69-07-N09-119

# AFFIDAVIT OF ROBERT B. MACLEAN

I am Robert B. MacLean of 314 S. Berkley, Dearborn, Michigan. On August 4, 1971, I made an affidavit concerning the preparation under my supervision of a study estimating the effectiveness of various, alternative restraint systems for occupants of passenger cars. In that affidavit I stated that detailed materials supporting the principal assumptions and general methodology of that study were then under preparation.

The attached report, entitled "Restraint System Effectiveness," constitutes those materials. A few comments on its contents are in order. First, the estimates of lives saved shown in Figures 27 and 28 differ slightly from the estimates set forth in our earlier report because it was determined in the course of preparing this report that our treatment of the multiple impact accident placed too large a portion of the fatalities in the first impact.

Second, it should be understood that calculation of these estimates was based on test and design data derived from experimental designs pre-dating the computations, which were completed in July, 1971. Thus the head and chest decelerations assumed to be experienced by adult-sized occupants were derived from test data or air bag system designs current in the period January through March, 1971, rather than the later designs that have been developed to reduce the loads imposed on standing children by deployment of the air bag. Test results show that a consequence of this redesign of the air bag system has been to increase the decelerations experienced by adult-sized occupants. Accordingly, the estimates of lives saved by air bag systems tend to overstate the effectiveness of such systems as they are now designed.

The attached report was prepared under my supervision, and I believe that it fairly and accurately reflects the basis for the estimates set forth in the report attached to my affidavit of August 4, 1971.

Robert B. MacLean
Robert B. MacLean.

National [illegible]
DOCKETS
SEP

Subscribed and sworn to before me
this 21 day of September, 1971.

Notary Public - WAYNE COUNTY
STATE OF MICHIGAN.

1-9-67-009-119

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# RESTRAINT SYSTEM EFFECTIVENESS

by

Ernest S. Grush, Sherman E. Henson, and Orville R. Ritterling

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# INTRODUCTION

The general objective of the study reported here was a comprehensive assessment of the injury-reducing potential of various automobile occupant safety restraint systems, including both existing and proposed systems, some of which require occupant participation (active systems), some of which do not (passive systems), and some systems with both active and passive elements. An analysis of different systems employing the same benefit criterion and the same basic assumptions should enhance confidence in the comparative, if not the absolute, nature of conclusions about the effectiveness of the systems.

This report contains a main body discussing the model used in generating the results along with the results themselves. In addition, a number of technical appendices are included which describe in detail the underlying assumptions and computational procedures by which certain of the model parameters were developed. Each appendix is referenced in the main text at the time the relevant technique described in the appendix is discussed. Thus, if the main text is read by itself and the appendices disregarded, the findings of the study and the general outline of the method used will be revealed. On the other hand, some readers with in-depth interest will want to review each appendix as it is referenced in the main text.

## Restraint Systems Studied

Fifteen restraint systems were studied. The driver in each system was assumed to have protection from a third-generation, energy-absorbing (E/A) steering column. A more complete description of the characteristics of this E/A column and the restraint systems studied will be found in later sections of this report. The 15 systems categorized by the restraint available to occupants in each seated position of the automobile, are listed below.

1. Lap Belts Only: 6 lap belts, one for each seated position.
2. Present Harness Configuration, Current Webbing: 6 lap belts plus shoulder belts for driver and right-front passenger.
3. Present Harness Configuration, Constant-Force Webbing.
4. Front-Seat Air Bag System: Air bags for center and right-front passengers, 3 lap belts in rear seat.
5. Front-Seat Air Bag System With Lap Belts: Air bags for center and right-front passengers plus 6 lap belts.
6. Front and Rear-Seat Air Bag System: 5 air bags for all occupants but driver.
7. Front and Rear-Seat Air Bag System With Lap Belts: 5 air bags plus 6 lap belts.

8. High-Impact Panel: Impact resistant instrument panel for center and right-front passengers, 3 lap belts in rear seat.

9. High-Impact Panel With Lap Belts: Impact resistant panel for center and right-front passengers plus 6 lap belts.

10. High-Impact Panel Front and Rear Seat: Impact resistant panel for all occupants but driver.

11. High-Impact Panel Front and Rear Seat With Lap Belts: Impact resistant panel for all occupants but driver plus 6 lap belts.

12. Harness System For All Occupants But Driver, Current Webbing.

13. Harness System For All Occupants But Driver, Constant-Force Webbing.

14. Harness System For All Occupants, Current Webbing.

15. Harness System For All Occupants, Constant-Force Webbing.

## Selection Of The Benefit Criterion

The benefit criterion used in this study was the number of motor vehicle fatalities among unrestrained occupants which would be avoided through use of a safety restraint system. Although a number of additional criteria incorporating economic considerations and casualties other than fatalities could have been included, this analysis was made strictly in terms of lives saved, for the following reasons:

- The jump from fatalities to injuries and/or to dollar-loss as a criterion would be a large one. Analysis in terms of fatalities alone is complex and difficult; consideration of other criteria not only would increase the intricacy manyfold but, at the same time, would decrease enormously the validity of the necessary assumptions. This introduction of more-questionable assumptions, while expanding the scope of analysis, would reduce considerably the confidence with which the conclusions can be treated.

- Among other advantages of considering only lives saved is the unambiguity of fatality—an occupant is either dead or not dead. The same finality cannot be associated with non-fatal injuries. No universally accepted scale of injury severity has yet been developed. Attempting to rank different injuries on some scale of trauma involves either the adoption of an existing, questionable scale of injury, or the construction of a new scale. Developing injury-rating schemes is beyond the scope of this study. The problem is further confounded by the necessity of including fatality on the injury scale. The use of economic loss as a criterion involves establishing a dollar value for a life, among other necessary procedures; such analysis is, again, beyond the scope of this study.

- The higher reliability of fatality data provides additional justification for its use alone. Essentially all the motor vehicle fatalities which occur are counted; fatality is not a condition which can be faked or not reported for insurance reasons. The seriousness of the consequences of a fatal accident also enhances the likelihood that the accident investigator will be conscientious in collecting the relevant pieces of information about the accident.

## Cautions In Interpreting Results

No attempt should be made to determine the benefit of a combination of restraint systems by summing benefits computed separately for each system. The population of lives saved by each system may overlap; in this case, summing the separate benefits constitutes eliminating a fatality more than once. In other situations the combination of systems may interact to produce benefits exceeding the sum of the benefits for each system considered alone. For example, the benefit of diagonal harnesses alone would be minimal, but when combined with a lap belt, the resulting system becomes extremely beneficial.

## GENERAL DESCRIPTION OF METHOD OF THIS STUDY

The two major tasks in this study were, first, to develop a common method of assigning an effectiveness value to any automobile-occupant restraint system and, second, to compare one restraint system with another on the basis of number of occupant lives saved by applying this effectiveness value to fatal accident data.

The first task was accomplished by using mathematical models. Of necessity, the approach requires the formulation of a number of assumptions. However, each assumption is carefully formulated so as to have obvious boundaries and is reviewed completely in terms of the implications that assumption holds for the results of the study. Wherever any assumption tends to favor one restraint system over another, this fact and the reasons for it are pointed out.

Even though this approach to determining restraint effectiveness is limited principally to single-impact, frontal type collisions, its development is significant and will be fully explained in the next section of this report, which also deals with single-impact fatalities. The single-impact, frontal collision is by far the greatest producer of automobile occupant fatalities, and the approach developed provides an organized, methodical way of assigning the effectiveness of a restraint in preventing impact fatalities.

The second major task was an analysis of accident data to determine the relative frequency with which the various kinds of fatal accidents occur.

Two major sources of accident data were used. Total accident fatality data were drawn from the report of the National Safety Council for 1969, the latest year for which a report has been published. Distribution of fatalities by type of accident was developed using data provided by the Automotive Crash Injury Research activity of the Cornell Aeronautical Laboratory. After an effectiveness value was calculated for each restraint system studied, it was applied to each type of fatality-producing accident at the frequency with which each occurred, thus indicating lives saved in that type of accident. Adding lives saved in each type of accident showed total life savings for each restraint.

## METHOD OF CALCULATING EFFECTIVENESS VALUES

The general approach taken in this study is outlined below; details of the method will be found in appropriate sections of this report.

For each restraint listed above, mathematical modeling of the occupant-restraint-vehicle system established potential head and chest decelerations of the occupants in a number of narrowly categorized crash situations. Human tolerance formulations were used to convert these decelerations into effectiveness values for each crash situation studied. These effectiveness values, which reflect the ability of a restraint to save lives in each given crash situation, were then applied to accident data showing the relative frequency of fatalities occurring in each such situation. This gave the number of these fatalities which would not have occurred had the restraint system been used. Summing the results for all situations leads to an overall estimate of lives saved by each restraint; this technique thus provides a direct comparison of the life-saving potential of each of the 15 occupant restraint systems studied.

The Computer Simulation of the Automobile Crash Victim (1), developed at the Cornell Aeronautical Laboratory, was used for all simulations except the air bag. Since the Cornell model does not presently include an air bag simulation, another model developed especially for air bag simulation was used. Ranges of occupant sizes and crash situations were used as inputs to both models.

### Human Tolerance

Effectiveness values calculated in this study, as indicated above, reflect the ability of a restraint to save lives. As the severity of an impact increases, the probability of surviving that impact decreases. The more effective restraints will attenuate impact severity to a greater degree than the less effective ones. The measures of impact severity used in this study were peak head and chest deceleration. The relationship of these measures to probability of survival is shown in Figure 1.* For example, the probability (in percent) of surviving an accident in which the measured peak head and chest decelerations are 140 and 65 g's, respectively, would be obtained from Figure 1; the lower of the two probabilities, 32 in this case, is the effectiveness value. The derivation of Figure 1 is explained in detail in Appendix A.

### Cornell Occupant Simulation

In motor vehicle crash simulation, an eleven-degree-of-freedom planar model of an occupant and a vehicle interior during a frontal collision, developed by the Cornell Aeronautical Laboratory, provides the highest degree of realism attainable at this time. A schematic of the model is shown in Figure 2.

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*Figure 1 is on the next page. All Figures are included within the text, near the point of first reference.

