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Design for Crash Survival of Automobile Occupants

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The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

This Record discusses inputs from some of the interacting fields of research that must be properly integrated for successful design of a crashworthy highway transportation system. The objective of the symposium from which these papers were taken was to stimulate cross communication between those responsible for crash safety design of the automobile and of the roadway. The papers in this RECORD present values, techniques, and opinions of the various disciplines that are completely interwoven into contemporary highway and occupant crash safety and serve to encourage the highway designer to be more circumspect in his or her approach to provisions for crash safety.

Garrett demonstrates the statistics of crash injury causation in accidents and ties these statistics to the realities of actual accidents. This approach is reiterated in the papers by Friedman and Tanner and Warner and Petersen, but they use slightly different emphases and methodologies.

An overview of results and methods from the field of biomechanics is presented by Melvin, Mohan, and Stalnaker as a means of quantifying the processes of injury causation and design for injury prevention. Friedman and Tanner discuss the results of a development program that substantially upgraded the crashworthiness of a production Pinto automobile and look ahead to the time when subcompact cars will constitute the largest class of vehicles sold in the United States.

Ross and Nixon suggest a method for judging field performance of median barriers and propose principles of choice for selection of appropriate barrier hardware.

In a predictive sketch of future vehicle-barrier interactions, Warner and Petersen attempt to set forth guidelines and criteria for economically feasible crash attenuation devices that will be compatible with the smaller, stiffer, more crashworthy cars likely to be in use a decade from now.

The specialized detail in automotive safety research imposes some limits on our perspective that can handicap true productivity. The papers in this RECORD should serve to broaden perception of the task of highway safety design teams, and enhance their competence to deal with that task.

—Charles Y. Warner

THE CRASH ENVIRONMENT

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This paper attempts to define the crash environment for recent model cars in terms of specific accident circumstances such as the object struck, the area of impact, and the direction of force. For each accident situation, details for a number of specific impact types and resultant injuries are provided. Details include comparison of single-car and two-car accidents and comparisons of severe injury accidents with all accidents in the study population from which they are drawn. National Safety Council and police-reported data are examined and discussed. The remaining data used in this study are selected from cases investigated by Calspan personnel in a trilevel accident study. Approximately 8,000 police cases collected during 1972 and a subset of 360 in-depth cases are available for study. For perspective purposes, the population of injury and property damage accidents from which the latter cases are drawn is described.

•DEFINING the crash environment requires, first, some understanding of the data on which the definition is based. Today, the most common sources of highway accident data are

1. Police and involved drivers,
2. Multidisciplinary accident investigation teams,
3. Trilevel studies of the U.S. Department of Transportation, and
4. Special studies.

Police reports of accidents are available in huge volume but provide a limited amount of detail concerning each accident. Multidisciplinary team data provide the greatest amount of detail but are available in limited quantity. In addition, because of varying team objectives, these data do not provide an adequate statistical sample of accidents in the United States. Trilevel studies provide basic data from the police and other state agencies augmented by specially collected data and by in-depth investigations of a relatively small number of cases. Data from these studies also may not be representative of the entire United States but generally serve to adequately describe the region from which they are drawn. Special studies usually provide detailed information concerning a specific topic, such as accident type, highway situation, single-vehicle accidents, rollovers, intersection accidents, and accidents involving drinking drivers. In these studies, data volume varies considerably; it is difficult to place the data in perspective, and there is no study continuity so that trend analyses (ongoing comparisons of data) are impossible to conduct.

In this paper, the crash environment is described based on two sources of data, police reports and in-depth data. The influence of different data sources, injury indexes, and study criteria on study results also is discussed to emphasize the importance of understanding criteria used in data collection and analysis when data are reviewed.

DATA SOURCES

Data summarized by the National Safety Council (1) from police-reported information collected in a number of states are used to broadly define the extent of the highway accident problem. Data from the Calspan trilevel program then are used to provide more detail concerning the broad accident types identified in the National Safety Council data and to compare results obtained by using police and in-depth data (both from the trilevel program).

Calspan Trilevel Program

The Calspan trilevel program is conducted in an eight-county area of western New York that encompasses approximately 6,000 miles^2 (15 540 km^2). Nearly 1 million vehicles are registered in this area, there are nearly 900,000 licensed drivers, and approximately 40,000 accidents occur annually. The three levels of data collection are briefly described below. In this paper, only data from study levels 2 and 3 are used.

Level 1

The level 1 accident file is produced through a merging process performed by the New York State Department of Motor Vehicles and contains data from accidents occurring in the eight-county area that are merged with the drivers' license files and vehicle registration files.

Level 2

The level 2 accident file contains all police-investigated accidents involving a current model automobile or a recent model truck in the study area. Calspan personnel obtain a copy of all police reports by personally visiting all the police stations regularly, and a copy of all driver reports is provided by New York State for the eight counties. Medical data are obtained from hospital records prepared by the attending physican for all injured occupants of all vehicles involved in the accident. Data from approximately 8,000 accidents are obtained annually.

Level 3

The level 3 file contains accidents that are investigated by the Calspan multidisciplinary team (approximately 350 accidents annually). Each accident involves a current model automobile or a recent model truck in which at least one occupant requires hospital treatment and thus represents a subset of the more serious injury accidents from the level 2 file. The major output of level 3 consists of detailed case reports in which descriptions of the accident sequences are provided and causal factors are enumerated. Drivers involved in these accidents are interviewed by Calspan personnel, and the interior and exterior of each case vehicle are examined and photographed extensively. Evidence at the scene is also measured and photographed. For each case, a 1974 annotated collision performance and injury report and supplementary forms are completed.

National Safety Council

Up to the present time, national highway accident statistics have been based largely on police reports collected and summarized by the National Safety Council. Information from all states is not available, and reporting is not always complete for all data items. Additional data also are obtained by the safety council from the National Center for Health Statistics, the Federal Highway Administration, the Federal Railroad Administration, and other sources, including special studies. Thus, the data are not homogenous but, rather, represent a best effort to provide useful information from a variety of sources.

The type of information available from police through the National Safety Council is given in Table 1, in which accident types reported by police are summarized for fatal accidents and for all accidents in rural and urban areas. The data indicate that the pedestrian accident occurs primarily in urban areas in terms of both accident occurrence and fatality. In general, the only accident type that occurs more frequently in rural areas than in urban areas is the noncollision (rollovers, primarily). Except for pedestrian accidents, more fatal accidents of all types occur in rural areas than in urban areas.

Most accidents involve two vehicles, and the two-vehicle accidents result in more fatalities than any other accident type. Noncollisions and pedestrian accidents rank second and third respectively, in terms of numbers of fatalities.

In Table 1, two-vehicle accidents can be further subdivided as given. The categories shown, however, are not sufficiently detailed to provide useful research data for vehicle studies. Noncollision accidents and other collisions (largely single-vehicle impacts) generally cannot be further subdivided in terms of the accident type or the vehicle area impacted for use in vehicle studies. Data such as those in Table 1 are also subdivided in terms of the time of occurrence (day or night), directional analysis, improper driving, day of week, and a number of other factors. Additional details concerning the vehicle area impacted, direction of force, and injury are not available however.

Injury Indexes

National Safety Council data generally provide information concerning all accidents, injury accidents, and fatal accidents. The data collected by police also provide additional injury classifications that are not used by the safety council. Injury definitions are based on the 2nd edition of the Manual on Classification of Motor Vehicle Traffic Accidents. Perhaps the major shortcoming in police reporting involves these injury definitions. The police rating and the abbreviated injury scale (AIS) ratings (2), which are used in highway safety research, are as follows:

Police Rating		AIS Rating	
Notation	Definition	Notation	Definition
K	Killed	6	Fatal
A	Incapacitating injury	4, 5	Dangerous
B	Nonincapacitating evident injury	2, 3	Not dangerous
C	Possible injury	1	Minor
O	No injury	0	No injury

Individual police ratings of injuries were anticipated to compare reasonably well with the AIS ratings given; however, comparison of police-reported injury with injuries reported by physicians and classified according to AIS in a Calspan study (3) revealed a considerable number of discrepancies in rating injury. In general, the data revealed that police were unable to discriminate between injury levels and, consequently, the only reasonably reliable information from this source was deemed to be the occurrence of any injury to an occupant and the occurrence of fatality.

In the study, AIS and police ratings of injuries for the same occupants were compared. Data for a total of 1,618 occupants were analyzed. Table 2 gives the percentage distribution of AIS injury ratings for each police-rated injury to the 1,618 occupants of cars included in the study. Anticipated correlations between the two indexes are underscored.

The data indicate that 82.5 percent of the police C ratings were in the anticipated AIS 1 category and that all of the police K ratings were in the AIS fatal ratings. Of the B ratings, however, only 37.6 percent were in the anticipated AIS 2 and 3 categories. Almost all of the remaining B ratings appeared in the AIS 1 category, which indicated

Table 1. Number of accidents by type and area for 1972.

	Fatal			All		
Accident Type	Urban	Rural	Total	Urban	Rural	Total
Pedestrian	6,800	3,700	10,500	350,000	50,000	400,000
Two-vehicle collision	5,500	13,400	18,900	10,400,000	2,700,000	13,100,000
Angle	2,100	3,000	5,100	2,100,000	500,000	2,600,000
Head-on	1,200	6,600	7,800	400,000	400,000	800,000
Rear-end	600	1,600	2,200	3,300,000	700,000	4,000,000
Other two-vehicle	1,600	2,200	3,800	4,600,000	1,100,000	5,700,000
Other collision total	2,400	4,000	6,400	700,000	400,000	1,100,000
Noncollision total	2,400	10,600	13,000	750,000	1,650,000	2,400,000
Total	17,100	31,700	48,800	12,000,000	4,800,000	17,000,000

Table 2. Percentage distribution of abbreviated injury scale ratings for each police rating.

Police	AIS Scale						
Scale	0	1	2	3	4	5	6
C	1.2	82.5	14.1	2.2			
B	0.5	61.3	32.2	5.4	0.3	0.2	0.2
A		34.8	33.0	26.5	2.9	1.4	1.4
K							100.0

rather mild injuries. Only 4.3 percent of the police A ratings appeared in the anticipated AIS 4 and 5 categories. Even if the 1.4 percent of A rated injuries that later resulted in death were added to this, approximately 94 percent of the A rated injuries would not be included in the anticipated AIS categories.

Essentially, the foregoing information means that death and the lowest level injury C as rated by police were more consistent with anticipated AIS ratings than other categories. The more serious injury ratings B and A generally were not consistent with anticipated AIS ratings. Note that 98.9 percent of the B ratings and 94.3 percent of the A ratings were distributed among the 1, 2, and 3 AIS categories. Perhaps the least discrimination is evidenced in the A category, where roughly 33 percent of the injuries fall into each of the 1, 2, and 3 AIS categories, although an A rating is intended to indicate serious injury.

These data indicate that the anticipated correlation between AIS ratings and police ratings is poor except for fatalities and reflect the fact that definitions provided the police do not permit them to discriminate between injury severities. As an example, a minor AIS injury (rating 1) is generally a laceration, abrasion, contusion, or bruise without extensive bleeding. A bleeding injury may well be classified as an A, B, or C injury depending on the officer's interpretation of the extent of bleeding. The AIS scale does not permit discrimination among specific types of injuries.

Comparison of Levels 2 and 3 From Calspan Program

Accident data collected by the Calspan program and by other teams throughout the country provide more detailed information than police data provide for the study of accidents. With respect to accident type, vehicle damage, and occupant injury, for example, the use of the vehicle deformation index (VDI) (4) and the AIS can clarify the relationship between site and extent of vehicle damage and associated occupant injuries. If necessary, further damage details may be obtained by using the actual crash measurements that are available, as well, in level 3 data.

Level 2 data are based on police reports of accidents involving all current model cars and recent model trucks in the eight-county study area. Medical reports for injured occupants in all vehicles are obtained. Level 3 data represent a subset of these data, investigated by Calspan personnel, in which at least one occupant was injured seriously enough to require hospital treatment. Thus, the latter accidents represent the most serious injury accidents found in the combined injury and property damage data from level 2.

Comparison of these data sets should reveal how the more serious accidents differ from all accidents with respect to a number of accident, vehicle, and occupant variables. Since the crash environment of the more serious injury accidents is the target in most highway safety studies, it should be useful to provide additional details concerning the general accident types shown in police and National Safety Council data.

Accidents and Vehicles

During 1972, there were 8,145 level 2 accidents and 358 level 3 accidents in the Calspan study area. Selected accident-vehicle data from these collisions are discussed in this section, and related occupant information is presented later.

The following table gives the percentage of level 2 and level 3 accidents according to the number of vehicles involved.

No. of Vehicles	Level 2	Level 3
1	16.4	36.9
2	74.7	52.8
3 or more	9.0	10.3

It is evident that there are more single-vehicle accidents and fewer two-vehicle accidents in level 3 data. This confirms earlier findings of Calspan and other researchers that single-vehicle accidents are generally more serious than multivehicle accidents. There were 15,866 vehicles involved in the 8,145 accidents from level 2 or 1.95 vehicles/accident. There were 626 vehicles in the 358 accidents from level 3 or 1.75 vehicles/accident. This reflects the larger proportion of single-vehicle accidents in level 3 data. (Note that numbers in the tables may vary because not reported categories are omitted most of the time.)

The percentage of level 2 and level 3 accidents according to the number of occupants in those vehicles is given below. There were 12,633 level 2 accidents and 615 level 3 accidents.

Occupants	Level 2	Level 3	Occupants	Level 2	Level 3
0	9.9	1.9	4	3.7	4.1
1	55.5	62.0	5	1.2	0.3
2	22.3	26.0	6 or more	1.2	1.5
3	6.2	4.2			

Fewer unoccupied cars were struck in level 3, however.

The percentage of accidents according to the area of the car impacted is given below.

Area	Level 2	Level 3	Area	Level 2	Level 3
Front	42.4	56.1	Top	0.7	4.6
Left	16.2	13.4	Undercarriage	0.2	1.0
Right	13.4	15.5	Unclassified	6.2	0.3
Back	20.9	9.1			

The level 3 accidents include more front, right side, top, and undercarriage impacts than level 2 accidents (all). There are twice as many rear impacts in level 2 as in level 3. These accidents usually produce fewer serious injuries than the impact areas mentioned for level 3.

Occupant Seat Position

The percentage of accidents according to occupant seat position indicates that for level 3 the proportion of drivers is smaller and the proportion of occupants in other seats is larger than for level 2:

Seated Position	Level 2	Level 3	Seated Position	Level 2	Level 3
Driver	66.4	62.4	Center rear	0.9	1.5
Center front	1.7	2.7	Right rear	1.9	3.5
Right front	9.3	18.6	Third seat	0.1	0.1
Left rear	1.6	3.2	Not reported	18.1	8.0

The number of accidents was 21,920 and 984 respectively for levels 2 and 3.

The percentage of level 2 (N = 21,892) and level 3 (N = 983) accidents according to whether the occupant was ejected is as follows:

Ejection	Level 2	Level 3
Ejected	0.2	1.3
Not ejected	99.2	98.5
Not reported	0.6	0.2

Ejection occurs about five times more frequently in the level 3 cases than in level 2 cases. This reflects the fact that ejection is a major source of serious injury in accidents.

Restraint use was not reported in about half of the level 2 cases. The percentage of accidents according to known restraint use by occupants is given below:

Restraint Use	Level 2	Level 3
None	71.2	79.7
Lap belt	6.1	15.5
Shoulder belt	0.1	0.1
Lap and shoulder belt	0.1	1.1
Restraint used (not specific)	22.5	3.6

A higher percentage of level 2 accidents (N = 10,627) involved seat-belted occupants, altogether 28.8 percent, than did level 3 accidents (N = 871), altogether 20.3 percent. Level 2 data are based on police reporting, and level 3 data are based on Calspan investigation and interviews. This finding tends to support a thesis developed by Mela (5) that there may be overreporting of restraint use in police data. It could also suggest, however, that those involved in serious accidents are less likely to be using restraints than others.

The percentage of accidents according to the apparent physical conditions of drivers is given below:

Condition	Level 2	Level 3
Felt normal	91.9	82.3
Felt ill	0.4	1.1
Had physical defect	0.1	0.4
Fell asleep	0.4	1.1
Had been drinking	7.0	14.2
Had taken drugs	0.05	0
Other	0.1	0.9

Level 3 data (N = 542) indicate a higher proportion of abnormal driver conditions than level 2 data (N = 9,357). The largest category, had been drinking, is twice as large in the more serious level 3 accidents as in the level 2 accidents. Other categories also tend to be larger in the level 3 data.

Accident Type, Accident Severity, and Injury for Level 3

A more detailed examination of the relationship between vehicle damage and injury may be made by using VDI and AIS. The data used are from the Calspan level 3 in-depth file. Data were collected for about 3 years and included 1,185 cases. Only single- and two-car accidents are presented. There were 238 single-car accidents and 386 two-car accidents or a total of 624 cases. Before these data are discussed, VDI codes are shown in Figure 1. A detailed description of VDI appears elsewhere (4). For simplification of discussion of the data in this section, the vertical area of damage (code 5) and the type of damage distribution (code 6) are omitted. Also, various categories are combined as necessary to illustrate certain points.

Single-Car Accidents

The area of the car impacted and the direction of force for single-car accidents have been combined in Figure 2 to show well-defined accident types. Omission of other directions of force and unusual impacts reduced the number of single-vehicle accidents available from 238 to the 191 shown in Figure 2. The data reveal that front impacts and rollovers are the predominant types of single-car accidents. The center front is the front area most commonly impacted, and impacts to both sides are about equally distributed. In side collisions, front fenders or compartment impacts are most frequent.

The following table gives the percentage of severe or worse injury (AIS ≥ 3) for each general area of impact and for vehicle damage ratings of ≤3 and ≥4:

Car Area	≤3	≥4	Total
Front	16.3	46.4	24.6
Left	6.7	60.0	20.0
Right	30.0	83.3	50.0
Back	50.0	66.7	60.0
Rollover	19.0	44.4	30.8
Total	17.2	52.6	27.7

Overall, slightly more than half of the occupants (52.6 percent) sustained AIS ≥ 3 injuries when the damage rating was 4 or greater compared with 17.2 percent when AIS ≤ 3. Limited data volume precludes precise interpretation of many categories, but it is clear that the frequency of severe or worse injury is much higher as damage increases.

Two-Car Accidents

Two-car accidents are presented in a format similar to that for single-car accidents. Throughout this section it should be kept in mind that the level 3 data represent current model car accidents in which at least one occupant was injured sufficiently to warrant hospital treatment. Thus, the other car in a two-car accident appears in the data only because it was in a collision with a car meeting the above criteria. Logically, it can be hypothesized that, if an impact to any car area is more likely to produce serious injury than an impact to another area, that area should appear more frequently for the late model car than for the car it impacts. (The converse should also be true.) As an example, if a front to rear impact results in more serious injury to occupants of the striking vehicle than to those in the struck vehicle, one would expect more front impacts among current model cars in the level 3 data and fewer rear impacts (because the current model car determines which accidents enter level 3). This is a useful point to keep in mind because it illustrates the importance of understanding data collection criteria when data are reviewed or analyzed.

Data for both the case car and the other car (N = 652) in the accident are given independently in Table 3. Single-car accidents are also shown for perspective purposes. The data indicate that there are indeed more front impacts and fewer rear impacts for the current model car than for the other car, as hypothesized previously. Single-car accidents produced fewer side and back area impacts than two-car accidents, but, effectively, these collisions were replaced by rollovers.

Figure 3 shows the area of impact and direction of force information for the current model cars involved in two-car accidents. In front impacts, cars impacted the left front far more frequently than the right. This contrasts markedly with single-vehicle accidents in which there were more center front impacts and other front impacts were equally distributed on either side. Front impacts in single-vehicle accidents also involved a smaller front area, LCR, than that in two-car accidents, YZD. Back impacts generally involved a large area of the back, YZD. Back impacts were relatively infrequent in single-car accidents (Table 3). Side impacts for cars in two-car accidents were generally similar in frequency for both sides and involved a wide area, YZD.

