Crash Injury Analysis of Measurement Needs for an Improved Anthropomorphic Test Device

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ABSTRACT

The purpose of this paper is to provide a rationale for setting measurement goals for the next generation of frontal and frontal oblique Anthropomorphic Test Devices (ATD's). More specifically, the requirements for the thorax-abdomen are examined.

An examination of field accident data from the frontal crash direction has provided insight into the opportunities for injury reduction and the needs for future ATD's. The United States files of the National Accident Sampling System are used for this analysis. Field injury patterns are assessed according to injury frequency and severity to determine injury measurement needs. Other injury files containing a higher proportion of restrained occupants are reviewed for comparison with the US national files.

INTRODUCTION

The next generation of anthropomorphic test devices for frontal/oblique crash safety evaluation will be used with a variety of restraint configuraions. These will include 3-point belts, 2-point belt with knee bolster, air bag restraint, air bag with supplemental belt, and restraint via vehicle interior components (e.g., the steering assembly and instrument panel). The projected use of the new test device in this range of environments presents a significant design challenge, since the device must reliably assess the probability of injury arising from the widely varying loading patterns and loading rates which are presented by these restraint systems. Examples of needs identified by safety researchers can be found in the literature.

Grosch of Daimler Benz has reported difficulty in assessing the optimum design for the 3-point belt with an emergency locking retractor in combination with an air bag, using existing dummies (reference 1). With the numbers of vehicles with the 3-point belt and air bag restraint combination increasing, the need to assess optimum designs is of primary importance.

Toyota researchers have reported difficulty in using the chest deflection measurements of the Hybrid III dummy for optimum safety belt design because of the measurement's sensitivity to belt placement (reference 2). The Toyota researchers suggest that the dummy clavicle and lower ribs provide load paths which make the chest deflection measurement sensitive to the way the belt crosses the chest. The need to accurately assess ways to further improve the safety of shoulder belt restraint systems is a continuing requirement.

Wilson of General Motors suggested that large reductions in harm are possible by improving the energy absorbing properties of the vehicle interior (reference 3). The benefits would accrue to those occupants who persist in not using their belts, and to those restrained occupants who contact vehicle interiors during severe or complex crashes. The wide range of interior contacts which may be possible in designing energy absorbing interiors, presents significant challenges for an advanced ATD design.

The research needs identified by these authors suggest that future dummies should be able to compare the protection offered by interior energy absorbing systems alone with that offered by the various restraint systems. Further, there is a need to assess the optimum design of belt systems when used in conjunction with other chest/abdominal loadings. These other loadings could be distributed as by an air bag, or concentrated as by a steering rim or hub.

FIELD ACCIDENT DATA FILES

Insight into the relative magnitude and severity of the fatality and injury problem can be gained by examining available accident data. The accident data files are useful in establishing ATD goals for the injuries to be measured, and the severity ranges for which the measurements are needed.

Figures 1A and 1B show the distribution of passenger car occupant fatalities and harm by crash direction. The fatalities are based upon the 1986 census of United States fatal accidents, as recorded in the Fatal Accident Reporting System (FARS). The "harm" distribution is based upon the 1979-1986 National Accident Sampling System (NASS) files. Harm is a quantification of the consequence of all injury, accounting for both frequency and severity. The concept was developed by Malliaris, et.al. in reference 4 and further used to set priorities in injury reduction by Digges, et.al. in reference 5.

It may be noted from Figure 1 that the frontal crash direction continues to be the largest source of occupant fatalities and serious injuries, accounting for more than 45 percent of both populations. The need for continued attention to safety features for frontal protection is self evident. This paper focuses on the frontal crash mode and the expected crash environment for the next generation of frontal ATD's. In the analysis to follow, events which resulted in vehicle rollover or occupant ejection have been excluded, because these environments have specialized requirements which are not addressed by this paper.

The NASS file is useful for evaluating the severity of crashes which produce serious injury. The combined 1979-1986 NASS file contains 1,023 cases of serious injuries to unrestrained passenger car occupants in frontal impacts for which the crash severity is known. Figure 2A shows the distribution of serious injuries (AIS 3 and greater) to unrestrained passenger car occupants in frontal impacts by crash severity. Figure 2B shows the distribution of specific thoracic injuries as function of delta V.

