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ABDOMINAL INJURY IN MOTOR-VEHICLE CRASHES

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16. Abstract

A review of the biomechanical and epidemiological literature on abdomen injury in motor-vehicle crashes was performed. Results of this review demonstrate that (1) there are limited data on abdomen injuries in real-world crashes of newer model airbag-equipped vehicles, (2) there are insufficient useful data on the force-deflection characteristics of the abdomen under loading conditions that represent those that occur to near-side occupants in T-type side impacts, (3) data are needed on the response of the abdomen to lap-belt loading using realistic belt geometry and loading conditions, and (4) data are needed on the dynamic response of spleen tissue and on failure criteria for spleen and liver tissue.

To address the first identified need, analyses of the NASS and CIREN datasets were performed to determine how abdomen injuries occur in frontal and side crashes of airbag-equipped vehicles when seatbelt use is high. Based on the NASS analysis, approximately 19,000 adult occupants sustain AIS 2+ abdomen injuries each year, with just over half of these injuries occurring in frontal collisions. The risk of abdomen injury is 3 to 8 times higher for unbelted occupants compared to belt-restrained occupants in frontal impacts, but airbag deployment does not substantially affect abdomen injury risk. Overall, seatbelt use reduces abdomen injury risk in side impacts for both near- and far-side occupants. Near-side right-front passengers have the highest risk of AIS 3+ abdomen injuries side impacts, with a risk level that is 2.7 times higher than for drivers in left-side impacts. The risks of injury to the liver, spleen, kidney, and hollow organs do not vary with occupant age in frontal or near-side impacts. Analysis of the relationship between abdomen injury and rib fractures indicates that the odds of an abdominal injury are much higher if the occupant also sustains AIS 2+ rib fractures. These results indicate that loading conditions likely to cause abdomen injuries are also likely to cause rib fractures, suggesting that the abdomen is rarely loaded in isolation in vehicle crashes.

The CIREN dataset was used to analyze occupant contacts with vehicle interior components that were attributed to abdomen injuries. For drivers in frontal impacts, the steering-wheel and lap/shoulder belt were most often coded as the sources of abdomen injury. For right-front passengers in frontal impacts, the airbag, lap/shoulder belt, and instrument panel are commonly coded sources for abdominal loading and injury. The mean deltaV for drivers with abdomen injuries attributed to steering-wheel contact is higher than for abdomen injuries to drivers without steering-wheel contact (57 vs. 47.5 kph, $p=0.011$). Unbelted drivers restrained by a frontal-impact airbag had greater proportion of steering-wheel contacts than expected, while drivers restrained by both lap/shoulder belts and frontal-impact airbags had fewer steering-wheel contacts than expected. For near-side occupants who sustained both liver and spleen injuries in side impacts, the mean residual lateral door intrusion was 35 cm, while for near-side occupants who sustained only a liver or a spleen injury in side impacts, the mean lateral door intrusions ranged from 22 to 27 cm.

Because the risk of abdomen injury is highest for near-side occupants in side impacts, an analysis of FMVSS 214 and SNCAP data was performed to characterize near-side occupant loading by the intruding door in T-type side impacts. Results of this analysis indicate that door velocity at the time of initial contact with the abdomen is between 8 m/s and 12 m/s in these staged tests.

Results of this study indicate that the highest priority for future research on abdomen injuries should be to define abdomen force-deflection characteristics for near-side occupants in T-type impacts using high-speed loading conditions that better represent those that occur in real-world crashes.

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Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
In	inches	25.4	millimeters	Mm
Ft	feet	0.305	meters	M
Yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per	6.89	kilopascals	kPa

	square inch			
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Executive Summary

A review of the relevant literature on abdomen injuries in motor-vehicle crashes and the tolerance and response of the abdomen in frontal and side impacts was performed to identify areas where further research is required. Results of this review suggested a need for a new analysis of current crash/injury databases to document the factors associated with abdominal injury in front and side collisions, since most of the data used in previous studies were for crashes of vehicles not equipped with airbags. Results of the literature review also indicate a lack of data on the force-deflection response of the abdomen for loading conditions that are representative of those that occur to near-side occupants in T-type side impacts. Additional data on the response of the abdomen to lap-belt loading using more realistic belt angles are also needed, as are tissue-level response data for the spleen, and tissue-level failure criteria for the spleen and liver for use in validating finite-element models.

The NASS (1998-2004) and CIREN (1995-2005) databases were analyzed to determine the frequencies and patterns of abdomen injuries, as well as the crash and restraint factors associated with abdomen injuries in side and frontal impacts of airbag-equipped vehicles in which seatbelt use was high. The NASS analysis is occupant-based and therefore evaluates the risk of abdomen injuries using data on occupants with and without abdomen injuries. This approach differs from that used in many previous NASS analyses of abdomen injury, which typically used an injury-based analysis that only used occupants who sustained abdomen injuries.

Results of the NASS analysis indicate that approximately 19,000 adult occupants sustain AIS 2+ abdomen injuries each year, with just over half of these occurring in frontal collisions. About 40% of these occupants sustain AIS 3+ abdomen injuries. For AIS 4+ injuries in frontal and side impacts, the risk of abdomen injury ranks behind only the risks of AIS 4+ head and thorax injuries. As expected, the risk of abdomen injury increases with crash severity. For near-side impacts, the risk of AIS 2+ abdomen injury is above 5% at crash severities from 21-30 mph delta V. For far-side and frontal impacts, the risk of AIS 2+ abdomen injury reaches 5% at crash severities of 31-40 mph.

In frontal impacts, use of a three-point reduces the risk of abdomen injuries, with the risk of abdomen injury ranging from 3 to 8 times higher for unbelted compared to belt-restrained front-row occupants. Airbag deployment does not affect abdomen injury risk. Belt use also reduces abdomen injury risk in side impacts for both near- and far-side occupants, although the effectiveness varies with the location of damage to the vehicle.

Across all combinations of crash type and front-row occupant seating location, right-front passengers in near-side impacts have the highest risk of sustaining an AIS 3+ abdomen injury. The risk is 2.7 times higher for right-front passengers in right-side impacts than for drivers in left-side impacts. Three factors have been identified as contributing to this higher risk. First, the liver is the largest solid organ in the abdomen and is located on the right side of the body, which is directly loaded by the intruding door for right-front passengers in right-side impacts. Second, right-front passengers are more likely than

drivers to be involved in T-type side impacts (52% vs. 42%), which are more likely to result in injuries to near-side occupants than L-type side impacts because the striking vehicle directly loads the passenger compartment. Third, loading of right-front passengers by unbelted drivers who move towards the right in right-side impacts increases the risk of spleen injuries to right-front passengers. In contrast, because right front-passengers are present only 20% of the time, loading of the driver by unbelted right-front passengers is much less likely.

In frontal impacts, the liver is the most frequently injured abdominal organ for drivers, while the spleen is the most frequently injured for right-front passengers. The opposite is true in side impacts for near-side occupants, since the spleen is on the struck side for drivers and the liver is on the struck side for right-front passengers. In far-side impacts, the kidneys are most frequently injured for drivers, but the liver is still the most frequently injured abdominal organ for right-front passengers. For front and side impacts, the risk of injury to the liver, spleen, kidney, and hollow organs does not vary with age, while the risk of rib fractures increases with age.

Further analysis of the relationship between abdomen injury and rib fractures indicates that the odds of sustaining an AIS 2+ abdomen injury in both front and side impacts are much higher if the occupant also sustains AIS 2+ rib fractures. Because the risk of rib fractures increases with age, but the risk of abdomen injury does not, these results suggest that fractured ribs generally do not directly cause abdomen injuries. Rather, this finding most likely indicates that loading conditions that cause abdomen injuries are the same loading conditions that cause rib fractures, and that abdominal organs are rarely loaded in isolation.

To further explore the association between rib fractures and abdomen injury, a detailed investigation of the CIREN database, which includes information on the specific locations of abdominal injuries and rib fractures, was performed to characterize the relationships between the locations of rib fractures and the presence of liver and spleen injuries. In frontal crashes, spleen injuries are not associated with rib fractures located near the spleen. The same is true for near-side occupants in side impacts. In frontal crashes, there are more liver injuries than expected statistically when ribs are fractured in any region except in the lower-left region of the ribcage. For drivers in left-side impacts, the occurrence of right-side rib fractures corresponds to greater frequencies of liver injuries than expected.

An analysis of occupant contact points with vehicle interior components associated with abdomen injuries was also conducted with the CIREN dataset. For drivers in frontal impacts, steering-wheel contact is often coded as the source of abdomen injuries, with the lap/shoulder belt also a frequently coded abdomen injury source. For right-front passengers, the deploying airbag, the lap/shoulder belt, and the instrument panel are commonly coded injury sources for abdominal injuries in frontal impacts.

In CIREN cases, the mean frontal crash severity (delta V) for abdomen-injured drivers with steering-wheel contact is higher than for abdomen-injured drivers without any steering-wheel contact (57 vs. 47.5 kph, p=0.011). Abdomen-injured unbelted drivers in frontal crashes in which the steering-wheel airbag deployed had a greater proportion of steering-wheel contacts than expected statistically, while drivers restrained by both lap/shoulder belts and frontal-impact airbags had fewer steering-wheel contacts than expected.

For near-side occupants in CIREN side impacts, analysis of the dataset indicates that the side interior is the most frequently coded injury source for abdomen injuries, with the belt restraints being the next most frequently coded injury source. The extent of lateral residual intrusion of the door for near-side occupants with abdominal injuries was also examined in the CIREN database. Abdomen-injured occupants were grouped into those with only liver, only spleen, liver and spleen, and other abdomen injuries. For occupants with injuries to both the liver and spleen, the mean lateral intrusion is 35 cm. In comparison, when near-side occupants sustained only liver or only spleen injuries, the mean lateral intrusion ranges from 22 to 27 cm.

Because the risk of injury to the abdomen is highest for near-side occupants in side impact, data from selected cases from FMVSS 214 and SNCAP tests were analyzed to characterize the expected loading conditions to near-side occupants. The focus of this analysis was to document door velocity histories and establish door velocity at the time of contact with the crash dummy's thorax, abdomen, and pelvis. Results of this analysis indicate that door velocity at the time of abdomen contact is between 8 m/s and 12 m/s and that door velocity drops rapidly after the time of abdomen contact as the struck vehicle is accelerated laterally.

The CIREN and NASS analyses, together with a review of the available biomechanical literature on abdomen impact response and injury thresholds, lead to the following list of priorities for future abdominal impact-response and injury research:

- Characterize abdominal side-impact response, particularly force-displacement measures, using door velocity histories with peak values of 8-12 m/s that represent those from recent FMVSS 214 tests, and an impactor size and shape that loads the abdomen, thorax, and pelvis in a manner than represents loading by an intruding door and interior.
- Characterize abdomen response to lap belt loading in frontal impacts using a realistic angle of the belt (side-view angle within FMVSS 210 requirements rather than horizontal).
- Conduct dynamic tissue-level testing of spleen tissue to characterize its mechanical properties and failure criteria for use in human finite element models.

1. Introduction

This study was performed to document trends in abdomen injury patterns in motor-vehicle crashes reported in the biomechanical literature, and compare them to current abdomen injury patterns and risk factors based on analysis using the NASS and CIREN databases. The current datasets have a higher proportion of airbag-equipped vehicles and higher rate of belt use than prior studies. This combination of literature review and new analysis has identified some changes in abdomen injury patterns and factors related to abdominal injury causation.

Because results of the new analyses indicate that the highest risk of abdomen injury is to near-side occupants in side impacts, analysis of data from staged crash tests was performed to characterize near-side occupant loading conditions in terms of door velocities. In addition, studies of abdominal injury response using human surrogates were reviewed to document key results of abdominal impact response research. The studies of abdominal loading were categorized as frontal loading, lateral loading, belt-loading, and tissue-level loading.

The final section of this report summarizes and discusses key trends in abdomen injury resulting from motor-vehicle crashes and identifies priorities for additional research that is needed to characterize abdomen impact response. This research will provide data for improved crash dummies and computational models for using in mitigating abdominal injuries to occupants in front and side motor-vehicle crashes.

2. Abdominal Injury Patterns in Motor-Vehicle Crashes

Section 2.1 summarizes work from individual papers that used crash databases to analyze abdominal injury in motor-vehicle crashes. All papers involving analysis of abdominal injury are included, even if some do not adhere to recommended methods of analysis. Section 2.2 presents results of a NASS analysis on abdomen injury, while Section 2.3 describes results of a CIREN analysis on abdomen injury. Section 2.4 compares results of the current study to those presented in the literature.

2.1 Summaries of Crash Database Studies in the Literature

Huelke (1990) Near Side Passenger Car Impacts – CDC, AIS, and Body Areas Injured (NASS data)

Huelke analyzed near-side crashes in the National Automotive Sampling System (NASS) database for years 1980 – 1986 to understand the injury patterns of unrestrained drivers. The database was filtered for left-side impacts to passenger cars where the occupant sustained an injury of Abbreviated Injury Scale (AIS) = 1+ to any region of the body. Principle direction of force (PDOF) was not considered. Cases involving a rollover or a secondary collision were excluded. Cases in which the driver was ejected or where the driver was younger than sixteen years old were also excluded. Cases were also limited to those where the driver was the sole occupant.

There were 758 cases (of approximately 67,000) that met the criteria, of which 694 had known injuries. Sixty of these cases (9%) had at least one AIS 3+ injury. Among these cases, there were 124 AIS 3+ injuries, twenty of which were to the abdomen.

The abdomen-specific results are highlighted in Table 1 and Table 2. These numbers represent the number of injuries and not the number of crashes. Since the number of different crashes involving abdomen injury is not reported in this paper, the small sample size may allow one particularly severe crash to skew the results. Of the twenty severe abdominal injuries, ten (50%) were from distributed side (D) crashes, even though this crash mode only accounted for 30% of the crashes resulting in severe injuries and 17% of the crashes producing any injury. The second most common collision type for abdominal injury was the front and center side (Y), which accounted for five of the abdominal injuries. Figure 1 shows the distribution of abdominal AIS 3+ injuries with respect to the coded damage zone and compares it to the distribution of all AIS 3+ injuries. These data suggest that distributed-damage crashes present the most risk to the abdomen, even though crashes with this type of damage account for slightly less than one-third of all AIS 3+ injuries and one-third of all drivers with an AIS 3+ injury. Figure 2 groups together impact with damage to the occupant compartment (D, Y, Z, P). Occupant compartment damage occurs in 80% of the impacts, yet 90% of the abdominal injuries occur in impacts with occupant compartment damage. The author's main conclusion was that side impact research should not be limited only to T-type impacts involving direct damage to the passenger compartment, because this type of impact only accounts for 11% of all left-side impacts studied.

For over half of the abdomen injuries, the occupant contact points were unknown. For the nine abdomen injuries with a known contact point, the injuries resulted from contact with the side interior, windshield, A-pillar or steering assembly. Appendix A details the NASS contact point categories.

Table 1. Number of abdominal injuries by left-side vehicle damage description (Huelke 1990)

Impact Zone (from CDC code)	Abdominal AIS 3+ injuries	Total AIS 3+ injuries	No. of Drivers	No. of Crashes
D: distributed	10	37	20	131
Y: front side (F + P)	5	41	18	212
P: center side	1	28	15	82
B: rear side	2	2	2	33
Z: rear side (B + P)	2	15	4	183
F: front side	0	1	1	117
Total	20	124	60	758

Table 2. Distribution of abdomen contacts by left-side vehicle damage description (Huelke 1990)

	Abdomen	
Impact	Side Interior	Unknown
D: distributed	6	4
Y: front side (F + P)	1	4
P: center side	0	1
B: rear side	1	1
Z: rear side (B + P)	1	1
F: front side	0	0
Total	9	11

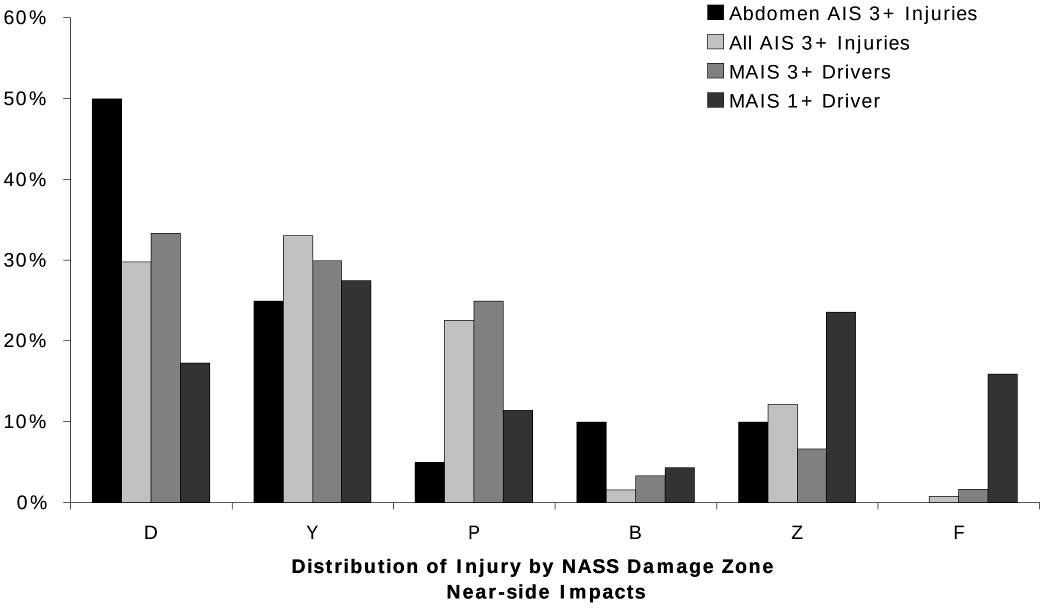


Figure 1. Injuries in near-side crashes (Huelke 1990)

Figure 2. Occupant compartment damage and abdominal injuries (Huelke 1990)

Loo (1996) Airbag Protection Versus Compartment Intrusion Effects Determines the Pattern of Injuries in Multiple Trauma Motor Vehicle Crashes

Loo et al. (1996) investigated the effect of seat belt and airbag protection on drivers and front seat passengers in terms of how well they mitigate injuries. Two hundred crash victims that were admitted to two Level-1 trauma centers (NJ, MD) were used in this study. For inclusion in the study, the patients had to sustain an Injury Severity Score (ISS) of 16+ (or, if airbag protected, they must have had a lower extremity ISS of 5+). Additional occupant selection conditions were an age of at least sixteen years, not pregnant, and be either a driver or a right-front passenger of a coupe, sedan, sport utility vehicle or light van. The crash had to be either a frontal or side impact. Ejected occupants, rollover crashes, and rear impacts were excluded from this study.

A Crash Reconstruction Team (CRT) examined the crash scenes as well as the damaged vehicles. The vehicle and crash data were stored in an electronic database that also held the patients' medical records relating to the crash. These methods of data collection later served as a model for the Crash Injury Research and Engineering Network (CIREN) database. The analysis in this paper compares outcomes by crash type and restraint use for a population of injured occupants. Analyzing outcomes when the population is selected on outcome, without using an outside estimate of overall exposure to crashes, does not lead to meaningful results. Thus the usefulness of the analysis is limited.

There were 138 frontal crashes and 59 side-impact crashes. Of the 138 frontal crashes, fifty-five had no belt or airbag restraints, twenty-three had airbag but no belt restraints, thirty-seven had belt but no airbag restraints, and twenty-three were restrained by both a belt and an airbag. There were no vehicles equipped with side airbags in this study, so the lateral cases were divided into belted or unbelted. Twenty-eight occupants were belted, while thirty-one were unbelted.

Comparing the ISS and mean change in velocity (ΔV) of the cases in each crash direction and restraint type shows no statistically significant difference in the mean ΔV. However, there was a statistically significant difference ($p < 0.05$) in the mean ISS values between all frontal airbag cases and all frontal non-airbag cases, between frontal belted airbag cases and frontal belted non-airbag cases, and between frontal non-belted airbags and frontal non-belted non-airbags. In all three instances, the airbag group sustained a much lower ISS value.

Table 3 shows the proportion of occupants with abdomen injuries in each group, as well as thorax injuries and pelvic fractures. While not explicitly stated, all injuries from AIS levels 1 through 6 appear to be included. Figure 3 shows the proportion of occupants with injury to the liver, spleen, and kidney in frontal impacts with and without airbag deployment, while Figure 4 shows the proportion of injuries to these organs by restraint type. The study did not differentiate between near-side and far-side impacts.

Table 3. Occupant injuries by crash direction and restraint type from Loo (1996)

	Belt	Airbag	ΔV mph	Liver %	Spleen %	Kidney %	Thorax %	Pelvic Fx %	No. of Occupants
Front	All	No	28.5	16	17	1	55	27*	92
Front	All	Yes	28.0	22	7	2	59	20	46
Lateral	All	All	21.8	20	19	15	58	59*	59
Front	No	Yes	23.5	30	4	4	61	22	23
Front	No	No	30.3	18	16	2	49	25	55
Front	Yes	No	25.5	14	19	0	65	30	37
Front	Yes	Yes	30.0	13	9	0	57	17	23
Lateral	Yes	All	20.4	18	25	14	57	57	28
Lateral	No	All	24.5	23	13	16	58	60	31

*p < 0.001

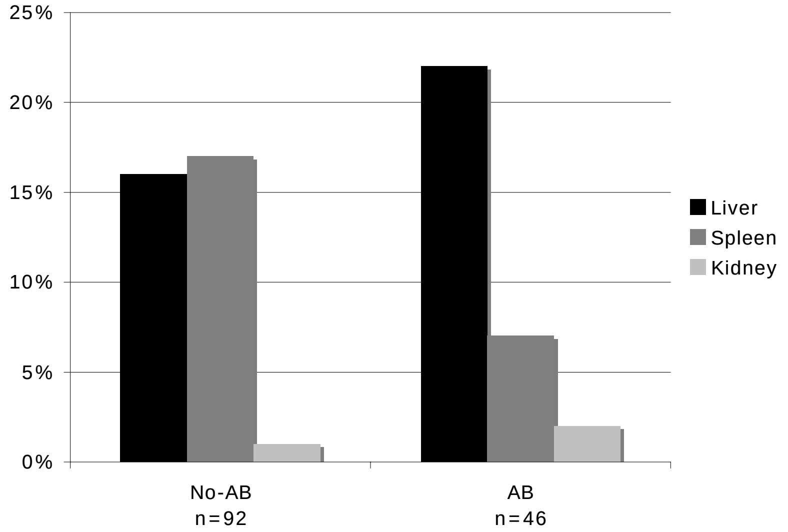


Figure 3. Proportion of injured occupants with abdominal injury in frontal impacts by airbag deployment, including both belted and unbelted occupants (Loo 1996)

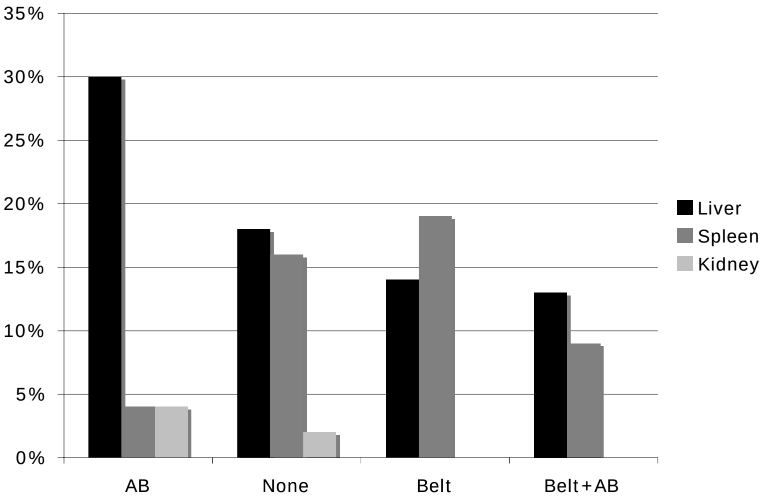


Figure 4. Proportion of injured occupants with abdominal injury in frontal impacts by restraint type (Loo 1996)

In this study, the only statistically significant difference between any two groups was the higher percentage of pelvic fractures in lateral impacts compared to frontal impacts. However, there are other notable patterns that are not statistically significant. The rate of spleen injury decreased from 17% for all frontal impacts with no airbag to 7% to all frontal impacts with airbag deployment. This trend appears to be independent of belt use, since 16% of unbelted and 19% of belted occupants with no airbag deployment suffered a spleen injury, while only 4% of unbelted and 9% of belted occupants restrained by an airbag sustained a spleen injury. In lateral impacts, the belt appears to have an adverse effect on spleen injury rate, because the frequency of spleen injury (25%) in the belted occupants was higher than that of the unbelted occupants (13%). The results suggest that in frontal crashes, the airbag helps to prevent spleen injury. In lateral crashes, the belt may contribute to the occurrence of spleen injuries.

The rate of liver injury appears to be similar between frontal and side-impact crashes. The restraint/impact condition with the highest rate of liver injury is the frontal, unbelted, airbag-protected group with a 30% frequency of liver injury (and only a 4% rate of spleen injury). Occupants with the lowest frequency of liver injury are those restrained by belts and airbags in frontal impacts. The authors suggest that the airbag may lead to liver injury when not used in conjunction with a belt.

This study also investigated injury to the kidney. While not statistically significant, the results indicate a substantially higher rate of kidney injury in lateral impacts than in frontal impacts. Belt use did not affect outcome in lateral crashes. In frontal crashes, no belted occupants sustained a kidney injury, but kidney injuries were sustained by 4% of the airbag-restrained occupants and 2% of the unrestrained occupants. Direction of impact has the strongest effect on the occurrence of kidney injury, while to a lesser extent, belt use may decrease the risk of kidney injury in frontal crashes. Like the kidney, pelvic fractures increased in frequency for lateral crashes. This study did not examine whether or not these two injury types were related. No other correlation between abdominal injury and thorax or pelvic injury is presented.

This paper also investigated the effect of occupant compartment intrusion on injuries to the driver in frontal crashes. For this analysis, only cases involving a driver were used and both belted and unbelted drivers were included. In cases with no intrusion, of the thirteen occupants protected by an airbag, none received an abdominal or thoracic injury. However, of the thirteen occupants not protected by an airbag, five (13%) did sustain an abdominal/thoracic injury. The difference between the results is statistically significant ($p = 0.05$). In the cases with steering wheel assembly intrusion, of the twenty-four drivers protected by an airbag, eleven (46%) sustained an abdominal/thoracic injury. Of the twenty-seven drivers not protected by an airbag, eighteen (48%) sustained an abdominal/thoracic injury. While there is no difference in abdominal/thoracic injury outcome between airbag protected and non-airbag protected drivers when there is passenger compartment intrusion, there was a significant ($p < 0.05$) difference in the amount of intrusion between the two groups. In the airbag-protected group, the mean intrusion was 23.3 ± 17.7 cm, while for the non-airbag protected group, the mean intrusion was 11.5 ± 12.0 cm. Despite experiencing twice as much intrusion, the group protected by an airbag sustained abdominal/thoracic injuries no more frequently than those not protected by an airbag.

Elhagediab (1998) Patterns of Abdominal Injury in Frontal Automotive Crashes

Elhagediab and Rouhana evaluated data on abdominal injuries in frontal crashes from the NASS database for years 1988 - 1994. The database was filtered for crashes with a PDOF of 10 – 2 o'clock involving passenger cars and light trucks. Occupants studied were limited to non-ejected drivers and right-front passengers. Data collected from each case included type of restraints used, AIS injury score, most severe organ/tissue injured (abdominal injuries only), and contact point (abdominal injuries only). The weighted frequencies of AIS 3+ injuries were reported. However, because cases with unknown injuries and/or unknown contact points were excluded, weighted frequencies would be inaccurate. Therefore, the authors reported their findings as percentages and not total numbers.

The results show that as injury severity level increases, so does the incidence rate of abdominal injuries. Among AIS 3+ injuries, those to the abdomen account for 8% of all injuries, while at AIS 4+, they account for 16.5% and at AIS 5+ they account for 20.5%. Using only those cases with an abdominal injury of AIS 3+ (n = 83,322, weighted), the unbelted driver accounted for 59% of all those injured. The next highest injured occupant was the lap/shoulder-belted passenger (12%), the unbelted passenger (11%), the shoulder-belted driver (8%), the lap/shoulder-belted driver (4%), the shoulder-belted passenger (3%), and the lap-belted driver (1%). Equal exposure is not assumed in the results, and incidence rates are highly dependent on the number of each type of occupant in the general population. Therefore these results cannot be directly used to relate injury incidence to restraint use.

Elhagediab reports that the steering wheel was the most frequent contact point, accounting for 68% of all abdominal injuries. The second and third most common contact points were the belt and interior, accounting for 17% and 14% of all abdominal AIS 3+ injuries, respectively.

Separating the results for drivers and passengers, two different patterns emerge. As one would expect, passengers have very little contact with the steering wheel. Instead, passengers, who sustained 27% of the abdominal AIS 3+ injuries, owed the majority (54%) of their injuries to the belt system and most of the remainder (45%) to interior contacts. The remaining 1% of injuries resulted from steering wheel contact, all of which were sustained by unbelted occupants. All of the belt-associated injuries were sustained by lap/shoulder-belted occupants (75%) and shoulder-belt-only occupants (25%). The interior-associated injuries were largely to unrestrained occupants (83%), while a small number were lap/shoulder-belted (17%). None of the injuries occurred to airbag-protected (belted or unbelted) passengers.

Drivers sustained 73% of all the abdominal AIS 3+ injuries. The abdomen injury source for 93% of these drivers was steering-wheel contact. 87% of these drivers were unbelted and 12% were using only a shoulder belt. The belt was the next most common injury contact point for drivers, accounting for 4% of all injuries to drivers. Lap-shoulder belted drivers accounted for 45%, lap-belted and shoulder-belted each accounted for 18%, and lap-shoulder belted with airbag protection accounted for 18% of all injuries due to the belt. Unrestrained drivers accounted for the remaining 8% of belt injuries. The proportion of injuries due to the interior was 3%, with 57% of these injuries occurring in unrestrained drivers and 29% in lap/shoulder-belted drivers.

In Table 4, each occupant/restraint type is listed, followed by the proportion of AIS 3+ abdominal injuries sustained by each occupant/restraint combination. The next column lists the most common injury contact point for each occupant/restraint type, followed by the proportion of abdomen injuries associated with the most common injury contact point. For example, drivers restrained by lap/shoulder belts and airbags sustain 0.48% of all AIS 3+ abdomen injuries. The most common injury contact point is the belt, and 73% of abdomen injuries sustained by this type of restrained occupant result from the belt.

Table 4. Most common sources of occupant injuries by occupant position and restraint (Elhagediab 1998)

Occupant/restraint type	Proportion of abdomen injuries associated with occupant/restraint type	Most common injury contact point	Proportion of injuries associated with commonest contact point
Driver: lap/shoulder belted + AB	0.48%	Belt	73%
Driver: lap/shoulder belted	2.19%	Belt	58%
Driver: AB	0.33%	Airbag	39%
Driver: shoulder belted	8.59%	Steering wheel	92%
Driver : lap	0.93%	Belt	54%
Driver: unrestrained	60.90%	Steering Wheel	98%
Passenger: lap/shoulder belted	12.82%	Belt	85%
Passenger: shoulder belted	3.63%	Belt	100%
Passenger: unrestrained	10.13%	Interior	98%

Another way of looking at injury contact points is their interactions with specific abdominal organs. Elhagediab reports the frequency of abdominal organs with respect to the associated injury contact points. For these results, both the driver and passenger data were combined. The steering wheel was the most frequent contact point overall and, individually, for the liver, spleen, arteries, respiratory and urogenital organs. The only two regions not primarily injured by the steering wheel were the digestive organs and the kidneys, both of which sustained the majority of their injuries from the belt. The liver was the most frequently injured organ (39%) followed by the spleen (23%), the digestive organs (17%) and the arteries (12%). The most frequent type of injury/contact-point pair was the liver-steering wheel, which accounted for 34% of all abdominal AIS 3+ injuries. Table 5 shows the top five combinations of abdominal organs injured and associated contact points, which together account for almost three-quarters of all the abdominal AIS 3+ injuries in frontal crashes.

Table 5. Abdominal organs injured and contact points (Elhagediab 1998)

Top 5 abdominal organs with AIS 3+ injuries	Contact point	Proportion of all abdominal AIS 3+ injuries
Liver	Steering Wheel	34.31%
Spleen	Steering Wheel	13.72%
Digestive	Belt	9.62%
Arteries	Steering Wheel	9.07%
Spleen	Interior	6.89%
Total		73.31%

The three most injured areas are the liver (39.2%), spleen (23.1%) and digestive system (17.13%). This agrees with an earlier study on abdominal injury by Bondy (1980). For testing purposes, the authors conclude that steering wheel contact should be the highest priority followed by belt contact and then interior contact. However, they note that the presence of airbags may reduce the likelihood of abdominal injury from steering wheel contact.

Yoganandan (2000) Patterns of Abdominal Injuries in Frontal and Side Impacts

Yoganandan et al. compared and evaluated the frequency and severity of abdominal injuries in both frontal and side impact crashes. They analyzed the NASS-Crashworthiness Data System (NASS-CDS) database for years 1993 – 1998. Cases selected involved passenger cars and light trucks with occupants sixteen years old or older who were drivers or right-front passengers. Cases involving a rollover or an ejected occupant were excluded. The cases were then categorized by PDOF into either frontal (11 – 1 o'clock PDOF), right side (2 – 4 o'clock PDOF) or left side (8 – 10 o'clock PDOF) crashes. For side impacts, the authors also reported whether it was a far-side or near-side occupant impact. Cases with unknown injuries and/or contact points were ignored, so the total number of cases does not reflect the actual weighted frequencies. The abdominal injuries were categorized into liver, spleen, kidney, pancreas, arteries, urogenital, digestive and diaphragm.

Analysis of weighted data indicated 129,269 AIS 2+ abdominal injuries. In this sample of both frontal and side impacts, the percentage of injuries associated with the abdomen increased with injury severity level. Abdominal injuries accounted for 3.69% of all AIS 3+ injuries, 10.26% of all AIS 4+ injuries, 20.32% of all AIS 5+ injuries and 1.07% of all AIS 6+ injuries.

Figure 5 shows the proportion of abdominal injuries by crash type for each AIS severity level. Over half of all abdominal injuries at every AIS level come from frontal impacts. At lower AIS levels, left-side impacts cause a greater proportion of AIS 2-4 injuries than right-side impacts, but right-side impacts cause a greater proportion of AIS 5 and AIS 6 injuries than left-side impacts. The distribution of abdominal injuries by AIS level is also presented in Figure 5 for each crash type. Side impacts have a greater proportion of AIS 2 injuries than frontal impacts.

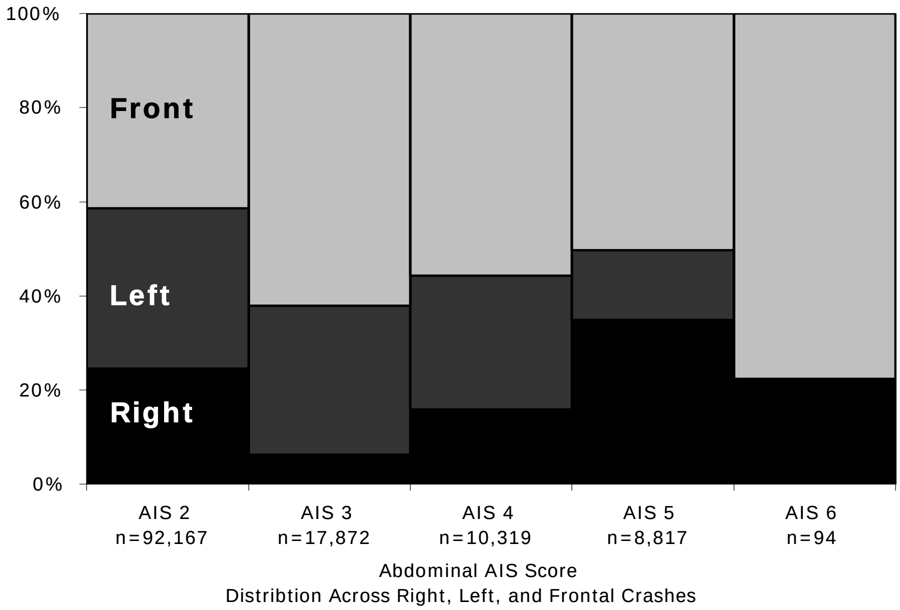


Figure 5. Percentage of abdominal injuries in frontal, left and right side crashes by AIS score (Yoganandan 2000)

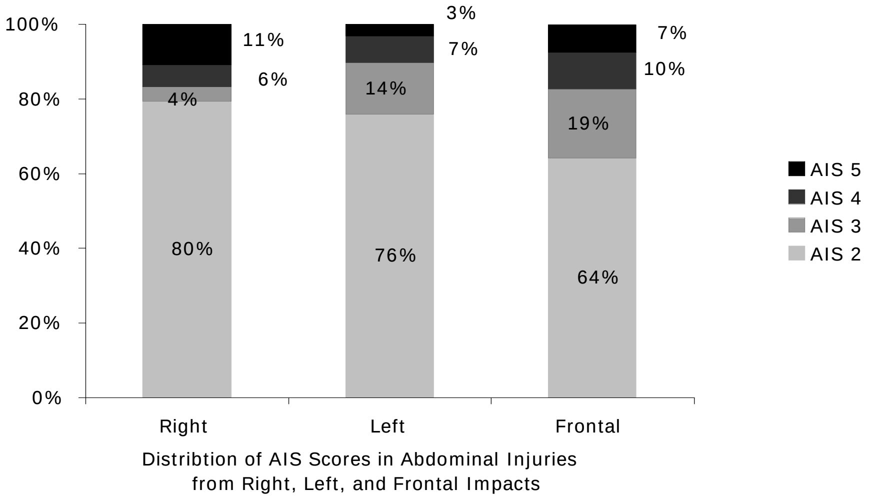


Figure 6. Distribution of abdominal injury severity, grouped by direction of impact (Yoganandan 2000)

For all the cases with abdominal injury scores of AIS 2+, the frequency of injury was reported for each abdominal organ or region. This was done separately for frontal impacts, left versus right and near- versus far-side impacts. The paper did not examine left near-side versus right near-side or left far-side versus right far-side. The procedure was repeated using only AIS 3+ cases. The results are plotted in Figure 7a – e. In general, liver and spleen injuries account for more of the severe (AIS 3+) injuries, even when they were not the most frequently injured organs when AIS 2+ injuries were evaluated.

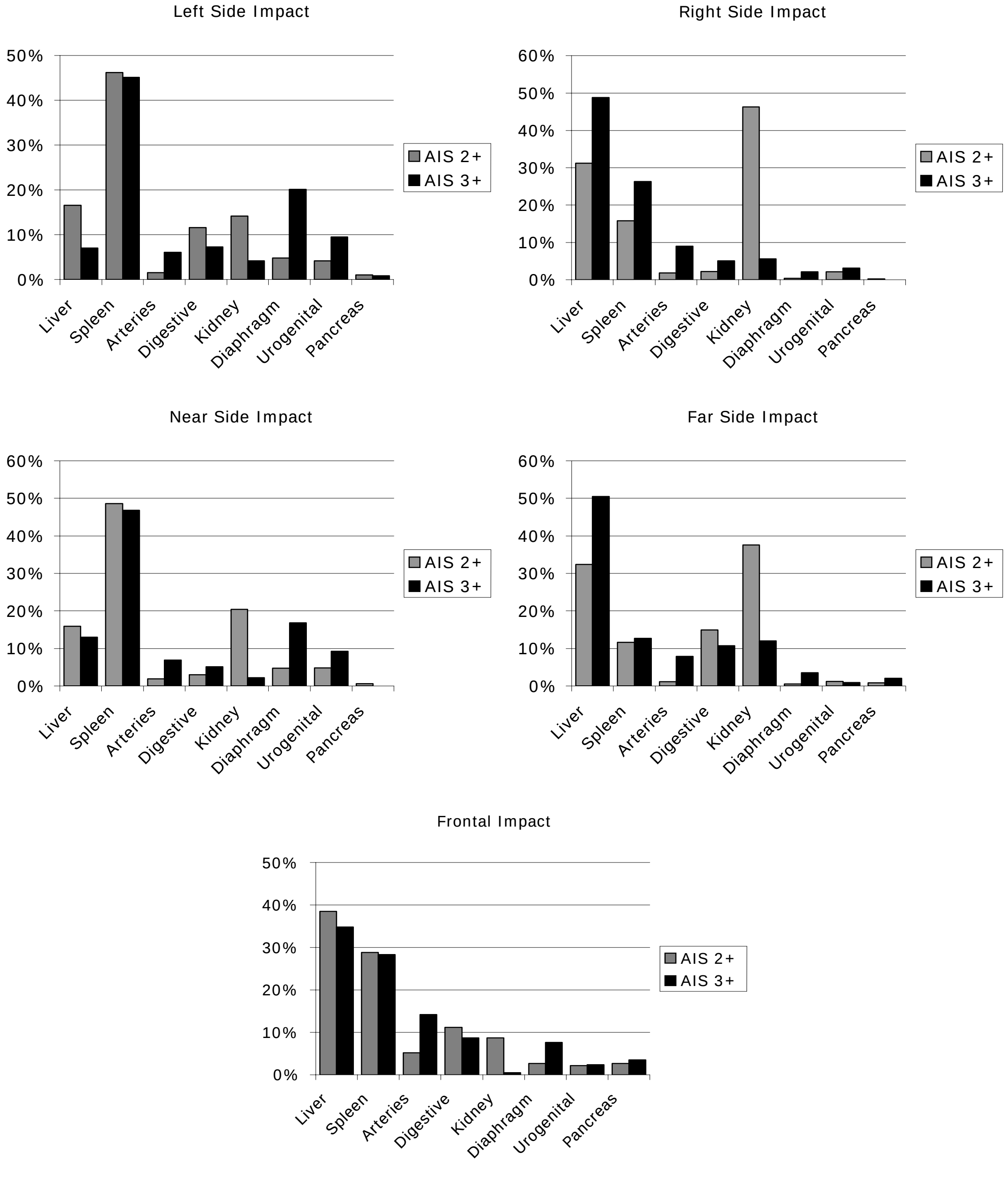


Figure 7. (a – e) Distribution of organ injury by type of impact (Yoganandan 2000)

Finally, the authors calculated the median change in velocity (ΔV) of crashes resulting in AIS 2+ or 3+ abdomen injuries for left, right, near-side, far-side and frontal crashes as shown in Figure 8. Because this analysis only addresses abdomen injuries and does not consider uninjured occupants, it is not the delta V associated with a 50% risk of abdomen injury. As expected, mean ΔV was always greater for AIS 3+ injuries. Injuries in left-side impacts occurred at a lower ΔV than right-side impacts, and these both occurred at lower ΔV's than frontal impacts. The report's final conclusion was that side impacts account for more abdominal injuries and that injuries from side impact occur at lower delta V's.

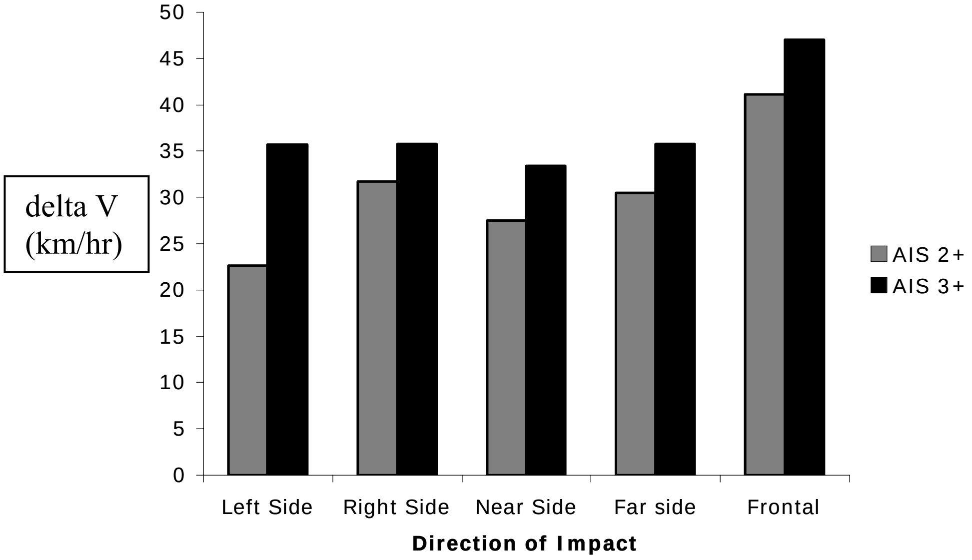


Figure 8. Median change in velocity (ΔV in km/hr) associated AIS 2+ or AIS 3+ abdominal injuries (Yoganandan 2000)

Augenstein (2000b) Injuries to Restrained Occupants in Far-Side Crashes

Augenstein et al. investigated the injury patterns in far-side crashes using the NASS-CDS data from 1988 – 1998. The authors also examined case reports of seriously injured occupants from the William Lehman Injury Research Center (WLIRC) at the University of Miami for the years 1994 – 1998. These in-depth reports were used to investigate how occupants sustained serious injury. The results from the NASS-CDS were reported as raw numbers, without applying weighting factors. The absence of weighting factors in the NASS analysis may skew results, because they are needed for the dataset to be considered a representative sample. Injuries to the abdomen were combined with those to the chest and reported as abdomen/thorax injuries.

The NASS-CDS data were filtered for cases involving a PDOF of 1 – 5 o'clock and 7 – 11 o'clock, and for belted occupants in the driver's seat or the right-front passenger seat. Rollover cases, children less than sixteen years old, and cases in which the occupant was ejected were excluded.

There were 4,696 case occupants that met the criteria. Of these, 3,576 (76%) were drivers and 1,120 (24%) were right-front passengers. There were 653 injuries in 235 drivers and 123 injuries in 52 passengers with an AIS score of 3 or greater. Table 6 summarizes these results as well as those specific to the abdomen and thorax, which were grouped as one category. Abdomen/thorax injuries accounted for 48% of all AIS 3+ injuries. Separating these data by occupant position shows that for the driver, 46% of all AIS 3+ injuries were to the abdomen/thorax, while for the passenger, 65% of all AIS 3+ injuries were to the abdomen/thorax. Abdomen/thorax injuries in the driver were most often due to the belt (22%) and the right side interior (14%). Passengers, however, were more likely to sustain their injuries from the seat (24%).

Table 6. Results from NASS-CDS database for far-side impact (Augenstein 2000b)

	Drivers (n = 3,576)	Passengers (n = 1,120)	Total (n = 4,696)
Number of occupants with AIS 3+ injuries	235	52	287
Number of AIS 3+ injuries (whole body)	653	123	776
Portion of AIS 3+ injuries to the abdominal/thorax	45.5%	64.5%	48.0%
Contact points for abdominal/thorax injuries			
Belt	22.3%	8.5%	20.6%
Right side interior	13.5%	<2.0%	11.8%
Seat	2.7%	23.9%	5.4%
Other occupant	1.2%	10.4%	2.3%
Non-contact	1.9%	4.5%	2.2%
Dash	0.5%	9.0%	1.6%

In the WLIRC cases, there were thirteen that met the criteria of a far-side, belted occupant with a maximum AIS (MAIS) = 3+. This analysis did not exclude rear-seat occupants or children. In five of these cases, the most serious injury was to the liver or spleen and all five were due to contact with the belt. Table 7 summarizes the main details of these five cases. Four of the occupants were seated on the left side, and these four all sustained liver injuries, with one also sustaining a spleen injury. Three of these were drivers who were only restrained with a shoulder belt. The other left-side occupant was a 12-year-old seated in the rear seat, restrained with a lap and shoulder belt, who was the only fatality among these five cases. The fifth occupant sustained a spleen injury, was seated in the right-front seat and was restrained by a lap and shoulder belt.

An interesting observation from the WLIRC data is that, while three of the five occupants with abdominal injuries were only restrained by shoulder belts, all of the eight remaining occupants without abdominal injuries were restrained by both shoulder and lap belts. Seven of these occupants sustained injuries to the brain or cervical spinal cord and one sustained an injury to the aorta. Six of these cases were fatal.

Table 7. Cases of belt-induced abdominal injury from the WLIRC data (Augenstein 2000b)

Occupant Location	Maximum Injury	MAIS	Contact	Restraints	Fatal	Lateral ΔV (km/hr)
Left rear	Liver	5	Belt	Lap & Shoulder	Yes	18.5
Left	Liver	4	Belt	Shoulder	No	12.8
Left	Liver/Spleen	4	Belt	Shoulder	No	72.2
Left	Liver	3	Belt	Shoulder	No	12.8
Right	Spleen	3	Belt	Lap & Shoulder	No	15.4

Based on the NASS data, the authors concluded that the presence of a nearside occupant mitigates injuries to any region of the body from the opposite side interior (right side for drivers, left side for passengers). Furthermore, the authors suggest that vehicles should be evaluated in far-side impacts based on the frequency and severity of injuries to occupants on the non-struck side.

Augenstein (2000a) Injury Patterns in Near-Side Collisions

Augenstein et al. examined the NASS-CDS database for near-side impacts in the years 1988 – 1996. They then examined near-side impacts from the William Lehman Injury Research Center Database (WLIRC), which contains more severe impact cases for the years 1995 – 1998. The WLIRC data were used to investigate how occupants are injured in near-side crashes involving vehicle-to-vehicle impacts.

Over the period studied, an average of 925,000 occupants were involved in side impacts (both near- and far-side impacts) each year. Of these, 36,000 sustained at least one AIS 3+ injury and 11,230 were killed. On average, of the injured occupants, there were just over two injuries/occupant, with multiple injuries more common in higher severity crashes. This suggests that when investigating crashes, results will depend on whether the researcher chooses to only investigate the maximum AIS (MAIS) injury per occupant or all the injuries per occupant. In this paper, both MAIS 3+ and all AIS 3+ injuries were studied, and the authors concluded that it is better to study all injuries and not just the MAIS injury.