The percentages of vehicles (current model car only) with severe or worse injury (AIS ≥ 3) to an occupant are shown in Figure 3 for each general area of impact. The data indicate that, as in single-car accidents, the percentage of occupants with AIS ≥ 3 is far greater in the more severe accidents. Comparison with data for single-car accidents, however, shows that AIS ≥ 3 injuries is far more frequent in single-car accidents than in two-car accidents, regardless of severity. The percentage of AIS ≥ 3 injuries for each general area of impact and for vehicle damage ratings of ≤3 and ≥4 is as follows:

Car Area	≤3	≥4	Total
Front	9.0	39.0	15.0
Left	6.9	33.3	11.4
Right	7.7	20.0	9.1
Back	—	—	—
Total	7.8	31.7	12.3

Figure 1. Vehicle deformation index.

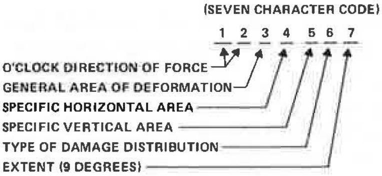
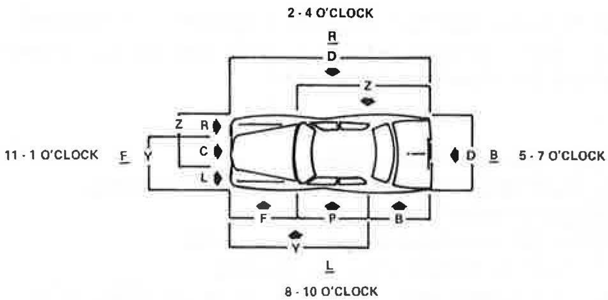


Table 3. Accident data for area of impact.

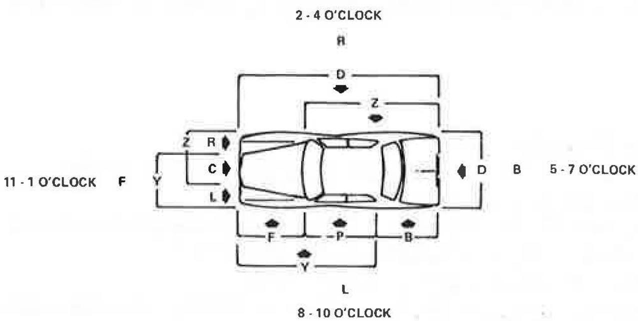
Accident	Front	Back	Left	Right	Rollover
Single-car	59.7	2.1	9.4	8.4	20.4
Two-car					
New car	65.3	9.8	11.0	13.9	–
Other car	54.9	16.0	12.5	16.7	–

Figure 2. Area of impact and direction of force for single-car accidents.



FRONT		BACK		LEFT		RIGHT		ROLLOVER	TOTAL
L	22	L	1	F	6	F	5		
C	30	C	2	P	5	P	8		
R	21	R	0	B	2	B	1		
Y	12	Y	0	Y	2	Y	1		
Z	15	Z	1	Z	1	Z	1		
D	14	D	0	D	2	D	0		
F =	114	B =	4	L =	18	R =	16	39	191
%	59.7		2.1		9.4		8.4	20.4	100.0

Figure 3. Area of impact and direction of force for two-car accidents.



CURRENT MODEL CAR

FRONT		BACK		LEFT		RIGHT		TOTAL
L	45		1	F	8		9	
C	2		3	P	5		2	
R	16		1	B	0		2	
Y	34		5	Y	11		13	
Z	40		7	Z	8		14	
D	70		14	D	3		4	
F =	207	B =	31	L =	35	R =	44	317
%	65.3		9.8		11.0		13.9	100.0

SUMMARY

Currently, data summarized by the National Safety Council provide an overview of accidents on a national scale. In a trilevel program, additional details may be obtained by improved analysis of police reports and collection of additional medical data from attending physicians (level 2 data). In-depth investigations by trained teams provide the required detail and accuracy for detailed analysis, and supplement data from level 2. In this paper, National Safety Council data indicate that two-vehicle accidents are more frequent and result in more fatal accidents than other types of accidents. The single-vehicle noncollision accident ranks second, but the proportion resulting in fatal injury is higher than that in two-vehicle accidents. Police ratings of injuries cannot discriminate among injury levels and appear to be adequate only to identify the occurrence of injury or fatality.

From Calspan data, level 3 accidents that required hospital treatment for at least one occupant were selected from the police-reported population of injury and property damage accidents. The level 3 accidents involved the following:

1. More single-car accidents;
2. More impacts from the front and fewer from the rear;
3. More impacts to the front, top, and undercarriage and fewer to the rear;
4. More right front occupants and fewer drivers;
5. More occupant ejection (about five times greater than in level 2);
6. Less restraint use (possibly because of better reporting); and
7. More drivers who had been drinking (about twice as many as in level 2), who were ill, or who fell asleep.

Two-car accidents involving severe or worse injuries (AIS $\geq$ 3) differed from single-car accidents and involved the following:

1. More impacts to the left front area,
2. Larger impact areas,
3. More rear impacts, and
4. Fewer severe (AIS $\geq$ 3) injuries.

Perhaps the most important point in this paper is the need for the influence of the data selection process on results to be understood when data are analyzed or reviewed.

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HUMAN INJURY MECHANISMS AND IMPACT TOLERANCE

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This paper is a brief review of the complex subject of human injury mechanisms and impact tolerance. Automotive accident-related injury patterns are briefly described, and the status of knowledge in the biomechanics of trauma of the head, neck, chest, abdomen, and extremities is discussed.

•EVERY year over 6 million people are injured and 200,000 are killed in road accidents around the world. Of these injuries and deaths, an estimated 25 percent occur in the United States annually, where accidents are the third highest cause of fatality after cardiovascular disease and cancer. Furthermore, data for deaths of persons under 45 years old show that 20,000 are caused by cardiovascular disease, 25,000 by cancer, and 38,000 by road accidents. Clearly, the young people in the country run a relatively substantial risk of death due to road accidents.

This awesome toll can be reduced by prevention of accidents through better education of road users and more efficient traffic control on one hand and the prevention of injuries and improved emergency treatment to accident victims on the other. To design automobiles and their occupant restraint systems such that accident injuries are reduced to a minimum requires a clear idea about the epidemiology of injuries and the biomechanics of injury causation.

Many studies have been conducted to delineate the anatomical distribution of injuries in road accidents, but the numbers reported vary widely from one study to another, especially if the reports originate in different countries. The reasons are twofold: (a) Traffic type and distribution vary greatly from region to region, and (b) different definitions are used for injury levels and fatalities. For example, in some studies, a fatality is reported only if the victim dies on the spot; in others, those dying within 30 days are counted as fatalities. Although it is difficult to give exact numbers to the frequency of injuries, it can be said that head and chest injuries are the most critical followed by the abdomen and then the extremities. A rough estimate of injury distribution is shown in Figure 1 (6, 11, 13, 36).

Head and neck injuries are the most frequent but are not of a critical nature as often as thoracic injuries. The introduction of improved windshields and collapsible steering columns seems to have reduced the incidence of serious head and chest injuries (16). Seat belts and shoulder harnesses have also helped prevent injuries to the head and upper torso. However, lap-belt-related abdominal trauma is known to occur and has caused some concern since it is hard to diagnose and manage. The extremities get injured quite frequently, but the injuries are not life threatening and may be minimized by improved design of car interiors.

The following sections of this paper will briefly discuss the status of knowledge in the biomechanics of trauma of the human body in terms of head injury, neck injury, chest injury, abdominal injury, and injury to the extremities.

HEAD INJURY

The automotive crash environment encompasses a wide range of impulse durations and directions. Thus, a valid head injury criterion must provide appropriate mechanisms that realistically account for the frequently observed, but poorly documented, relations of head impact tolerance and impulse duration and direction. Head injuries may be produced by direct impact that involves short durations and high accelerations or by inertial loading that has associated large angular motions and longer time periods. Brain injury may be produced in both cases, but skull fractures and cracks are the result of head impacts only. Therefore, automobile interiors have to be designed to avoid head impacts or to reduce their severity, and the structural design should be manipulated to minimize decelerations. Head injury research as such has not been directly restraint related but focuses more on determination of the limits of tolerance to both linear and angular acceleration.

The relative contribution of linear and angular accelerations in head injury has been a matter of heated debates. Holbourn (14) contended that rotational acceleration was the main cause of all head injuries; Gurdjian, Hodgson, Thomas, and Patrick (12) emphasized linear accelerations. However, experiments done by McElhaney, Stalnaker, and Roberts (24) and Ommaya (31) indicate that either mechanism acting singly or in conjunction with the other may result in brain injury. The type of injury produced may differ according to the type of loading; e.g., contrecoup (opposite the point of impact) lesions are observed primarily in cases of direct impacts when linear accelerations are very high and diffuse brain injuries occur more often as a result of rotation of the brain relative to the skull.

A detailed analysis of brain injury in humans and its relation to the associated loading mechanism is difficult to perform since details of injuries become available only when there is an autopsy if the victim dies. Otherwise, only clinical information, which is subjective and at times incomplete, is available. Moreover, animal modeling is difficult since it is not possible to determine onset of headaches, losses of memory or cognitive functions in animals. In spite of all these difficulties, many researchers have attempted to come up with models that predict tolerance limits.

One method of presenting experimental data on the tolerance of regions of the body to acceleration is the tolerance curve shown in Figure 2 (41). For the automotive crash situation, the time regime of interest is from 1 to 300 msec, the two regions on the left of Figure 2. Such a representation leaves much to be desired when a wide variety of acceleration-time profiles are dealt with. This difficulty has led to the development of head injury criteria as shown in Figure 3 that for the most part are either weighted-impulse criteria (severity index and head injury criterion) or simple, single degree-of-freedom mechanical models (J-tolerance index, revised brain model, and effective displacement index) that were fitted to the two left time regions of the tolerance curve of Figure 2. The maximum strain criterion model is unique in that it was developed from mechanical impedance experiments on human cadaver heads and experimental lower primates. The weighted-impulse human injury criterion is currently the method used for head injury evaluation by the National Highway Traffic Safety Administration (NHTSA).

All of these models predict the severity of an impact by considering linear acceleration and impact duration. None of them considers angular accelerations, nor do most of them simulate the structural properties of the head. In the past few years, models have been proposed that incorporate rotational accelerations as well (1, 39). These models, as shown schematically in Figure 4, are still in the conceptual stage, since there is still not sufficient information that separates the effects of rotational and angular accelerations or of impact duration. The experimental techniques that were used in the past were not generally sophisticated enough to make such an analysis. Only recently have investigators made attempts to experiment by using instrumentation that will permit the complete linear and angular motion to be determined. It will be some time before sufficient research will have been done to allow a complete determination of the interplay between linear motion, angular motion, and time duration in assessing head injury potential.

In the meantime, automobiles will continue to be produced, and designers must try to optimize their safety. Dummy-based head injury criterion (HIC) measurements are just relative indicators of restraint system performance since they measure only linear acceleration. Until better evaluation techniques are developed, the design of restraint systems and automobile structures should be such that both angular and linear accelerations of the head during the crash are reduced and the head does not contact any part of the interior. Although these design considerations are complicated, they require a systems

Figure 1. Approximate anatomical distribution of injuries due to accidents.

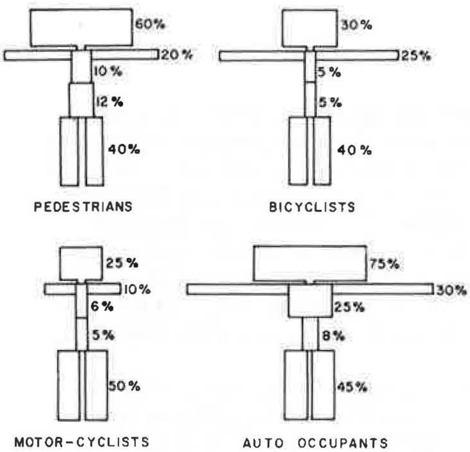


Figure 2. Human tolerance curves for +Gx acceleration.

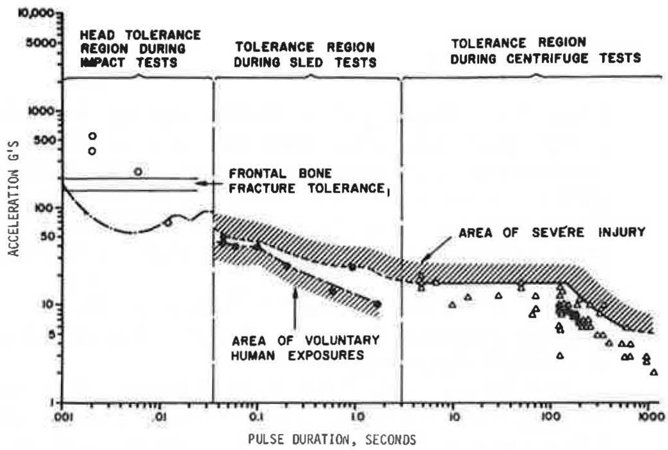
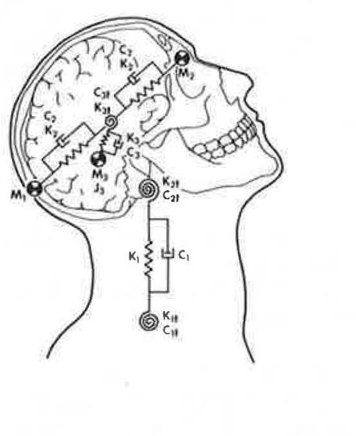


Figure 3. Head injury criteria.

SI	HIC	JTI	RBM	EDI	MSC
SEVERITY INDEX (GADD)	HEAD INJURY CRITERION (VERSACE & NHTSA)	J-TOLERANCE INDEX (SLATTENSCHEK)	REVISED BRAIN MODEL (FAN)	EFFECTIVE DISPLACEMENT INDEX (BRINN)	MAXIMUM STRAIN CRITERION (STALNAKER)
Weighted Impulse of a(t) $SI = \int_0^T [a(t)]^{2.5} dt$ Time in seconds Acc. in g-units	Weighted Impulse of a(t) Let $\bar{a}_{12} = \frac{\int_{t_1}^{t_2} a(t)dt}{(t_2 - t_1)}$ $HIC = \left\{ \max_{\text{all } t_1, t_2} \left[\bar{a}_{12}^{2.5} (t_2 - t_1) \right] \right\}$ $0 \le t_1 < t_2 \le T$	a(t) k c m X(t) $\omega_n = \sqrt{k/m}$ (rad/sec) $\beta = c/c_c$ $\omega_n = 635.$ $\beta = 1.0$	a(t) k c m X(t) $\omega_n = 175.$ $\beta = 0.4$	a(t) k c m X(t) $\omega_n = 482.$ $\beta = 0.707$	a(t) m_1 k c m_2 X(t) $m_1 = 0.6$ (lbs) $m_2 = 10.0$ (lbs) $c = 2.0$ (lb sec/in) $k = 50000.$ (lb/in)
$SI_{tol} = 1500$	$HIC_{tol} = 1000$	$J = \frac{X_{max}}{0.0925}$, in/in; $J_{tol} = 1.0$	T< 20ms: $\dot{X}_{tol} = 135.3 \frac{in}{sec}$; T >20ms: $X_{tol} = 1.25$ in	X_{tol} = A-P / RES.: HUMAN 0.15 in / 0.18 in; DUMMY 0.17 in / 0.2 in	$\varepsilon = X_{max}/L$; HUMAN: $L = 5.75$ in (A-P); $\varepsilon_{tol} = 0.0061$ in/in

Figure 4. Schematic lumped parameter head injury model for linear and angular two-dimensional motion.



approach so that the correct trade-offs can be made among structural integrity of the vehicle, its crush profile, occupant restraints, and interior packaging.

NECK INJURY

From the standpoint of accidental injury, the neck does not appear to react to impact in the same manner as other body regions (41), in that some low-velocity impacts often produce injury as severe as, or even more severe than, high-velocity impacts. Neck injuries can occur in many ways, but the most common cause of fractures and dislocations of the cervical spine itself is the automobile accident (3). A common form of neck injury associated with automobile accidents is the so-called whiplash injury due to indirect impact to the unsupported head-neck region of the body. At present, over 200 papers concerning whiplash types of injuries have been published; yet, to date, its precise definition, nature, measurement, diagnosis, and treatment are still subjects of medical disagreement.

In contrast to the large body of literature describing neck injuries, there are few definitive studies that attempt to quantify the loading conditions and magnitudes that can cause neck injury in humans. Mertz and Patrick (28) have performed crash sled tests on human cadavers and on a human volunteer in which the inertial forces and moments acting on the neck due to the head have been calculated. Their work did not address itself directly to injury mechanisms in the neck, however. Gadd, Nahum, and Culver (8) conducted static and dynamic bending tests on dissected unembalmed segments of human cervical spines and static bending tests on four intact cadaver necks. In both studies, only the marginal ligamentous injury stage was reached. The most comprehensive study to date on the mechanical properties of the cervical spine is the work of Sonoda (43), in which the strength of the human cervical spine was determined for compression loading, tensile loading, and torsional loading.

Experimental impacts to the cervical spines of monkeys have been studied by Gosch, Gooding, and Schneider (10). In this study, direct impacts were delivered to the vertex of the animal whose neck was extended, flexed, or aligned along the loading axis. Both bone destruction and ligamentous damage were produced, and it was found that rotation was necessary in addition to extension or flexion to produce dislocations. The presence of muscular tone at the time of injury was also found to have a notable influence on the ability to produce cervical lesions.

In most cases of severe cervical spine injury, the automotive occupant is propelled into head contact with the surrounding passenger compartment. The position of the head and neck, the impact site, and the direction of cervical spine loading determine the resulting cervical fracture. The head and neck area is either flexed (forward inclination), neutral, extended (rearward inclination), laterally flexed or rotated, and the cervical spine is subjected to bending, compression, tension, shear, or torque. Impacts about the face and frontal regions tend to produce bending in extension, and flexion results from parietal (top) or occipital (rear) head contact. When the impact is off center, a lateral flexion or rotary component may also be imparted to the head and neck. For the purposes of classification of common types of automotive accident-related cervical spine injury, the following three groups of conditions are useful:

1. Head and neck extended, cervical spine subjected to tension (extension-tension fractures);
2. Head and neck extended, cervical spine subjected to compression (extension-compression fractures); and
3. Head and neck flexed, cervical spine subjected to compression (flexion-compression fractures).

These basic groups are further modified by lateral bending and rotation. In some instances, the head is not injured, the cervical fracture being the result of direct trauma. A summary of a study of 50 clinical cervical spine fractures (37) grouped as above is shown in Figure 5.

Mechanical models of the neck have been developed by Melvin, McElhaney, and Roberts (26) and by Culver, Neathery, and Mertz (5), and mathematical models have been proposed by Bowman and Robbins (2) and McKenzie and Williams (25). Both types of models are meant to simulate the response of the neck to load. Definitive tolerance information is needed, however, before evaluations of injury potential based on such models can be made.

CHEST INJURY

The human chest (or thorax) is a ribbed shell that contains the following important organs: heart, lungs, trachea, esophagus, great blood vessels, and nerves. The size and shape of the thorax depend on the age and sex of the individual, but roughly it may be described as a truncated cone with its depth less than its breadth (aspect ratio < 1). The chest cage is semirigid in structure and not only provides protection to the internal organs but also facilitates mechanics of respiration.

Thoracic injuries may be divided into two types: injuries to the endothoracic organs and injuries to the thoracic cage. Injuries to the endothoracic organs include atrial and ventricular ruptures, aortic ruptures, damage to the electrical conducting system and the cardiac muscle, pneumothorax, hemothorax, pulmonary contusions, and rupture of the bronchi. Of these, the most frequent and most serious is the rupture of the thoracic aorta. The cardiac injuries are probably caused by the impingement of the heart between the spinal column and the sternum. Also, there is an increased possibility of cardiac rupture if the heart is full of blood. Aortic tears usually occur immediately above the heart or in the descending aorta at the isthmus. The tears are usually transverse to the vessel axis, and the exact mechanism of failure is not yet understood.

