CHARACTERISTICS OF MULTIPLE IMPACT CRASHES THAT PRODUCE SERIOUS INJURIES

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ABSTRACT

Researchers analyzed the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) 1998-2002 to examine the characteristics of single and multiple impact crashes. In addition to a statistical analysis, individual cases were studied to determine factors that contributed to injury risk.

Multiple impact crashes (MICs) make up 42 percent of all tow-away crashes that occurred on US roadways between 1998 and 2002. The risk for high-severity injuries is about 1.5 times greater in MICs than single impact crashes in moderate and high-range delta velocities. The average delta velocity values of single impact crashes (SICs) and MICs are similar in all tow-away crashes. Impact speeds for MICs resulting in MAIS3+ (Maximum Abbreviated Injury Scale: level 3 or greater) injuries are lower than that for SICs. A frontal crash followed by a second frontal crash occurs most often, followed by near-side/near-side and front/near-side multiple impact crashes.

After the initial investigation of MICs, belted drivers became the focus of this study, because the kinematics of unrestrained occupants is often too complicated. The most harmful category is front followed by front MICs for the population of belted drivers analyzed.

Based on case reviews, the researchers found that multiple impact crashes could be better described by separating them into two categories – incidental and consequential. For the incidental cases, only one impact was influential in the injury outcome. In consequential cases, both impacts were 15 mph (24 km/h) or greater delta velocity. Cases with higher severity secondary impacts were also classified as consequential.

The following were associated with increased injury severity in consequential MICs: more than one injurious impact; initial injury exacerbated by the second impact; the first impact caused the occupant to be out of position for subsequent impacts; crumple zones exhausted by the first impact; safety devices deployed during the first impact making them unavailable for subsequent impacts.

The frequency and injury risks for each combination of MICs are shown in this paper.

INTRODUCTION

A multiple impact crash is one in which a vehicle undergoes two or more impacts during a single crash sequence. Neither the initial impact nor the subsequent impact(s) is limited in any direction, sequence, or impacted object. After the initial investigation, the data analysis portion of this research considers only multiple impact crashes that do not involve rollover, where the drivers were not ejected, and where the drivers were belted. This population of multiple impact crashes will be referred to as “MICs”. The population of crashes that involve only one impact will be referred to as single impact crashes or “SICs”.

Several recent statistical studies of multiple impact crashes have been published (Digges, 2003 and Lenard, 2004). The purpose of the present study is to build on the past statistical analysis and introduce in-depth reviews of accident cases involving multiple impacts in order to better understand these crashes.

From 1998 through 2002, approximately 5,333,129 multiple impact, tow-away crashes occurred on U.S. roadways, based on NASS/CDS data. This is approximately 42 percent of all tow-away crashes. These crashes contributed 43 percent of all drivers’ MAIS3+ injuries and 47 percent of all driver fatalities. The fatality equivalent is almost 11,000 lives per year (all occupants). The average yearly cost of this phenomenon is about $37 billion.

The economic impact and human toll of multiple impact crashes is significant, therefore further research, analysis, and testing are needed to adequately address this issue.

ANALYSIS OF MULTIPLE IMPACT CRASHES

The researchers queried the NASS/CDS database to tabulate how often each direction of impact occurred during the first and second impacts. This query includes those crashes involving two or more impacts, but only the first and second most significant impacts were considered.

The "most significant impact" indicates the most severe impact whether it is the first, second or any other subsequent impact. The "other significant impact" indicates the second most severe impact. In a crash where the first and the third events are the most significant, the second event is not considered in the discussion to follow. Most MICs (59 percent) consist of two impacts while the remaining (41 percent) represent two or more impact MICs.

Table 1 shows the distribution of the 5.3 million multiple impact crashes by crash direction of the first and second significant impacts. The side impacts have been separated according to their direction. The near category indicates the impact was on the driver's side. The far category indicates the impact was on the passenger's side.