Based on the MAIS 3+ data, abdominal injuries accounted for 5% of those in the NASS data and 20% of those in the WLIRC data, which the authors considered an indication that the proportion of abdominal injuries increase with injury severity. The authors noted that in all fatal cases from the WLIRC with rib fractures, there was an internal chest or abdominal injury that was a significant factor in the cause of death.

In Table 8, the frequency of liver, spleen, bladder, intestine, pubic and pelvis injuries are tabulated as percent of total AIS 3+ injuries, total MAIS 3+ injuries and total AIS 4+ injuries that occurred in fatal cases. The data come from vehicle-to-vehicle, near-side crashes with occupant compartment damage. In a comparison of all AIS 3+ injuries (n = 170), all MAIS 3+ injuries (n = 53), and all AIS 4+ injuries in fatal cases (n = 33), spleen injuries are the only abdominal injuries to increase in frequency from all AIS 3+ injuries to MAIS 3+ injuries and to AIS 4+ injuries in fatal cases. The frequency of liver injuries remains relatively constant between all AIS 3+ injuries and MAIS 3+ injuries, but has a lower frequency among AIS 4+ injuries in fatal cases. The bladder increases in frequency from AIS 3+ to MAIS 3+ injuries, but does not account for any of the AIS 4+ injuries in the fatal cases. The intestine only sustained 1.8% of the AIS 3+ injuries and no MAIS 3+ or AIS 4+ injuries. Overall, the authors conclude that abdomen injuries increase in frequency with injury severity, but not with fatalities.

Table 8. Abdominal organs injured in far-side crashes from NASS database (Augenstein 2000a)

	All AIS 3+ n = 170		MAIS 3+ n = 53		AIS 4+ injuries in fatal cases N = 33	
	Freq.	No.	Freq.	No.	Freq.	No.
Liver	5.9%	10	5.7%	3	3.0%	1
Spleen	6.5%	11	11.3%	6	12.1%	4
Bladder	1.8%	3	3.8%	2	-	-
Intestine	1.8%	3	-	-	-	-
Lung	15.9%		18.9%		18.2%	
Heart	3.5%		11.3%		18.2%	
Diaphragm	2.4%		1.9%		0%	
Pubic	11.2%	19	5.7%	3	-	-
Pelvis	4.7%	80	-	-	0.0%	0

*Percentages are based on all injuries to the body in that category

With regard to all lateral impacts that resulted in injured occupants, the authors note that the two most important factors in side crashes are the location of impact relative to the passenger compartment and whether the crash is near-side or far-side relative to the occupant. Based on both the NASS-CDS data and the WLIRC data in this study, as well as NASS 1985 data from Hackney (1987), the most frequent type of crash for injured occupants was vehicle-to-vehicle, near side, with damage at the location of the passenger compartment and a principle direction of force equal to 2 o'clock or 10 o'clock. Comparing crash variables of injured occupants in the NASS-CDS and WLIRC data, the WLIRC data had a higher percentage of angular impacts (2 and 10 o'clock), larger cars as the struck vehicle (versus small car, medium car and light truck) and light trucks/vans as striking vehicles (versus cars and heavy trucks).

Siegel (2001) Factors Influencing the Patterns of Injuries and Outcomes in Car versus Car Crashes Compared to Sport Utility, Van, or Pick-up Truck versus Car Crashes: Crash Injury Research Engineering Network Study

Siegel et al. compared the injury patterns between car-to-car crashes and car-SUVT (sport utility, van, light truck) crashes using cases from the CIREN database. The cases selected involved either a left- or right-front occupant who was at least sixteen years or older and sustained an ISS score of at least sixteen (unless protected by an airbag, in which case the lower extremities must have sustained an ISS score of at least five). In addition, the occupant must have arrived to the trauma center alive with an expectancy to live at least two more hours. Occupants involved in rollover or rear impact crashes were excluded, as were those who were ejected during the crash. Again, since the analysis studied outcome as a function of vehicle type and other factors for an injured population sampled on outcome, and no corrections to account for exposure were made, the value of these results is limited.

Table 9 summarizes the analysis conducted. The proportion of occupants with liver, spleen, kidney, thorax, and pelvis fracture injuries are indicated for different subsets of crash variables: frontal vs. lateral, with and without airbag deployment, above and below 30 mph ΔV, and type of impacting vehicle. The statistical significance of the difference between the two groups was determined by applying a paired t-test. Data pairs marked with * are significantly different ($p<0.05$).

Table 9. Proportion of cases involving abdominal and other injury by impact direction, airbag use, delta V, and impacting vehicle (Siegel 2001)

				%	%	%	%	%	
Impact	ΔV	AB	Impacting Vehicle	Liver	Spleen	Kidney	Thorax	Pelvic Fx	N
F	All	All	All	14	11	3	56	23*	309
L	All	All	All	15	18	14	59	53*	103
F	All	Yes	All	13	8	3	54	23	166
F	All	No	All	15	15	3	57	22	143
F	<30	Yes	All	9*	7	2	46*	21	102
F	>30	Yes	All	21*	10	5	68*	27	62
F	All	All	mid-SUVT	17	17	3	56	19	36
F	All	All	lg-SUVT	13	13	0	56	13	16
L	<30	All	All	10	17	9	56	51	87
L	>30	All	All	29	24	29	65	59	17
L	All	All	Car	10	20	10	47*	67	30
L	All	All	lg-SUVT	25	17	17	83*	50	12

Pelvis fractures are significantly more prevalent in lateral vs. frontal crashes. In frontal crashes, a deployed airbag did not have a significant effect on abdominal injury outcome. The type of impacting vehicle (mid-size SUVT or a full-sized SUVT) also did not affect abdominal injury outcome in frontal crashes. The only factor of significance in frontal crashes is ΔV, which affects the proportion of liver and thorax injuries. Frontal crashes in which the ΔV is less than or equal to 30 mph result in 9% of injuries to the liver, while those crashes with a ΔV greater than 30 mph have 21% of injuries to the liver. Neither ΔV nor impacting vehicle type affects abdominal injury outcome in lateral impacts, although being struck by a large SUVT increases the likelihood of thoracic injury.

Lee (2002) Abdominal Injury Patterns in Motor Vehicle Accidents: A Survey of the NASS Database from 1993 to 1997

Lee and Yang used the NASS database for years 1993 – 1997 to characterize abdominal injury patterns. From this dataset there were about 150,000 injuries total, of which 7,634 (5.2%) were to the abdomen, placing the abdomen as the seventh most injured body region, out of eight. At the AIS 3+ level, there were 17,859 injuries total, of which 1,194 (6.7%) were to the abdomen, making it the fifth most frequently injured region of the body. The head, thorax, and lower and upper extremities were all more frequently injured than the abdomen.

6,520 of the abdominal injuries could be attributed to an injury contact point. The remaining 1,114 (14.6%) of abdominal injuries were coded as resulting from either indirect contact, noncontact or unknown contact. Figure 9 shows the distribution of contact points causing abdominal injuries. Appendix A lists which vehicle components are grouped together into categories of front, left, right, interior, roof and floor. The front, left, right and interior are all significant contributors to abdominal injury, while the floor and roof are not. When the less severe injuries of AIS 1 and 2 were excluded, the front, left and right contact points are more frequent contact points, while the interior contact points become less frequent. When the left and right results are combined, the rate of AIS 3+ injuries is greater from side impact than frontal impact.

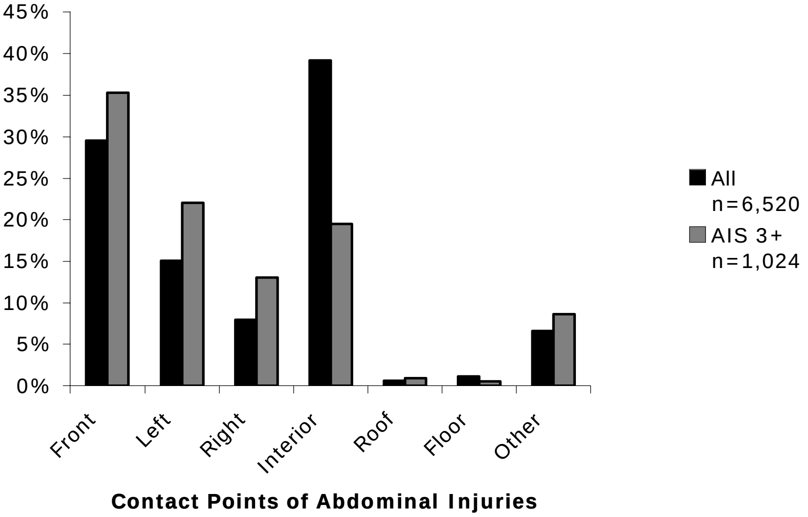


Figure 9. Distribution of contact points for all abdominal injuries (black) and AIS 3+ severe abdominal injuries (gray) from Lee (2002)

A more detailed investigation of the front, left, right and interior contact points shows that while the belt system causes more abdominal injuries than any other contact, the majority of these injuries are less severe. The most frequent contact points causing AIS 3+ abdominal injuries are the steering assembly, the left and right interior vehicle, and the belt restraints.

Lee and Yang then investigated the specific organs injured and their injury frequency relative to all abdominal injuries and to all AIS 3+ abdominal injuries. The six primary organs/regions are the liver, spleen, kidney, artery/vein, digestive, and integument. These six account for 4,439 (99%) of abdominal injuries. The distribution, plotted in Figure 10, shows that the integument sustains the majority of all abdominal injuries, yet accounts for less than 1% (3 of 685) of AIS 3+ abdominal injuries. The liver and spleen account for the majority of the more severe abdominal injuries, followed by injuries to the digestive system, arteries/veins, and the kidneys.

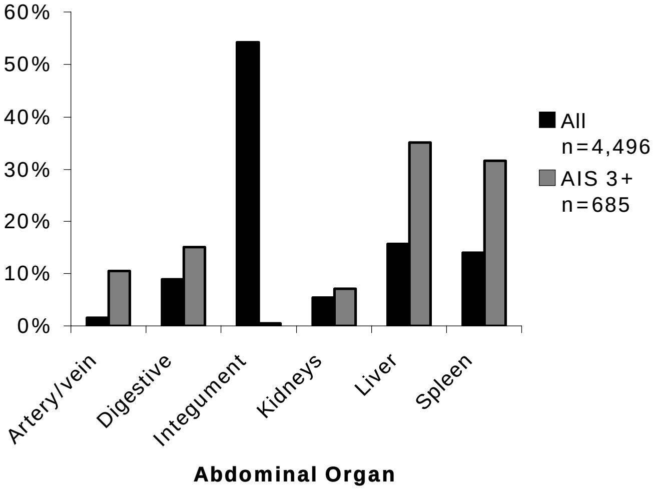


Figure 10. Distribution of organ/region injury in all abdominal injuries (black) and more severe abdominal injuries (gray) from Lee (2002)

Expanding on these results, the authors then looked at the injury contact points for each organ. The distribution is plotted in Table 9. The liver is most frequently injured by front contacts, followed by right side contacts. The spleen is injured at about the same rate from front and left side contacts.

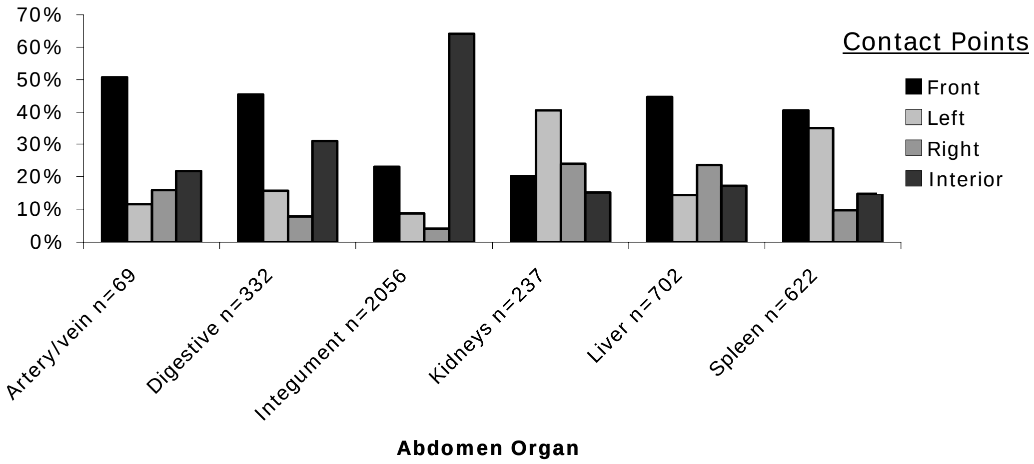


Figure 11. Distribution of all abdominal injury by region and contact point (Lee 2002)

Finally, specific contact points were compared with the AIS 3+ injuries to the kidney, liver and spleen. The proportion of each associated injury contact point is plotted with respect to the total number of injuries for each organ in Figure 12. The primary contact for kidney injury is the left door hardware and armrest. For the liver it is the steering wheel and for the spleen it is the left door hardware followed by the steering wheel.

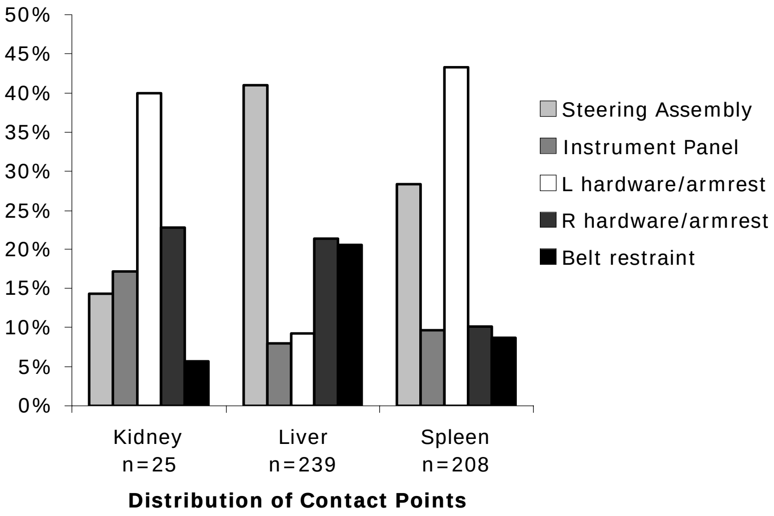


Figure 12. Distribution of contact points for AIS 3+ injuries of the solid abdominal organs (Lee 2002)

The authors also found that 19% of injuries from front compartment contacts are AIS 3+ injuries, while 24% of injuries from side compartment contacts are AIS 3+ injuries. Solid organ injuries (kidney, liver, and spleen) are more likely to be AIS 3+ (32%) than hollow organ injuries (6%). Solid organs are more often injured from contact with side components (left and right combined) than from front contact points. The liver is more often injured from right contact points, while the spleen is more often injured from left contact points.

Gabler (2005) Side Impact Injury Risk for Belted Far Side Passenger Vehicle Occupants

Gabler et al. investigated injury patterns to belted occupants in far-side impacts using the NASS-CDS database for years 1993 – 2002. They defined a side crash as any crash with the general area of damage in the most harmful event to the side of the car, light truck, or van. All analyses used NASS weighting factors with the data.

Gabler et al. report that in far-side impacts, 5.2% of all AIS 3+ injuries are to the abdomen. They also report that abdominal injuries account for a larger percentage of injuries to occupants of passenger cars than to occupants of light trucks or vans; 8% of all AIS 3+ injuries to occupants of passenger cars are to the abdomen while only 2% of all AIS 3+ injuries to occupants of light trucks and vans are to the abdomen.

Gabler reports that 58% of all abdominal injuries occurred in crashes with a principle direction of force (PDOF) of 90 degrees (3 and 9 o'clock) while 32% occurred with a PDOF of 60 (2 and 10 o'clock) and 8% occurred with a PDOF of 30 (1 and 11 o'clock). In contrast, the direction that presents the most risk of any injury is 60 degrees. Gabler reports that the PDOF of 60 degrees accounts for 60% of all MAIS 3+ injuries and a PDOF of 90 degrees only accounts for 24%. Gabler also reports that a PDOF of 60 degrees is the most frequently occurring PDOF in far-side crashes, accounting for crashes with 42% of all case occupants, while a PDOF of 90 degrees accounts for just 24% of all occupants. Thus, 58% of all abdominal AIS 3+ injuries occur in just 24% of far-side impacts.

While not specific to the abdomen, Gabler also reports that when the location of impact is either the front two-thirds (Collision Deformation Classification (CDC) code 'Y'), rear two-thirds ('Z'), center one-third ('C') or distributed along the entire side ('D'), there is a greater risk of injury. 66% of all far-side occupants are in crashes with damage to these areas, as are 86% of all far-side occupants with MAIS 3+ injuries. 9% of far-side occupants are in crashes with damage to the rear one-third ('B') of the vehicle; crashes with damage to this area resulted in no far-side occupants with MAIS 3+ injuries. 24% of far-side occupants are in crashes with damage to the front one-third ('F') of the vehicle, as are 14% of far-side occupants with MAIS 3+ injuries.

2.2 UMTRI Analysis of Abdominal Injury Patterns in NASS database

2.2.1 Approach and overview

Analysis of the NASS database began by restricting case years to 1998 to 2004. Crashes were limited to front and side impacts, using location of vehicle damage from the CDC as the criteria. Occupants were limited to drivers and right-front passengers aged 16 or greater who were not pregnant. Vehicle model years were limited to 1985 or later. All analyses in this report use weighted NASS data.

Side impact crashes/occupant positions were classified as follows. "Near-side" impacts are those involving left-side damage with drivers as the case occupant, or right-side damage with right-front passengers as the case occupant. "Far-side impacts" are those involving right-side damage with drivers, or left-side damage with right-front passengers.

The resulting database contained 53% male occupants, and an 80%/20% split between drivers and right-front passengers. The occupants in the dataset had a 74% belt-use rate. The age distribution by crash type shown in Figure 13 indicates a fairly constant distribution of age for each crash type.

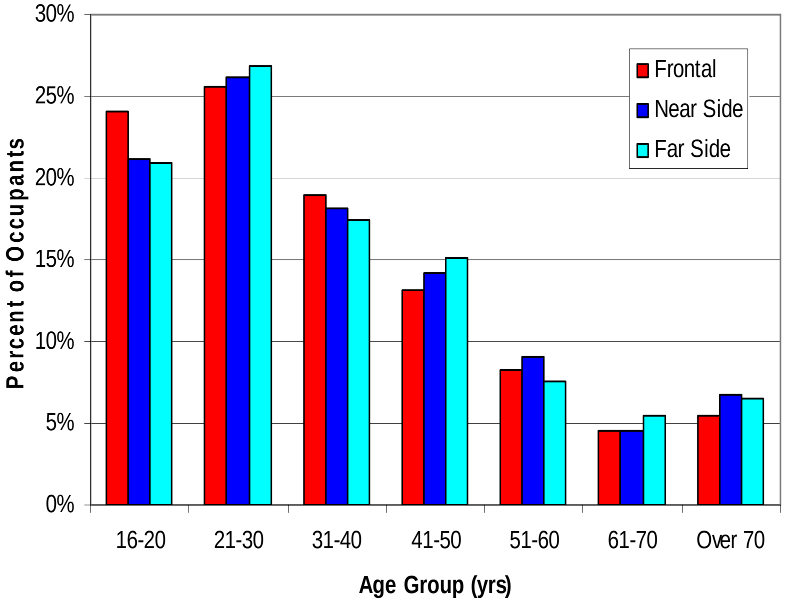


Figure 13. Distribution of occupants by age group and crash type in selected NASS database

The distribution of crashes by crash severity (delta V in mph) for frontal, near-side, and far-side impacts is shown in Figure 14. The majority of these crashes have severities less than 20 mph.

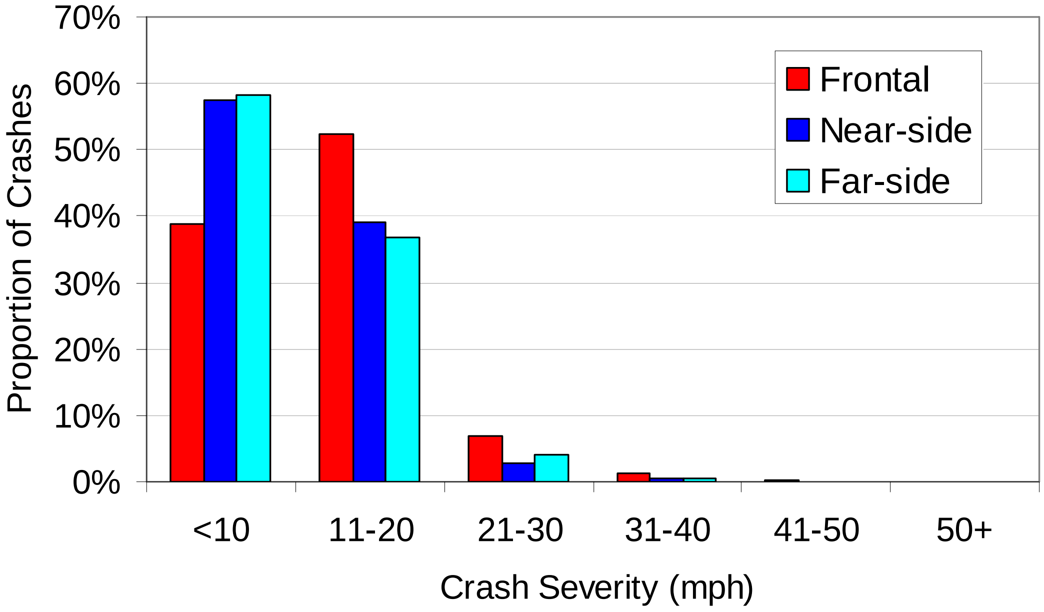


Figure 14. Distribution of NASS crashes by severity (in delta V, mph) for frontal, near-side, and far-side impacts

2.2.2 Risk of injury

Using this database, the risk of injury to different body regions was assessed for frontal, near-side, and far-side crashes. Injury levels were evaluated for AIS 2+, AIS 3+, and AIS 4+ injuries for the eight main body regions coded using the AIS. Figure 15 through Figure 17 show the percent of occupants with injuries to each body region for frontal, near-side, and far-side crashes, at AIS 2+, AIS 3+, and AIS 4+, respectively. For all three categories of impacts, abdomen injury ranks 5th in risk of injury behind head, thorax, lower extremity, and upper extremity when evaluating AIS 2+ injuries. For AIS 3+ injuries, abdomen ranks fourth in risk for near-side crashes, and 5th for frontal and far-side impacts. However, when considering AIS 4+ injuries as shown in Figure 17, abdomen ranks third in risk behind head and thorax for frontal and side impacts.

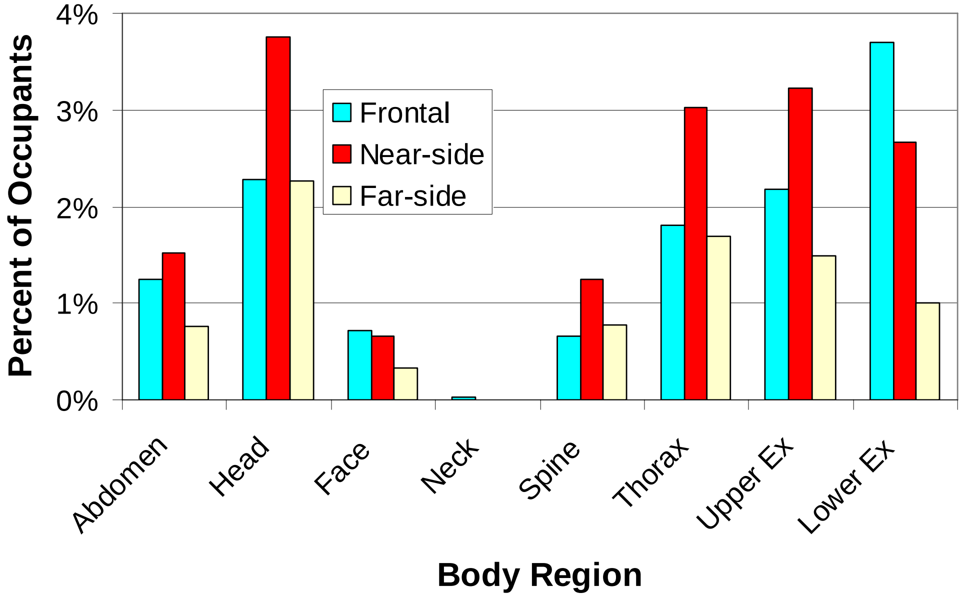


Figure 15. Risk of AIS 2+ injury by body region for frontal, near-side, and far-side impacts

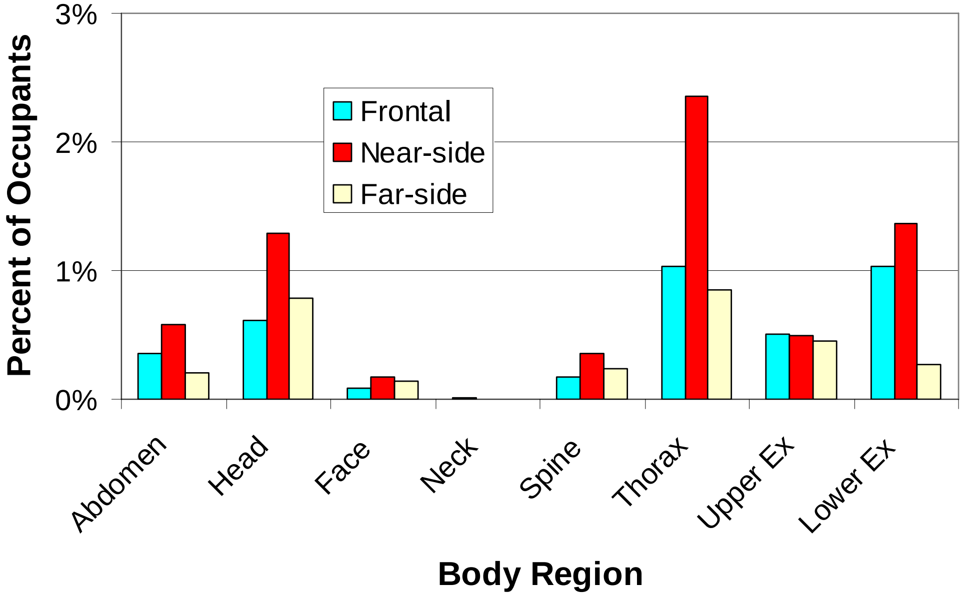


Figure 16. Risk of AIS 3+ injury by body region for frontal, near-side, and far-side impacts.

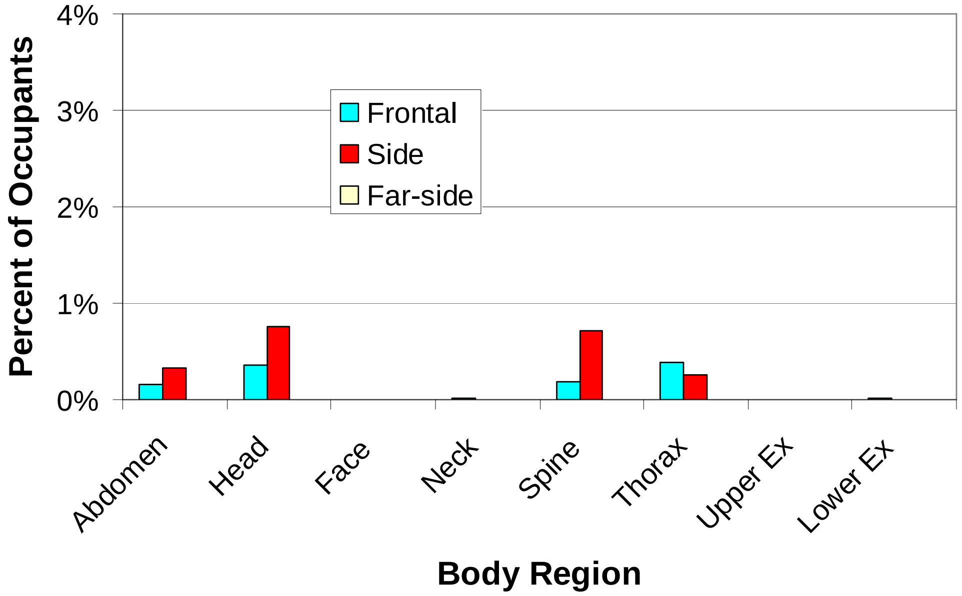


Figure 17. Risk of AIS 4+ injury by body region for frontal, near-side, and far-side impacts

Figure 18 shows the estimated number of occupants sustaining abdomen injuries each year in the United States based on the injury risks presented in Figure 15 and Figure 16. About half of the abdomen injuries occur in frontal impacts, and half in side impacts. The number of occupants with abdomen injuries is split about 60%-40% between AIS 2 injuries and AIS 3 and greater injuries.

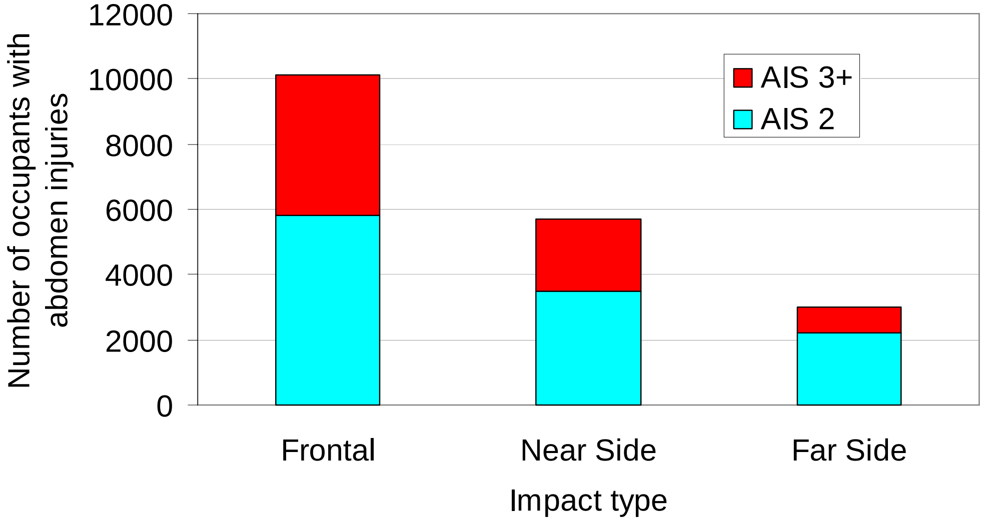


Figure 18. Estimated number of occupants sustaining AIS 2 and AIS 3+ abdomen injuries each year in the United States in frontal, near-side, and far-side crashes

2.2.3 Factors affecting abdominal injury risk

The risk of abdomen injury as a function of crash severity was assessed for frontal, near-side, and far-side impacts. Figure 19 shows the risk of AIS 2+ abdomen injury versus crash severity, while Figure 20 shows the risk of AIS 3+ abdomen injury versus crash severity. For both injury levels, the risk of abdomen injury increases substantially in near-side impacts for crash severities greater than 20 mph. For both injury levels, the risk of abdomen injury increases substantially for frontal and far-side impacts at crash severities greater than 30 mph. The risk of abdomen injuries for NASS cases where delta V is unknown is also listed, and is similar to the risk at delta V's from 11-20 mph.

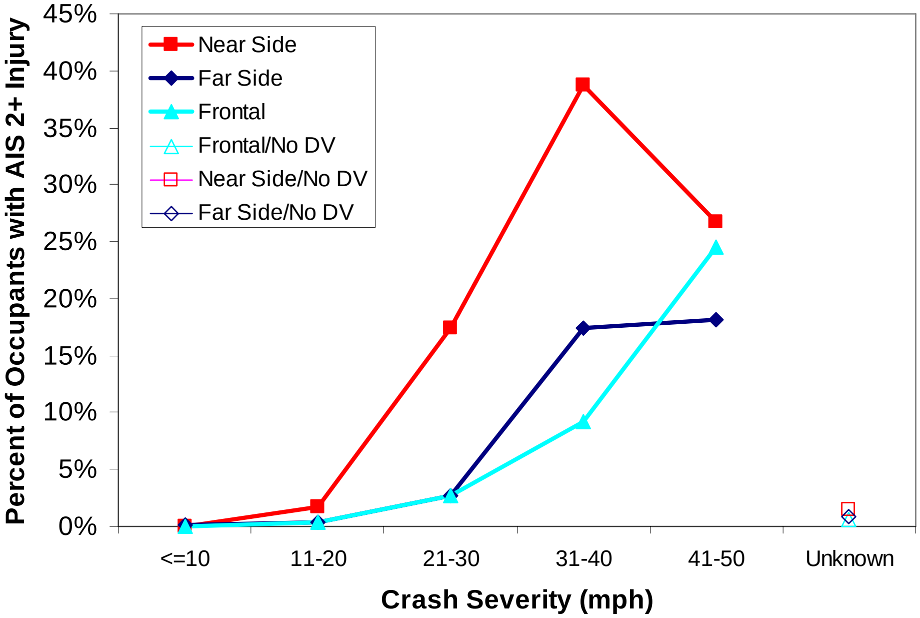


Figure 19. Risk of AIS 2+ abdomen injury by crash severity (delta V in mph) in frontal, near-side, and far-side crashes

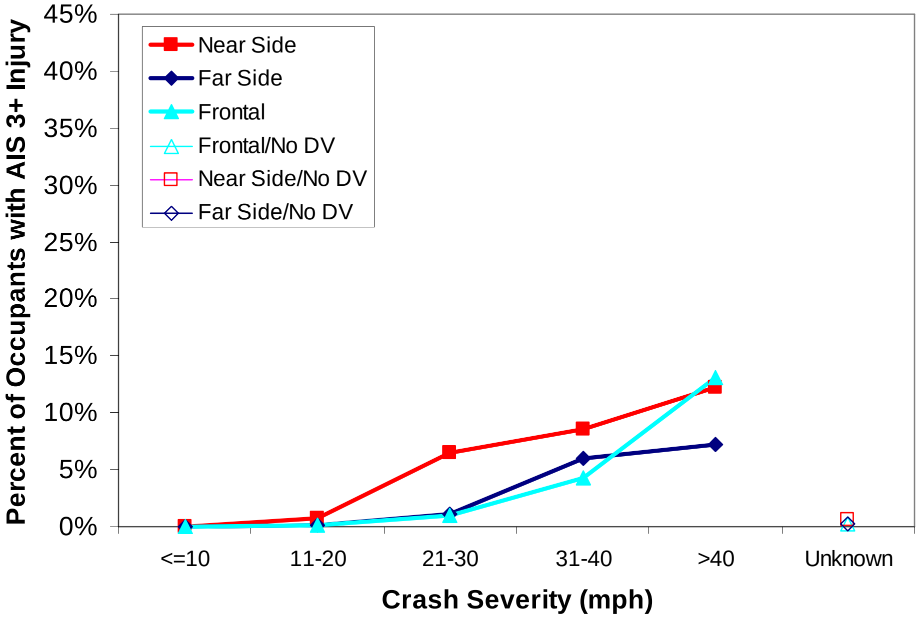


Figure 20. Risk of AIS 3+ abdomen injury by crash severity (delta V in mph) in frontal, near-side, and far-side crashes

The effect of restraint on risk of abdomen injury is shown in Figure 21 for frontal impacts and Figure 22 for near- and far-side impacts. In frontal impacts, use of a three-point belt reduces the rate of both AIS 2+ and AIS 3+ abdomen injuries, with and without airbag deployment. Abdomen injury risk for unbelted occupants is 3 to 8 times higher than that for belted occupants. The risk of abdomen injury is essentially the same with and without airbag deployment, indicating that airbags do not appear to be a significant factor in reducing the risk of abdomen injury in frontal impacts.

When evaluating the effect of restraint use in side impacts, only belt use was evaluated because the number of airbag deployments in side impacts was small. Figure 22 shows that both near- and far-side occupants restrained by a three-point belt in side impacts have a substantially lower risk of abdomen injury than unbelted occupants, when evaluating abdominal injury risk at both AIS 2+ and AIS 3+ levels. For near-side occupants in side impacts, effectiveness varies with the area of damage to the vehicle. With damage only to the passenger compartment (12% of near-side occupants), belts do not reduce abdomen injury risk. With damage to the front two-thirds or rear two-thirds of the vehicle (52% of near-side occupants), risk of abdomen injury to unbelted near-side occupants is about twice that of occupants using the three-point belt. In L-type crashes with damage only in front of the passenger compartment, AIS2+ risk of abdomen injury to unbelted near-side occupants is 5.7 times that of belt-restrained occupants.

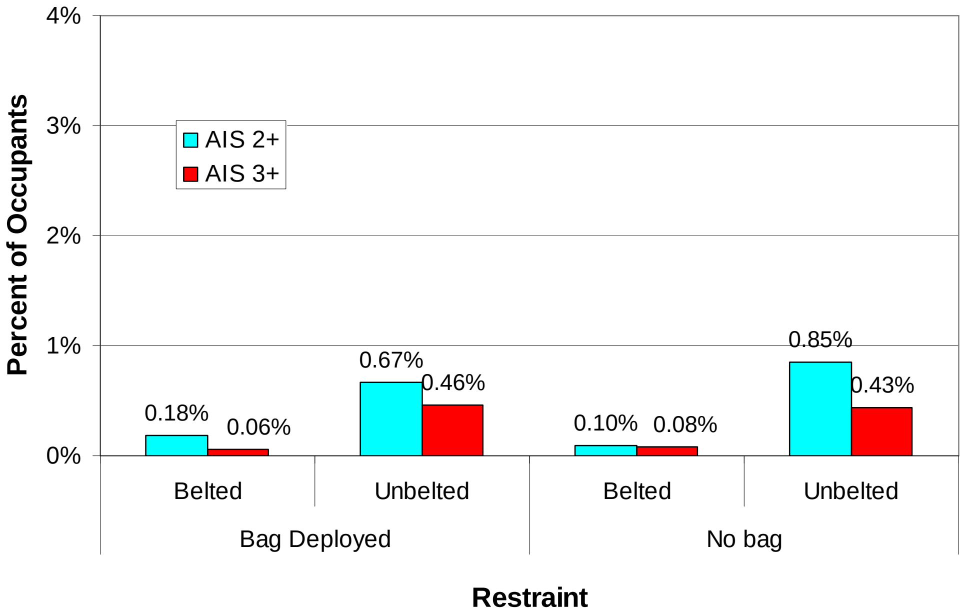


Figure 21. Risk of AIS 2+ and AIS 3+ abdomen injury by belt and airbag restraint in frontal impacts

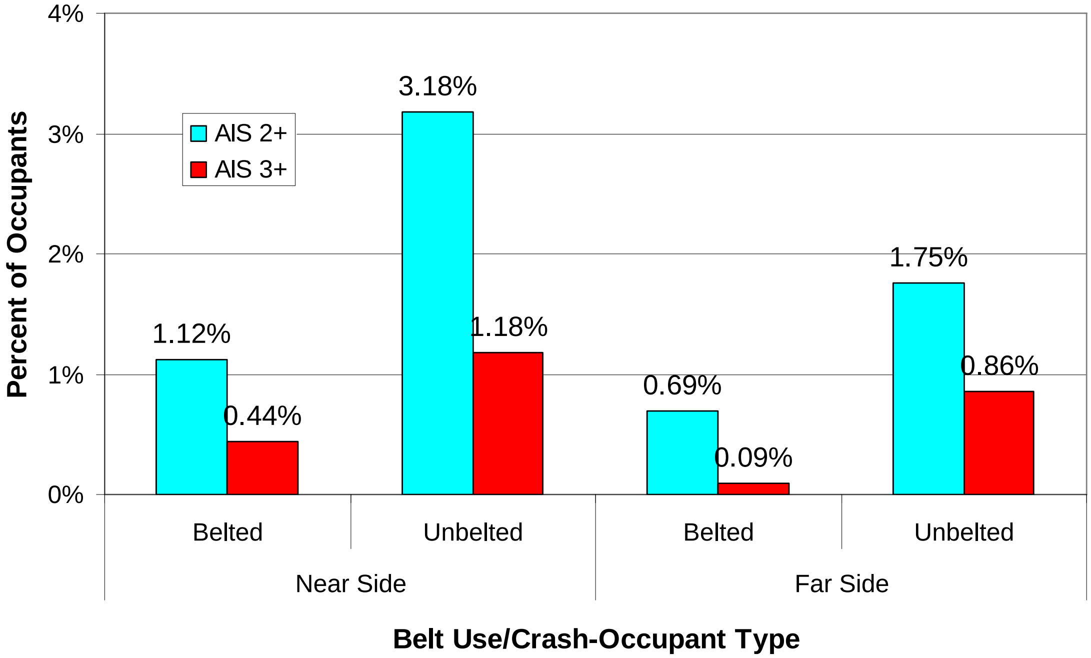


Figure 22. Risk of AIS 2+ and AIS 3+ abdomen injury by belt restraint in near-side and far-side impacts

The risk of AIS 3+ abdomen injury for drivers and right-front passengers in frontal, near-side, and far-side impacts is shown in Figure 23. For all three crash types, the risk of abdomen injury is higher for right-front passengers than for drivers. In particular, the risk of AIS 3+ abdomen injury to right-front passengers in near-side impacts is 2.7 times higher than the risk of AIS 3+ abdomen injury to drivers in near-side impacts.

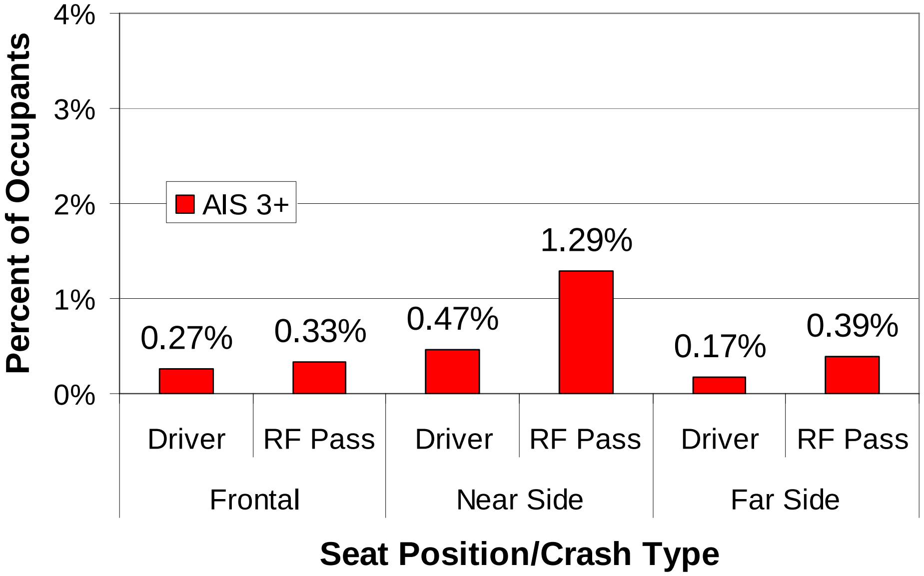


Figure 23. Risk of AIS 3+ abdomen injury by crash type and occupant position

2.2.4 Analysis of high abdominal injury risk to right-front passengers in near-side impacts

The large difference in risk of abdominal injuries between drivers and right-front passengers in near-side impacts led to additional analysis to explore why this is the case. The primary explanation for these differences is simply that the liver, which can be directly loaded in a near-side impact to a right-front passenger, is larger and less protected by the ribs than the spleen, which can be directly loaded in a near-side impact to a driver. However, other factors that might contribute to the higher abdominal injury risk for right-front passengers in near-side impacts were also investigated.

One possible explanation is that right-front passengers may be involved in more severe near-side impacts than drivers. As shown in Figure 24, right front passengers are more likely to be in a T-type near-side impact (52%) than drivers (42%), although the mean delta Vs for drivers and right-front passengers in near-side T-type crashes are statistically the same (12.7 vs. 12.9 mph). However, as shown in Figure 25, when looking at abdomen injury rates for near-side occupants in T-type impacts, the risks of spleen and liver injuries to right-front passengers are still higher than the risks of spleen and liver injuries to drivers (2.3% vs. 1.5% for the spleen and 3.3% vs. 0.7% for the liver). While the higher risk of liver injury for right-front passengers in near-side impacts is understandable because the liver is located primarily on the right side of the body, the higher risk of spleen injuries for right-front passengers is unexpected. The abdominal injury rates in near-side L-type crashes are substantially lower than those in T-type crashes, and the injury patterns in the L-type crashes are consistent with drivers having higher rates of spleen injury and right-front passengers having higher rates of liver injury.

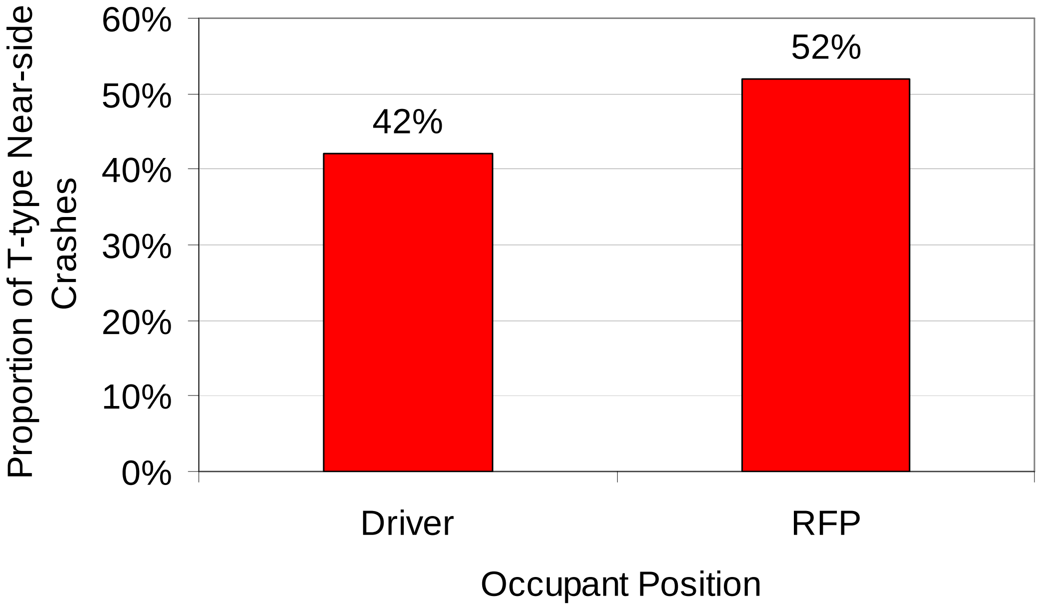


Figure 24. Proportion of near-side T-type side crashes for drivers and right-front passengers

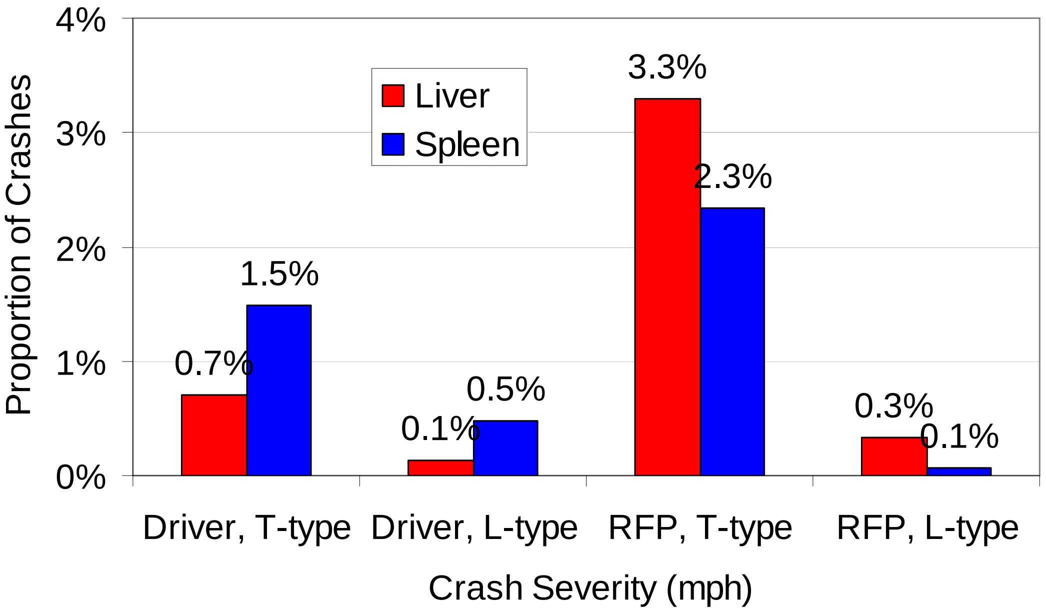


Figure 25. Risk of AIS 3+ liver and spleen injury to drivers and right-front passengers in T-type and L-type near-side impacts

One hypothesis for this injury pattern in T-type crashes is that the risk of abdomen injury to right-front passengers in near-side T-type impacts may be higher than for drivers because there is always a driver present who will move toward the passenger and thereby be a potential source of loading from the left side. For drivers, potential loading by the right-front passenger is only possible in the 20% of impacts where a right-front passenger is present. Two additional analyses were performed in NASS to explore this hypothesis. The first analysis was limited to T-type side impacts of vehicles with both drivers and right-front passengers. Figure 26 shows the risks of AIS 2+ liver, spleen, and rib injuries for drivers and right-front passengers in near-side T-type impacts where there are two occupants in the front row. The mean delta V and maximum lateral intrusion for the drivers and right-front passengers in this set of crashes are statistically the same. These results show nearly equal risks of rib fracture for drivers and right-front passengers, suggesting that the lateral loading levels to drivers and passengers are similar in this set of crashes. Right-front passengers have a higher risk of liver injury than drivers, while drivers have a higher risk of spleen injury than right-front passengers. These injury patterns are consistent with left-side loadings to drivers where the spleen is located and right-side loading to right-front passengers where the liver is primarily located.

