in a collision experienced a delta-v of 15 mph.

[6] Throughout this work, the impacts in a multiple impact collision sequence will be referred to in two ways. When referred to sequentially, the impacts will be referred to as the first or initial impact and the second or subsequent impact. When referred to in terms of severity, the most severe impact will be referred to as the primary impact and the second most severe impact will be referred to as the secondary impact. Note that the references in terms of severity (primary / secondary) are assigned to impacts, independent of their order in the collision sequence.

[7] Data from 1988-2006 was selected for the initial analysis to capture data on all multiple impacts which were present in the available data at the time the study was conducted. Analysis of individual variables was limited to shorter time periods that depended on the availability of the variable.

when case images and scene diagrams were readily available for review. Figure 1 illustrates the subsets which were created from the overall NASS CDS 1988-2006 dataset.

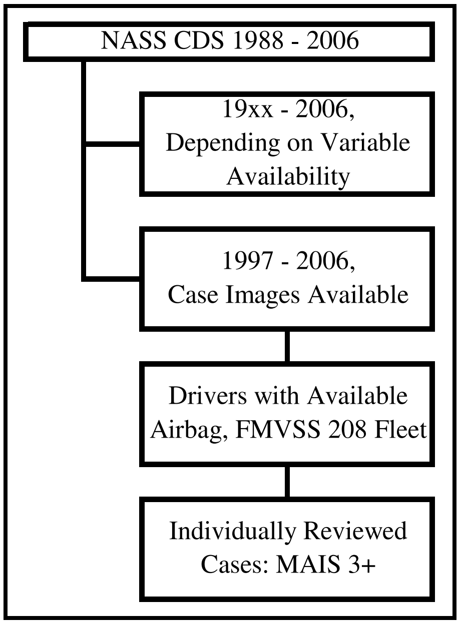

Figure 1. Schematic of Data Subsets.

The CDS database was first examined for a means of identifying multiple impacts in general. Manipulation of the vehicle number (VEHNO) and object contacted (OBJCONT) elements in the event file were necessary to create collision sequence histories for each vehicle in the database.[8] The modified database was then used to identify vehicles involved in two or more collisions in the course of a single crash sequence.

Multiple impacts were then classified by the general area of damage elements defined for the most severe (primary) impact (GAD1) and the second most severe (secondary) impact (GAD2). Due to their rarity and the lack of safety systems designed for and available to address them, collision sequences involving undercarriage impacts were eliminated from the analysis. Similarly, rollovers involve markedly different dynamics than planar crashes and collision sequences involving them were also eliminated from the analysis. Serious injury rates per 100 exposed occupants were then examined to identify possible relationships with the directions of impacts in a collision sequence. Unidirectional multiple-impacts, impacts in which a vehicle sustained more than one impact in the same direction (frontal, side, rear) were identified for further analysis based upon frequency and injury rate. Of the population of unidirectional multiple-impacts, multiple frontal impacts were selected to for examination of possible countermeasures. Rates of serious injury in multiple frontal impacts were contrasted with the injury rates in single frontal impacts which have a high effectiveness for current countermeasures in preventing serious injury. The occupant protection analysis was limited to belted drivers in vehicles equipped with airbags to identify more specifically where current frontal impact occupant protection countermeasures were failing to address multiple frontal impacts.

The general population of vehicles and occupants were used to examine multiple frontal impacts from the perspectives of countermeasures to prevent or predict multiple frontal impacts. A specific subset of the population, seriously injured belted drivers in vehicles with frontal airbags in multiple frontal impacts, was then selected for individual case reviews to examine possible occupant protection countermeasures.

The analyses were oriented so as to address three safety areas in which countermeasures might be developed. The pre-crash environment was examined in order to assist in developing safety systems to prevent the crash from occurring. The elements of the pre-crash and crash environment that could lead to the prediction of a multiple impact were examined to assist in developing crash protection countermeasures. Finally, in depth studies of multiple impact crashes with injuries were undertaken in order to better define opportunities for crash protection.

Prevention

To identify opportunities for the prevention of multiple frontal impacts, an analysis of the pre-impact location (PREILOC), accident type (ACCTYPE), and approximate travel / impact speed (IMPACTSP, TRAVELSP, SPLIMIT) elements was conducted. The rates of occurrence of multiple frontal impacts in relation to each of the variables were examined to identify pre-impact conditions which were correlated with the occurrence of

[8] The events in a collision are saved in an EVENT file in the NASS dataset, with a single entry for each event. In the case of a vehicle being involved in more than one event in a collision, the vehicle may have multiple entries in the EVENT file associated with it. The EVENT file was manipulated so all ordered events pertaining to a given vehicle collision sequence appeared in a single entry.

additional frontal impacts after an initial frontal impact.

Prediction

The data was further examined to characterize the dynamics of the vehicle during the crash sequence which could indicate an increased likelihood of the occurrence of multiple frontal impacts when compared to single frontal impacts. The principal direction of force (PDOF), specific horizontal location (SHL), type of damage distribution (TDD), and the object contacted (OBJCONT) elements were examined. The rates of occurrence of multiple frontal impacts in relation to each of the variables were examined to identify conditions during the initial impact which were correlated with the occurrence of additional frontal impacts. The data element only analysis was supplemented using reconstructions of the vehicle motion in the individual case reviews. An examination was conducted of the relationship between the proportion of kinetic energy remaining after the first impact and the occurrence of a second impact.