Table 1.
Percent Frequency of
Collision Sequence for All MICs

		2nd Impact				Total
		front	near	far	rear	
1st Impact	front	16%	12%	11%	6%	45%
	near	4.0%	6.0%	4.0%	1.0%	15%
	far	5.0%	4.0%	8.0%	1.0%	18%
	rear	20%	0.5%	2.0%	1.0%	24%
		45%	23%	24%	9%	

The most frequent first impact is the frontal impact at 45 percent of the total. The most frequent second impact is also a frontal impact at 45 percent. A rear impact, as the first impact, followed by a frontal impact (rear-front) is the most frequent collision combination at 20 percent. This collision sequence is a typical rear-end collision followed by a frontal impact. The front-front, at 16 percent, is next most frequent. The least frequent collision sequence is the rear-near MIC at 0.5 percent.

The researchers used the same method to find the frequency of MIC collision sequences with regard to restrained drivers. The population of MICs with restrained drivers from 1998 to 2002 is 3.2 million. Belted drivers became the main focus of the research because often times the mechanics of an unrestrained occupant in multiple impacts is too difficult to analyze. Table 2 shows the percent frequency outcomes for collision sequence in this population.

Table 2.
Percent Frequency of Collision Sequence
For Belted Drivers

		2nd Impact				Total
		front	near	far	rear	
1st Impact	front	17%	13%	11%	7%	48%
	near	5.4%	6.5%	4.1%	0.68%	17%
	far	5.3%	4.5%	8.2%	1.2%	19%
	rear	15%	0.61%	0.73%	0.63%	17%
		42%	24%	24%	9%	

The collision sequence occurring most often in this dataset is the front-front collision at 17 percent. This category is followed by the rear-front (15 percent), front-near collisions (13 percent) and front-far collisions at (11 percent).

The total number of MAIS3+ injured and belted drivers in MICs is 89,125 (973 unweighted). Table 3 is the corresponding percent frequency by MIC collision sequence for this population. The front-front sequence is most common (20 percent) when MAIS3+ injuries result. Next is near-near (15 percent), front-far (13 percent) and front-near (11 percent). The near-near category is seventh most common in frequency for belted drivers, but second most common in resulting MAIS3+ injuries.

Table 3.
Percent Frequency of MAIS3+ Injured and Belted Drivers by Collision Sequence

		2nd Impact				Total
		front	near	far	rear	
1st Impact	front	20%	11%	13%	3.9%	48%
	near	8.5%	15%	9.2%	2.1%	35%
	far	4.3%	2.4%	7.5%	0.4%	14%
	rear	2.2%	0.2%	0.2%	0.2%	3%
		35%	28%	30%	7%	

The total number of AIS3+ (Abbreviated Injury Scale: level 3 or greater) injuries for belted drivers in MICs is 129,168 or 48 percent of all AIS3+ injuries.

Figure 1 shows the breakdown by body region for MICs and SICs.

MICs result in more than one-half of the serious head injuries reported for belted drivers. The trunk and extremities make up close to one-half of the serious injuries in each body region. These findings are remarkable in that MICs are 42 percent of the total crash population, but result in almost one-half, if not more, of the reported serious injuries.

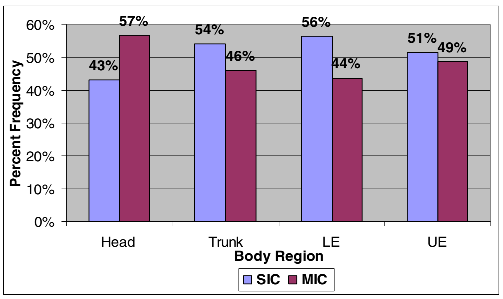

Figure 1. Percent Frequency of AIS3+ Injuries by Body Region For Belted Drivers - NASS/CDS 1998-2002.