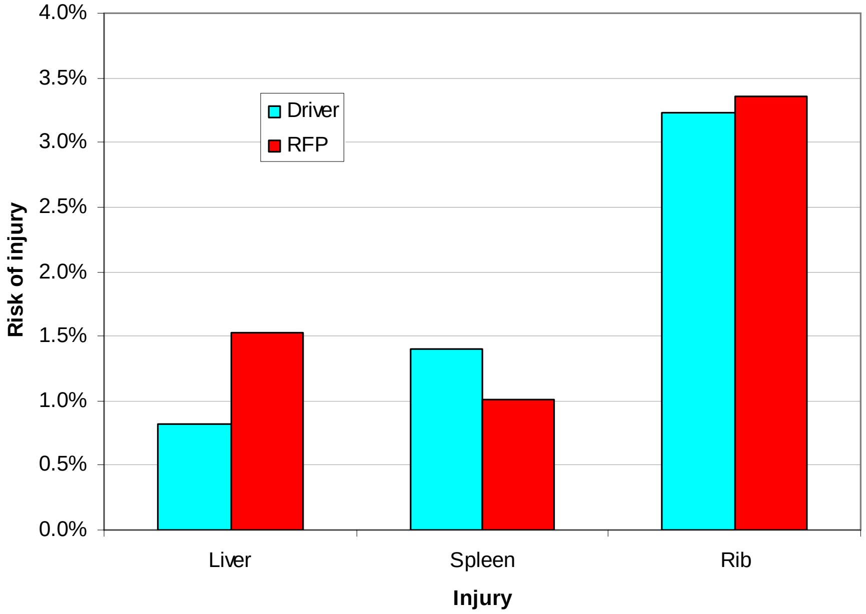


Figure 26. Risks of AIS 2+ liver, spleen, and rib injuries to drivers and right-front passengers in near-side T-type impacts with both a driver and right-front passenger in the case vehicle

The second analysis performed to examine the possible effect of loading in a near-side impact by another occupant was to compare abdominal injury rates for 1) drivers without right-front passengers, 2) drivers with unbelted right-front passengers, and 3) drivers with belted right-front passengers. As shown in Figure 26, drivers in near-side T-type impacts who are seated next to an unbelted right-front passenger have a higher risk of liver injury compared to drivers with no right-front passenger, after controlling for crash severity using delta V. Although not shown, liver injury risk is the same for drivers seated next to belted right-front passengers as it is for drivers without a right-front passenger. The risk of spleen injury to drivers in near-side impacts is not affected by the presence or restraint condition of a right-front passenger. As shown in Figure 28, a similar analysis of right-front passengers in near-side impacts shows a higher risk of spleen injury for right-front passengers seated next to unbelted drivers than for those seated next to belted drivers. The risk of liver injury for these right-front passengers does not change with the restraint condition of the driver.

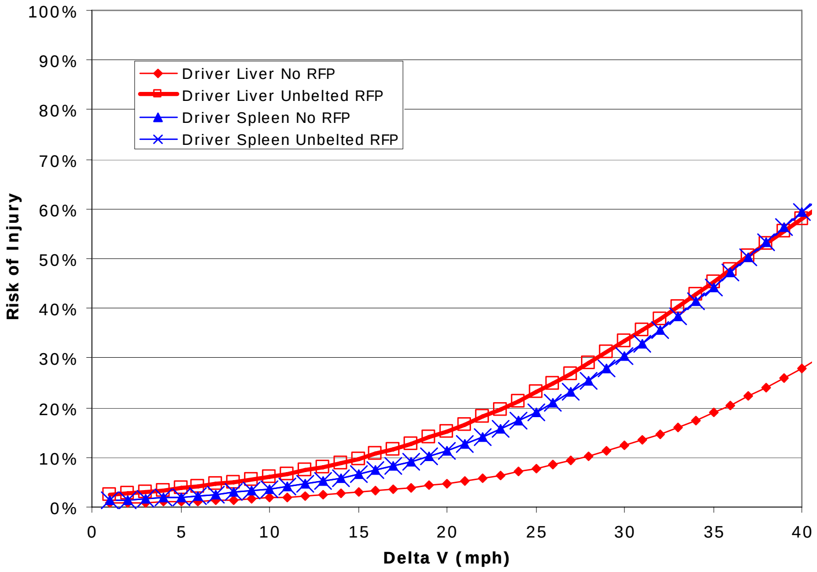


Figure 27. Risks of liver and spleen injury to drivers in near-side T-type impacts as a function of delta V for unbelted and no-right-front-passenger conditions

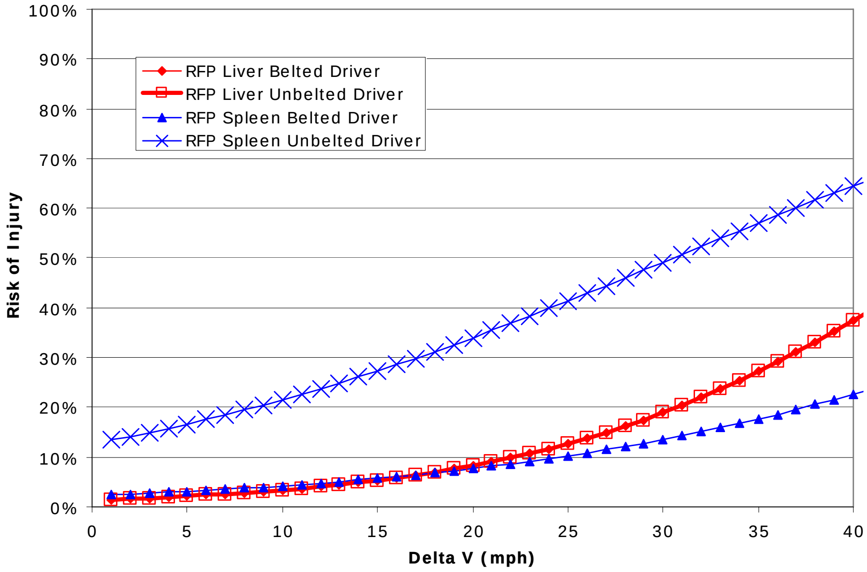


Figure 28. Risks of liver and spleen injury to right-front passengers in near-side T-type impacts as a function of delta V for unbelted- and belted-driver conditions

In summary, right-front passengers in near-side impacts have the highest risk of abdomen injury compared to other combinations of occupant position and crash type because:

- The liver is located on the right side of the body, which is directly loaded in near-side impacts.
- Right-front passengers are more likely than drivers to be in T-type impacts (52% vs. 42%).
- Loading by unbelted drivers increases risk of spleen injury in right-front passengers.

2.2.5 Abdomen organs injured

Figure 29 shows the risk of AIS 2+ injury to the liver, spleen, kidney, and hollow organs for drivers and passengers in frontal, near-side and far-side impacts. Risk of two or more rib fractures is also included on this plot. Figure 30 shows the same information for only the liver and spleen to allow easier visual analysis of relationships between side of loading and side of abdomen injury. In frontal crashes, the liver is the most frequently injured organ for drivers, while the spleen is the most frequently injured organ for right-front passengers. This may partly result from the orientation of the shoulder belt relative to the locations of the liver and spleen for drivers and right-front passengers. Hollow organs are the next most frequently injured abdominal organs in frontal crashes for both drivers and right-front passengers, while kidney ranks last. In near-side impacts, the liver is most frequently injured for right-front passengers, while the spleen is most frequently injured for drivers. For right-front passengers, the spleen, kidney, and hollow organs, rank second, third, and fourth among abdomen organs injured, while for drivers, the ranks are kidney, liver, and hollow organs. In far-side impacts, drivers have the highest risk of kidney injury, followed by liver, spleen, and hollow organs. For right-front passengers in far-side impacts, the abdominal organs injured in order by injury risk are liver, kidney, spleen, and hollow organs.

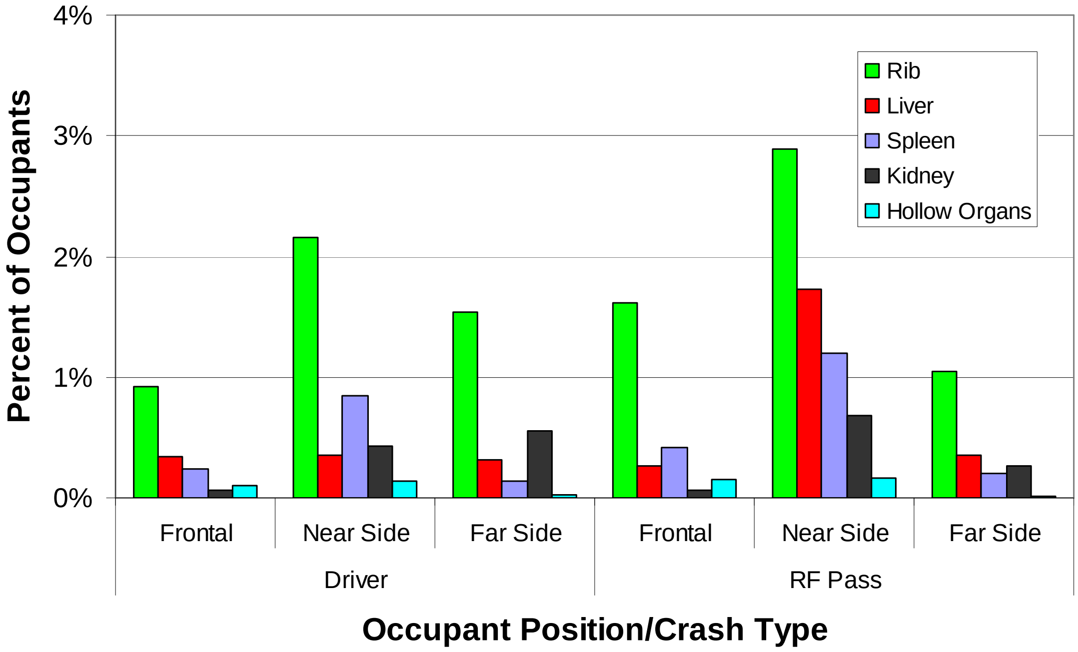


Figure 29. Risk of injury to abdominal organs, plus risk of rib fractures, for drivers and right-front passengers in frontal, near-side and far-side impacts

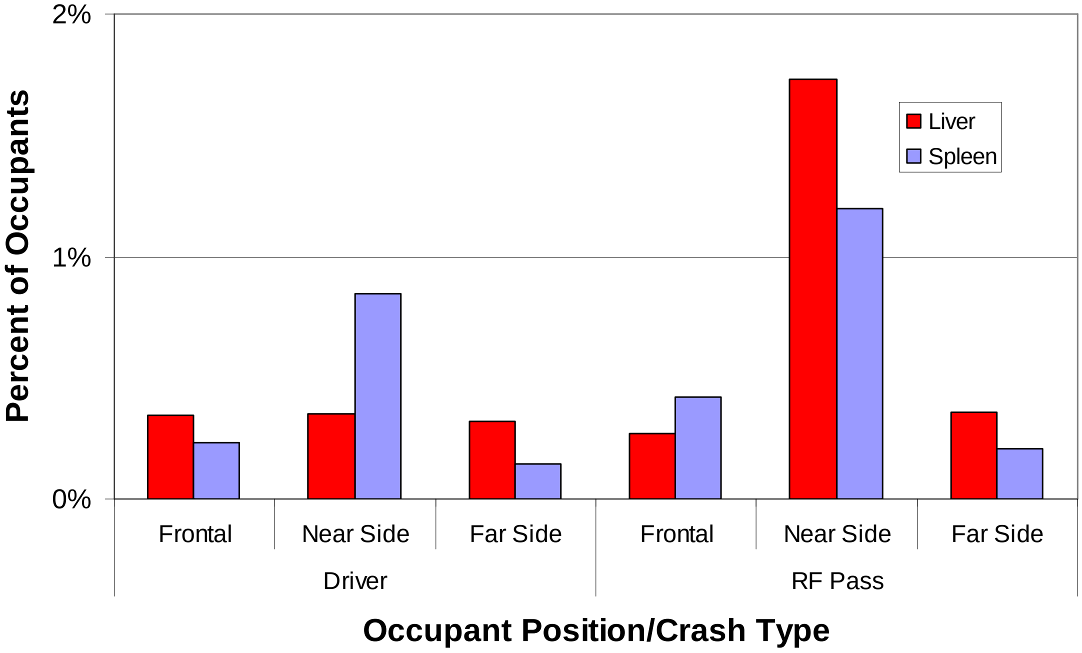


Figure 30. Risk of injury to the liver and spleen for drivers and right-front passengers in frontal, near-side and far-side impacts

Figure 31 through Figure 33 show the risk of injury to abdominal organs (plus rib fracture) versus crash severity for frontal, near-side, and far-side crashes, respectively. In all types of crashes, injury risk for all abdomen organs increases with crash severity. For both types of side impact, the apparent drop in risk for crashes above 40 mph delta V is a result of the small sample of side impacts with crash severities that high.

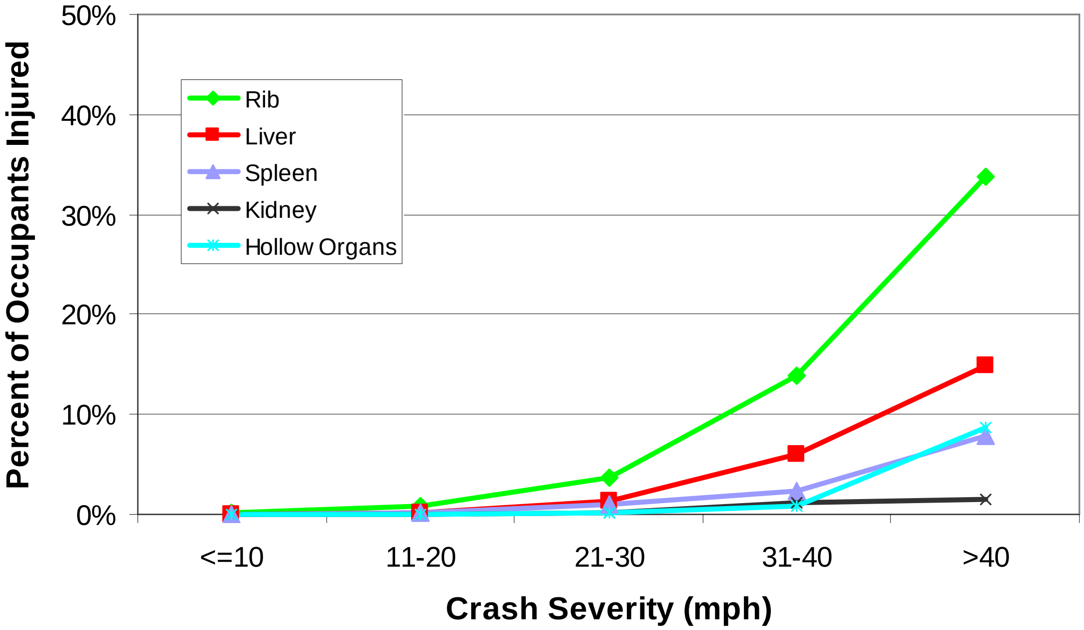


Figure 31. Risk of injury to abdominal organs, plus risk of rib fractures, for frontal crashes versus crash severity (delta V in mph)

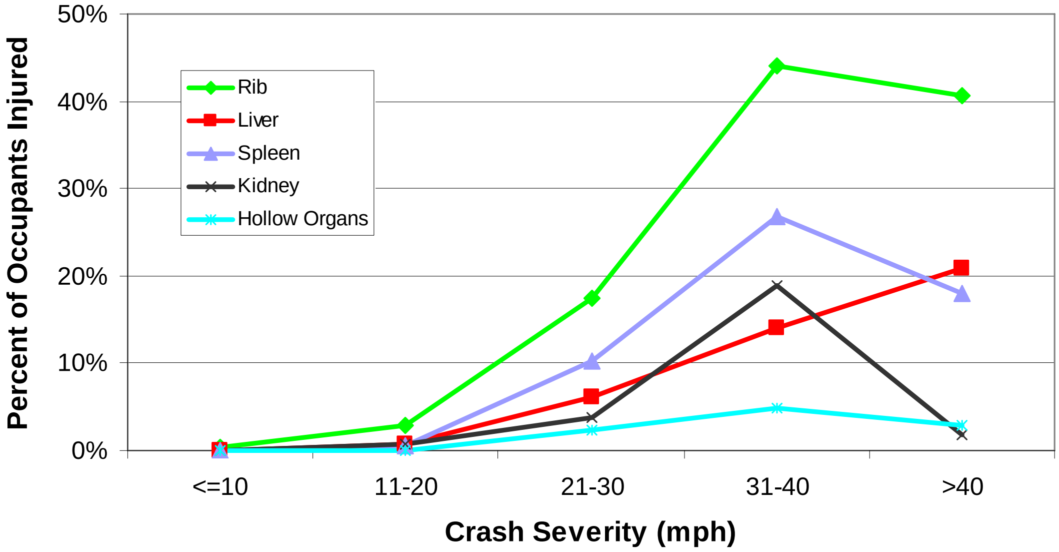


Figure 32. Risk of injury to abdominal organs, plus risk of rib fractures, for near-side impacts versus crash severity (delta V in mph)

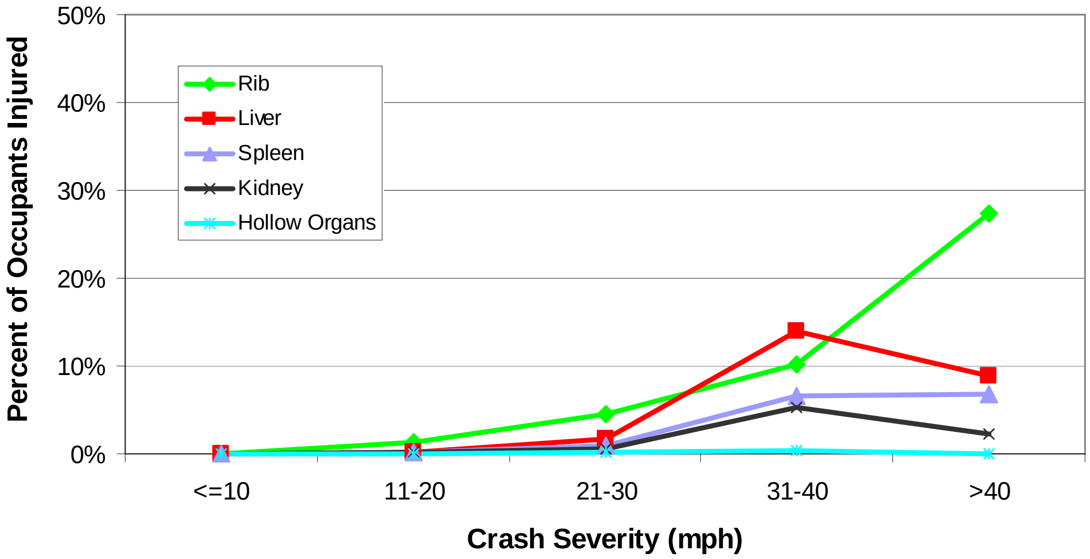


Figure 33. Risk of injury to abdominal organs, plus risk of rib fractures, for far-side impacts versus crash severity (delta V in mph)

Figure 34 through Figure 36 show the risks of injury to the abdomen organs as well as rib fracture versus age for frontal, near-side, and far-side impacts. For all three types of crashes, the risk of injury to any abdomen organ is nearly constant with age, even though the risk of rib fracture increases substantially with age. These data suggest that rib fractures are not a primary cause of injury to abdominal organs, because if this was the case, the risk of abdomen organ injuries would be expected to increase with the incidence of rib fractures.

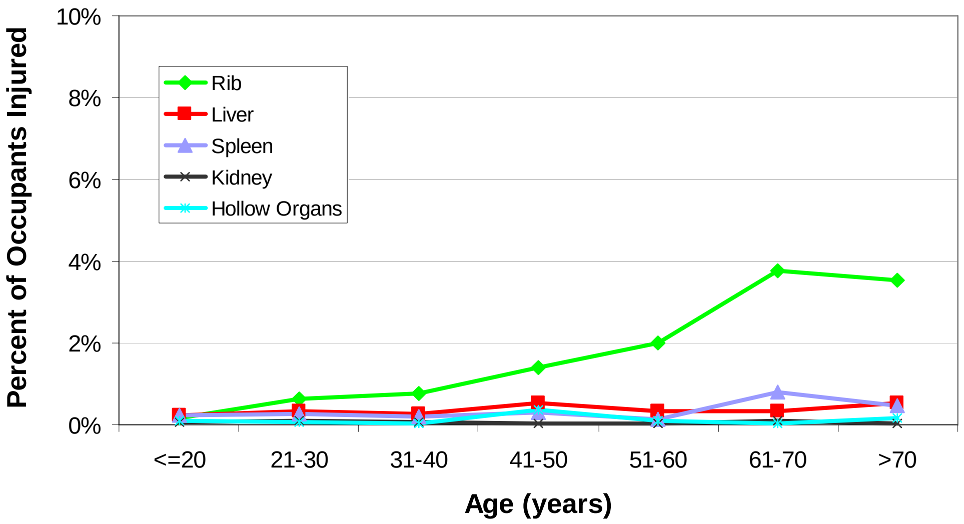


Figure 34. Risk of injury to abdominal organs, plus risk of rib fractures, for frontal impacts versus age

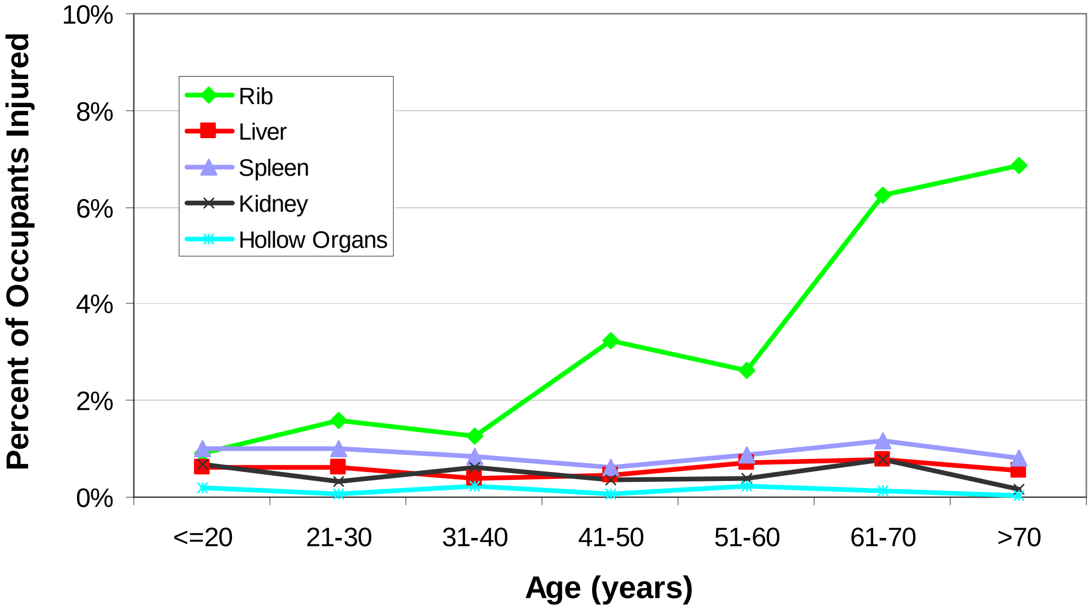


Figure 35. Risk of injury to abdominal organs, plus risk of rib fractures, for near-side impacts versus age

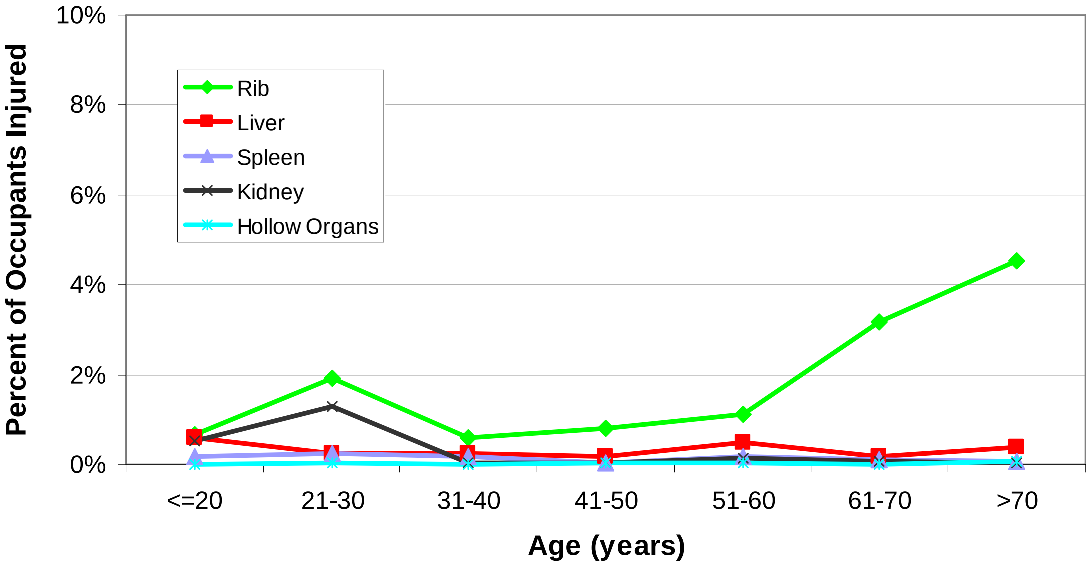


Figure 36. Risk of injury to abdominal organs, plus risk of rib fractures, for far-side impacts versus age

2.2.6 Abdomen injury and rib fracture

The previous analyses prompted a closer look at the incidence of rib fracture and abdominal organ injury. Each occupant with an AIS 2+ injury was evaluated as to whether they sustained a liver, spleen, or kidney injury, and was then coded as having two or more rib fractures (i.e. an AIS 2+ rib fracture) or zero or one rib fractures. The percentage of injured occupants with AIS 2+ and without AIS 2+ rib fractures are shown in Figure 37 according to abdominal organ injured and crash type. For all crash directions and for each abdomen organ, the percentage of injured occupants without rib fracture and abdomen injury was very small relative to the percentage of occupants with rib fracture and abdomen injury.

Because the presence or absence of rib fracture is closely related to crash severity, and also affected by belt loading and crash type, an analysis was performed to estimate risk of abdomen injury with and without rib fracture versus crash severity and controlling for belt use and occupant position. Results are shown in Figure 38 for belted drivers in frontal impacts, and in Figure 39 for belted drivers in near-side impacts. In frontal impacts, the odds of a belted driver sustaining a liver injury are 16 times higher with AIS 2+ rib fractures than without, the odds of sustaining a spleen injury are 30 times higher, and the odds of sustaining a kidney injury are 12 times higher. In near-side impacts, the odds of a belted driver sustaining a liver, spleen, or kidney injury are 45, 26, and 9 times higher, respectively, if the occupant sustains AIS 2+ rib fractures.

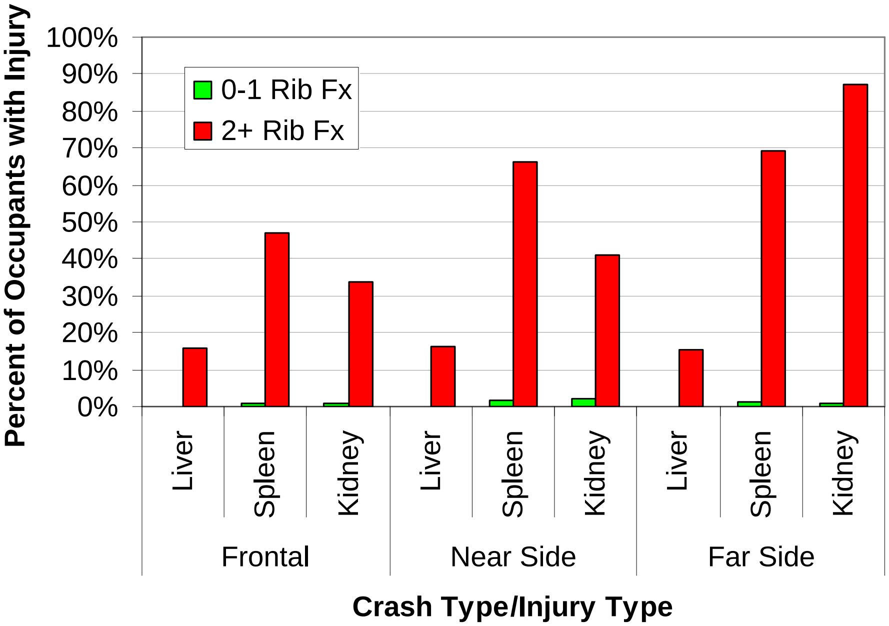


Figure 37. Percentage of injured occupants with and without AIS 2+ rib fractures by crash type and abdomen organ injured

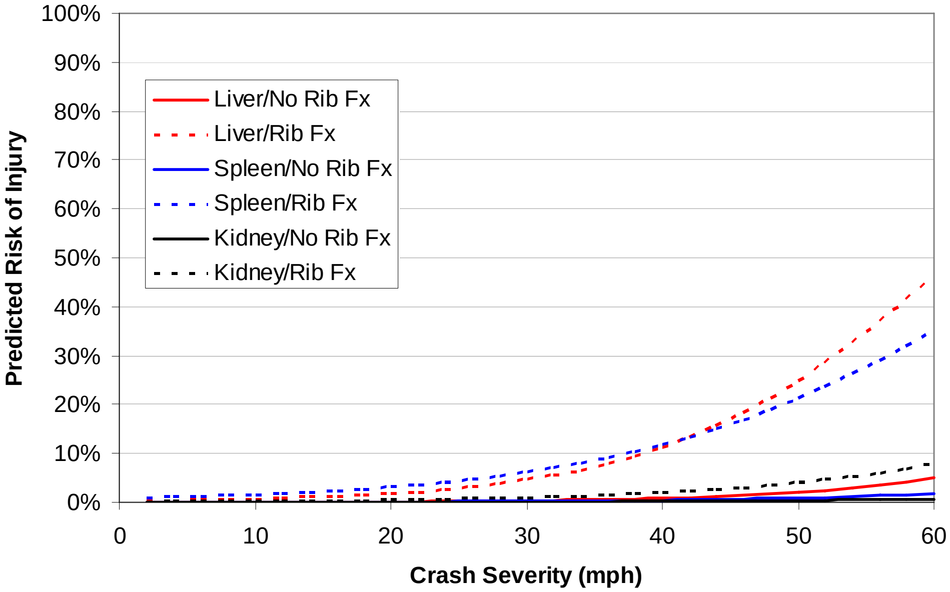


Figure 38. Risk of liver, spleen and kidney injury in frontal crashes, with and without AIS 2+ rib fracture, versus crash severity

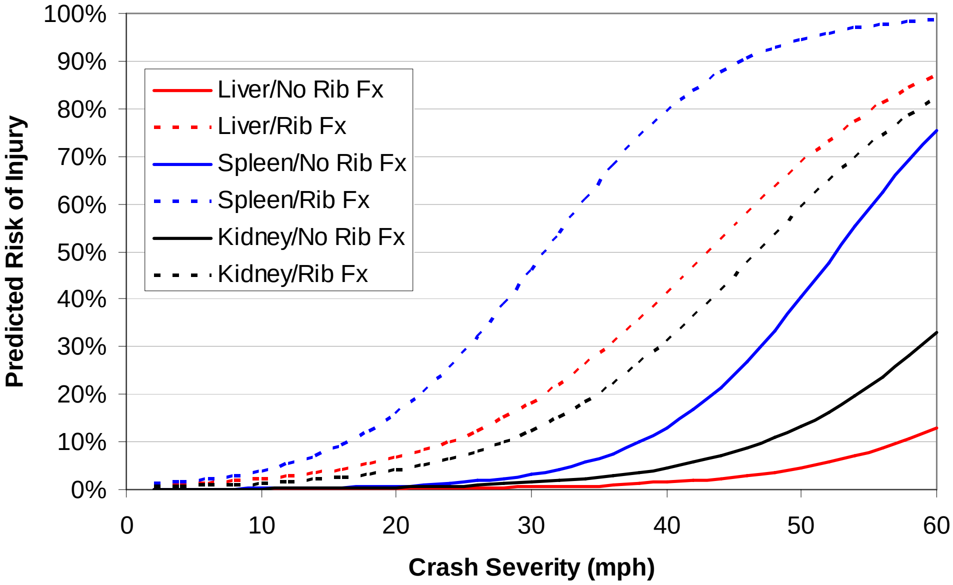


Figure 39. Risk of liver, spleen and kidney injury in near-side crashes, with and without AIS 2+ rib fracture, versus crash severity

2.3 UMTRI Analysis of Abdominal Injury Patterns in CIREN Database

2.3.1 Overview

The CIREN database was downloaded in August 2005. All occupants with an AIS 2+ abdomen injury were included. Pregnant occupants and those under age 16 were excluded, as were those involving a rollover. The remaining 526 cases were analyzed. Throughout this report, this dataset will be referred to as the CIREN Abdomen-Injured Occupants (AIO). Figure 40 through Figure 53 show the distribution of these occupants by various factors. The crash severity distribution of Figure 40 shows cases with calculated delta V in red, and estimated crash severity in blue. The majority of the CIREN AIO are in crashes of moderate-to-severe severity.

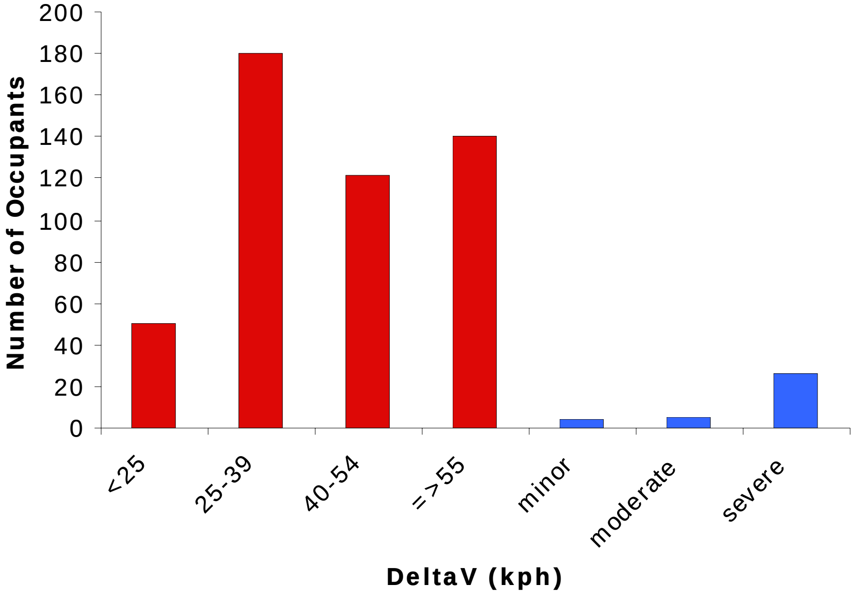


Figure 40. Distribution of CIREN AIO by crash severity

The distribution of CIREN AIO by vehicle model year is shown in Figure 41. Although the emphasis in CIREN is on later-model vehicle years, there are quite a few occupants who sustained abdomen injuries in crashes to older vehicles.

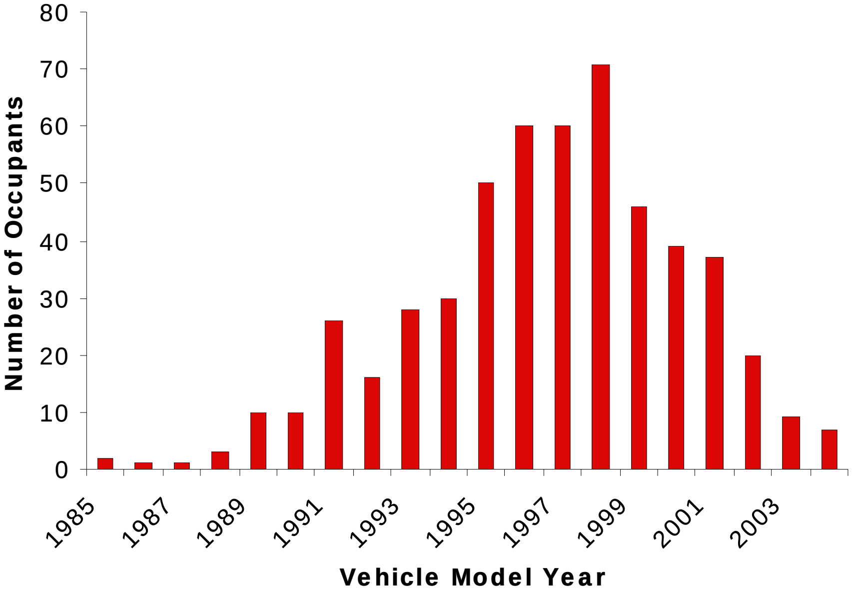


Figure 41. Distribution of CIREN AIO by vehicle model year

Figure 42 shows the distribution of the CIREN AIO by crash type. Over half are involved in frontal impacts. The low frequency of far-side impacts partly results from excluding these types of crashes during some CIREN data collection years. The distribution of CIREN AIO by occupant position is shown in Figure 43. The distribution of occupants is close to the 80%-20% distribution of drivers/right-front passengers seen in NASS.

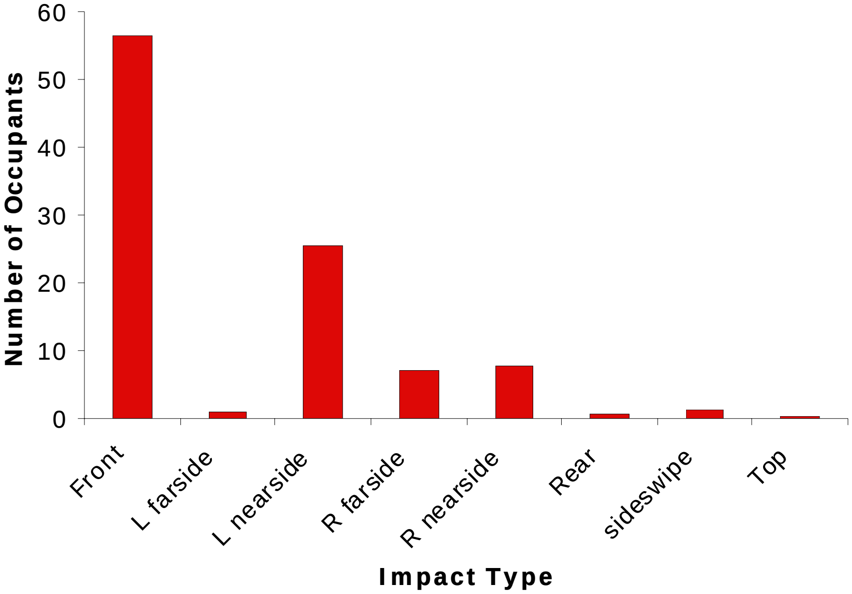


Figure 42. Distribution of occupants by impact type

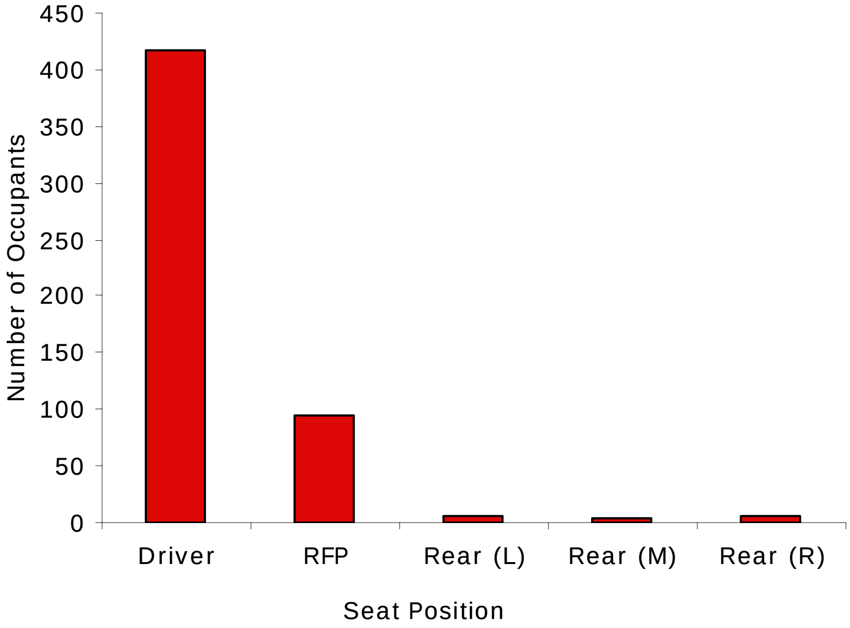


Figure 43. Distribution of occupants by seating position

Figure 44 through Figure 46 illustrate the restraints used by CIREN AIO. Figure 44 shows the distribution by belt type. Approximately half of these occupants used lap/shoulder belts, about 10% used shoulder belt only, and about 40% used no belt. Figure 45 shows the distribution by airbag type. All different combinations of airbags are shown, and grouped into categories of no airbag, frontal-impact airbag, frontal- and side-impact airbags, and side-impact airbags. Approximately one-third of cases involved no airbag deployment, and almost two-thirds of cases involved frontal airbag deployment. Only a small fraction of cases involved side impact airbags, with or without frontal airbag deployment. Figure 46 shows the distribution of CIREN AIO by combined belt and airbag restraint. On this plot, the different types of frontal-impact and side-impact airbags are grouped together into frontal-impact or side-impact airbags. The combined restraint classifications are grouped into unrestrained, airbag only, other (lap or shoulder belt only or shoulder belt + airbag), and lap/shoulder belt, with or without airbag deployment. The majority of cases were restrained by 3-point-belt and frontal airbag, 3-point-belt, or frontal airbag only.

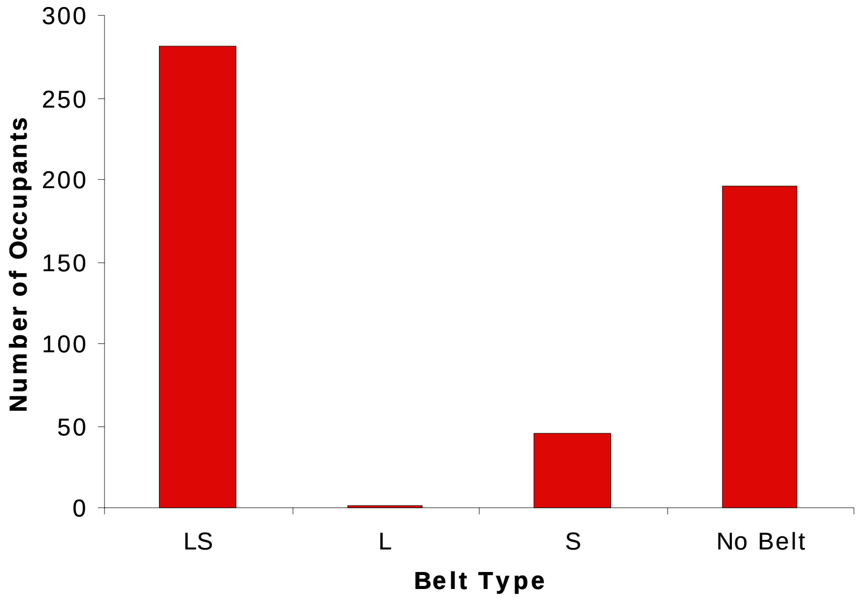


Figure 44. Distribution of occupants by belt type

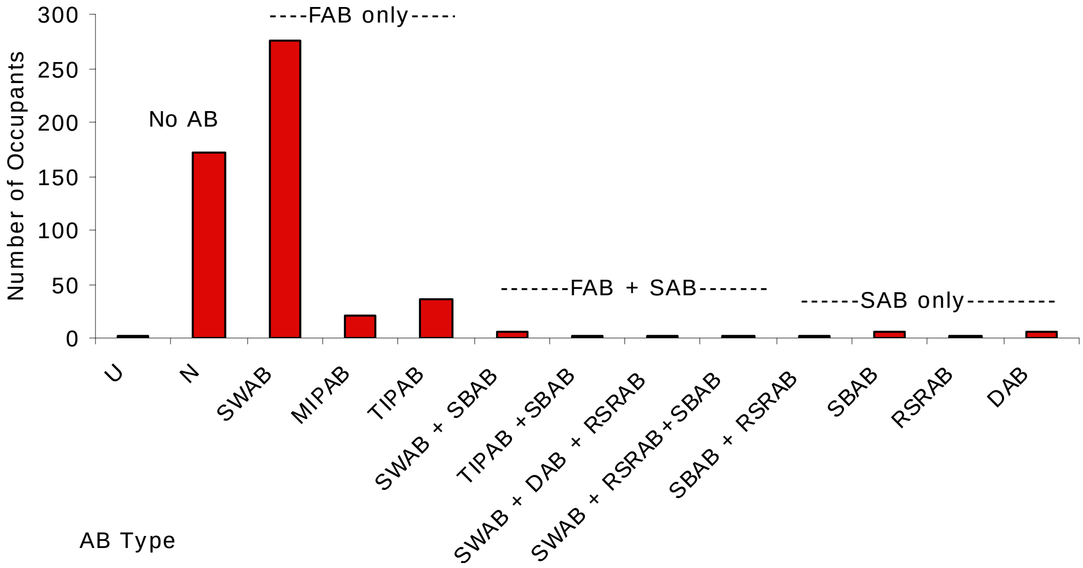


Figure 45. Distribution of occupants by airbag type. AB=airbag, F=frontal-impact, S=side impact, SW=steering wheel, MIP=mid instrument panel, TIP=top instrument panel, SB=seatback, D=door, RSR=roof siderail

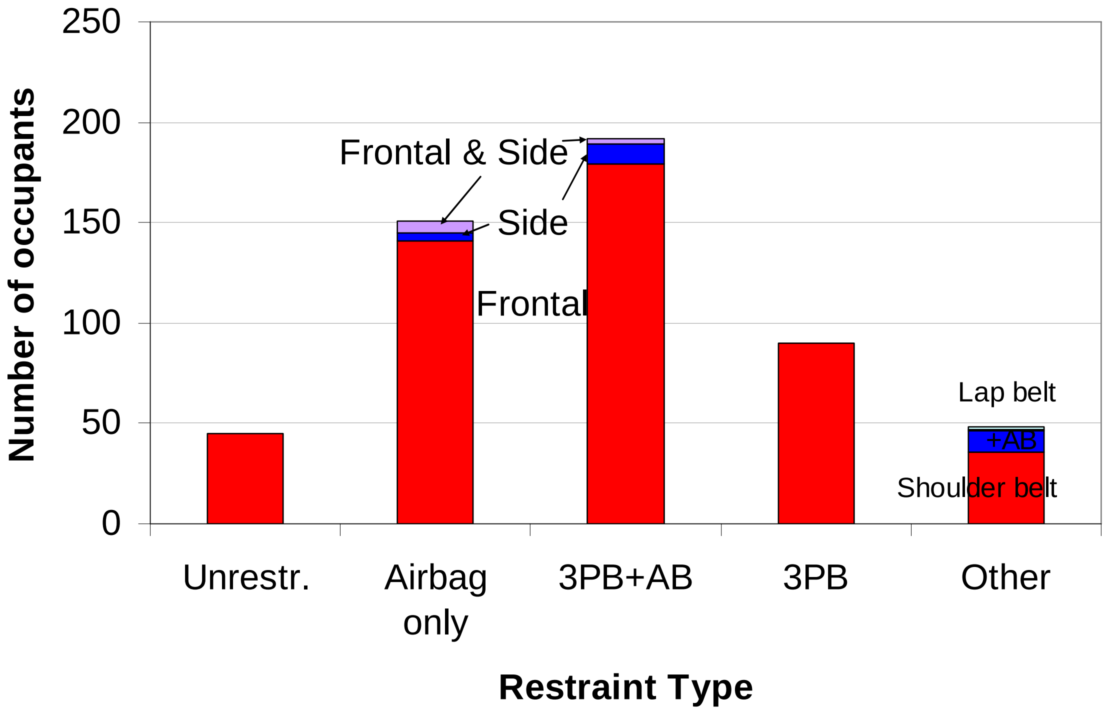


Figure 46. Distribution of occupants by combined belt/airbag restraint

The distribution of CIREN AIO by occupant characteristics are shown in Figure 47 through Figure 49. The occupants are almost equally distributed by gender, and approximately normally distributed by statures. The dataset includes relatively few people in the lowest weight category, while it includes a substantial number weighing over 235 pounds.

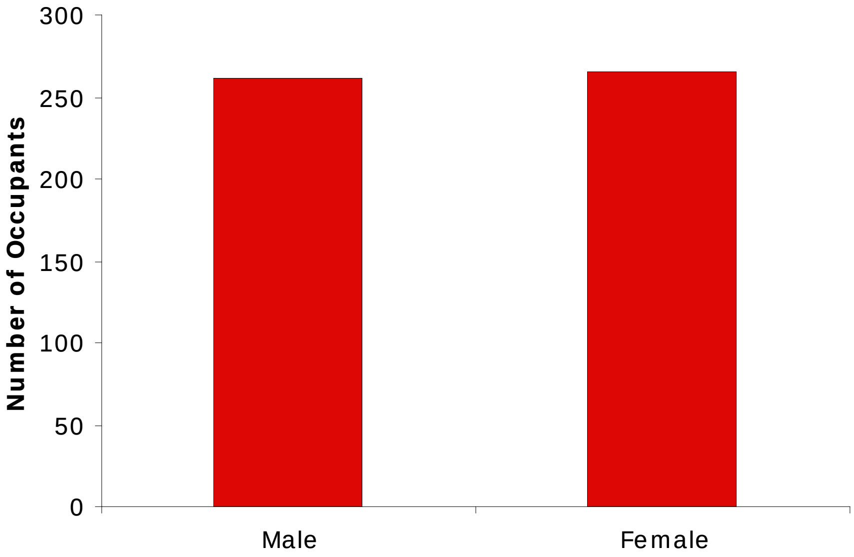


Figure 47. Occupants by gender.