Protection

Data to characterize the motion of the vehicle throughout the multiple frontal impact collisions were limited in the original dataset. Cases involving belted drivers in vehicles with airbags available were reviewed individually and the motion of the vehicle throughout the collision was reconstructed to examine opportunities for occupant protection countermeasures. The order of severity of the impacts, impact speeds, delta-v's, objects contacted, and injury description variables were all analyzed to determine possible differences in injury severity and causation between single frontal impacts and multiple frontal impacts. The reconstructions of the vehicle motion in the individually reviewed cases were used to estimate the distance and time between impacts, and the relationship of lane / roadway departure relative to the impact sequence.

RESULTS

Population Identification

Table 1 displays the distribution of all occupants of all vehicles by number of recorded events. Approximately 25% of vehicles and occupants are involved in collision sequences with multiple events. Two-event collisions constituted approximately 75% of multiple event collision sequences (Table 2).

Table 2.
Distribution of Vehicles and Occupants By Number of Events, NASS CDS 1997-2006 [9]

No. of Events	Vehicles		Occupants	
	Raw	*Weighted*	*Raw*	*Weighted*
1	53,539	33,921,445	76,418	45,164,629
2	18,583	8,424,865	28,336	11,853,331
3+	8,909	2,774,325	13,940	3,999,423

Table 2 displays the MAIS 3+ injury rates for single and multiple impact crashes by crash direction. Nearly all multiple impact types sustain higher rates of serious injury when compared with single impacts. Unidirectional multiple impacts have higher rates of serious injury that single impacts. Unidirectional multiple frontal impacts have higher rates of serious injury than all types of single impacts. Only multiple impacts involving an initial impact to the side of the vehicle have higher rates of serious injury than unidirectional multiple frontal impacts (Table 3).

Table 3.
MAIS 3+ Injury Rate per 100 Exposed Drivers, NASS CDS 1997 – 2006 [10]

Single Impact		Multiple Impact			
		Uni-directional		*Multi-directional*	
Frontal	12	Frontal-Frontal	21	Side-Frontal	29
				Frontal-Rear	17
				Frontal-Side	16
				Rear-Frontal	5
Side	15	Side-Side	24	Side-Frontal	29
				Side-Rear	25
				Frontal-Side	16
				Rear-Side	11
Rear	3	Rear-Rear	18	Side-Rear	25
				Frontal-Rear	17
				Rear-Side	11
				Rear-Frontal	5

[9] The NASS CDS is a statistically based sample of certain types of crashes on U.S. roads. Unweighted refers to the raw number of cases present in the NASS CDS dataset. Weighted data refers to the raw cases when multiplied by a weighting factor which relates individual raw cases to the number of actual cases predicted by the sampling system to have occurred on U.S. roads.

[10] All drivers with a known MAIS in vehicles with a known GAD were included in this tabulation to provide an understanding of general injury rates while also providing a distribution of all vehicles. No account was made for belts use or airbag availability / deployment status. Calculated using data in Tables A-2 and A-3.

When examining the distribution of seriously injured (MAIS 3+) drivers in the general population, multiple impacts initiated with a frontal impact accounted for 24% of the population, second only to single frontal impacts. (Figure 2)

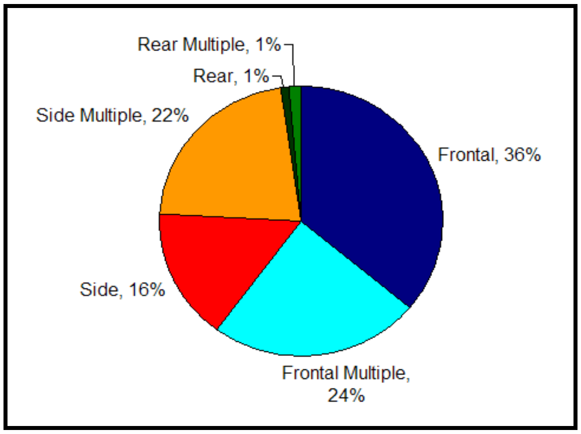

Figure 2. Distribution of MAIS 3+ Drivers by General Area of Damage of First Impact and Type of Impact, CDS 1997-2006. [11]

Prevention

The rate of occurrence of multiple frontal impacts for vehicles that departed the roadway prior to any impact was over five times the rate for vehicles which remained in their lane and was two and a half times the rate for vehicles which departed their lane but remained on the roadway prior to any impact (Table 4).

