PATTERNS OF ABDOMINAL INJURY IN FRONTAL AUTOMOTIVE CRASHES

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ABSTRACT

The Hybrid III, which is the only universally used frontal crash anthropomorphic test device, lacks a biofidelic abdomen that can be used for different loading surfaces and loading rates. The Frangible Abdomen, developed by General Motors in 1989, is the only commercially available, dynamically tuned insert. While the Frangible Abdomen has biofidelity under belt loading conditions, it has neither the loading rate sensitivity nor the appropriate mechanical response (biofidelity) for assessing injury from non-belt impacts (e.g., airbags or steering wheels). A loading rate sensitive abdomen that is also capable of assessing injury is currently under development by the General Motors Safety Research Department. In order to develop such a device, it is important to identify the frequency and severity of injury to the various regions and organs in the abdomen to prioritize their instrumentation with the appropriate sensors.

In this study, crash data collected between 1988 and 1994, contained in the database of the National Automotive Sampling System (NASS), were analyzed to identify the frequency and severity of injury to the abdominal organs in frontal crashes. Results are summarized and compared with previously published studies.

INTRODUCTION

Anthropomorphic Test Devices are used as human surrogates to assess crash injuries. The Frangible Abdomen developed by General Motors in 1989 is the only commercially available, dynamically tuned, biofidelic insert used to assess abdominal injuries. The insert is a crushable Styrofoam® designed to be biofidelic under belt loading conditions (~3m/s) (Rouhana 89,90, Schneider 92). Crush of the foam is used as an indicator of submarining and the amount of crush quantifies the injury risk. This design, however, does not prove to be useful in assessing the interaction of the abdomen with the steering wheel, the airbag, or other objects in the vehicle.

There have been a number of attempts to produce an instrumented abdominal insert (Ishiyama 94, Biard 93, Czernakowski 87, Mooney 86, Melvin 86, Maltha 81, and Walfisch 80). But these systems have also only dealt with the belt interaction. They have used either deflection, force, fluid pressure measurements, or contact switch signals to indicate injury level in the abdomen. There have been many methods proposed to define abdominal injury criteria. However, the most promising criterion is the Viscous Criterion (VC) proposed by General Motors in 1985 (Rouhana 85, 93, Lau 86). VC is the maximum of the velocity multiplied by the normalized compression of the abdomen during the impact $[(V(t)*C(t)]_{max}$.

An instrumented, rate-sensitive, reusable abdomen is currently under development by General Motors Safety Research Department. To assess injuries to the abdomen, the location of sensors and parameters to be measured must be defined. This study is a part of that program and was undertaken to set instrumentation priorities by determining the frequency and severity of injury to various organs in the abdomen as suggested by field crash data.

METHOD

Abdominal injury data from the National Automotive Sampling System (NASS) database was retrieved for the years 1988 to 1994. Data were restricted to passenger cars and light trucks involved in frontal impacts without rolling over (PDOF 10-2 o'clock). Also, data were limited to non-ejected drivers and right front seat passengers (RFP). The weighted frequency for injuries with AIS ≥ 3 and the corresponding contact objects were collected.

Unknown variables were ignored, thus the total number of injuries and associated contact points collected do not represent the actual total weighted frequencies. Therefore, relative percentages and not the absolute numbers are the focus of this study. In order to directly associate injuries with contact objects, cases with either unknown injuries or unknown associated contact object were ignored.

RESULTS

The database was analyzed to provide a comparison to other injuries in frontal crashes. Table 1 shows a comparison of injuries by body region for different AIS levels. The body regions chosen are the head, neck, chest, abdomen, and the femur. As the AIS severity increases, abdominal injuries become more prominent. Abdominal injuries constituted 8% of all injuries of AIS ≥ 3, 16.5% of all injuries of AIS ≥ 4, and 20.5% of all injuries of AIS ≥ 5. Throughout the figures that follow, a number of abbreviations are used for clarity. Tables 2 and 3 give the key to deciphering those abbreviations for restraint type and associated contact objects, respectively.

Table 1.
A Comparison of Injuries by Body Region for Different AIS Levels. As AIS Level Increases, Abdominal Injuries Become More Prominent

	AIS ≥ 3	AIS ≥ 4	AIS ≥ 5
Head	27.8%	35.3%	34.1%
Neck	3.4%	1.8%	2.2%
Chest	37.6%	46.3%	43.3%
Abdomen	8.0%	16.5%	20.5%
Femur	23.2%	0.2%	0.0%
Total	100%	~100%	~100%

Table 4 and Figure 1 show the normalized frequency (100% = 83,322) of abdominal injuries reported for drivers and right front seat passengers with different restraint systems. The unbelted driver (59%) followed by the lap/shoulder belted passenger (12%) sustained the highest frequency of abdominal injuries. The liver is the most frequently injured organ (38%), followed by the spleen (23%), the digestive system (17%), the arteries and veins (12%), the respiratory system (4%), the kidney (4%), and the urogenital system (3%).