Several parameters have been suggested for evaluating injuries to the thoracic cage, in particular acceleration, force, displacement, or some combination of these. Chest impact studies have been conducted by a number of researchers (20, 21, 32, 33) by using both embalmed and unembalmed cadavers for their studies and human volunteers for quasistatic chest load-deflection studies. Chest-impact studies at the Highway Safety Research Institute (HSRI) (44) have used rhesus monkeys for evaluating injury tolerance, unembalmed cadavers for skeletal trauma, and human volunteers for static load-deflection tests. The results from these tests indicate that rib fractures do not occur at chest deflections of less than 2 in. (5 cm) for front or side impacts. For young people, this limit seems to be higher. As this deflection limit does not change appreciably from quasistatic deflection rates to dynamic impact velocities of 30 ft/sec (9 m/s), it would appear that rib fractures primarily depend on the extent of chest deflection and not on impact forces.

There are some problems associated with the use of the cadaver chest for obtaining tolerance information, and careful consideration must be used when chest impact data are interpreted. Recent studies indicate that the effects of muscle tension and air-filled lungs can contribute significantly to the load-carrying ability of the thorax. The effects of tensing of thoracic muscles are shown in Figure 6 (21, 44). The data bands cover the range for all the data gathered by various investigators, and, therefore, the wide range is due to both anatomical differences among volunteers and different testing procedures. It is worth nothing that the maximum stiffness of the tensed volunteers is about twice that of the maximum stiffness of the relaxed volunteers and almost eight times their minimum stiffness. When these curves are compared with those obtained for embalmed and unembalmed cadavers (Figure 7) (44), the stiffness of the chests of unembalmed cadavers is found to lie in the lower range of relaxed volunteers' chest stiffnesses. This is probably due to the lack of muscle tone and lung inflation. Figures 8 (33, 45) and 9 (44) show response corridors for front and side chest impacts to cadavers without lung inflation. Here the forces are almost 10 times those recorded in quasistatic tests on cadavers. In the HSRI tests, in which the impactor was a 6-in.-wide (15-cm) flat disk, the force penetration trace showed a pattern where there was an initial load spike followed by a plateau. Whereas when the chest was impacted by a simulated arm rest, the force rises progressively to a peak. This is because the force increases succes-

Figure 5. Mechanism of cervical spine injury as related to level of cervical fracture or dislocaton.

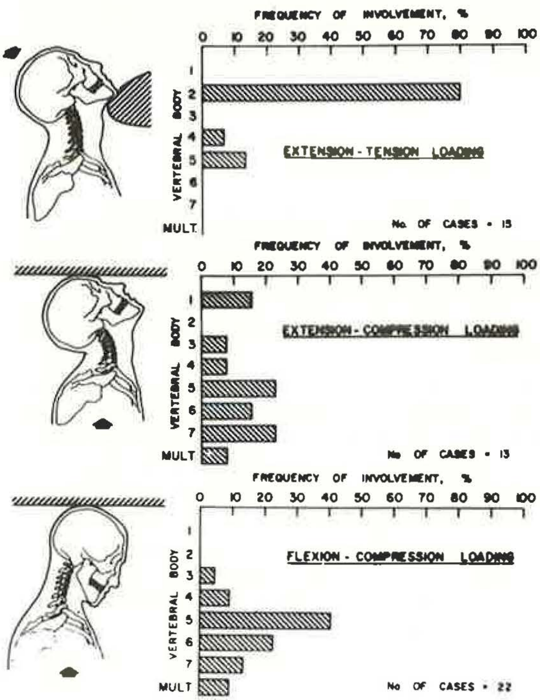


Figure 6. Range of force-penetration data for quasistatic front chest compression tests on human volunteers.

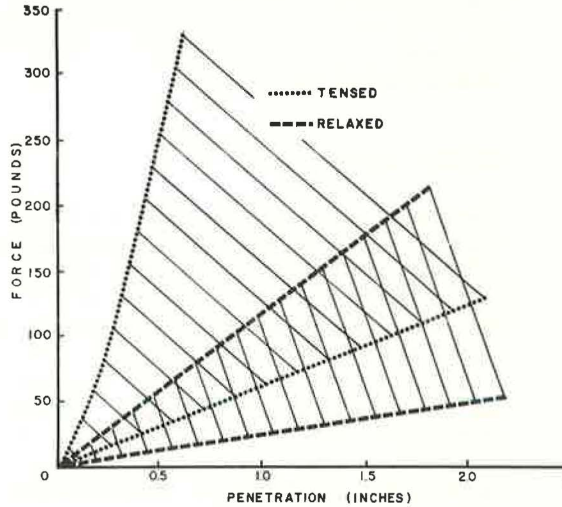


Figure 7. Range of force-penetration data for quasistatic front chest compression tests on human cadavers.

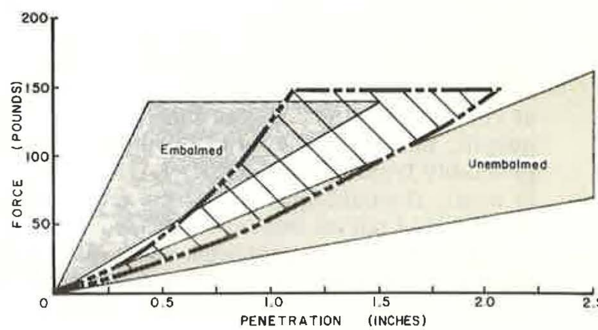
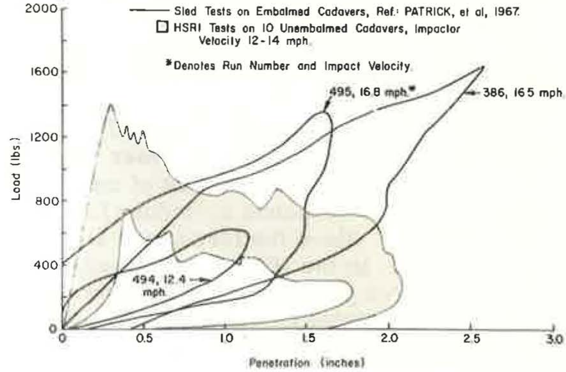


Figure 8. Dynamic load-penetration curves for human cadaver front chest impacts.



sively as more of the armrest comes in contact with the chest. This is unlike the occurrence with the flat disk, where total contact is made on impact.

Specification of thoracic impact tolerance is complicated further by the lack of biomechanical fidelity of current dummy chest structures. A deflection criterion for thoracic impact can be used directly only if the dummy chest responds to load in a manner similar to the living human thorax. Under certain well-controlled loading environments, an equivalent deflection response of a dummy chest might be usable, but it would not be useful in general applications with a variety of loading conditions. For frontal chest impact tolerance, a deflection of 1.75 in. (4.4 cm) has been suggested (44) if rib fracture is to be avoided. A tolerance value based on the American Medical Association abbreviated injury scale (AIS) level of 3 (severe, but not life threatening) would be in the 2.5 to 3.0 in. (6.4 to 7.6 cm) range for the average male (20, 44). This corresponds to approximately a 30 to 35 percent reduction in the chest depth. A similar value for the percentage reduction in chest width was found for side impact studies at HSRI (44) by using experimental lower primates. The corresponding deflection levels for an average male would be 2.65 in. (6.70 cm) for a nonfracture level and 3.72 in. (9.44 cm) for an AIS level 3 injury in side impact.

ABDOMINAL INJURY

Blunt abdominal trauma is a common cause of accidental injury and death, and motor vehicle accidents are the most frequent cause of nonpenetrating abdominal trauma. The sources of abdominal loading interior to the vehicle include steering wheel rims, lap belts, armrests, and protruding dashboard structures, knobs, and levers. Ejection of the vehicle occupants during a crash or pedestrian impact frequently produces severe abdominal trauma. The organs most frequently injured as a result of blunt abdominal trauma are the liver, kidneys, spleen, pancreas, and intestines. Diagnosis and localization of organ injury in the abdomen are difficult, and the serious threats of hemorrhage and infection require prompt surgical intervention when these organ injuries are present.

Much clinical literature has evolved over the years that documents the various forms of injuries produced by blunt abdominal trauma. In contrast, there are few quantitative data available on the loading conditions, force levels, and impact velocities that characterize typical accident situations. In particular, there are almost no quantitative data on the mechanical response of the critical abdominal organs to direct loading.

Injury to the liver due to blunt trauma can take many forms ranging from subcapsular hemotomas and superficial lacerations to the severe crushing and bursting types of injuries with stellate capsular lacerations and gross destruction and devitalization of the parenchyma (30). Bursting injuries are vastly more severe than the more common simple tears or lacerations of Glisson's capsule (23). In bursting injuries, hemorrhage is massive and the mortality rate is high regardless of the treatment instituted (7).

To simulate the trauma sustained by the liver in automobile accidents, Mays (23) dropped cadaver livers from various heights ranging from 8.5 to 91 ft (2.6 to 27 m). An important finding of this work, which was also reported by Glenn, Mujahed, and Grafe (9), is the necessity of maintaining the turgor of the liver at a level comparable to normal hemodynamic pressures so that realistic bursting injuries can be produced. Mays achieved this pressure by injecting the livers with saline solution before they were dropped and was able to produce bursting injuries as seen clinically by using energies on the order of 285 to 360 lbf-ft (386 to 488 J).

The kidneys in the adult are paired bean-shaped organs, measuring about 5 in. (13 cm) long, 3 in. (8 cm) wide, and 2 in. (5 cm) thick. They are buried in a mass of fat on each side of the vertebral column, behind all the other abdominal organs. The injury types sustained in blunt trauma (7) range from renal contusions in which there is minor disruption of the renal parenchyma to complete tears in which there is complete disruption of the organ.

Direct loading tests (27) of both liver and kidney demonstrated the sensitivity of these organs to rate of loading. The effects of loading rate were most pronounced in the liver.

Examination of Figure 10 shows that the onset of severe trauma (AIS-3) under dynamic loading occurs at a threshold stress level of approximately 45 psi (310 kPa) in the liver (27). The severity of the injury past the 3+ level is primarily related to the additional stress and strain produced in the specimen above the threshold stress level and is best characterized by the maximum average strain energy density produced in the material of the organ.

The stresses produced in the kidneys were higher than those in the livers; this indicates the effect of the tough, thick capsule of the kidney. Figure 11 shows that the dynamic stress levels necessary to cause injuries ranging from a 1 to 2 AIS rating to a 4 to 5 rating did not vary significantly and that the injury level was ordered more effectively according to the strain level (27). This effect may be attributed to the properties of the capsule.

The injury modes observed in the dynamic tests of both livers and kidneys were similar to those seen clinically. The AIS rating of these injuries correlated well with the mechanical input parameters and indicates the effectiveness of using a rating system to describe mechanical damage to tissue.

Besides liver and kidney injuries, the spleen, colon, and jejunum also get injured because of abdominal impacts. Seat belts are known to cause injuries (40) like a lacerated spleen or colon. This is especially true when the seat belts are not worn properly and the buckle is in front of the abdomen rather than the side.

Abdominal tolerance to injury is rather low, and therefore loading of this area must be avoided. Safety belts must remain below the iliac crests, and the pelvis should bear all the load. Seat belt designs that make it almost impossible for the wearer to keep them loose or twisted are necessary. Serious thought must be given to belt placement, automatic retraction, load limiting energy absorbing devices, and last but not least, comfort. Unless the belts are convenient and comfortable, occupants will always find ways to avoid using them.

EXTREMITIES

As mentioned earlier, both the upper and lower extremities are injured rather frequently in automobile accidents. Injuries to the upper extremities are not very serious and do not cause disability. They may be reduced by eliminating rigid edges in the interior of the car. However, leg injuries, though not life threatening, do cause disabilities and days lost from work. Thus, only the biomechanics of leg injury will be considered in this discussion.

In the automobile crash situation, the fractures of the upper leg are more serious than those of the lower leg. Lower leg fractures are common in pedestrians, and Kramer, Burow, and Heger (18) impacted tibia bones of more than 200 human cadavers frontally to obtain basic information for construction of safer vehicle fronts. The lowest force level recorded for fracture was 2,200 lbf (9786 N) for an impact with an 8.5-in.-diameter (28-cm) cylinder. Researchers have shown greater interest in the biomechanics of the upper leg, and there are numerous papers dealing with this subject. The hip and knee joints are critical areas of injury and more difficult to treat.

The most common form of leg loading to a vehicle occupant in an accident is a knee impact that may damage the knee, the femur, and the pelvis. A variety of studies have been conducted on the various aspects of knee impact (4, 15, 32, 38). Although the assessment of functional disability to the knee joint itself in cadaver knee impacts is difficult, one can establish fracture levels for the knee-femur-pelvis complex. The tolerable force level of axial load to the flexed knee has been established at 1,700 lbf (7562 N) by NHTSA for its standards activities. This level was based on embalmed cadaver data (33) and has recently been criticized for being too low (17). Studies presently underway at HSRI based on unembalmed cadavers indicate that the fracture load level for the unembalmed knee-femur complex may be much greater. This difference may be attributed to modification of the fracture characteristics of bone when embalmed.

Figure 9. Response envelopes for side impacts on unembalmed human cadavers.

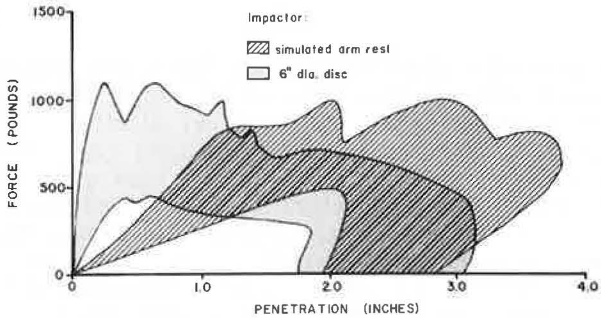


Figure 10. Dynamic stress-strain behavior of lower primate livers under direct impact.

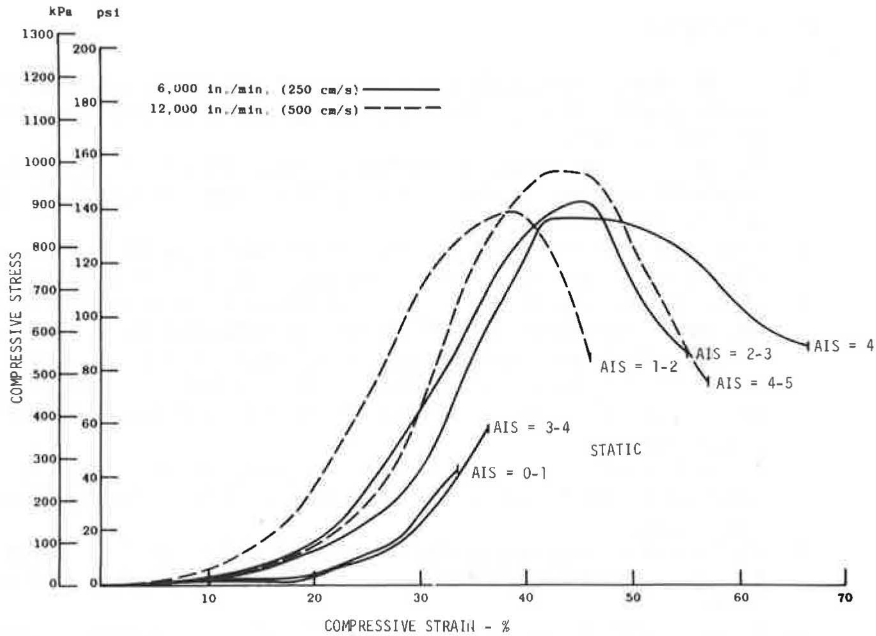
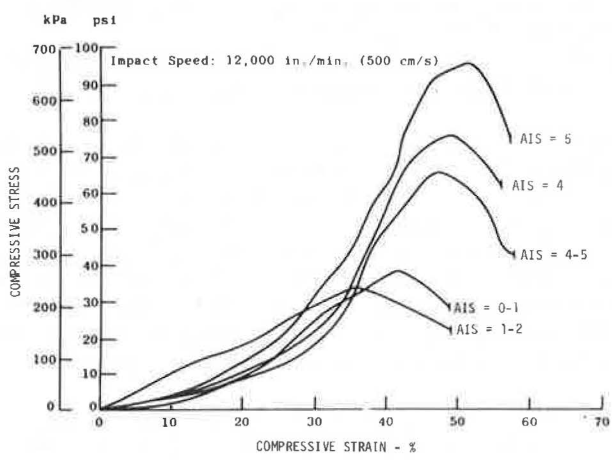


Figure 11. Dynamic stress-strain behavior of lower primate kidneys under direct impact.



SUMMARY

The increasing numbers of road accidents around the world have prompted serious research in human injury mechanisms and impact tolerance. However, lack of documentation, complicated human structures, difficulty in evaluating injury, inadequate instrumentation, and imperfect animal models make this job rather difficult. Although many researchers have spent a great deal of time studying head and chest injury, appropriate levels for tolerable impact forces, accelerations, or deflections have not yet been established, and the criteria being used are sometimes uncertain and disputable. Until the time when research provides more definitive information, the designer will have to rely on conservative estimates and values. Using these guidelines, one can design safer and more comfortable energy-absorbing restraint systems, windshields, and car interiors. These improvements in themselves will reduce the hazards of accident injury.

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SUBCOMPACT CAR CRASHWORTHINESS

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Design modifications were made and tested on 1974 Pintos so that the crashworthiness of the subcompact car could be improved. These modifications consisted of replacing the sheet metal with bulk structure, i.e., foam-filled (stabilized) sheet metal, and of altering the passenger compartment configuration. The effective safe barrier equivalent velocity of the modified vehicle in conjunction with an advanced airbag restraint was found to be approximately 50 mph (80 km/h) in head-on and angled-barrier crashes and in two-car angular and offset collisions. The result of this study has been to provisionally establish the prototype feasibility of meeting the proposed 1979 Federal Motor Vehicle Safety Standard 208 amendments requiring 45 to 50-mph (72 to 80-km/h) barrier equivalent velocity frontal crash protection with a subcompact car.

•THE phenomenal growth rate of the subcompact class of automobiles indicates that it will represent as much as 40 percent of the U.S. vehicle population by 1990 (1). This projected increase, along with the actual growth in the number of subcompact cars, has resulted in much attention being focused on the safety problems of this vehicle class. Identifying and correcting some of those problems were the objectives of the Minicar, Inc., contract to the National Highway Traffic Safety Administration (NHTSA) (2). The results of this effort to September 1974, which are described in this paper, may be found in a more detailed form elsewhere (3).

The dramatic increase in the subcompact car population will result in their being more frequently involved in accidents than they are currently. In trying to help mitigate the deaths and injuries that will result from these accidents, decisions must be made on which of the accident modes is most common and costly, and, then, proportionate efforts should be expended for improving the crashworthiness of those modes. As shown in Figure 1, the 1972 societal cost of frontal offset and angular impacts is greater (because they are more frequent and severe) than that of pure frontal impacts and should, therefore, be given priority (4, 5).

A large share of those costs is due to vehicle-to-vehicle accidents that are not closely simulated by the barrier tests often used in validating past structural improvements (6). Unfortunately, Federal Motor Vehicle Safety Standard 208 also focuses attention on barrier crash tests. To ameliorate this problem, we tried to take the two-car real-world accident compatibility problem into consideration in the program to improve subcompact car crashworthiness. In particular, we found that the relationship between frontal structure improvements and consideration for protecting occupants of vehicles struck in the side has not received sufficient attention. Minicars, Inc., studies (7) show that there may be a need to adjust the optimal force-deflection characteristics of the structure for a frontal impact so that its intrusion on the impacted car in front-to-side impacts can be limited.