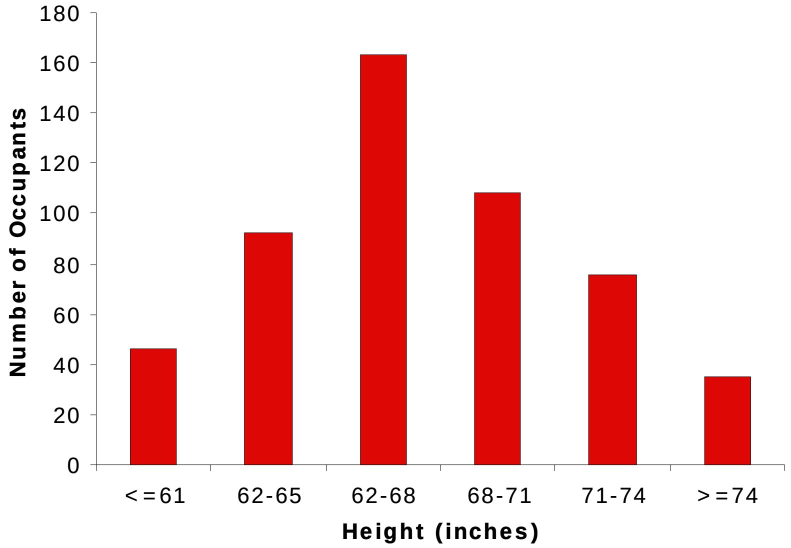


Figure 48. Occupants by stature group

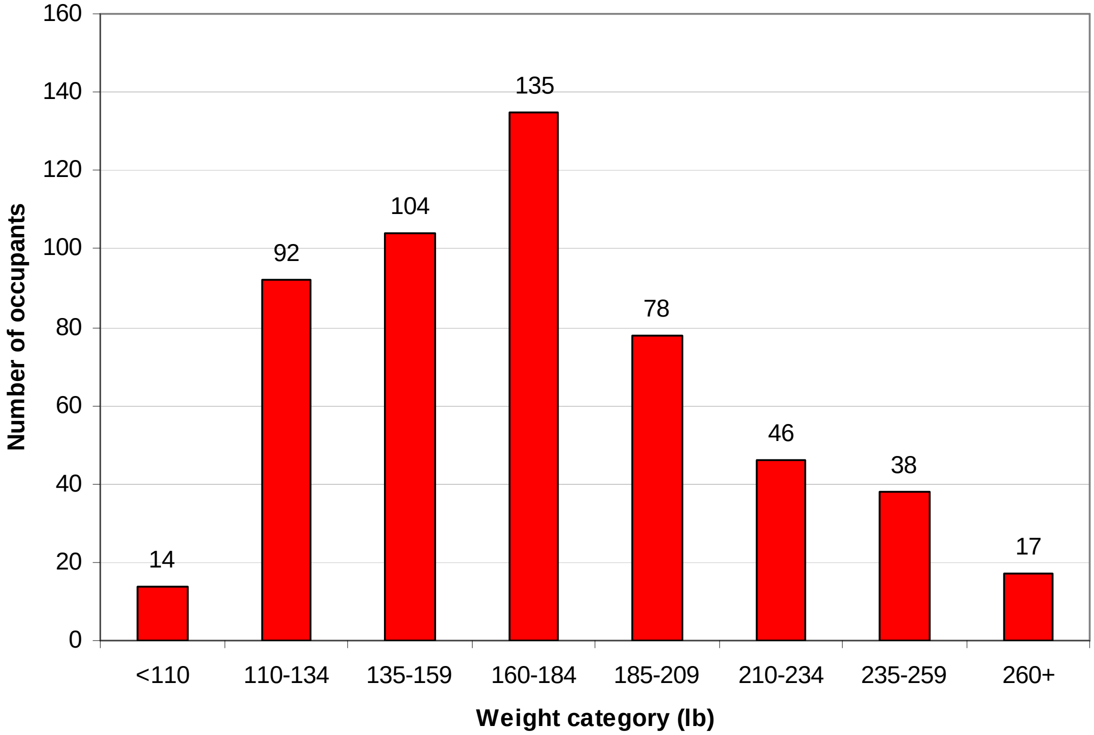


Figure 49. Occupants by weight group

The next series of plots describes information about the injuries sustained by the CIREN AIO. Figure 50 shows the distribution of occupants according to the total number of injuries they sustained, including AIS 1 injuries. Most occupants sustained 3 to 9 coded injuries, although there are some occupants with over 20 coded injuries. Figure 51 shows the percentage of occupants with injuries to different abdominal organs. About half of occupants sustained injuries to the liver and/or spleen, about 15% sustained kidney injuries, and approximately one-third sustained other abdominal organ injuries. (More details on the abdomen injuries are included in the following section.) The percentage of occupants with other key types of AIS 2+ injuries is shown in Figure 52. Almost three-quarters of the CIREN AIO sustained thoracic injuries, including over half with rib fractures. Half of the CIREN AIO sustained head injuries, while almost 40% sustained pelvis fractures. Figure 53 shows the distribution of occupants by their overall MAIS score, as well as their MAIS for the abdomen region. Comparison of the MAIS 2 levels shows that about one-third of the CIREN AIO had a more serious injury to another body region.

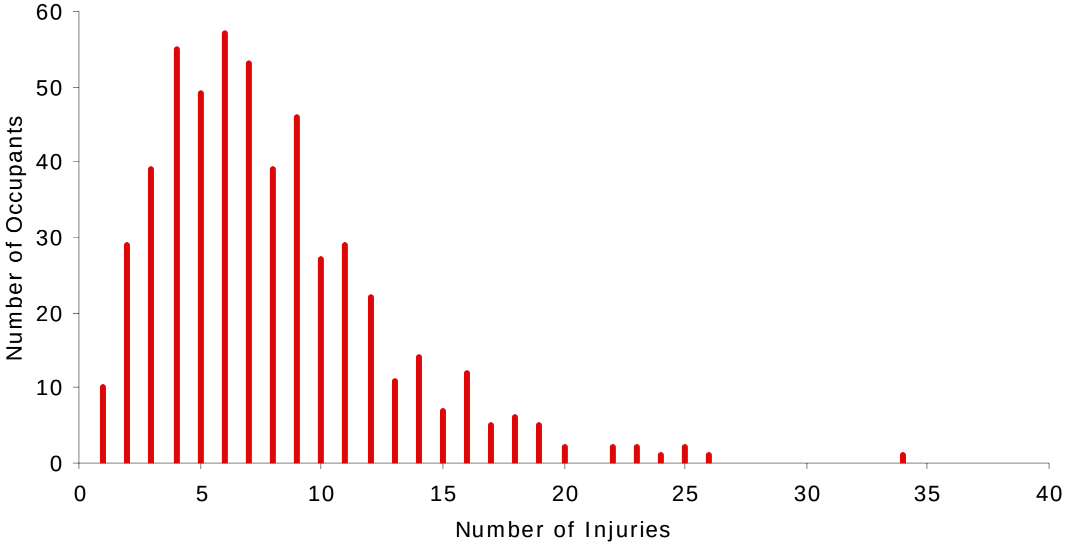


Figure 50. Occupants by total number of injuries

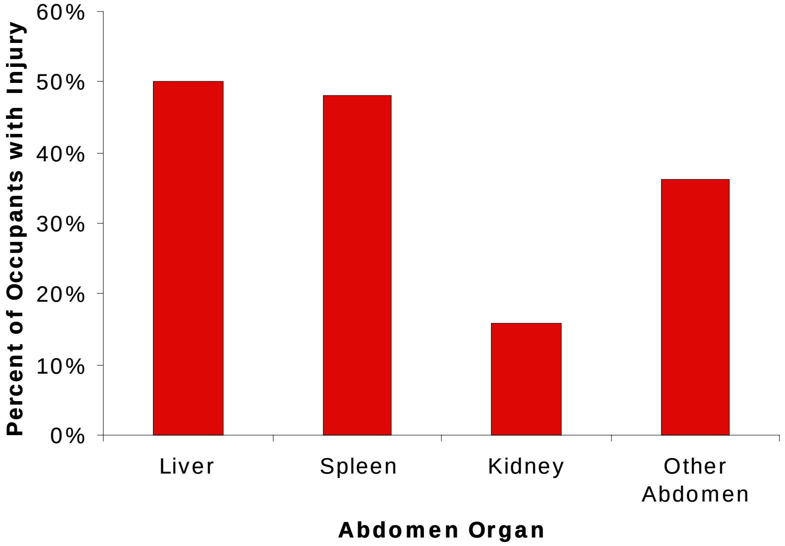


Figure 51. Percentage of occupants with injuries to each abdomen organ

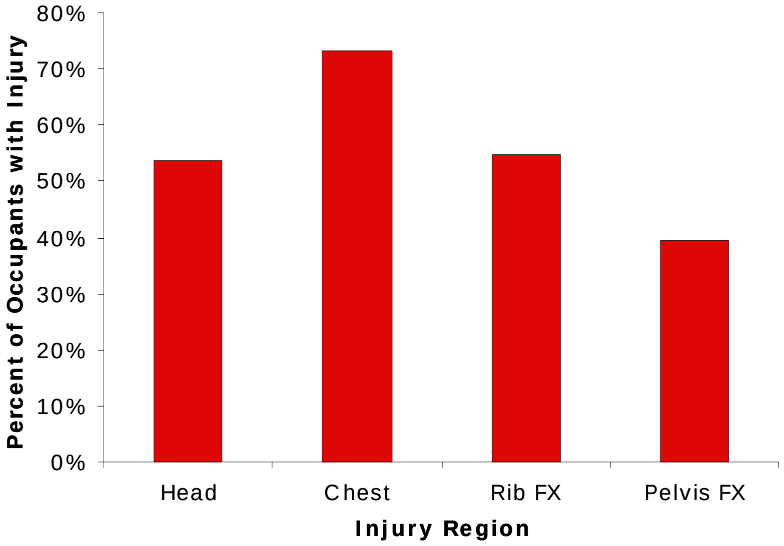


Figure 52. Percentage of occupants sustaining other types of injuries

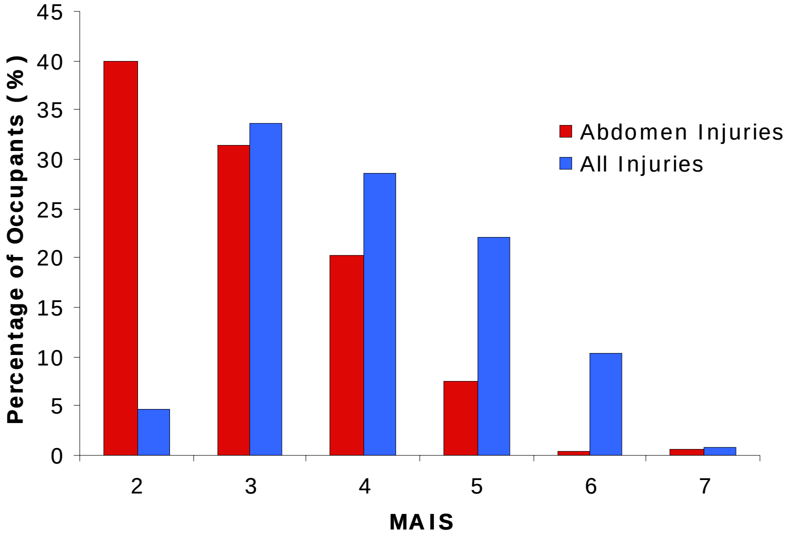


Figure 53. Distribution of occupants by overall MAIS and abdomen MAIS

2.3.2 Types of injuries

The 526 occupants in the dataset sustained a total of 1,663 AIS 2+ abdominal injuries. This section describes the types of injuries sustained by drivers and right-front passengers according to impact type.

There were 245 drivers involved in frontal impacts. 63% of these drivers sustained only one abdominal injury. The distribution of organs injured for these 154 drivers is shown in Figure 54.

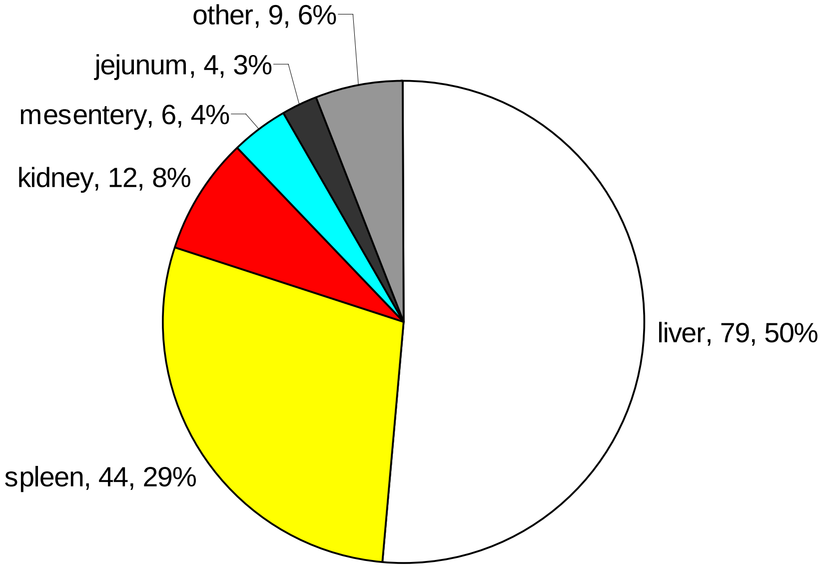


Figure 54. Distribution of organs injured for drivers in frontal impacts sustaining a single abdomen injury among CIREN AIO

Table 10 shows the abdominal organ injured for drivers in frontal impacts with multiple abdominal injuries. 58 of the 245 drivers (24%) sustained two abdominal injuries; 51 of these were to the liver and/or spleen.

Table 10. Organs injured in drivers in frontal impacts with multiple abdominal injuries among CIREN-AIO

	BloodVessel	Bladder	Colon	Gallbladder	Sum of Jejunum-Ileum	Mesentery	Pancreas	Stomach	Liver	Spleen	Kidney	Total
BloodVessel		1				2			5	1		9
Bladder	1											1
Colon					1	3			1			5
Gallbladder									1			1
Jejunum-Ileum			1						2	1		4
Mesentery	2		3						2	2		9
Pancreas									2	2		4
Stomach									1			1
Liver	5		1	1	2	2	2	1		23	7	44
Spleen	1				1	2	2		23		1	30
Kidney									7	1		8
Total	9	1	5	1	4	9	4	1	44	30	8	116

There were 50 right-front passengers involved in frontal impacts that sustained abdominal injury. Thirty-four of them (68%) sustained only one abdominal injury. The distribution of their abdominal organs injured is shown in Figure 55.

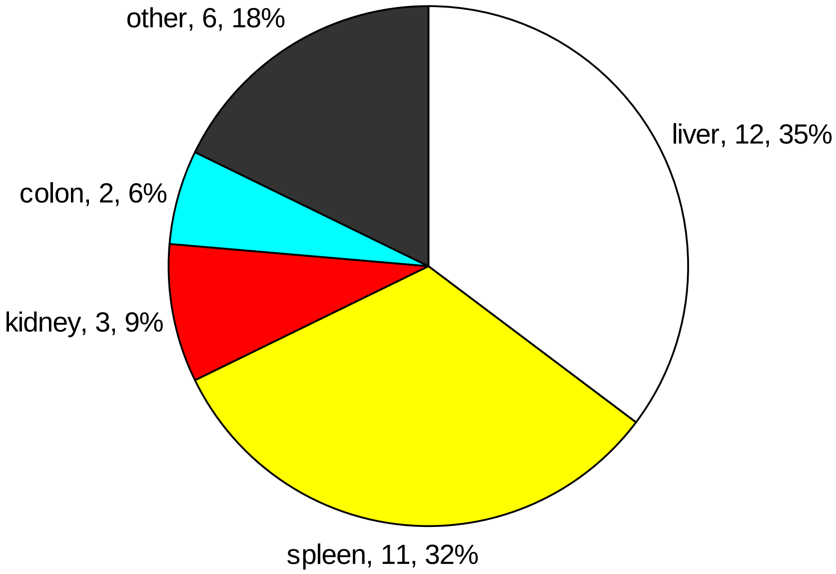


Figure 55. Distribution of organs injured for right-front passengers in frontal impacts sustaining a single abdomen injury among CIREN-AIO

Table 11 shows the distribution of organs injured for right-front passengers in frontal impacts with multiple abdomen injuries. Nine right-front passengers (18%) had two abdominal injuries, while eight had injuries to the liver and/or spleen.

Table 11. Organs injured in right-front passengers in frontal impacts with multiple abdominal injuries among CIREN-AIO

	BloodVessel	Duodenum	Mesentery	Pancreas	Liver	Spleen	Kidney	Total
BloodVessel					1			1
Duodenum			1					1
Mesentery		1						1
Pancreas					1			1
Liver	1			1		4		6
Spleen					4		2	6
Kidney						2		2
Total	1	1	1	1	6	6	2	

This dataset had 136 drivers with abdominal injuries involved in left-side impacts. Eight-one of them (60%) had only one abdominal injury. The distribution of their abdomen organ injured is shown in Figure 56.

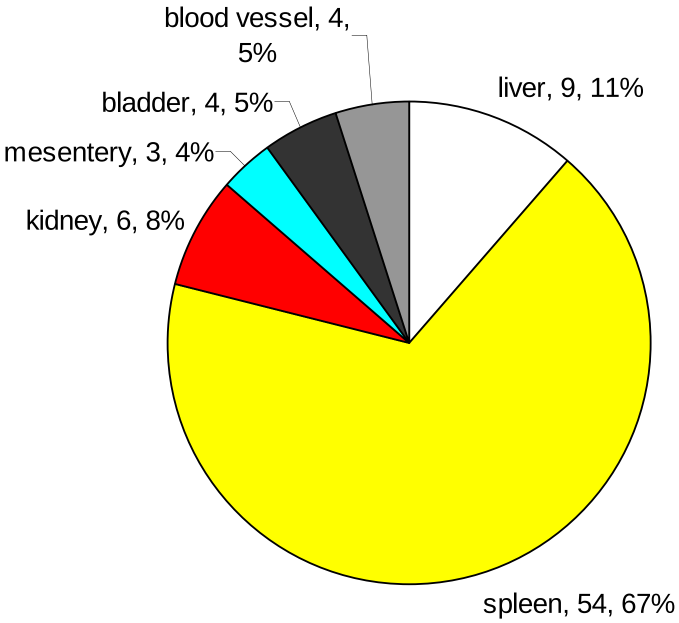


Figure 56. Distribution of organs injured for drivers in left-side impacts sustaining a single abdomen injury among CIREN-AIO

Table 12 shows the distribution of organs injured for drivers with multiple abdomen injuries sustained in left-side impacts. Thirty-two of these drivers had only two injuries, and all of them sustained injury to the spleen, liver, and/or kidney.

Table 12. Organs injured in drivers in left-side impacts with multiple abdominal injuries

	BloodVessel	Adrenal	Bladder	Colon	Pancreas	Liver	Spleen	Kidney	Total
BloodVessel							1	1	2
Adrenal						2	2		4
Bladder						1		1	2
Colon							1		1
Pancreas						1	1		2
Liver		2	1		1		12		16
Spleen	1	2		1	1	12		9	26
Kidney	1		1				9		11
Total	2	4	2	1	2	16	26	11	64

Thirty-eight occupants were involved in right-side impacts while seated in the right-front passenger seat. Eighteen of them sustained only one abdominal injury, and the distribution of their organs injured is shown in Figure 57.

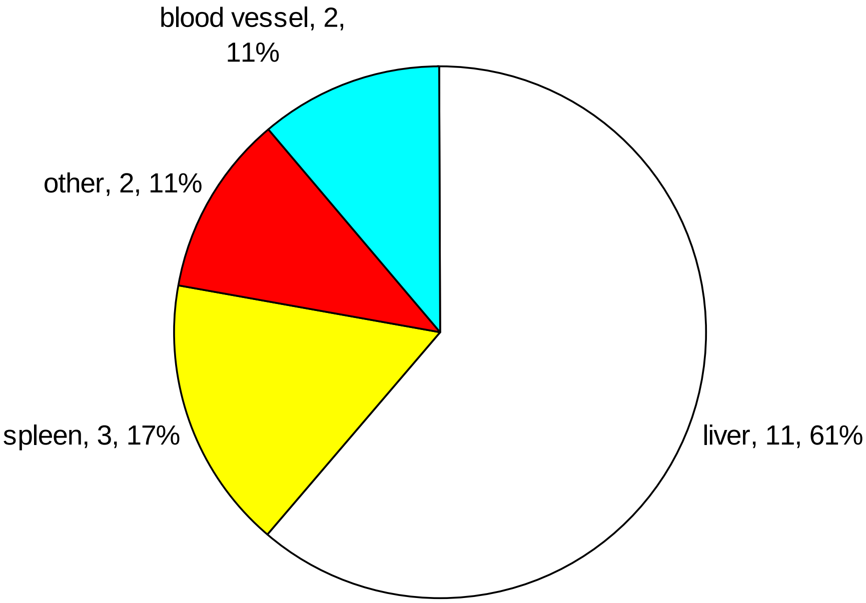


Figure 57. Distribution of organs injured for right-front passengers in right-side impacts sustaining a single abdomen injury among CIREN-AIO

Table 13 shows the distribution of right-front passengers with multiple abdominal injuries sustained in right-side impacts according to the organs injured. Nine of these occupants had two injuries, all to the liver and/or spleen.

Table 13. Organs injured in right-front passengers in right-side impacts with multiple abdominal injuries among CIREN-AIO

	BloodVessel	Adrenal	Liver	Spleen	Kidney	Total
BloodVessel			1	1		2
Adrenal			2			2
Liver	1	2		4	1	8
Spleen	1		4			5
Kidney			1			1
Total	2	2	8	5	1	

2.3.3 Statistical analysis of abdominal injury patterns in CIREN

Occupants were classified into four categories based on the type of abdominal injuries sustained: spleen, liver, liver and spleen, and neither liver nor spleen. Chi-squared analysis was performed using the independent variables listed in Table 14. Analysis was first performed on all occupants, and then repeated for front impacts and side impacts. P-values for each analysis are also listed in Table 14, with significant quantities highlighted.

Table 14. P-values for chi-squared analysis of abdominal injury type by vehicle, crash, occupant, restraint, and injury variables

Variable		p-value		
Type	Name	All impacts	Front impacts	Side impacts
Vehicle	Vehicle type	.264	4.95	.513
	Vehicle model year	.955	.230	.510
Crash	Delta V	.278	.490	.561
	PDOF category	.000	.469	.000
	Impact type	.000	NA	.000
Occupant	Age category	.409	.220	.896
	Stature category	.011	.434	.065
	Weight category	.723	.80	.604
	Gender	.281	.632	.795
	Position	.682	.236	.018
Restraint	Airbag type	.217	.751	.411
	Belt type	.096	.119	.568
	Side airbag deployment	.117	.407	.448
	Seatback airbag deployment	.090	.696	.167
	Combined restraint	.030	.322	.282
	Optimally restrained	.005	.083	.328
Injury	Head injury	.220	.479	.531
	Chest injury	.000	.019	.028
	Rib fracture	.016	.036	.069
	Pelvis fracture	.016	.104	.817

Figure 58 through Figure 60 show the variation in PDOF for occupants classified according to their abdomen injuries (spleen only, liver only, spleen and liver, and other). Figure 58 shows the distribution for all four categories, while Figure 59 shows liver-only and spleen-only to more clearly show the effect of PDOF on organ location. Incidence of liver only-injury is highest in frontal crashes, followed with those with PDOF towards the right. Incidence of spleen injury is highest in frontal crashes, followed by left-side crashes, then left-corner crashes. Occupants sustaining both liver and spleen injuries were primarily in frontal impacts, with the frequency in left and right impacts similar. The same is true for occupants who sustained injury to abdomen organs other than the liver or spleen. Figure 60 repeats the information in Figure 58, but presents it as a percentage of occupants in each PDOF direction by each abdomen-injury grouping. Viewing the results in this manner more clearly shows the “sidedness” of spleen-only and liver-only cases, a fairly even distribution of both spleen and liver cases, and a slight trend for other abdomen injuries to occur in crashes with PDOF from the right rather than the left.

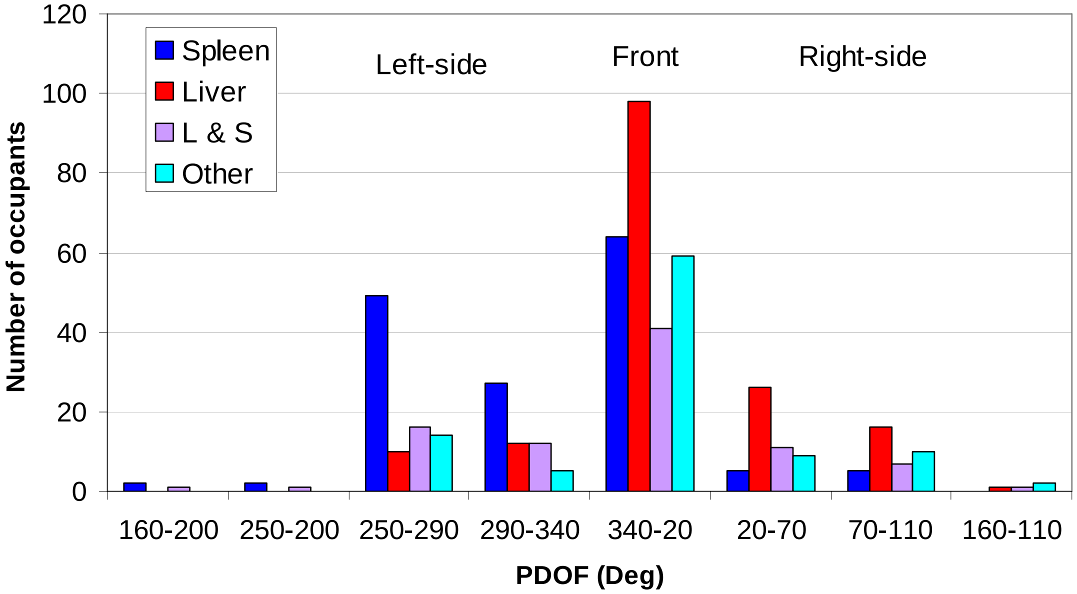


Figure 58. Distribution of CIREN-AIO by PDOF and abdomen injury classification (spleen, liver, liver and spleen, or other)

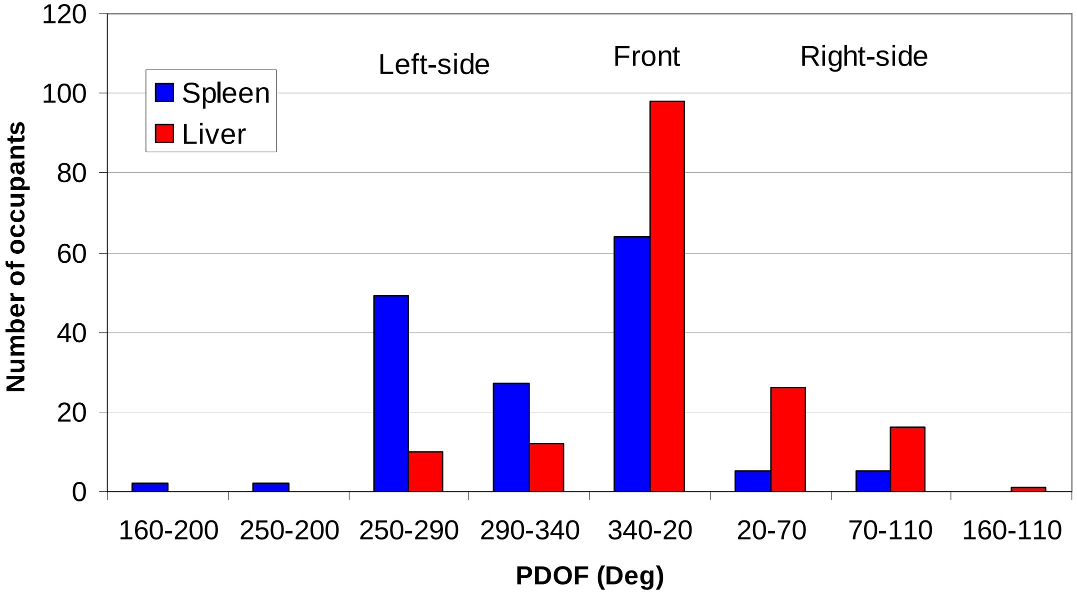


Figure 59. Distribution of CIREN-AIO by PDOF for spleen-injury-only and liver-injury-only occupants

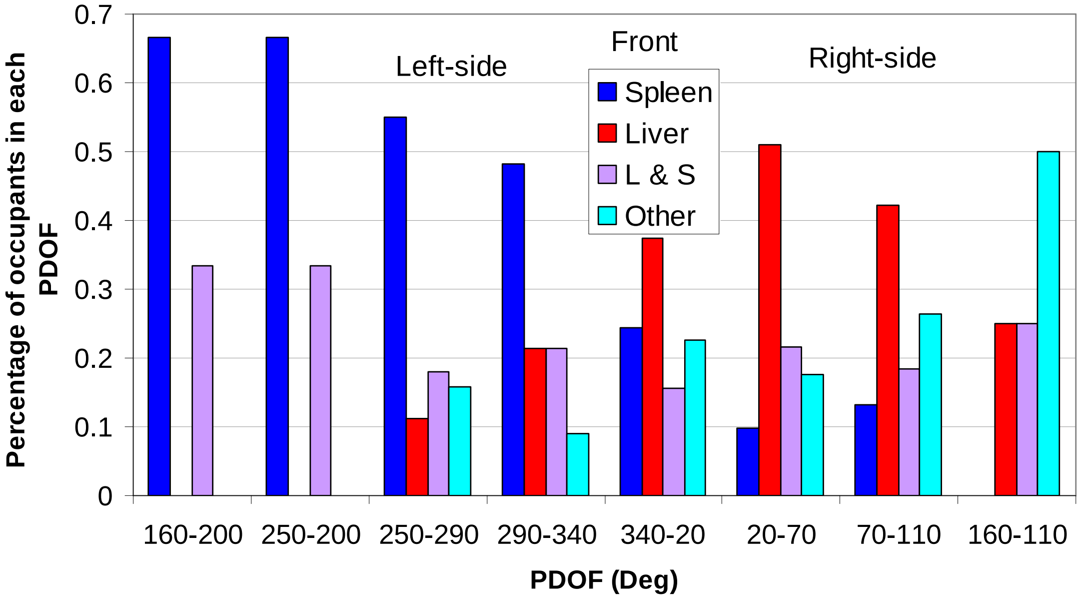


Figure 60. Proportion of CIREN-AIO in each PDOF for each abdomen injury classification (spleen, liver, liver and spleen, or other)

When analyzing the CIREN-AIO injury patterns relative to occupant variables, only stature was significant. When analyzing frontal and side impacts separately it was only marginally significant (p=0.065) for side impacts. When reviewing the trends with stature, subjects in the 5’1”-5’4” stature group sustained both liver and spleen injuries in side impact more frequently than expected statistically. This may have some implications with respect to how the abdominal organs are positioned relative to door components for occupants of these statures. For the analysis of the CIREN-AIO using restraint variables, some predictors were significant when all cases were considered, but none were when frontal and side impacts were assessed separately.

When assessing possible relationships between abdomen injuries and the presence of other types of injuries, the presence of rib fractures and thoracic injuries was statistically significant for both frontal and side impacts. Cases without rib fracture had more other abdomen injuries than expected, while cases with rib fracture had more spleen and liver injuries than expected. These patterns seem reasonable, as cases without rib fracture may be more likely to have loading at a region below the liver and spleen, injuring other abdomen organs. Cases with loading severe enough to have rib fracture would also seem most likely to have injurious loading to both the liver and spleen. The same trends are seen when using any thoracic injury as a predictor, since many thoracic injuries are rib fractures.

2.3.4 Abdominal injury sources in frontal impacts in CIREN

This section investigates the contact points of liver and spleen injuries sustained by drivers and right-front passengers in frontal collisions. The analysis looks at drivers and right-front passengers separately, and analyzes contact points for those with liver, those with spleen, and those with liver and spleen injuries. Occupants with both liver and spleen injuries were included in the analysis three separate times: in the liver group, in the spleen group, and in the liver plus spleen group. For each type of occupant and injury, contact points are examined as a function of restraint use: unrestrained (No Belt + No AB), three-point belt only (LS + No AB), frontal airbag only (No Belt + FAB), and three-point belt plus frontal airbag (LS + FAB). Any occupants not falling into one of the four restraint categories were excluded.

Table 15 summarizes the contact points for all liver-injured drivers in frontal impacts. The first number in each cell is the number of occupants with liver injuries, while the three numbers in parentheses afterwards indicate the number with liver contusions, lacerations, and ruptures. The most common injury sources are highlighted. Liver injuries to drivers in frontal impacts are most commonly attributed to contact with the steering wheel. The exception to this was drivers restrained by both the 3-point belt system and a frontal airbag (LS + FAB). Two-thirds of the liver injuries to these drivers were attributed to the belt while a third were to the steering wheel.

Table 15. Number of drivers in front impacts with liver injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (driver's)		2 (0/2/0)		1 (1/0/0)
Belt			1 (0/1/0)	32 (5/28/0)
Center		1 (0/1/0)		
IP		3 (0/3/0)		1 (0/1/0)
Other		2 (0/1/0)		
Other Occupant		1 (0/1/0)		
Seat				
Side Interior		1 (0/1/0)		1 (0/1/0)
SW	5 (1/5/0)	51 (8/44/0)	3 (0/3/0)	15 (2/13/0)
Total	5 (1/5/0)	61 (9/53/0)	4 (0/4/0)	50 (8/43/0)

Total n (n contusions, n lacerations, n ruptures)

Table 16 summarizes the mean ΔV for all groups and also lists the number of drivers in each group. Results include estimated ΔV; mean values did not change more than 1 km/hr when the cases with estimated ΔV were excluded. Since the only occupants with more than one significant source of injury were the LS + FAB drivers, statistical analysis comparing the ΔV and PDOF characteristics of the belt injured and steering wheel injured occupants was limited to occupants in the LS + FAB group. The mean ΔV for the belt-injured drivers in this group is 53 km/hr while the mean ΔV for the steering wheel-injured drivers is 64 km/hr. Using a single variable Anova test for variance, there is no significant difference between these mean ΔV (p-0.129), although the variances within each of the two groups were rather large. The distribution of drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags according to delta-V for each liver-injury contact point is shown in Figure 61, reflecting the lack of significant difference in ΔV for occupants with different contact points.

Table 16. Mean ΔV of drivers (km/hr) with liver injury by contact point and restraint use

TOTALDELTAV ΔVnum	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (driver's)		48.5 (n=2)		38 (n=1)
Belt			29 (n=1)	51.04 (n=32)
Center		74 (n=1)		
IP		53 (n=3)		72 (n=1)
Other		60 (n=2)		
Other Occupant		66 (n=1)		
Seat				
Side Interior		86 (n=1)		11 (n=1)
SW	71.8 (n=5)	57.08 (n=51)	38.33 (n=3)	62.20 (n=15)
Total	71.8 (n=8)	57.58 (n=61)	36 (n=4)	53.98 (n=50)

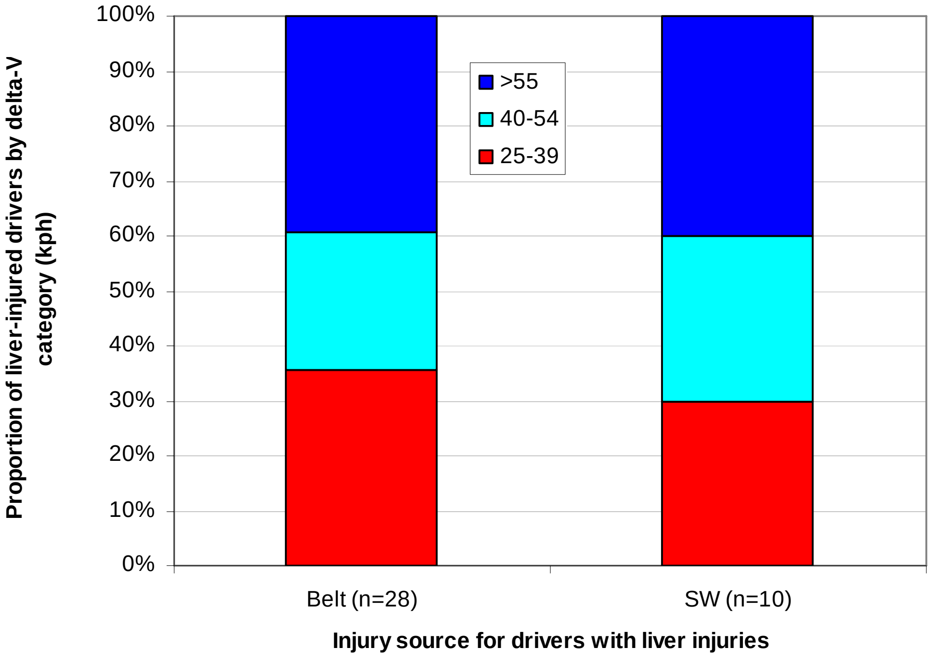


Figure 61. Proportion of liver-injured drivers, restrained by lap/shoulder belts and frontal airbags, by delta-V category for each liver-injury contact point

The proportion of drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags by PDOF for each liver-injury source is shown in Figure 62. The proportion of occupants at the 360 degree PDOF is similar. The occupants whose liver injuries were attributed to the steering wheel had no PDOF to the left. The range of PDOF is wider for the liver-injured drivers with the belt coded as the source compared to the steering wheel.

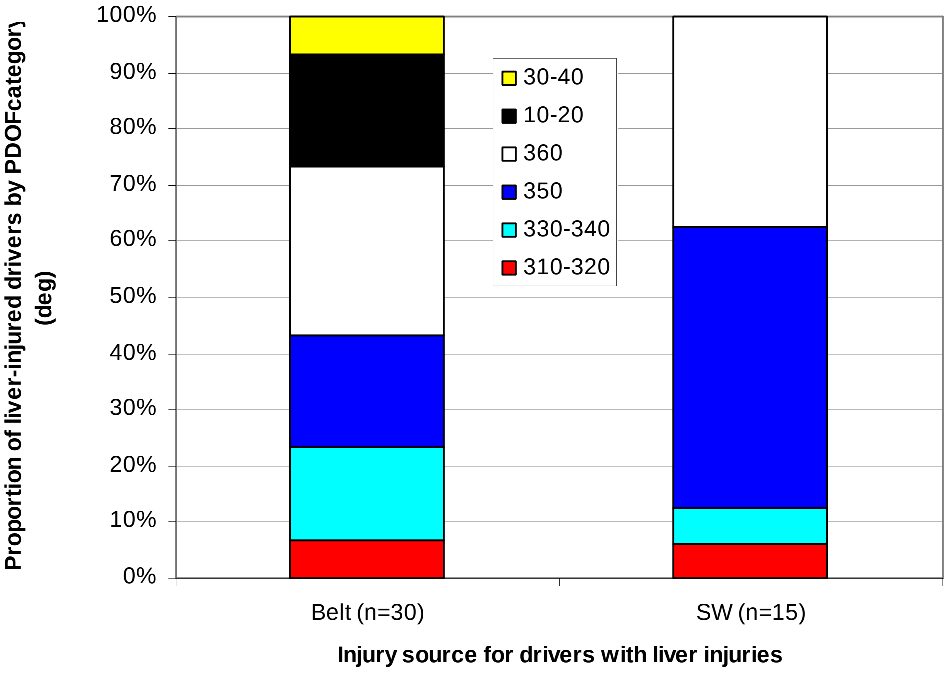


Figure 62. Proportion of liver-injured drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags by PDOF for each liver-injury contact point

Table 17 lists the number of drivers in frontal impacts according to spleen injury source and restraint type. In each cell, the number indicates the total number of drivers with spleen injuries, while the numbers in parentheses in each cell indicate the number with spleen contusions, lacerations, and ruptures. The most frequent injury sources for each restraint type are highlighted. The steering wheel is the most common contact point for spleen injuries to drivers in frontal impacts. Unlike liver injuries, two restraint groups had another frequently cited spleen-injury contact point. For drivers restrained only by frontal airbags, the steering wheel was the primary contact point, while the side interior accounted for almost one-third of the spleen injuries. For drivers in the LS + FAB group, injury contact points were almost evenly distributed between the belt, the left side interior and the steering wheel.

Table 17. Number of drivers in front impacts with spleen injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (driver's)		2 (0/2/0)		
Belt				10 (3/7/0)
Center				
IP		1 (0/1/0)		
Other		2 (1/1/0)		2 (0/2/0)
Other Occupant				
Seat				1 (0/1/0)
Side Interior*		10 (1/9/0)	1 (0/1/0)	12 (3/8/1)
SW	4 (0/4/0)	25 (5/20/0)	2 (0/2/0)	13 (0/13/1)
Total	4 (0/4/0)	40 (7/33/0)	3 (0/3/0)	38 (6/31/1)

Table 18 lists the mean ΔV for frontal impacts with drivers for each spleen-injury source/occupant restraint category. The number of drivers in each category is also listed. Differences in mean ΔV ranged from 0 to 10 km/hr when estimated ΔV values were excluded. For the LS + FAB group, the mean ΔV for belt-injured, side interior-injured and steering wheel-injured drivers are 51 km/hr, 37 km/hr, and 57 km/hr, respectively. As determined by a single-factor Anova test for variance, these values are not statistically different (p=0.34). The mean ΔV for the side-interior-injured (49 km/hr) and the steering-wheel-injured (53 km/hr) drivers restrained by only a frontal airbag were also statistically the same (p=0.578)

Table 18. Mean ΔV (km/hr) of drivers in frontal impact with spleen injury by contact point and restraint use

TOTALDELTAV ΔVnum	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (driver's)		52 (n=2)		
Belt				51.13 (n=10)
Center				
IP		43 (n=1)		
Other				52 (n=2)
Other Occupant				
Seat				55 (n=1)
Side Interior		48.56 (n=10)	79 (n=1)	37 (n=12)
SW	86.67 (n=4)	52.92 (n=25)	25.5 (n=2)	50 (n=13)
Total	86.67 (n=4)	50.84 (n=40)	43.33 (n=3)	47 (n=38)

The proportion of drivers with spleen injuries restrained by only airbags in frontal impacts for each ΔV category and spleen injury contact is shown in Figure 63. The proportion at the highest ΔV category is the same for both injury contact sources, while the distribution among the three remaining categories is more variable for those whose spleen injury was attributed to the steering wheel. The distribution by ΔV category for spleen-injured drivers restrained by lap/shoulder belts and frontal airbags is in Figure 64 for each injury source. The distributions are more similar for the steering wheel and belt contact sources compared to the side interior source.

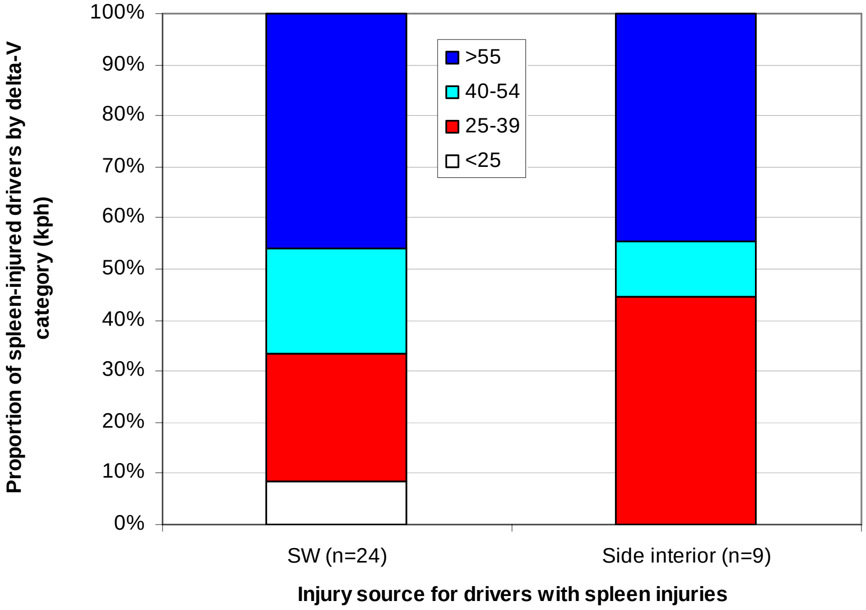


Figure 63. Proportion of spleen-injured drivers in frontal impacts restrained by frontal airbags in each ΔV category by spleen-injury contact point

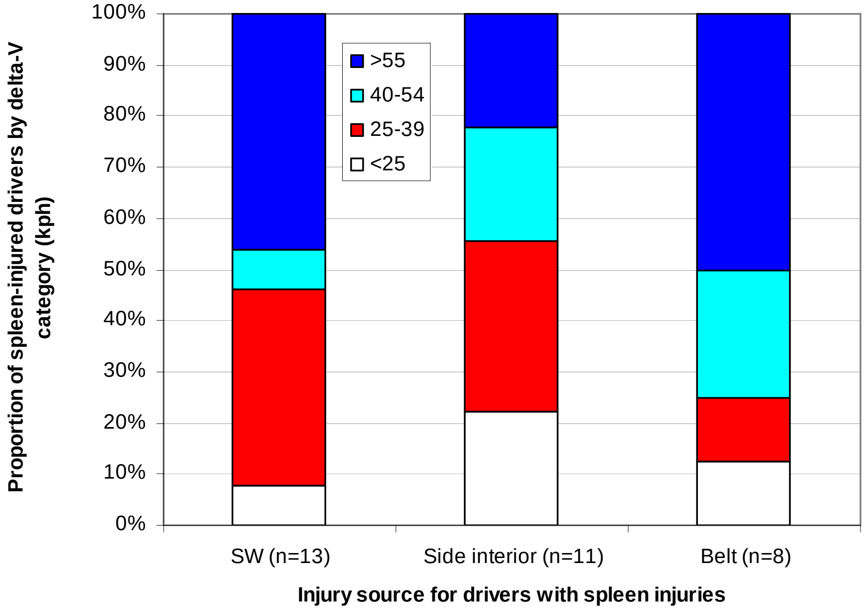


Figure 64. Number of drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags by ΔV category and spleen-injury contact point

Figure 65 and Figure 66 show the distribution of spleen-injured drivers in frontal impacts by PDOF and spleen-injury contact point for frontal airbag-restrained and lap/shoulder plus frontal airbag-restrained drivers, respectively. For the airbag-only restrained drivers, a clear pattern emerges for injury contact point, with side interior more commonly attributed as the injury source in PDOF toward the left, and steering wheel attributed with PDOF more central and to the right. For the drivers restrained by both airbags and lap/shoulder belts, the belt-induced injuries result from impacts with a left direction of impact (310 – 0 degrees) while the steering wheel-induced injuries result from impacts with a centralized direction of impact (350 – 10 degrees). The side interior-induced injuries are the result of left and center impacts (340 – 10 degrees).

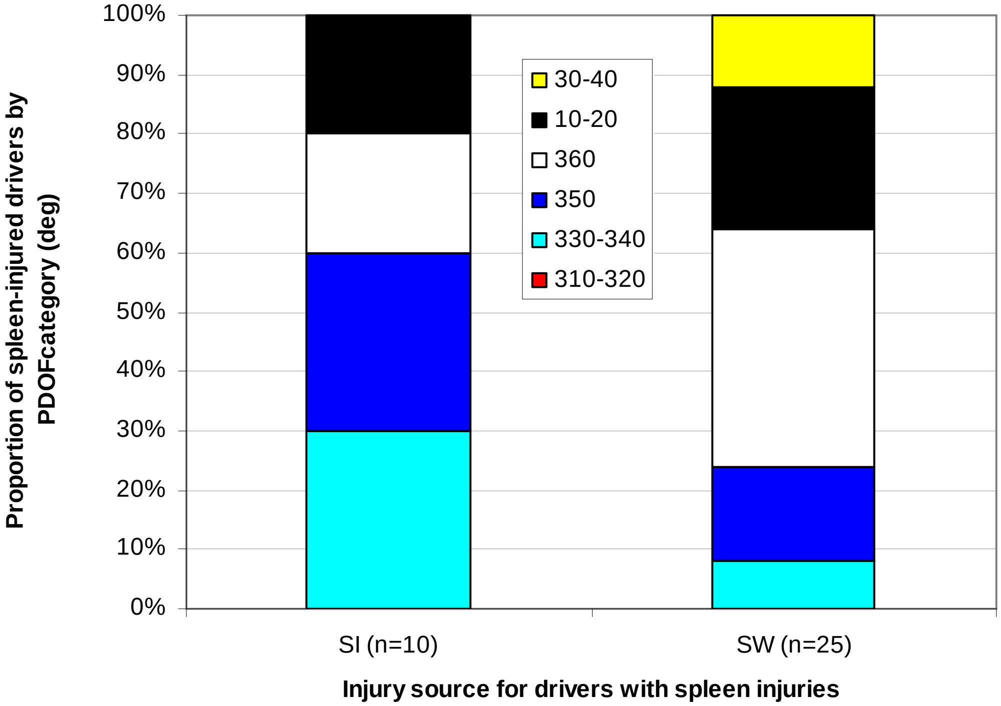


Figure 65. Proportion of spleen-injured drivers in frontal impacts restrained by frontal airbags according to PDOF and spleen-injury contact point

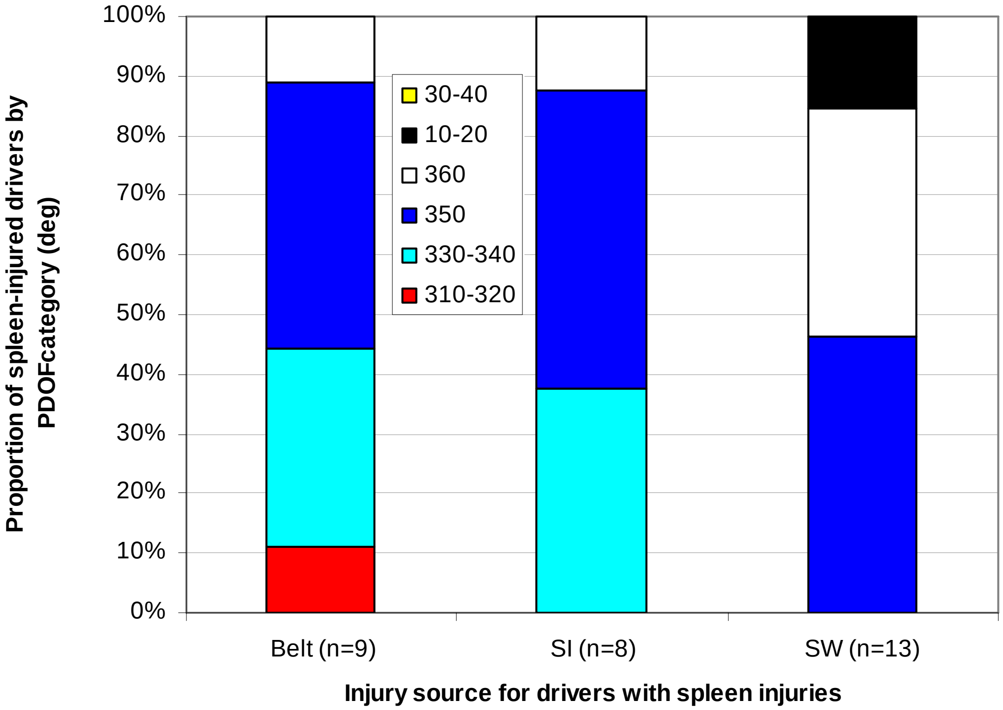


Figure 66. Proportion of spleen-injured drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags according to PDOF and spleen-injury contact point

Table 19 shows the number of drivers with both spleen and liver injury according to injury source and belt restraint. In most cases, the same source was attributed to causing both the liver and spleen injuries. In two cases shown in the last row, the steering wheel was coded as the source of the liver injury and the side interior was coded as the source of the spleen injury. Drivers with concurrent liver and spleen injuries were most often struck by the steering wheel. As with the previous analyses of liver or spleen injuries, a significant number of drivers restrained by the three-point belt system and front airbag were also coded as sustaining injuries from the belt. Figure 67 shows the distribution of drivers in frontal impacts with both liver and spleen injuries by ΔV category and injury source.