Table 5 and Figure 2 show the normalized frequency (100% = 78,992) of objects contacted that were associated with abdominal injuries. The highest percentage of abdominal injuries were associated with the steering wheel (68%), then with the belt system (17%), the interior (14%), and the airbag (0.13%). The abdominal injury frequency of the driver and the passenger is similar to that shown in Table 4 and Figure 1; 59% for the unbelted driver and 12 % for the lap/shoulder belted passenger.

Table 6 and Figure 3 directly relate NASS investigators' estimates of objects contacted with the associated injured organs. The steering wheel is most often associated with liver injuries (34%), and spleen injuries (14%). The seat belt is most often associated with injuries to the digestive system (10%). The airbag is only associated with spleen injuries (0.33%). Other interior objects are mostly associated with spleen injuries (7%), and liver injuries (3%).

Tables 7 to 9, and their corresponding graphic representations shown in Figures 4 to 6, show detailed injury distributions associated with the seat belt, the steering wheel, and the interior, respectively. These tables and graphs show the normalized frequency of associated injuries to abdominal organs as they relate to the driver and the right front seat passenger with different restraint systems.

Table 7 and Figure 4 show that the belt is mostly associated with digestive injuries in lap/shoulder belted passengers (48%). Passengers wearing only shoulder belts show more spleen (11%) injuries than liver (4%) injuries. In contrast, drivers wearing only shoulder belts show no spleen injuries and 3% liver injuries.

Injuries associated with the steering wheel are shown in Table 8 and Figure 5. The data show that the steering wheel is mostly associated with injuries to the unbelted driver (87%) and drivers wearing only shoulder belts (12%). The most prevalent injuries sustained by the unbelted driver are in descending order: liver (39%), spleen (20%), arteries and veins (13%) and the digestive system (8%). Drivers wearing only shoulder belts mostly sustained liver injuries (11%).

Data for airbag associated injuries show that 100% of injuries occurred to the unbelted driver with airbag. Table 9 and Figure 6 present abdominal injuries associated with the vehicle interior. The data show that of those injured by vehicle interior components, 70% were unrestrained passengers. Splenic injuries were most prevalent (49%) followed by the liver (23%).

Table 2.
Abbreviation Definition for the Driver and Front Seat Passenger with Different Restraint Systems

	Driver	Front Seat Passenger
Lap belt + Shoulder belt + Airbag	D/LSB	P/LSB
Lap belt + Shoulder belt	D/LS	P/LS
Airbag only	D/B	P/B
Lap belt only	D/L	P/L
Shoulder belt only	D/S	P/S
No restraint	D/	P/

Table 3.
Abbreviation Definition for the Contact Objects Used in this Study

Label	Object
Belt	Seat belt
SW	Steering wheel
Bag	Airbag
Interior	Windshield, Left IP, Left interior, Left armrest, Other front, Center IP, Shift lever, Right IP, Glove box, Right interior, or Right A-pillar

Table 4.
Normalized Frequency of Abdominal Injuries for Drivers and Front Seat Passengers with Different Restraint Systems (100%=83,322)

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEY	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.03%	0.42%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.45%**
D/LS	0.66%	0.47%	0.01%	0.25%	2.63%	0.00%	0.00%	**4.03%**
D/B	0.13%	0.18%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.31%**
D/L	0.00%	0.04%	0.00%	0.94%	0.00%	0.00%	0.00%	**0.98%**
D/S	7.58%	0.00%	0.00%	0.32%	0.08%	0.17%	0.00%	**8.14%**
D/	26.32%	13.65%	8.81%	5.82%	0.63%	2.40%	1.84%	**59.47%**
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/LS	0.39%	1.75%	1.34%	7.88%	0.12%	0.52%	0.47%	**12.48%**
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/S	0.71%	1.81%	0.29%	0.63%	0.00%	0.00%	0.00%	**3.44%**
P/	2.03%	4.27%	1.20%	0.97%	0.13%	1.23%	0.87%	**10.70%**
TOTAL	**37.85%**	**22.60%**	**11.65%**	**16.81%**	**3.59%**	**4.32%**	**3.17%**	**100.00%**