Table 4.
Vehicles by Pre-Impact Location and Type of Frontal Impact, NASS CDS 1997-2006 [12]

Pre-Impact Location	Type of Frontal Impact	
	Single	*Multiple*
Stayed in lane	71.7%	35.3%
Left travel lane	13.8%	15.4%
Departed Roadway	13.9%	48.2%

For seriously injured belted drivers in vehicles with an airbag available in multiple frontal impacts, cases in which the vehicle departed the roadway prior to any impact constituted 60 percent of the population. These occupants were twice as likely to sustain serious injury when compared to those multiple frontal impact cases where the vehicle did not depart the roadway prior to any impact. (Table 5)

Table 5.
Belted Drivers w/ Airbag Available, Multiple Frontal Impacts, NASS CDS 1997-2006 [13]

Pre-Impact Location (PREILOC)	Maximum AIS	
	2-	*3+*
Stayed in lane	605	51
Left travel lane	194	30
Departed Roadway	548	127
Unknown if left lane	9	0
Remained off road	5	1
Entered roadway	1	0
Returned to road	6	2
Unknown	1	1

Four of the five accident types involving only frontal impacts with the highest rates of occurrence of multiple frontal impacts involved roadway departure. (Table 6)

Table 6.
Frontal Impact Accident Types with Highest Rates of Multiple Frontal Impacts, NASS CDS 1992 – 2006 [14]

Frontal Impact, Accident Type (ACCTYPE)		
Category, Configuration, Accident Type	**% of Population**	**Rate of Multiple Impacts**
Single Driver, Right Roadside Departure, Drive Off Road	6.72%	36%
Single Driver, Left Roadside Departure, Drive Off Road	3.87%	36%
Same-Trafficway - Opposite Direction, Sideswip Angle, Lateral Move	1.08%	36%
Single Driver, Right Roadside Departure, Control / Traction Loss	2.87%	29%
Single Driver, Left Roadside Departure, Control / Traction Loss	2.51%	26%

[11] Calculated using data in Tables A-2 and A-3.

[12] Calculated using data in Table A-4. Percentages are of vehicle population with known pre-impact location. Pre-Impact locations of 'remained off road', 'entered roadway', and 'returned to road' accounted for only approximately 1% of each population and were left off of this summary chart.

[13] MAIS 2- indicates occupants with a Maximum Abbreviated Injury Score of 2 or less (0,1,2).

[14] There are 99 possible accident types across 6 categories and 13 configurations. 18 accident types accounted for 88% of the population. This table presents the five categories which each accounted for more than 1% of the population with the highest rates of multiple frontal impacts. The additional categories have been excluded for brevity.

The results of the analyses identified that lane departure prior to a frontal impact was associated with a more than doubling of the rate of occurrence of multiple frontal impacts and roadway departure was associated with a rate of occurrence more than five times that of vehicles which remained in their lane prior to any frontal impact. Multiple frontal impacts involving roadway departure accounted for 60% of the seriously injured population and were associated with rates of serious injury double that of multiple frontal impacts not involving roadway departure.

Prediction

Offset impacts and sideswipes or collisions with narrow object were associated with higher rates of multiple frontal impacts when compared to single frontal impacts (Tables 7 and 8).

Table 7.
Frontal and Multiple Frontal Impacts
by Specific Horizontal Location of First Impact,
NASS CDS 1992 – 2006 [15]

Specific Horizontal Location (SHL) of First Impact	% of Population		Rate of Multiple Frontal Impacts
	Single	Multiple	
Center	1%	2%	*20%*
Distributed	53%	34%	*7%*
Driver's Side 1/3	10%	23%	*21%*
Passenger's Side 1/3	9%	22%	*24%*
Driver's Side 2/3	15%	10%	*7%*
Passenger's Side 2/3	12%	8%	*8%*
Total % / Average Rate	100%	100%	*11%*

Table 8.
Frontal and Multiple Frontal Impacts
by Type of Damage Distribution of First Impact,
NASS CDS 1992-2006 [16]

Type of Damage Distribution (TDD) of First Impact	% of Population		Rate of Multiple Frontal Impacts
	Single	Multiple	
Narrow Impact	3%	12%	*34%*
Corner	8%	12%	*16%*
Sideswipe	1%	6%	*45%*
Wide Impact Area	60%	34%	*7%*
No CDC	24%	24%	*12%*
Unknown	3%	13%	*33%*
Total % / Average Rate	100%	100%	*12%*

Elevated rates of occurrence of multiple frontal impacts were also associated with initial impacts with objects likely to yield or redirect a vehicle (highlighted in yellow) (Table 9).

Table 9.
Multiple Frontal Impacts
By Object Contacted in First Impacts,
NASS CDS 1992-2006 [17]

Object Contacted (OBJCONT) in the First Impact	Type of Impact		Rate of Multiple Frontal Impacts
	Single	Multiple	
Moving Vehicle	82.48%	45.77%	*7%*
Small / Breakaway Narrow Object	0.90%	13.76%	*67%*
Roadside Terrain / Object	1.30%	13.04%	*57%*
Large / Non-Breakaway Narrow Object	7.67%	8.87%	*13%*
Fixed Object: Concrete Barrier / Other Barrier / Wall	2.82%	7.73%	*27%*
Vehicle Not In Transit	2.39%	3.69%	*17%*
Fixed Object: Other / Unknown	0.37%	3.15%	*53%*
Non-motorist / Non-fixed	1.00%	2.54%	*25%*
Fixed Object: Impact Attenuator / Building / Bridge	0.88%	0.98%	*13%*
Unknown Narrow Object	0.14%	0.40%	*27%*
Unknown Event or Object	0.00%	0.02%	*50%*
Other: Train	0.03%	0.02%	*8%*
Non-collision	0.01%	0.02%	*33%*
Other: Other Event	0.01%	0.02%	*33%*
Total % / Average Rate	100.00%	100.00%	*12%*

The analyses identified the connection between increased rates of multiple frontal impacts in offset / narrow first impacts and first impacts with objects likely to yield under impact or redirect the impacting vehicle.