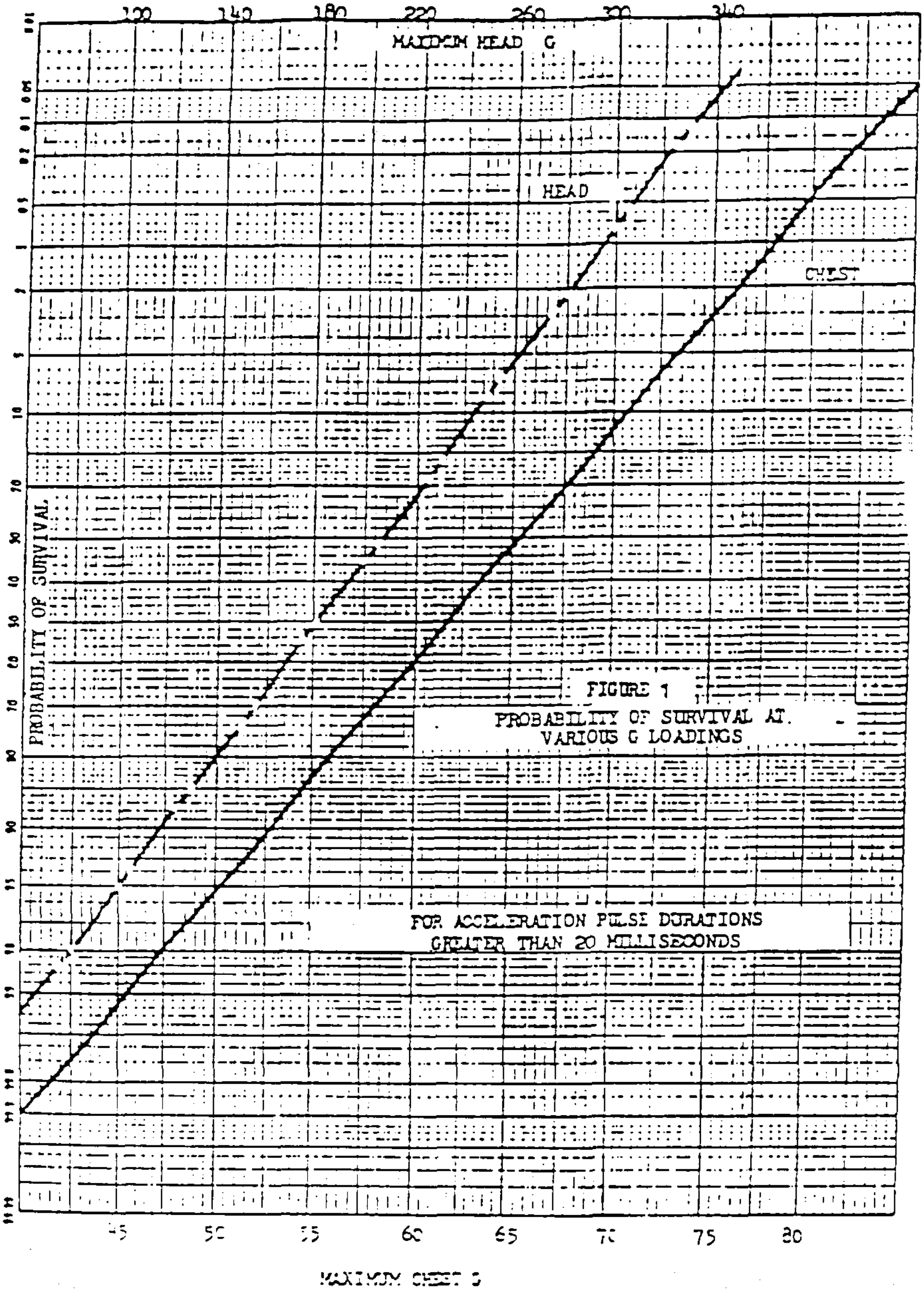
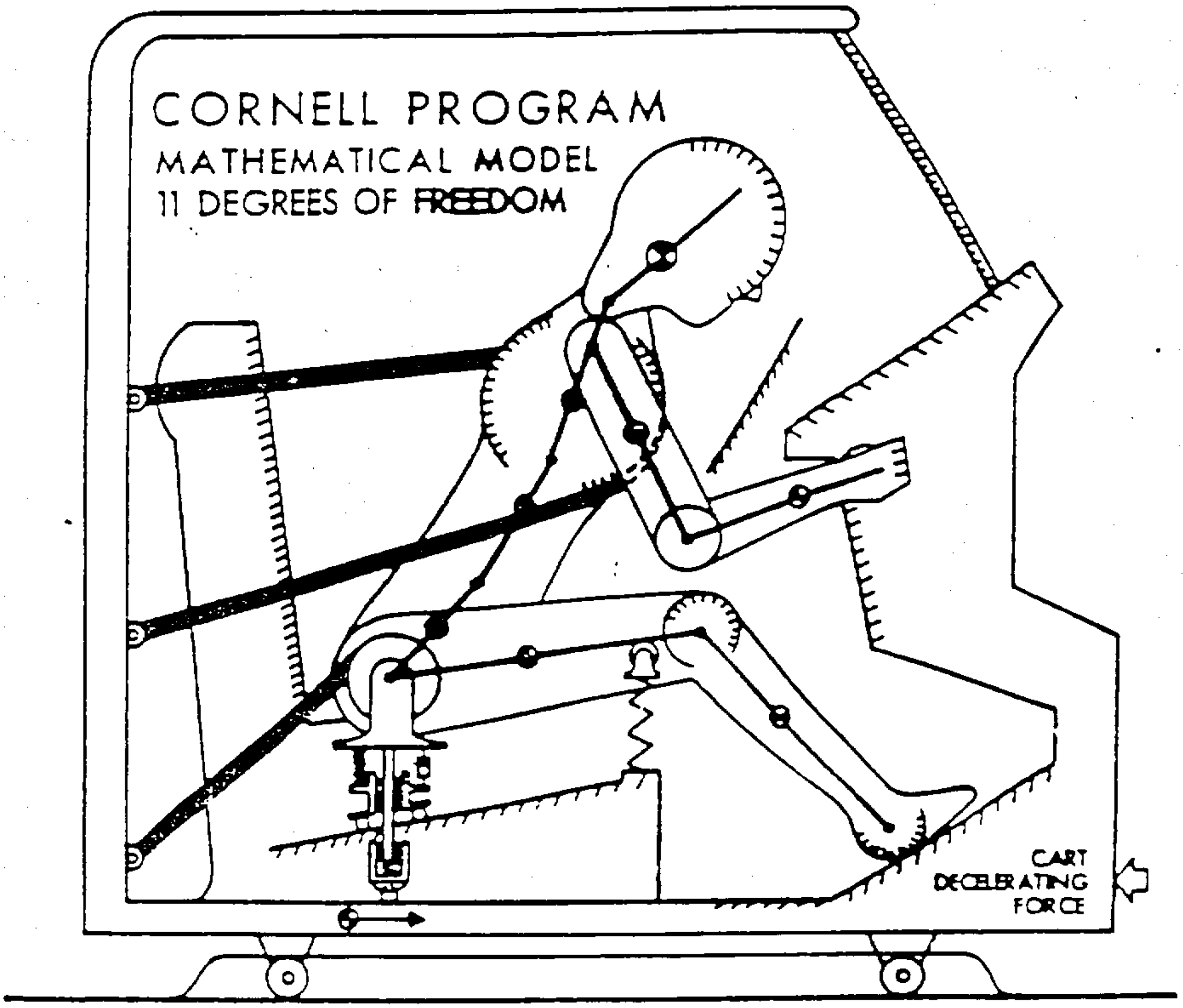


FIGURE 1
PROBABILITY OF SURVIVAL AT
VARIOUS G LOADINGS

FOR ACCELERATION PULSE DURATIONS
GREATER THAN 20 MILLISECONDS

FIGURE 2


CORNELL PROGRAM
MATHEMATICAL MODEL
11 DEGREES OF FREEDOM
CART
DECELERATING
FORCE

The model of the human body consists of an articulate assembly of eight rigid mass segments whose dimensions and inertia properties are sufficient to provide characteristic motion of the torso and extremities.

These rigid segments are connected by pin joints which incorporate adjustable friction, motion-limiting stops and elasticity.

The lap belt is assumed to remain tangent to a circle with center at the hip pivot and is rigidly anchored in 2-dimensional space.

The shoulder restraint consists of an upper torso strap which is assumed to pass through the shoulder pivot, and a lower strap whose intersection with the torso centerline remains fixed. The material characteristics of the restraint system are simulated by 5th order polynomials of displacement and velocity.

The seat cushion is represented by two separate vertical forces. The primary force is a non-linear function of vertical cushion deflection, assumed to act through the hip. The secondary force is a linear function of vertical deflection of the front edge of the seat cushion.

The belt, seat, and contact forces which act on the occupant are calculated from the relative displacements and velocities within the model system during the stepwise numerical intergration of the equation of motion. The dynamic characteristics of the seat and contact surfaces are represented by 5th order polynomials of displacement and velocity. The position and direction of the contact forces are made determinant by approximating the contact surfaces of the torso with circular arcs and representing the interior surfaces of the vehicle with plane surfaces.

The independent or input parameters to the Cornell Program detail the shape and material characteristics of physical components and subsystems such that the math model performs as a real-world event. These independent parameters, of which there are some 350, define:

- The Occupant -- which includes the dimensions and inertial properties of the articulated body segments, body joint characteristics and body initial conditions.
- The Vehicle -- which includes a special description of the vehicle interior relative to the time-zero position of the occupant's hip point and the vehicle initial conditions.
- The Material Characteristics — which define the load-deflection properties of the restraint system and of the vehicle interior contact surfaces.
- The Excitation Force -- which is the time-variant vehicle deceleration.

The dependent or output parameters of the Cornell Program define the response of the Cornell math model for a particular set of independent parameters. The simulated response includes the following:

- Occupant Kinematics — the time-variant position of the occupant and the acceleration of specific points on the articulated body such as the head, chest and hip.
- Contact Forces — the deflection and the velocity of deflection for the contact surfaces and the force of contact between the occupant and the vehicle interior.
- Belt Response — the elongation and the rate of elongation of the restraint system and the belt forces.

The responses of primary importance in this study were head and chest decelerations. The load-deflection properties of various restraint systems and the pertinent interior geometry contact surface locations are the variables affecting occupant response.

### Occupant And Vehicle Package Assumptions

Small, medium and large occupants were simulated, corresponding to the 5th percentile female, 50th percentile male, and 95th percentile male. It was assumed that small occupants would have the front seat full-forward and large occupants full-rearward. A mid-H-point position of the front seat was assumed for the medium occupant and for all rear-seat occupants.

The interior geometry selected for this study was that of the 1973 Ford car. Vehicle deceleration-time characteristics were approximated by the curves shown in Figure 3 for 20, 30, 40 and 50 mph fixed barrier crashes.