It may be noted from Figure 2A that nearly 40% of the serious chest and abdominal injuries occur at crash severities greater than 30 mph. However, as shown in figure 2B, the various injuries are not equally distributed. For skeletal injuries, 70% occur below 30 mph. For arterial/veinous injuries, only 30% occur below 30 mph. These injury distributions give insight into the severity range for which measurements of various injuries should be considered.

Figure 3 illustrates the distribution of serious injuries and harm by body region for both restrained and unrestrained passenger car occupants in frontal crashes. The harm data are for all injuries reported in the 1979 through 1986 NASS file, while the AIS category includes only those injuries with a severity of three or greater. The injury counts have been weighted by a national expansion factor which is used to make the NASS files representative of the population of accidents which occur in the United States. The unweighted values of AIS 3+ injuries and "harm" are the "N" values shown in the legend of the figure. The harm unweighted "N" values refer to the count of all injuries AIS 1 and above. All accidents except those involving rollover and ejections are included. In the NASS file, up to six individual injuries for each injured occupant may be coded into the computerized file, and it is all these injuries that are included in this analysis. This approach is considered appropriate for providing guidance on dummy development and instrument location priorities. Other characterizations, such as the maximum injury received by each occupant are considered less useful for the purposes of assessing dummy needs.

An examination of Figure 3 shows that injury distributions are generally similar for unrestrained and belt restrained occupants. However, it should be noted that restrained occupants experience much lower risk of injury. The reduction in injury risk for restrained occupants is not apparent from the data presented in this paper. For the purposes of this study, only the distribution of injuries within the restrained and unrestrained populations are examined. A more refined analysis of the NASS data permits further examination of the nature of chest/abdominal injuries in frontal impacts.

ANALYSIS OF THORAX AND ABDOMINAL INJURY REPORTED IN NASS

For the driver and right front passenger, the 1979-86 NASS data base has been interrogated for the frequency of system/lesion pairs for the thorax/abdominal region, defined as containing the NASS body regions chest, back (thoracolumbar spine), shoulder, and abdomen. Further selection restrictions included the following: Passenger cars only; General area of damage—frontal; No rollover or ejection.

For purposes of this analysis, actual injury counts (unweighted data) were used for the AIS 3 and greater analysis. The "harm" concept analyses were performed in a manner similar to that explained in the previous section, except actual injury counts were used.

Distribution of AIS 3+ injuries and of harm for restrained and unrestrained drivers and unrestrained right front passengers are shown in Table I. There was insufficient data on restrained right front passengers to include them in this analysis. Several observations from the data of unrestrained occupants are of interest:

- Serious injuries are widely distributed among many sites. Arterial, heart, liver, pulmonary, and skeletal injuries account for 65% of total driver AIS 3+ counts and 63% of passenger AIS 3+ counts. Kidney, spleen, and digestive organ injuries account for an additional 16% of driver AIS 3+ counts and an additional 17% of passenger AIS 3+ counts.

- The relative frequency of heart injuries appears to be higher on the driver side.
- Harm weighting significantly alters the apparent importance of the injury sites:
  - Arterial injuries, although representing approximately 10% of AIS 3+ counts, constitute between 23% (driver) and 31% (passenger) of harm, and are the greatest source of estimated harm.
  - Liver injuries similarly represent approximately 11 percent of AIS 3+ counts, but account for 16 percent of driver harm.
  - The relative significance of injury to the pulmonary system, skeletal system, kidney, and spleen is markedly reduced in the harm accounting scheme.

For the lap and shoulder belt restrained driver, it may be noted that serious injuries also are widely distributed among several injury sites, including the heart, kidney, liver, pulmonary system, and skeleton. In terms of harm, the relatively large contribution of liver injuries to total harm (21 percent) is notable.

A comparison of major contributors to total harm for the unrestrained driver vs. the belted driver is made in Figure 4. Relative reductions of arterial and heart injuries occur in the belt restrained data, offset by relative increases in liver and pulmonary injuries.