Risk of Injury

Risk is a calculation that reveals the chances that something will occur given certain conditions. For instance, the risk of injury in a frontal crash is the total number of injuries sustained in a frontal crash divided by the total number of occupants who were exposed to a frontal crash.

The researchers calculated the risk associated with tow-away single and multiple impact crashes where the driver was belted and no rollover or ejection occurred. Almost 2 (± 0.34 percent) out of 100 drivers involved in an SIC will sustain an MAIS3+ injury. Over 4 (± 1.1 percent) out of 100 drivers involved in an MIC will sustain an MAIS3+ injury. For this population, the trend shows that the risk of an MAIS3+ injury in an MIC is higher than that in an SIC.

The relative risk for MAIS3+ injuries in this populations is 2.2, indicating that a driver is 2.2 times more likely to sustain an MAIS3+ injury in an MIC compared to an SIC.

Figure 2 shows the belted drivers' risk of AIS3+ injuries by body region for both MICs and SICs. Note that the risks for the head and the trunk in MICs are both statistically significantly higher than those for SICs. Although multiple impact crashes occur less frequently on U.S. roadways, they represent a higher risk of serious injury than single impact crashes.

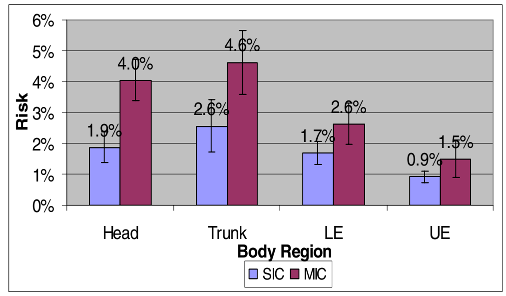

Figure 2. Risk of AIS3+ Injuries by Body Region For Belted Drivers - NASS/CDS 1998-2002.

Table 4 shows that of the 16 MIC categories, the greatest risk of MAIS3+ injury to belted drivers is in the near-rear MIC at 11 percent. This is followed by rear-far (9.7 percent), near-near (8.3 percent), and near-front (7.9 percent). Three of the top four risk categories have a near-side component. Risks for each collision sequence and the associated confidence intervals are shown in Table 4.

Table 4.
Risk of MAIS3+ by Collision Sequence
For Belted Drivers
with Associated Confidence Interval

		2nd Impact			
		F	N	Far	R
1st impact	F	5.2% (±2.9%)	5.6% (±1.7%)	5.3% (±2.1%)	2.0% (±1.4%)
	N	7.9% (±6.1%)	8.3% (±3.6%)	7.6% (±4.6%)	11% (±11%)
	Far	3.9% (±2.9%)	4.8% (±2.0%)	4.3% (±2.5%)	4.1% (±5.0%)
	R	0.52% (±0.26%)	3.2% (±2.8%)	9.7% (±9.9%)	1.8% (±2.8%)

For the sake of comparison, Table 5 shows the risks associated with SICs for belted drivers with MAIS3+ injuries. A near-side impact poses the greatest risk at 3.8 percent and is lower than that of 10 MIC categories.

Table 5.
Risk of MAIS3+ by Collision Sequence
For Belted Drivers in SICs
with Associated Confidence Intervals

Front	Near	Far	Rear
2.2%	3.8%	1.9%	0.4%
±0.5%	±1.4%	±0.81%	±0.26%

Delta Velocity

The researchers divided the MICs and SICs from NASS/CDS 1998-2002 into three groups of delta velocity values: <15 mph (24 km/h); 15-25 mph (24-40 km/h); 25+ mph (40+ km/h). The MIC cases were subdivided according to the most severe delta velocity. For instance, if the case consisted of a 12 mph (19 km/h) first impact and a 17 mph (27 km/h) second impact, it was categorized as a 15-25 mph (24-40 km/h) case. For comparison to the SIC, the researchers chose the higher delta velocity, the predominant delta velocity, of the MIC. Figure 3 shows the risk of MAIS3+ injury distribution over the delta velocity ranges for both MICs and SICs for belted drivers.