Table 19. Number of drivers in front impacts with liver and spleen injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (passenger)		1		
Belt				6
Center				
IP		1		
Other		1		
Other Occupant				
Seat				
Side Interior				
SW	3	13	1	7
Other Combinations (Liver Contact – Spleen Contact)				
SW-Side Interior		1		1
Total	3	17	1	14

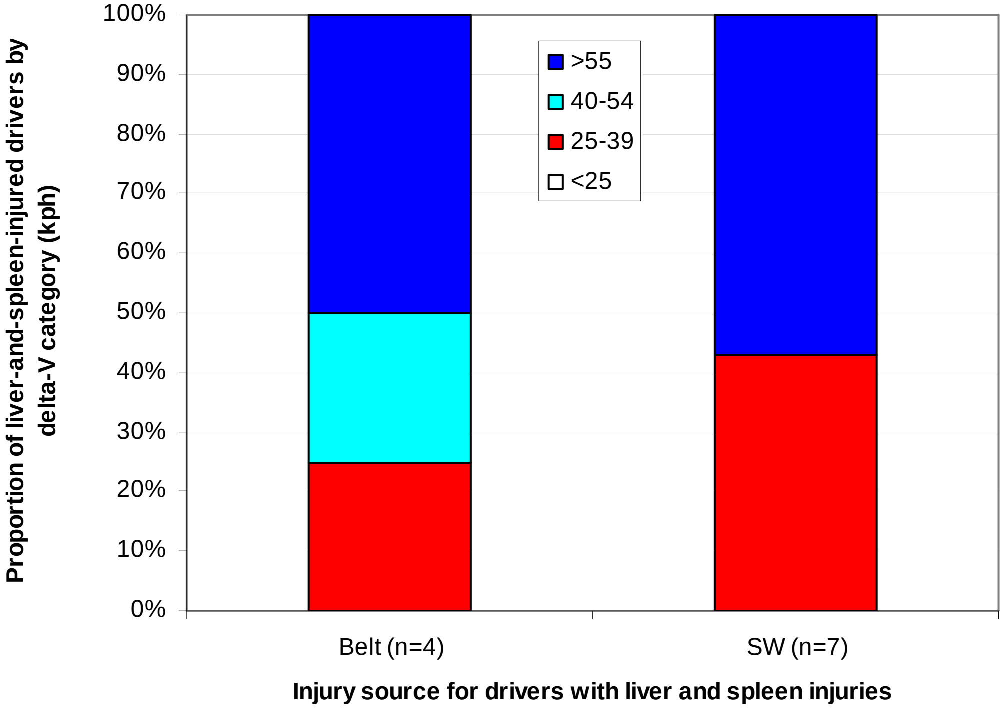


Figure 67. Number of drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags by ΔV category and liver/spleen-injury contact point

Figure 68 shows the distribution of drivers in frontal impacts with both liver and spleen injuries according to PDOF and injury contact source. The PDOF from belt-induced injured occupants were skewed more left while the steering wheel-induced injuries came from more central directions of impact.

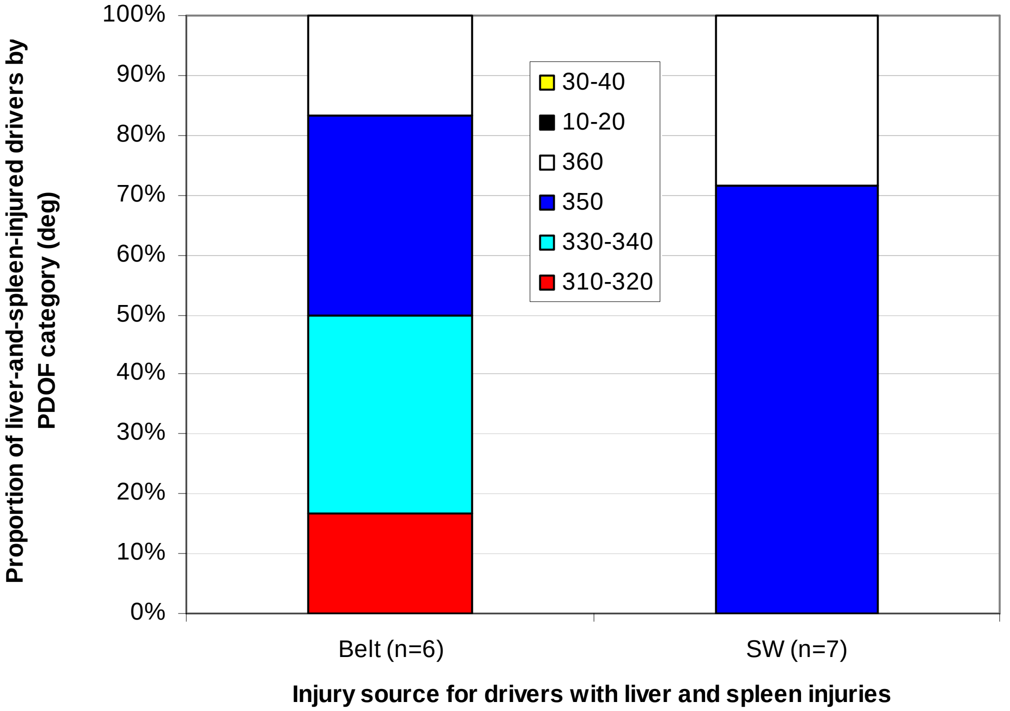


Figure 68. Number of drivers in frontal impacts restrained by lap/shoulder belts and frontal airbags according to PDOF and liver/spleen-injury contact point

Table 20 shows the number of right-front passengers in frontal impacts with liver injury according to coded injury source and restraint type. Results show that belted right-front passengers, with or without a frontal airbag, were most often coded as sustaining their liver injury from the belt. For right-front passengers only restrained by a frontal airbag, sources were evenly distributed among the airbag, the instrument panel and 'other'. None of the seven unrestrained right-front passengers in frontal impacts sustained a liver injury. The small number of right-front passengers with liver injury in frontal impacts prevented meaningful analysis of variations in mean ΔV or PDOF.

Table 20. Number of right-front passengers in front impacts with liver injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (passenger)		2 (0/2/0)		
Belt			2 (0/2/0)	7 (1/6/0)
Center				
IP		3 (1/2/0)		1 (0/1/0)
Other		2 (1/1/0)		
Other Occupant				
Seat				1 (0/1/0)
Side Interior				1 (0/1/0)
SW				
Total	0	7 (2/5/0)	2 (0/2/0)	10 (1/9/0)

Table 21 shows the number of right-front passengers with spleen injury in frontal impacts by coded injury source and restraint type. Only one unrestrained passenger sustained a spleen injury, which was attributed to the instrument panel. Four of the five passengers who were only restrained by the frontal airbag were also coded as being injured by the instrument panel. Only two passengers were restrained solely by 3-point belt. One of their spleen injuries was attributed to the belt, while the other was attributed to the instrument panel. For passengers restrained by the 3-point belt plus a frontal airbag, the primary source of injury was coded as the belt. The small number of right-front passengers with spleen injury in frontal impacts prevented meaningful analysis of variations in mean ΔV or PDOF.

Table 21. Number of right-front passengers in front impacts with spleen injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB				
Belt			1 (1/0/0)	7 (0/7/0)
Center				
IP	1 (0/1/0)	4 (1/3/0)	1 (0/1/0)	
Other		1 (0/1/0)		1 (0/1/0)
Other Occupant				
Seat				
Side Interior				
SW				
Total	1 (0/1/0)	5 (1/4/0)	2 (1/1/0)	8 (0/8/0)

Table 22 shows the number of right-front passengers with both liver and spleen injuries in frontal impacts according to contact point and restraint type. Belted occupants were coded as being injured by the belt, regardless of the airbag presence. One of the two passengers restrained by only an airbag was reportedly injured by the instrument panel, while the second was injured by an ‘other’ object. There were no unrestrained passengers who sustained both a liver and a spleen injury. The small number of right-front passengers with liver and spleen injury in frontal impacts prevented meaningful analysis of variations in mean ΔV or PDOF.

Table 22. Number of right-front passengers in front impacts with liver and spleen injuries according to contact points and restraint use

	No Belt + No AB	No Belt + FAB	LS + No AB	LS + FAB
AB (passenger)				
Belt			1	3
Center				
IP		1		
Other		1		
Other Occupant				
Seat				
Side Interior				
SW				
Other Combinations (Liver Contact – Spleen Contact)				
IP-Belt				1
Total	0	2	1	4

2.3.5 Analysis of steering-wheel contact in frontal impacts in CIREN

These results show that steering wheels continue to be coded as a source of abdomen injury despite increased belt use and the presence of airbags. These results were investigated further by examining the 212 drivers in frontal impact by restraint type and presence or absence of at least one injury attributed to steering-wheel contact as shown in Figure 69. This analysis did not include drivers with restraints other than those listed. Steering-wheel contact included occupants with any injury attributed to steering-wheel contact, and was not limited to abdomen injuries attributed to steering-wheel contact. The proportion of steering-wheel contacts was higher than expected for the AIO drivers restrained only by airbags, while it was less than expected for the AIO drivers restrained by airbags and lap/shoulder belts. The mean value of delta V for drivers with steering-wheel contact, regardless of restraint condition, is 57 km/hr, while it is 47.5 km/hr for those without steering wheel contact, which are statistically different (p=0.011). The mean values for delta V with each restraint condition and presence of SWC are in Table 23. Only the lap/shoulder + frontal airbag condition had a statistically higher mean value of delta V for cases involving steering-wheel contact.

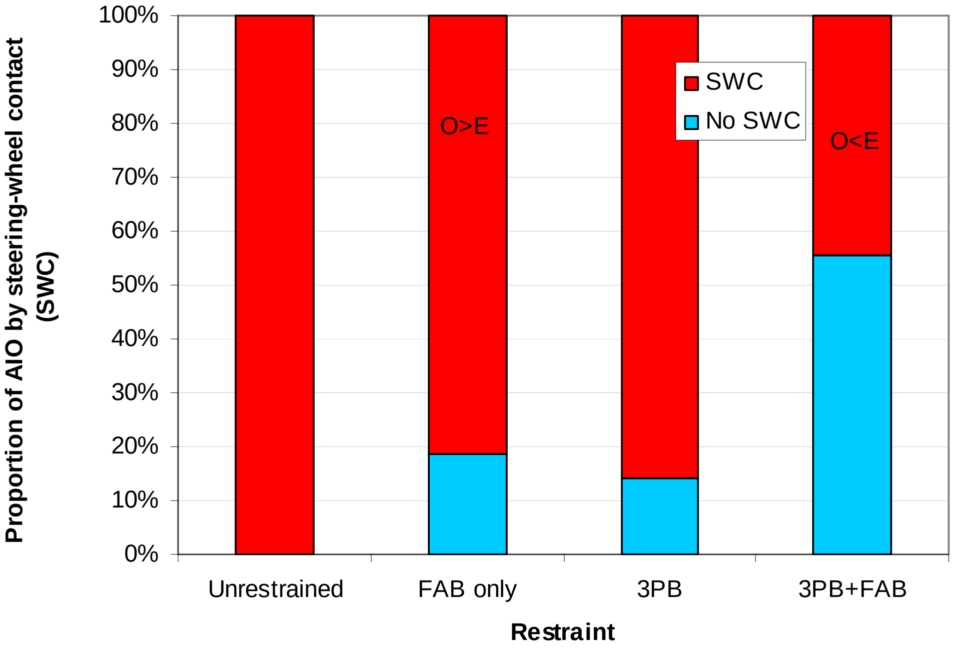


Figure 69. Proportion of AIO drivers in frontal impacts by steering-wheel contact and restraint type

Table 23. Mean delta V for AIO drivers in frontal impacts by restraint condition and steering wheel contact

	Mean delta V (km/hr)			
	Unrestrained	FAB	Lap/shoulder belt	Lap/shoulder belt + FAB
No SWC		52.2	29.0	46.5
SWC	61.7	57.3	43.8	58.1
p-value	NA	0.423	0.519	0.034

There may be an issue complicating the analysis of steering-wheel contact. It is common in crash investigation to associate a deformed steering wheel with occupant contact. However, laboratory experiments have shown that airbag deployment alone can sometimes deform steering wheels, although this typically deforms the upper half of the steering wheel. If steering-wheel deformation happens in a crash, steering-wheel contact may be inappropriately coded as resulting in an injury.

The next phase of this analysis examines possible effect of steering wheel intrusion. This section looks at differences in the magnitude of intrusion relative to how occupants were restrained. The first part reviews longitudinal steering-wheel intrusion (ignoring vertical and lateral intrusions) in three-point belted drivers and unbelted drivers. Shoulder-belt and lap-belt only drivers are excluded from this analysis.

In the CIREN database, intrusions are assigned a number 0 – 8 that correspond to intervals of increasing magnitudes of deformation. The highest two numbers, 7 and 8, correspond to 'catastrophic' and 'unknown', respectively. The unknown intrusions (three steering-wheel intrusions) were excluded from analysis. To distinguish between no intrusion and the smallest interval of intrusion, 0, in our analysis, the intrusions were shifted to a scaled from to 1 – 9. The intervals that correspond to each category of magnitude are given in Table 24.

Table 24. Intrusion categories with the corresponding interval and the interval mean

Magnitude category	Interval (cm)	Interval mean
1	≤ 2	1
2	3 – 7	5
3	8 – 14	11
4	15 – 29	22
5	30 – 45	37
6	46 - 60	53
7	≥ 61	73
8	Catastrophic	-none in this dataset-

Mean values of steering wheel intrusion category were compared for unrestrained and three-point belt restrained drivers using a one-way ANOVA test. Results are summarized in Table 25. Results indicate that differences in mean steering-wheel intrusion category and value are not statistically significant.

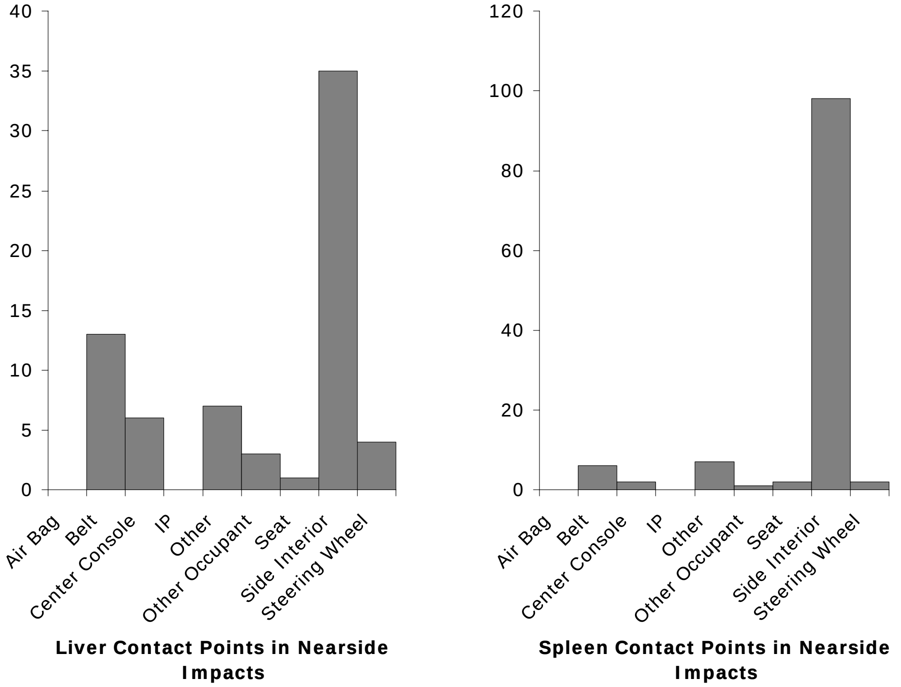
Table 25. Summary of steering wheel intrusion category and n, mean, and standard deviation for unbelted and lap/shoulder belted drivers

	Unbelted			Lap/shoulder belted			Comparison
	N	mean	Std	N	Mean	Std	p-value
Intrusion category	108	0.9	1.6	107	1.1	1.8	.603

2.3.6 Abdominal injury sources in near-side impacts

Figure 70 illustrates the contact points in near-side crashes attributed to liver injuries on the left, and spleen injuries on the right. A vast majority of the liver and spleen injuries in nearside impacts are caused by contact with the side interior of the vehicle. Figure 71 illustrates why the number of spleen injuries in near-side impacts is so much larger than the number of liver injuries in near-side impacts. Drivers, who represent the majority of the occupants in this database, mostly injured their spleens, while the right-front passengers usually injured their liver. This is consistent with the anatomical locations of the liver and spleen relative to the direction of a near-side impact for drivers and passengers.

Figure 71 also illustrates the other contact points for liver and spleen injury to drivers and right-front passengers in near-side impacts. For drivers, liver injuries are attributed to contact with the belt, the center console, the steering wheel, the side interior, or other occupant, or ‘other’. The ‘other’ categories included three injuries due to a floor or console mounted transmission lever. There are only eight instances when the side interior was not listed as the contact point for spleen injuries in drivers. Four of these were grouped into the ‘other’ category, which included one injury from each of the following sources: other interior object, other vehicle or object, injured source unknown, and ‘other injury’. The remaining four cases were split between contact with the seat and the steering wheel. For right-front passengers, only one liver injury was attributed to belt contact rather than contact with the side interior. For spleen injuries to right-front passengers, injury contact points include the belt, the center console, ‘other occupant’ and ‘other’. The three ‘other’ cases included two injuries due to a floor or console mounted transmission lever and one due to another vehicle or object.



Liver Contact Points in Nearside Impacts

Spleen Contact Points in Nearside Impacts

Figure 70. Distribution of contact points in nearside impacts for liver injury and spleen injury

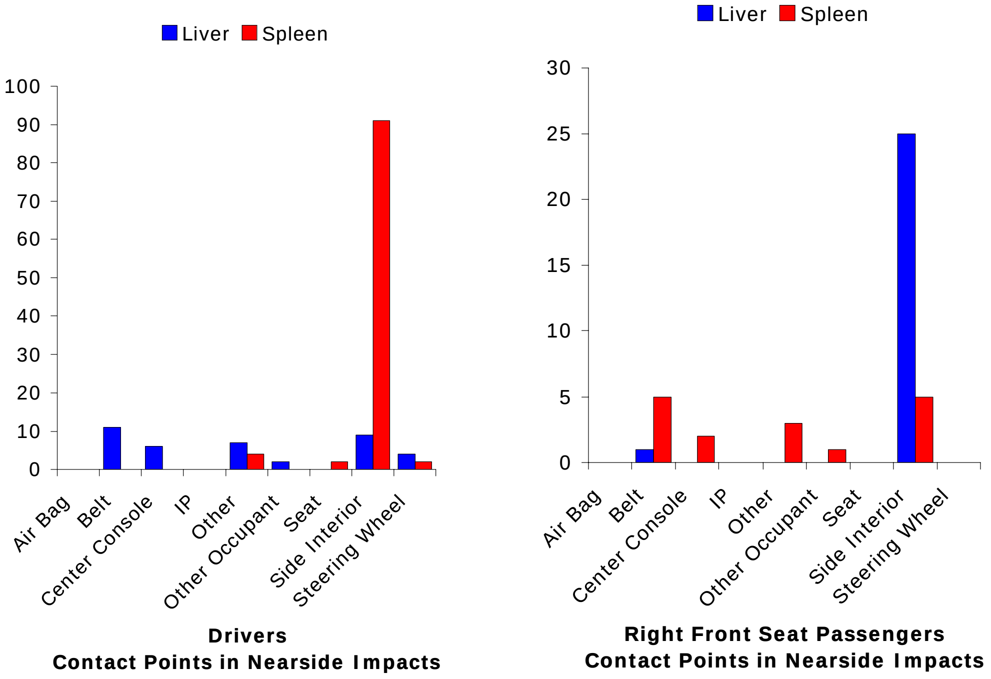
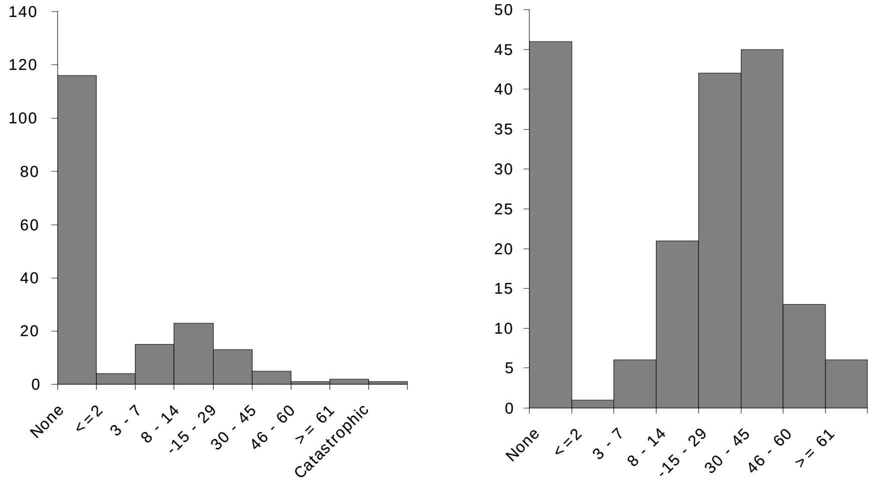


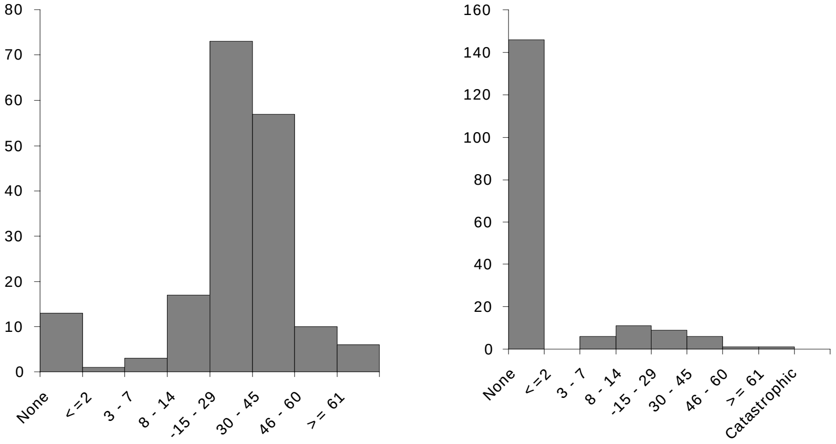
Figure 71. Liver and spleen contact points for drivers and passengers in near-side impacts

Because contact with the side interior is the most prominent source attributed to causing spleen or liver injury, an analysis of intrusion in side impacts was performed. Figure 72 shows the distribution of lateral intrusion levels for the six most commonly intruded vehicle components: A-pillar, B-pillar, door panel, front seat back, seat cushion, and side panel forward of A-pillar. The door panel and B-pillar experienced the highest frequency and levels of intrusion. Table 26 shows the frequency and levels of intrusion of three less frequently intruded components: the C-pillar, window frame, and side panel B.



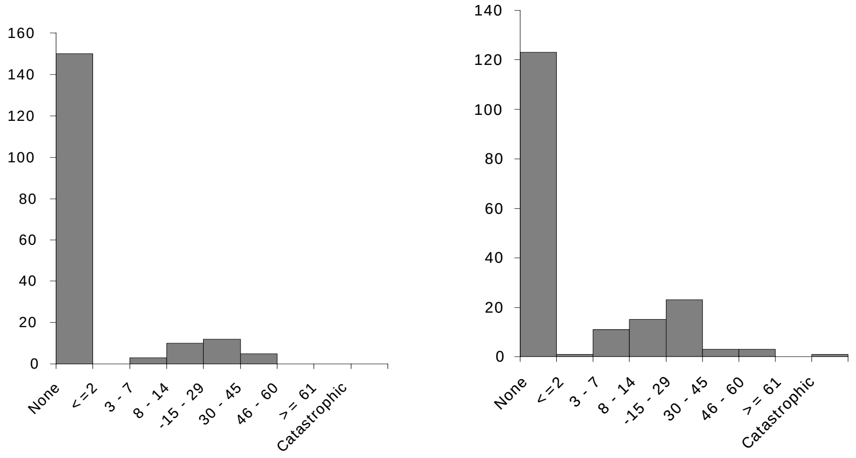
Lateral Intrusion of A-Pillar (cm)

Lateral Intrusion of B-Pillar (cm)



Lateral Intrusion of Door Panel (cm)

Lateral Intrusion of Front Seat Back (cm)



Lateral Intrusion of Seat Cushion (cm)

Lateral Intrusion of Side Panel Forward of A-Pillar (cm)

Figure 72. Distributions of lateral intrusion for several vehicle components

Table 26. Other components with lateral intrusion

Component	Intrusion Magnitude (number of cases)
C-Pillar	8 – 14 cm (2) 15 – 29 cm (1)
Side Panel – B	8 – 14 cm (1)
Window Frame	8 – 14 cm (1) 15 – 29 cm (4) 30 – 45 cm (4)

To examine the effects of door intrusion on liver and spleen injuries, each occupant was categorized into four abdomen injury categories: liver injury, spleen injury, both liver and spleen injuries, or other abdomen injuries (neither liver nor spleen injuries). The mean value of door intrusion for occupants sustaining both liver and spleen injuries was 35.5 cm, which is statistically greater (p=0.003) than the mean intrusion levels near 25 cm for the three other types of abdomen injured occupants that were statistically the same.

When the same intrusion analysis was repeated while restricting the case occupants to either drivers or right-front passengers, trends were similar as shown in Table 27. For drivers, the mean lateral door intrusion of 35.4 cm for occupants with both liver and spleen injuries is statistically higher (p=0.039) than the 24 to 29 cm of mean lateral door intrusion experienced by the occupants in other abdomen injury categories. For right-front passengers, the mean lateral door intrusion of 35.8 cm for occupants with both spleen and liver injuries is statistically higher than the mean intrusions for the three other categories. In addition, right-front passengers who sustained other abdomen injuries had mean lateral door intrusions of 14.3 cm, although the small number of cases in each category does not make this statistically different than the liver only or spleen only categories.

Table 27. Mean lateral door intrusion for drivers and right-front passengers in near-side impacts by each abdomen injury category

	Mean lateral door intrusion (cm)	
Abdomen Injury Category	**Drivers**	**Right-front Passengers**
Liver only	27.8	24.2
Spleen only	24.8	22.0
Liver and spleen	**35.4**	**35.8**
Other abdomen	29.0	*14.3*

2.3.7 Rib fracture analysis

The strong association between the presence of rib fracture and abdominal injuries led to a more detailed investigation of the locations of rib fractures in occupants with abdomen injury. As shown in Table 28, out of 536 cases with AIS 2+ abdominal injury, 284 (53%) sustained at least one rib fracture. Occupants in frontal impacts experienced the lowest rate of rib fractures (47%) while occupants in near-side and far-side impacts sustained roughly the same rate of rib fractures (59% and 61%, respectively).

Table 28. Number and proportion of occupants with rib fractures by crash type

	No. of rib fxs	% of all rib fxs	% of all specified impacts
Front	141	50%	47%
Nearside	108	38%	59%
Left	*83*	*29%*	*60%*
Right	*25*	*9%*	*61%*
Farside	27	10%	61%
Left	*3*	*1%*	*50%*
Right	*24*	*8%*	*63%*
Rear/ss/top	8	3%	73%
Total	284	100%	-

The next step involved examining where the rib fractures occurred. As shown in Table 29 and Table 30, for the 284 abdomen-injured occupants with at least one rib fracture, 280 specified the side of fracture. There were 92 left-side fractures, 66 right-side fractures and 122 bilateral fractures. Of the 280 cases in which the side of the fracture was specified, 171 (61%) also specified the fracture(s) location by rib number. Only 50% of the bilateral fracture cases reported rib fracture location while 70% of both left and right fracture cases reported the specific location.

Table 29. Number of occupants with rib fractures according to crash direction and aspect of rib fracture

	Front	Left Farside	Left Nearside	Right Farside	Right Nearside	Rear/ SS/Top	*Total*
Bilateral	70	1	31	6	13	1	*122*
Left	34	2	48	2	1	5	*92*
Right	34	0	3	16	11	2	*66*
Unknown	3	0	1	0	0	0	*4*
Total	*141*	*3*	*83*	*24*	*25*	*8*	*284*

Table 30. Percentage of occupants with rib fractures according to crash direction and aspect of rib fracture

	Front	Left Farside	Left Nearside	Right Farside	Right Nearside	Rear/SS/ Top	Total
Bilateral	51%	33%	38%	25%	52%	13%	44%
Left	25%	67%	59%	8%	4%	63%	33%
Right	25%	0%	4%	67%	44%	25%	24%
Total	100%	100%	100%	100%	100%	100%	100%

The next step in the analysis looked for possible relationships between the location of the rib fracture and the abdomen organ injured. Results of chi-squared analysis are summarized in Table 31. The first column lists the impact types considered in each analysis. The second column describes how rib fractures were evaluated relative to abdominal injury: all, by aspect (left, right, bilateral), and by location (upper left, lower left, upper right, lower right). The remaining columns list the p-values for the analysis comparing rib fracture with liver injury or spleen injury. Significant p-values are highlighted. The positive and negative signs indicate whether the injury is more likely or less likely than expected statistically for the rib fracture quality being evaluated.

When all crashes are considered, there were more occupants with liver injuries than expected statistically for any type of rib fracture except for those with lower left rib fractures. For any type of crashes with spleen injuries, occupants with rib fractures on the left side had more spleen injuries than expected statistically.

In frontal crashes, liver injuries are more likely to occur when there is any rib fracture, a left, right, or bilateral rib fracture, or fractures in the upper left, upper right, or lower right ribs. However, in frontal impacts, injury to the spleen was not significantly correlated with any location of rib fracture.

For both left and right far-side crashes, there was no significant difference in likelihood of liver or spleen injury with rib fracture location. For left, near-side crashes, there were more occupants with liver injuries than expected statistically when occupants sustained bilateral or right rib fractures or fractures to the upper right ribs. For right, near-side crashes, there were more occupants with liver injuries than expected if any rib fracture occurred.

Table 31. P-values for chi-squared analysis examining rib fracture location and occurrence of liver or spleen injury by impact type

Impact	Rib location	Liver	Spleen
All	All	0.002	0.561
	Aspect	0.000 (B/R)	0.000 (L)
	UL	0.037 (+)	0.864
	LL	0.120	0.011
	UR	0.000 (+)	0.074
	LR	0.000 (+)	0.003 (-)
Front	All	0.023 (+)	0.975
	Aspect	0.001	0.213
	UL	0.049 (+)	0.804
	LL	0.131	0.714
	UR	0.011	0.263
	LR	0.001 (+)	0.264
Left farside	All	0.414	0.273
	Aspect	0.513	0.549
	UL	0.189	0.549
	LL	0.189	0.549
	UR	0.083	0.439
	LR	0.083	0.439
Left nearside	All	0.116	0.971
	Aspect	0.004 (B/R)	0.692
	UL	0.546	0.719
	LL	0.715	0.940
	UR	0.015 (+)	0.446
	LR	0.847	0.416
Right farside	All	0.064	0.385
	Aspect	0.218	0.247
	UL	0.189	0.446
	LL	0.060	0.586
	UR	0.109	0.706
	LR	0.239	0.155
Right nearside	All	0.050 (+)	0.812
	Aspect	0.263	0.834
	UL	0.095	0.784
	LL	0.804	0.399
	UR	0.081	0.726
	LR	0.349	0.967

2.4 Comparison of Current Analysis with Reports from the Literature

2.4.1 Abdomen injuries in frontal impacts

Comparison of methods

The information regarding abdominal injuries in frontal crashes comes from the following three reports: Abdominal injuries in the National Crash Severity Study (Bondy 1980), which covers the National Crash Severity Study (NCSS) database for years 1977 – 1979; Patterns of abdominal injury in frontal automotive crashes (Elhagediab 1998), which covers the NASS database for years 1988 – 1994; and Patterns of abdominal injuries in frontal and side impacts (Yoganandan 2000), which covers the NASS database for years 1993 – 1998. The current study uses NASS years 1998-2004. All four analyses included both restrained and unrestrained adult occupants in the driver and right-front passenger seats. The current study excluded pregnant occupants, which were not always coded in the earlier NASS database.

In Bondy's report and the current study, frontal crashes were defined as those with the most severe damage to the front of the vehicle according to CDC coding. Elhagediab and Yoganandan, on the other hand, identified frontal crashes by the PDOF. Elhagediab sorted for all crashes with a PDOF of 10 – 2 o'clock, while Yoganandan narrowed the scope to 11 – 1 o'clock.

Restraint use

One of the most significant differences among the four studies is the variation in restraint use. As shown in Figure 73, the number of belt restrained occupants with an abdominal AIS 3+ injury has varied dramatically, from 1% to 60% of all the occupants with an abdominal injury. This change has occurred largely because belt usage rates have also increased over the years included in each study. This value is lower in the most recent analysis because of the greater frequency occupants protected by both lap/shoulder belts and airbags. The number of occupants with an abdominal injury who were unrestrained has decreased from 97% to 36%, before increasing to 42%. Occupants restrained only by an airbag now account for 12% of all abdominally injured occupants in the current study.

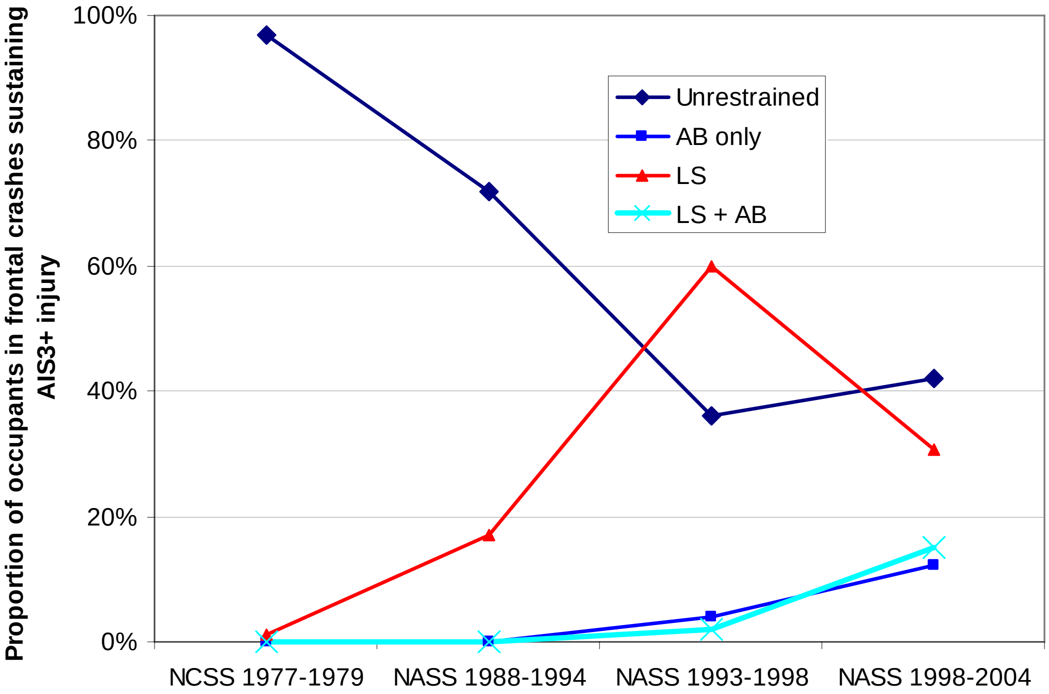
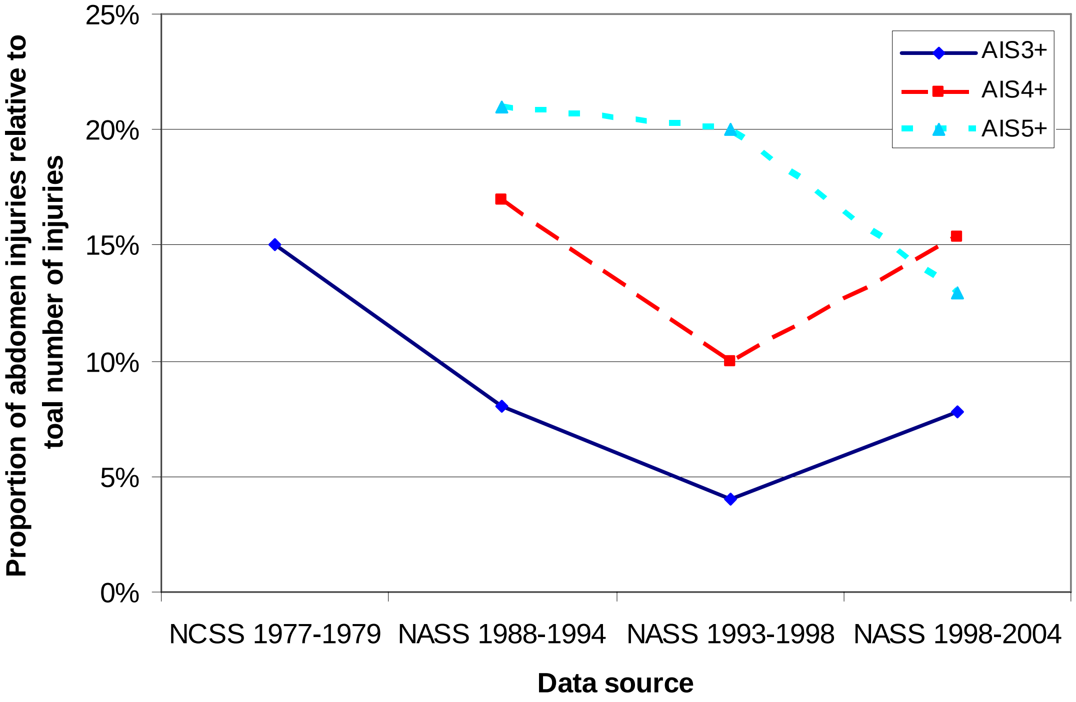


Figure 73. Proportion of occupants in frontal crashes sustaining AIS 3+ abdominal injury versus crash year by restraint type

Abdominal injury frequency

Figure 74 shows the proportion of abdominal injuries with respect to all injuries at severity levels of AIS 3+, 4+ and 5+ as reported by Bondy (1980), Elhagediab (1998), Yoganandan (2000), and the current study. The Elhagediab study counted only frontal impacts, while the remaining three studies considered both front and side impacts. The current study shows a decrease in the proportion of AIS 5+ abdomen injuries compared to the two earlier studies (13% vs. 20%). However, the current proportion of AIS 4+ abdomen injuries (16%) is similar to that found by Elhagediab (17%) and greater than that found by Yoganandan (10%). The proportion of AIS 3+ abdomen injuries declined in the first study but increased in the current study. It is possible that recent safety advances have resulted in some of the most severe AIS 5+ injuries shifting to now be less severe AIS 4+ or AIS 3+ injuries. In the two intermediate studies, the proportion of abdominal injuries relative to all injuries increased as the severity of injury increased. For example, the Yoganandan (2000) study indicated that abdominal injuries accounted for only 4% of all AIS 3+ injuries, while they accounted for 20% of all AIS 5+ injuries. In the current study, abdomen injuries account for 8% of all AIS 3+ injuries, while they have similar proportions (15% and 13%) of AIS 4+ and AIS 5+ injuries, respectively.



*Studies except for NASS 1988-1994 include both front and side impacts

Figure 74. Proportion of abdominal injuries relative to total number of injuries versus crash year by injury severity level

Figure 75 shows the proportion of abdominal AIS 3+ injuries by specific organs. In the three earliest studies, the most frequently injured abdominal organ is the liver. Liver injuries account for about 38% of abdominal AIS 3+ injuries in the reports by Bondy and Elhagediab, and 35% in the report by Yoganandan and the current study. Spleen injury is most frequent in the current study, at 38%, and is the second most common injury in the three previous studies, showing an increase in frequency over time. The frequency of kidney injuries varies, with similar levels in the earliest and latest studies, with lower rates in the intervening years. Likewise, injuries to the digestive system are similar in the current and first two studies, but not in the third study. The current study did not include abdominal blood vessel injuries, because initial reviews in the CIREN dataset showed them to be infrequent. However, they were more frequently present in the two middle studies. It is possible that some of the variations in frequencies result from differing definitions of categories between the studies. In addition, because these percentages are out of all AIS 3+ abdomen injuries, a decrease in percentage for one organ could result from an increase in percentage for another organ, or from different numbers of occupants sustaining AIS 3+ abdomen injuries within each time period.

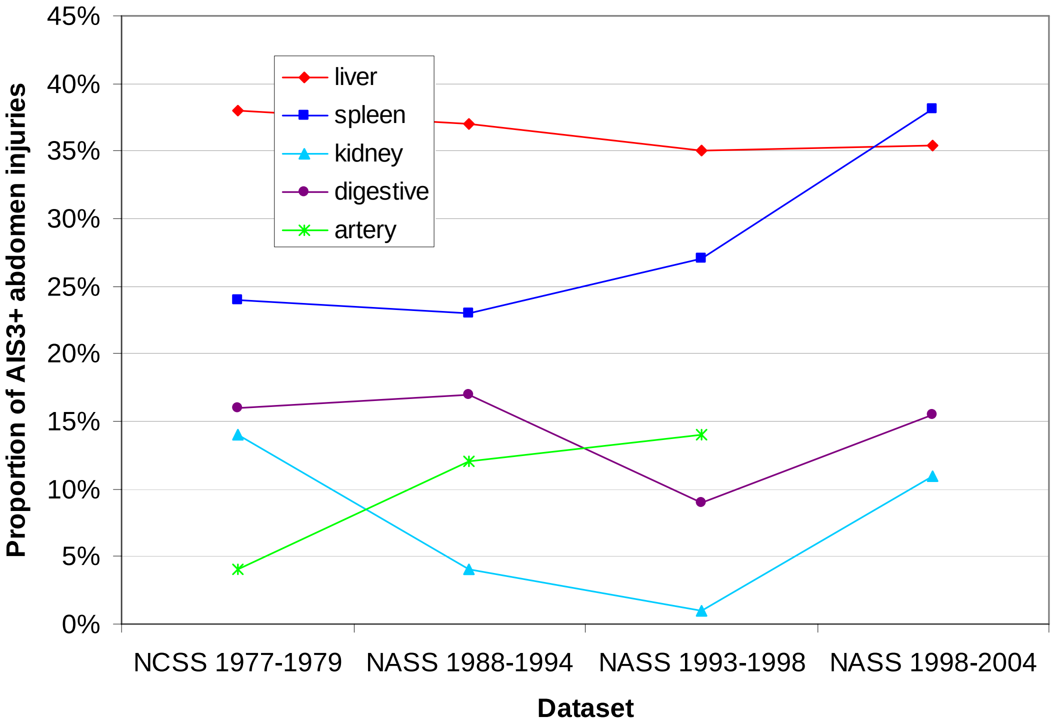


Figure 75. Proportion of injuries to each organ among all AIS 3+ abdominal injuries

Contact points

Yoganandan reported the distribution of abdominal injuries due to interior contact points (not including the belt). According to the NASS coding guidelines, interior contacts include the seat, head restraint system, other occupants, and interior loose objects. Yoganandan reports that 64% of the abdominal AIS 3+ injuries from interior contacts are to the spleen, 15% to the diaphragm, 14% to the liver, and 5% to the digestive organs. Injuries from interior contacts to the arteries, kidneys, urogenital organs and pancreas are each 1% or less. In Elhagediab's report, contact with the interior was distributed as follows: 49% to the spleen, 23% to the liver, 10% to the arteries, 7% to the urogenital organs, 6% to the digestive organs, 5% to respiratory organs, 1% to the kidneys. In both reports, the spleen was the most commonly injured organ, followed by the liver. The three most common injury contact points were the steering wheel (68%), interior (14%) and belt (17%). Bondy's results (1980), on the other hand, indicate more injuries due to the interior (48%) and less due to the belt (1%). This is most likely due to the increase in belt use over the time period between the studies. With regard to correlation between different contact points and different abdominal organs injured, the steering wheel most often injured the liver and spleen, the seat belt most often injured the digestive organs and the airbag most often injured the spleen.

In the current study, analysis of injury contact points was performed with the CIREN dataset rather than NASS and focused on liver and spleen injuries. For drivers, steering wheels and belts were the most commonly listed contacts resulting in liver injuries, with the steering wheel attributed primarily when the PDOF was -10 to 10 degrees. For drivers with spleen injuries, steering wheel, belt, and side interior were the most frequently listed contact points. Drivers with both liver and spleen injuries were most often indicated as contacting the steering wheel. For right-front passengers, belted occupants with liver, spleen, or liver and spleen were most frequently coded as contacting the belt. For the few unbelted right-front passengers with liver or spleen injury, sources included the airbag, instrument panel, or other sources.

2.4.2 NASS studies of abdominal injuries in near-side crashes

Comparison of methods

Three studies in the literature report on abdomen injuries in near-side crashes: Near Side Passenger Car Impacts – CDC, AIS & Body Areas Injured (Huelke 1990), Injury Patterns in Near-Side Collisions (Augenstein 2000a) and Patterns of Abdominal Injuries in Frontal and Side Impacts (Yoganandan 2000). Huelke studied the NCSS database using case years 1980 – 1986, Augenstein studied the NASS database using case years 1988 – 1996, and Yoganandan studied the NASS database using case years 1993 – 1998. The current study uses NASS case years 1998-2004 and vehicle models 1985 and later. Huelke only evaluated cases in which the driver was the only vehicle occupant and Augenstein did not filter for occupant location, while Yoganandan and the current study focus on drivers and right-front passengers. None of the studies filtered for restraint use. In addition to the NASS database search, Augenstein studied a group of patients admitted to a trauma center.

Huelke, Augenstein, and the current study defined a side impact as one in which the principle area of damage was to the side of the vehicle, as defined by the NCSS and NASS database. However, Yoganandan defined side impact by the principle direction of force. For drivers, near-side impact occurred with a PDOF of 8 – 10 o'clock, while for right-front passengers, near-side impacts occurred with a PDOF of 2 – 4 o'clock. Thus the Huelke, Augenstein, and current studies include sideswipe type crashes, while the Yoganandan study does not. The variation in defining side impacts may affect comparisons between the four studies.

Abdominal injury proportions

Huelke reported that 16% of all AIS 3+ injuries from the NCSS-80/86 database were to the abdomen. Augenstein reported that abdomen injuries represent 5% of the MAIS 3+ injuries in car-to-car impacts from the NASS-88/96 database. Augenstein further reported that 20% of the MAIS 3+ injuries in the WLIRC database are to the abdomen, suggesting that abdomen injuries increase in frequency as the severity of the crashes increase. It is difficult to directly compare these incidence rates because of differences in how each reported the frequency (AIS verse MAIS) as well as the fact that Augenstein did not include fixed-object impacts, which comprise 25% of the MAIS 3+ injured occupants in side (near and far) impacts from the NASS-88/96 database. However, the large difference in the frequency of AIS 3+/MAIS 3+ abdominal injuries between the two studies suggests that there may have been a decrease in the rate of AIS 3+ abdominal injuries relative to injuries in other regions of the body. The current study indicates that 8% of AIS 3+ injuries in side impact are to the abdomen, a reduction from the Huelke study but an increase from the Augenstein study.

Yoganandan reported that the spleen is the most commonly injured organ of the abdomen when both drivers and right-front passengers are combined. With respect to all abdominal AIS 3+ injuries, the spleen accounted for 47%, the diaphragm accounted for 17%, and the liver accounted for 13%. Because the spleen and liver are on different sides of the abdomen, their distributions are a function of the occupant's position. The proportion of abdominal AIS 3+ injuries to drivers was 72%, while in passengers it was 29%, which likely reflects the distribution of drivers vs. passengers in the dataset. In the current study, risk of abdomen injuries in near-side impacts was 3 times higher for right-front passengers than drivers. Although the liver is the most frequently injured abdomen organ injured in right-front passengers, the risk of spleen injury for right-front passengers in near-side impacts is higher than the risk of spleen injury for drivers in near-side impacts, probably from loading by unbelted drivers.

From the WLIRC cases, Augenstein notes that in every single fatal case with rib fracture there was an internal chest or abdominal injury that was a "significant factor in the cause of death." The current study also shows an association between abdomen injury and rib fracture, with the odds of a belted driver sustaining a liver or spleen injury in a near-side impact being 45 or 26 times higher, respectively, if the occupant sustains AIS 2+ rib fractures.