REVIEW OF OTHER INJURY STUDIES FOR BELTED AND UNRESTRAINED OCCUPANTS

A study by Dalmotas, Reference 6, discusses mechanisms of injury to Canadian 3-point belt wearers, and contains 314 cases which include all principal directions of force. If frontal data only is extracted, 91 drivers and 30 right front passengers remain in the data base. Findings from the frontal data indicate that:

- Abdominal/pelvic injuries are, relatively speaking, much more prevalent on the passenger side. These injuries represent only 4.5 percent of AIS 2+ counts on the driver side but 22 percent of passenger AIS 2+ counts.
- Whereas the few abdominal injuries on the driver side are attributed to wheel rim contact, all abdominal injuries on the passenger side are attributed to local belt intrusion. Concurrent loading of the seat back by a rear seat occupant is cited as an important contributing factor in some cases.
- A distinction was made between those drivers who contacted the steering assembly and those who did not. Those who were assessed as not making wheel contact experienced only thoracic skeletal fractures, usually following the path of the belt on the torso. Fractures of the clavicle, sternum, and ribs were seen. Drivers who were assessed as making wheel contact did sustain intrathoracic injuries associated with skeletal fractures. Abdominal injuries in these cases, although infrequent, were observed.
- Passenger side thoracic skeletal fractures again followed the path of the shoulder belt. Internal thoracic injuries were apparently infrequent, but one case of myocardial contusion was observed.

Rutherford (7) discusses the influence of the introduction of compulsory seat belt wearing in the United Kingdom upon injury patterns observed.

Although it is not possible to extract frontal exposures from the general data presented, the findings of this study do provide guidance with respect to the overall shift of thoracic/abdominal injury patterns. Injuries changes post-belt law included:

Decreased Injury	Increased Injury
o Lung and pleura	o Sternal fractures
o Kidney	o Thoracic contusions
o Severe intrathoracic	o Abdominal wall contusions
o Driver rib fractures	o G I tract & mesentery
o Driver abdominal contusions	o Pancreas

Friedel, et. el., Reference 8, reports the distribution of injuries by body area before and after August 1984, when increased penalties for nonuse of front seat belts in the Federal Republic of Germany raised usage above 90 percent. Frontal accidents not involving multiple collisions were considered in the analysis. The data presented in reference 8 were utilized by extracting only thorax and abdominal injury data, and by removing injuries to the "soft parts" under the assumption that these injuries were of relatively low severity. The distribution of remaining injuries to the thorax and abdomen is presented in Figure 5, for both the pre-August 1984 and post-August 1984 periods. It would appear that all major classes and sites of injury continue to occur in the post-August period.

Schmidt (9) reports the results of autopsies conducted on 117 car crash victims, also in the Federal Republic of Germany, of whom 54 were known to have been restrained by 3-point belts. Although frontal crash exposures were not specifically reported, a major finding of the study was that passenger compartment intrusion often potentiated serious injury, regardless of belt restraint use or nonuse. In general, however, belted front seat occupants were found to primarily sustain injuries to the trunk, whereas non-belted counterparts received primarily head, limb, and pelvic injuries.

An examination of Figure 4 shows that belt use reduces the relative incidence of arterial and heart injuries. This trend is confirmed by the Rutherford (7) observation of reduced severe intrathoracic injuries post belt law. Although different restraint modes produce some differences in injury patterns, a great deal of commonality also exists. It would be highly desirable for a future ATD to be able to measure all major injury types, regardless of restraint mode.

INJURY PATTERNS FOR AIR BAGS AND BELT/BAG COMBINATIONS

Injury data for air bag and bag/belt exposures are similarly limited at this time. The possibility has been raised, based upon animal studies, that under certain conditions a bag system could deliver a high velocity impulsive load (bag slap) to the human thoracic wall, resulting in blast type injury (10). However, evidence of the occurrence of this type of injury has not been confirmed in the field accident data involving fleets of installed driver bag/belt systems. Backaitis (11) analyzed 112 air bag deployment crashes in the U. S. Government 5,300 car fleet of air bag equipped Ford Tempos and found no air bag related injury greater than AIS 1. Kallina (12) examined injuries in Mercedes Benz air bag cars and found only 3 drivers with AIS 3 chest injuries, and none higher. All injuries were in crashes with speed changes greater than 51 km/h (30 mph). The three injuries were:

- o Thorax/heart contusions with sternum fracture
- o Thorax/heart contusion without sternum fracture
- o Multiple rib fracture

Some of these injuries may have been induced by combined belt and air bag loading.