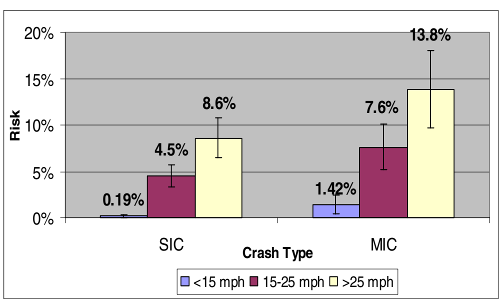

Figure 3. RISK of MAIS3+ Injuries to Belted Drivers by Delta Velocity - NASS/CDS 1998-2002.

In all three delta velocity categories, the risk is greater in MICs than in SICs. The difference in risk of MAIS3+ injury between SICs and MICs is not statistically significant, though for belted drivers the trend shows that MICs typically pose a greater risk for high-severity injuries than SICs.

Impact Speed

The impact speed is a reconstructed value of vehicle speed at the time of collision. The researchers queried the impact speed of SICs and MICs in NASS/CDS 1998-2002 where the impact speed was below 90 mph (145 km/h) to eliminate extremely high and questionable impact speeds.

The average impact speed for SICs was 33 mph (53 km/h) whereas that for the most significant impact in MICs was 44 mph (71 km/h). Note that in this query the researchers only considered MICs for which there were two documented delta velocities, because the confidence and accuracy of the impact speed is greater with two known values for delta velocities.

The impact speed of MICs is generally 10 mph (16 km/h) faster than that of SICs. Although this is based on a limited number of cases, it could imply that multiple impact crashes are higher energy events than single impact crashes.

The researchers also determined the percent frequency of impact speeds where the injury level was MAIS3+. Most high-severity injury multiple impact crashes lie in the 30-40 mph (48-64 km/h) range. The remaining crashes are in the 40+ mph (64+ km/h) range in this MAIS3+ category. The majority of the high-severity injury SICs are in the 40+ mph (64+ km/h) impact speed range. Figure 4 shows the distribution of impact speeds for this MAIS3+ grouping.

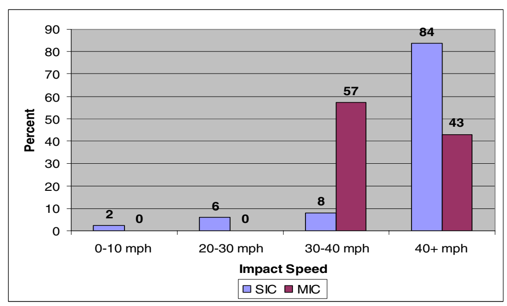

Figure 4. Percent Frequency of Impact Speeds: SIC vs. MICs for MAIS3+ crashes.

The average impact speed was 53 mph (83 km/h) for SICs whereas that for the most significant impact in MICs (with at least two known delta velocities documented) was 46 mph (74 km/h). In this MAIS3+ grouping, the SICs require higher impact speeds than the MICs to result in MAIS3+ injuries. This implies more severe crash characteristics in MICs than SICs, as they are resulting in the same injury severity but at a lesser impact speed.

HARM

The unit cost of crash injuries has been published by NHTSA (DOT HS 809 446). These unit costs can be used to calculate the total annual cost for injuries of all severities that are associated with any category of crashes (Fildes, 1996). The total yearly HARM (a metric for quantifying costs of injury associated with motor vehicle crashes) for all MIC categories is more than $37 billion. See Table 6 for HARM values in all MIC categories. The highest HARM values are in the front-front, front-far, front-near, and near-near categories. Relative to the number of occupants exposed to these crashes, the cost of multiple impact crashes outweighs that of single impact crashes by more than $3,200 per occupant exposed every year.