The proportion of kinetic energy remaining after the first impact, P_{ke} was approximated as the ratio of the squares of the estimated speed after the first impact, $V_{pre\ first\ impact}$, and the estimated speed before the first impact, $V_{post\ first\ impact}$. (Equation 1)

$$P_{ke} = (v_{post\ first\ impact})^2 \,/\, (v_{pre\ first\ impact})^2 \quad (1).$$

A logistic regression modeling the occurrence of injurious (driver MAIS 3+, belted, airbag available) multiple frontal impacts when compared with the population of injurious single frontal impacts identified the proportion of kinetic energy remaining after the first impact as an indicator of increased likelihood.[18] The model has a maximum rescaled R-squared of 0.4005, with an intercept estimate of -

[15] Calculated using data in Table A-5.

[16] Calculated using data in Table A-6.

[17] Calculated using data in Table A-7.

[18] See Results in appendix B.

4.4601 and a coefficient for the proportion of kinetic energy remaining of 6.8073, both of which were statistically significant ($P < 0.0001$). The probability of a frontal impact resulting in a multiple-frontal impact crosses the 50% mark at a proportion of kinetic energy remaining of 66%. The model shows promise for the utility of the predicted proportion of kinetic energy remaining to predict multiple frontal impacts. The strength of the model could likely be improved with future refinement of the data system to capture more and accurate information about multiple impacts. (Figure 3)

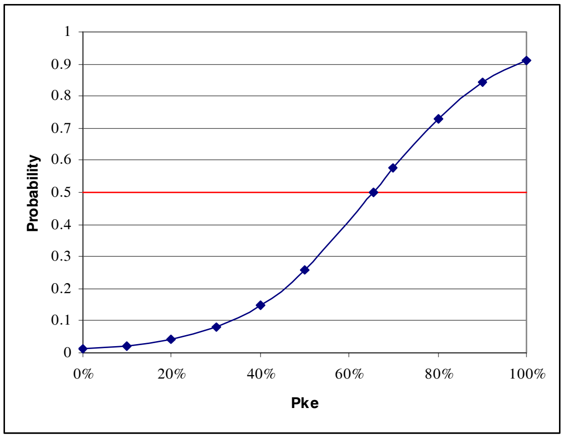

Figure 3. Plot of Probability of Multiple Frontal Impact as a Function of the Proportion of Kinetic Energy Remaining After an Initial Frontal Impact.[19]

Protection

Table 10 shows that multiple frontal impacts are twice as likely to result in serious injury to a belted driver in a vehicle with an airbag available than a single frontal impact. This table also illustrates how other analyses which ignore impacts beyond the most severe impact or which eliminate multiple impacts all together may be missing important information regarding the causation of injuries. Note that despite the rate of serious injury in multiple frontal impacts being double that of single frontal impacts, the overall serious injury rate of 8% for frontal impacts is driven by the preponderance of single frontal impacts in the data set. (Table 10)

Table 10.
Belted Drivers, Airbag Available,
By Collision Type,
NASS CDS 1997-2006 [20]

Crash Type	Exposed	MAIS 3+	Rate	Percent of Population	Percent of MAIS 3+
Frontal Single	10,148	740	7%	88%	79%
Frontal-Frontal	1,409	195	14%	12%	21%
Total	11,557	935	8%	100%	100%

Multiple frontal impacts in which the more severe impact occurred after the first impact (Secondary / Primary) were nearly twice as likely to result in serious injury among belted drivers of vehicles with airbags available. (Table 11)

Table 11.
Belted Drivers, Airbag Available,
By Order of Severity of Impacts,
NASS CDS 1997 – 2006, Unweighted Data

Impact Order	MAIS 2-	MAIS 3+	MAIS 3+ Rate
Primary - Secondary	818	91	10%
Secondary - Primary	483	114	19%

Multiple frontal impacts in which the more severe impact occurred first in the collision sequence (Primary / Secondary) had a higher concentration of seriously injured occupants at delta-v's below 20 mph. Comparatively, when the most severe impact occurred after the first collision in the impact sequence (Secondary / Primary), the concentration of seriously injured occupants extended into higher delta-v's up to 40 mph. This difference may be related to the combination of delta-v's of the impacts. In primary-secondary type impacts, a lower primary delta-v is necessary to cause injury when combined with a secondary impact. Conversely, in a secondary – primary type impact, a higher impact speed may be required at the first impact (regardless of delta-v) which is then carried over to the second impact (primary delta-v). Seriously injured occupants in single frontal impacts were concentrated in the delta-v range of 11 to 30 mph (Table 12, Figures 4 and 5).

[19] Detailed results of model fit may be found in reference [1].