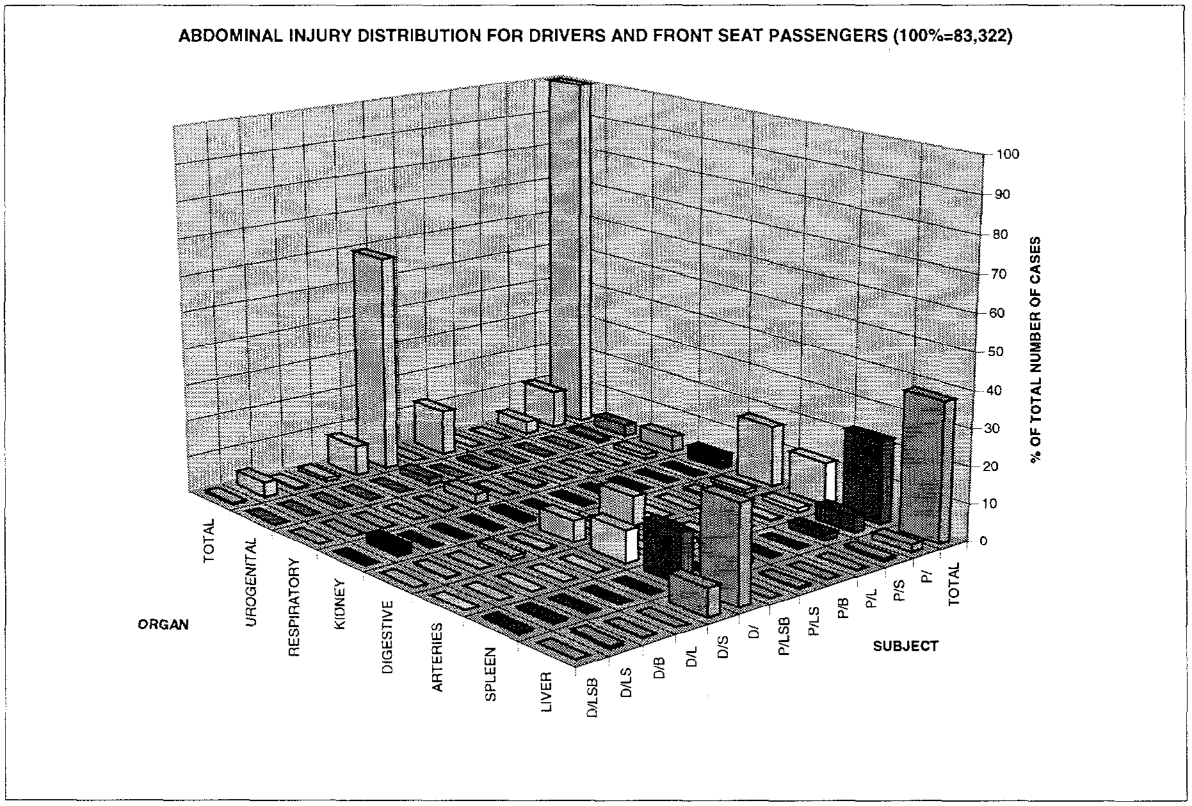

Figure 1. Normalized frequency of abdominal injuries for drivers and front seat passengers with different restraint systems.

Table 5.
Normalized Frequency of Objects Associated with Abdominal Injuries for Drivers and Front Seat Passengers with Different Restraint Systems (100%=78,992)

	BELT	SW	BAG	INTERIOR	TOTAL
D/LSB	0.35%	0.06%	0.00%	0.07%	**0.48%**
D/LS	1.27%	0.27%	0.00%	0.65%	**2.19%**
D/B	0.00%	0.12%	0.13%	0.08%	**0.33%**
D/L	0.50%	0.44%	0.00%	0.00%	**0.93%**
D/S	0.50%	7.91%	0.00%	0.18%	**8.59%**
D/	0.23%	59.39%	0.00%	1.28%	**60.90%**
P/LSB	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/LS	10.85%	0.00%	0.00%	1.98%	**12.82%**
P/B	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/L	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/S	3.63%	0.00%	0.00%	0.00%	**3.63%**
P/	0.00%	0.18%	0.00%	9.95%	**10.13%**
TOTAL	**17.31%**	**68.38%**	**0.13%**	**14.18%**	**100.00%**