Impact location, direction, and magnitude

Augenstein investigated the distribution of AIS 3+ injuries with respect to PDOF and found that 64% of all AIS 3+ injuries (abdomen and other) were from crashes involving a PDOF of 2 or 10 o'clock. In the focused study of WLIRC cases, this proportion increased to 76%. They did not specifically explore how PDOF relates to abdominal injuries. However, they noted that in near-side crashes, the PDOFs of 10 and 2 o'clock were the most common impact directions, but crashes with PDOFs of 3 and 9 o'clock account for the majority of the abdominal AIS 3+ injuries.

Huelke analyzed the distribution of abdominal injuries by location of damage along the length of the car. In the study, there were 20 abdominal AIS 3+ injuries in an unknown number of occupants. Ten of these injuries occurred in crashes with a distributed (NASS coding 'D') damage area, five were from the forward one-third ('Y'), two were from rear one-third ('B'), two were from the rear two-thirds ('Z'), and one was from the center side ('P'). These data suggest that distributed-damage crashes present the most risk to the abdomen, even though crashes with this type of damage account for slightly less than one-third of all AIS 3+ injuries and one-third of all drivers with an AIS 3+ injury. Augenstein reports that occupant compartment damage occurs in 94% of the NASS-88/96 cases involving an occupant with at least one AIS 3+ injury.

The current study illustrates a correlation between PDOF and organ injured in the CIREN-AIO dataset, but this trend was not statistically significant in the NASS-CDS dataset beyond the trends seen for drivers vs. passengers in different types of crashes.

A third crash variable studied concerning abdominal injuries is crash severity, measured by ΔV. Yoganandan reported that the median crash severity associated with AIS 3+ abdominal injuries occurs at a ΔV of 33 km/hr. As expected, this value is lower than the ΔV reported for frontal and far-side crashes in the same report, indicating that abdominal injuries in near-side crashes have a lower threshold of severity. The current study also shows higher risk associated with lower delta V for near-side impacts compared to frontal and far-side impacts. However, when an occupant-based risk of abdomen injury is assessed as a function of delta V, rather than the median crash severity associated with abdomen injury, crash severities from 21-30 mph delta V are associated with an approximately 7% risk of AIS 3+ abdomen injury in near-side impacts.

2.4.3 Abdominal injury in far-side impacts

Comparison of methods

Far-side crashes have been studied by Augenstein (2000b), Yoganandan (2000) and Gabler (2005), as well as the current study. Augenstein used data from the NASS-CDS database for years 1998 – 1998 and defined a side impact as any with a PDOF of 1 – 5 o'clock or 7 – 11 o'clock. Yoganandan used data from the NASS-CDS database for years 1993 – 1998 and defined a side crash as any with a PDOF of 2 – 4 o'clock and 8 – 10 o'clock. Gabler used data from the NASS database for years 1993 – 2002 and defined a side impact as any crash with the general area of damage in the most harmful event to the side of the car. The current study uses NASS case years from 1998-2004, limits vehicle model years to 1985 or later, and defines a side impact using the CDC coding. Both Augenstein and Gabler limited their studies to belted occupants, while Yoganandan and the current study included all restrained and unrestrained occupants. The studies by Gabler, Yoganandan, and the current study applied NASS weighting factors. However, Yoganandan ignored cases in which no contact point or injury was identified, so the total number of cases does not reflect the actual weighted frequencies.

Specific abdominal injuries and frequencies

Augenstein combined the results for the abdomen and thorax together and reported that 48% of all AIS 3+ injuries are to the abdomen/thorax. Gabler reported that 40.5% of all AIS 3+ injuries are to the abdomen/thorax. The current study shows that 6% of all AIS 3+ injuries are to the abdomen and 29% are to the thorax, which continues the drop from the prior studies. The current study also estimates that approximately 3000 occupants sustain AIS 2+ abdomen injury each year in far-side impacts. The overall risk of AIS 2+ abdomen injury in far-side impacts is less than 1%.

Yoganandan showed that the liver is the most frequently injured abdominal organ, accounting for 50% of all AIS 3+ abdominal injuries. Following the liver, in order of frequency, are the spleen (13%), kidney (12%), and digestive organs (10%). The rates of liver and spleen injuries may have more to do with the occupant position in the vehicle rather than the tolerances of the two organs. In a small study of thirteen patients admitted to a trauma center following a far-side crash, Augenstein (2000) found that of five occupants whose most serious injury was to the abdomen, the four seated on the left side sustained liver injuries while the one seated on the right side sustained a spleen injury. All five of these injuries were attributed to the belt system. In addition, there appears to be a correlation between the distribution of drivers and passengers and the distribution of liver and spleen injuries; the ratio of liver to spleen injuries is 3.85:1 (Yoganandan 2000) and the ratio of exposed drivers to exposed right-front seat passengers is 3.89:1 (Gabler 2005).

The current study also shows that when reviewing the frequency of injury to each abdomen organ as a function of delta V, the order of frequency in terms of injury risk is liver, spleen, and kidney over the full range of delta V's. However, when looking at the risk of injury to each organ for drivers and right-front passengers, drivers had the highest risk of kidney injury, followed by liver and spleen, while the order for right-front passengers was liver, kidney, and spleen. This variation may partly result from a high rate of kidney injury noted for occupants in the 21-30 year age range, which is the age range with the highest frequency of crash involvement.

Occupant seat position and restraint

Gabler reported that 73% of all MAIS 3+ occupants are drivers, 25% are right-front passengers and 2% are rear passengers. Augenstein reported that 45.5% of all AIS 3+ injuries in drivers and 64.5% in right-front passengers are to the abdomen/thorax. Thus, while passengers represent a minority of occupants involved in far-side crashes, they incur higher rates of abdomen injury. The current study also shows a higher risk of abdomen injury for right-front passengers in far-side crashes compared to drivers in far-side crashes, with risks of AIS 2+ abdomen injury of 0.39% and 0.17%, respectively.

Contrary to Augenstein's report, Yoganandan (who strictly reported abdominal injuries), reported that 91.4% of all AIS 3+ abdominal injuries occurred in drivers and 8.7% occurred in passengers. The disparity becomes even greater when only belted occupants are included; 99% of all AIS 3+ abdominal injuries occurred to drivers. It is difficult to compare results from these two papers because Augenstein combined the abdomen with the thorax and reported the percentage of occupants with an injury to these regions, while Yoganandan reported the percentage of abdomen injuries occurring with a specific type occupant.

Yoganandan also reported the rate of abdominal injuries by restraint type. Lap/shoulder-belted drivers account for 42% of all the abdominal AIS 3+ injuries and unrestrained drivers account for 37%. Unrestrained passengers are the third largest group, accounting for 8%. When all AIS 2+ injuries are included, these three groups of occupants remain the top three. However, unrestrained passengers account for the most, with 49% of all abdominal AIS 2+ injuries. Lap/shoulder-belted drivers account for 26.0% and unrestrained drivers account for 20.6%. There is a remarkable difference in the proportion of AIS 2+ abdominal injuries and AIS 3+ abdominal injuries attributed to unrestrained passengers, suggesting that passengers are more likely to sustain minor injuries while drivers are more likely to sustain serious injuries in far-side crashes. This may support one of Augenstein's conclusions about far-side crashes that the presence of a near-side occupant mitigates serious injuries by providing a buffer from the opposite side interior. It is possible that for right-front occupants, the presence of a near-side driver is enough to reduce the severity of abdominal injuries.

The above results are reflective of the frequency of restraint use and seat location in the general population, and equal exposure is not assumed.

The current study shows that the risk of AIS 2+ abdomen injuries is 0.69% for belted occupants in far-side crashes and 1.75% for unbelted occupants in far side crashes. Using a belt offers even greater protection for reducing AIS 3+ abdomen injuries, with risks of 0.09% and 0.96%, respectively, for belted and unbelted occupants.

Injury contact points

Gabler, who only studied belted occupants, reported that the seat belt/buckle restraint system accounts for 86.9% of all abdominal AIS 2+ injuries. Augenstein's report showed that the contact points for abdomen/thorax injuries are different between drivers and right-front passengers. In drivers, 47% of abdominal/thorax AIS 3+ injuries are attributed to the belt system and 27% are attributed to the right-side interior. For right-front passengers, 42% of the abdominal/thorax AIS 3+ injuries are due to the seat and 18% result from contact with the near side occupant. Without an occupant in the near-side seat, far-side occupants are more likely to experience higher loading on the belt restraints and strike the opposite side interior. The current study used the CIREN dataset to study contact points, and the small number of far-side impacts included in that dataset prevented any statistically significant assessment of common contact points.

Crash direction and severity

When evaluating abdominal injury in far-side impacts, crash severity (ΔV) and direction of impact have also been analyzed. Yoganandan reported that when reviewing delta V's associated with AIS 3+ abdomen injuries, the median crash severity is 36 km/hr ΔV. In the same report, the median crash severity in frontal impacts is 47 km/hr, indicating that the severity threshold for abdominal injuries is lower in far-side than in frontal crashes. Gabler also looked at the cumulative frequency of MAIS 3+ injuries; his study has a median crash severity of 32 km/hr delta V, slightly lower than the value reported by Yoganandan for only the abdomen.

The current study examines overall risk of AIS 3+ abdomen injury to occupants in far-side impacts, rather than a median delta V associated with AIS 3+ abdomen injury. In other words, the current study considers all occupants with and without abdomen injuries, rather than looking only at abdomen injuries. The estimated risk of AIS 3+ abdomen injury in far-side impacts in the current study is 3% at crash severities ranging from 21-30 mph (33.6 to 48 km/hr). As a function of delta V, risk of AIS 2+ abdomen injury in far-side impacts is similar to the risk in frontal impacts for delta V's up to 30 mph. When reviewing AIS 3+ abdomen injury risk, the rates are similar for frontal and far-side impacts at delta V's up to 40 mph. Beyond these crash severities, risks are higher for frontal compared to far-side impacts.

3. Characterization of Current Side-Impact Loading

3.1 Overview

Because the risk of injury to the abdomen is highest for near-side occupants in T-type side impacts, an analysis of FMVSS 214 and SNCAP test data was performed to characterize the occupant loading conditions in these simulated collisions. The focus of this analysis was to document door velocity histories and establish door velocity at the time of contact with the thorax, abdomen, and pelvis.

3.2 Analysis of FMVSS 214 tests

Door velocity profiles were determined using data from six FMVSS 214 tests in which single-axis accelerometers were attached to the interior structure of the driver door and oriented so that their sensitive axis was initially aligned with the lateral axis of the vehicle. Table 32 summarizes vehicle and ATD information for these tests. In each test, acceleration of the driver door was measured at four locations using one of the two patterns as shown in Figure 76. Data from door accelerometers located at either the "Left Front Door @ Mid Rib" or the "Left Front Door Upper" positions were integrated to compare door velocity at about the mid level of the ATD's thorax. Accelerometers located at either the "Left Front Door @ Pelvis" or the "Left Front Door Rear" locations on the door were integrated to compare vehicle door velocity at about the level of the ATD abdomen/pelvis.

Table 32. Vehicle and ATD information for FMVSS 214 tests with door-mounted accelerometers

Test No.	Vehicle Manufacture	Vehicle Model	Year of Manufacture	ATD Type
3522	Ford	Taurus	1996	Prototype ES-2
3668	Nissan	Maxima	2000	ES-2
3669	Cadillac	Deville	1999	ES-2
4549	Ford	Focus	2001	ES-2
4609	Ford	Focus	2001	SID IIs
4642	Chevrolet	Impala	2002	SID IIs

The average door velocity histories at the levels of the thorax and pelvis/abdomen, along with corridors corresponding to +/- one standard deviation and points representing the average times of pelvis and thorax contact, are shown in Figure 77 and Figure 78. In each of these plots, t_{zero} is the time of first contact with the ATD, which was defined as the time of the first rise in either the ATD rib or pelvis acceleration signal. The average door velocity at the level of the thorax at the time of door-to-ATD contact is 10.6 m/s, with a peak average door-to-ATD thorax velocity of 11.8 m/s. Average door-to-pelvis velocity at the time of ATD pelvis contact is 10.5 m/s, which is nearly identical to the peak door-to-pelvis velocity of 10.6 m/s at the time of thorax contact. In the majority of tests, door contact with the pelvis occurred just before thorax contact, and the door velocity at the level of the thorax increased after the time of pelvis contact, indicating that the velocity of the intruding door is not affected by contact with the ATD.

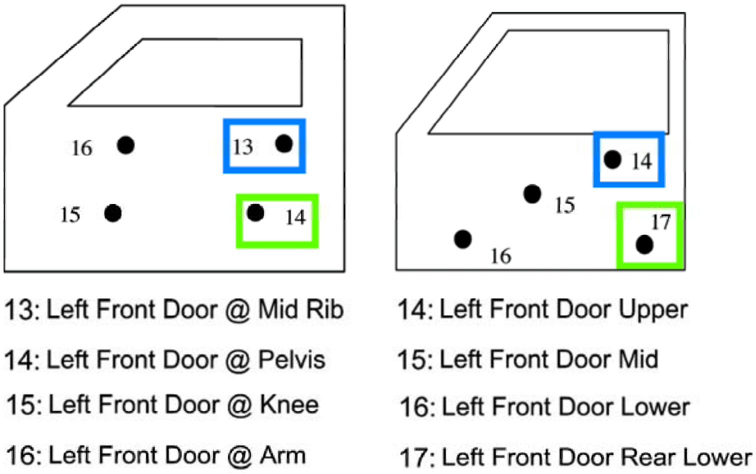


Figure 76. Locations and labels of driver-door accelerometers used in FMVSS 214 tests from the NHTSA database

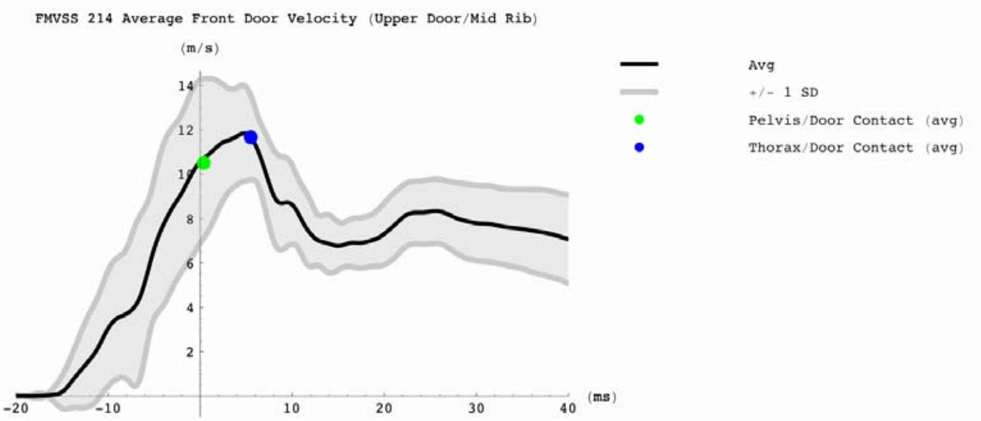


Figure 77. Average struck-side driver-door velocity history and corridor at the Upper Door/Mid Rib location from six FMVSS 214 tests

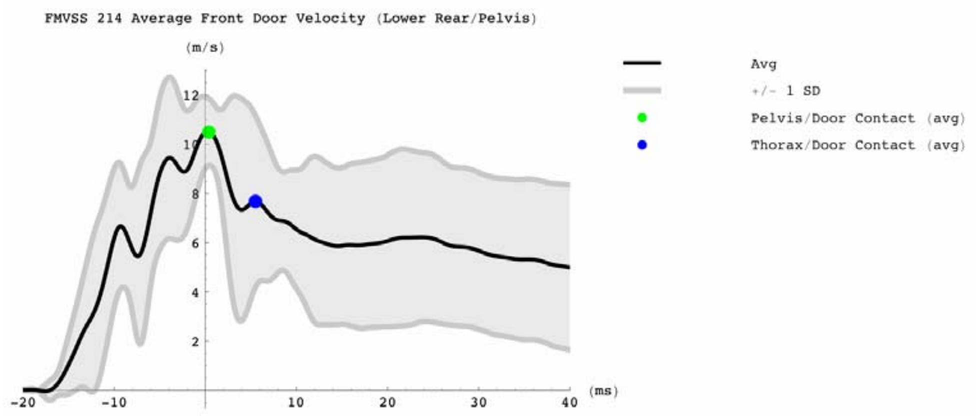


Figure 78. Average struck-side driver-door velocity history and corridor at the Lower Rear/Pelvis location from six FMVSS 214 tests

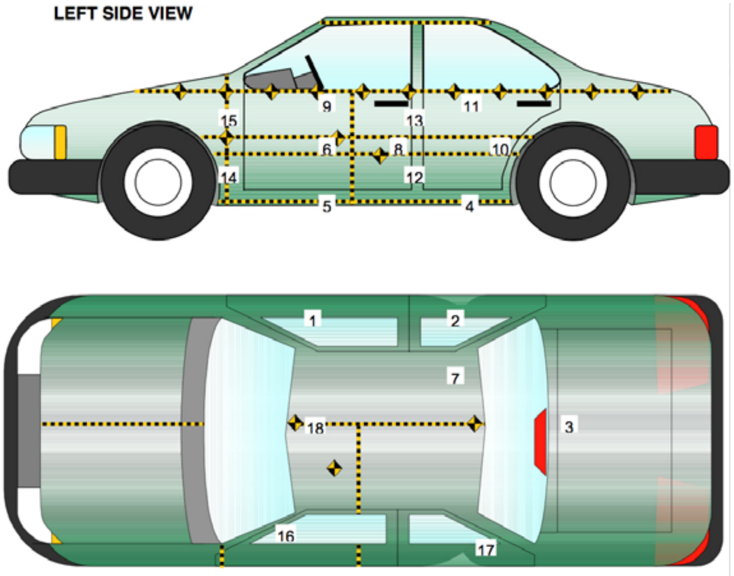
3.3 Analysis of SNCAP tests

Door velocities were also calculated by integrating door-mounted accelerometer data from the 27 SNCAP tests listed in Table 33. Vehicles with and without side-impact airbags were included in this analysis. Figure 79 illustrates the locations on the door where single-axis accelerometers were located in these tests. Accelerometers in locations 6, 8, and 9 (left-front door at centerline, left-front door at mid-rear, and left-front door at upper centerline, respectively) were integrated and used to estimate door velocity in the direction of the vehicle lateral axis at the time of ATD contact. Only signals that were coded as valid and without error were included in the analysis.

To compare door velocities from different vehicles, integrated accelerometer signals were time shifted so that t_{zero} corresponded to the time of first contact between the struck-side door and the driver ATD, as determined by either an increase in pelvis velocity or the development of a velocity differential between the ribs and spine.

Table 33. Vehicle information and door accelerometer locations in SNCAP tests used to estimate door velocities

Test No.	**Vehicle Manufacture**	**Vehicle Model**	**Year of Manufacture**	**Center Line Accel.**	**Mid-Rear Accel.**	**Upper Centerline Accel.**
3164	VW	Beatle	1999	X		X
3265	Chevy	Malibu	2000	X	X	X
3291	Buick	Le Saber	2000	X	X	X
3383	Hyundai	Sonata GLS	2000	X	X	X
3446	Saturn	SL2	2000	X	X	X
3463	Honda	Civic	2001	X		X
3464	Honda	Accord Ex	2001	X	X	
3465	Honda	Civic Lx	2001	X	X	X
3478	KIA	Sophia	2000	X	X	X
3486	Hyundai	Elantra	2001	X	X	X
3731	Mitsubishi	Eclipse	2001	X	X	X
3797	Saturn	L100	2002	X	X	X
3846	Chevy	Malibu	2002		X	X
3900	KIA	Sedona	2002		X	X
4082	Honda	CR-V Ex	2002		X	
4083	Honda	CR-V Lx	2002			X
4226	Subaru	Outback	2002	X	X	X
4302	Honda	Pilot	2003		X	X
4573	Chrysler	Pacifica MPV	2004	X		X
4658	Hyundai	Accent	2003	X	X	X
4728	Honda	Accord	2003	X	X	X
4810	Ford	Freestar	2004		X	X
4932	Chrysler	Town n Country	2005	X	X	X
5268	Chevy	Malibu	2005		X	X
5323	Saturn	Relay	2005	X		X
5377	Pontiac	G6	2005	X	X	X



No.	Location
1	Right Sill at Front Seat
2	Right Sill at Rear Seat
3	Right Floor Pan Above Axle
4	Left Sill at Rear Door
5	Left Sill at Front Door
6	Left Front Door Centerline
7	Right Rear Occupant Compartment
8	Left Front Door at Mid Rear
9	Left Front Door, Upper Centerline

No.	Location
10	Left Rear Door, Mid Rear
11	Left Rear Door, Upper Center Line
12	Left Lower B-Pillar
13	Left Lower B-Pillar
14	Left Lower B-Pillar
15	Left Lower A-Pillar
16	Front Seat Track
17	Rear Seat Track or Structure
18	Vehicle C

Figure 79. Locations of door accelerometers used in SNCAP testing

The average velocity profiles at the centerline, mid-rear, and upper centerline locations, along with corridors corresponding to +/- one standard deviation velocity profiles are shown in Figure 80, Figure 81, and Figure 82. In almost all SNCAP tests that were analyzed, first contact between the intruding door and the ATD occurred at the pelvis. As a result, t_{zero} in Figure 80, Figure 81, and Figure 82 represents the time of pelvis contact. It was difficult to establish the time of thorax contact from the rib and t-spine velocity data because the deformations of the thoracic ribs were small in most of the tests. Consequently, the differential velocity between the upper rib and t-spine was also small.

Average door velocities at the left-front, mid-rear, and upper-centerline locations at the time of pelvis contact are 9.2 m/s, 9.5 m/s, and 8.0 m/s. For the left-front and mid-rear positions, door velocities at pelvis contact are close to peak door velocity, which is reasonable since the left-front and mid-rear accelerometers are both mounted at the same height on the door. For the upper centerline velocity in Figure 82, peak velocity is 9.8 m/s and occurs after ATD contact.

In general, the calculated door velocities are slightly lower than those estimated from the FMVSS 214 tests. This may result from differences in locations of door accelerometers between the SNCAP and FMVSS 214 tests, a larger number of vehicles analyzed in the

SNCAP tests, and/or the newer average model year for vehicles in the SNCAP tests that may have resulted in improved side impact protection.

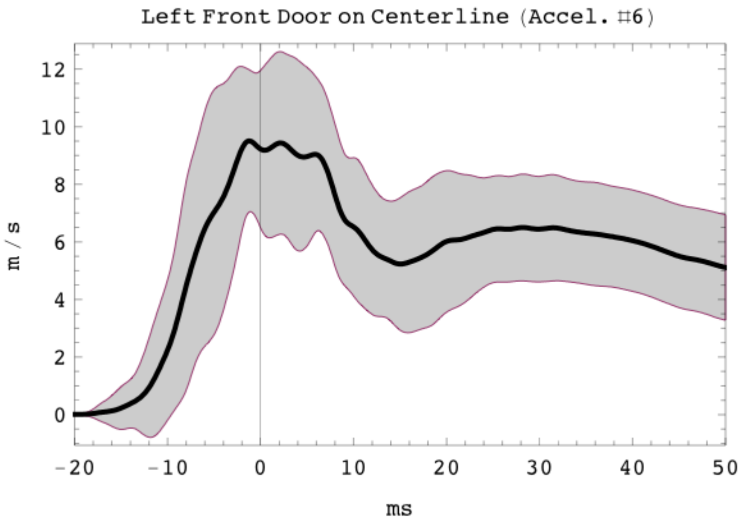


Figure 80. Average driver-door velocity history and and +/- one standard deviation corridor from left-front accelerometer in 27 SNCAP tests

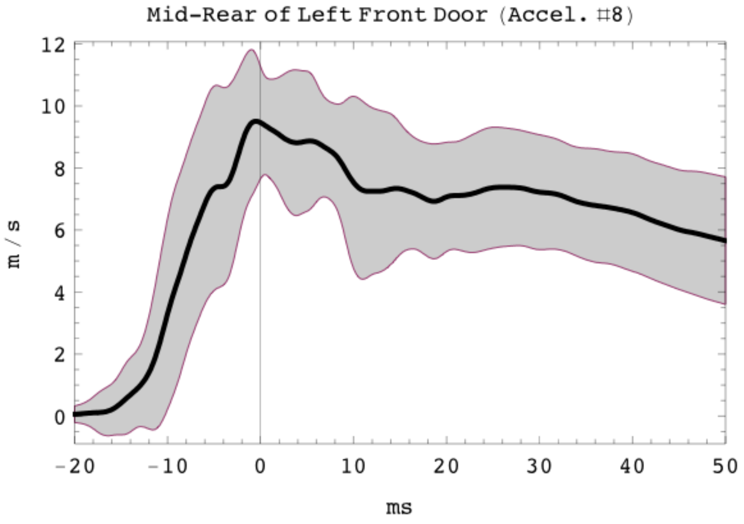


Figure 81. Average driver-door velocity history and +/- one standard deviation corridor from mid-rear accelerometer in 27 SNCAP tests

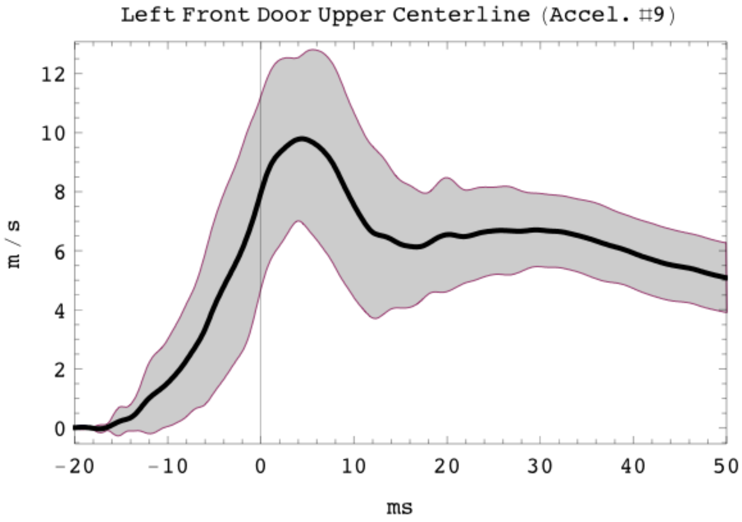


Figure 82. Average driver-door velocity history and +/- one standard deviation corridor from upper-centerline accelerometer in 27 SNCAP tests

4. Abdominal Impact Response Studies

4.1 Frontal Loading

This chapter summarizes research performed to investigate the impact response of the abdomen to frontal loading. Table 19 summarizes the studies explained in more detail in the following sections of the report.

Table 34. Summary of human cadaver and animal front-impact testing

Study	Horsch 1985	Cavanaugh 1986	Morgan 1987	Nusholtz 1988	Miller 1991	Hardy 2001		Shaw 2004
Subjects	17 anesthetized porcine	12 human cadavers	12 human cadavers	6 human cadavers	25 anesthetized porcine	9 human cadavers	1 human cadaver	4 human cadavers
Subject Position	Free-back	Free-back	Sled buck Unrestrained	Free-back	Fixed-back Supine	Free-back	Fixed-back	Fixed-back
# Tests	17	12	12	48	29	9	7	4
Impactor	Wheel	Rigid Bar	Wheel	Semi-circular tube	Wheel	Rigid Bar	Rigid Bar	Wheel
Impactor	Rim: Soft/stiff/rigid Column angle: 20°/30° Spokes: vert./horiz.	25 mm diam. 32 kg (n=8) 65 kg (n=4)		Rim: Stiff 18 kg	Production-level 90° to body	25 mm diam. 48 kg	25 mm diam. 48 kg	Rim: Stiff 64 kg 45° to body
Velocity	8.9 m/s	4.87-13.02 m/s	6.7 m/s 9.4 m/s 11.1 m/s	2-3 m/s (n=43) 6.5 m/s (n=5)	1.7 – 12.4 m/s	6 m/s (n=5) 9 m/s (n=4)	3 m/s (n=2) 6 m/s (n=3) 9 m/s (n=2)	4 m/s
Location	5 cm below xiphoid (level of liver)	L3	Ribs 8-10	L2	L4	L3 (n=6) T11 (n=3)	L3	T12
Soft Tissue Injuries	Liver lacerations	Liver lacerations Mesenteric laceration	Liver lacerations	Liver lacerations Kidney contusions Mesenteric tear Stomach contusion Diaphragm lacerations Jejunum contusion	Cecum rupture Lg. Bowel transection Rectum rupture Spleen transection Jejunum transection, laceration Mesentery laceration, contusion	Liver lacerations Spleen lacerations Diaphragm lacerations Cecum lacerations	None	None

Study	Horsch 1985	Cavanaugh 1986	Morgan 1987	Nusholtz 1988	Miller 1991	Hardy 2001		Shaw 2004
Findings	Cmax=32-50% VCmax=0.9-2.4 m/s Injury correlation: Rim stiffness VCmax Cmax	Abd. Stiffness: 20.8 kN/m (6.1 m/s) 70.3 kN/m (10.4 m/s) Cmax=66% VCmax=2.6-9.42 m/s	Compared Hybrid III and cadaver motions.	Injury correlates with impact energy transfer	Abd. Stiffness: 23.6 kN/m (3.73 m/s) 70.8 kN/m (7.74 m/s) Cmax=50%	Abd. Stiffness: 27 kN/m (6 m/s) 63 kN/m (9 m/s)	Abd. Stiffness: 10 kN/m (3 m/s)	THOR and Hybrid III responses are stiffer than cadaver responses.

Stalnaker (1985) Abdominal Trauma – Review, Response, and Criteria

In a review of abdominal frontal impact studies, Stalnaker et al. (1985) reexamined data from primate studies done in the early seventies and one human cadaver study (Walfisch 1980). Six different types of impactors (three bars, three wedges) as well as three different impact locations (upper, middle, lower) were used. The data were averaged together regardless of impactor location and shape. The authors then used this averaged data to create an impact response corridor at 12.1 m/s. This corridor assumes no difference between species, type of impact (lateral vs. frontal), direction of impact, or impactor shape. The corridor was then scaled to an impact velocity of 10 m/s as shown in Figure 83. The authors concluded that the viscous criterion (VC, velocity times compression) is relevant for predicting injury in primates and that primate results are an appropriate predictor for human abdominal injury.

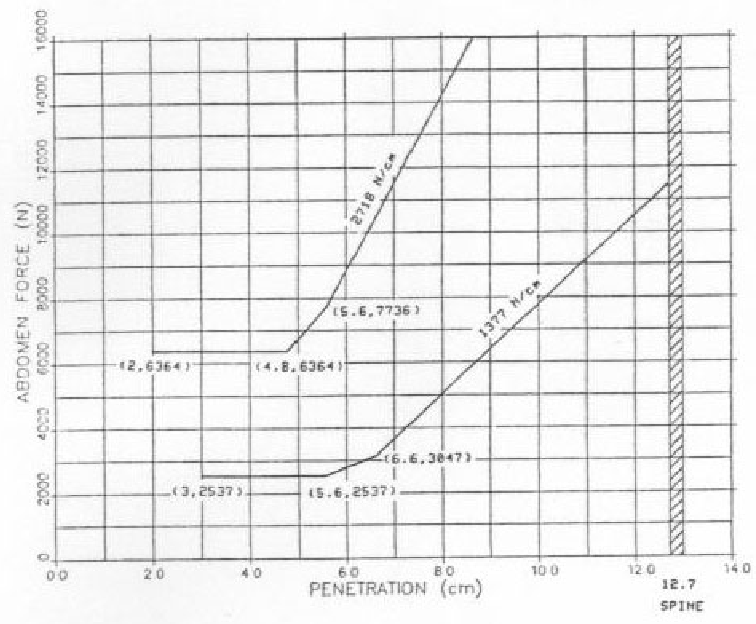
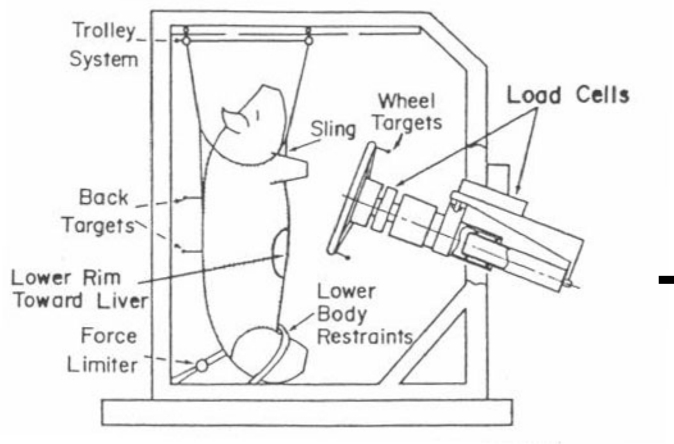


Figure 83. Scaled abdomen force-deflection corridor for 10m/s (Stalnaker 1985)

Horsch (1985) Mechanism of Abdominal Injury by Steering Wheel Loading

Horsch et al. investigated the effects of steering wheel design on abdominal injury using impact tests on seventeen anesthetized porcine specimens. Using the test setup illustrated in Figure 84, the animals were impacted 5 cm below the xiphoid process (at the level of the liver) while suspended upright in a trolley system and accelerated into the lower rim of a steering wheel. The steering wheel variables tested were rim stiffness (soft, stiff, rigid), column angle (20° and 30° to horizontal), and the two-spoke position (vertical, horizontal).



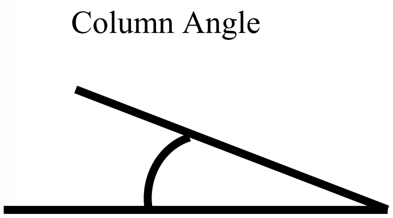


Figure 84. Test set-up for steering-wheel impact experiment (Horsch 1985)

In the stiff rim tests, all eight animals sustained liver lacerations rated AIS 5. The same AIS 5 level liver injury also occurred in the one rigid rim test. For the soft rim tests, three of four animals sustained liver injuries rated AIS 4 when the column was angled at 30°, although none of the four animals sustained injuries when the column was angled at 20°. Statistically, the abdominal AIS score correlated slightly with column angle ($p = 0.038$) and strongly with rim stiffness ($p = 0.002$); severe injuries were associated with the stiffer rims. Similarly, the number of liver lacerations per subject correlated marginally with column angle ($p = 0.12$) and strongly with wheel stiffness ($p = 0.0001$). There was no correlation between injury severity and the position of the spokes. Sixteen of the subjects sustained rib fractures. There was no correlation between rim stiffness, column angle or spoke position and the occurrence of rib fractures.

Abdominal compression in this experiment ranged from 32 – 50%, and generally increased with the abdominal injury AIS score ($R = 0.62$, $p = 0.0077$). The Viscous criterion (VCmax) also correlated with the abdominal AIS score ($R = 0.72$, $p = 0.0012$) and had a range of 0.9 – 2.4 m/s. There was no correlation between spine acceleration and injury.

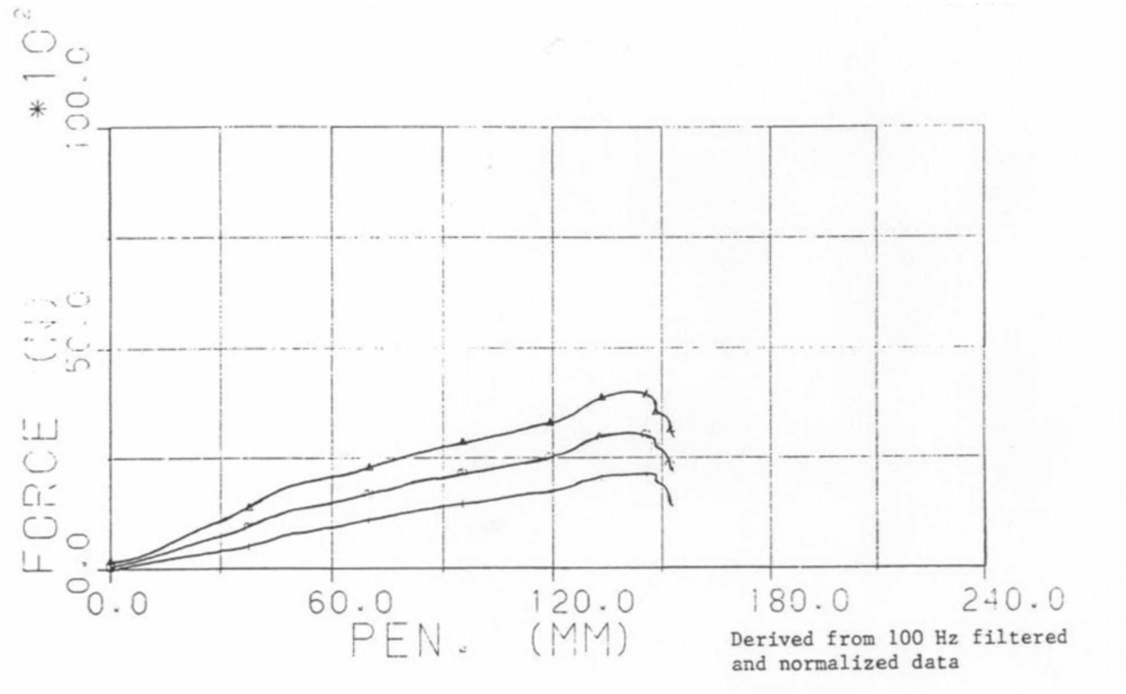
Abdominal forces were not high enough to compress the energy-absorbing steering column even though they were high enough to cause severe abdominal injury. According to the investigators, this suggests that the steering wheel is better suited for limiting abdominal injury than the steering column.

Cavanaugh (1986) Lower Abdominal Tolerance and Response

Cavanaugh et al. used a rigid bar impactor to estimate the force-penetration response of steering wheel impacts to the abdomen in twelve human cadavers at the level of the L3 vertebra. Each unenbalmed, pressurized cadaver was seated in an upright, free-back position with the legs stretched out horizontally forward. The impactor was a straight bar with a length of 381 mm, a diameter of 25 mm, and a mass of either 32 kg (n = 8) or 64 kg (n = 4). The velocity of impact ranged from 4.87 – 13.01 m/s. All results were normalized to 76 kg using the equal-velocity/equal-stress method (Eppinger 1984).

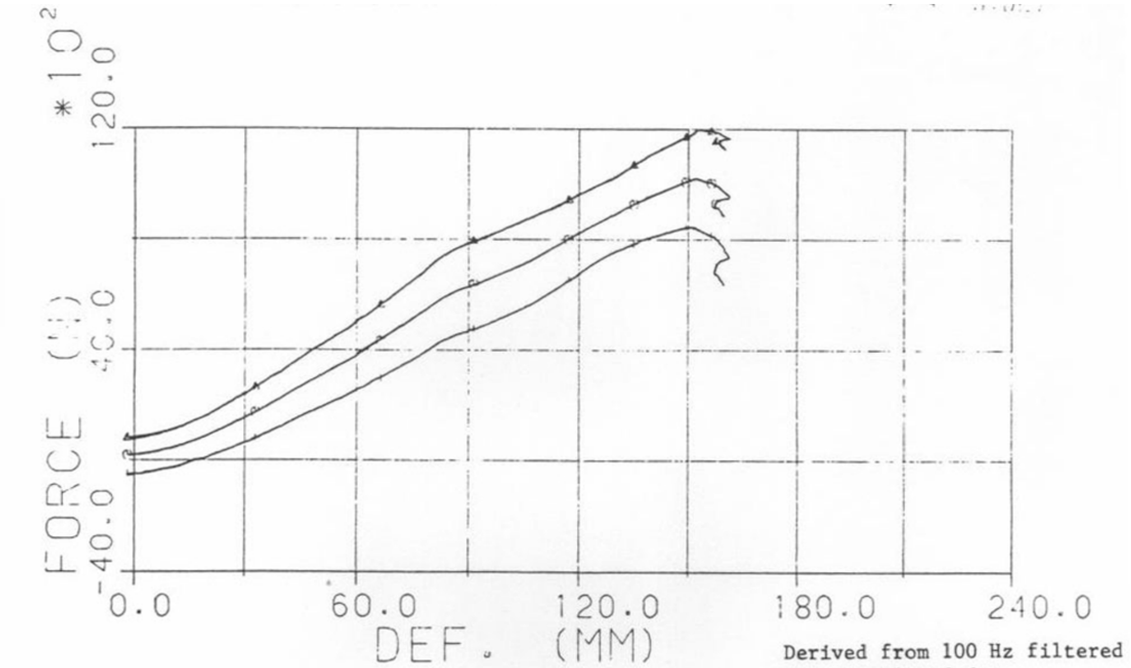
Two of the cadavers sustained liver injuries, both of which were AIS 4. A third cadaver sustained a mesenteric injury that scored an AIS 3. Only two other cadavers sustained injuries, both of which were rib fractures rated AIS 2 and AIS 3. The remaining seven cadavers sustained no abdominal injuries. The authors noted that using cadavers to study injury has the shortcoming of not being able to assess organ contusion (bruising), which usually scores AIS 2-3, because adequate perfusion of the small blood vessels is impossible even when the larger vessels are pressurized. The authors also noted that in one of the two cadavers with liver injuries, the liver was softer than normal due to metastatic carcinoma. In the second case of liver injury, there were severe spleen lacerations as well. The impact level for this test was actually at the L1 vertebra, which placed the impactor directly over the liver and spleen. The investigators also mention that the mesentery laceration may have been a pre-impact condition.

The force-penetration results are shown in Figure 85. The authors noted that results were strongly affected by scaling techniques. Stiffness was proportional to impactor speed and mass, suggesting rate sensitivity of the response. At low velocities (6.1 m/s average, n = 5), the abdomen has an initial stiffness of 20.8 ± 5.4 kN/m. At higher velocities (10.4 m/s average, n = 7), the abdomen has an initial stiffness of 70.3 ± 5.9 kN/m. The unloading phase of the force-deflection response is a vertical line, indicating no restorative forces. Maximum compression ranged from 36 – 72.4%. On average, bottoming out of the abdominal organs occurred at 66% of abdominal depth. The Viscous criterion (VC) ranged from 2.6 – 9.42 m/s. No correlation between injury and VC was attempted.



Derived from 100 Hz filtered and normalized data

Low-Velocity Force-Penetration Corridor



Derived from 100 Hz filtered and normalized data

High-Velocity Force-Penetration Corridor

Figure 85. Mid-abdomen response corridors (Cavanaugh 1986)

Morgan (1987) Interaction of Human Cadaver and Hybrid III Subjects with a Steering Assembly

In a series of sled tests, Morgan et al. investigated the injury response and kinetics of twelve cadavers and the Hybrid III mid-sized male anthropomorphic test device (ATD) when involved in an unrestrained impact with a steering wheel. The subjects were seated in a sled buck equipped with an energy-absorbing column assembly and had their knees partially restrained by foam. Tests were run at sled velocities of 6.7 (n=4), 9.4 (n=1) and 11.1 (n=7) m/s. The average changes in velocity (ΔV) for these tests were 7.3, 10.5 and 12.6 m/s, respectively. The steering wheel rim impact location was at ribs eight through ten on the cadavers and at the equivalent sixth rib of the Hybrid III ATDs. For one of the cadavers in the low-velocity group, no data were reported other than the injury response.

Three of the seven high-velocity cadavers and one of the four low-velocity cadavers sustained abdominal injuries, all of which were to the liver. Of the injuries in the high-velocity group, one was rated AIS 5 and two were rated AIS 4. The injury sustained by the cadaver in the low-velocity group was rated AIS 4. The thorax sustained the majority of injuries with ten of the twelve cadavers sustaining at least an AIS 2+ injury. Rib fractures accounted for most of these injuries.

Comparing the kinetics of the cadavers to those of the Hybrid III, the authors noted that the axial column loading and effective mass on the steering wheel matched up well, as did the force-time histories of the column loading. However, the cadavers deformed the upper rim more and the lower rim less than the Hybrid III and had higher initial peak spinal accelerations. The cadavers also absorbed more of the initial kinetic energy than the Hybrid III. The authors found that using film analysis to measure abdominal compression was unreliable, so no compression or VC data is available.

Nusholtz (1988) Steering System Abdominal Impact Trauma

The study by Nusholtz et al. used an impactor to simulate steering wheel loading in a manner similar to the experiment by Cavanaugh (1986). However, instead of a rigid bar, this experiment used an 18 kg, semicircular tube angled to approximate automobile steering-wheel geometry. In total, eighty-eight impacts were performed on six cadavers, of which forty-eight were to the abdomen. Forty-three of these abdominal impacts were in the low-velocity range of 2-3 m/s and were carried out on all six cadavers. Five of the abdominal impacts were high-velocity (6.5 – 10.8 m/s) and were carried out on five of the cadavers. The impacts were aimed at the midway point between the most inferior point of the tenth rib and the most superior point of the iliac crest. This point is approximately at the level of the L2 vertebra. The cadavers were positioned in a free-back, seated position with their lower legs hanging over the edge of a table.

An accurate account of abdominal injuries resulting from specific impacts is not possible due to the multiple impacts on each cadaver, including impacts to the thorax. After all the impacts, abdominal injuries sustained were liver lacerations, kidney contusions, a mesenteric tear, a stomach contusion, a diaphragm laceration, and a jejunum contusion.

Of the two cadavers that received only abdominal impacts, one sustained no injuries (the only one to do so), while the other sustained a liver laceration with no other injuries. The one cadaver that received no high-velocity impacts sustained one superficial liver laceration. The authors believe that this liver laceration, which could only be a result of low-velocity impacts, was not realistic due to the extreme stiffness of the impactor.

In determining the best predictor of abdominal injury, the authors conclude that energy transfer is the best measure. Of the measurable variables, Viscous criterion (VC), specific absorbed energy, abdominal injury criterion (VmaxCmax), deflection, peak force and impactor velocity all correlated well with the amount of energy transferred. The only variable they examined that would not be a good indicator of abdominal injury is spinal acceleration. Of the variables that did correlate with energy transfer, other considerations such as ease of acquisition and accuracy of measurement would contribute to determining the best measure for abdominal injury.

Miller (1991) Tolerance to Steering Wheel-Induced Lower Abdominal Injury

Miller (1991) investigated steering wheel impacts with twenty-five anesthetized porcine subjects. A V-shaped support held the animals in a supine position with the steering wheel held perpendicular above the abdomen at the level of the L4 vertebra. The steering wheel was a production-level type, with no further specifications given. On a few of the subjects, multiple low-velocity impacts were done for a total of twenty-nine impact tests. While the velocity at impact was not reported for each test, the peak velocity of abdomen deformation was 1.7 – 12.4 m/s.

The abdominal injury results, summarized in Table 35, show that there were eight AIS 5, one AIS 4, four AIS 3 and two AIS 2 injuries. The severe (AIS 4, 5) injuries were cecum rupture (n = 4), large bowel transection (n = 2), rectum rupture, spleen transection, and jejunum transection (AIS 4). The less severe injuries (AIS 2, 3) were spleen rupture, jejunum laceration (n = 3), mesentery laceration and mesentery contusion. There was a strong correlation between sustaining an injury of AIS 4+ and VCmax, as determined by a chi-square test. No threshold for sustaining a severe injury was established.

Table 35. Injury by location and severity (Miller 1991)

Organ injured	Number of Injuries			
	AIS 5	AIS 4	AIS 3	AIS 2
Cecum	4	-	-	-
Large Bowel	2	-	-	-
Rectum	1	-	-	-
Spleen	1	-	1	-
Jejunum	-	1	3	-
Mesentery	-	-	-	2

From the force-deflection results, which were normalized to 76 kg by equal-stress/equal-velocity scaling (Eppinger 1976), two response corridors were developed. Based on sixteen tests with a low velocity of deformation (v = 3.73 ± 0.31 m/s) the abdomen stiffness is 23.6 ± 2.75 kN/m. From nine tests at the high velocities of deformation (v = 7.74 ± 0.829 m/s), the abdomen stiffness is 70.8 ± 12.3 kN/m. These force-deflection responses are linear until about halfway between initial impact and peak force, at which point the abdominal organs bottom out against the spine. On average this occurred at 50% of abdominal compression. During the unloading phase, the force-deflection curve was approximately vertical.

While the stiffness measurements are similar to those of Cavanaugh (1986), the author noted that stiffness results were expected to be smaller because of differences in the experimental setup. Cavanaugh's stiffness corridors are for higher velocities (6.1 and 10.4 m/s versus 3.7 and 7.7 m/s) and Cavanaugh used a thinner bar. Miller suggests that the use of live subjects, thus making muscle tone present and the organs more firm, accounts for the higher than expected stiffness measured in her study. She also indicates that the higher values may result from the difference in subject positioning (supine versus seated), which changes the amount of abdominal depth because a paunch develops when human cadavers are seated. The porcine subjects had a smaller comparable abdominal depth, thus causing forces to increase more per increment of compression. This may also account for the reason why Miller noticed bottoming out at 50% while Cavanaugh noticed bottoming out at 66% of abdominal depth.

Hardy and Schneider (2001) Development and Refinement of Abdominal-Response Corridors

Hardy and Schneider investigated steering wheel impacts to ten human cadavers using a bar with the same dimensions as that used by Rouhana (1986). The subjects were in a seated position with legs stretched out horizontally. The testing conditions are summarized in Table 36. Nine of the cadavers were used in free-back tests, six of which were impacted at the mid-abdomen (L3 vertebra) and three at the upper abdomen (T11 vertebra). The impact velocities for the mid-abdomen tests were 6 m/s (n = 3) and 9 m/s (n = 3). Likewise, the upper abdomen impact velocities were 6 m/s (n = 2) and 9 m/s (n=1). One cadaver was used in seven fixed-back tests, all at the mid-abdomen with impact velocities of 3 m/s (n = 2), 6 m/s (n = 3) and 9 m/s (n = 2).

Table 36. Text matrix (Hardy 2001)

Position	Location	Velocity	Number
Free-back	L3	6 m/s	3
		9 m/s	3
	T11	6 m/s	2
		9 m/s	1
Fixed-back	L3	3 m/s	2
		6 m/s	3
		9 m/s	2

Abdominal injuries sustained by the cadavers in the free-back, mid-abdomen tests were tears to the diaphragm, liver and cecum. In the free-back, upper-abdomen tests, the abdomen injuries were tears to the liver, diaphragm, and spleen. The autopsy results from the fixed-back test revealed no abdominal injuries, but did report several bilateral rib fractures. Every cadaver sustained an injury score of at least AIS 3; there were three MAIS 5, four MAIS 4 and two MAIS 3 injuries. No correlation between abdomen MAIS and response parameters could be distinguished.