[20] Calculated using data in Table A-8

Table 12.
Belted Drivers, Airbag Available,
By Delta-V of Most Severe Impact,
NASS CDS 1997-2006, Unweighted Data [21]

Delta-V Range of Most Severe (Primary) Impact (mph)	MAIS 3+ Rate		
	Single Frontal	Multiple Frontal	
		Primary - Secondary	*Secondary - Primary*
x <= 10	1%	2%	2%
10 < x <= 20	4%	9%	11%
20 < x <= 30	18%	11%	31%
30 < x <= 40	36%	37%	50%
40 < x <= 50	67%	100%	67%
50 < x <= 60	89%	100%	50%
60 < x <= 70	100%	-NA-	100%
Average	7%	9%	19%

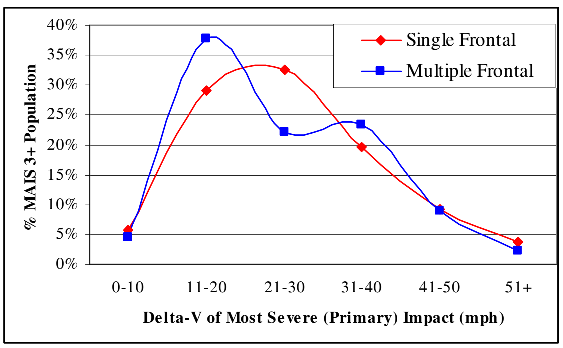

Figure 4. Belted Drivers, Airbag Available, MAIS 3+ Population, By Crash Severity, NASS CDS 1997-2006, Unweighted Data.[22]

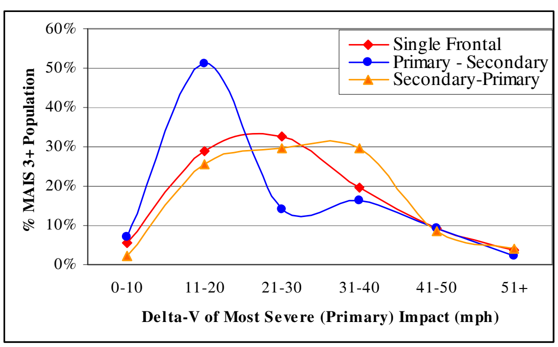

Figure 5. Belted Drivers, Airbag Available, MAIS 3+ Population, By Crash Severity, NASS CDS 1997-2006, Unweighted Data. [23]

When comparing single and multiple frontal impacts where the belted driver of a vehicle with an airbag available sustained a serious injury, it was found that unlike single frontals where other vehicles are most often the object contacted, multiple frontal impacts involved more collisions with fixed objects. (Table 13)

Table 13.
MAIS 3+ Belted Drivers, Airbag Available,
Single and Multiple Frontal Impacts
By Object Contacted, NASS CDS 1997-2006 [24]

Object Type	Object Contacted (OBJCONT)			
	Single Frontal	*Multiple Frontal*		
		All Impacts	First Impact	Second Impact
Vehicle	80%	31%	19%	12%
Fixed Object	18%	43%	13%	30%
Small / Breakaway Object & Non-Fixed Object	2%	17%	10%	6%
Roadside Terrain / Object	1%	9%	7%	2%
Total	100%	100%	50%	50%

Using the same data, when the distribution of objects contacted was examined according to each impact, it was observed that in multiple frontal impacts, while the first object contacted is still most often another vehicle, the second object contacted is often a fixed object. (Table 14)

[21] Calculated using data in Table A-9.

[22] Calculated using data in Table A-9.

[23] Calculated using data in Table A-9.

[24] Calculated using data in Table A-10.

Table 14.
MAIS 3+ Belted Drivers, Airbag Available, Single and Multiple Frontal Impacts, Objects Contacted by Impact, NASS CDS 1997-2006 [25]

Object Type	Object Contacted (OBJCONT)		
	Single Frontal	*Multiple Frontal*	
		First Impact	Second Impact
Vehicle	80%	38%	23%
Fixed Object	18%	27%	60%
Small / Breakaway Object & Non-Fixed Object	2%	21%	13%
Roadside Terrain / Object	1%	14%	4%
Total	100%	100%	100%

For multiple frontal impacts in which the most severe impact occurred after the initial impact, the head / face / neck ranked body region group was the most often injured region of the body, accounting for 56% of the MAIS 3+ injuries by ranked body region. This is an increase when compared with the overall multiple frontal impact population in which the head / face / neck only accounts for 47% of the serious injuries. In multiple frontal impacts in which the most severe impact occurred first in the collision sequence, the head / face / neck accounted for a smaller proportion of injuries, 36%, with an increase in extremity injuries when compared with single frontal impacts. (Table 15)

Table 15.
Individually Reviewed Cases, By Ranked Body Region [26]

Ranked Body Region	MAIS 3+ Drivers		
	All	Primary - Secondary	Secondary - Primary
Head / Face /Neck	47%	36%	56%
Thorax / Abdomen / Spine	13%	11%	15%
Lower Extremity	20%	25%	16%
Upper Extremity	19%	27%	13%

Over half of the multiple frontal impacts had impacts after the initial collision occurring within 100 ft of the initial impact. (Table 16)

Table 16.
Individually Reviewed Cases By Distance Between Impacts [27]

Distance Between Impacts (ft)	Population %
x <= 100	51%
100 < x <= 200	29%
200 < x <= 300	10%
300 < x <= 400	1%
400 < x <= 500	6%
500 < x	4%
Total	100%

Approximately half of the multiple frontal impacts had impacts after the initial collision occurring less than 2 seconds after the initial impact. (Table 17)

Table 17.
Individually Reviewed Cases By Time Between Impacts [28]

Minimum Time Between Impacts (S)	Population %
t <= 1	15%
1 < t <= 2	36%
2 < t <= 3	15%
3 < t <= 4	7%
4 < t <= 5	7%
5 < t	19%
Total	100%

While only 49% of all multiple frontal cases in the original dataset were reported as having involved roadway departure, 77% of the multiple frontal impacts cases individually reviewed involved roadway departure. Roadway departure, as determined from the individual case reviews, identified 19 cases (out of the total of the 108 individually reviewed cases) where the pre-impact location variable in the original dataset (PREILOC) did not accurately identify the involvement of roadway departure (highlighted in yellow). 80% of the individually reviewed cases with roadway departure involved roadway departure prior to any impact. (Table 18)

[25] Calculated using data in Table A-10.