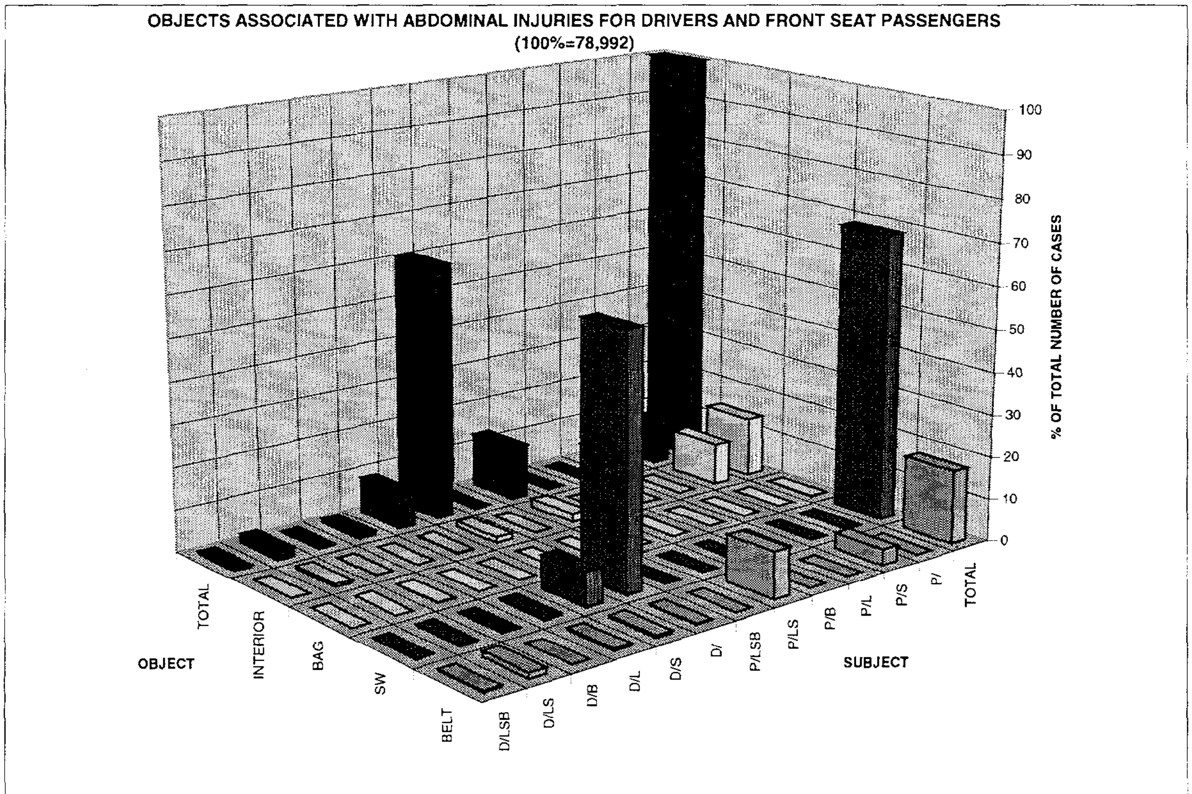

Figure 2. Normalized frequency of objects associated with abdominal injuries for drivers and front seat passengers with different restraint systems.

Table 6.
Contact Object Association with Injured Organs (100%=38,972)

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
BELT	1.63%	2.34%	1.54%	9.62%	1.26%	0.56%	0.00%	**16.95%**
SW	34.31%	13.72%	9.07%	6.68%	0.76%	2.69%	1.49%	**68.72%**
BAG	0.00%	0.13%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.13%**
INTERIOR	3.26%	6.89%	1.37%	0.84%	0.14%	0.77%	0.93%	**14.19%**
TOTAL	**39.20%**	**23.08%**	**11.98%**	**17.13%**	**2.17%**	**4.02%**	**2.41%**	**100.00%**

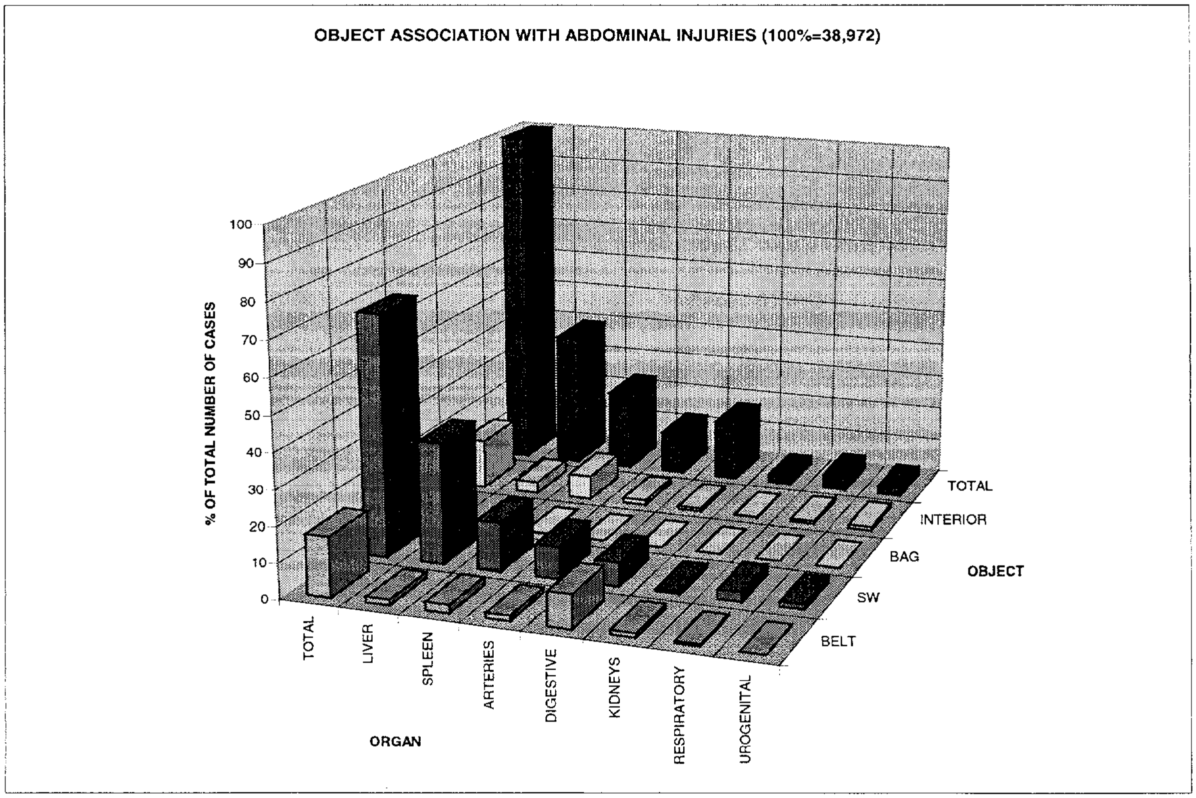

Figure 3. Contact object association with injured organs.