Force-deflection corridors were developed for the mid-abdomen, free-back tests. The corridors from the free-back, mid- and high-velocity tests are shown in Figure 86. The average stiffness of the mid-velocity (6 m/s) group is 27 kN/m and is 63 kN/m for the high-velocity (9 m/s) group. The two mid-abdomen, fixed-back, low-velocity (3 m/s) tests have an average stiffness of 10 kN/m.

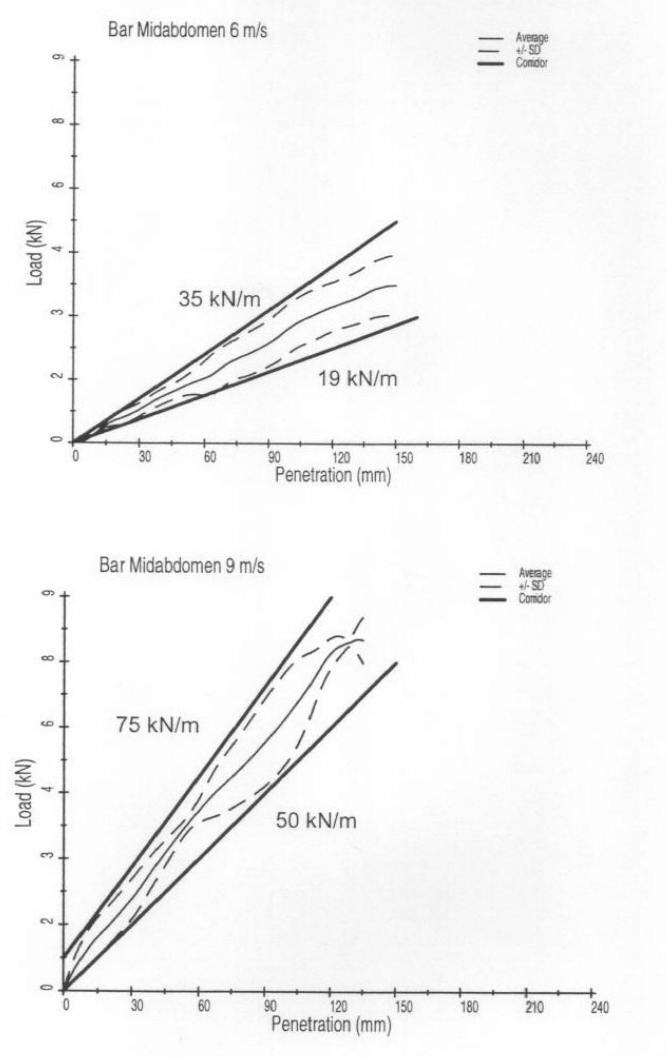


Figure 86. Stiffness corridors of 6 m/s (left) and 9 m/s (right) rigid bar, free-back tests (Hardy 2001)

The fixed-back tests run on a single cadaver were carried out to eliminate the response due to the motion of the spine and the mass of the whole body. The results show that the abdomen is rate sensitive, even when the whole body motion component is removed. It is still largely unknown to what degree the abdomen's rate sensitivity is due to mass recruitment or tissue viscosity. The initial portion of the fixed-back force-deflection response matches up with the free-back responses, after which the stiffness of the abdomen in the fixed-back tests decreases. The investigators suggest that the larger stiffness values in the free-back tests are likely due to the acceleration of the whole body.

Shaw (2004) Assessment of the Thor and Hybrid III Crash Dummies: Steering Wheel Rim Impacts to the Upper Abdomen

Shaw et al. impacted the abdomens of THOR and Hybrid III dummies and four cadavers. While the THOR and Hybrid III were impacted at the lower, mid and upper abdomen, the cadavers were only impacted in the upper abdomen (T12 vertebra). The impactor was a 64 kg, stiff steering wheel oriented at 45°. All impact velocities were 4 m/s and penetration was limited to 30% of abdominal depth. The cadaver results were normalized to 78 kg (Eppinger 1984).

There were no soft-tissue injuries to the cadavers, only rib fractures. The authors attributed this fact to the slow velocities, low penetration and inadequate perfusion of the liver and spleen.

The force-deflection corridor derived from these tests, shown in Figure 87, shows a linear loading with a near vertical unloading. The softer response of cadavers two, three, and four are attributed to subcutaneous air pockets caused by the investigator's pressurization technique. Cadaver four had a low bone density, which led to multiple rib fractures, resulting in a higher amount of compression.

THOR and Hybrid III responses were stiffer than those of the cadavers. The response of THOR was more cadaver-like when its jacket was removed. Similarly, when a gel-based insert developed by Rouhana (2001) for the Hybrid III was used, the results of the Hybrid III also became more cadaver-like. In both the THOR and Hybrid III dummies, the embedded sensors underestimated rim penetration.

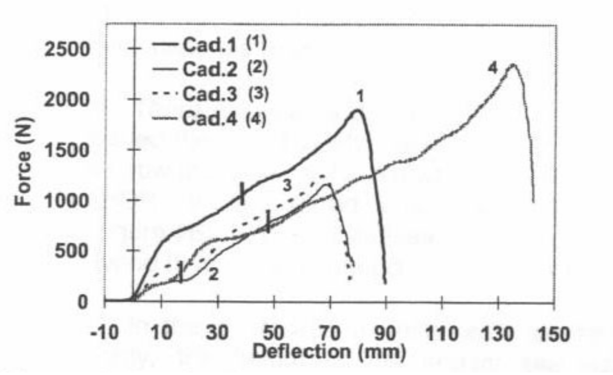


Figure 87. Human cadaver force-deflection results (Shaw 2004). Vertical dash indicates first rib fracture (Cad 1, 2, 4)

4.2 Lateral Impact

This section discusses the results of lateral impact studies performed on human cadavers and animal surrogates. Table 37 summarizes the experimental set-ups and key results. Each experiment is discussed in detail in the following section.

Table 37. Summary of lateral impact tests

	Walfisch 1980	Rouhana 1986	Viano 1989	Viano 1993	Talantikite 1993	Cavanaugh 1996	Pintar 1997
Subjects	11 human cadavers	214 anesthetized rabbits	14 human cadavers	10 anesthetized porcine	7 human cadavers	17 human cadavers	25 human cadavers
Tests	11	214	14	10	7	17	
Impactor	7 cm wide 2.5 cm tall	Face of 7.6 cm diameter Rigid 1.5 kN force-limiting 1 kN force-limiting	Face of 15.2 cm diameter impactor 23.4 kg	12.7 cm protrusion 2.54 cm diameter edge 1.1 kN crush force (n=5) 3.7 kN crush force (n=5)	Face of 15.2 cm diameter impactor 23.4 kg	Flatwall Unpadded Soft 55-69 kPa Stiff 90-72 kPa	Flat wall, flat padded wall, rigid wall with 12 cm protrusion near pelvis
Velocity	4.43 m/s (n=7) 6.26 m/s (n=4)	5-15 m/s	3.6 – 10.2 m/s	9.1 m/s	4 – 7 m/s	6.7 m/s 8.9 m/s	24 km/hr 32 km/hr
Location	9th rib, Right side 90°	90°	7.5 cm below xiphoid L/R 60°	3.75 cm below xiphoid Left 90°	7.5 cm below xiphoid Right 90°	Left 90°	Left side
Position	Free-back Horizontal	Free-suspended Horizontal	Free-suspended Upright	Free-suspended Upright	Free-suspended Upright	Free-back Seated	Seated ridig back
Injuries	Rib fractures Liver laceration	Liver	Diaphragm lacerations Liver lacerations Rib fractures	Liver lacerations Spleen lacerations Hepatic arteries/veins tears Hemoperitoneum	Liver lacerations Diaphragm wound Internal hepatic parenchyma contusion Rib fractures	Liver lacerations Spleen lacerations Rib fractures	Rib fractures Hip fractures Spleen and liver lacerations
Findings	AIS 3+: Fmax = 4.5 kN Pmax = 260 kPa No Injury: Cmax = 14%	1 kN is too stiff to prevent liver injury Renal injury reduced by using 1 kN face	50% risk AIS 3+: VC = 2.01 m/s Cmax = 51% AIS 4+: VC = 2.26 m/s Cmax = 47%	Softer armrest reduced injury severity TTI in SID, BioSID do not predict injury C, VC criteria in BioSID good injury predictors	AIS 3+: Fmax = 4.4 kN VC = 1.98 m/s	BioSID TTI better than SID TTI ASA not a good injury predictor VC of BioSID is best criteria No Injury: < 69 kPa padding	AIS 4+ injury risk curves using TTI, max VC, max %C

Walfisch (1980) Designing of a Dummy's Abdomen for Detecting Injuries in Side Impact Collisions

Walfisch et al. investigated the force-penetration response and corresponding injuries of the abdomen when laterally impacted. The authors dropped eleven cadavers from a height of either 1 or 2 meters onto a stationary "armrest" at the ninth right rib. The armrest measured 7 cm wide and 2.5 cm tall but the specific shape and stiffness characteristics are not reported in detail

Only eight of the eleven cadavers were evaluated for injury due to pre-existing conditions in the other three. One of the remaining subjects had a substantially different response from the rest. The remaining cadavers incurred two AIS 5, two AIS 4, two AIS 3 and two AIS 0 abdominal injuries. All abdominal injuries were to the liver.

Threshold levels for sustaining an injury of AIS 3+ were: maximum force = 4.50 kN and maximum pressure = 260 kPa. While no correlation between penetration and injury could be established, the authors concluded that a penetration of less than 14% of total abdominal thickness would result in no injury.

The results of this study were used by the authors to develop a side impact abdominal insert for Part 572 that would detect forces greater than 4.50 kN concurrent with deflections greater than 14%.

Problems with this study are that lateral drops of the cadaver onto the armrest may not allow realistic positioning of abdomen organs as they are in the driving postures. The impact velocities of 4 to 6 m/s are well below door-to-ATD contact velocities in recent FMVSS 214 tests. The displacement data were based on film analysis, but the paper is unclear how the subjects were targeted for digitizing.

Rouhana (1986) The Effect of Limiting Impact Force on Abdominal Injury: a Preliminary Study

Rouhana et al. impacted 214 rabbits on the left and right sides with the flat side of a 7.6 cm diameter impactor. The rabbits were anesthetized and suspended by a sling in a supine position as shown in Figure 88. Impact velocities ranged from 3 – 15 m/s and compression levels ranged from 10% to 50%. For 94 of the tests, the impactor was modified with a Hexcel force-limiting face. Two types were used with different crush strengths of 1 kN and 1.5 kN. In the remaining 128 tests, a rigid impactor face was used.

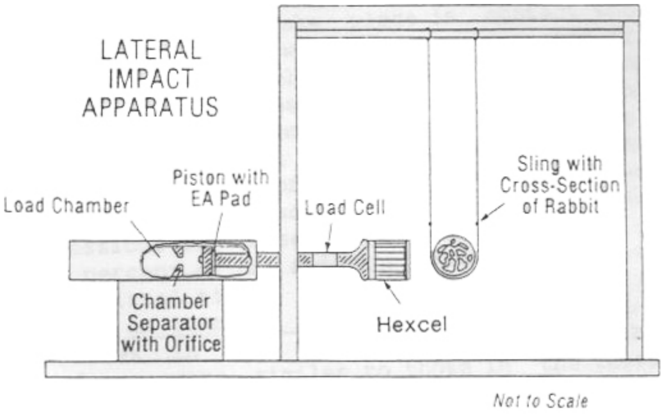


Figure 88. Set-up of Rouhana 1986 experiment

Results from the Hexcel testing indicate that a force-limiting impactor does reduce peak pressure by as much as one third, and it does reduce the risk of renal injury but not liver injury. From this, two major conclusions were drawn. One was that renal injury occurs at the time of peak force and the second was that the force-limiting material needs to have a crush strength less than 1 kN to protect the abdomen. The study resulted in very few spleen injuries, but the rabbit spleen is proportionally smaller than the human spleen.

The authors also investigated the correlation between injury and (1) the product of maximum velocity and maximum compression (VmaxCmax), (2) compression, (3) peak force and (4) velocity. The results are shown in Figure 89. While VmaxCmax correlates well with injury, the authors note that VCmax (the maximum of instantaneous velocity and compression), which, unlike VmaxCmax, is a function of time, provides more insight as to when injury is likely to occur. Therefore, where possible, they recommend that this criterion be used as an injury predictor. Finally, the authors remark that, for velocities above 5 m/s, compression alone is not a good indicator for injury; velocity must also be taken into account.

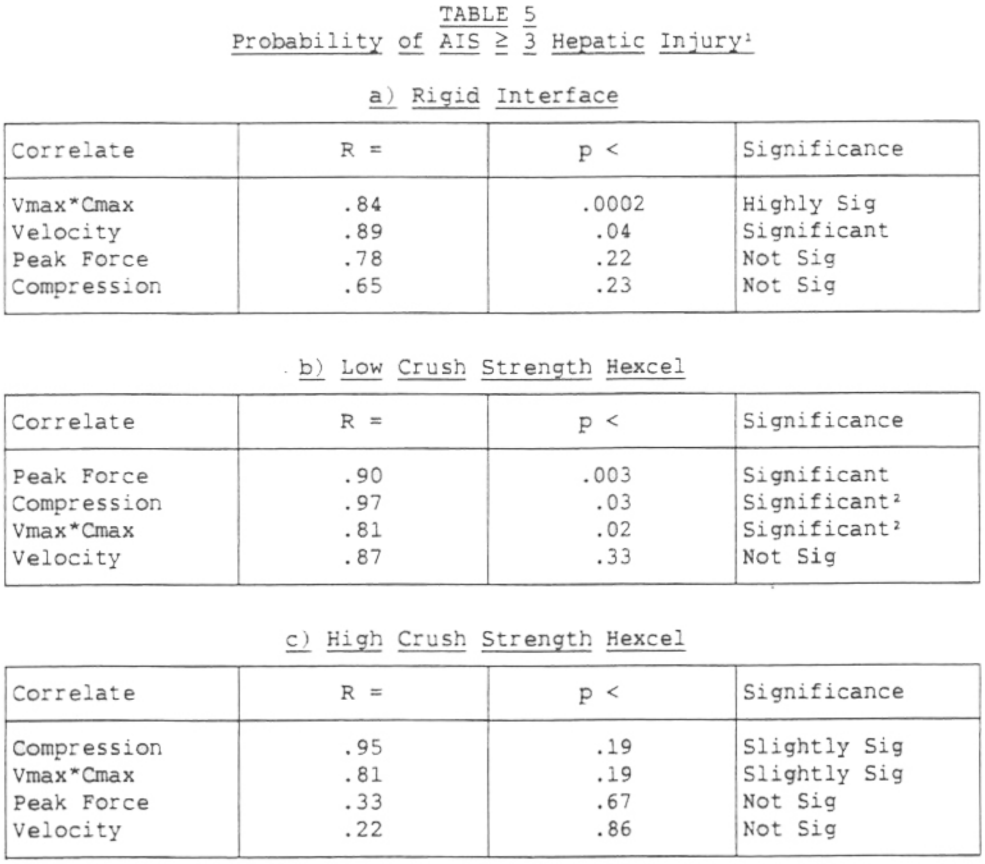


TABLE 5

Probability of AIS $\geq$ 3 Hepatic Injury[1]

a) Rigid Interface

Correlate	R =	p <	Significance
Vmax*Cmax	.84	.0002	Highly Sig
Velocity	.89	.04	Significant
Peak Force	.78	.22	Not Sig
Compression	.65	.23	Not Sig

b) Low Crush Strength Hexcel

Correlate	R =	p <	Significance
Peak Force	.90	.003	Significant
Compression	.97	.03	Significant[2]
Vmax*Cmax	.81	.02	Significant[2]
Velocity	.87	.33	Not Sig

c) High Crush Strength Hexcel

Correlate	R =	p <	Significance
Compression	.95	.19	Slightly Sig
Vmax*Cmax	.81	.19	Slightly Sig
Peak Force	.33	.67	Not Sig
Velocity	.22	.86	Not Sig

Figure 89. Injury correlations (Rouhana 1986)

Viano (1989) Biomechanical Responses and Injuries in Blunt Lateral Impact

Viano performed tests using fourteen human cadavers to study lateral impact response of the thorax, abdomen and pelvis. Forty-four tests were run, of which fourteen were to the abdomen using ten of the cadavers. As shown in Figure 90, the cadavers were suspended upright with their hands and arms overhead. All harnesses were released at impact. For the abdominal impacts, the impactor was centered 60° right or left of the midsagittal plane, through the center of gravity and 7.5 cm below the xiphoid process. The impactor was a pendulum with a flat face diameter of 15.2 cm and a mass of 23.4 kg. Impact velocities ranged from 3.6 – 10.2 m/s, which approach the range of ATD impact velocities in recent FMVSS 214 tests. Abdomen deflection was measured through film analysis, although the method of targeting is not detailed. A maximum stroke of 40 cm after initial contact was allowed to occur during the impacts.

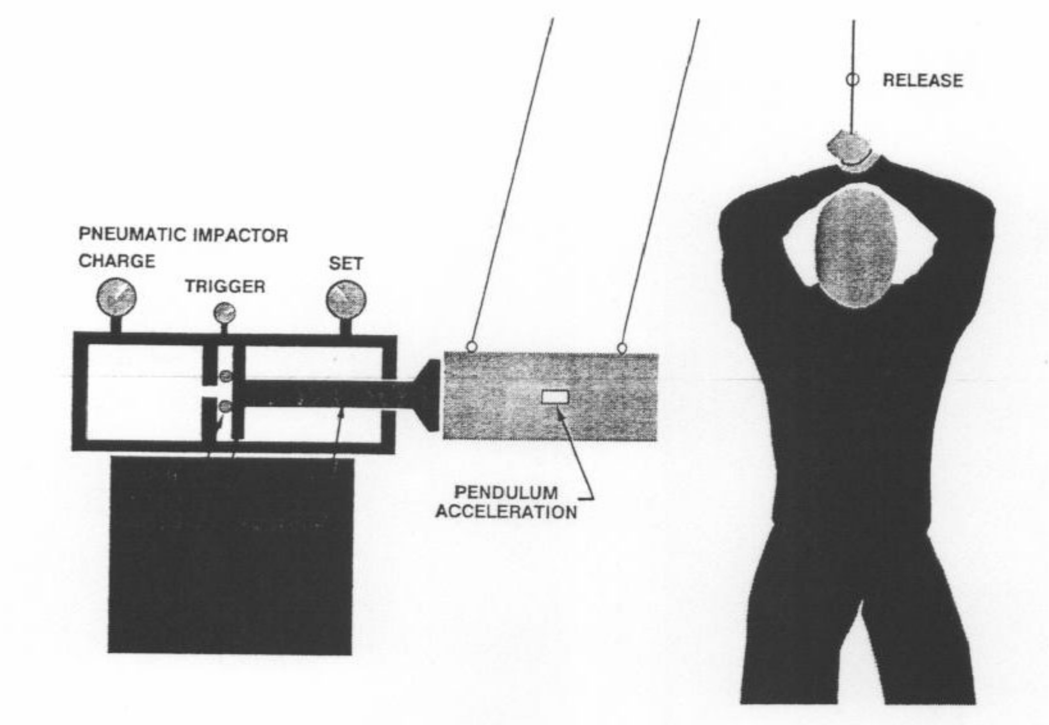


Figure 90. Experimental set-up for Viano 1989

Results were all normalized to a mid-sized male (Mertz 1984) and then grouped by low-, mid- and high-velocities (n = 6, 4, 4, respectively). These data were then averaged and renormalized to 4.3, 6.7 and 9.5 m/s. The force-deflection curves indicate an initial stiffness followed by a force-plateau. In the unloading phase, there appears to be some restorative forces, which may indicate rib involvement. The low-, mid- and high- force-deflection plots, as well as the force-time plots, are shown in Figure 91, together with the response corridors developed from these experiments.

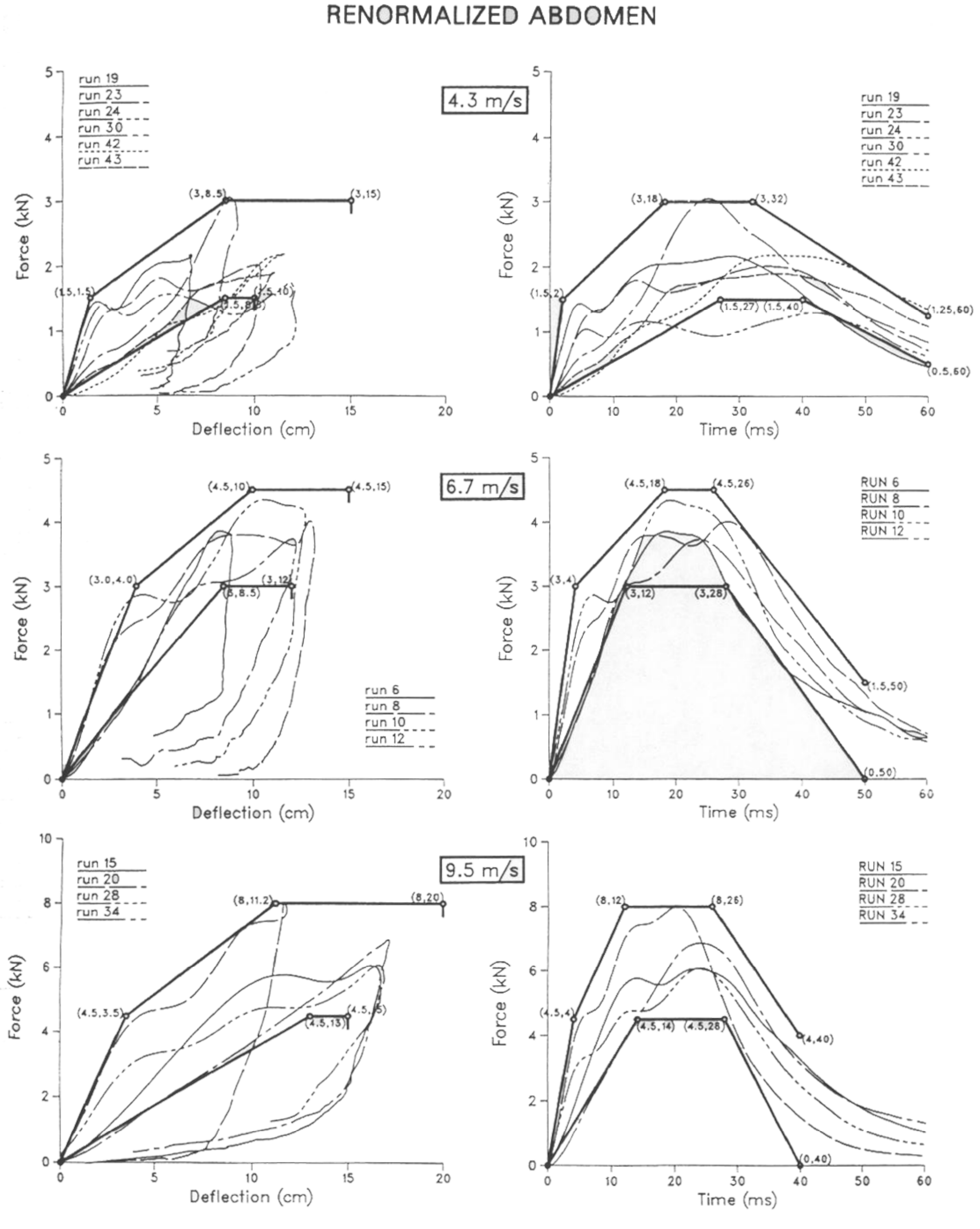


Figure 91. Abdomen response corridors by Viano (1989)

Of the cadavers used in this study, one sustained an abdominal injury rated AIS 4. This cadaver was impacted on the left side at 9.8 m/s and suffered lacerations to the diaphragm and liver. Only one other cadaver sustained any soft tissue damage, which was a lacerated liver (AIS 3). This cadaver was impacted on the right side at 9.8 m/s. Three other cadavers sustained AIS 3 injuries, all of which were rib fractures. Some cadavers were used in multiple tests, which may compromise injury assessment.

Using logist analysis, the authors calculated that the threshold for a 50% risk of serious abdominal injury (AIS 4+) is VC = 2.26 m/s and C = 46.8% of total abdominal depth. Likewise, for AIS 3+ (4 or more rib fractures), the tolerance limit is VC = 2.01 m/s and C = 51.2%. The apparent inconsistency in the compression criteria illustrates its limitation for use in high velocity impacts.

Viano and Andrzejak (1993) Biomechanics of Abdominal Injuries by Armrest Loading

Viano and Andrzejak accelerated ten anesthetized porcine subjects sideways into an 'armrest' to further study lateral impact response. The pigs were suspended in an upright position with the armrest positioned 3.75 cm below the xiphoid process. The armrest was a 5" (12.7 cm) protrusion with a 1" (2.54 cm) diameter rounded edge. For five of these tests, the armrest had a crush strength of 1.1 kN (soft). For the other five tests, the armrest had a crush strength of 3.7 kN (stiff). The impact velocity was 9.1 m/s. The near- and far-side ribs were instrumented with accelerometers. Signals from these accelerometers were integrated to estimate velocity of deformation, but rib displacements were not reported.

The stiff armrest caused deep liver and spleen lacerations, tears to major hepatic arteries and veins and serious peritoneum injuries. The average abdominal injury severity for the stiff group was AIS = 5.3 ± 1.0 while the average for the soft group was AIS = 2.3 ± 1.3. Statistically, the mean AIS scores of the two groups were significantly different ($p<0.005$).

Viano and Andrzejak also evaluated the SID and BioSID dummies in the same experiment. The Thoracic Trauma Index (TTI) was computed for the animal, SID and BioSID tests. The TTI scores for the SID and BioSID were lower than the animal scores, with the SID scoring lower than the BioSID. The compression (C) and Viscous (VC) responses of the BioSID were higher in the stiff armrest tests compared to the soft armrest tests. When evaluated against risk function developed by Viano (1991), the predicted injury risk levels were consistent with the animal results. Thus the authors suggest that Federal Motor Vehicle Safety Standard (FMVSS) 214 be revised to use the BioSID dummy instead of the SID dummy and to use VC and C injury criteria instead of the TTI.

Talantikite (1993) Abdominal Protection in Side Impact

Using a test procedure similar to that of Viano (1989), Talantikite et al. impacted seven human cadavers. However, instead of impacting the cadaver at 60° from the mid-sagittal plane, the cadavers were struck on the right lateral side. The same height of 7.5 cm below the xiphoid process was used, which approximately covers ribs seven through ten. The velocity of impact in this study was 4 – 7 m/s. Rib and spine accelerations and external displacement of the anterior and posterior surfaces of the abdomen are reported.

Injuries sustained by the cadavers were two AIS 4, one AIS 3 and three AIS 0. The AIS 4 cadavers suffered multiple liver lacerations and three rib fractures each. The injuries incurred by the AIS 3 cadaver were superficial liver wounds, a small diaphragm wound, and an internal hepatic parenchyma contusion. The authors report the primary injury mechanism to be compression of the ribs against the hepatic tissue. From these findings, the authors calculated the tolerance for AIS 3+ injuries to be Fmax = 4.4 kN and VC = 1.98 m/s.

Cavanaugh (1996) Abdominal Injury and Response in Side Impact

Cavanaugh et al. performed left-side impact sled tests of PMHS and SID and BioSID dummies into a flat wall. Seventeen cadavers were used in seventeen tests, and all were impacted on the left side, with their arms up. The velocity of impact was either 6.7 m/s (low) or 8.9 m/s (high). The test conditions were varied among two different types of padding, and unpadded protrusion at the pelvis, and an unpadded flat condition. Padding stiffness was either soft (8 - 10 psi; 55 – 69 kPa) or stiff (13 - 25 psi; 90 – 172 kPa). The cadaver tests set-ups are summarized in Table 38. Rib, spine, pelvis, and head accelerations were measured, as well as abdominal loading with two load cells.

Table 38. Cadaver tests by Cavanaugh (1996)

Wall Padding	Impact Velocity	No. of Tests
Unpadded	8.9 m/s	2
Unpadded	6.7 m/s	3
Soft	8.9 m/s	5
Stiff	8.9 m/s	4
Unpadded pelvic offset	8.9 – 10.5 m/s	3

Injuries sustained by the cadavers were liver lacerations (AIS = 2, n = 3), spleen lacerations (AIS = 2, n = 3; AIS = 3, n = 1; AIS = 4, n = 1) and rib fractures. Four of the eight unpadded tests produced liver and spleen lacerations, while only two of nine padded tests did. Force histories are reported, but no deflection data were collected.

When examining how the SID and BioSID Thoracic Trauma Index (TTI) responses compared to the cadaver injuries, they found that the BioSID was a better predictor of injury than the SID. Neither the BioSID nor SID Average Spinal Acceleration (ASA) criteria were good predictors of injury. The authors recommend the Viscous (VC) response of the BioSID as a good criterion for abdominal injury.

Based on the wall padding results, abdominal injury/lower rib cage injury occurs with 138 kPa crush strength at impact velocity of 8.9 m/s. Furthermore, a padding crush strength of 69 kPa results in little or no injury.

Pintar et al. (1997) Chestband Analysis of Human Tolerance to Side Impact

Pintar et al. (1997) reports on sled tests in which the left sides of 25 cadavers were decelerated into a Heidelberg-style impactor. The shape of the impactor was varied so that it represented a flat rigid wall, a flat padded wall, and a rigid wall with a 12-cm protrusion near the pelvis. Tests were performed at low (24 km/hr) and high (32 km/hr) velocities. All of the loading walls were segmented so that loading of the thorax, abdomen, pelvis, and legs could be separately measured by load cells attached to each segment of the impactor. The height of the wall was set to represent a door below the sill. Displacement data were collected using chestbands located at the levels of the 4th rib, xiphoid process, and 10th rib (which is also at the level of the upper abdomen). They used results to propose TTI-based injury risk curves for thoracic injury, but did not report the abdomen force-displacement results.

Data from the upper abdomen chestband used by Pintar et al. have been re-analyzed to investigate the possibility of generating force-displacement data for the abdomen. Results are shown in Figure 92 for the tests in which the chestband data were reasonable. Most of the signals involve an initial increase in force without a corresponding increase in abdominal deflection. This is thought to result from loading of the abdominal portion of the impactor by parts of the cadaver other than the area where the chestband was attached prior to loading by the area where the chestband was attached. The wide variation in measured force-deflection responses makes it difficult to define a force-displacement corridor for the abdomen. However, these data do give some idea of the magnitude of abdomen displacements under these loading conditions. It should also be noted that the chestband data for the abdomen may not be as reliable as that for the thorax, because fewer channels were originally used, many channels failed, and because it may be more difficult for the chestband to maintain contact with the abdomen than the thorax.

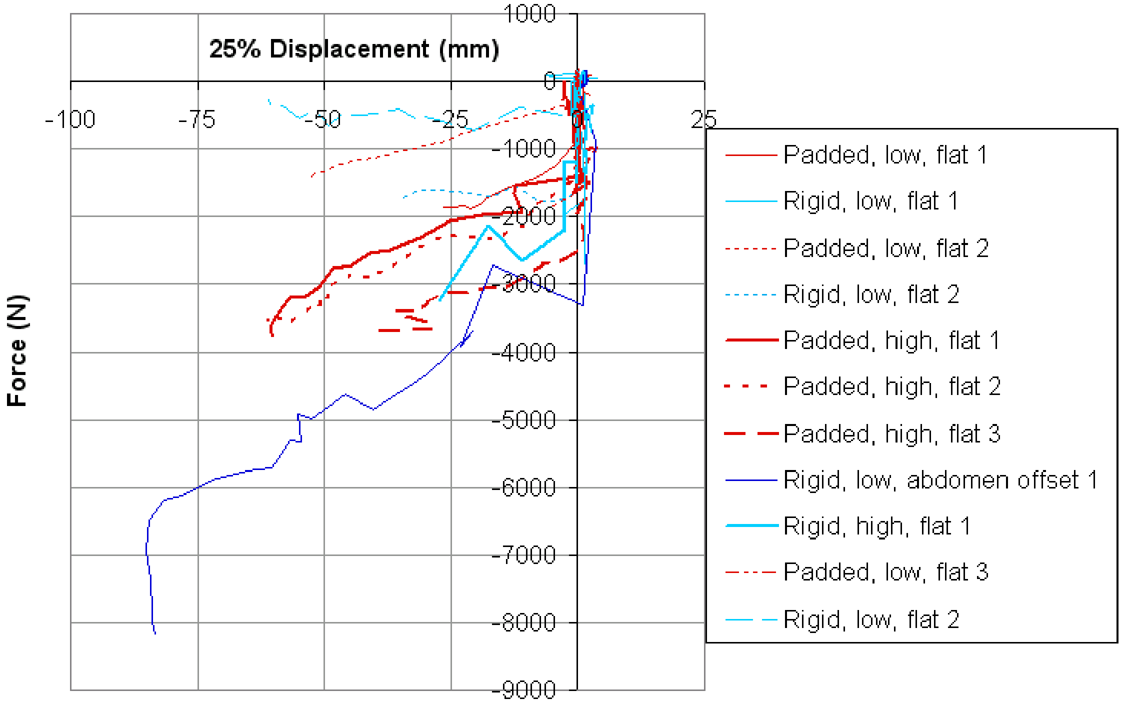


Figure 92. Abdomen force vs. displacement (measured at location 25% along the chestband) from Pintar et al. (1997) data

4.3 Belt Loading

This section reviews published papers that investigated the biomechanical and injury response of the abdomen to lap-belt loading. In the first two, porcine subjects were used (Miller 1989, Rouhana 1989) while the latter two used human cadaver subjects (Hardy 2001, Trosseille 2002). Table 39 summarizes the results of the abdomen lap-belt loading tests, the details of which are discussed in further detail in this chapter.

Table 39. Summary of belt-loading results at the mid-abdomen

	Miller 1989	Miller 1989 reexamined Rouhana 1989		Rouhana 1989	Hardy 2001	Trosseille 2002	Kent 2006
Subjects	25 anesthetized porcine	13 anesthetized porcine	2 anesthetized porcine	5 porcine cadavers	3 human cadavers	6 human cadavers	47 pediatric porcine cadavers
Tests	25	13	2	5	3	6	65
Position	Fixed-back Supine	Fixed-back Supine	Fixed-back Supine	Fixed-back Supine	Free-Back Upright	Fixed-back upright	Fixed-Back Supine
Velocity (m/s)	1.6 – 6.6 3.6 avg	3.7 ± 0.84	6.3 ± 0.42	0.55 ± 0.32	3.5 ± 1.0	8.2-11.7	Quasistatic, 3-8
Compression	6 – 67%	12 – 60%	52 – 56%	45 – 69%	33 – 36%	25-32%	23-68%
Belt positioning	L4	L4	L4	L4	L3	L3/L4	Upper and lower
Injuries (AIS 2+)	Mesenteric laceration Jejunum rupture Cecum ruptures Bladder laceration Rectum laceration			Lg. Intestine rupture Sm. intestine rupture Hemo-peritoneum *Multiple impacts per subject	Rib fractures	Spleen rupture Omentum tear Mesentery tear Muscle tear	
Stiffness (kN/m)	30 ± 10	23 ± 10	63 ± 13	31 ± 9	120	12.9 *static stiffness (765 Ns/m damping)	Rate dependent

Miller (1989) The Biomechanical Response of the Lower Abdomen to Belt Restraint Loading

Miller investigated the injury response to lap-belt loading by testing twenty-five anesthetized porcine specimens. The experimental procedure consisted of placing subjects in a supine position against a V-shaped support as shown in Figure 93. The belt was attached to a yoke actuator positioned above the subjects and loaded the subjects at the level of the L4 vertebra. According to Rouhana (1989), the internal anatomy at this level is equivalent to the L3 vertebra level in humans. Peak loading velocity ranged from 1.6 – 6.6 m/s (3.6 m/s average). Maximum compression ranged from 6 – 67% of abdominal depth.

The most common injuries in this study were to the mesentery (AIS 2-3). Five subjects sustained injuries of AIS 4+, three of which were due to cecum rupture, one was a jejunum-ileum rupture, and one was bladder and rectum laceration. Table 40 summarizes the frequency of injury by location.

The results indicated that maximum compression, maximum Viscous (VC) response, and the product of maximum force and maximum compression correlate well with AIS 3+ injury occurrence. The results, summarized in Table 41, show the expected levels of compressions (Cmax), force (Fmax), pressure (Pmax), and FmaxCmax for which 25% (ED25) and 50% (ED50) of subjects will exhibit an abdominal injury of AIS 3+ or 4+. Figure 94 illustrates the Viscous criterion threshold and the range of velocities and compression for which it is valid. Figure 95 illustrates that the VC threshold at which there is a 25% risk of sustaining an AIS 3 injury is 1.4 m/s and that the range of validity is 3 – 30 m/s. Below this range, compression is a better indicator of abdominal injury. The average abdominal stiffness, measured from the force-deflection curve of the abdomen, is 30.0 ± 10 kN/m.

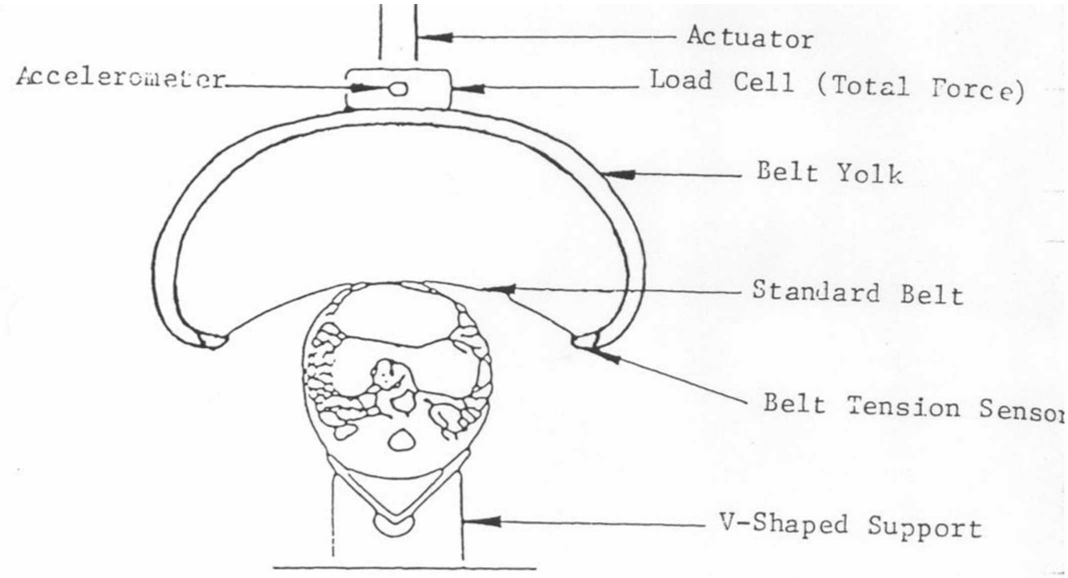


Figure 93. Miller test set-up for porcine belt-loading tests (1989)

Table 40. Frequency of injury in Miller 1989 belt-loading experiment

Organ	Number of Injuries
Mesentery	33
Small Bowel	4
Large Bowel	1
Cecum	7
Rectum	3
Bladder	1
Spleen	3

Table 41. Injury response to belt-loading tests on porcine cadavers by Miller (1989)

	ED25		ED50	
	3+	4+	3+	4+
Cmax (%)	37.8	48.3	48.4	54.2
Fmax (kN)	2.93	3.76	3.96	4.72
Pmax (kPa)	166	216	226	270
FmaxCmax (kN)	1.33	2.00	1.96	2.67

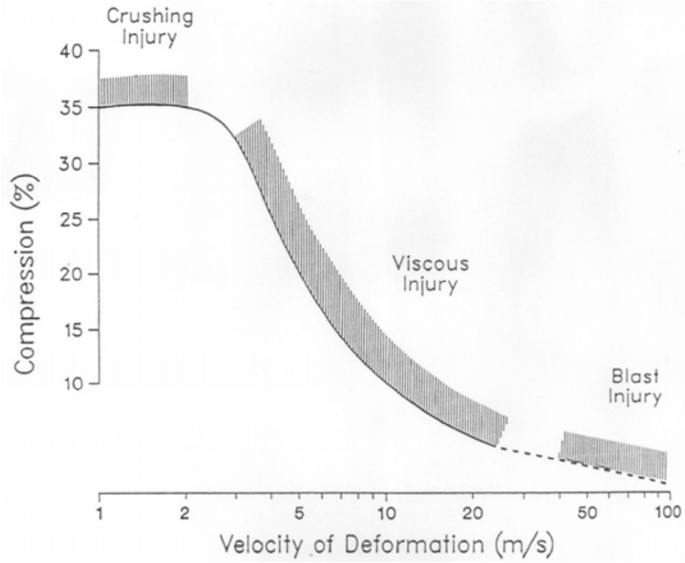


Figure 94. Injury threshold and the range of the viscous criterion based on belt-loading tests on porcine cadavers by Miller (1989)

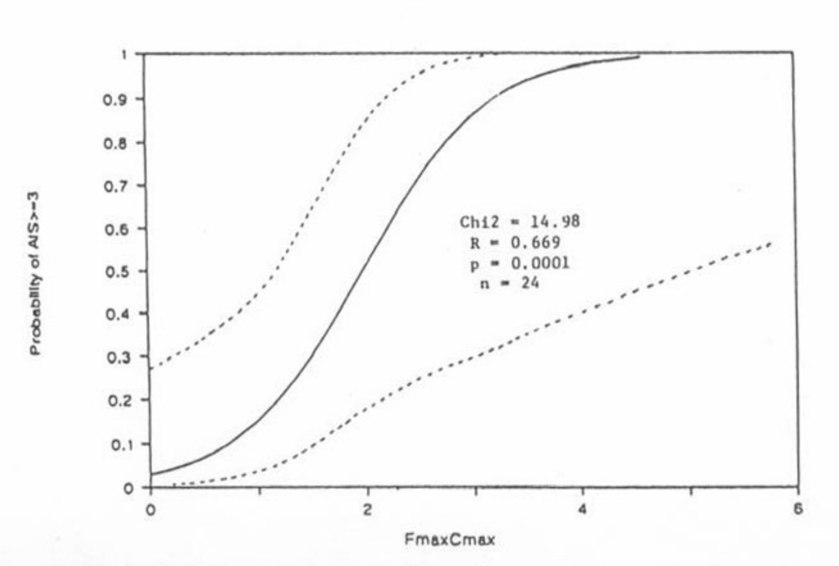


Figure 95. Threshold of for 25% risk of AIS 3+ injury as a function of compression and loading velocity (Miller 1989)

Rouhana (1989) Assessing Submarining and Abdominal Injury Risk in the Hybrid III Family of Dummies

In a follow-up of Miller's experiment (1989), Rouhana et al. investigated the belt-loading response of porcine cadavers. The purpose of this test was to compare the cadaver results to the live results to allow estimation of live human responses from human cadaver test results. Rouhana et al. used the same experimental procedure as Miller (1989). The loading velocities ranged from 0.2 – 5.3 m/s and maximum compression ranged from 45 – 69% of abdominal depth. Fifteen tests were performed on seven subjects. For subjects used in more than one experiment, velocity increased with each successive test. Based on five low-velocity (0.55 ± 0.32 m/s average) tests, each of which was the first test performed on the porcine cadaver, the abdominal stiffness was 31 ± 9 kN/m.

The data from Miller's study (1989) were reanalyzed to allow comparison to results of the current study. From Miller's study, the fifteen tests with complete data were divided into low- and high-velocity groups with thirteen in the low-velocity group and two in the high-velocity group. The low-velocity group has an average velocity of 3.7 ± 0.84 m/s and an average stiffness of 23 ± 10 kN/m. For the two high-velocity cases, the average velocity is 6.3 ± 0.42 m/s and the average abdominal stiffness is 63 ± 13 kN/m. Only the low-velocity group was used for comparison with the porcine cadaver results. Using a single-factor analysis of variance (ANOVA), no significant ($p<0.05$) difference was found between the mean stiffness of the porcine cadavers and the live porcine subjects.

The authors also compared the porcine cadaver results to results from human cadavers (Cavanaugh 1986). Because no human belt-loading data were available, the human cadaver results came from an experiment that used a rigid bar at higher velocities (4.9 – 7.2 m/s). In the Cavanaugh study, human abdominal stiffness was 23 kN/m (n=5). The porcine cadaver results were then scaled to human data by the equal-stress/equal-velocity scaling method (Mertz 1984) and compared to the human cadaver data. The authors found no significant ($p<0.05$) difference between the mean stiffness of (1) porcine cadaver and human cadaver and (2) porcine cadaver scaled to human cadaver and human cadaver.

In the porcine cadavers, there were two AIS 5 injuries, two AIS 4 injuries, one AIS 3 injury and one AIS 2 injury. One subject did not sustain any injuries. The injuries incurred were large intestine rupture (AIS 4, 5), small intestine rupture (AIS 3), hemoperitoneum (AIS 2) and a spiral colon rupture (AIS 4). Conclusions regarding injury are limited because subjects were used in multiple tests.

The results were used to develop an abdominal insert for the Hybrid III ATD. Since belt loading is a low-velocity event in automobile crashes (Verriest 1981), the authors decided to use the maximum compression criterion, as this is more suitable than the Viscous response at velocities below 3 m/s (Miller 1989). The abdominal insert was designed to detect 48% abdominal compression, which corresponds to a 25% risk of an AIS 4+ injury (Miller 1989). The stiffness of the abdominal insert was designed to be 23 kN/m.

Hardy and Schneider (2001) Development and Refinement of Abdominal-Response Corridors

Hardy and Schneider investigated the biomechanical response of belt loading on human cadavers. Six tests with a peak-loading rate of 3.5 $\pm$ 1.0 m/s were performed on three seated cadavers. One free-back, mid-abdomen (at the level of the L3 vertebra) test was performed on each of the three cadavers. On two of the cadavers, a second test was then run to load the lower abdomen. In the remaining third cadaver, another mid-abdomen test was run with the cadaver in a fixed-back configuration.

In this experiment, the belt was wrapped around the front of the abdomen and then extended posteriorly along a line tangent to the most lateral abdominal points. The results were all scaled to 78 kg using the equal-stress/equal-velocity method (Mertz 1984). Peak compression of the mid-abdomen, free-back tests ranges from 33 – 36%. For the low-abdomen tests it is 26 and 37%, while for the fixed-back test it is 29%.

A few rib factures and no soft-tissue injuries were noted. The authors combined the results from the three mid-abdomen, free-back tests to develop the force-penetration corridor in Figure 96. The average initial stiffness in these three tests is 120 kN/m. The initial force-penetration response of the fixed-back test is similar to those of the free-back tests, but the peak force is higher. The force-penetration response of the lower abdomen is, in general, higher than the mid-abdomen response.

The stiffness measured in this experiment (120 kN/m) is four times stiffer than that reported by Miller in 1989 (30 kN/m). The authors believe that the largest contributor to this difference is in how the belt wrapped around the abdomen. In Miller's experiment, the lateral aspects of the abdomen were unconstrained allowing the abdomen to deform.

However, in the experiment performed by Hardy, the belt wrapped around the sides of the subject, constricting the abdomen's shape. The stiffness measured in this experiment is also larger than that measured by Cavanaugh (1986). Two key differences between the studies are (1) the study by Cavanaugh used a higher impact velocity of 10 m/s and (2) Cavanaugh used a rigid bar instead of a belt. Generally, as impact velocity increases, so does the stiffness; the opposite is true for these two experiments. Hardy and Schneider reasoned that the abdomen is stiffer in belt loading because of the way the belt is distributed across the abdomen, in addition to the effect caused by constraining the sides.

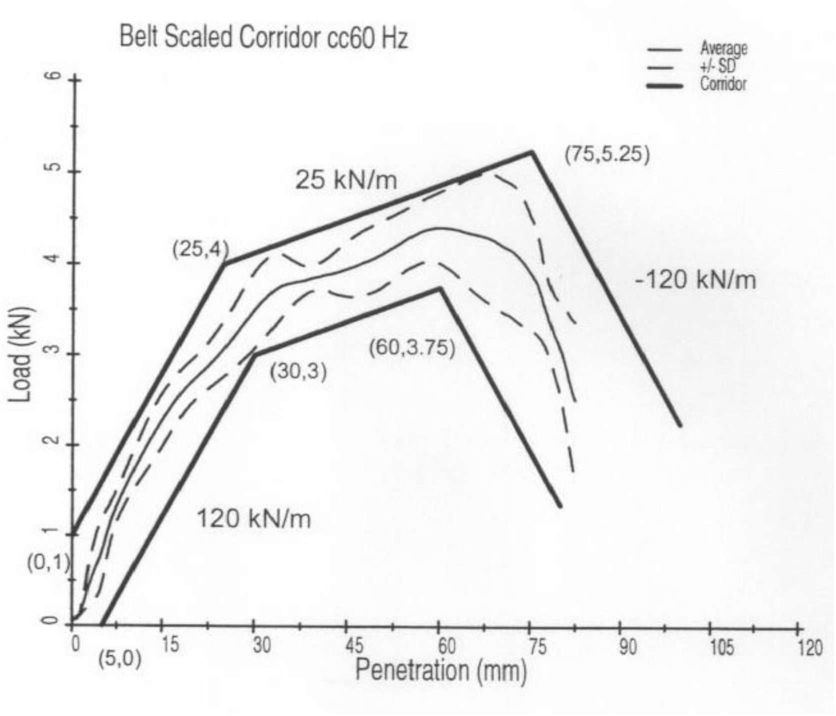


Figure 96. Force deflection results of belt-loading tests of cadavers in free-back position (Hardy 2001)

Trosseille (2002) Abdominal Response to High-Speed Seatbelt Loading

Trosseille et al. investigated high-speed belt loading by performing six tests on six cadavers in a seated, fixed-back position. Like the subjects in the Hardy (2001) experiment, these subjects were placed in an upright position with the belt wrapped around the abdomen, as shown in Figure 97. The belt was placed just above the iliac crest and loaded the abdomen at a peak velocity of 8.2 – 11.7 m/s. Maximum compression ranged from 25 – 32% of abdomen thickness. For comparison, four tests were also performed on the THOR dummy. The authors looked at symmetric vs. asymmetric loading with no apparent different in the results.