Field data on passenger air bag injuries is inadequate to assess any chest injuries induced by the restraint system. Testing of passenger air bags at 30 mph with human volunteers reported by Brinkley (13) produced no injury greater than AIS 1. Tests of driver and passenger air bags using cadavers are summarized in reference 14. In a series of 30 mph crash tests of the 1974 GM production air bag system, no chest/abdominal injuries greater than AIS 1 were reported.

A series of cadaver tests involving a device intended to apply distributed load to the chest has also been reported by Cheng (15). This test series produced both skeletal and soft tissue injuries. However, the distributed load test device was not representative of present day air bags. Consequently, the nature of AIS 3+ chest injuries which may be induced by air bags is still unclear.

DESIGN IMPLICATIONS FOR THE ATD

The data presented above indicates that the major sites of injury to the thorax and abdomen are widely distributed. Those sites accounting for more than approximately 10% of either AIS 3+ counts or of harm are as follows:

<u>Unrestrained Drivers and Passengers</u>

- o Arterial
- o Liver
- o Heart
- o Skeletal
- o Pulmonary/Lung

<u>Belted Drivers</u>

- o Arterial
- o Liver
- o Heart
- o Skeletal
- o Pulmonary/Lung
- o Kidney
- o Spleen (Ref. 8)

In addition, for the <u>belted passenger</u>, the soft abdominal "digestive" sites are added to the list, based upon the findings of reference 6. The <u>air bag</u> induced thorax/abdominal injuries observed to date are limited and fall within the categories listed above.

It is evident from the lists above that nearly the entire projected area of the rib cage and of the soft abdomen represents area which is at serious injury risk. The clear implication for ATD thorax/abdomen design is that local measurements will be required at several locations to properly monitor for the widely distributed injuries. To the extent possible, instrumentation selected for the ATD should reflect our current understanding of general mechanisms of injury (see, for example, references 16-24). Candidates for measurement would appear to include:

- o Local deflection
- o Local deflection rate
- o Local stored energy/unit mass or volume
- o Local dissipated energy/unit mass or volume
- o Rates of energy storage and dissipation
- o Whole-body acceleration (selected sites)
- o External pressure distribution on body surface
- o Load measurement (e.g., at clavicle)

The introduction of local instrumentation, of course, presupposes that appropriate regional dynamic response is provided by design over the range of loading rates of interest. It is considered essential that both the requirement for correct local response and the requirement for appropriate local instrumentation be integrated at the beginning of the design process.

Other design requirements for the thorax/abdomen do not arise directly from examination of regional injury data. For example, reference 25 concludes, based upon analysis of 3-point belt and air bag/steering column restrained cadaver sled tests, that significant dynamic articulation occurs in the thoracic spine. Further, frontal model simulations of a belted occupant reported in reference 25 show that introduction of thoracic spine flexibility significantly increases forward and downward head excursion. These results lead to the conclusion that thoracic spine flexibility is necessary in the ATD if potential head/face strikes onto the steering assembly are to be effectively monitored in the belted driver configuration.

SUMMARY OF PRELIMINARY DESIGN REQUIREMENTS

Future safety system designs indicate a need to evaluate the injury potential of belt systems when used alone, in conjunction with air bags, or in conjunction with concentrated-loading energy-absorbing-devices such as steering wheels. Additional safety needs include the evaluation of concentrated-loading energy-absorbing-devices alone and with air bags.

The field accident data for unrestrained and belt restrained occupants show general similarity with regard to the nature of the chest/abdominal injuries for severely injured occupants. Consequently, capability to assess the potential for injuries at many common locations is required by both environments. Serious chest/abdominal injuries to vehicle occupants are widely distributed within the rib cage and in the soft abdomen, suggesting that the next-generation thorax/abdomen design should incorporate multiple sensing locations. Correct regional dynamic response should be provided to permit the meaningful introduction of this local instrumentation. Load sensing should be incorporated in the shoulders of the new design, both to monitor clavicle loads and to assess the degree of partitioning of belt load between the upper and lower thorax.