Table 7.
Frequency of Abdominal Injuries Associated with the Seat Belt for Drivers and Front Seat Passengers with Different Restraint Systems (100%=6,608)

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.00%	2.08%	0.00%	0.00%	0.00%	0.00%	0.00%	**2.08%**
D/LS	0.87%	0.00%	0.00%	0.00%	6.69%	0.00%	0.00%	**7.56%**
D/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
D/L	0.00%	0.00%	0.00%	2.97%	0.00%	0.00%	0.00%	**2.97%**
D/S	2.99%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**2.99%**
D/	0.00%	0.00%	0.00%	1.35%	0.00%	0.00%	0.00%	**1.35%**
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/LS	1.29%	0.28%	7.29%	48.41%	0.76%	3.31%	0.00%	**61.34%**
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/S	4.48%	11.42%	1.81%	4.00%	0.00%	0.00%	0.00%	**21.71%**
P/	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
TOTAL	**9.62%**	**13.78%**	**9.10%**	**56.73%**	**7.46%**	**3.31%**	**0.00%**	**100.00%**

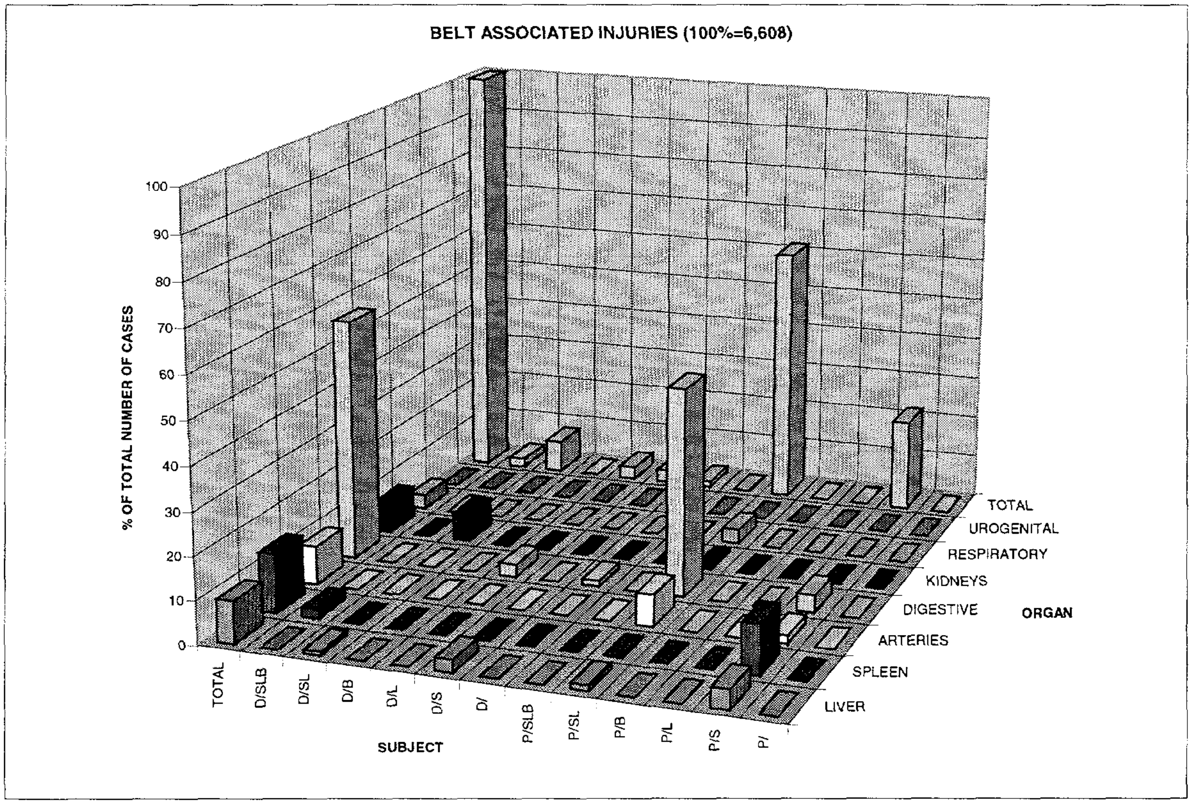

Figure 4. Frequency of abdominal injuries associated with the seat belt for drivers and front seat passengers with different restraint systems.