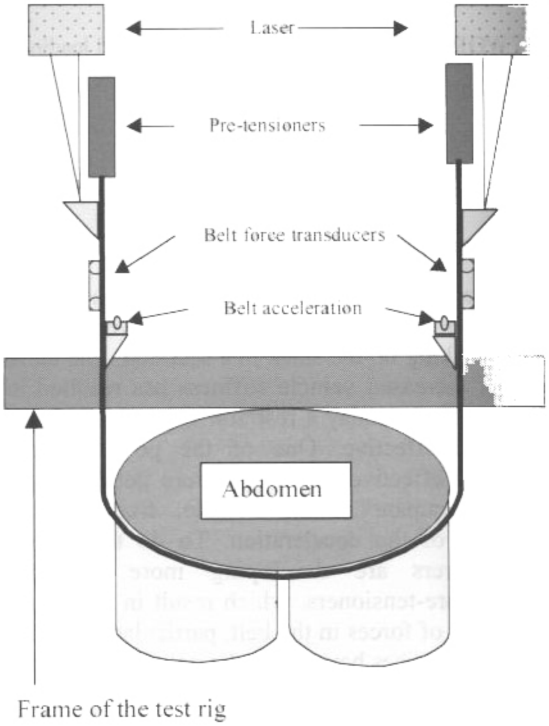


Figure 97. Set-up of belt-loading experiment by Trosseille (2002)

Of five cadavers examined for injury, the only severe injury noted was a rupture of the spleen (AIS 5). Two cadavers sustained AIS 2 injuries (incomplete tear of the musculus rectus abdominis and small mesentery tear) while the other two sustained only AIS 1 and 0 injuries. No injury above AIS 2 was observed for a maximum force less than 7.6 kN, maximum velocity less than 11.7 m/s, and maximum Viscous criterion less than 1.69 m/s.

The authors used the results to model the abdomen as a spring-damper system shown in Figure 98, with a static stiffness of 12.9 kN/m and damping coefficient of 765 Ns/m. Comparing the cadaver results to the THOR results, the authors found that the THOR static stiffness is too high while the dynamic stiffness is too low.

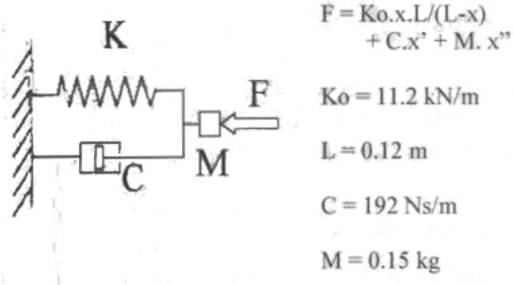


Figure 98. Spring-damper model of human abdomen (Troseille 2002)

Unlike the previous studies, these authors investigated high-speed belt loading to study possible effects of lap-belt pretensioners. Automobile manufacturers are installing these devices to remove slack from vehicle seatbelts during the initial, rapid deceleration of a frontal impact. However, if the occupant submarines, these pretensioners may effectively accelerate the belt into the abdomen, causing the loading velocities investigated in this experiment.

Kent et al. (2006) Biomechanical Response of the Pediatric Abdomen, Part 1: Development of an Experimental Model and Quantification of Structural Response to Dynamic Belt Loading

Kent et al. performed testing to examine the force-displacement response of porcine cadavers as an estimate of the abdomen response of a 6YO human. Based on comparison of anthropometric measurements and organ masses, a pig aged 77 days with a total body mass of 21.4 kg was identified to be the best representation of a 6YO human. Quasistatic lap belt loading of the lower abdomen of the pig corresponded well with similar subinjury tests performed on humans.

Dynamic tests were performed with the belt over the upper and lower abdomen, at penetration levels from 23% to 68%, with and without simulated muscle tension, and belt penetration rates from 3 to 8 m/s on 47 post-mortem subjects. Testing was conducted in a supine, fixed-back condition. Muscle tension affected quasistatic force-displacement response, but not the dynamic response. The upper abdomen was became stiffer with increasing loading rate, while the lower abdomen stiffness was not sensitive to loading rate. Quasistatically, the upper abdomen is stiffer than the lower abdomen, while the opposite is true at higher loading rates.

4.4 Tissue Testing

4.4.1 Liver

Anatomy

The human liver is situated in the upper right portion of the abdomen, with a portion of it extending to the left side of the body (Figure 99). On the right, it can extend as high up as the fifth rib, while on the left it can extend as high up as the fifth intercostals space. A small portion of the lower right liver will also extend below the rib cage. Both the diaphragm's movement during breathing as well as the body's posture will affect the liver's exact location. The liver sits anterior to the gallbladder, superior to the right kidney, and inferior to the diaphragm. The falciform ligament connects the anterior liver to the anterior abdominal wall as well as the diaphragm. There are also ligaments connecting the superior borders of the liver to the diaphragm and ligaments running from the posterior fissure to the stomach. The falciform ligaments as well as the posterior fissures separate the liver into left and right lobes, with the right lobe being the larger of the two. The entire surface of the liver is encapsulated by peritoneum. (Hamilton, pp. 395 – 403)

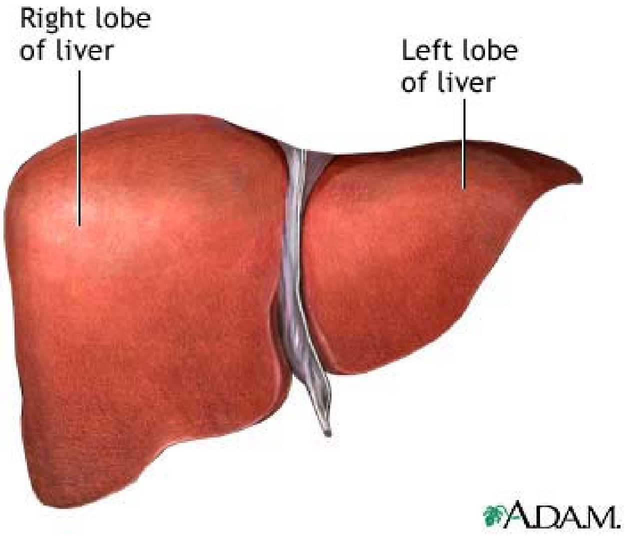


Figure 99. Anterior view of liver (MedlinePlus Medical Encyclopedia)

Melvin (1973) Impact Injury Mechanisms in Abdominal Organs

Melvin et al. conducted seventeen constant velocity uniaxial compression tests on the isolated livers of Rhesus monkeys *in vivo*. The three loading rates used were 0.05, 2.5, and 5.0 m/s. Each test controlled the maximum strain from 40% to 75% to produce various levels of injury. Trauma was identified as sustaining an estimated severity of injury (ESI) rating of 3+. This roughly corresponds to an abbreviated scale injury (AIS) of 4 – 5 (Tamura 2002).

The results indicate that the mechanical properties of the liver are sensitive to the loading rate. Figure 100 shows the stress-strain results of the liver at the three impact speeds. Under high-speed (2.5 and 5.0 m/s) loading rates, the researchers concluded that the onset of trauma begins at compressive stress levels of 310 kPa. Since the area of the load cell was 11.6 cm^2, the force to produce these injuries was 360 N. Injuries above the ESI 3+ rating are best described by the maximum strain energy density, which was defined as the area under the stress-strain curve measured up to the maximum stress and the maximum strain. Because the tests were done locally on the liver tissue, any anatomical differences between Rhesus monkey and human livers were thought to be minimal. At the low velocity of 5 cm/s, the reported injuries were parenchymal crushing without capsular tearing. At the higher velocities, the injuries reported were subcapsular hemorrhaging, tears and fractures.

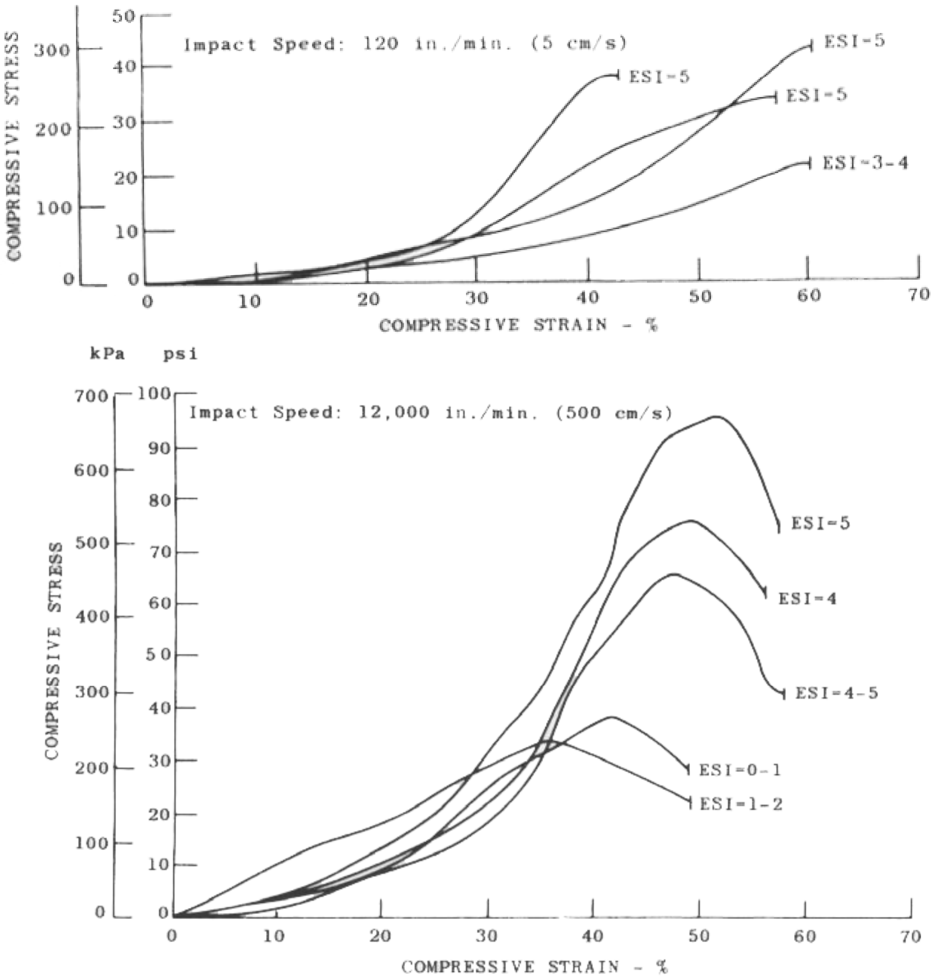


Fig. 5C—Liver compression stress-strain behavior

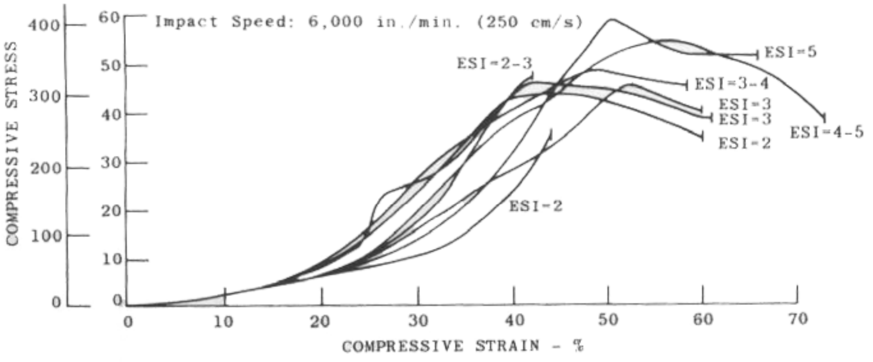


Fig. 5B—Liver compression stress-strain behavior

Figure 100. Stress-strain results for *in vivo* compression testing on Rhesus Monkey liver (Melvin 1973)

Talantikite (1993) Abdominal Protection in Side Impact – Mechanisms and Protection Criteria

Talantikite et al. reported on uniaxial compressive loading of human liver. In the experiment, twenty-five fresh, isolated livers were loaded by a disk impactor with a 15-cm-diameter face (88 cm^2 area) at loading rates of 3.1 – 4.1 m/s and a controlled amount of compression. Prior to testing, the livers were injected with a solution of water formol and ink to fix the organs and visualize the injuries. The researchers report that the liver can sustain forces up to 340 N without any injury. A force of 500 N is required to produce AIS 3 injuries and a force of 650 N is required to produce AIS 5 injuries.

Tamura (2002) Mechanical Characterization of Porcine Abdominal Organs

Tamura et al. tested 20 x 20 x 10 mm specimens of fresh porcine liver. The uniaxial compressive tests were performed at loading rates of 0.05, 0.5 and 5 m/s, which roughly corresponded to strain rates of 0.005, 0.05 and 0.5 s^{-1}. The liver specimens were loaded until failure. Failure was defined as the point at which the force measured on the force plate was abruptly reduced, which corresponded to rupture of the organ. The results are shown in Figure 101 and Table 42. The ultimate (rupture) stress increases with increasing loading velocity, while the ultimate (rupture) strain remains fairly constant. The authors suggest that ultimate strain should be used as the injury predictor for liver injury. Failure strain of the porcine liver is 44%.

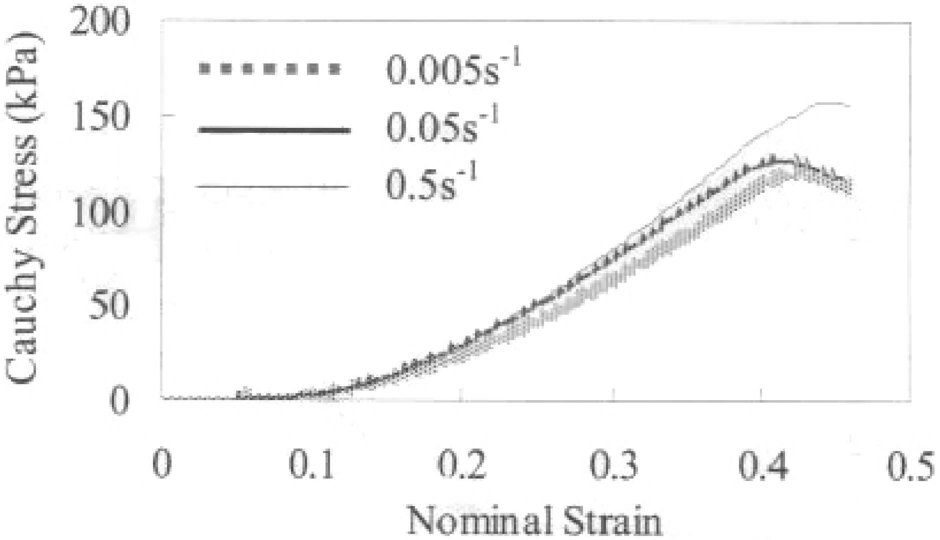


Figure 101. Stress-strain relationship of the liver at different loading rates (Tamura 2002)

Table 42. Rupture stress and strain of porcine liver samples (Tamura 2002)

Load Rate	Strain Rate	Rupture Stress σ_{max} (kPa)	Rupture Strain ε_{max}
0.05 mm/s	0.005 s^{-1}	123.4	0.432
0.5 mm/s	0.05 s^{-1}	135.2	0.420
5 mm/s	0.5 s^{-1}	162.5	0.438

Sparks et al. (2007) Using Pressure to Predict Liver Injury Risk from Blunt Impact

Sparks et al. (2007) performed drop tests onto 14 isolated, perfused livers. The specimens were instrumented with pressure transducers. Nominal maximum compression was 30%, while impact velocities ranged from 1 to 6 m/s. Injury levels were best correlated with the product of rate of tissue pressure and peak tissue pressure, with a value of 1370 kPa^2 corresponding to a 50% risk of AIS 3+ liver injury.

4.4.2 Kidney

Anatomy

Humans have two kidneys, one on the left and one on the right (Figure 102). They are situated on the posterior wall of the abdomen, behind the parietal peritoneum of the abdominal cavity, lateral to the vertebral column with the left kidney slightly higher than the right. In general, the superior edges of the kidneys are level with the superior border of the 12th thoracic vertebra (T12), while the inferior edges of the kidneys are level with the third lumbar vertebra (L3). The kidneys are bean-shaped, with the long axis roughly parallel to the spine. The average dimension of each kidney is 11 cm long, 6 cm wide and 3 cm thick. Each kidney weighs about 135 – 150 g. The kidneys are covered by a renal capsule. (Hamilton, pp. 410 - 411)

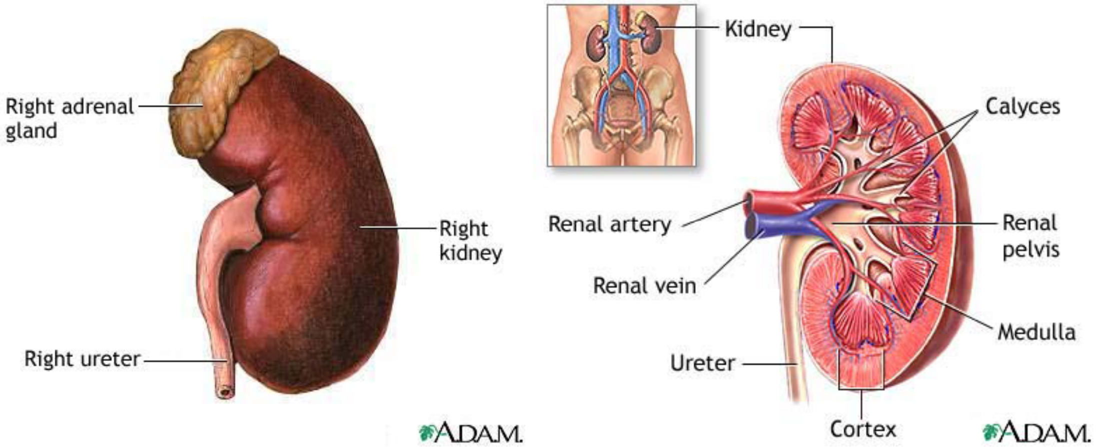


Figure 102. (a,b) Posterior view of the right kidney (left) and kidney cross-section (right) from MedlinePlus Medical Encyclopedia

Melvin (1973) Impact Injury Mechanisms in Abdominal Organs

As they did for liver tissue, Melvin et al. (1973) performed *in vivo* compression experiments with the kidneys of Rhesus Monkeys. The stress-strain results are shown in Figure 103. The results indicate that kidney trauma begins at stresses of 900 kPa (corresponding to a force of 1 kN), which is a much higher tolerance than the liver. The authors attribute this to the tough renal capsule. However, the authors also caution that the stresses causing 1 – 2 ESI injuries do not vary much from the stresses causing the 4 – 5 ESI injuries. Therefore, they conclude that the strain level is a better indicator of injury.

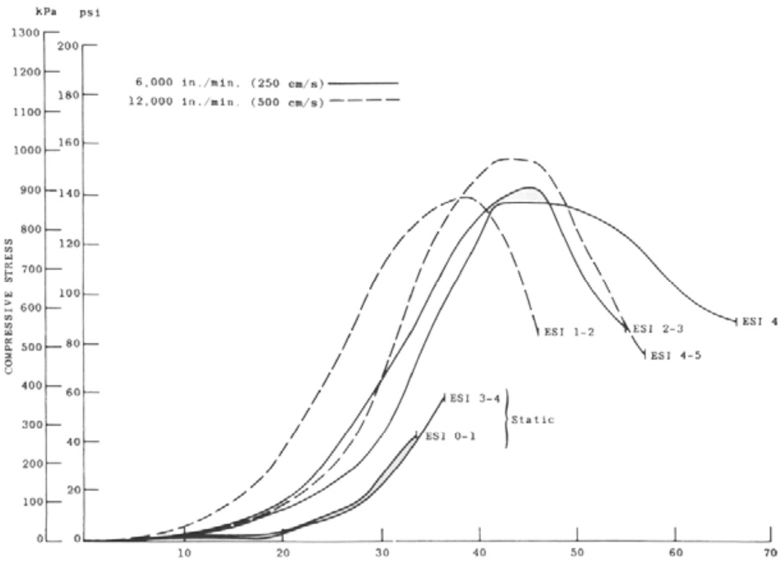


Fig. 6—Kidney compression stress-strain behavior

Figure 103. Stress-strain properties of the kidney (Melvin 1973)

Farshad (1999) Material Characterization of the Pig Kidney in Relation with the Biomechanical Analysis of Renal Trauma

Farshad et al. studied 10 x 10 x 10 mm tissue samples of porcine kidney samples. In uniaxial compressive tests, the samples were loaded at rates of 1, 10, 100 and 500 mm/min (0.00002, 0.0002, 0.002, 0.008 m/s). As shown in Figure 104, the direction of the loading was specified as either in the radial direction or the tangential direction, with the radial direction being defined as pointing outwards from the center of the kidney and the tangential direction being perpendicular to this. The kidneys were loaded until failure (rupture).

The maximum nominal stress (force per unit *undeformed* area) at rupture is 250 kPa in the radial direction and 180 kPa in the tangential direction. In both directions, the rupture strain is about 50%. The authors also note that rupture stress increases and rupture strain decreases as the loading rate increases. Furthermore, the difference in the rupture strain between the radial and tangential directions becomes more pronounced. Figure 105 shows the stress-strain results at a loading rate of 100 mm/min.

Farshad et al. also developed a non-linear elastic model of the kidney under compression using the Blaztz model, which relates the Cauchy stress ($\sigma_{0,}$ force per unit *deformed* area) to the deformation as:

$$\sigma_0 = \frac{\gamma}{\alpha+1}\left(\lambda e^{\alpha(\lambda^2-1)} - \frac{1}{\lambda^2} e^{\alpha(\frac{1}{\lambda}-1)}\right) \quad \text{Farshad 1999}$$

σ_0 : Cauchy Stress
λ : ratio of deformed length to the initial length
γ, α : material parameters

The material parameters of the kidney in the radial and tangential directions were determined by curve-fitting the model to the experimental data. In the radial direction, $\alpha = 3.9$ and $\gamma = 0.0025$. In the tangential direction, $\alpha = 6.8$ and $\gamma = 0.005$. Figure 106 shows the model and the experimental results of the nominal stress as a function of the compression ratio.

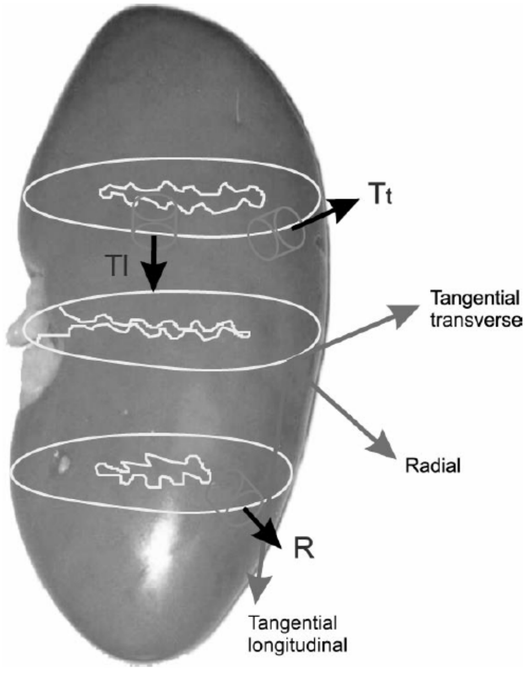


Figure 104. Illustration of the radial and tangential direction of kidney tissue (Farshad 1999)

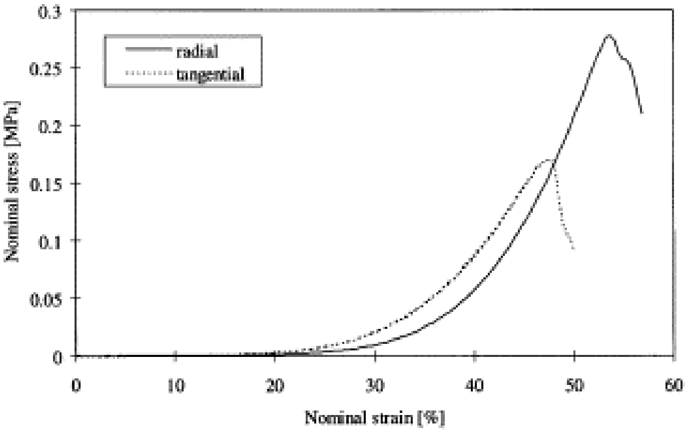


Figure 105. Stress-strain relationship of the kidney in the tangential and radial directions under uniaxial compression at 100 mm/min (Farshad 1999)

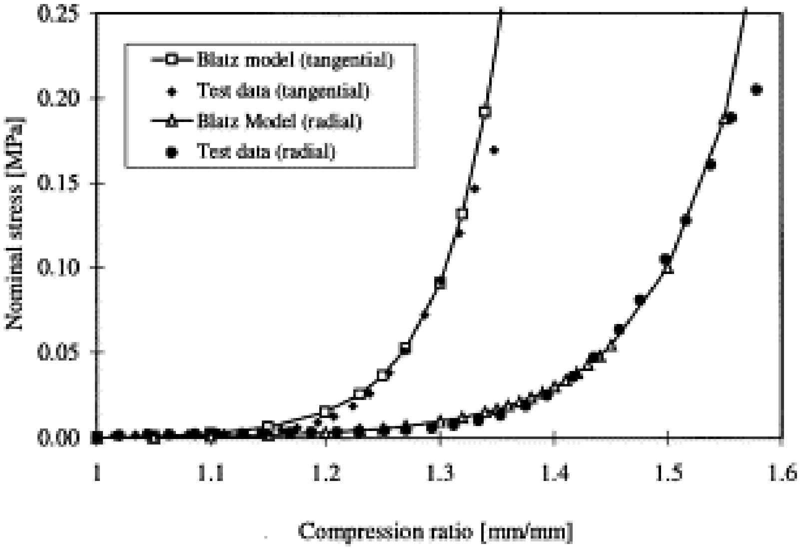


Figure 106. Model of the kidney in compressions in the radial and tangential directions. The test data is plotted against the model (Farshad 1999)

Tamura (2002) Mechanical Characterization of Porcine Abdominal Organs

Tamura et al. tested porcine kidney specimens and include results in the same publication in which they report test results on liver specimens. The methods were the same for the kidney and liver tissue, and the authors suggest that failure (ultimate) strain be the injury predictor, as they did for liver tissue. Figure 107 shows the stress-strain results of the kidney at all three loading rates. The failure strain of porcine kidney is 36%, which is slightly less than the 43% failure strain of porcine liver. The ultimate stress and strain for each loading rate are shown in Table 2.

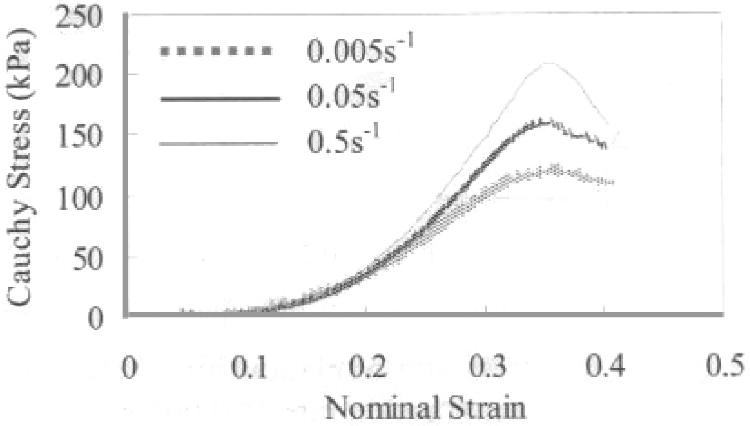


Figure 107. Stress-strain relationship of the kidney at different loading rates (Tamura 2002)

Table 43. Rupture stress and strain of porcine kidney samples (Tamura 2002)

Load Rate	Strain Rate	Rupture Stress σ_{max} (kPa)	Rupture Strain ε_{max}
0.05 mm/s	0.005 s^{-1}	135.1	0.354
0.5 mm/s	0.05 s^{-1}	175.5	0.358
5 mm/s	0.5 s^{-1}	214.8	0.359

Snedeker (2005) Strain Energy Density as a Rupture Criterion for the Kidney: Impact Tests on Porcine Organs, Finite Element Simulation, and a Baseline Comparison Between Human and Porcine Tissues

Snedeker et al. measured the high-velocity mechanical properties of porcine kidneys by testing cylindrical tissue samples as well as the whole organ. The tissue samples were all extracted from the cortex and had diameters of 11, 20, or 30 mm with a height of 7 – 9 mm. For both the cortex samples as well as the whole organ, compression was accomplished by one of two methods. The first method used falling weights to achieve loading rates between 3 and 7 m/s while the second method used a pneumatic projectile impactor to achieve loading rates up to 25 m/s. Care was used in all tests to ensure uniform, distributed loading. Each sample was repeatedly impacted by an increasing amount of energy until visible material failure. In the case of the tissue samples, the failure mode sometimes occurred due to tensile strains along the axis perpendicular to the loading axis, while at other times, failure occurred due to rupture.

To characterize the mechanical properties of the kidney tissue, the researchers measured the strain energy density (SED) at failure. SED was calculated by dividing the volume of the sample into the kinetic impact energy, with the underlying assumption that the impacts were perfectly plastic. Results for the tissue samples indicate that kidney cortex tissue fails at SED of 25 – 60 kJ/m^3, while the whole organ fails at SED equal to 15 - 30 kJ/m^3. The authors attributed the lower tolerance level of the whole kidney to inhomogeneous loading within the organ, giving rise to local areas of high SED concentration. This theory was supported by a finite element model (FEM) of the kidney, also presented in this paper.

SED is a function of both the stress and the strain in tissue. In general, for all soft tissues, including renal tissue, the ultimate stress increases with increasing strain rates while ultimate strain decreases. Furthermore, the strain rate dependency of soft tissue properties becomes less pronounced at high strain rates. This is confirmed by the SED data, which became less sensitive to the strain rate above deformation rates of 1 m/s.

One last aspect of this study compared the mechanical properties of porcine kidney samples to human kidney samples under quasi-static compression. The stress-strain curves of the two samples had the same shape, with a toe region, followed by an increase in stiffness before reaching ultimate stress. To approximate these properties, the tissues were assigned two Young's moduli, one for the toe region of the curve (E1) and the second for the stiffer region (E2). In addition to these two parameters, the authors compared ultimate stress (σ_{max}), ultimate strain (ε_{max}), and the SED at failure. Table 44 lists the properties of both the human and kidney tissue samples, while Figure 108 shows the stress-strain relationship of the tissues. Note that the porcine data came from a previously published report (Farshad 1999). The only parameter with a common value between the two species was ε_{max}. In the human samples, ε_{max} is 63 $\pm$ 6.3% and in the porcine samples, ε_{max} is 57%. Otherwise, the porcine specimens exhibit stiffer properties than the human samples.

Table 44. Mechanical properties of porcine and human kidney tissue by Snedeker (2005)

	Human	Porcine
E1 (kPa)	19	40
E2 (kPa)	530	1470
σ_{Max} (kPa)	116	245
ε_{max} (%)	63	57
SED at failure (kJ/m^3)	17	26

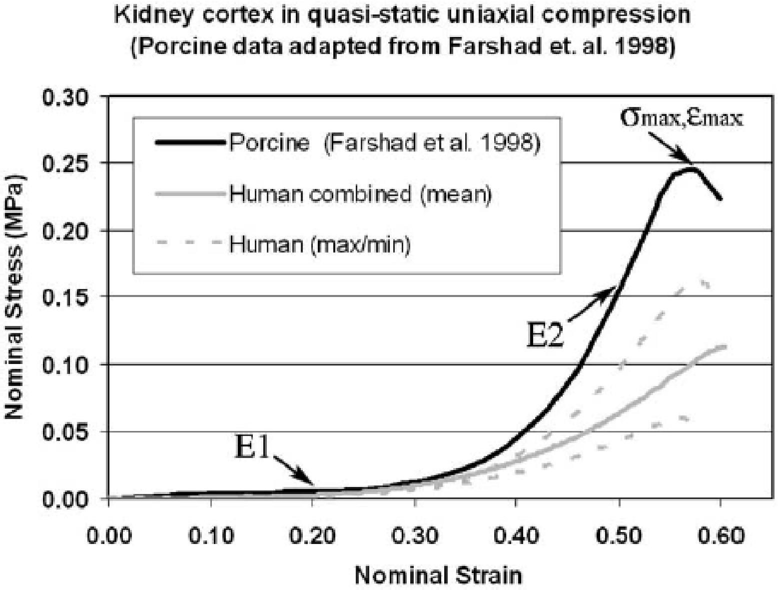


Figure 108. Stress-strain relationship of human and porcine kidney tissue samples under quasi-static compression by Snedeker et al. (2005)

4.4.3 Spleen

Anatomy

The spleen is located in the upper left portion of the abdominal cavity, roughly between the 9th and 11th ribs (Figure 109). The spleen's location is posterior to the stomach, inferior to the diaphragm and superior to the left kidney. Its shape can be described as an irregular tetrahedron with approximate dimensions of 12 cm in length, 7 cm in width and 3 – 4 cm in thickness. The average weight of the spleen is 150 g, but it becomes smaller in old age. It is enclosed in a fibro-elastic capsule, which is surrounded by peritoneum (Hamilton, p. 501).

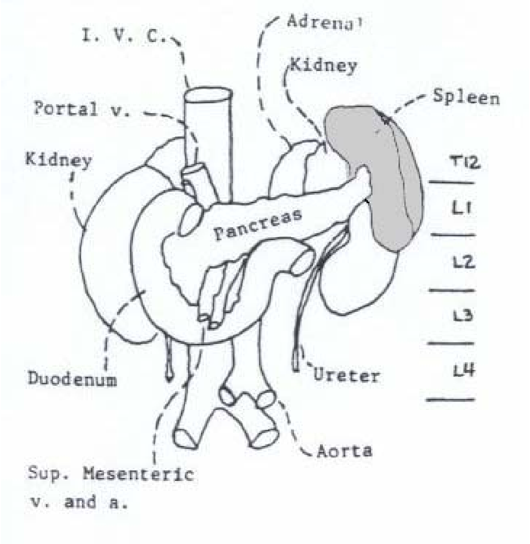


Figure 109. Location of abdominal organs relative to the spleen and the vertebral column (Cavanaugh 1986)

Tamura (2002) Mechanical Characterization of Porcine Abdominal Organs

Tamura et al. appear to be the only investigators to report on the compressive properties of spleen tissue. As they did for liver and kidney, 20 x 20 x 10 mm samples of spleen were uniaxially loaded until failure at rates of 0.05 – 5.0 mm/s. The results for rupture stress and rupture strain at each of the three loading rates are shown in Table 45, and the stress-strain results are shown in Figure 110. Rupture stress increased with loading rate while rupture strain did not. Therefore, the authors conclude that a rupture strain of 83% would be a good injury predictor in porcine spleen. This is considerably higher than the 36% for kidney and 44% for liver.

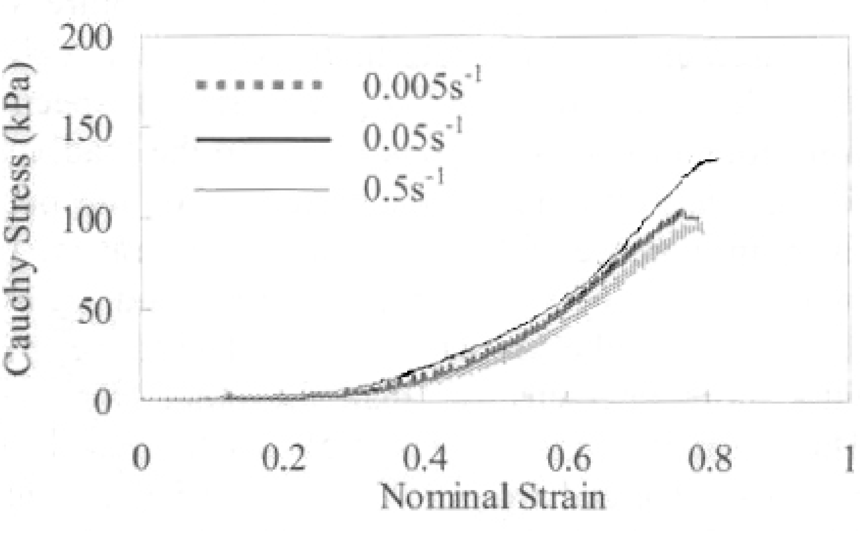


Figure 110. Stress-strain relationship of the spleen at different loading rates (Tamura 2002)

Table 45. Rupture stress and strain of porcine spleen samples (Tamura 2002)

Load Rate	Strain Rate	Rupture Stress σ_{max} (kPa)	Rupture Strain ε_{max}
0.05 mm/s	0.005 s^{-1}	107.5	0.825
0.5 mm/s	0.05 s^{-1}	114.6	0.809
5 mm/s	0.5 s^{-1}	146.3	0.834

Tamura et al. also performed stress-relaxation compression tests to develop a quasi-linear viscoelastic model of the liver, kidney and spleen tissues. During the instantaneous loading of the tissue, the elastic response, σ^e, can be described as:

$$\sigma^e = C(e^{D\varepsilon(t)} - 1) \quad \text{Tamura 2002}$$

In the above equation, C and D are material properties to be determined by experiment. The strain rate ε(t) was held constant at 0.005, 0.05, or 0.5 s^{-1}. The results for C and D at each loading rate are given in Table 46. A stress-strain plot at a strain rate of 0.05 s^{-1} is shown in Figure 111. Note that the kidney is stiffer than the liver, which in turn is stiffer than the spleen.

Table 46. Material constants for the instantaneous elastic response of liver, kidney and spleen tissue samples (Tamura 2002)

	0.005 s^{-1}		0.05 s^{-1}		0.5 s^{-1}	
	C	D	C	D	C	D
Liver	1.677E+04	6.78	1.897E+04	6.14	1.286E+04	6.83
Kidney	9.55E+03	11.78	5.34E+03	11.78	4.84E+03	11.90
Spleen	3.54E+03	5.74	3.49E+03	5.45	3.87E+03	5.01

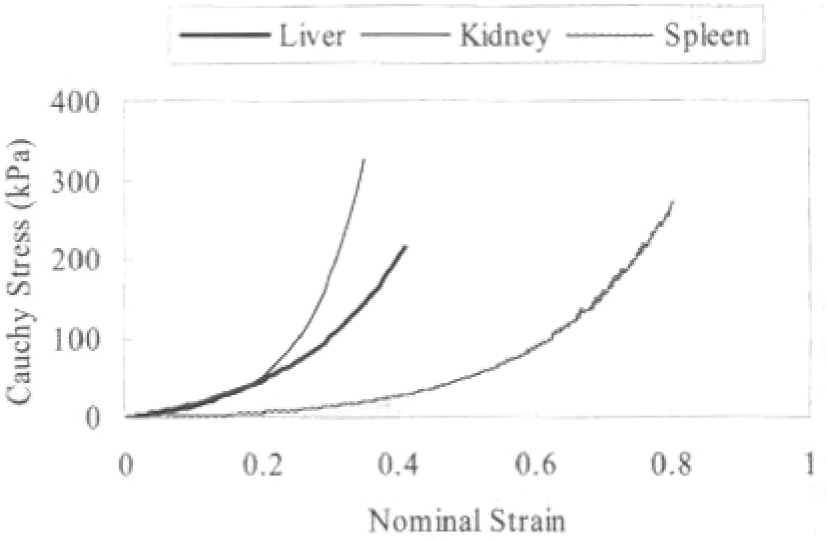


Figure 111. Predicted stress-strain plot of the instantaneous elastic response of the liver, kidney and spleen at a strain rate of 0.05 s^{-1} (Tamura 2002)

5. Future Research Needs on Abdominal Injury and Impact Response

5.1 Frontal impact

The abdomen injury analysis indicates that over half of AIS2+ abdomen injuries occur in frontal impacts. Use of lap/shoulder belts reduces abdominal injury risk in frontal impact by 75% to 85%, but airbag deployment has no noticeable effect. Most abdominal injuries in frontal collisions are attributed to contact with the steering wheel or loading by the seatbelt. Results of the injury analysis suggesting that loading conditions resulting in abdomen injury also result in rib fracture indicate that loading of the abdomen in isolation from the thorax is not very common.

Much of the previous research on abdominal injury and impact response in frontal impacts has focused on defining the isolated response of the mid-abdomen at a variety of velocities using loading devices that represent steering-wheel rims. Two studies have examined upper abdominal response under similar loading conditions (Hardy et al. 2001 and Shaw et al. 2004). Based on the results of the current study's injury analysis, additional testing with a steering-wheel-shaped impactor that loads both the thorax and abdomen together may be warranted. Response of the lower abdomen to steering-wheel-rim loading has not been studied but is likely not justified, since this region of the abdomen is most likely to be loaded by lap belts rather than steering-wheel rims. Additional research on the response of the abdomen to airbag loading is also probably not necessary, since the data indicate that airbags do not seem to have a positive or negative effect on the risk of abdomen injury.

Abdominal response to oblique impacts has only been studied by Viano (1989), who loaded the upper abdomen and lower thorax with a 15-cm diameter circular impactor face angled at 60 degrees from the midsagittal plane. Although the tests produced abdominal injuries, the cadaver subjects were impacted multiple times. Because this may compromise injury assessments resulting from a particular loading condition, a more thorough examination of oblique abdominal response may be warranted.

No studies have examined the effects of muscle tension on abdominal response to steering-wheel loading. However, Kent et al. (2006) examined the response of porcine abdomens to belt loading with and without simulated muscle tension. Muscle tension stiffened the abdomen at quasistatic rates, but had negligible effect at dynamic rates. As a result, further investigation of the effects of muscle tension on abdomen response would not be considered a high priority.

5.2 Lateral impact

The occupants with the highest risks of AIS 2+ abdominal injury are right-front passengers involved in right-side impacts. Although right-front passengers most commonly sustain injuries to their liver in right-side impacts, their risk of sustaining spleen injuries in right-side impacts is higher than that for drivers in left-side impacts because of loading to the left side of the abdomen by unbelted drivers. While the risk of abdominal injuries is higher for right-front passengers than for drivers, the higher exposure of drivers to near-side impacts (because there is always a driver in a vehicle) also makes left-side loading abdomen an important consideration. These observations indicate that the highest priority in abdominal-impact response research is near-side impact loading for both drivers and right-front passengers.

Table 47 summarizes test conditions and data from the literature on side-impact abdominal response testing using animal and human subjects. The greatest deficiency in the existing lateral-impact abdominal response data is the lack of reliable abdominal displacement or compression data for human subjects. In studies using human surrogates that report abdomen displacement, displacements were usually obtained by digitizing film targets that were not clearly described. The most thorough studies of lateral-impact abdomen response have been performed on anesthetized rabbits, which provide insight on injury thresholds and injury mechanisms but do not provide force-deflection data that can be used to design side impact ATDs.

Table 47. Summary of studies in the literature reporting on abdomen response to side-impact loading

	Subject	Direction	Velocity	Displacement	Impactor Size/Shape
Walfisch 1980	PMHS	Lateral drops	4-6 m/s	Film	Armrest
Rouhana 1986	Rabbits	Lateral	3-15 m/s	Film	6.7-cm diameter disc
Viano 1989	PMHS	Oblique		Film	15-cm diameter disc
Viano 1993	Pigs	Lateral	9 m/s	None	Armrest
Talantikite 1993	PMHS, Liver	Lateral	3-10 m/s	Film, external targets on front and back of abdomen	15- cm diameter disc
Cavanaugh 1996	PMHS	Lateral	6.7-8.9 m/s	None	Segmented flat wall
Pintar 1997	PMHS	Lateral		Chestband	Segmented wall with protrusion at pelvis level

PMHS=post-mortem human subject

Most of the lateral-impact response tests were also conducted prior to the most recent revisions of FMVSS 214. Thus lateral abdominal response using impactors representing the current side-impact-loading environments (i.e. door interiors with armrests that protrude less than in older model vehicles) has not been evaluated. In addition, the analysis of injury patterns that indicates that AIS 2+ abdomen injuries are usually accompanied by rib fractures and other thoracic injuries suggests that the abdomen is rarely loaded in isolation in side impacts. Thus testing with an impactor that has a size and shape representative of intruding door interiors is important. In addition, most of the lateral abdominal response data have been collected at impact speeds below the door loading velocities of 8-12 m/s at the time of ATD contact as determined from recent FMVSS 214 crash tests.

Maximum-force and viscous criteria (V*C) values have been proposed for abdominal tolerance to side-impact loading. However, no study has compared the tolerance of the liver during right-side loading to that of the spleen under left-side loading. If one organ has a substantially different tolerance, injury assessment reference values should be based on the lower tolerance to protect both left- and right-side occupants, even if vehicles are only assessed using left-side impacts.

5.3 Belt loading

The seatbelt is the second-most commonly coded injury source resulting in abdominal injuries in both frontal and side impacts. However, most abdominal response data to belt loading in the literature are from animal testing, which cannot be used to derive reliable human force-displacement response corridors. Some researchers have reported force-displacement data of the mid-abdomen under frontal belt loading, but results vary depending on how the belt was routed around the test subject. Data are therefore needed on abdominal force-displacement response under belt loading with the belt routed in a realistic manner around the abdomen and pelvis such that the side-view angle meets FMVSS 210 criteria. Belt-loading response data of the lower abdomen, including investigation of belt interaction with the flesh in front of the anterior superior iliac spines of the pelvis, are also needed to provide guidance for ATD design features needed to achieve more humanlike belt interactions.

5.4 Tissue testing

Tissue-level impact response and injury criteria are needed to develop biofidelic finite element models of the human abdomen. The liver and spleen are the most commonly injured abdominal organs in most types of impacts. As reviewed in this document, most of the abdominal organ tissue testing has been conducted on kidney and liver tissues. While one study compared the stress-strain response of the spleen, kidney and liver under dynamic compressive loading, additional testing of spleen tissue is needed using the methods previously used to quantify properties of liver and kidney tissues. In addition, further testing of liver tissue may be required to provide material properties for use in finite element models. Comparison of the relative failure tolerances of the liver and spleen would also be beneficial to ensure that abdomen injury thresholds are based on the organ with the lowest injury tolerance.

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Appendix A: NASS Injury Contact Points

FRONT
Windshield
Mirror
Sunvisor
Steering wheel rim
Steering wheel hub/spoke
Steering wheel (combination of codes 004 and 005)
Steering column, transmission selector lever, other attachment
Cellular telephone or CB radio
Add on equipment (e.g., tape deck, air conditioner)
Left instrument panel and below
Center instrument panel and below
Right instrument panel and below
Glove compartment door
Knee bolster
Windshield including one or more of the following: front header, A (A1/A2)-pillar, instrument panel, mirror, or steering assembly (driver side only)
Windshield including one or more of the following: front header, A (A1/A2)-pillar, instrument panel, or mirror (passenger side only)
Windshield reinforced by exterior object (specify)

LEFT SIDE
Left side interior surface, excluding hardware or armrests
Left side hardware or armrest
Left A (A1/A2)-pillar
Left B-pillar
Other left pillar (specify):
Left side window glass
Left side window frame
Left side window sill
Left side window glass including one or more of the following: frame, windowsill, A (A1/A2)-pillar, B-pillar, or roof side rail.

RIGHT SIDE
Right side interior surface, excluding hardware or armrests
Right side hardware or armrest
Right A (A1/A2)-pillar
Right B-pillar
Other right pillar (specify):
Right side window glass
Right side window frame
Right side window sill
Right side window glass including one or more of the following: frame, window sill, A (A1/A2)-pillar, B-pillar, or roof side rail.

INTERIOR
Seat, back support
Belt restraint webbing/buckle
Belt restraint B-pillar or door frame attachment point
Other restraint system component (specify):
Head restraint system
Other occupants (specify):
Interior loose objects
Child safety seat (specify):

ROOF
Front header
Rear header
Roof left side rail
Roof right side rail
Roof or convertible top

FLOOR
Floor (including toe pan)
Floor or console mounted transmission lever, including console
Parking brake handle
Foot controls including parking brake

Appendix B: ISO Abdominal Impact Response and Injury Assessment Recommendations

ISO document 12350 identifies the injury risk curves of the abdomen in lateral crash testing for the EuroSID and BioSID dummies. The test procedures and dummy biofidelity are specified in ISO 10997 and ISO 9790, respectively.

The EuroSID measures abdominal injury through spinal acceleration, exterior abdominal force, and interior abdominal force. In the BioSID, abdominal injury is measured through spinal acceleration, abdominal deflection and the viscous criterion. The recently developed WorldSID dummy is able to assess abdominal injury by measuring the deflection of two abdominal ribs.

ISO standards for dummy biofidelity in lateral impact are based upon five separate tests. The first two involve dropping the dummy onto its side from 1.0 meters (test 1) and 2.0 meters (test 2). Walfisch et al. (1980) developed the force-time response corridors from cadaver testing. The last three tests involve accelerating the SID into a flat wall. Tests 3 and 4 accelerate the SID into a rigid wall at 6.8 m/s and 8.9 m/s, respectively. Test 5 accelerates the SID into a rigid wall covered with padding at 8.9 m/s. The padding is specified to have a crush strength of 0.10 N/mm^2 and 0.16 N/mm^2. Cadaver testing by Cavanaugh et al. (1990) is the source of the force-time response corridors for these three tests.

In frontal impacts, ISO standards identify the risk curves of thoracic injury based on sternal deflection due to shoulder belt loading, peak shoulder belt load, and the viscous criterion. The risk curves are listed in the ISO document TR 7861. No abdomen specific injury curves are identified.

ISO/TR 7861:2003 Injury risk curves for evaluation of occupant protection in frontal impact

ISO/TR 9790:1999 Anthropomorphic side impact dummy – Lateral impact response requirements to assess the biofidelity of the dummy

ISO 10997:1996 Side impact with deformable barrier

ISO/TR 12350:2004(E) Injury risk curves for evaluation of occupant protection in side impact

ISO 15830:2005 Design and performance specifications for a 50th percentile male side impact dummy (WorldSID)