The design should incorporate improved anthropometry (references 26 and 27), specifically with regard to lower rib cage shape and shoulder geometry and mass. Lower rib cage shape (together with dynamic stiffness) appears important both as a determinant of degree of abdominal penetration by the lower rim of the steering wheel and of realistic shoulder belt engagement. Realistic shoulder anthropometry and compliance are similarly essential for proper belt interaction at that location.

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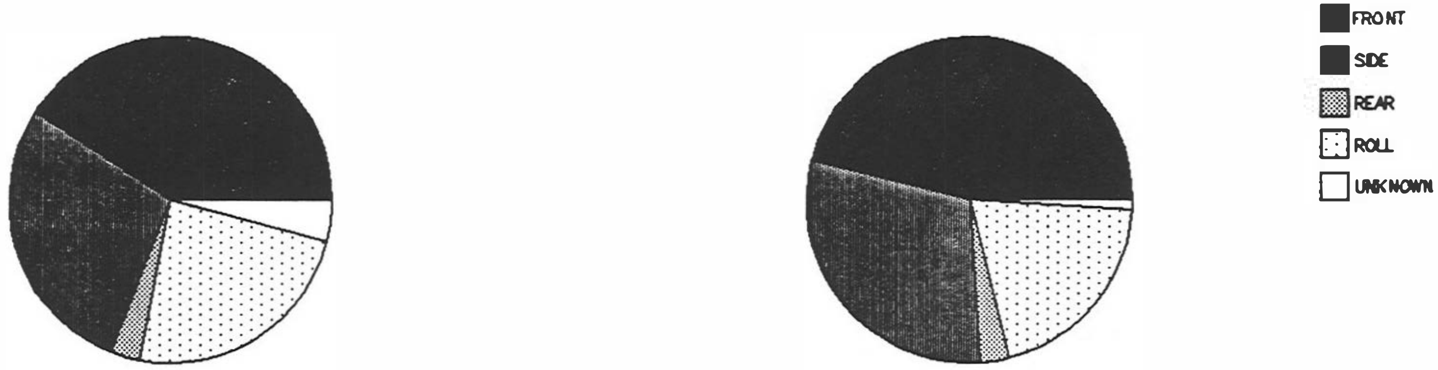
TABLE I
INJURY DISTRIBUTION (%) IN FRONTAL COLLISIONS- AIS 3+ AND HARM

	RESTRAINED DRIVER		UNRESTRAINED DRIVER		UNRESTRAINED RF PASS.	
INJURY	AIS 3+	HARM	AIS 3+	HARM	AIS 3+	HARM
ARTERIAL	3	10	9	23	11	31
SPINAL CORD	0	0	0	1	0	0
DIGESTIVE	7	5	5	5	3	1
UROGENITAL	0	0	2	0	2	3
HEART	9	9	12	15	6	5
INTERGUM.	0	3	0	2	0	2
JOINTS	4	1	3	0	2	0
KIDNEY	9	1	5	1	7	1
LIVER	15	21	11	16	11	15
NERVOUS SYS.	1	0	0	0	0	0
LUNG/PULMON.	16	10	16	5	15	7
SPLEEN	4	1	6	2	7	5
RESPIRATORY	1	0	1	1	1	0
SKELETAL	16	10	17	8	20	10
UNKNOWN	11	19	10	14	12	15
VERTEBRAE	1	0	0	0	2	2
ALL/CRUSH	3	10	3	7	0	2
ENDOCRINE	0	0	0	0	1	1

FATALITIES AND HARM BY CRASH MODE
PASSENGER CAR OCCUPANTS



FATALITIES
Figure 1A

TOTAL HARM
Figure 1B

1986 FARS
1979-86 NASS

24,712 FATALITIES IN 1986

SERIOUS CHEST & ABDOMINAL INJURIES
AIS 3+ DISTRIBUTION WITH DELTA V
(PASSENGER CAR OCCUPANTS, FRONTAL IMPACTS)