Table 8.
Frequency of Abdominal Injuries Associated with the Steering Wheel for Drivers and Front Seat Passengers

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.00%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.09%**
D/LS	0.00%	0.00%	0.02%	0.38%	0.00%	0.00%	0.00%	**0.40%**
D/B	0.09%	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.18%**
D/L	0.00%	0.07%	0.00%	0.58%	0.00%	0.00%	0.00%	**0.64%**
D/S	11.05%	0.00%	0.00%	0.50%	0.12%	0.00%	0.00%	**11.67%**
D/	38.79%	19.72%	13.18%	8.26%	0.99%	3.65%	2.17%	**86.75%**
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/LS	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/	0.00%	0.00%	0.00%	0.00%	0.00%	0.26%	0.00%	**0.26%**
TOTAL	**49.93%**	**19.97%**	**13.20%**	**9.72%**	**1.11%**	**3.91%**	**2.17%**	**100.00%**

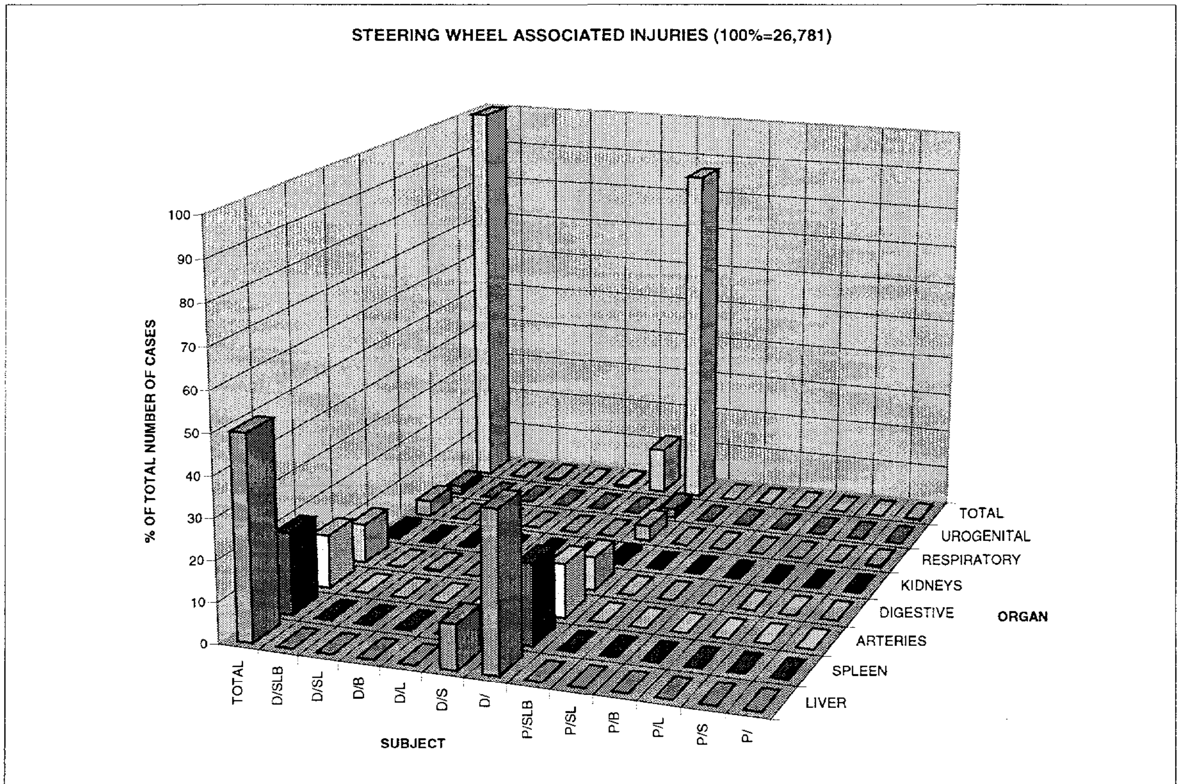

Figure 5. Frequency of abdominal injuries associated with the steering wheel for drivers and front seat passengers with different restraint systems.

Table 9.
Frequency of Abdominal Injuries Associated with the Interior for Drivers and Front Seat Passengers with Different Restraint Systems (100%=5,532)

	LIVER	SPLEEN	ARTERIES	DIGESTIVE	KIDNEYS	RESPIRATORY	UROGENITAL	TOTAL
D/LSB	0.24%	0.24%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.47%**
D/LS	1.06%	3.56%	0.00%	0.00%	0.00%	0.00%	0.00%	**4.63%**
D/B	0.56%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.56%**
D/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
D/S	0.00%	0.00%	0.00%	0.00%	0.00%	1.27%	0.00%	**1.27%**
D/	6.08%	0.60%	0.57%	1.87%	0.00%	0.00%	0.00%	**9.13%**
P/LSB	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/LS	1.15%	12.40%	0.00%	0.58%	0.00%	0.00%	0.00%	**14.13%**
P/B	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/L	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
P/	13.88%	31.76%	9.06%	3.44%	1.00%	4.16%	6.52%	**69.81%**
TOTAL	**22.97%**	**48.56%**	**9.63%**	**5.89%**	**1.00%**	**5.43%**	**6.52%**	**100.00%**