As a result, a ramped crush characteristic has been derived that is acceptable for all accident modes, although not ideal for any. In 50-mph (80-km/h) frontal barrier impacts, it results in a total crush of about 37 in. (94 cm) with less than 2 in. (5 cm) A post intrusion (to guarantee occupant living space). In angular or offset impacts, because only a portion of the structure is involved, the total crush is about 54 in. (137 cm). These force-deflection characteristics allow the impacting vehicle in a two-car front-to-side impact to take most of the crush and thereby minimize the intrusion in the side-impacted car.

These crush characteristics are not ideal from the restraint point of view either

(8) because they result in less occupant ride down and, therefore, require more occupant interior stroke at a given velocity. In future programs, a further compromise between an optimum restraint pulse and the derived structural characteristics should be effected by trading off interior occupant stroke against frontal crush distance. However, the ideal frontal crush pulse, the available occupant interior stroke, the acceptable intrusion, and so on are all peripheral to the real problem to minimize occupant injuries in all real-world impacts.

In this program, as in the past, the solution to this problem was considered to be separable into structural and restraint approaches. Structural performance was judged on crash deceleration pulse and intrusion; occupant packaging was judged on pulse and resulting dummy injury criteria. Because these criteria could not be adequately related to the injuries in real-world accidents, the structural and restraint areas have not been integrated for high-velocity performance.

There are many schools of thought regarding the relationship between accident injuries and dummy injury measures. Results of tests in which unrestrained cadavers and dummies impact interior vehicle padding and plastic laminate glass, supported by Minicars' computer evaluations, indicate that a relationship exists between the abbreviated injury scale (AIS) and dummy chest severity index (CSI) such as shown in Figure 2 (9). A suggested combination of the head injury criteria (HIC) and CSI injury levels can be based on the findings of Baker, O'Neill, Haddon, and Long (10). On the other hand, in accordance with Tarriere, Fayon, and Walfisch (11) and Warner et al. (12), when the occupant is decelerated at a particular g level, the chest injury level resulting from belts may be more represented by the upper bounds of the curves, and airbag restraints may be closely related to the performance indicated by the lower bounds. Therefore, for a clear understanding of how to solve the real problem, these relationships must be more adequately treated.

Currently lacking this capability, we have used estimates of the societal cost as a function of velocity for various impact modes (Figure 3) to assess the value of a particular structural or restraint system alternative (4). This was done by determining the effective safe velocity performance of the existing structural system with the best available restraint, and, then, by estimating the portion of the societal costs (the benefits) that would be eliminated.

Through a series of baseline car crash tests, the effective safe velocity of the unmodified Pinto was established in various impact directions (assuming an advanced airbag restraint), and the portion of the societal cost eliminated was compared to the societal cost in 1975 from Figure 1, as shown in Figure 4. This indicates that baseline structure with an advanced restraint could only accrue perhaps 30 percent of the societal benefit possible.

For achievement of a greater portion of the societal savings, the effective safe velocity goals for the project became 50 mph (80 km/h) for frontal, 100 mph (161 km/h) for front-to-front, 40 mph (64 km/h) for frontal pole, 40 mph (64 km/h) for side-structure [20-mph (32-km/h) barrier equivalent velocity], 60 mph (97 km/h) for rear [30-mph (48-km/h) barrier equivalent velocity], and 10 mph (16 km/h) for low-speed impacts. The weight, cost, length, and producibility of the vehicle were to be virtually unchanged (i.e., within about 5 percent of baseline). The simultaneous development of a driver passive restraint was undertaken, and these programs were to be combined at some later date; eventually the driver would be protected at the highest velocity with the best benefit-cost ratio possible (8).

The overall force-deflection characteristics of the baseline car and the desirable modifications were determined by use of various computer models and static crush test data for eight elements of the front end such as shown in Figure 5 (13). Various potential energy management techniques were investigated in addition to the originally proposed foam-filled (stabilized) sheet metal approach. Among the alternative concepts were collapsible tube structures. The failure characteristics of the collapsible tube structures proved to be highly susceptible to loading anomalies (resulting in buckling) even in the frontal mode, and their potential for adequately handling the angular impacts was extremely limited. The uniaxial structure was quickly abandoned in favor of the original concept of an omnidirectional, foam-filled bulk structure.

Figure 1. Estimated 1972 societal cost of subcompact car injuries.

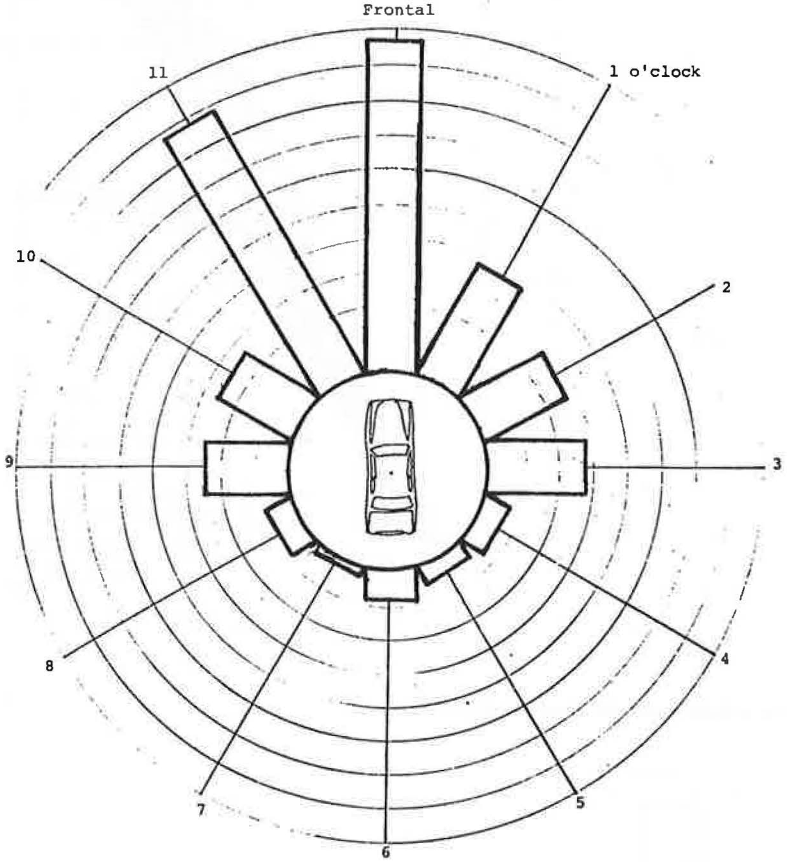


Figure 2. Relationship between chest severity index and abbreviated injury scale level.

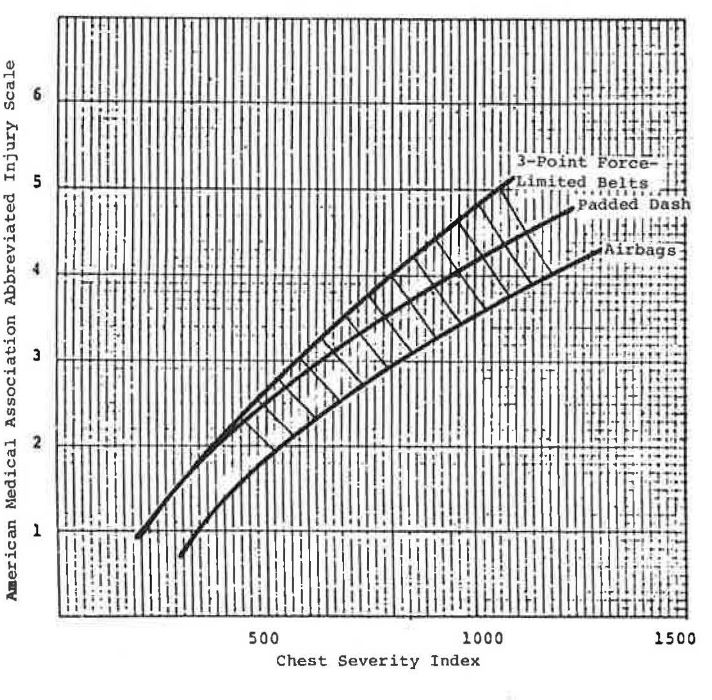


Figure 3. Cumulative 1972 societal costs for various types of vehicle involvement for all vehicles.

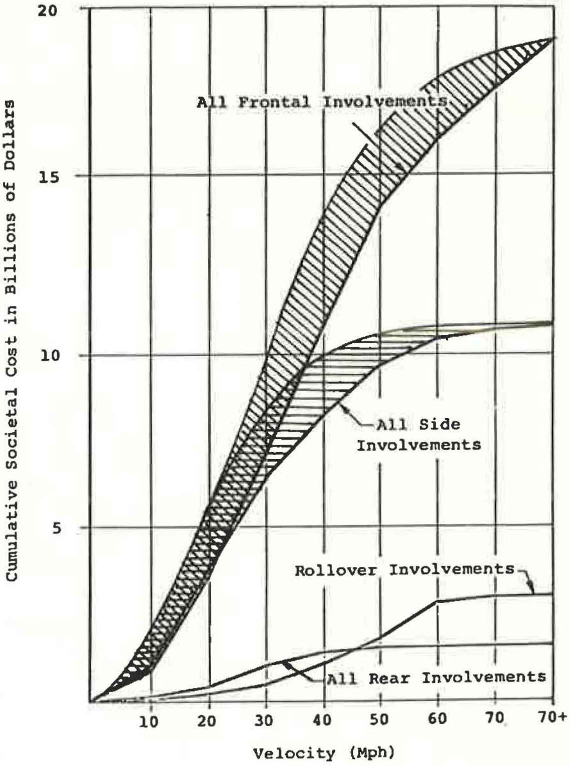
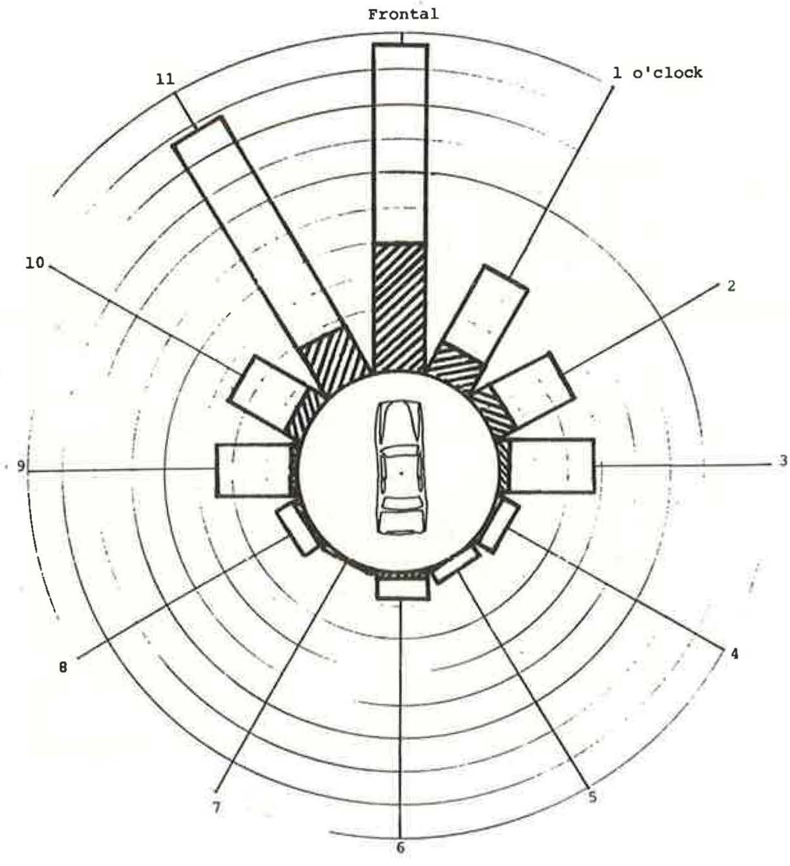


Figure 4. Savings from baseline structure with advanced restraints relative to societal cost.



One possibility for attaining the desired frontal performance was to simply foam fill the fenders and slightly modify the lower frame members and firewall. Three potential problems, however, kept this approach from being used:

1. The baseline vehicle exhibited excessive pitch that was felt to significantly affect the restraint performance during barrier impact ranging from 14 to 34 deg,
2. The side-impact protection required raising and reinforcing the sill structure to limit intrusion, and
3. The baseline structure exhibited substantially poorer performance in the angular mode than could be expected to be corrected by this simple approach.

To reduce the pitch, modifications of the force-deflection characteristics were made so that more energy was absorbed above the center of gravity and less below; in other words, the lower structure was weakened and the upper structure was strengthened. Pulse shaping further required an important reduction in the engine-firewall, force-deflection characteristics.

Improvement of side-impact performance required that the sills be raised for better alignment with impact bumpers. It was also felt that restraint performance could be enhanced by increasing the available interior stroke of the occupant before he or she struck the windshield in the frontal mode. So that both goals could best be accomplished, the body was raised relative to the running gear by 6 in. (15 cm). This was accomplished by removing the vehicle floor and replacing it with a new sheet metal section containing footwells, an enlarged tunnel, and two transverse cross members, one under the seat and one at the B post. The aft portion of the subframe member was reattached to the new floor, which, when combined with larger rear suspension hangers, resulted in raising the body (Figure 6).

The driver seating position in the car is assumed to be fixed with movable controls but is adjustable vertically so that, in conjunction with the sloped hood, forward visibility is improved. Since the running gear and engine of the car are in stock positions, the center of gravity is only raised about 1½ in. (3.8 cm) so that an antisway (roll stabilizer) bar on the rear axle keeps handling virtually unaffected. The raised body created a 6-in.-thick (15-cm) hood section over the engine and left the engine in a position that allows it to translate into the enlarged tunnel during impact. A breakaway (sliding section) drive shaft and breakaway engine cross member assembly made it possible to reduce the lower structure force-displacement level.

An equivalent amount of force was introduced into the upper structure by mounting a 6-in.-thick (15-cm) foam-filled, sheet metal hood. This was designed to cover both the original engine compartment area and the upper fender sections that were now 6 in. (15 cm) thicker than before. The design provides a monolithic section the width of the car with omnidirectional capability to load the firewall, A post, and plenum areas and to complement the lower structure in restricting pitch and resisting intrusion in angular impacts.

For an increase in the force early in the frontal impact and for support of the 10-mph (16-km/h), 6-in. (15-cm) stroke frictional energy-absorbing (E-A) bumper mounts, the original frame forward of the cross member was replaced by 0.083-in. (0.211-cm) notched-steel, 2 by 4-in. (5 by 10-cm) tubing. The fender aprons were replaced by foam-filled sheet metal sections that add support to the frames. The bumper is made of two 3 by 3 by 0.375-in. (7.6 by 7.6 by 0.953-cm) wall-welded and heat-treated aluminum tubes mounted to the E-A units. So that the forces produced during asymmetrical loading (angular and offset collisions) could be increased, the outer fender volume forward of the wheels was also filled with a foamed box.

The doors were modified to include a tubular compression strut from the upper hinge to the latch plate on the B post. This would allow the maximum frontal stroke possible in angular impacts at the target velocity and still provide support to the A post. The foam-filled transverse members and enlarged sill area were augmented by providing a larger section, load-distributing, foam-filled lower door structure for resisting pole impacts.

The rear structure required only the replacement of the lower floor with double-

Figure 5. Force-displacement curves for 1974 Pinto.

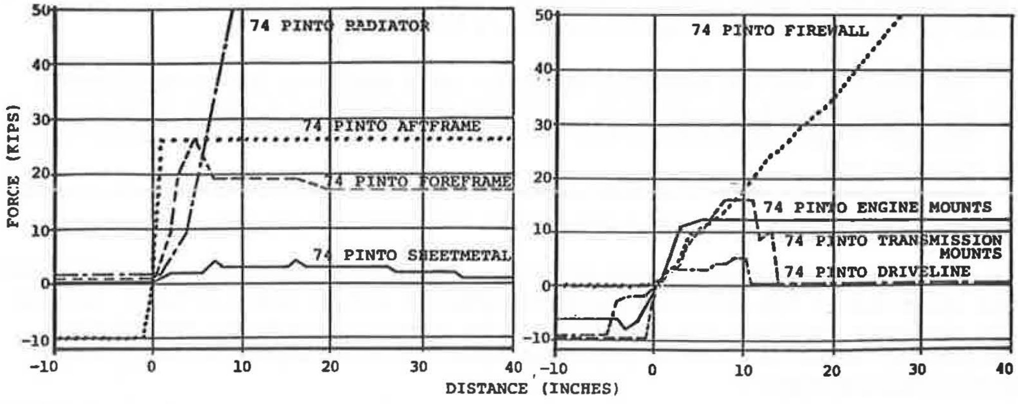


Figure 6. All subcompact car design modifications.

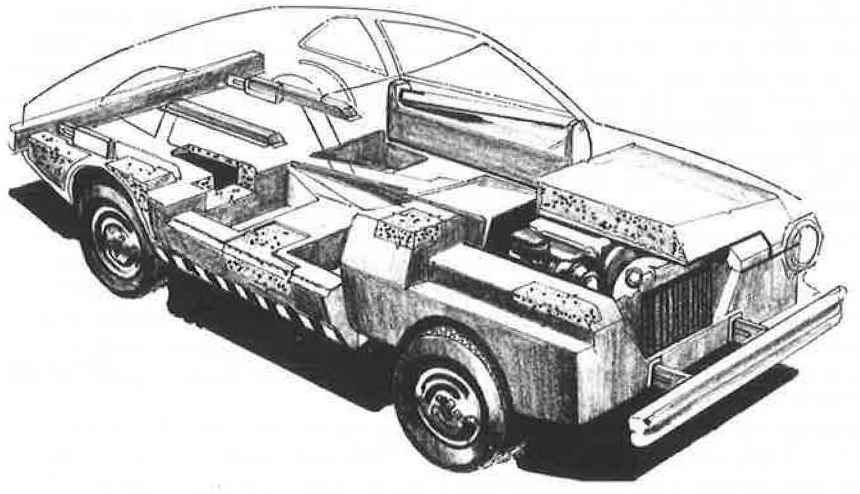
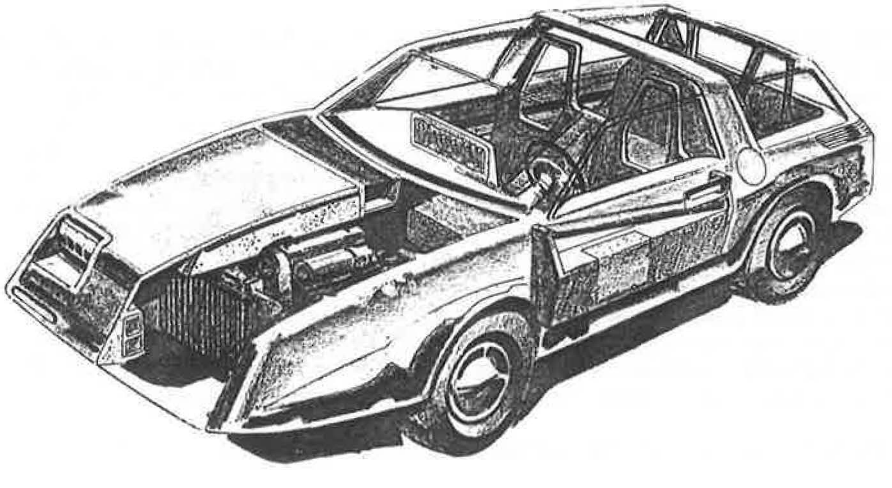


Figure 7. Final styling configuration.



walled, form-filled sheet metal about 3 in. (7.6 cm) thick with three enlarged longitudinal box sections abutting the transverse rear cross member. The rear quarter panels were enclosed and foam filled.