### Occupant Restraint Descriptions

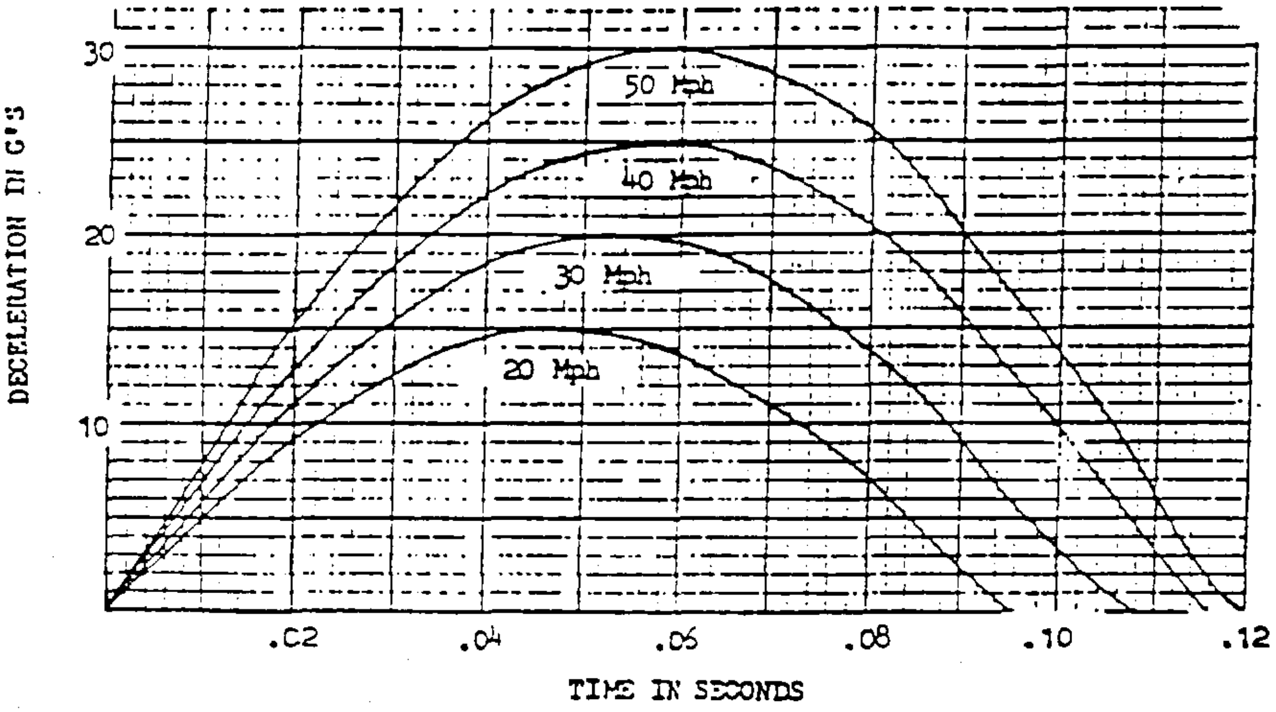
A review of the 15 occupant restraint systems (combinations of restraint components) included in the study shows that 7 basic restraints were evaluated. Each of these restraints is discussed separately, as follows:

#### 1. Third Generation Energy-Absorbing Steering Column

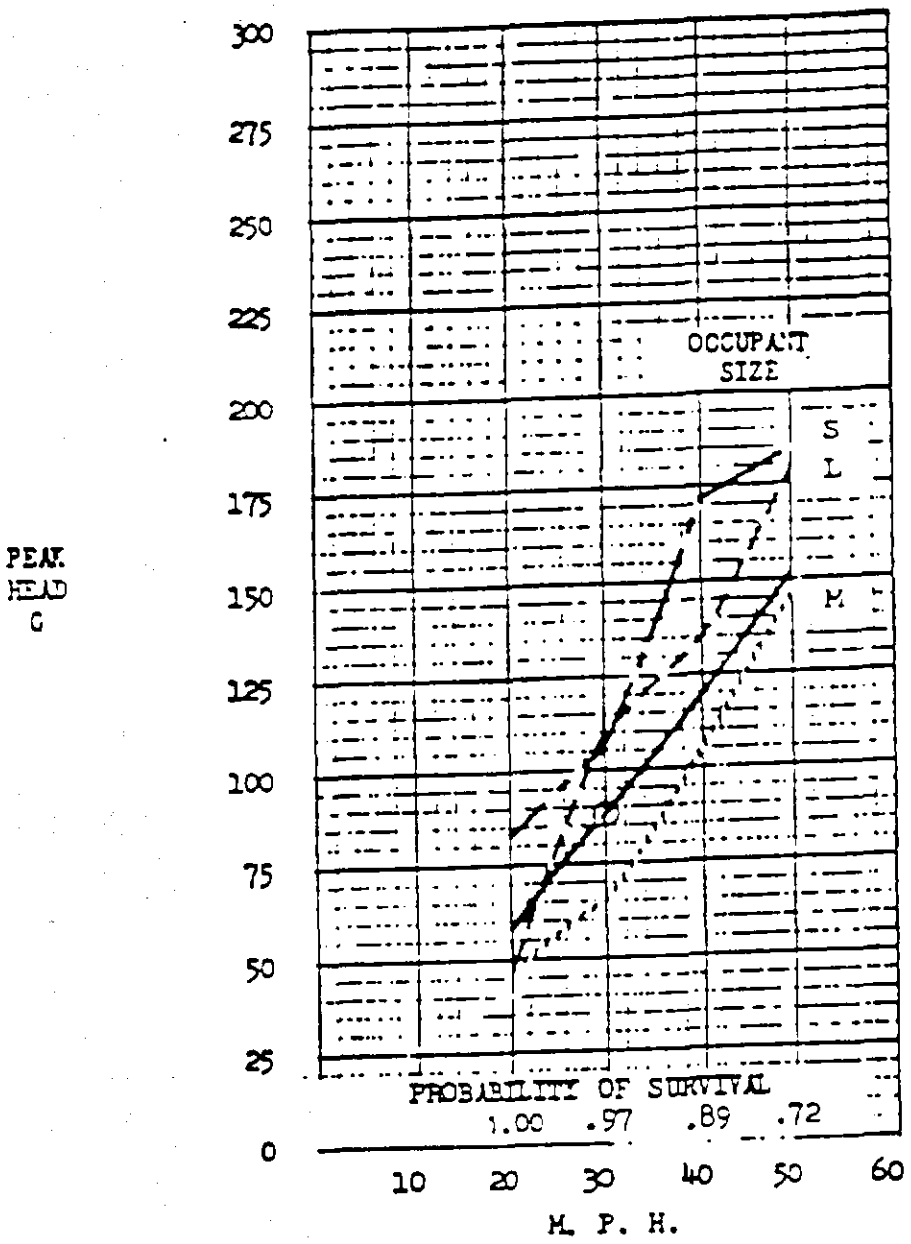
This is an advanced-design steering column system being developed to provide a higher level of safety than the current system, which has been effective in reducing fatalities and injuries. The force-deflection characteristics of the third generation column were obtained from impact tests. The curve was approximated by a polynomial because input to the Cornell mathematical model requires a polynomial of the fifth or lower order. This technique was used for all restraints evaluated with the Cornell model. The peak head and chest decelerations resulting from application of the model, for the three occupant sizes, are shown as a function of barrier impact speed in Figure 4. The solid line in this and the succeeding figures represents the value used to

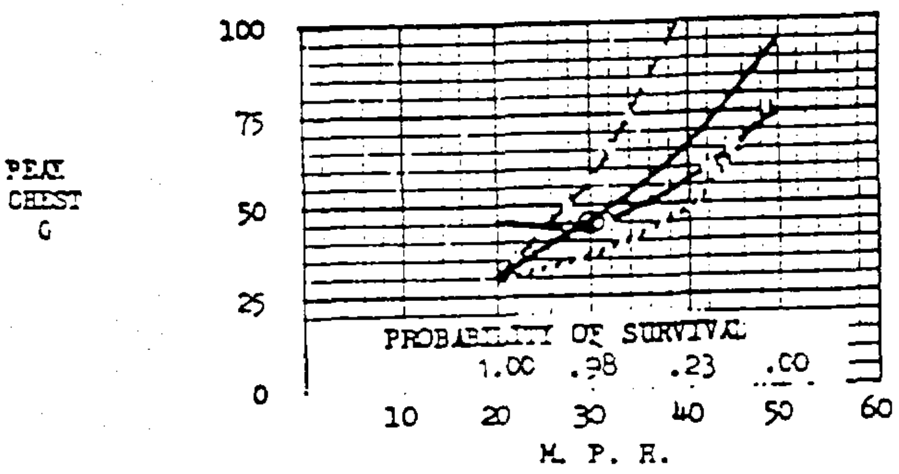
FIGURE 3

VEHICLE DECELERATION-TIME CHARACTERISTICS



## RESTRAINT 1: THIRD GENERATION E/A COLUMN





estimate overall probability of survival at 20, 30, 40, and 50 mph, utilizing the tolerance curves of Figure 1. In Figure 4 and subsequent figures, a circle represents the mean of test data and S, M, and L represent the curves for small, medium, and large occupants, respectively. The minimum probability at each speed is indicated on Figure 4, and it is used to obtain a speed-probability matrix that describes the overall effectiveness of the restraint in a 12 o'clock impact.

Because approximately 30 percent of vehicles on the road in 1969 were equipped with an E/A steering column, the effectiveness of the 3rd generation column was modified by the following technique:

$$E = .7 \times E_{3G} + .3 \times I$$

where $E_{3G}$ = unmodified effectiveness of new system

$I$ = improvement in effectiveness over current E/A column.

The calculation is shown in the following Table:

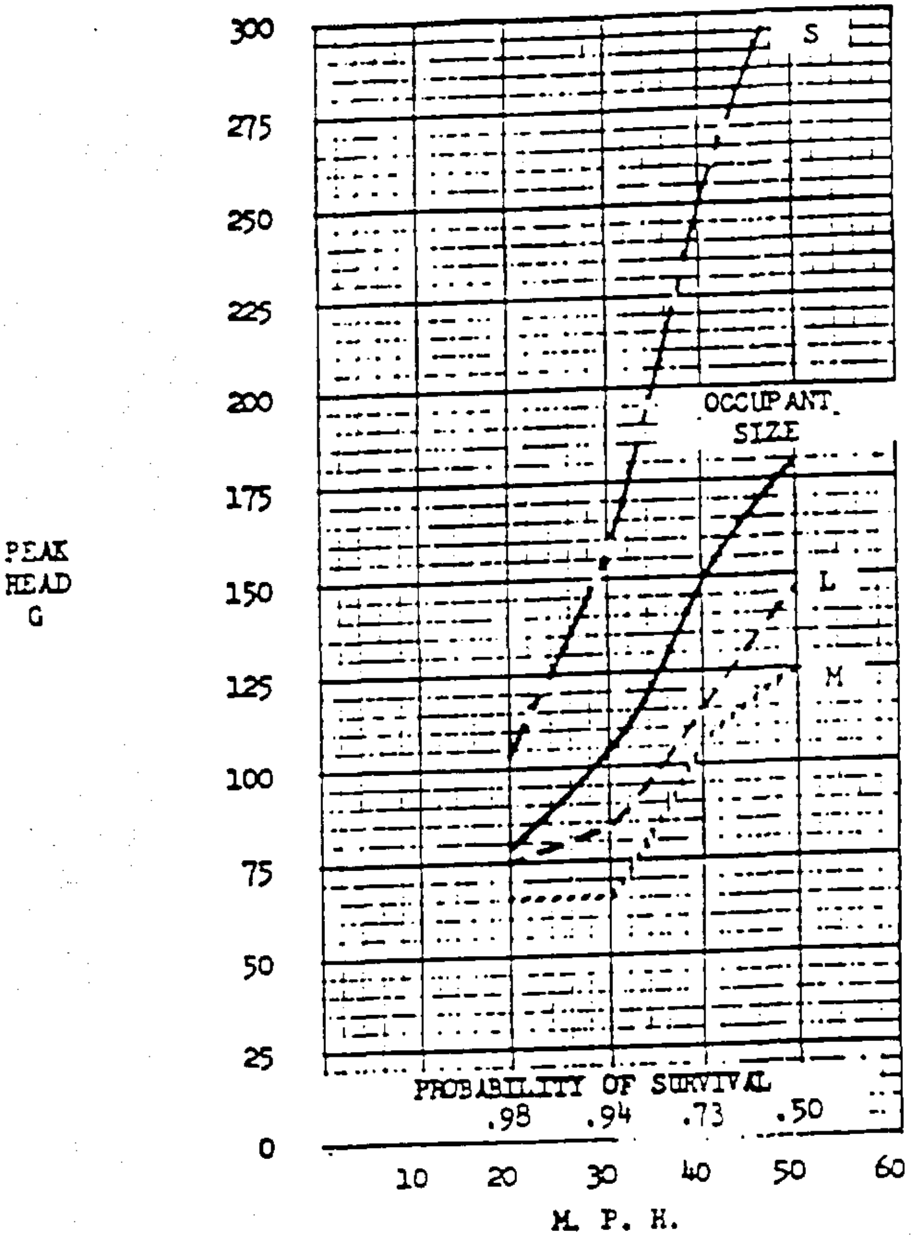
| Barrier-Equivalent Speed, MPH | Effectiveness,% | | Improvement I | .3 x I | .7 x $E_{3G}$ | Modified E |
|---|---|---|---|---|---|---|
| | $E_{3G}$ | $E_{current}$ | | | | |
| 0-15 | 100 | 93 | 7 | 2 | 70 | 72 |
| 16-25 | 100 | 70 | 30 | 9 | 70 | 79 |
| 26-35 | 97 | 45 | 52 | 15 | 68 | 83 |
| 36-45 | 23 | 10 | 13 | 4 | 16 | 20 |
| 46-55 | 0 | 0 | 0 | 0 | 0 | 0 |
| 56 & Up | 0 | 0 | 0 | 0 | 0 | 0 |