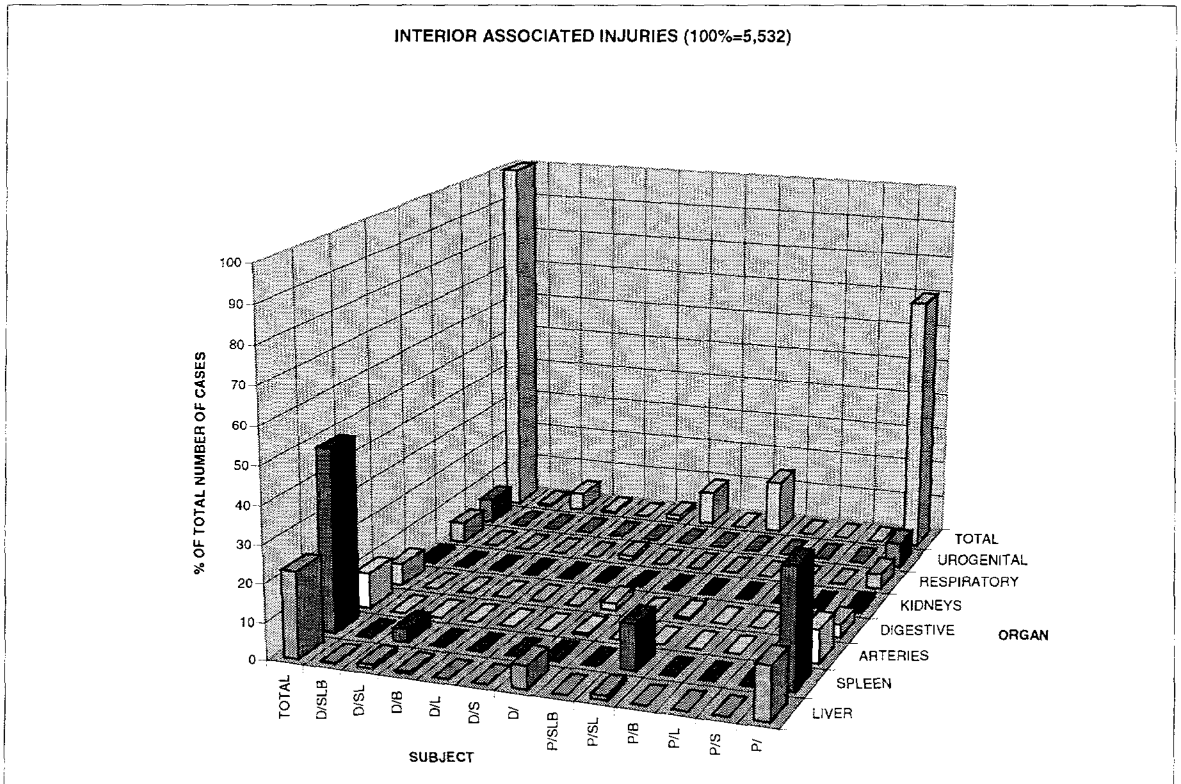

Figure 6. Frequency of abdominal injuries associated with the interior for drivers and front seat passengers with different restraint systems.

DISCUSSION

It is important to note that this study is not intended for the comparison of injury from various restraint systems. Such evaluation is problematic unless equal exposure is assumed, which is clearly not the case in this study. A clear example is the exposure of occupants restrained with lap/shoulder belt only versus with airbag only. The 1988 to 1994 NASS data used in this study were collected when less than 10% of the vehicles on the road are estimated to be equipped with airbags.

Thus, the results of this work only define the injury frequency for organs in the abdomen and the contacts associated with those injuries for the period studied. This is appropriate for the prioritization objective of this study and for injury mitigation research. Studying the association of injuries and individual occupant contacts with different restraints can serve to guide the types of measurements to be made in the crash test dummy.

The overrepresentation of abdominal injuries for higher severity corroborates the findings of previous studies (Ricci 80, Rouhana 85). This fact emphasizes the seriousness of abdominal injuries and the need for an abdominal injury detection device. Wells et al (1986) showed that belt malpositioning by occupants was common. In their study 89% of the occupants placed part of their belts above the anterior superior iliac spines (ASIS). Figure 4 highlights the need for continued effort of public education on the proper manner to wear seat belts and the need for continued research towards improved restraints.

It is well known that seat belts have an overall effectiveness of approximately 50% but the belt itself can occasionally be associated with harm to occupants (Hill, 92). Our results show that belted passengers have sustained slightly more abdominal injuries than unbelted passengers. However, these statistics do not show the fatalities and injuries to the head, neck, and chest that were prevented by these same belts. In general, the risks from the use of seat belts are overwhelmed by their ability to mitigate injury and death as has been emphasized by the literature (Backaitis 85, Rouhana 93, Evans 95).

Figure 1 also shows the higher vulnerability of the liver, spleen, and the digestive system compared to other organs in the abdomen. This is in agreement with results of a frontal impact study of the National Crash Severity Study (NCSS 1977-1988) performed by Bondy et al in 1980 (as cited in King, 1985). These results showed that the order of serious abdominal injury was liver (39%), spleen (25%), and digestive (16%). However, our study differs with Bondy's regarding kidney injury wherein he reported a frequency of 14% while we found a frequency of 4%. Since both studies agree on the three most injured organs in the abdomen, a priority for instrumentation can be determined with respect to organs injured. Instrumentation priority from these statistics should be (in descending order): liver, spleen, and digestive system.