In an effort to mitigate injuries to pedestrians that account for about 10,000 fatalities and 330,000 injuries each year, the vehicle-to-vehicle impact structure was intentionally recessed relative to the exterior surface. This design allows a 2-in.-thick (5-cm) plastic section to provide a resilient surface for pedestrian strikes. The final styling configuration adjusts the front end shape for this purpose but incorporates the same structural modifications as shown in Figure 7.

The front and side modifications resulted in a net increase in weight of 39 lb (18 kg) over the baseline car in the same state of trim. On the other hand, the costs due to the use of 151 lb (69 kg) of aluminum in the bumper and sheet metal sections plus some 67 lb (30 kg) of foam amount to an estimated increased cost of $213.60 to the consumer for a further developed and production-engineered version. Uncertainties in cost estimating suggested a range of cost from $200 to $400.

The results are shown in Figure 8. The additional societal benefits resulting from the revised performance are shown by the striped area and represent the improvement over the baseline vehicle performance shown in Figure 3.

To ascertain the benefit-cost ratio of these modifications, one had to assess the consumer cost of the restraints. The driver airbag restraint was estimated to add 30 lb (14 kg) with a consumer cost of $63.90; however, the front passenger airbag, because of common elements, would add only 23.5 lb (10.7 kg) and would cost the consumer $31.40. Consumer cost, then, is 53.5 lb (24.3 kg) and $79.30, less the existing interlock, inertia reels, and three-point harness weighing 13.6 lb (6.2 kg) and costing $28; therefore, there is a net increase of 39.9 lb (18.1 kg) and $51.30. Because of manufacturing cost uncertainties, we assumed a range of cost from $50 to $200.

The benefit-cost ratio was calculated by dividing the societal benefits by the estimated costs for the restraints in an unmodified structure and in the front- and side-modified structure. Figure 9 shows that benefit-cost ratios of near four are likely, in spite of differences in estimated cost. By using this same procedure, we determined that the rear-end structure modification would not produce a comparable benefit-cost ratio to front and side modifications. The limited rear seat occupancy lowers the societal benefits to be accrued in that mode.

In conclusion, one can say that this structural program and its restraint counterpart have demonstrated, from a preprototype point of view, that, with little sacrifice in cost, weight, or marketable features, the subcompact car can be designed to meet the proposed 1979 modification of Federal Motor Vehicle Safety Standard 208 (14).

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Figure 8. Estimated savings from modified-structural and advanced-restraint performance relative to societal cost.

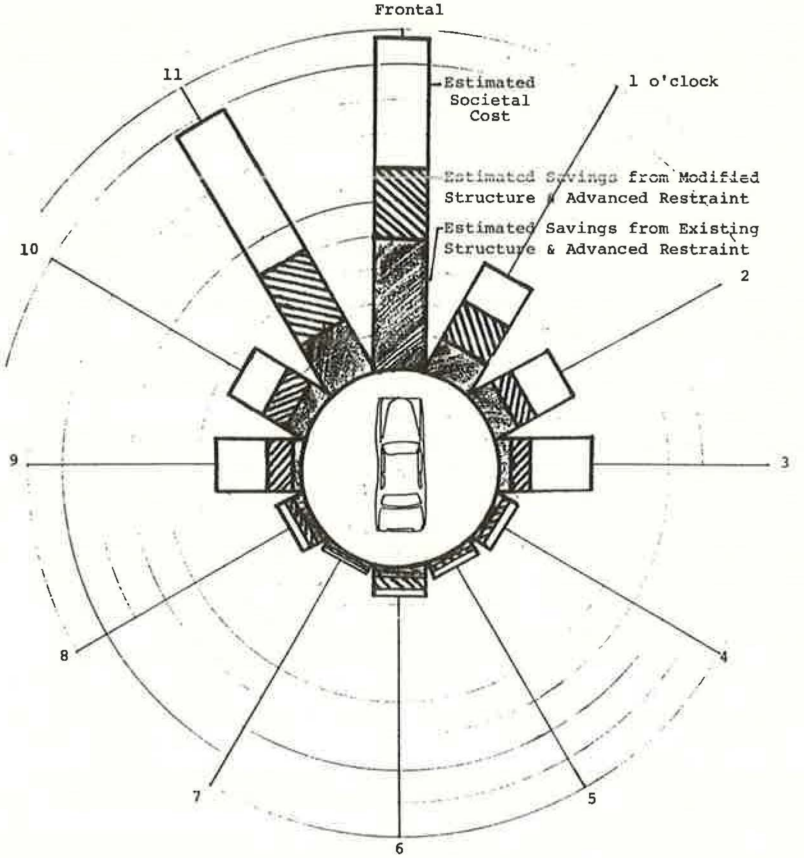
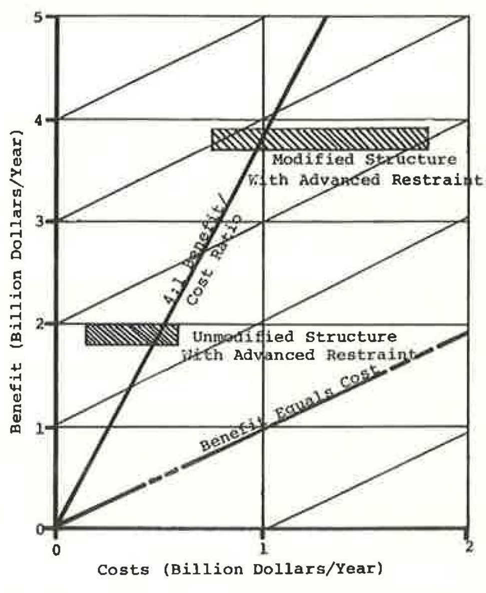


Figure 9. Benefit-cost ratio of subcompact modifications.



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IMPACT PERFORMANCE AND AN EVALUATION CRITERION FOR MEDIAN BARRIERS

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This study involves the determination of the impact performance of the Texas metal beam guard fence median barrier and a comparison of its performance with that of the Texas concrete median barrier. The metal beam guard fence consists of two standard W-shaped guardrails mounted back to back on a support post; the concrete barrier is a solid concrete barrier. The impact performance of the guard fence was determined from a combination of crash tests and from crash simulations by the Highway-Vehicle-Object Simulation Model. Standard-sized automobiles were used in both the crash tests and the crash simulations. A close comparison of test and simulated results verified the accuracy of the model in simulating impacts with the metal guard fence. The impact performance of the concrete barrier was obtained from another study. Inspection of 135 median barrier impacts on various urban freeways in Texas was made to determine the distribution of impact angles. These field measurements, supplemented by data from the highway simulation model, provided impact angle probabilities as a function of median widths. This study provides an evaluation criterion that can be used for objectively comparing the impact severity of the metal beam guard fence and the concrete median barrier as a function of the median's dimensions. The criterion is based on a design speed of 60 mph (97 km/h) and on impacts with a full-sized automobile.

•TO PREVENT median crossover accidents, the Texas State Department of Highways and Public Transportation (TSDHPT) uses, in most cases, two basic median barriers: the concrete median barrier (CMB) and the metal beam guard fence (MBGF). The CMB is for all practical purposes a rigid unyielding barrier; the MBGF is considered to be a flexible barrier, one that deforms on impact.

Several studies have been conducted to determine the impact performance of the CMB (1, 2, 3). It has been shown that for small impact angles the CMB can safely redirect an encroaching vehicle; however, these studies also showed that, as the impact angle increases, the impact severity increases considerably. Only limited impact performance data about MBGF existed before this study. One of the objectives of this study was therefore to determine the impact performance of MBGF so that objective comparisons could be made between the CMB and the MBGF. Crash tests and the Texas Transportation Institute version of the Highway-Vehicle-Object Simulation Model (HVOSM) computer program were used to accomplish this objective. The HVOSM was developed at Calspan Corporation for the Federal Highway Administration (9). Before applying the HVOSM, however, an extensive validation study was performed. Crash test data were compared with the HVOSM predictions. Some modifications were made to the HVOSM so that an acceptable comparison could be achieved.

This study also analyzed the relationship between median width and the probable angle of impact into a median barrier for errant vehicles. This relationship was needed to develop an evaluation criterion for the two barrier systems. It has been postulated that the CMB is best for narrow medians, where high impact angles are improbable, and that the MBGF should be used for wide medians. However, objective criteria to quantify what narrow and wide mean had to be developed. To accomplish this task, a combination of field measurements and HVOSM computer simulations was used.

TSDHPT personnel conducted the field measurements, and median barriers on selected urban freeways were inspected for impact damage. Where impacts had occurred, measurements of the angle of impact, median width, etc., were made. These data were then statistically analyzed to determine impact angle probabilities. The HVOSM was used to supplement the field data by defining upper limits on impact angles as a function of median widths.

This study result was an objective criterion that can be used in the median barrier selection process. The criterion, which is in the form of a graph, shows the relationship between impact severity and median width, on a probability basis, for the CMB and the MBGF. Other factors, such as installation and maintenance costs, must of course be considered in the selection process; however, an evaluation of these factors was not within the scope of this study. Full details of the study are given in a Texas Transportation Institute research report (10).

METAL BEAM GUARD FENCE BARRIER

Before the tests were conducted in this study, only one full-scale crash test had been conducted on the MBGF (2). In that test, an automobile impacted the barrier at 57.3 mph (92.2 km/h) at an impact angle of 25 deg. That test was denoted T4-1 (2) and will be referred to in the same way in this paper.

The impact conditions of two tests conducted in this study were 60 mph (97 km/h) at 8 deg, and 63.4 mph (101.4 km/h) at 14.7 deg. These two tests and the one mentioned above provided considerable insight concerning the impact performance of the MBGF for 60-mph (97-km/h) impacts. The tests also provided a data base from which the HVOSM could be validated. After validation, the HVOSM was used to determine the impact performance of the MBGF at speeds below and in excess of 60 mph (97 km/h).

Details

The as-tested MBGF (B)-74 barrier (TSDHPT designation) is shown in Figure 1. In some installations, a ⅜-in. (9.5-mm) steel wire pedestrian control cable is placed below the guardrail. Also a headlight-barrier fence is sometimes placed on top of the barrier; however, it is assumed that neither of these features will significantly affect the impact performance of the barrier.

On impact, the MBGF support posts break away from their base, allowing the back-to-back guardrail to deform. The ⅜-in. (9.5-mm) fillet welds connecting the outer faces of the two post flanges to the ⅝-in. (15.9-mm) baseplate are designed to fracture at relatively low impact forces. Since the posts shear off at the base at a relatively low impact force, the rail does not rotate significantly; therefore, the possibility of vehicle ramping is minimized.

Crash Tests

The two crash tests conducted in the study are referred to as MB-1 and MB-2. The MB-1 test refers to the 60-mph (97-km/h), 8-deg impact, and the MB-2 test refers to the 63.4-mph (101.4-km/h), 14.7-deg impact.

Test Vehicles and Test Dummy

A 1965 Plymouth, weighing about 4,200 lb (1905 kg), was used in test MB-1. Figure 2 shows the vehicle before and after the test. A 1964 Plymouth, weighing approximately 4,200 lb (1905 kg), was used in test MB-2. Figure 3 shows the vehicle before and after the test. In each of the two tests a 50th percentile male dummy was placed in the driver's seat and lap belted.

Figure 1. Texas metal beam guard fence barrier, MBGF (B)-74.

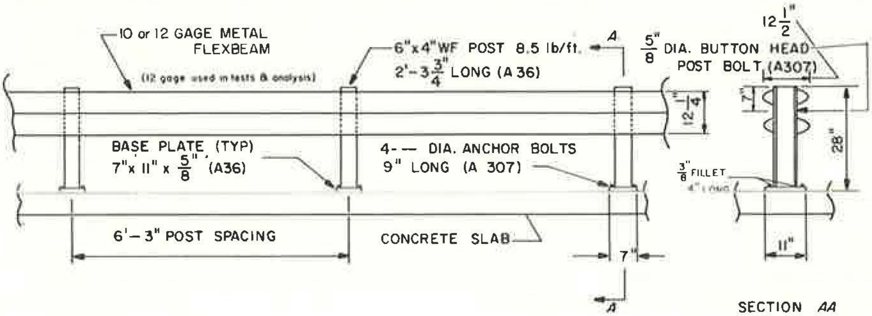
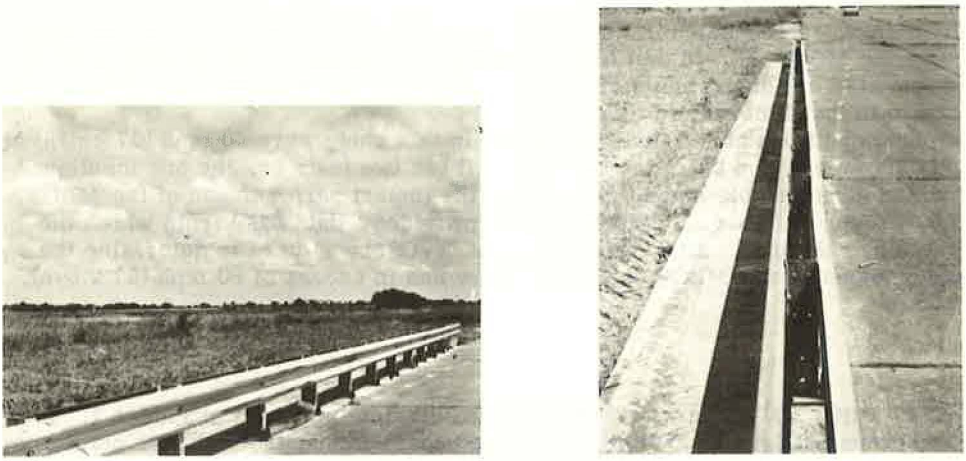
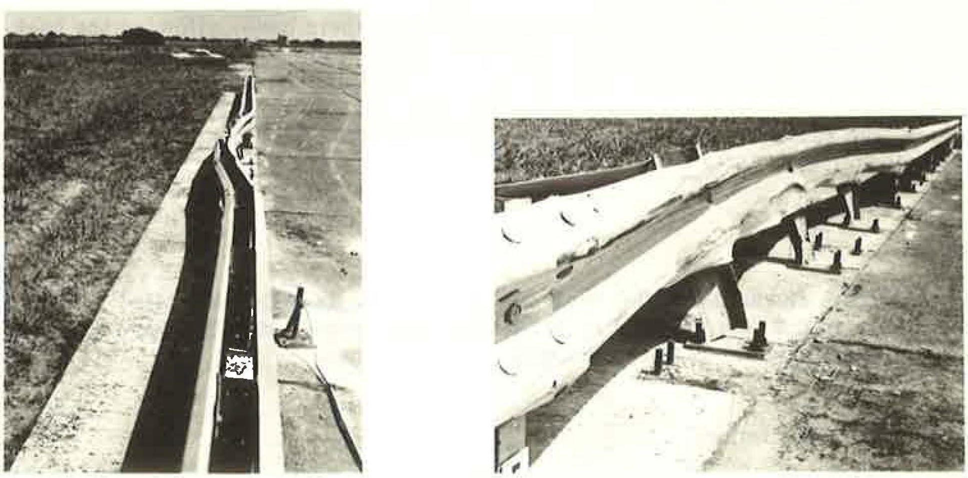


Figure 2. MB-1 test vehicle.



AFTER MB-1 TEST



AFTER MB-2 TEST

Data Acquisition

Crash test data were recorded by electronic instrumentation placed in the vehicle and by high-speed cameras that photographed the impacts. Three accelerometers were positioned near the center of gravity of the automobile. These accelerometers measured the longitudinal, lateral, and vertical accelerations, all with respect to a vehicle-fixed axis. The force in the dummy's lap belt during impact was measured. In addition, accelerometers were placed in the dummy's chest to measure accelerations in the fore and aft direction (eyeballs in or out) as well as in the left and right (lateral) direction. One high-speed camera was positioned with a field of view parallel to the longitudinal axis of the barrier, and the other camera's field of view was perpendicular to the barrier's longitudinal axis. Film speed was approximately 500 frames/sec. The film provided a time history of the vehicle's motion.

Test Results

The results of tests MB-1 and MB-2 are given in Table 1. Vertical accelerations were found to be small in comparison to the longitudinal and lateral accelerations and are therefore not shown. Damage to the MBGF after each test is shown in Figure 4. As can be seen, damage to the barrier after test MB-1 was negligible, and no repairs were necessary. Repairs to the barrier after test MB-2 would consist of replacing two 25-ft (7.5-m) W-beam guardrails, three support posts, and the necessary bolts, nuts, and so on. Damage to the automobile after each test is shown in Figures 3 and 4. The test car in MB-1 was still operable after the test; however, damage to the left front wheel assembly of the vehicle in test MB-2 prevented its operation after the impact.

VALIDATION OF MODEL FOR METAL BEAM GUARD FENCE IMPACT SIMULATIONS

The three full-scale crash tests described in the previous section provided impact performance data for the MBGF when impacted by a standard-sized automobile at about 60 mph (97 km/h); however, more data were desired concerning its performance since impacts in the field could be expected to occur at speeds both below and above 60 mph (97 km/h).

In lieu of additional crash tests (that were not within the budget), it was decided to determine if HVOSM could simulate an automobile impacting the MBGF. To make this determination, the three MBGF crash tests (MB-1, MB-2, and T4-1) were simulated by HVOSM, and the results were compared with the test results.

Process

The validation process actually involved a trial and error procedure. Errors were also uncovered in an impact subroutine of HVOSM, and these were corrected. Adjustments were made in the vehicle and barrier stiffness parameters until the HVOSM simulation converged on the results of the MB-2 test. However, these same stiffness parameters were used in the simulation of the other two tests (MB-1 and T4-1), and the resulting comparisons were very good. Except for the coefficient of friction between the vehicle and the barrier, parameters did not need to be adjusted in each test simulation. As a consequence, it was thought that these parameters could be used in HVOSM to simulate impacts with the MBGF at speeds above and below 60 mph (97 km/h). The value of the vehicle-barrier friction coefficient had to be adjusted upward as the angle of impact increased. This increase was necessary to simulate the effects of the slight pocketing that occurred, i.e., pocketing of the vehicle by the barrier.

Figure 3. MB-2 test vehicle.

BEFORE TEST

AFTER TEST

Table 1. Data from metal beam guard fence tests.

Item	Test Number MB-1	Test Number MB-2
Vehicle		
Year	1965	1964
Make	Plymouth	Plymouth
Weight, lb	4,200	4,200
Film		
Impact speed, mph	60.0	63.4
Impact angle, deg	8.0	14.7
Dynamic barrier deflection, in.	1.0	12.0
Departure angle, deg	4.0	3.8
Departure speed, mph	47.0	52.0
Accelerometer		
Longitudinal		
Peak, g	2.0[b], 5.3[c]	5.5[b], 5.4[c]
Highest average, g[a]	0.03[b], 4.2[c]	0.90[b], 4.3[c]
Lateral		
Peak, g	5.3[b], 4.0[c]	7.0[b], 8.2[c]
Highest average, g	3.2[b], 2.9[c]	4.7[b], 6.3[c]

Note: 1 lb = 0.45 kg, 1 mph = 1.6 km/h, 1 in. = 2.54 cm.
[a]Averaged over 50 msec. [b]Vehicle. [c]Dummy.

Figure 4. Metal beam guard fence damage.

BEFORE TEST

AFTER TEST

Comparisons Between Simulation and Test Results

Comparisons between HVOSM and the test results were made on two basic types of data: vehicle motion and accelerations at the vehicle's center of gravity.

Vehicle Motion

Figure 5 shows a comparison of test and simulation of vehicle motion for the MB-1 test [60 mph (97 km/h) and 8 deg]. Similar plots were made for the other two tests. The HVOSM perspective drawings were generated by a computer program (6) whose input is the HVOSM output. Hidden lines were removed from the perspective drawings by hand for clarity. The test photographs are prints made from selected high-speed film frames. The general motion of the HVOSM compares well with the test results. Note that the automobile does not roll appreciably after impact with the MBGF, as was the case in all three tests.