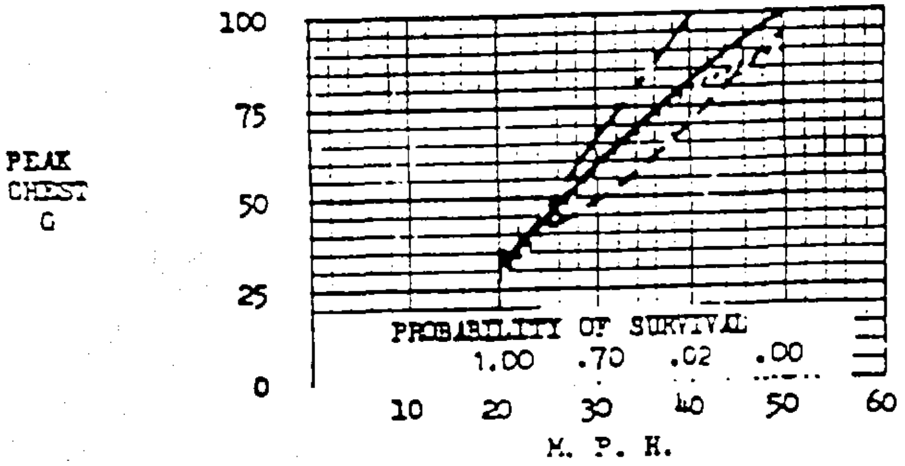
For multiple impacts and rollovers, the benefit for the driver behind an E/A column can be enhanced by a lap belt, since the lap belt will keep the operator in position, preventing ejection and reducing hazards of secondary impacts.

## 2. Lap Belts

The lap belts used in these effectiveness estimates are simulations of belts used in current vehicles. That they are reasonably effective at crash speeds up to 30 mph is seen in Figure 5. In the absence of an effective upper-torso restraint, lap belts are comparatively ineffective in reducing fatalities at higher impact speeds. However, the lap belt does provide an important function at higher speeds by retaining vehicle occupants inside the vehicle during rollover accidents.

## RESTRAINT 2: LAP BELTS





### 3. Current Harness, Driver

The current harness is made of webbing having essentially linear force-elongation characteristics. It consists of a lap belt and diagonal shoulder belt. The responses for this restraint are given in Figure 6.

### 4. Current Harness, Passenger

This restraint is identical to that described in the preceding section. The minor differences in effectiveness shown in Figure 7 are due to a difference in package geometry.

### 5. Harness With Constant-Force Webbing

Lap belts and diagonal shoulder belts made of force-limiting webbing can substantially reduce peak decelerations sustained by victims of an automobile crash, as shown in Figure 8. The shoulder belts are designed to elongate at a constant force of 950 lbs, thus dissipating energy more efficiently than linear belts. Tests show that these belts also provide large hysteresis, thereby reducing the possibility of injury due to rebound into seat backs or other occupants.

In the 50 mph crash, the driver restrained by a constant-force harness received slightly lower chest accelerations than the passenger. This raised the driver's probability of survival to .38, compared to .33 for the passenger.

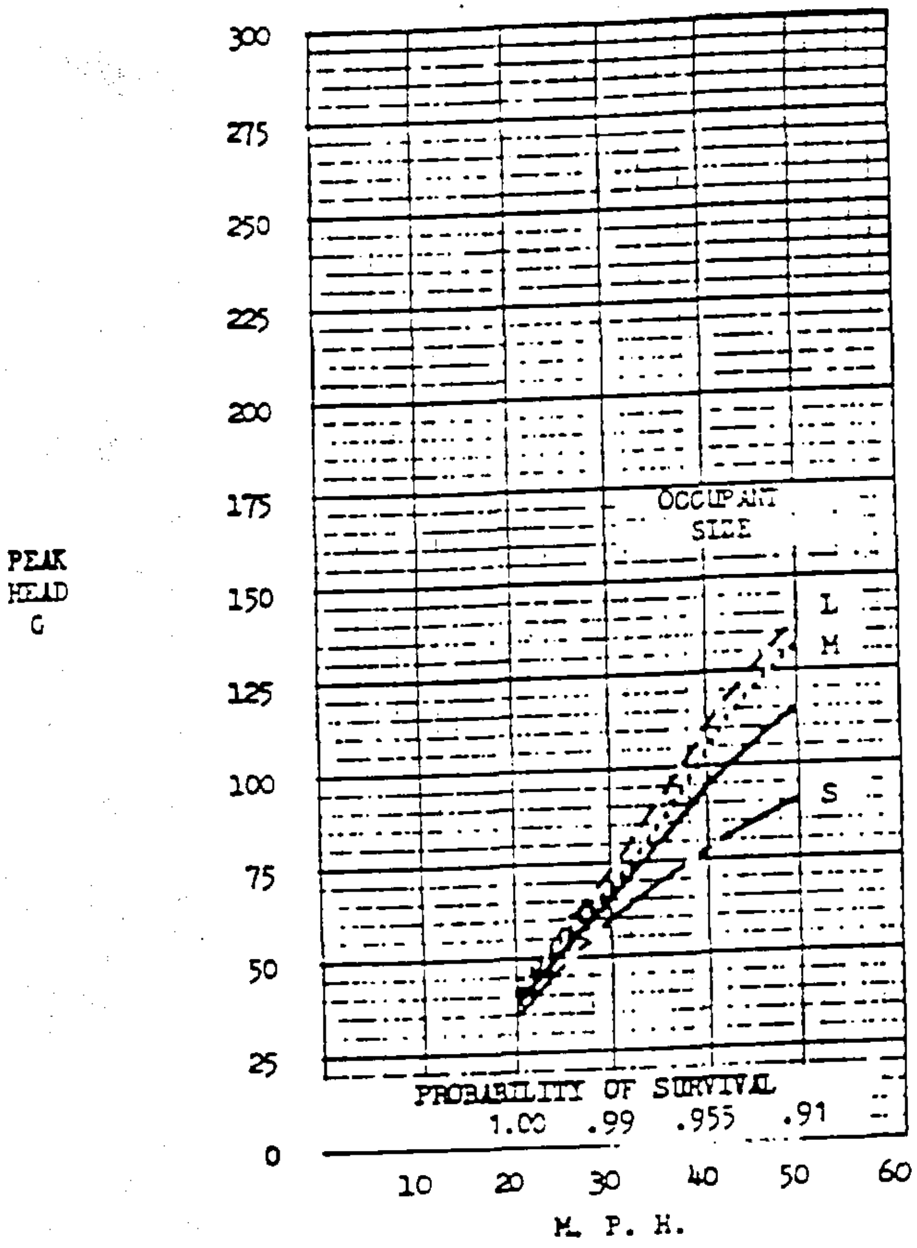
### 6. Air Bag

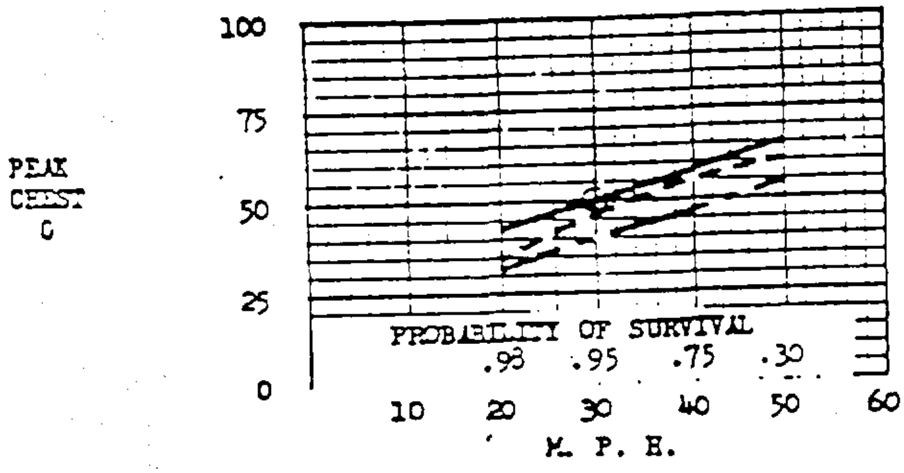
Since at the time of this study the Cornell model could not simulate occupant dynamics when restrained by air bags, it was necessary to use another model. The only model in existence suitable for occupant simulation with air bag restraint was a single-degree-of-freedom model developed by Ford in 1968. This model is shown in Figure 9, and is described in detail below.