Table 6.
HARM by MIC Category

Sequence	HARM	Sequence	HARM
FF	$ 4.0	NF	$ 1.2
FN	$ 3.1	NN	$ 3.0
FFar	$ 3.4	NFar	$ 1.6
FR	$ 1.0	NR	$0.22
FarF	$ 1.3	RF	$ 1.1
FarN	$ 1.4	RN	$0.08
FarFar	$ 1.6	RFar	$0.34
FarR	$0.26	RR	$0.10

CLINICAL CASE REVIEWS

Injuries resulting from SICs and MICs are documented and readily available in the NASS/CDS data. For MICs, however, the data is not clear as to *when* during the multiple impact collision each of the injuries was sustained.

Perhaps all of the significant injuries were sustained during the initial impact, therefore implying the subsequent impacts were minor. Or the reverse could be true. Either way, the NASS/CDS database is not constructed in such a way that one can query *when* (during which impact) the injuries occurred.

For this reason, the researchers conducted a clinical review of numerous multiple impact crashes to determine *when* the injuries occurred. The goal was to better decipher the problems inherent in multiple impact crashes. See "Characteristics and Crash Factors Producing High-Severity Injuries in Multiple Impact Crashes", reference [1], for detailed information regarding these clinical reviews.

The team reviewed a group of 50 NASS/CDS cases and 13 Crash Injury Research and Engineering Network (CIREN) cases in detail. Cases were selected for review if the vehicle did not rollover, if the driver was belted and not ejected, and if the two most significant events were either of a frontal or near-side nature. The crash may have contained impacts to other sides of the vehicle, but the team required that the two most significant impacts involve the front or near-side (in any combination thereof). This limitation served to narrow the research scope.

The crashes were broken down into two phases: most significant impact and other significant impact. This assignment enabled the reviewers to look at only the two highest injury-causing impacts, as there were more than two impacts in some crashes.

In addition, the researchers characterized and referred to the two impacts under review as the first and second significant impacts. This is different than the most significant impact and the other significant impact in that either could have been the first or second impact.

After reviewing the documented injuries, vehicle inspection data, vehicle inspection photographs, and scene diagrams, the researchers determined the injury mechanism. Subsequently, they determined the timing of injury, that is, during which significant impact the injury was sustained.

The clinical reviews revealed five properties of multiple impact crashes.

- A crash with multiple impacts may result in injuries due to more than one impact.
- Injuries sustained during the first impact can be exacerbated during subsequent impacts.
- After the first impact, an occupant is likely moved out of position prior to the subsequent impact(s).
- The vehicle's crumple zones, intended for occupant protection, are exhausted during the first impact and are therefore unavailable for subsequent impacts.
- Occupant protection devices, such as airbags, may be depleted after the initial impact, and therefore are unavailable for subsequent impacts.

CONSEQUENTIAL VERSUS INCIDENTAL MICs

The clinical case reviews led the researchers to expand the definition of multiple impact crashes. In some instances, the data showed that the first impact either caused injury or in some way influenced the injury incurred during the second impact. In other cases, the researchers found that only one of the significant impacts had any noteworthy bearing on the injury outcome. Perhaps the first impact caused the injury, but the second impact was a minor side slap that did not influence the injury outcome in any way. Clearly these examples are both multiple impact crashes, but now the question arises: Do both impacts influence the injury outcome?

The researchers conducted a review of more than 100 additional NASS/CDS multiple impact crashes from 1998 through 2002. The purpose was to find a way to further define or classify the multiple impact crashes. The researchers subdivided the MIC crashes into two classifications based on the characteristics of the crashes themselves: incidental and consequential multiple impact crashes.

An incidental MIC (IMIC) is defined as a single collision sequence in which the subject vehicle incurs more than one impact but only one of those impacts is influential in the injury outcome. Following is an example of an IMIC.