Acceleration

Figure 6 shows a comparison of test and simulation lateral acceleration for test MB-1. Similar comparisons were made for the other two tests. Comparisons were also made between test and simulation longitudinal accelerations. The HVOSM accelerations generally followed the trend of the test accelerations. In some instances test data were characterized by rapid changes, and HVOSM values were somewhat smoother. This high-frequency vibratory nature of the test data is attributed in part to ringing or high-frequency response of the sprung mass of the vehicle. HVOSM does not have the capability to simulate this type of response; however, the contribution of such accelerations to overall impact severity is not considered significant. Another reason for sudden and large changes in the test values is that, as the vehicle crushes, various members of various stiffnesses are encountered. HVOSM can simulate this effect to a small degree by hard points. A summary of the acceleration data is given in Table 2. Although some disparity occurs between test values and the HVOSM values for peak accelerations and the times at which these occur, the average accelerations reasonably agree. In most cases, more significance is placed on the highest average accelerations than on the highest peak accelerations. This is especially true when vehicle accelerations are used as a measure of severity (to the occupant or occupants of the vehicle).

After the validation efforts were evaluated, it was concluded that HVOSM (as modified) could be used to supplement crash test data for the MBGF. When the complex nature of the MBGF impacts was considered, the HVOSM predicted the gross motion of the vehicle and vehicle accelerations quite accurately.

PARAMETRIC STUDIES

Metal Beam Guard Fence

To supplement the MBGF crash test data, nine HVOSM simulations were made. Impacts at speeds of 50, 70, and 80 mph (80, 113, and 129 km/h) in combination with impact angles of 5, 15, and 25 deg were simulated. Table 3 gives the results of these nine simulations (runs 1 through 9). Also given in Table 3 are the results of the simulations of the three crash tests (runs 10, 11, and 12). The accelerations given in Table 3 are the highest average accelerations occurring over any 50-msec period. A small utility computer program was written to compute these maximum averages as well as the maximum severity index. The program scanned the data, computed the average accelerations and the severity index for all 50-msec periods, and selected and printed the maximums. The time period over which the maximum average longitudinal acceleration occurred did not necessarily correspond to that for the average lateral acceleration.

Figure 5. Test versus model vehicle motion, test MB-1.

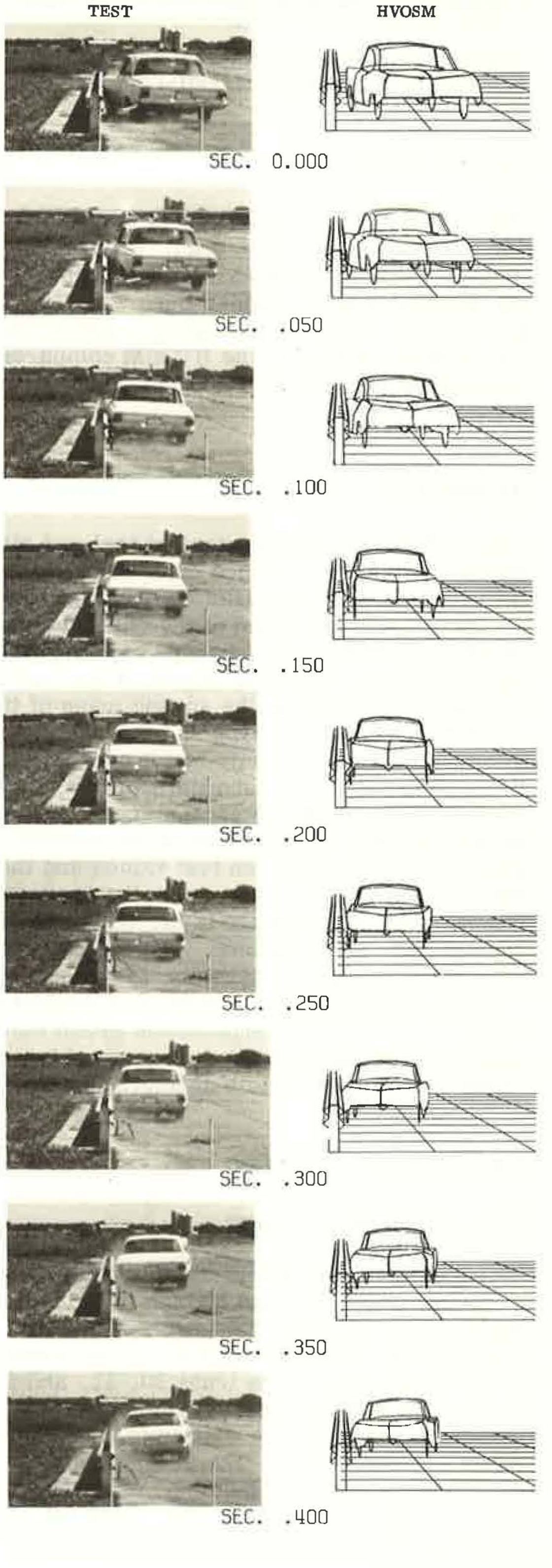


Figure 6. Lateral acceleration, test MB-1.

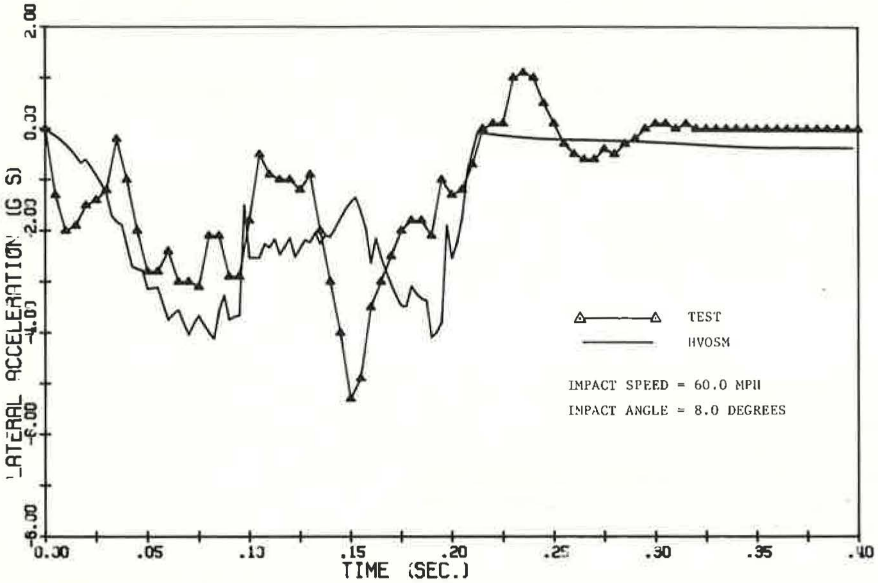


Table 2. Acceleration comparisons.

	Results (g/sec)					
	MB-1		MB-2		T4-1[a]	
Acceleration Type	Test	HVOSM	Test	HVOSM	Test	HVOSM
Peak lateral	5.3/0.16	4.1/0.19	7.0/0.070	6.2/0.113	—[b]	9.4/0.25
Peak longitudinal	2.8/0.08	1.4/0.07	5.0/0.080	2.8/0.058	12.0/0.13	11.0/0.103
Highest average lateral	3.2/0.14 to 0.19	3.6/0.045 to 0.095	4.7/0.17 to 0.22	4.8/0.173 to 0.223	—[b]	7.2/0.23 to 0.28
Highest average longitudinal	1.0/0.045 to 0.095	1.2/0.045 to 0.095	2.5/0.035 to 0.085	2.6/0.048 to 0.098	10.0/0.10 to 0.15	10.0/0.088 to 0.138

[a]Right frame member. [b]Not available.

Table 3. Parametric study results for metal beam guard fence and concrete median barrier.

		Impact Conditions				Max Avg Accelerations[b]			
Item	Run No.	Speed (mph)	Angle (deg)	Exit Angle (deg)	Max Roll Angle (deg)	g_{Long}	g_{Lat}	g_{Vert}	Max S.I.[c]
MBGF	1	50	5	1.9	1.8	0.56	1.92		0.39
	2	50	15	5.1	5.0	2.45	4.14		0.90
	3	50	25	12.2	9.6	7.80	5.50		1.57
	4	70	5	1.2	1.5	0.76	2.70		0.55
	5	70	15	2.9	2.3	2.87	5.51		1.15
	6	70	25	7.8	10.1	12.03	8.98		2.49
	7	80	5	1.0	1.6	0.88	3.15		0.64
	8	80	15	2.7	3.0	3.41	6.60		1.39
	9	80	25	7.0	9.7	15.30	11.53		3.17
	10	60	8	2.5	1.8	1.20	3.60		0.73
	11	63.4	14.7	3.6	5.0	2.59	4.80		0.98
	12	57.3	25.0	9.2	8.4	9.03	6.83		1.88
CMB	1	50.0	5.0	1.1	1.3	0.49	1.61	0.12	0.33
	2	70.0	5.0	0.3	2.2	0.72	2.53	0.43	0.52
	3	80.0	5.0	0.1	3.3	0.21	2.90	0.54	0.58
	4	50.0	10.0	2.5	4.2	1.13	2.99	0.94	0.64
	5	70.0	10.0	1.2	19.5	0.16	5.06	2.03	1.07
	6	80.0	10.0	1.2	34.6	1.92	6.42	2.61	1.38
	7	50.0	15.0	3.6	15.0	0.47	4.29	1.38	0.91
	8	70.0	15.0	—[d]	—[d]	2.81	6.44	3.16	—[d]
	9	80.0	15.0	—[d]	—[d]	3.24	7.49	3.29	—[d]
	10	50.0	25.0	—[e]	—[e]	4.45	7.41	4.28	1.76
	11	63.0	25.0	5.1	37.0	6.47	11.23	4.38	2.54
	12	70.0	25.0	—[e]	—[e]	9.37	12.27	1.78	2.81

Note: 1 mph = 1.6 km/h.

[a]When vehicle lost contact with barrier.

[b]Averaged over 50 msec at center of gravity. Maximum average longitudinal and lateral accelerations do not necessarily occur during the same time period.

[c]As computed over 50 msec.

[d]Vehicle rolled over on exiting from barrier. Severity was considered intolerable.

[e]Data unavailable.

In addition, the time period over which the maximum severity index occurred did not necessarily correspond to that for the maximum average longitudinal acceleration or to that of the maximum average lateral acceleration.

A severity index (SI) was used to quantify the severity (to an occupant) of the vehicle impacts with the MBGF. It is defined as follows (7):

$$SI = \sqrt{\left(\frac{G_{Long}}{G'_{Long}}\right)^2 + \left(\frac{G_{Lat}}{G'_{Lat}}\right)^2 + \left(\frac{G_{Vert}}{G'_{Vert}}\right)^2} \qquad (1)$$

where

G_{Long} = average longitudinal acceleration,
G_{Lat} = average lateral acceleration,
G_{Vert} = average vertical acceleration,
G'_{Long} = tolerable average longitudinal acceleration,
G'_{Lat} = tolerable average lateral acceleration, and
G'_{Vert} = tolerable average vertical acceleration.

The terms in the numerator of equation 1 are the average accelerations of the vehicle, and the terms in the denominator are the limiting vehicle accelerations an occupant can withstand without serious or fatal injuries. It is assumed that $SI > 1$ indicates that an occupant would sustain serious or fatal injuries. A detailed description of the index is given in the literature (5, 6).

Limiting accelerations used in this study were as follows (7): $G'_{Long} = 7$, $G'_{Lat} = 5$, and $G'_{Vert} = 6$. For the MBGF, the vertical accelerations were negligible, and therefore only the first two terms of the SI were included. However, the severity indexes on the CMB involved all three terms since all three acceleration components were significant.

Concrete Median Barrier

The SI for the MBGF is compared with that of the CMB. Values of the SI for the CMB were obtained from a previous study (1), with two exceptions. For adequate comparison of the two barriers, two impacts had to be simulated with the CMBs that were not in the previous study. Impacts at 50 mph (80 km/h) and 25 deg and at 70 mph (113 km/h) and 25 deg were simulated. The results of these two runs, together with all other CMB data, are given in Table 3.

COMPARISON OF IMPACT PERFORMANCE OF CONCRETE MEDIAN BARRIER AND METAL BEAM GUARD FENCE

Impact Severity

SI versus impact speed for the CMB and the MBGF for three different impact angles is shown in Figure 7. Data in Figure 7 were taken from Table 3. For small impact angles, the two barriers are approximately equal in impact severity; however, as the impact angle increases, the difference in impact severity of the two barriers is more pronounced, and the MBGF provides the less severe impact. This result was expected since the MBGF does have flexibility and can dissipate a considerable amount of the energy of the impacting vehicle. The CMB is for all practical purposes a rigid barrier.

It can be seen in Table 3 that the MBGF can redirect a vehicle without introducing large roll angles, i.e., the potential for rollover appears to be minimal. This could be a significant factor when the MBGF and the CMB are compared since at high speeds and large impact angles the latter has shown a tendency to cause the impacting vehicle to roll over (1).

Damage Costs

Evaluation of the impact performance of a barrier should include consideration of repair costs to both the barrier and the vehicle. The following cost figures, which admittedly are based on limited data, give a quantitative measure of the damage costs incurred after impact with the MBGF and the CMB.

With regard to barrier damage, the CMB requires no repair for all practical purposes, at least for the impact conditions investigated. Damage to the MBGF for an impact at 60 mph (97 km/h) at 7 deg was negligible. Damage to the MBGF for 60-mph (97-km/h) impacts at 15 deg and 25 deg is approximately the same. Repair cost in these cases is based on previous estimates (2); a factor of 1.2 has been applied to estimate cost increases since those data were published. Estimated dollar costs to repair the barriers and the automobiles after impact with the respective barriers are as follows:

Impact Angle	Barrier	Vehicle
7-deg		
MBGF	Nil	490
CMB	Nil	615
15-deg		
MBGF	530	1,330
CMB	Nil	1,550
25-deg		
MBGF	530	1,430
CMB	Nil	1,500

Automobile repair costs were obtained in each case from a local automobile appraiser.

Based on the estimates and the corresponding impact conditions, impact with the CMB will cause more damage to the automobile than the MBGF. However, it is pointed out that, at impact angles of less than 7 deg, the CMB will redirect an automobile with little or no sheet metal damage; this reduces or eliminates damages. The MBGF does not have this capability, and some automobile damage can be expected for any impact.

IMPACT ANGLE PROBABILITIES

The study up to this point provided objective criteria for comparing the impact performance of the CMB and the MBGF for a given set of impact conditions, i.e., impact speed and angle. However, data in this form are of limited value if one cannot relate impact conditions (or probability thereof) to the particular median geometry in question. The objective of this phase of the study was therefore to determine the impact angle probability as a function of median width or the distance from the roadway to barrier's face. To accomplish this objective, the researchers relied on both field data and on data determined from the HVOSM. A description of each of these two approaches follows.

Field Data on Barrier Impacts

Valuable work on the nature of all vehicle encroachments has been done by Hutchinson and Kennedy (7); however, there was no apparent way to predict what number of these encroachments would have impacted a barrier, had there been one in the median, and at what impact angle this would have taken place. Therefore, a number of field evaluations were made to determine actual impact angles.

The field data were gathered by the research division of TSDHPT. The field sites were urban freeways of several large cities in Texas. The collection procedure involved the location of sites where median barrier accidents had occurred (as judged by barrier damage) in which impact angles could be measured, either through skid marks or tire tracks. In some cases, the barrier deflection (permanent set) was measured; however, there was no attempt to relate barrier damage to any other parameters, such as vehicle speed.

Median widths investigated ranged from 13 to 56 ft (4 to 16.8 m), and 135 cases were recorded. However, a large portion of these (111) were in the 22 to 26-ft (6.7 to 7.9-m) median width range. In a few instances, the barrier was located on a raised median; in such cases a roll curb was used and, therefore, it is doubtful that it would have a significant effect on the vehicle's path, at least for the short distances between the curb and the barrier.

Inspections of impacts with barriers on narrow raised medians were also made by the TSDHPT. The following statement by D. Hustace of the department concerns this phase of the inspection:

> The narrow median, although sustaining numerous impacts, had frequently not provided tire tracks due to the airborne tire after having struck the curb face. Although curb scuff marks and barrier damage is usually readily apparent, the nearness of the barrier face and overhang of the vehicle would normally result in an over conservative angle from a calculated value. This factor, combined with the extreme hazard of angle measurements on narrow medians, leads me to feel that the data generated by Hutchinson and Kennedy for vehicle departure angles should be adequate to represent the narrow median situations since vehicle-driver recovery-response would be minimum due to the close proximity of the barrier. Also, in turn, the absence of wide median barrier sites and the lack of serious consideration for median barrier installations in the wide median does not demand the same urgent attention as does the barrier installation for the medium and narrow width medians.

A statistical analysis of the 135 cases led to the following conclusions:

1. There were enough data to determine a relation between impact angle and probability of occurrence for median widths between 22 and 26 ft (6.7 to 7.9 m). The relation is shown in Figure 8. The data from the 22, 24, and 26-ft (6.7, 7.3, and 7.9-m) medians were combined to develop this curve because there was not a significant variation in the distribution to warrant a curve for each of these four widths.
2. There were not enough data to develop distributions of impact angles as a function of median widths because most of the data were for median widths between 22 and 26 ft (6.7 and 7.9 m).
3. Based on the data for the 22 to 26-ft (6.7 to 7.9-m) medians, it appears that the distribution of impact angles for a given median width can be approximated by the normal distribution. The mean impact angle for the data was 10.8 deg with a standard deviation of 6.2 deg. It can be seen in Figure 8 that a normal distribution having a mean impact angle of 10.8 deg and a standard deviation of 6.2 deg correlates well with the field data.

Model Simulations of Encroachment Angles

A series of HVOSM runs were conducted to supplement the field data. The objective of these runs was to develop relationships between encroachment angle and median width for different probability levels. In the research approach, the HVOSM was used to establish extreme encroachment angles (95th percentile values) for any given median width. Further details of the procedure used to determine these angles are given later in the paper. Based on these extreme encroachment angles and assuming a zero impact angle at the 5th percentile, a normal distribution was constructed for various median widths (a normal distribution is uniquely defined, given any two points on the curve). Use of the normal distribution in this manner appears reasonable because of its close correlation with field data (Figure 8). From these data, curves were drawn depicting impact angle versus median width for different levels of probability. It is important to note that the ability of the HVOSM to simulate an automobile during steering maneuvers has been demonstrated by other researchers (9).

Extreme Encroachment Angles

Much speculation has occurred concerning the highest angle at which an automobile can impact a barrier located a given distance from the roadway. This investigation did not provide data to end all speculations, nor did it purport to, but it did shed some light on the problem.

Basically, the HVOSM was used to determine the response and the encroachment angle of a standard automobile with standard tires as it was suddenly steered off the roadway while traveling at 60 mph (97 km/h). The automobile was assumed to be in a coast mode, i.e., with no traction after the steering maneuver began. The maneuver consisted of steering from a 0 steer angle to a prescribed angle in a prescribed time at a uniform rate. The turning rate was determined by observing the highest rates at which drivers had performed similar maneuvers in full-scale tests at the Texas Transportation Institute.

Four steering-angle limits were simulated in the HVOSM: 4, 8, 12, and 16 deg. The steer angle was increased to a selected limit at a constant rate and then held constant (most automobiles have a ratio of the steering wheel angle to steer angle of between 20 and 25). For example, an 8-deg steer angle would require between 160 and 200 deg of steering wheel turn.

A total of 12 simulation runs were made. For each of the four steering conditions described above, three tire-pavement friction coefficients were simulated, namely, 1.0, 0.75, and 0.5. The results were given in two basic forms: plots of the vehicle path and encroachment angle versus lateral distance. Figure 9 shows plots of the path of the center of gravity of the vehicle for a tire-pavement friction coefficient μ of 1.0 for the four steering angles. The lateral distance is a distance from the roadway tangent on which the steering maneuver began (roadway parallel to longitudinal distance axis). Note that an increase in the steer angle does not result in a proportionate increase in the path curvature, especially beyond steer angles of 8 deg. This is due primarily to the saturation of the side force capabilities of the front tires after the steer angle exceeds approximately 8 deg. It is conjectured that the curvature approaches a limiting value for steer angles of 16 deg. It is possible that other forms of steering input (e.g., nonlinear rates of steer application) could result in paths of larger curvature, but it is doubtful that the differences would be significant.