[26] Calculated using data in Table A-11.

[27] Calculated using data in table A-12.

[28] Calculated using data in Table A-13.

Table 18.
Individually Reviewed Cases,
Comparison of Roadway Departure
And Coded Pre-Impact Location

		Pre Impact Location			
From Case Analysis		**From PREILOC Variable**			
		Stayed in Lane	*Left Travel Lane*	*Departed Roadway*	*Returned to Road*
Stayed in Lane		2	0	0	0
Left Travel Lane	Before Any Impact	1	9	3	0
	After First Impact	8	1	1	0
Departed Roadway	Before Any Impact	1	2	62	1
	After First Impact	13	3	1	0

Multiple frontal impacts where the most severe impact did not occur first in the collision sequence had higher concentrations of injured occupants at higher severities than single frontal impacts. The head / face / neck body region constituted the highest proportion of the serious injuries in multiple frontal impacts where the most severe impact did not occur first in the collision sequence.

The individual case reconstructions also identified that over half of multiple frontal impacts had impacts after the initial impact occurring within 100 ft of the initial impact. Half of the cases had subsequent impacts occurring 2 seconds or less after the initial impact. More than three quarters of the individually reviewed cases involved roadway departure, most of which occurred before any impacts in the collision sequence.

DISCUSSION

This work examined the occurrence of multiple frontal impacts from the perspective of developing countermeasures to prevent these crashes from occurring, predict their occurrence in the course of a crash sequence, and protect occupants in multiple events.

Lane or roadway departure occurred in 64% of multiple frontal impact crashes and was associated with a nearly fourfold increase in the rate of occurrence of multiple frontal impacts when compared with single impacts. This finding holds great promise for possible safety benefits of lane / road departure warning systems being implemented in the vehicle fleet today and an analysis of the impact of electronic stability control systems with respect to the occurrence of multiple impacts may identify additional benefits of this existing technology.

The examination of the dynamics of the vehicle during the collision identified that increased rates of multiple frontal impacts are associated with offset impacts and impacts with objects which yield or are designed to re-direct a vehicle. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts. Combined, these findings indicate that the incorporation of algorithms to identify collisions which are unlikely to bring a vehicle to a stop or are resulting in re-direction would enable the design of occupant protection countermeasures to address multiple frontal impacts.

Multiple frontal impacts were identified as having an elevated rate of serious injury (MAIS 3+). Of the population of seriously injured drivers, 24% were involved in multiple impacts initiated by a frontal impact. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. These findings highlight the risk these collisions pose and the opportunity to improve safety by addressing them.

The in-depth study of individual cases found that the initial impact was the most severe in 44% of the crashes. A vehicle was the most frequent initial contact when the initial impact was most severe. For the 56% of the crashes in which subsequent impacts were most severe, a fixed object was the most frequent severe contact. The in-depth study produced the following observations. (1) The mean crash severity for multi-impact frontal crashes was higher than for single event frontal crashes. (2) The highest mean crash severity occurred when the subsequent impact was more severe than the initial impact (3) About half of the crashes had a distance greater than 100 ft between the impacts and a time interval greater than 2 seconds. (4) The body region most frequently injured was the head. Combined, these findings regarding the conditions within multiple frontal impacts in which optimally protected drivers (belted with airbag available) are being injured provide insight into parameters for a multiple frontal impact protection system. Such a system would have to be better suited to address acceleration pulses associated with higher severity collisions into fixed and generally narrow objects. The triggering system for any countermeasures must be able to sustain its capability for at least two seconds after the initial impact. Finally, multiple frontal impact countermeasures should be focused on protecting the head / face / neck body region.

OBSERVATIONS / LIMITATIONS

The study of multiple impacts suffers significantly from the current design of the databases recording information on crashes. While information regarding some aspects of multiple impacts could be ascertained from the current design, individual case analysis was required to properly identify and code important aspects of these complex collisions. Details about impacts other than the most severe impact in a collision sequence are often overlooked or dismissed. This work has expanded upon earlier works to indicate the dangers posed by these types of collisions and the benefits which added detail in current databases could provide. Most notably, and as indicated in the complete work by these authors, the study of multiple impacts in general could benefit significantly from the widespread adoption and proper implementation of electronic data recorders (EDRs) in vehicles. EDRs which can record multiple events would provide a wealth of data presently being left out of current databases for a variety of reasons. Despite data limitations, the findings of this study are consistent with earlier works and results from the general study and the individual case reviews are also consistent.