Our study also shows a difference with Bondy's regarding the contact points associated with abdominal injuries. Bondy reports 51% associated with the steering wheel, 48% with the interior, and 1% with the belt. Our study shows higher percentage for the steering wheel (68%) lower for the interior (14%) and much higher for the belt (17%). Those differences are most likely related to the much higher frequency of seat belt use in the period covered by our study. This might also explain the higher kidney injuries reported by Bondy. In 1977-1978, the period covered by the NCSS, belt use was around 10%. However, after the first mandatory belt use laws in 1984 belt use rose to over four times greater.

With respect to contacts associated with injury, our analysis suggests instrumentation to detect steering wheel contacts as the first priority. The second and third priorities are to the belt and interior contacts, respectively. However, given the change in restraint systems in today's vehicles, most notably the introduction of airbags, steering wheel contacts are expected to be reduced. Thus, other contacts might be higher in priority.

The direct association of the steering wheel with liver and spleen injury is expected due to the close proximity of these organs to it. Proximity may also explain the high association of the seat belt with injuries to the digestive system. Airbags were only associated with spleen injury in the abdomen. This fact highlights the vulnerability of this organ to high-pressure injuries as reported experimentally (Lau 93).

The lap/shoulder belted right front passenger shows more abdominal injuries than the right front passenger with lap belt only. The most likely reason for this is that most cars produced in the U.S. since 1972 have had lap/shoulder belts at the RFP position. Therefore, the percentage of right front passengers with lap belts only is negligible compared to those with lap/shoulder belts.

It is also interesting to compare injury frequency for the liver and spleen of drivers and passengers wearing only shoulder belts. The belted driver sustained more liver injuries compared to spleen injuries but the right front passenger saw the opposites. This can be explained by the location of the driver's shoulder belt which passes directly over the liver whereas the passenger's shoulder belt passes directly over the spleen.

The steering wheel association with the driver liver and spleen injuries can be attributed to the direct interaction of these organs with the wheel for mostly unbelted occupants. The more frequent liver injury could be due to the partial exposure of the liver outside the rib cage in contrast to the spleen, which is totally protected by the rib cage.

In contrast to steering wheel injuries, airbag and other interior objects in the vehicle are more associated with spleen than liver injuries. These results suggest that abdominal injury patterns depend on the type of the impacted surface. The airbag and the interior can be dealt with as more load distributing surfaces compared to the steering wheel or the seat belt. These results also raise a question about the appropriateness of having the same injury criterion for localized versus distributed impacts such as seat belts versus airbags. This concept is also supported by another statistical study comparing liver and kidney injuries for belted drivers with and without airbag (Dischinger 96). The study shows 19% decrease in liver injuries and approximately 3 times increase in kidney injuries for belted drivers with an airbag. This highlights the fact that injury patterns are not stagnant. There can be a shift in injury patterns as designs or use trends change. Using data of airbag factory installation in passenger cars and trucks (from AAMA, 1996 and 1997) the estimated percentage of airbag equipped vehicles is projected to be more than half the vehicles on the road in year 2000 (Figure 8). Therefore, to comply with the objective of this study, which is to define priorities for the instrumentation of a new abdomen for the Hybrid III ATD, we need to take the increase of airbag restraints into consideration.

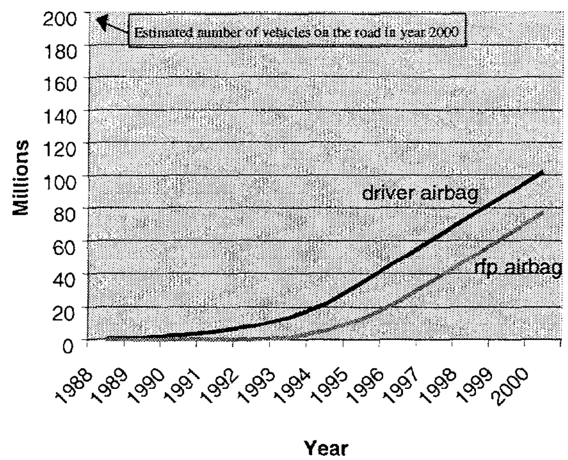

Figure 7. Estimated number of airbags available for drivers and right front seat passengers on the road.

CONCLUSION

The results of this study will help in setting priorities for building an abdominal insert for crash test dummies. The three most frequently injured organs are in descending order: the liver (38%), the spleen (23%), and the digestive system (17%). Therefore, the abdominal insert designed should be able to assess injury to these vital organs. If the viscous criterion is used, we need to measure individual displacement and velocity of these areas. For proper identification of submarining, multiple sensors might be required in the area over the digestive system.

The instrument most often associated with abdominal injuries was the steering wheel (68%) followed by the belt (17%) and the airbag and other interior objects (14%). One sensor over the area of the liver and one over the spleen are expected to be adequate to define injuries associated with the steering wheel. Up to three sensors over the area of the digestive system are also expected to be adequate for belt associated injuries. For more distributed loads, the type of sensor will be defined by other work as a continuation of this study.

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