The air bag system is functionally analogous to a piston, cylinder and orifice assembly. The energy of an impacting body is dissipated by compressing the gas in the bag and forcing the compressed gas through an exit orifice. The model was made to accurately predict occupant upper torso motion with the air bag restraint by adjusting some of the occupant parameters until correspondence with actual test results was achieved. The equations of motion for this model were developed as follows:

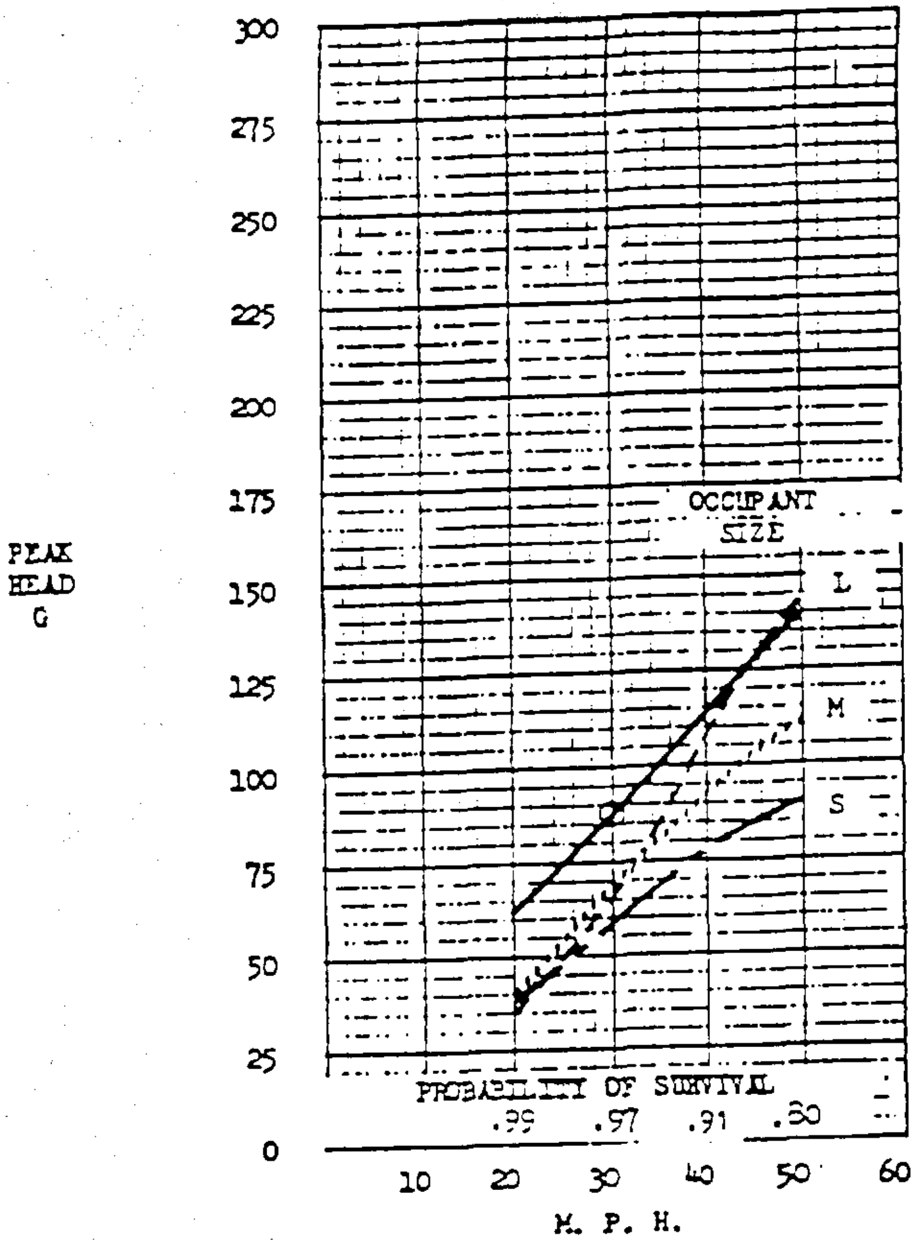
(Text continues on page 18.)

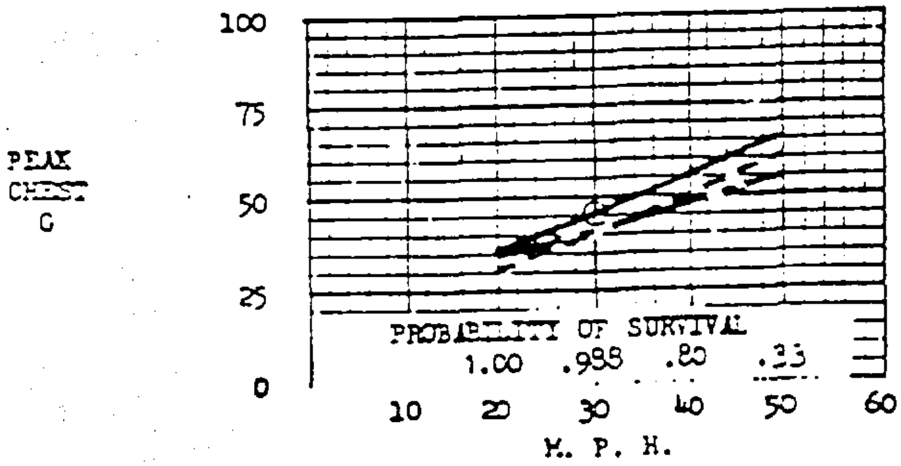
## RESTRAINT 3: CURRENT HARNESS, DRIVER



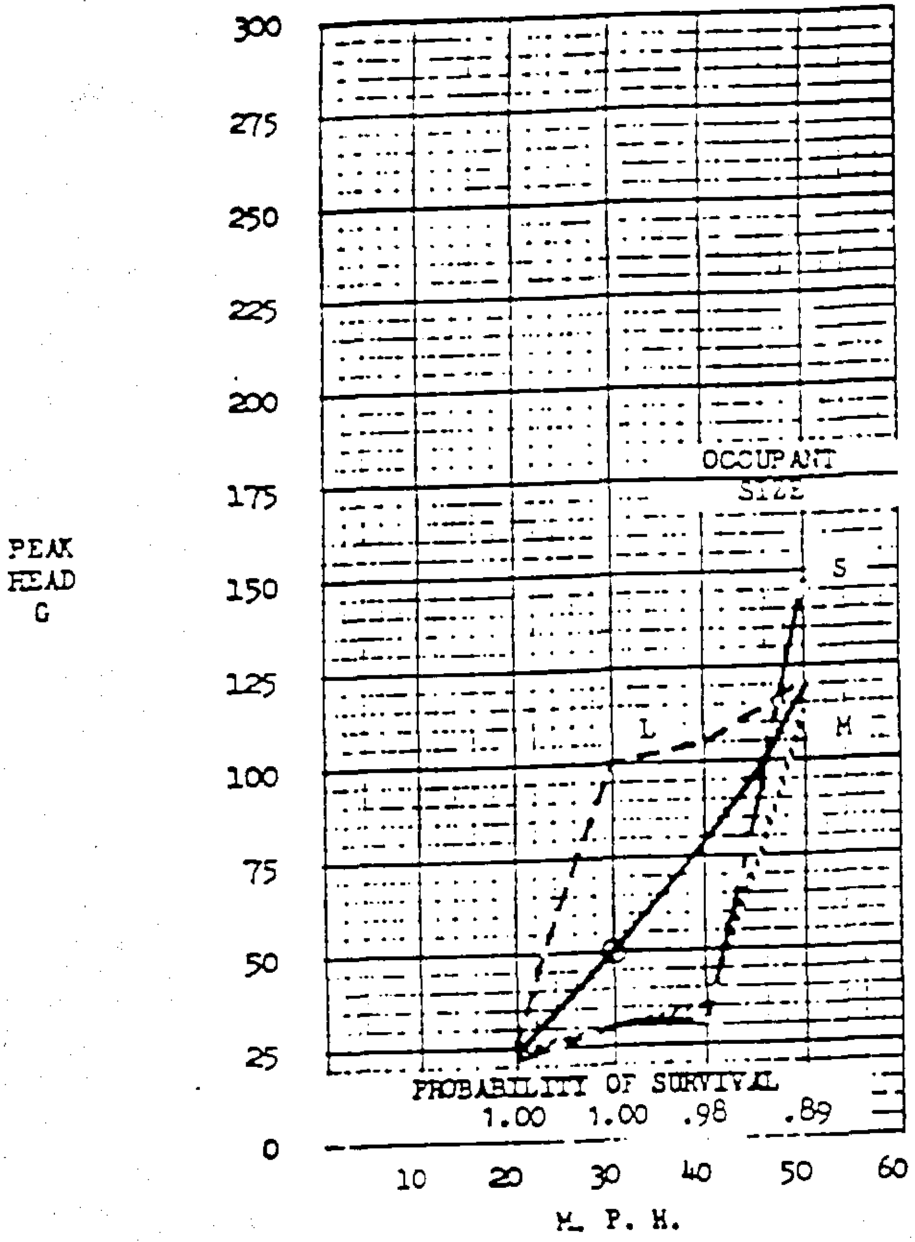


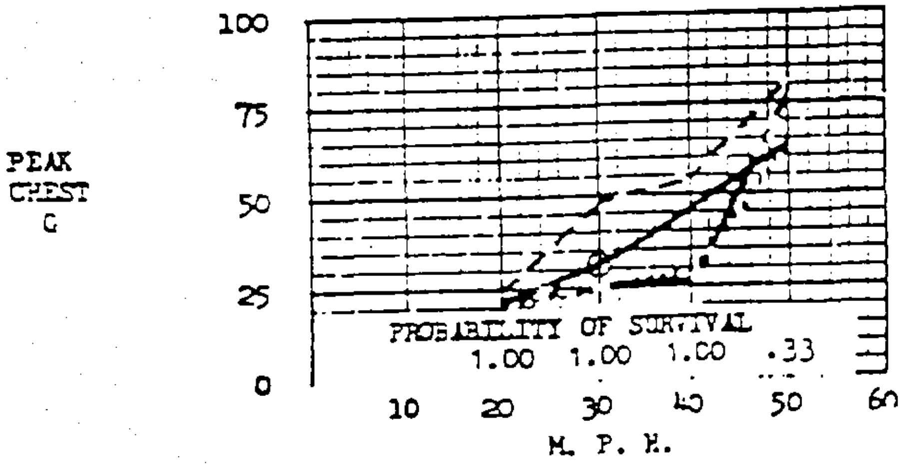
RESTRAINT 4: CURRENT HARNESS, PASSENGER





RESTRAINT 5: HARNESS WITH CONSTANT-FORCE WEBBING





As the mass impacts the system, Newton's law governing the motion of the mass and piston is:

$$M\ddot{X} = \sum F_x \qquad (1)$$

where:

$M$ = mass of the impacting body

$\sum F_x$ = sum of the forces acting in the X direction.