CONCLUSIONS

Multiple impacts initiated by a frontal impact account for about 24% of the population of seriously injured (MAIS 3+) drivers in recent model passenger vehicles. Multiple frontal impacts alone accounted for 10% of the seriously injured driver population. Lane departure and roadway departure were the most frequent pre-crash events. The proportion of kinetic energy remaining after the first impact was identified as a possible predictor of the likelihood of multiple impacts. About 50% of the crashes in an in-depth study had a time interval of 2 seconds or less between the impacts. In the majority of these crashes, the subsequent impact was more severe than the initial impact. The head / face / neck body region constituted a highest proportion of the serious injuries in multiple frontal impacts where the most severe impact did not occur first in the collision sequence. Countermeasures in both crashworthiness and crash avoidance appear possible to address this opportunity to reduce casualties. Crash imminent and crash triggered braking systems which would reduce velocity prior to and after an initial impact would reduce the probability of vehicles in frontal impacts being involved in subsequent impacts. Lane and roadway departure prevention and warning systems as well as ESC systems could also reduce the chances of multiple frontal impacts. Occupant protections systems developed to address multiple frontal impacts should focus on retaining capability for deployment for up to two seconds after the initial impact and maintaining safety belt protection for periods beyond 2 seconds.. Deployment strategies which allow occupant protection systems to function during subsequent impacts which are more severe than the initial impact would address those situation which are associated with elevated levels of serious injury.

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Contact Information: Dr. Shaun Kildare
skildare@ncac.gwu.edu

Definitions / Abbreviations:

ACCTYPE : NASS CDS variable, Accident Type.

ANCIS : Australian National Crash In-Depth Study.

CDS : Crashworthiness Data System.

GAD1, GAD2 : NASS CDS variable, General Area of Damage.

GIDAS : German In-Depth Accident Study.

IMPACTSP : NASS CDS variable, Impact Speed.

MAIS : Maximum Abbreviated Injury Score.

MAIS 3+ : Maximum Abbreviated Injury Score of 3 or greater (3,4,5,6)

MAIS 2- : maximum Abbreviated Injury Score of 2 or less (0,1,2)

NASS: National Automotive Sampling System.

OBJCONT1, OBJCONT2 : NASS CDS variables, Object Contacted.

PDOF1, PDOF2 : NASS CDS variable, Principal Direction of Force.

P_{ke} : Proportion of kinetic energy remaining after an initial impact.

PREILOC : NASS CDS variable, Pre-Impact Location.

Primary Impact : most severe impact in a multiple impact collision sequence.

Primary – Secondary : Multiple impact collision sequence in which the first impact is the most severe impact.

Secondary Impact : impact in a multiple impact collision sequence which is not the most severe impact.

Secondary – Primary : Multiple impact collision sequence in which the first impact is not the most severe impact.

SHL1, SHL2 : NASS CDS variables, Specific Horizontal Location

SPLIMIT : NASS CDS variable, Speed Limit

TDD1, TDD2 : NASS CDS variables, Type of Damage Distribution

TRAVELSP : NASS CDS variables, Travel Speed

VEHNO: NASS CDS variable, identifies a particular vehicle in a crash.

$v_{post\ first\ impact\ t}$: Vehicle speed after the first impact

$v_{pre\ first\ impact}$: Vehicle speed prior to first impact

Appendix

Table A-1.
Population of Occupants by Impact Type, Comparison of GIDAS & NASS CDS data.

MAIS						
Impact Type	**GIDAS 1996 - 2000**		**NASS CDS 1996 - 2000**		**NASS CDS 2001 - 2006**	
	2-	3+	2-	3+	2-	3+
Single Frontal	3,103	96	10,274	1,841	12,967	1,984
Single Side	1,381	61	3,459	849	4,278	819
Single Rear	801	6	974	45	1,189	47
Single Rollover	31	3	545	255	713	316
Multiple Impact	2,040	125	8,099	2,932	11,014	3,912

Table A-2.
MAIS 2- Driver Population by Impact Type, NASS CDS 1997 – 2006

MAIS 2-					
Single Impact		**Multiple Impact**			
		Uni-directional		*Multi-directional*	
Frontal	16,401	Frontal-Frontal	2,339	Side-Frontal	946
				Frontal-Rear	598
				Frontal-Side	3,933
				Rear-Frontal	992
Side	5,569	Side-Side	2,996	Side-Frontal	946
				Side-Rear	246
				Frontal-Side	3,933
				Rear-Side	252
Rear	1,507	Rear-Rear	41	Side-Rear	246
				Frontal-Rear	598
				Rear-Side	252
				Rear-Frontal	992

Table A-3.
MAIS 3+ Driver Population by Impact Type, NASS CDS 1997 – 2006

MAIS 3+					
Single Impact		**Multiple Impact**			
		Uni-directional		*Multi-directional*	
Frontal	2,302	Frontal-Frontal	630	Side-Frontal	378
				Frontal-Rear	125
				Frontal-Side	766
				Rear-Frontal	54
Side	994	Side-Side	949	Side-Frontal	378
				Side-Rear	82
				Frontal-Side	766
				Rear-Side	31
Rear	43	Rear-Rear	9	Side-Rear	82
				Frontal-Rear	125
				Rear-Side	31
				Rear-Frontal	54

Table A-4.
Vehicles by Pre-Impact Location and Type of Frontal Impact, NASS CDS 1997-2006

Pre-Impact Location	**Type of Frontal Impact**	
	Single	*Multiple*
Stayed in lane	22,593	1,562
Left travel lane	4,348	680
Departed Roadway	4,364	2,134
Unknown if left lane	244	29
Remained off road	71	36
Entered roadway	63	2
Returned to road	57	14
Unknown if left lane	357	39
No Driver	1	1