A vehicle incurs a front-near impact with respective delta velocities of 15 mph (24 km/h) and 5 mph (8 km/h). The frontal collision deploys the airbag and forces the belted driver toward the front of the vehicle. The driver sustains bilateral tibia and fibula fractures and left radius/ulna fractures as a result of the frontal impact. The occupant is no longer in a pre crash position. The near-side impact is to the left rear fender at a 5 mph (8 km/h) delta velocity. No injuries are incurred during the second collision. This example shows that although the collision had multiple impacts, the injury outcome was dependent upon only one of the impacts.

A consequential MIC (CMIC) is defined as a single collision sequence in which the subject vehicle incurs more than one impact and where at least two of those impacts influenced the injury outcome. The impacts may influence the injuries in a number of different ways. An example of a CMIC follows.

A collision involves an 18-year-old female driver. She is belted and the driver's frontal airbag deploys during the first of three impacts. The first impact is a frontal impact at 30 mph (48 km/h) stretching across the front of the vehicle. This is followed by a minor impact to the left rear fender. The final impact is a frontal, 15 mph (24 km/h) delta velocity impact to a pole. The injuries sustained in the collision include four AIS1 abrasions; five AIS2 lacerations; contusions; concussions or fractures; and one AIS3 orbit fracture.

This collision is classified as a CMIC because of the high delta velocities and the injuries sustained. The nose and orbit fracture were likely sustained during the third impact. At that point the airbag had already been deployed and deflated as it was exhausted during the first impact. Had the airbag been available during the first *and* the third impacts, the injuries would have likely been mitigated.

Two predictors of consequential multiple impact crashes were uncovered in the case reviews. If the crash had either of the following characteristics, it could be considered a CMIC:

- At least two delta velocities are >15 mph (24 km/h)
- The second impact is more severe than the first

The following charts (Figures 5-8) show the risk of an MAIS3+ injury for a belted driver in CMICs and IMICs. They are separated by first impact direction. Near-near collisions pose the highest risk to this population. This is different from MICs in general where near-rear MICs pose the highest risk.

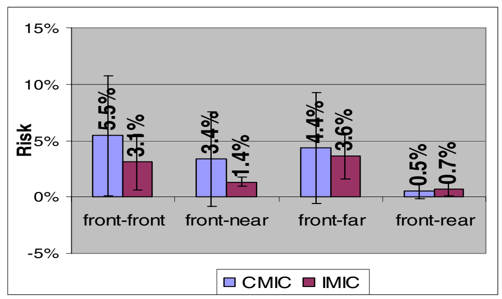

Figure 5. Risk of MAIS3+ Injury to Belted Driver in CMIC and IMIC – Front Impact First.

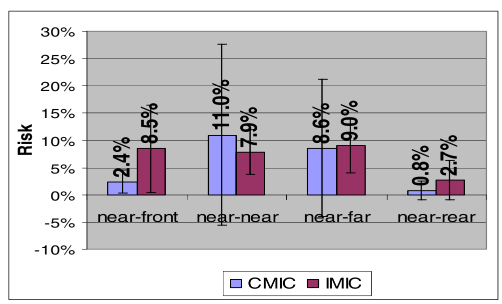

Figure 6. Risk of MAIS3+ Injury to Belted Driver in CMIC and IMIC – Near Impact First.

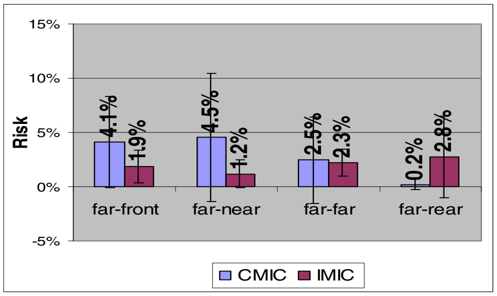

Figure 7. Risk of MAIS3+ Injury to Belted Driver in CMIC and IMIC – Far Impact First.