The forces acting on the piston are due to the pressure inside the cylinder and the atmospheric pressure outside the cylinder. Equation 1 becomes:

$$M\ddot{X} = P_o A - P_i A \qquad (2$$

where:

$P_o$ = atmospheric pressure
$P_i$ = pressure in the cylinder
$A$ = area of the piston

Since the compression occurs quickly, the heat transfer is small, and the process is nearly adiabatic. If the gas in the cylinder is ideal:

$$P_i v^n = C \qquad (3)$$

where:

$v$ = specific volume
$n$ = ratio of the constant pressure and constant volume specific heats of the gas
$c$ = a constant determined by the conditions at the beginning of the compression

By definition

$$v = \frac{V}{W} \qquad (4)$$

where

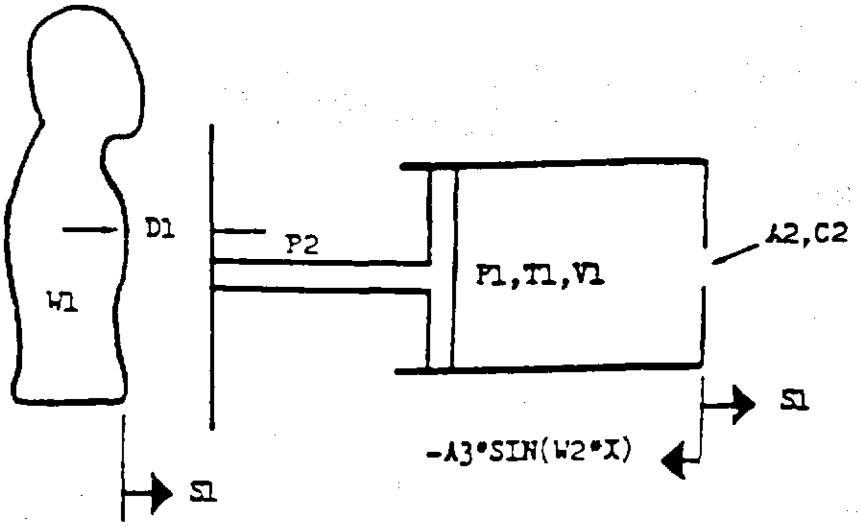
$V$ = the volume of the cylinder
$W$ = the mass of the gas in the cylinder

$$V = V_i - AX \qquad (5)$$

where $V_i$ = initial volume of the cylinder. Substituting 5 into 4, and the result into 3 and solving for $P_i$ gives:

FIGURE 9

SCHEMATIC FOR AIR BAG MODEL



| Independent Variable | Symbol | Units |
|---|---|---|
| Initial Bag Pressure | P1 | psi |
| Atmospheric Pressure | P2 | psi |
| Initial Temp. of Gas In Bag | T1 | °F |
| Gas Constant | R1 | |
| Orifice Discharge Coefficient | C2 | |
| Occupant Contact Area | A1 | $ft^2$ |
| Occupant Effective Weight | W1 | lb. |
| Bag Initial Volume | V1 | $ft^3$ |
| Orifice Area | A2 | $ft^2$ |
| Vehicle Impact Velocity | S1 | ft/sec |
| Maximum Vehicle Deceleration | A3 | $ft/sec^2$ |
| Frequency of Half-Sine Pulse | W2 | rad/sec |
| Initial Occupant Displacement | D1 | ft |

$$P_i = C\left(\frac{W}{V_i - AX}\right)^n \tag{6}$$

substituting 6 into 2 gives:

$$M\ddot{X} = P_o A - AC\left(\frac{W}{V_i - AX}\right)^n \tag{7}$$

W, the amount of gas in the cylinder at any time depends on the flow rate of the gas through the orifice, which is a function of the pressure and temperature inside the cylinder.

The expression for flow rate of air through an orifice for $P_i/P_o < 1.89$ is given by:

$$\frac{dW}{dt} = \dot{W} = -\sqrt{\frac{2g}{RT_i}}\; A_o \theta \; \sqrt{P_o\,(P_i - P_o)} \tag{8}$$

$$\theta = \sqrt{\frac{\frac{n}{n-1}\left(\frac{P_i}{P_o}\right)^{\frac{n-1}{n}}\left[\left(\frac{P_i}{P_o}\right)^{\frac{n-1}{n}} - 1\right]}{\frac{P_i}{P_o} - 1}}$$

where:

$g$ = gravitational constant
$R$ = universal gas constant
$T_i$ = temperature in the cylinder
$A_o$ = orifice area

from the perfect gas equation of state:

$$P_i v = RT_i \tag{9}$$

$$v = \frac{RT_i}{P_i}$$

equation 3 solved for v gives:

$$v = \left(\frac{C}{P_i}\right)^{1/n} \tag{10}$$

equating 9 and 10, and solving for $T_i$ :

$$T_i = \frac{P_i}{R}\left(\frac{C}{P_i}\right)^{1/n} = \frac{P_i^{\frac{n-1}{n}}\, C^{1/n}}{R} \tag{11}$$

substitute 11 into 8, and 6 into the result:

$$\dot{W} = \sqrt{\frac{\text{[illegible]}}{\left(\frac{W}{V_1-\lambda X}\right)^{n-1} C}} \cdot A_o \phi \sqrt{P_o\left[C\left(\frac{W}{V_1-\lambda X}\right)^n - P_o\right]} \qquad (12)$$

$$\phi = \sqrt{\frac{n}{n-1}\,\frac{\left[\frac{C}{P_o}\left(\frac{W}{V_1-\lambda X}\right)^n\right]^{\frac{n-1}{n}}\left\{\left[\frac{C}{P_o}\left(\frac{W}{V_1-\lambda X}\right)^n\right]^{\frac{n-1}{n}} - 1\right\}}{\frac{C}{P_o}\left(\frac{W}{V_1-\lambda X}\right)^n - 1}}$$

If $P_1/P_o \geq 1.89$ the orifice is choked and flow for air is given by:

$$\dot{W} = -.532\, A_o \frac{P_1}{\sqrt{T_1}} \qquad (13)$$

substituting equations 6 and 11 into 13 gives

$$\dot{W} = -.532\, A_o \sqrt{R}\; C^{1/2} \left(\frac{W}{V_1-\lambda X}\right)^{\frac{n+1}{2}} \qquad (14)$$

The right hand side of both equations 12 and 14 must be multiplied by a discharge coefficient. The value of the discharge coefficient ranges from .56 to .99 depending on the shape of the orifice.

Equation 7, when combined with 12 and 14 results in a system of non-linear differential equations which are discontinuous at $P_1/P_o = 1.89$. This system can be solved for $X$ as a function of time, and the associated derivitives to give the velocity and acceleration.

Before using this model in the present study, it was correlated with air bag test results on the Hyge sled. The limitation of this model to predict chest deceleration only does not affect the accuracy of the study since tests have shown that chest deceleration will be the predominant factor influencing fatality with the air bag design that was simulated.

In simulating the air bag, it was assumed that a sensor capable of responding to crashes up to plus or minus 30° from head-on will be available. At present, such a sensor is still under development.

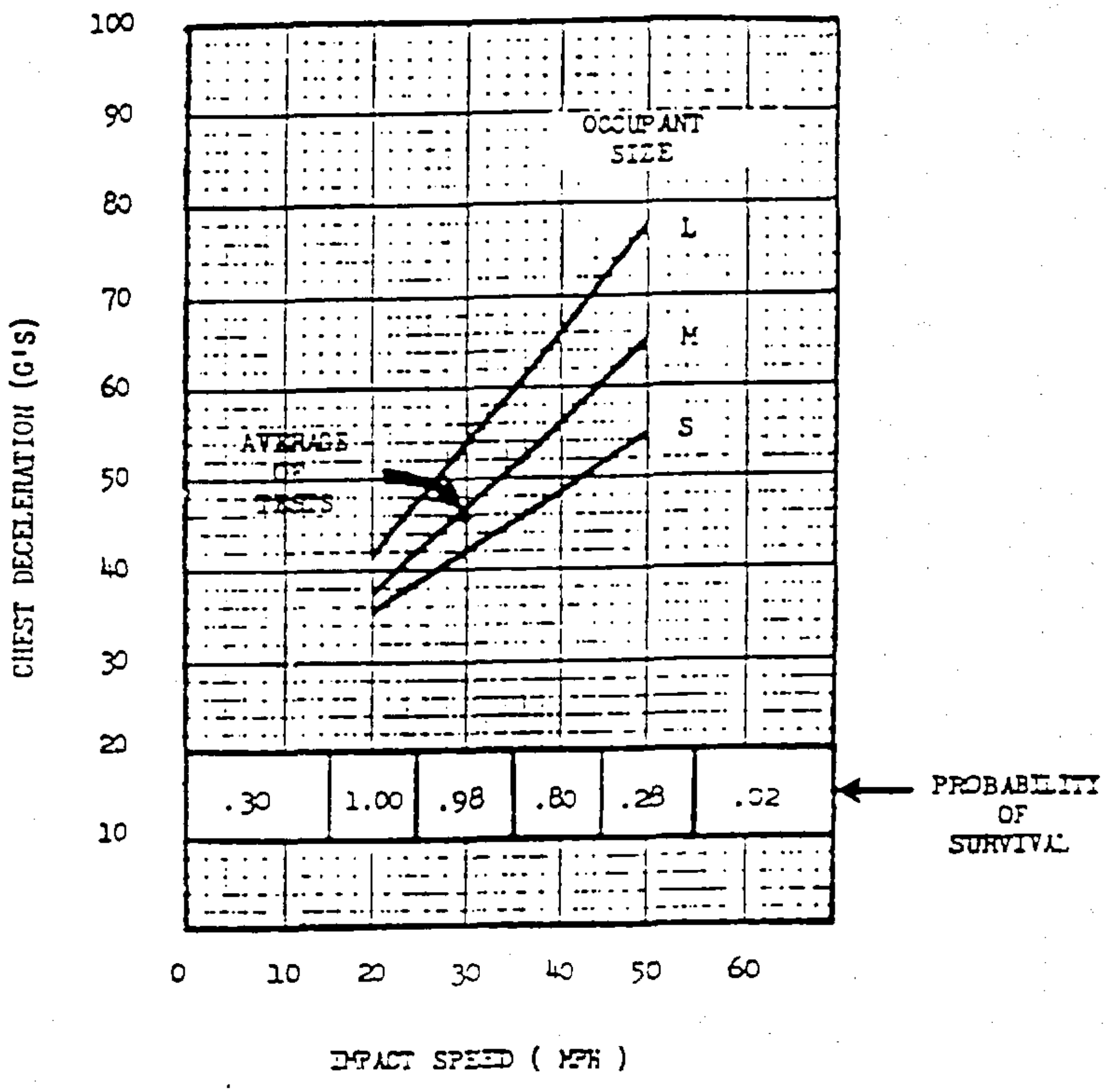
To allow for normal sensor actuation and air bag inflation time, the model allowed the occupant six inches of unrestrained forward motion before contacting the air bag. This distance is based on Hyge sled test results, and was used for all impact speeds included in this study.

With the above assumptions, the chest decelerations with air bags were calculated for the range of impact speeds and occupant sizes for collisions head-on and at 30°. The results, shown in Figure 10, indicate that the current air bag design will have the same effectiveness for all frontal collisions up to 30°. Laboratory test results for the 50th percentile male crash dummy at 30 mph show that the model results are realistic.

FIGURE 10

AIR BAG - FRONT AND REAR

PEAK CHEST DECELERATION AND PROBILITY
OF SURVIVAL VS. BARRIER IMPACT SPEED



determined by referring the mean peak chest decel[illegible] occupant sizes in the simulated crashes to the human tolerance curves. The results are shown in Figure 10.

Occupant Mis-positioning. The probability of survival with air bag restraint shown in Figure 10 assumed proper occupant positioning; however, studies have shown that occupant positioning relative to the instrument panel can vary at the time of air bag inflation for a number of reasons. The air bag may not be effective in preventing a fatality for some out-of-position occupants. Tests have also shown that the air bag can in some cases cause high decelerations on a mis-positioned occupant, higher than if the occupant were unrestrained.