Table A-5.
Frontal and Multiple Frontal Impacts by Specific Horizontal Location of First Impact, NASS CDS 1992 – 2006

Specific Horizontal Location (SHL) of First Impact	**Type of Impact**	
	Single	**Multiple**
Center	217	53
Distributed	9,934	781
Driver's Side 1/3	1,955	532
Passenger's Side 1/3	1,613	505
Driver's Side 2/3	2,757	219
Passenger's Side 2/3	2,308	188
Total	18,784	2,278

Table A-6.
Frontal and Multiple Frontal Impacts by Type of Damage Distribution of First Impact, NASS CDS 1992-2006

Type of Damage Distribution (TDD) of First Impact	**Type of Impact**	
	Single	**Multiple**
Narrow Impact	1,147	586
Corner	3,064	576
Sideswipe	341	281
Wide Impact Area	22,759	1,705
No CDC	9,192	1,203
Unknown	1,311	639
Total	37,814	4,990

Table A-7. Multiple Frontal Impacts By Object Contacted in First Impacts, NASS CDS 1992-2006

Object Contacted (OBJCONT) in the First Impact	Type of Impact: Single	Type of Impact: Multiple
Moving Vehicle	31,344	2,292
Small / Breakaway Narrow Object	343	689
Roadside Terrain / Object	493	653
Large / Non-Breakaway Narriow Object	2,915	444
Fixed Object: Concrete Barrier / Other Barrier / Wall	1,072	387
Vehicle Not In Transit	909	185
Fixed Object: Other / Unknown	139	158
Non-motorist / Non-fixed	381	127
Fixed Object: Impact Attenuator / Building / Bridge	334	49
Unknown Narrow Object	54	20
Unknown Event or Object	1	1
Other: Train	12	1
Non-collision	2	1
Other: Other Event	2	1
Total	38,001	5,008

Table A-8. Belted Drivers, Airbag Available, By Collision Type, NASS CDS 1997-2006

Number of Impacts		Impact Direction		Occupant		Belt Use		Population by MAIS	
Type	*Rate*	*Type*	*Rate*	*Type*	*Rate*	*Type*	*Rate*	*2-*	*3+*
Single	10%	Frontal	10%	Driver	10%	Belted	7%	9,408	740
						Unbelted	24%	1,396	448
				Other	8%	Belted	6%	2,301	149
						Unbelted	17%	409	83
		Other	11%	Driver	11%	Belted	9%	4,503	427
						Unbelted	31%	475	211
				Other	9%	Belted	7%	1,452	114
						Unbelted	21%	206	56
Multiple	17%	Frontal-Frontal	18%	Driver	19%	Belted	14%	1,214	195
						Unbelted	32%	354	164
				Other	18%	Belted	15%	285	51
						Unbelted	25%	89	29
		Other	17%	Driver	17%	Belted	13%	6,106	874
						Unbelted	35%	1,134	622
				Other	15%	Belted	12%	1,747	228
						Unbelted	28%	398	152

Table A-9. Belted Drivers, Airbag Available, By Delta-V of Most Severe Impact, NASS CDS 1997-2006, Unweighted Data

Delta-V Range of Most Severe (Primary) Impact	MAIS					
	Single Frontal		Multiple Frontal			
			Primary - Secondary		*Secondary - Primary*	
	2-	3+	2-	3+	2-	3+
x <= 10	2,607	30	142	3	52	1
10 < x <= 20	3,684	153	224	22	100	12
20 < x <= 30	782	172	48	6	31	14
30 < x <= 40	183	103	12	7	14	14
40 < x <= 50	24	49	0	4	2	4
50 < x <= 60	2	17	0	1	1	1
60 < x <= 70	0	3	0	0	0	1
Total	7,282	527	426	43	200	47

Table A-10. MAIS 3+ Belted Drivers, Airbag Available, Single and Multiple Frontal Impacts By Object Contacted, NASS CDS 1997-2006

Object Type	Object Contacted		
	Single Frontal	*Multiple Frontal*	
		First Impact	Second Impact
Vehicle	637	72	44
Fixed Object	141	51	113
Small / Breakaway Object & Non-Fixed Object	14	39	24
Roadside Terrain / Object	9	27	8
Total	801	189	189

Table A-11. Individually Reviewed Cases, By Ranked Body Region

Ranked Body Region	MAIS 3+ Drivers		
	All	Primary - Secondary	Secondary - Primary
Head / Face /Neck	47	16	31
Thorax / Abdomen / Spine	13	5	8
Lower Extremity	20	11	9
Upper Extremity	19	12	7
Total	99	44	55

Table A-12.
Individually Reviewed Cases
By Distance Between Impacts

Distance Between Impacts (ft)	N
x <= 100	43
100 < x <= 200	24
200 < x <= 300	8
300 < x <= 400	1
400 < x <= 500	5
500 < x	3
Total	84

Table A-13.
Individually Reviewed Cases
By Time Between Impacts

Minimum Time Between Impacts (S)	N
t <= 1	11
1 < t <= 2	26
2 < t <= 3	11
3 < t <= 4	5
4 < t <= 5	5
5 < t	14
Total	72