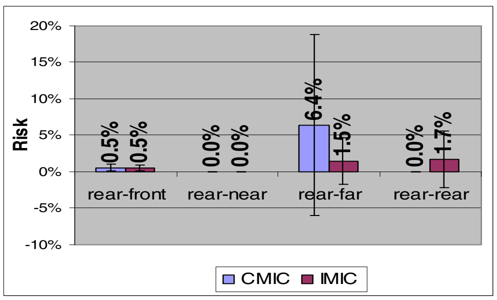

Figure 8. Risk of MAIS3+ Injury to Belted Driver in CMIC and IMIC – Rear Impact First.

Table 7 lists the risk of MAIS3+ injuries per CMIC and IMIC categories in addition to the frequency of MAIS3+ injuries associated with those risks and collision sequences.

Table 7.
Risk and Frequency of MAIS3+ Injuries in CMIC/IMIC Categories

	CMIC	# of Injuries	IMIC	# of Injuries
FF	5.5%	2611	3.1%	3786
FN	3.4%	439	1.4%	2356
Ffar	4.4%	587	3.6%	4607
FR	0.5%	150	0.7%	689
NF	2.4%	742	8.5%	4086
NN	11.0%	225	7.9%	6693
Nfar	8.6%	554	9.0%	2247
NR	0.8%	39	2.7%	175
FarF	4.1%	1348	1.9%	1417
FarN	4.5%	771	1.2%	943
FarFar	2.5%	460	2.3%	2389
FarR	0.2%	5.7	2.8%	152
RF	0.5%	467	0.5%	904
RN	0.0%	0	0.0%	0
Rfar	6.4%	53.1	1.5%	53.0
RR	0.0%	0	1.7%	51

CMICs emerged as the foremost component of multiple impact crashes, and therefore should be underscored and considered for further study. Where the IMICs could be classified as a single impact crash due to the insignificance of one of the impacts, CMICs are viewed as more noteworthy because they comprised the very safety problems inherent to multiple impact crashes.

FINDINGS AND CONCLUSION

The researchers defined and characterized multiple impact crashes, establishing a number of important findings:

- Multiple impact crashes make up 42 percent of all tow-away crashes that occurred on U.S. roadways in 1998 through 2002.
- The average yearly HARM value associated with MICs is $37 billion, which averaged over 42 percent of the total HARM per year for SICs and MICs combined.
- The majority of impact speeds of MICs are 10 mph (16 km/h) higher than those for SICs. Impact speeds for MICs resulting in MAIS3+ injuries are lower than that for SICs suggesting that delta velocities do not distinguish a high-severity/high-injury MIC from those of low severity.
- Front-front MICs occur most often with belted drivers, followed by near-near and front-near crashes. The most harmful category is front-front MICs.

The researchers divided MICs into two categories: incidental (IMIC) and consequential (CMIC):

- An IMIC is a single collision sequence in which the subject vehicle incurs more than one impact but only one of those impacts is influential in the injury outcome.
- A CMIC is a single collision sequence in which the subject vehicle incurs more than one impact and where at least two of those impacts influence the injury outcome.
- A crash is likely considered a CMIC if two delta velocities are 15 mph (24km/h) or greater or if the second impact is a higher severity than the first impact.
- Near-near CMICs pose the highest risk of MAIS3+ injury to belted drivers at 11 percent.

This research addressed the phenomena of multiple impact crashes and how their characteristics relate to high-severity injury outcomes. The researchers showed that in general, the risk of injury associated with MICs is higher than that of SICs. The study presents MICs as an occupant safety problem worthy of additional consideration by industry, regulators, and clinicians.

More specifically, the research shows that belted drivers, the population for whom the most occupant protection is designed, are at a greater risk in these MICs than those in SICs. The greater risk, coupled with the fact that $37 billion (in HARM) is associated each year with MICs, is enough to justify further research and countermeasures development for occupant protection in multiple impact crashes.

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