Also shown in Figure 9 is a path plot of the vehicle as simulated by a simple point mass model. It can be shown that the minimum radius r_{min} a point mass can follow is given by

$$r_{min} = \frac{v^2}{g\mu} \tag{2}$$

where

v = velocity of point mass,
μ = friction coefficient, and
g = gravitational acceleration.

From Figure 9, it can be seen that the actual paths (as determined by HVOSM) differ considerably from that of the point mass because of the inability of the point mass model to accurately represent the transient nature of vehicle handling. The point mass model assumes an instantaneous steady-state turn when the turn has been initiated, and the HVOSM accounts for the transient period of the vehicle's response.

Encroachment angles are shown in Figure 10 as a function of lateral distance. Coordinates of each of these curves were determined by computing the arc tangent of the

Figure 7. Severity index versus impact speed.

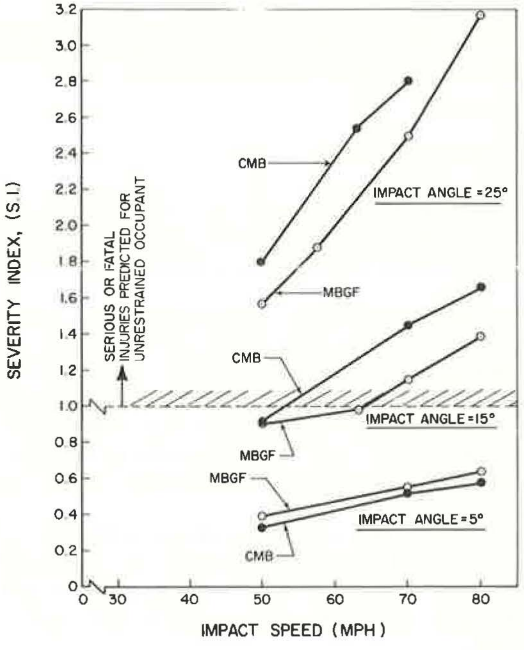


Figure 8. Distribution of impact angles for field data.

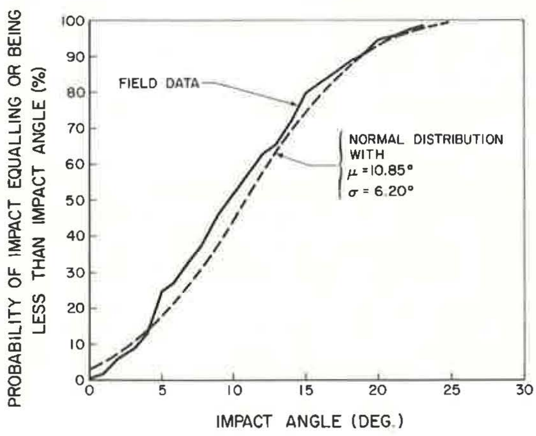
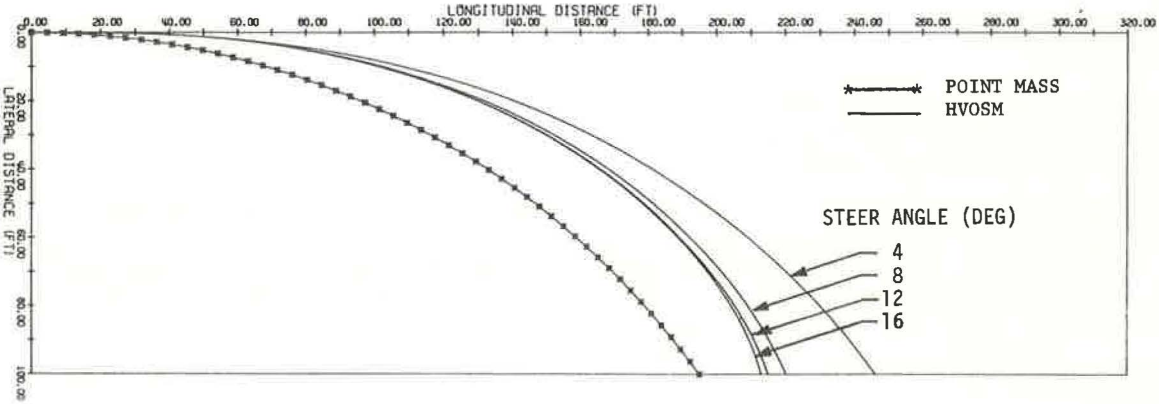


Figure 9. Vehicle path.



slope of the appropriate curve in Figure 9 as a function of lateral distance. The encroachment angle is the angle between a tangent to the center of gravity path and the roadway tangent.

Although the point mass model does not accurately simulate the vehicle's path, it does predict the encroachment angle quite accurately, at least for the extreme steering maneuvers simulated and for lateral distances up to about 40 ft (12 m). For lower friction coefficients, the comparison was found to be even better. In addition, many people felt that the point mass representation gave excessive encroachment angles; i.e., the vehicle could not attain the angles predicted by the point mass model. Such is not the case; in fact, for high skid-resistant pavements where large lateral distances are accessible, e.g., a wide median, the results indicate that the point mass predictions are too low.

For a relationship between extreme encroachment angle and median width (lateral distance), the values as determined for a steer angle of 16 deg and a friction coefficient of 1.0 were selected. In most cases these conditions would be extreme, and, as such, they represent what are considered to be limiting values.

Figure 11 shows the relationship between the extreme impact angle and the median distance D for two conditions: impact from lane 1 and impact from lane 2. Note that the median distance D is not the half-median width but rather is the distance from the edge of the roadway to the barrier face. It was assumed that the vehicle was in the center of the 12-ft (3.6-m) lane when the emergency steering maneuver began. The curves of Figure 11 were determined from Figure 10, and slight adjustments were made to account for the dimensions of a typical automobile (10, p. 59).

Note that the curve for the impact from lane 1 will intersect the vertical axis above zero for a zero median distance; i.e., there can be an impact angle even though there is no median distance because of the assumed 3-ft (0.9-m) gap between the vehicle and the face of the barrier for a vehicle traveling in the center of the lane.

Distribution of Probabilities

The probability distribution of impact angles for a given median distance was assumed to be a normal distribution. For determination of the distribution for a given median distance, the 95th percentile value of the impact angle was assumed to be that from the lane 1 curve of Figure 11, and the 5th percentile impact angle was assumed to be zero. These two points uniquely defined the distribution for any given median distance.

The decision to use these particular percentile values was arrived at through a trial and error procedure. Different combinations were tried, and the distributions were compared with the field data. Figure 12 shows that the predicted distribution (theoretical) compares reasonably well with the actual field data, for a median distance of 12 ft (3.6 m) [median width of about 24 ft (7.3 m)]. Although there are some differences in these two curves, the degree of correlation is considered to be good.

There are several factors that likely contributed to the differences that did occur in the curves of Figure 12. The first of these, and probably the most significant one, is the speed of the impacting vehicle. Unfortunately, there was no way to determine impact speeds from the field measurements. It is conjectured that the low-angle impacts occurred at speeds higher, on an average, than those of the higher angle impacts and that most of the impacts occurred at speeds of less than 60 mph (97 km/h). The theoretical distribution is based on an initial encroachment speed of 60 mph (97 km/h). Some slight decrease in speed occurred in the HVOSM simulations during the encroachment, but it was not considered significant [<2 mph (<3.2 km/h)].

Some of the barrier impacts likely occurred after the vehicle impacted another vehicle or object, and this could also cause differences. Actions of the driver during the encroachment, such as braking, could also have a significant effect on the vehicle's path. The number of lanes can also have an effect on the distribution of encroachment angles. Field data were taken on urban freeways with various numbers of lanes. As assumed, the theoretical distributions were based on encroachments from the inside lane; however, the effect of the combination of these factors could be represented by the as-formulated theoretical distribution.

EVALUATION CRITERION

Impact performance data and impact angle data that were needed to formulate an evaluation criterion were now available. The criterion is based on a design speed of 60 mph (97 km/h) and relates to full-sized automobiles. Values of the severity index of barriers at 60 mph (97 km/h) as related to impact angle are given below:

Impact Angle (deg)	MBGF	CMB
5	0.47	0.42
15	0.96	1.18
25	2.00	2.39

These values are from Figure 7. The criterion is shown in Figure 13. Coordinates of the SI versus impact angle curves were taken from the table above, and the plots of median distance versus impact angle were determined from the assumed normal distributions.

The criterion referred to is based on safety considerations only, does not include cost and maintenance factors, and depends on the design speed. For example, if the design speed were 50 mph (80 km/h), the severity curves of Figure 13 for the two barriers would have been closer together. However, at lower design speeds, higher impact angles can be expected, and the impact angle distribution curves would have to be determined for the lower speeds.

Figure 13 allows one to objectively compare the impact severity of the two barriers as a function of the median distance. For example, assume that one is interested in the impact severities of the two barriers when they are placed 12.5 ft (3.7 m) from the roadway [a median width of approximately 25 ft (7.6 m)], for the 80th percentile impact. Application of the curves is as shown in Figure 13. The severity indexes were 0.90 for the MBGF and 1.09 for the CMB. These results indicate the MBGF to be about 21 percent less severe for the given conditions.

As mentioned previously, the selection process involves the consideration of other factors, such as initial and maintenance costs of the barrier and the hazard to repair crews and motorists while the barrier is being serviced. We think that a selection procedure based on a cost-effective analysis can be formulated that incorporates the effects of all these factors. Such a formulation, however, was not within the scope of this work.

The TSDHPT used the results of this study to establish guidelines for the selection of median barriers. These guidelines were also determined through careful consideration of other factors, such as maintenance costs, safety to maintenance crews who must repair the barriers, and the disruption of traffic during repairs. The guidelines are as follows (1 ft = 0.3 m):

Median Width (ft)	Barrier
<18	Concrete
18 to 24	Concrete or double steel beam
24 to 30	Double steel beam

Figure 10. Encroachment angles.

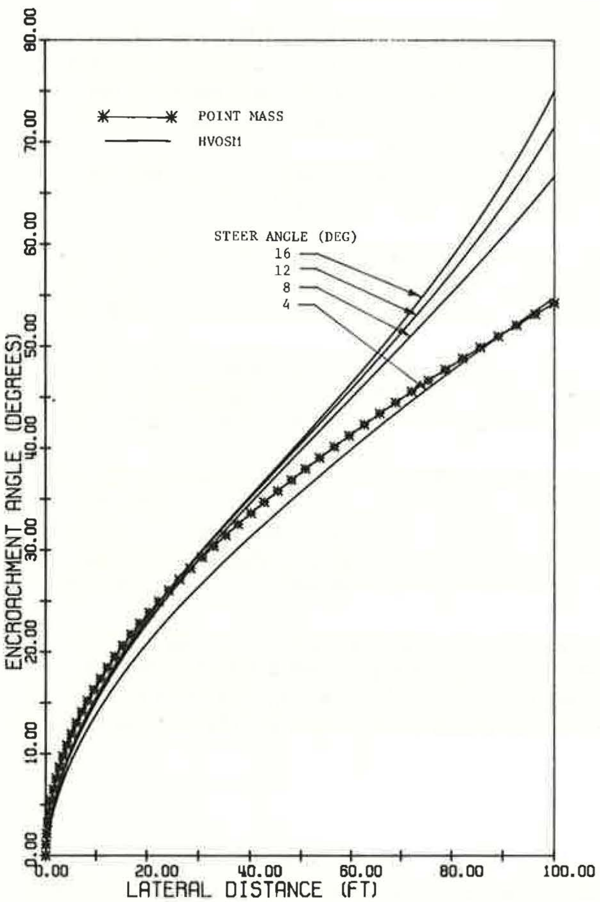


Figure 11. 95th percentile impact angle versus median distance.

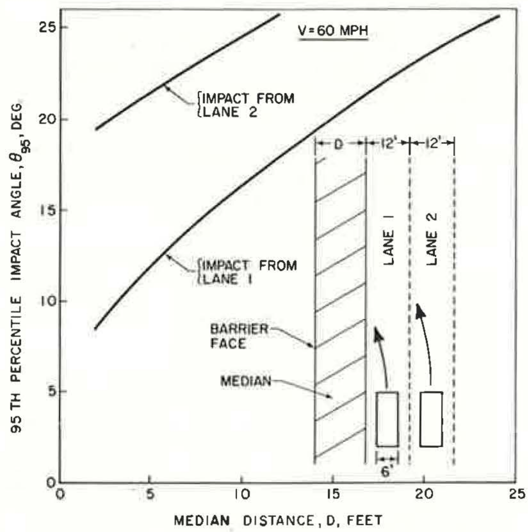


Figure 12. Impact angle versus probability of impact.

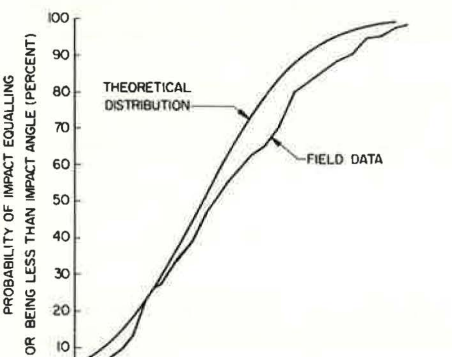
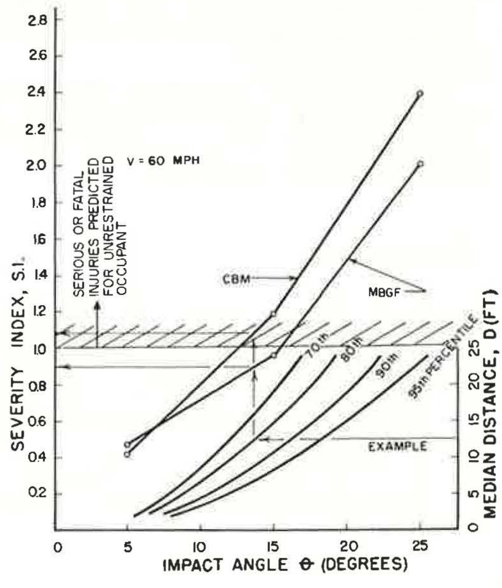


Figure 13. Selection criterion.



CONCLUSIONS

1. The Texas standard MBGF will contain and redirect an automobile impacting at 60 mph (97 km/h) at impact angles of 7, 15, and 25 deg. There is no tendency for the automobile to become unstable after impact with the MBGF, and the exit angle of the vehicle is not large. Serious or fatal injuries are not predicted for impacts at angles of less than 15 deg and speeds of less than 60 mph (97 km/h).
2. The as-modified version of the HVOSM can be used to simulate automobile impacts with the MBGF. Close correlations between test and simulated results form a basis for this conclusion.
3. The severity of impact with the Texas standard CMB at 60 mph (97 km/h) is approximately equal to that with the MBGF for impact angles of 7 deg or less. However, as the angle of impact increases, impacts become progressively more severe with the CMB than with the MBGF.
4. The CMB is practically maintenance free; repair of the MBGF after a 60-mph (97-km/h), 15-deg impact costs approximately $500. Based on gross estimates, automobile repair costs are slightly higher for a CMB impact than for an MBGF impact at 60 mph (97 km/h) and at 7 deg or more.
5. Sufficient field data were obtained to determine the percentile distribution of impact angles for a barrier placed in the center of a 24-ft (7.37-m) median. A theoretically derived distribution, obtained by application of the HVOSM, compared favorably with the field data. Percentile distributions of impact angles as a function of median distance (distance from roadway edge to barrier face) were obtained by the theoretical analysis.
6. An objective barrier evaluation criterion was developed from which the impact severity of the MBGF and the CMB can be determined for any given median distance. The criterion is based on a design speed of 60 mph (97 km/h) and impacts with a full-sized automobile. TSDHPT used this criterion to develop warrants for the use of these two barriers.

ACKNOWLEDGMENTS

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of FHWA. This paper does not constitute a standard, specification, or regulation.

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AUTOMOBILE-ATTENUATOR COMPATIBILITY IN 1985: SOME DESIGNER GUIDELINES

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Extensive analysis of automobile accident data from the designer's point of view reveals, among other things, the importance of fixed-object collisions in automobile societal losses. Moreover, the analysis has yielded information about the distributions of speed and injury in such crashes. As a result, the fixed-object collision situation can be described rather completely in terms of societal cost and can be extrapolated by assumption to the situation to be expected 10 years hence when smaller cars in greater numbers will be using our highway system. When combined with results of recent subcompact car crashworthiness efforts, the analysis makes possible a rough engineering characterization of the optimal crash attenuator for the occupants of tomorrow's family car.

•AS PART of the U.S. Department of Transportation contract to develop a crashworthy car based on the Ford Pinto, Minicars, Inc., has produced an extensive analysis of the accident picture that combines mass accident data and detailed information from multidisciplinary accident investigations (MDAI) in a way that simultaneously allows broad economic projections and discovery of detailed design information (2, 3, 4, 5, 6, 7, 8). Tables 1 and 2 give the results. That they include a sizable indictment of the fixed-object problem is not too surprising. Collisions with fixed objects wider than 16 in. (41 cm) accounted for 8,500 fatalities and 179,000 disabling injuries during 1971. Although this loss includes some impacts with large trees, it is mostly due to interference with obstructions that are amenable to treatment by removal or attenuation. Narrow [< 16-in.-wide (<41-cm)] fixed-object impacts undoubtedly include many trees, utility poles, and signposts. Although they account for a sizable annual societal loss (7,000 lives, 197,000 injuries), in general they would not be best treated by installation of highway crash attenuator devices (HCAD) but rather by removal or relocation of the objects in question.

In economic terms proposed by U.S. DOT (8), the total societal loss, due to wide fixed-object collisions, amounted to more than $7.2 billion in 1971 (2). It is this loss that deserves the attention of crash-attenuator designers.

The available accident data can give us a more complete picture of the design challenge. Figure 1 shows an approximate distribution of societal costs in fixed-object collisions by clock position of principal force and by obstacle width. Note that the frontal (11, 12, 1 o'clock) modes predominate but that the side-collision modes are also important. Figure 2 shows the distribution of frontal and side-mode fixed-object crash casualties with impact speed; in Figure 3, these casualties are shown cumulatively. The average cost per injury as a function of impact speed, the societal costs as a function of speed, and the total societal cost versus impact speed for classes of fixed-object collisions are shown in Figures 4, 5, and 6 respectively. Although the data show considerable scatter in some categories because of small samples, they suggest trends of injury distributions.

Table 3 gives apportionment of injuries (and fatalities) and estimated costs by object struck, as reported in the 4-year Pennsylvania study and in the MDAI file (5, 9). Although there is some indication that guardrail and ditch accidents are underrated and that sign accidents are overrated in the MDAI file, the bridge abutment or pier data and pole and tree data correspond reasonably well, and the sources agree on one point that

Table 1. Vehicles, occupants, injuries, and fatalities by accident mode.