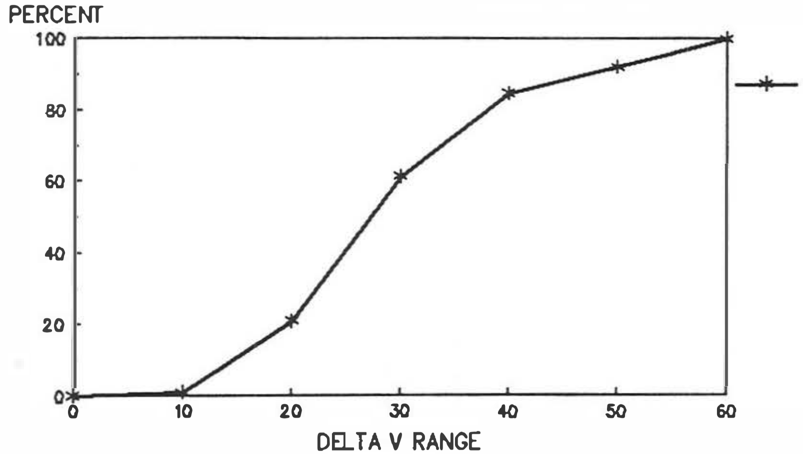


Figure 2A

1979-86 NASS

SERIOUS CHEST & ABDOMINAL INJURIES
AIS 3+ DISTRIBUTION WITH DELTA V
(PASSENGER CAR OCCUPANTS, FRONTAL IMPACTS)