For this study, the theoretical effectiveness values for the air bag were reduced to compensate for occupants who are out of position due to severe braking preceding the crash, and who are leaning forward prior to the impact. A recent study(3) has shown that up to 36 percent of crashes are preceded by heavy braking (20 mph or more speed change prior to impact in accident investigators' reports), and lab tests have shown that even an attentive occupant can be forced against the instrument panel by the braking force. While the actual number of out-of-position occupants is not known, it was assumed that all occupants in crashes preceded by heavy braking were potentially out of position, and that half of these were actually out of position. Thus, it was assumed that in 18 percent of the frontal accidents, occupants will be out of position due to severe braking. Another study(4) indicates that an additional 1 percent of occupants will be leaning forward at the time of the impact. It was further assumed that the effectiveness of the air bag for out-of-position occupants should be reduced only in the higher speed ranges (above 25 mph).

In addition, the air bag effectiveness was reduced for collisions in the 0-15 mph range since the air bag will not operate below 10 mph.

The above assumptions accounting for out-of-position occupants and low speed ineffectiveness reduced the probability of survival for the air bag by 19 percent, resulting in the final air bag effectiveness matrix shown in Figure 11.

### 7. High-Impact Instrument Panel

A high-impact panel was used in some of the restraint systems in this study to protect rear-seat passengers as well as front-seat passengers. This concept, whether incorporated in the instrument panel or whether in a rear seat protective panel, involves a fixed energy-absorbing composite structure extending closer to the passenger than current instrument panels. Panel design was assumed to be optimized for protection of unrestrained occupants and, hence, was not accorded the higher effectiveness valuation that would be appropriate for a design optimized to provide upper torso restraint to lap-belted occupants. The passenger H-point-to-panel relationship was maintained constant for the rear-seat occupants. The panel performance is depicted in Figure 12.

## Example Of Effectiveness Calculation

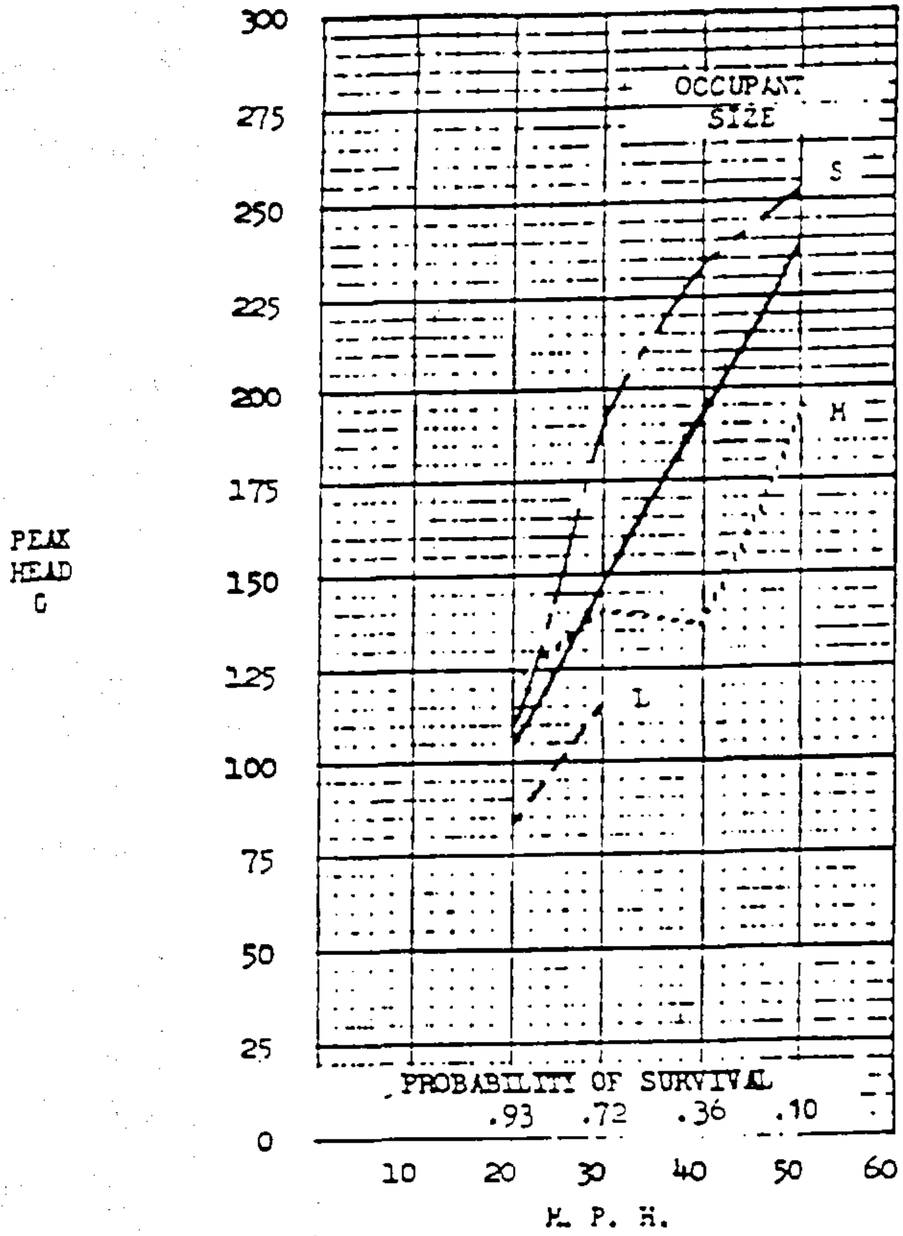
The method used to calculate the lives saved by a given restraint system was as follows:

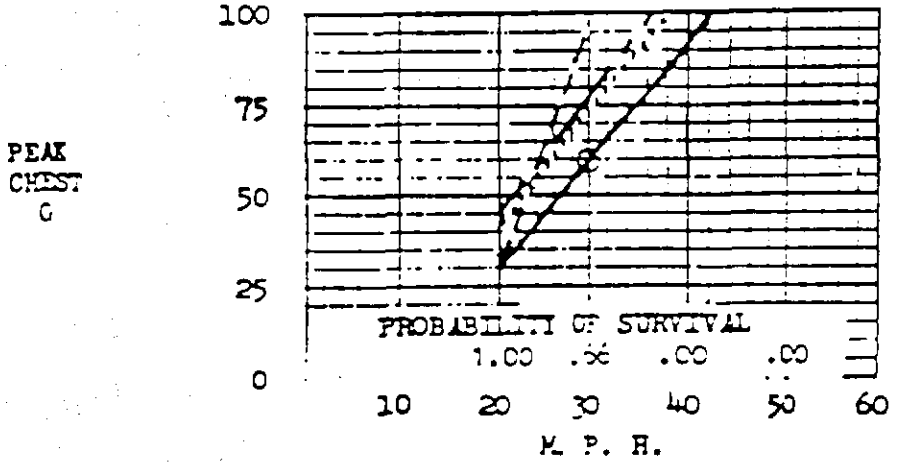
The effectiveness value table for the present harness configuration with current webbing is shown in Figure 13. Each of these values represents the

FIGURE 11

## AIR BAG EFFECTIVENESS

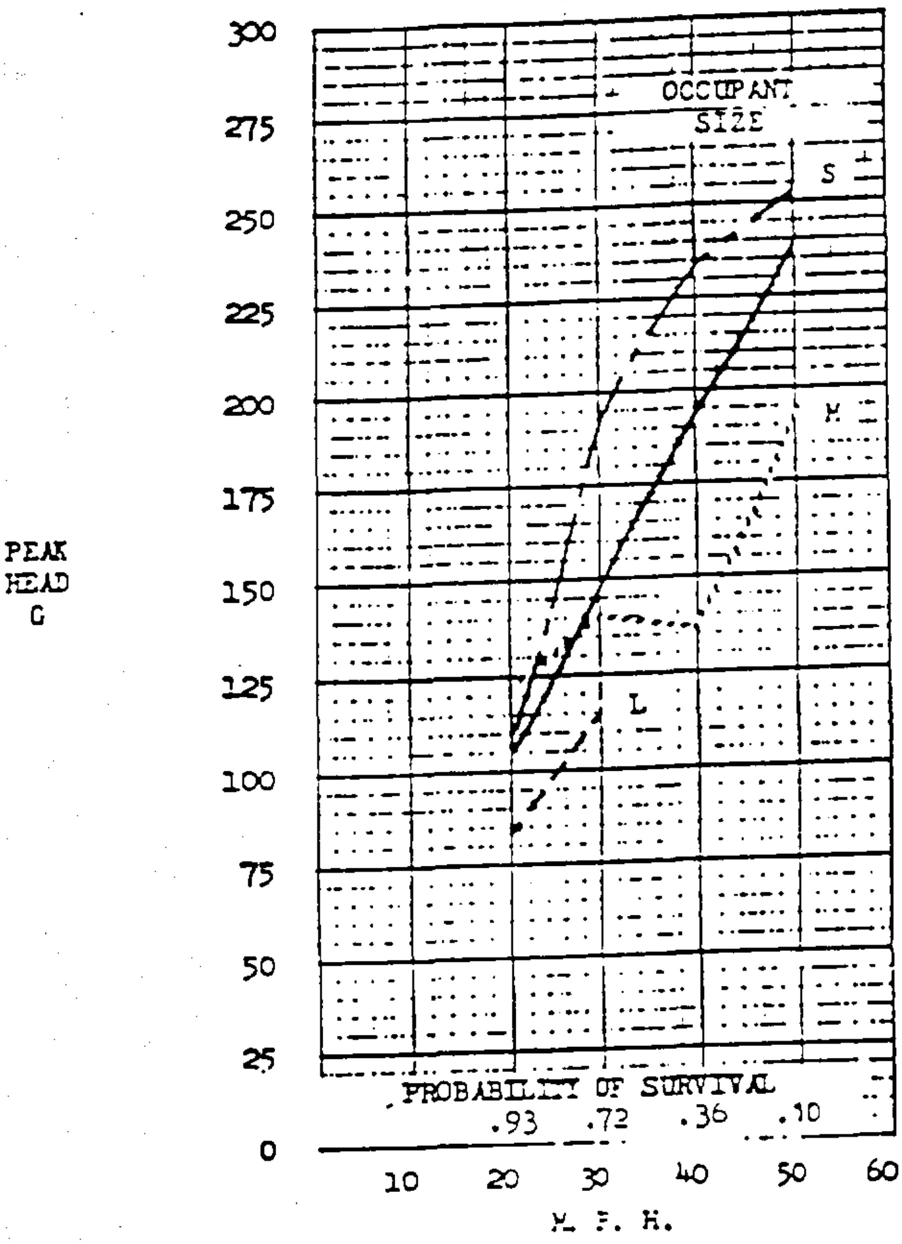
| | Impact Direction | | |
|---|---|---|---|
| BARRIER-EQUIVALENT IMPACT SPEED | 11 | 12 | 1 |
| 0-15 | 30 | 30 | 30 |
| 16-25 | 100 | 100 | 100 |
| 26-35 | 79 | 79 | 79 |
| 36-45 | 65 | 65 | 65 |
| 46-55 | 23 | 23 | 23 |
| 56 & Over | 2 | 2 | 2 |

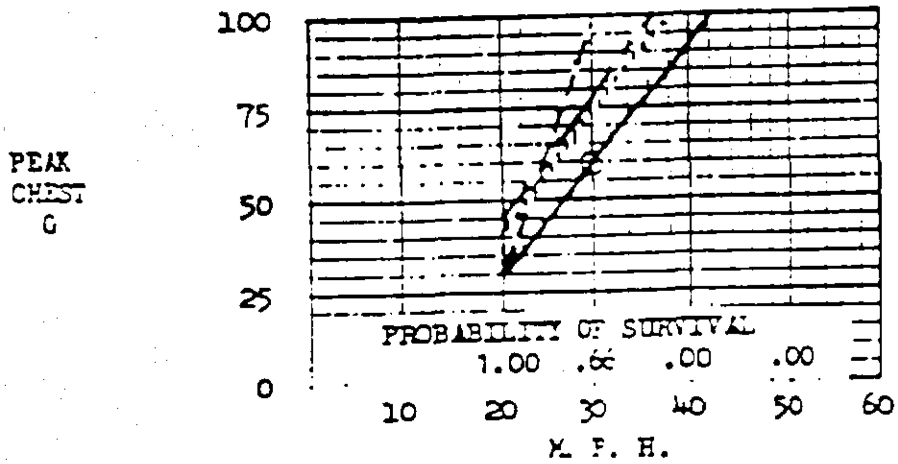

PEAK
HEAD
G
300
275
250
225
200
175
150
125
100
75
50
25
0
OCCUPANT SIZE
S
M
L
PROBABILITY OF SURVIVAL
.93 .72 .36 .10
10 20 30 40 50 60
M. P. H.