			Vehicle Accidents		
Accident Mode	Vehicles	Vehicle Occupants	Injuries (1)	Fatalities	Total
All accidents (2)	29,300,000	42,400,000	2,000,000	44,100	2,044,100
Fixed-object	2,210,000	3,310,000	389,000	16,200	405,200
Frontal	1,610,000	2,410,000	303,000	10,100	313,100
Narrow (3)	350,000	520,000	168,000	3,600	171,600
Wide (4)	1,260,000	1,890,000	135,000	6,500	141,500
Side	520,000	780,000	73,000	5,400	78,400
Narrow	160,000	240,000	29,000	3,400	32,400
Wide	360,000	540,000	44,000	2,000	46,000
Rear	80,000	120,000	13,000	700	13,700
Primary rollover (5)	310,000	460,000	75,000	3,800	78,800
Vehicle-to-vehicle	26,780,000	40,170,000	1,536,000	24,100	1,560,100
Frontal	13,050,000	19,570,000	841,000	11,500	852,500
Head-on	2,020,000	3,030,000	249,000	7,300	256,300
Front-to-side	5,520,000	8,280,000	379,000	2,600	381,600
Front-to-rear	5,510,000	8,260,000	213,000	1,600	214,600
Side	7,570,000	11,350,000	430,000	10,500	440,500
Side-to-front	4,910,000	7,360,000	372,000	10,000	382,000
Sideswipe	2,660,000	3,990,000	58,000	500	58,500
Rear	6,160,000	9,240,000	265,000	2,100	267,100

Table 2. Distribution of casualties and societal cost by crash mode.

Crash Mode	Casualties	Societal Cost[a]	Crash Mode	Casualties	Societal Cost[a]
Narrow frontal fixed-object	171,600	3.4	Vehicle-to-vehicle front-to-side	381,600	2.1
Narrow side fixed-object	32,400	2.0	Vehicle-to-vehicle front-to-rear	214,600	2.7
Wide frontal fixed-object	141,500	4.6	Vehicle-to-vehicle side-to-front	382,000	5.7
Wide side fixed-object	46,000	2.7	Sideswipe	58,500	0.3
Rear fixed-object	13,700	0.1	Vehicle-to-vehicle rear	267,100	1.5
Primary rollover	78,800	3.0	Total	2,044,100	34.2
Vehicle-to-vehicle head-on	256,300	6.1			

[a]In billions of dollars.

Figure 1. Societal cost by clock position of principal force.

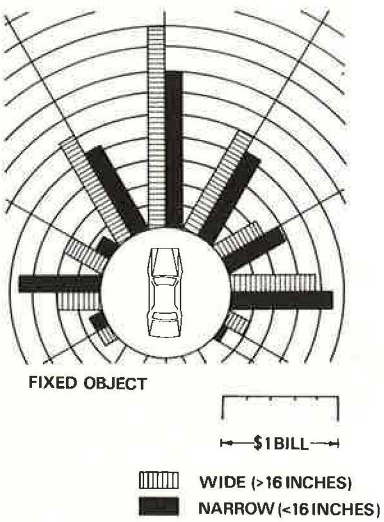


Figure 2. Distribution of casualties by velocity range.

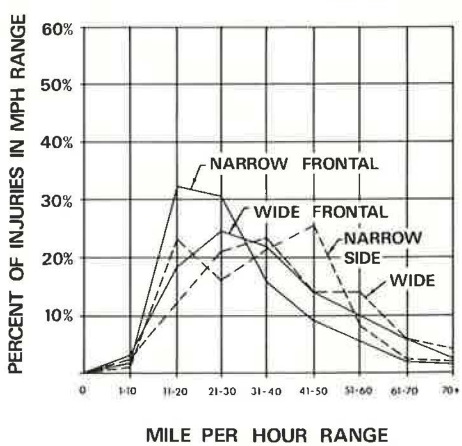


Figure 3. Cumulative distribution of collisions in fixed-object injuries.

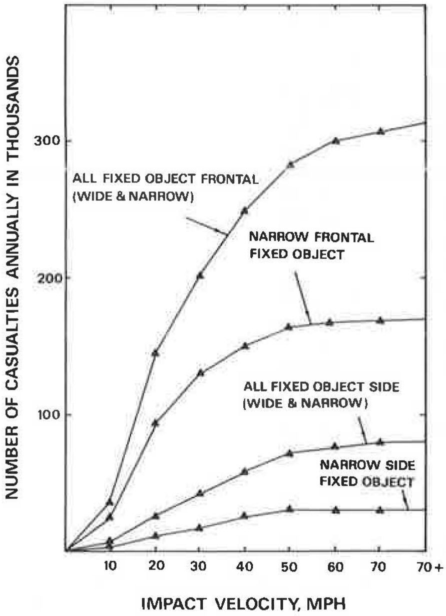


Figure 4. Frontal fixed-object average cost per injury.

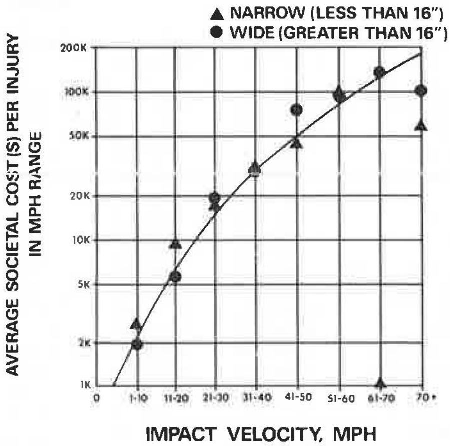


Figure 5. Cumulative societal cost of injuries in fixed collisions.

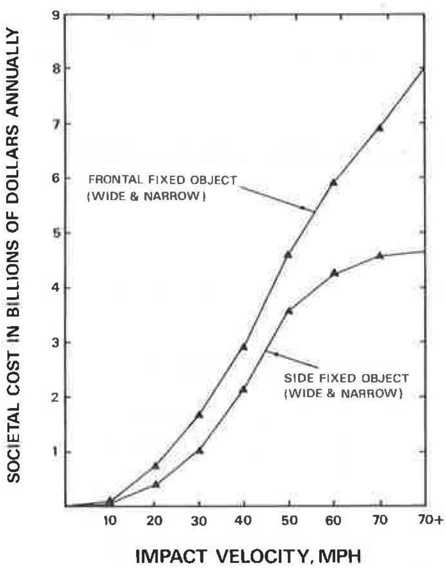
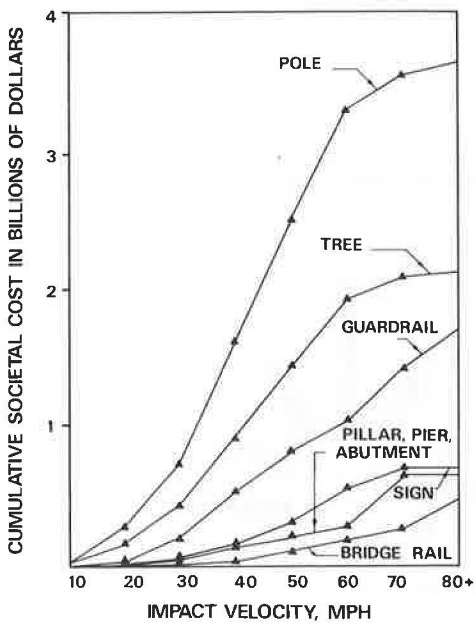


Figure 6. Societal cost as function of impact-speed, fixed-object crashes.



poles and trees are causing more than five times the losses caused by bridge structures and signs, the traditional sites for HCADs.

Figure 6 shows the task of the attenuator designer in the current accident picture, assuming widespread deployment of HCADs. It also shows that attenuator installations, in the traditional application, can only be a partial solution, unless each tree, pole, and sign is to be equipped. This is not to say that attenuator systems are ineffective; rather that abutments, piers, and pillars constitute only a modest part of the overall fixed-object problem.

Other factors must be considered before the HCAD program can be optimized. More important than any technical consideration in the current frame of reference is implementation. With fewer than 5,000 HCADs installed since 1967, there is much more to be done. In 1971, a total of 187,000 injuries were caused by wide fixed-object impacts, and for each object struck in a given year, there are probably several other fixed objects being narrowly missed. Attenuator implementation has so far reached less than 5 percent of the hazards. If implementation is to continue with priority given to those hazards having fatality experience, the designer should choose a high-speed system. If, on the other hand, an optimum benefit-cost ratio is sought, more hazards should be protected with lower speed attenuator designs; this means trading some losses in high-speed crashes for broader gains in obstacles protected. Although economic limitations may preclude installation of more than 30,000 attenuators of current design, development of ultracheap devices may expand candidate sites to as many as 1 million.

Other factors must be considered that are related to the vehicle system likely to be in use when attenuators now in design stages can finally be implemented (1). Events that have transpired during the past year suggest a high probability that widespread restraint use is likely to become a reality by 1980 (10, 11) and that vehicles having built-in frontal crashworthiness of >40-mph (>64-km/h) barrier equivalent velocity (BEV) will likely be available on showroom floors shortly thereafter (10, 12). These potentialities must be considered in a proper attenuator design. Widespread restraint use by itself can allow the reduction of attenuator size and cost by 50 percent or more since allowable vehicle forces can be doubled without increased probability of serious injury (13). Improvements in vehicle crashworthiness will further the trend toward greater numbers of smaller, cheaper attenuators and may preclude altogether the need for installations at some sites. A notable achievement in this vein is that of a modified subcompact structure and restraint system capable of >40-mph (>64-km/h) BEV frontal and improved side, rollover, and pedestrian crashworthiness, all at the expense of less than 100 lb (45 kg) of additional weight and $200 per car additional cost in a Pinto-sized vehicle (14).

SOME PROJECTIONS: THE 1985 ATTENUATOR CUSTOMER

Recent projections for 1985 suggested a total population of 150 million vehicles, 40 percent subcompacts, and improved crashworthiness for all passenger cars (1). The recent energy situation has significantly hastened the trend to small cars. By the end of 1973, 38.5 percent of all registered U.S. automobiles weighed less than 3,400 lb (1524 kg). The 1971-1973 U.S. new-car sales in the under 2,800-lb (1270-kg) class were estimated to be 25.6 percent (15). Today, with the benefit of some other opinions, more reasonable projections for the year 1985 are as follows (15, 16):

1. There will be 140 million vehicles, of which 125 million will be passenger cars;
2. Accidents will increase 25 percent over present levels;
3. Subcompact and smaller cars [<2,200 lb (<998 kg)] will represent 60 percent of new cars sold and 50 percent of all passenger miles (kilometers) accumulated; and
4. Improved construction in terms of restraints (passive and active use) and structures will bring the average car to a crashworthiness level exceeding proposed 1976 requirements [e.g., 30-mph (48-km/h) BEV frontal crashworthiness].

New standard, intermediate, and compact cars [>3,000 lb (>1361 kg)] marketed in

1985 will likely reflect some structural changes to achieve not only fixed-object impact survival but also compatibility in car-to-car crashes with likely collision partners, many of which will be less massive. Subcompacts and smaller cars [<2,000 lb (<907 kg)] on the other hand will require significant [but technically and economically feasible (14)] restructuring, in both the occupant compartment and the chassis frame.

The effect of these vehicular changes is estimated in Figure 7 for frontal crash casualties. If proposed U.S. DOT crashworthiness standards are implemented, over 30 percent of fatalities and well over half of nonfatal injuries could be avoided without any change to the highway environment.

FUTURE VEHICLE CHARACTERISTICS

One must use the best possible prediction of future vehicle performance as a basis for HCAD design. One such design specification was developed to meet a vehicle crush force of about 80,000 lbf (356 000 N) (1). It now appears, based on analysis of the accident casualty loss studies referred to above, that slightly lower vehicle crush forces can be tolerated. This is based primarily on the fact that offset, angular collisions among vehicles make up most of accident losses and that frontal structures that optimize flat barrier crash performance are probably less cost effective than those that optimize car-to-car performance. As a result of a car-to-car compatibility study, a modified subcompact car has been constructed that is theoretically safe and that has an advanced airbag restraint at the closing speeds in car-to-car collisions as shown in Figure 8 (17). This result suggests that present standard-sized [3,500 to 4,000-lb (1588 to 1914-kg)] cars have about the right frontal crash characteristics as they are and require relatively minor structural adjustments to smooth out peaks and valleys of crush force to give an average frontal structure force of about 80,000 lbf (356 000 N). It also suggests that the subcompact car frontal crash pulse will not exceed 85,000 lbf (378 100 N) in a barrier crash. Hence, attenuators should be designed to have a crush force not to exceed, say, 75,000 lbf (334 000 N) and could very well yield the same general pulseform as the standard-car frontal structure.

PHYSICAL CHARACTERISTICS OF 1985 ATTENUATORS

The built-in crashworthiness of the average 1985 passenger car suggests two physical characteristics for attenuators of that vintage. First, the total energy absorption capacity can be less since vehicles will be designed to absorb their own 30 to 40-mph (48 to 64-km/h) crash energy unaided. Second, the force levels can be higher since vehicle structure will probably be sized for over 75,000-lbf (334 000-N) average crush force. Both of these effects work to the advantage of attenuator implementation. The 1985 attenuators can be shorter and much less expensive.

Figure 9 shows the theoretical stroke requirement for 75-kip (333 600-N) attenuators compatible with the projected 1985 passenger vehicle population. Note that an attenuator stroke of 8 ft (2.4 m) will provide adequate distance for a safe frontal crash stop of any 1980+ passenger car from a speed as high as 70 mph (113 km/h) and would safely stop a 30-mph (48-km/h) BEV crashworthy truck [6,000 lb (2722 kg)] from a speed of more than 60 mph (97 km/h). Assuming a stroke efficiency of 80 percent (typical of current HCADs), the total length can be less than 10 ft (3 m). Problems of site preparation and attenuator sophistication requirements would be greatly reduced because attenuator buckling tendencies would be eliminated. It is likely that the 1985 attenuator can be much smaller, much cheaper, and much more broadly implemented than is possible with the present designs, primarily because of improvements in restraints used and vehicle performance.

Table 3. Percentage of injuries, fatalities, and costs by object struck.

Object Struck	Pennsylvania[a] (9) Injuries	Pennsylvania[a] (9) Fatalities	MDAI File (5) Injuries	MDAI File (5) Societal Cost
Wide				
Guardrail	15.8	16.0	10.2	11.8
Bridgerail	5.4	8.3	4.2	3.5
Ditch	10.6	10.9	5.9	4.2
Tree	15.6	21.5	48.1[b]	39.3[b]
Pier, pillar, abutment	3.1	3.9	2.7	4.4
Other[c]	21.3	17.0	24.5	31.9
Narrow				
Sign	1.2	1.1	4.4	4.8
Pole	26.9	21.0	48.1[b]	39.3[b]

[a]Paths 66, 67, 69, and 71. [b]Pole and tree data are lumped together. [c]For example, a parked car.

Figure 7. Estimated effectiveness of announced U.S. DOT passenger car occupant protection standards in frontal impacts versus time.

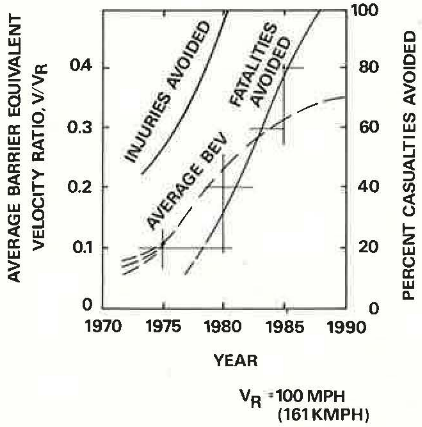


Figure 8. Estimated maximum head-on crash velocity for occupant survival in 1985 subcompact versus other mass cars.

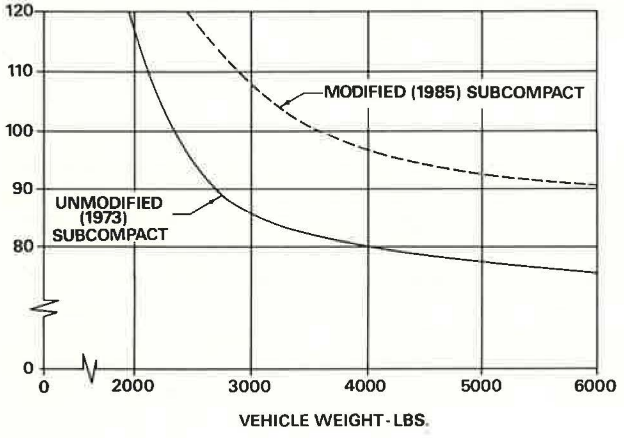


Figure 9. Fixed-force head crash attenuator device stroke versus impact velocity.

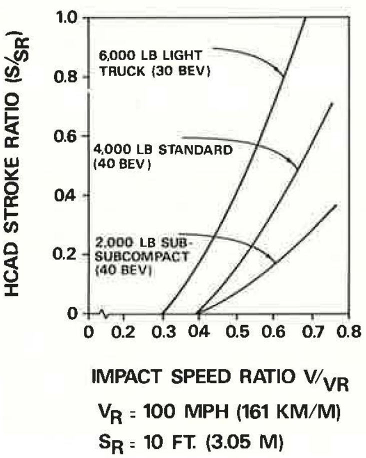


Table 4. Estimated annual societal loss costs of large sign, abutment, pillar, and pier impacts.

Loss	Societal Cost	1985 Level[a]	1985 Cost Base[a]	1985 Societal Benefit[b]	1985 HCAD[c]
Fatalities	200,000	1,450	290,000,000	58,000,000	39,000,000
Injuries	6,000	35,000	210,000,000	54,000,000	94,000,000
Total	—	36,450	500,000,000	112,000,000	133,000,000

Note: All costs and benefits are in 1971 dollars.

[a]Assumes no change in design past 1971, 25 percent increase in accidents.
[b]Of preventives, 1985 car.
[c]60 percent effective, full implementation.

ECONOMICS OF 1985 ATTENUATORS

From Tables 1 and 2, one can estimate that the total 1971 societal cost due to pillar, pier, and abutment impacts is about $555 million, or almost 4.4 percent of the total $12.7 billion loss in all fixed-object impacts. This should be added to some amount due to sign impacts so that large signpost crashes can be accounted for. This will be arbitrarily taken as half the total sign casualty cost or roughly $304 million. Hence, a reasonable total societal loss that may be moderated by the HCAD is roughly $850 million annually. [This is markedly lower than the crude estimate suggested by Warner (1)]. The dominance of pole and tree impacts, not capable of economical treatment by highway crash attenuators, is noteworthy. The rather distinct concentration of pillar, pole, and abutment casualties in the 50 to 60-mph (80 to 97-km/h) range is also striking. This may be an artifact of the rather small MDAI sample, but if true, it suggests that current HCAD designs [>60 mph (>97 km/h)] are about right for current automobiles and conditions; anything less would result in an abrupt decrease in benefit of those highway crash attenuator devices that are struck. On the other hand, if the cumulative benefits actually are better represented by the distribution labeled sign in Figure 6, a higher benefit-cost ratio may be achieved by reducing the full-stop velocity requirement to something like 50 mph (80 km/h). [Another reason for such reduction may be found if the national speed limit is set at 55 mph (88.5 km/h).]

Table 4 gives an estimate of the saving potential of a 60 percent efficient attenuator deployment—a societal benefit of $528 million/year.

If this benefit is to be fully accrued, the majority of pier, pillar, abutment, and large sign sites will need attenuators. If only 30,000 sites are involved, an average of $17,500/year may be expended to break even. If, on the other hand, 1 million sites are involved, any cost greater than $523/site/year represents a loss. Clearly, a more accurate idea about the number of appropriate sites is essential to valid economic forcasting of the benefit to be accrued.

There are those who claim that further safety expenditure is unwarranted in an inflationary economy; this is simply not true. Inflationary pressure is simply much stronger on labor-intensive health care, legal, and funeral costs than it is on manufactured goods (18). Highway safety, including HCADs, if properly engineered, can therefore become a better investment than it ever has been (19).

CONCLUSION

Crashworthiness compatibility between forthcoming passenger vehicles and the highway environment deserves some careful scrutiny in the immediate future. This paper shows the need for further, more detailed economic and engineering analysis. Its rough projections suggest that the HCAD of 1985, like the automobiles that will strike it, should be smaller, stiffer, and more cost effective than the current models. The techniques and analysis used in this paper can be applied in greater breadth and detail as a more quantitative and qualitative real accident data base develops. A broader and more effective implementation of cost-effective HCADs should be planned so that the economic and technical features of future attenuators are in harmony with the needs and features of future vehicles and highways.

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