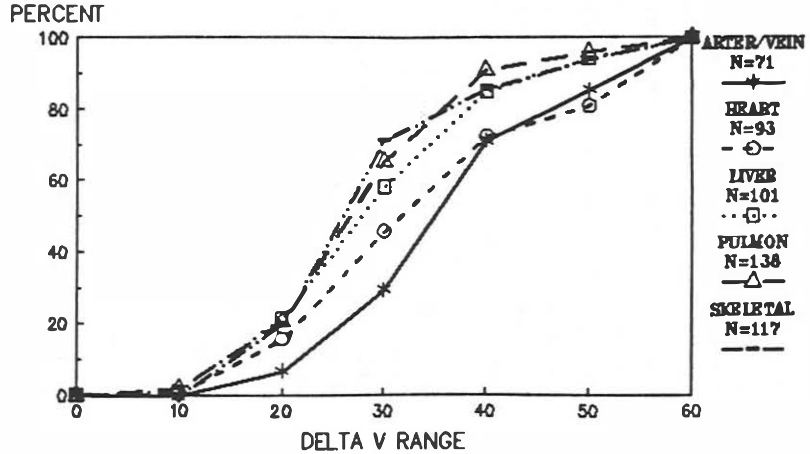


Figure 2B

1979-86 NASS

BODY INJURIES FOR FRONTAL CRASH MODE
AIS 3+ INJURIES & "HARM"
RESTRAINED & UNRESTRAINED

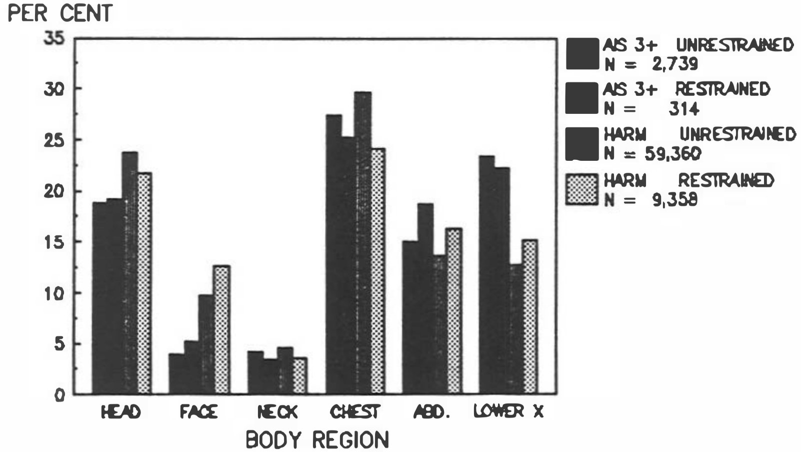


Figure 3

1979-86 NASS FILE

DISTRIBUTION OF INJURIES
FEDERAL REPUBLIC OF GERMANY
BEFORE AND AFTER BELT USE INCENTIVES

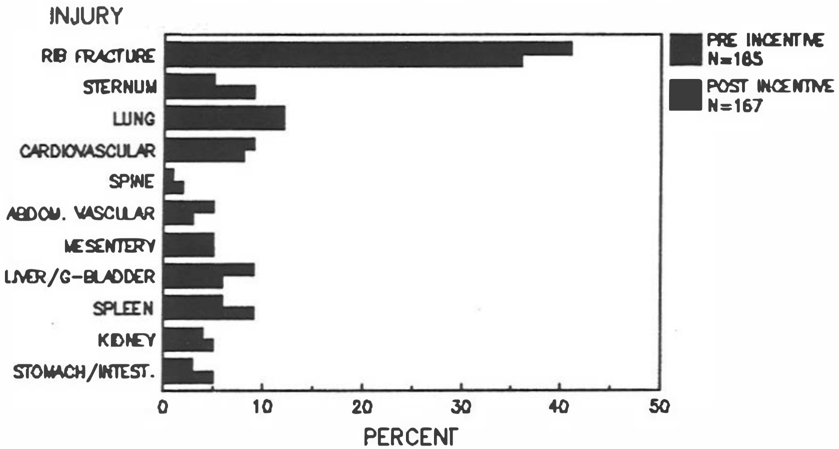


Figure 5

AFTER FRIEDEL
(REF. 8)

CHEST INJURY DISTRIBUTION - HARM
FRONTAL COLLISIONS - DRIVERS
UNRESTRAINED & RESTRAINED

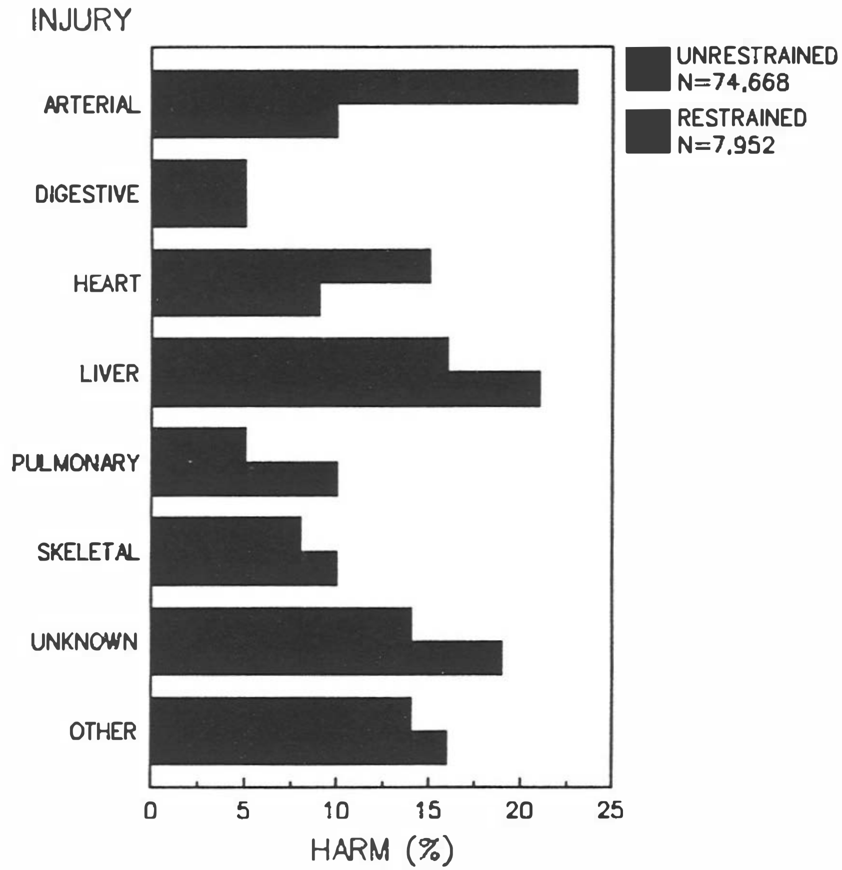


Figure 4

1979-86 NASS