PEAK
CHEST
G
100
75
50
25
0
PROBABILITY OF SURVIVAL
1.00 .56 .00 .00
10 20 30 40 50 60
M. P. H.

[illegible]

## RESTRAINT 7: HIGH-FLEX PANEL





## FIGURE 13

### EFFECTIVENESS (IN PERCENT) OF CURRENT HARNESS SYSTEM

| BARRIER SPEED MPH | DRIVER |  |  | CENTER FRONT |  |  | RIGHT FRONT |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  |
|  | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| 0 - 15 | 100 | 100 | 99 | 95 | 100 | 95 | 99 | 100 | 100 |
| 16 - 25 | 98 | 98 | 93 | 93 | 98 | 93 | 93 | 99 | 95 |
| 26 - 35 | 85 | 95 | 75 | 60 | 70 | 60 | 75 | 97 | 85 |
| 36 - 45 | 65 | 75 | 45 | 0 | 2 | 0 | 45 | 80 | 65 |
| 46 - 55 | 20 | 30 | 10 | 0 | 0 | 0 | 10 | 33 | 20 |
| 56 & up | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 |

| BARRIER SPEED MPH | LEFT REAR |  |  | CENTER REAR |  |  | RIGHT REAR |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | DIRECTION OF FORCE |  |  | DIRCETION OF FORCE |  |  | DIRECTION OF FORCE |  |  |
|  | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| 0 - 15 | 90 | 100 | 95 | 95 | 100 | 95 | 95 | 100 | 90 |
| 16 - 25 | 85 | 93 | 93 | 93 | 93 | 93 | 93 | 98 | 85 |
| 26 - 35 | 50 | 70 | 60 | 60 | 70 | 60 | 60 | 70 | 50 |
| 36 - 45 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 46 - 55 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 56 & up | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

life-saving effectiveness of the restraint in the particular accident situation, as resulted from exercising the Cornell model in the manner described in the preceding pages. The accident situation is defined in terms of occupant seated position, direction of force, and fixed-barrier-equivalent speed, as these were the variables used in the development of the estimates.

Figure 14 is drawn from accident statistics breakdowns, which are developed in subsequent sections of this report. This Figure lists the percentage of fatalities which were found in various accident situations. These situations are defined similarly to those in Figure 13, except that Cornell Aeronautical Laboratory (CAL) reported severity ratings are used instead of speed ranges. However, as will be clarified later, the speed ranges are the barrier-equivalents for each respective severity level. Thus, the Barrier Speed column of Figure 13 is compatible with the CAL Accident Severity rating column of Figure 14.

This compatibility allows the proportions in the two Figures to be multiplied. The product of a factor in a cell of the first Figure (the fatalities eliminated) times that in the corresponding cell of the second Figure (the actual proportion of total fatalities) gives the proportion of total existing fatalities which would be eliminated in that cell. The result of this cell-by-cell multiplication is shown in Figure 15.

The sum of the numbers in Figure 15, across the three accident-situation variables (seated position, direction of force, barrier-equivalent speed), gives the percentage of existing fatalities which would no longer occur, as a result of the given restraint system. In this case, for 100 percent usage of the present harness configuration, these numbers sum to 49 percent. This represents the proportional effectiveness of the present harness configuration and may be interpreted as indicating that 49 percent of the unrestrained occupants who lost their lives would have lived if all the occupants had availed themselves of the present harness arrangement.

This proportional effectiveness (49%), when multiplied by the anticipated number of single-impact passenger car occupant fatalities (23,600 in 1969, if no restraints had been used), produces the number of lives saved. For 1969, this number was calculated as 11,700 lives saved.

The procedure for determining life-saving effectiveness for each of the other restraint systems was the same as that outlined here, with a different table of effectiveness values for each system. For each restraint system, however, the actual fatality distribution based on current accident statistics (Figure 14) remains unchanged. This fact would allow effectiveness calculations for safety systems not discussed in this paper to be derived easily if effectiveness estimates could be generated.

An effectiveness value matrix for each restraint system considered in this study is shown in Appendix B. This Appendix constitutes the basic record of results from the crash dynamics modeling phase of this study.

## FIGURE 14

### PERCENTAGE DISTRIBUTION OF FATALITIES IN SINGLE IMPACTS DETERMINED FROM CORNELL ACCIDENT DATA

| CAL ACCIDENT SEVERITY RATING | DRIVER DIRECTION OF FORCE | | | CENTER FRONT DIRECTION OF FORCE | | | RIGHT FRONT DIRECTION OF FORCE | | |
|---|---|---|---|---|---|---|---|---|---|
| | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor | 0.19 | 0.83 | 0.11 | 0.02 | 0.07 | 0.01 | 0.08 | 0.39 | 0.09 |
| Moderate | 0.49 | 1.79 | 0.57 | 0.05 | 0.14 | 0.04 | 0.22 | 0.84 | 0.47 |
| Moderately Severe | 2.21 | 9.56 | 1.72 | 0.23 | 0.76 | 0.13 | 0.98 | 4.48 | 1.4[illegible] |
| Severe | 4.53 | 14.18 | 2.06 | 0.47 | 1.13 | 0.15 | 2.01 | 6.65 | 1.70 |
| Extremely Severe | 0.00 | 0.14 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.06 | 0.00 |
| Extreme | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| CAL ACCIDENT SEVERITY RATING | LEFT REAR DIRECTION OF FORCE | | | CENTER REAR DIRECTION OF FORCE | | | RIGHT REAR DIRECTION OF FORCE | | |
|---|---|---|---|---|---|---|---|---|---|
| | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor | 0.02 | 0.04 | 0.01 | 0.01 | 0.02 | 0.00 | 0.01 | 0.04 | 0.01 |
| Moderate | 0.05 | 0.08 | 0.04 | 0.02 | 0.04 | 0.01 | 0.03 | 0.08 | 0.05 |
| Moderately Severe | 0.21 | 0.41 | 0.11 | 0.10 | 0.24 | 0.04 | 0.24 | 0.44 | 0.14 |
| Severe | 0.42 | 0.61 | 0.13 | 0.20 | 0.35 | 0.05 | 0.29 | 0.65 | 0.17 |
| Extremely Severe | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Extreme | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

# FIGURE 15

## PERCENT OF TOTAL FATALITIES ELIMINATED (LIVES SAVED) WITH PRESENT HARNESS SYSTEM

| CAL ACCIDENT SEVERITY RATING | DRIVER |  |  | CENTER FRONT |  |  | RIGHT FRONT |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  |
|  | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor (0-15 mph) | 0.19 | 0.83 | 0.11 | 0.02 | 0.07 | 0.01 | 0.08 | 0.39 | 0.09 |
| Moderate (16-25 mph) | 0.48 | 1.75 | 0.56 | 0.05 | 0.14 | 0.04 | 0.22 | 0.83 | 0.47 |
| Moderately Severe (26-35 mph) | 1.88 | 9.08 | 1.29 | 0.14 | 0.53 | 0.06 | 0.74 | 4.35 | 1.22 |
| Severe (36-45 mph) | 2.94 | 10.64 | 0.93 | 0.00 | 0.02 | 0.00 | 0.90 | 5.32 | 1.[illegible]1 |
| Extremely Severe (46-55 mph) | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 |
| Extreme (56 up mph) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| CAL ACCIDENT SEVERITY RATING | LEFT REAR |  |  | CENTER REAR |  |  | RIGHT REAR |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  | DIRECTION OF FORCE |  |  |
|  | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor (0-15 mph) | 0.02 | 0.04 | 0.01 | 0.01 | 0.02 | 0.00 | 0.01 | 0.04 | 0.01 |
| Moderate (16-25 mph) | 0.04 | 0.08 | 0.04 | 0.02 | 0.04 | 0.01 | 0.03 | 0.08 | 0.04 |
| Moderately Severe (26-35 mph) | 0.11 | 0.29 | 0.07 | 0.06 | 0.17 | 0.02 | 0.08 | 0.32 | 0.07 |
| Severe (36-45 mph) | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 |
| Extremely Severe (46-55 mph) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Extreme (56 up mph) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

# [illegible] OF ACCIDENT DATA ANALYSIS

This report has thus far dealt mainly with the calculation of the effectiveness of each restraint system in a particular accident situation. Each situation was specified by three factors, the seated position of the occupant, the direction of impact, and the barrier-equivalent speed.

In this section of the report, accident statistics are analyzed to determine the current frequency of fatalities, in each type of accident situation. The number of lives each restraint could save was then determined by combining this statistical information with the effectiveness values.

The distribution of barrier-equivalent impact speeds representative of real-world accidents is also developed in this section.

## Distribution Of Data By Placement Of Fatality

Motor vehicle fatalities can be categorized in a number of ways; among these is classification by placement of the fatality: e.g., occupant of a car, or of a truck, or pedestrian, etc. Figure 16 shows a distribution of the 56,400 fatalities reported by the National Safety Council (NSC) for 1969. About one-fifth of these fatalities (10,700) were not occupants of motor vehicles—included here are pedestrians and bicyclists. Among the occupants, about one-fifth were in vehicles other than passenger cars; these 8,600 fatalities were primarily truck occupants and motorcyclists.

The remaining 37,100 fatalities, constituting about two-thirds of 1969 motor vehicle deaths, were occupants of passenger cars. This study is limited, because of the nature of the safety systems being considered, strictly to these passenger-car occupants.

## Distribution Of Fatality Vehicles By Type Of Impact

Passenger car occupant fatalities can be classified further according to the type of impact experienced by the vehicle. Perhaps the most important impact consideration, in terms of occupant kinematics, is whether or not the vehicle rolled over. Among non-rollovers, a "single impact" designation means that the vehicle in which the fatality occurred (fatality vehicle) had collided with exactly one other object (which may be another vehicle); the "multiple impact" category includes fatality vehicles which had collided with more than one object. An accident is classified as a "principal rollover" when the fatality vehicle overturns without striking any other substantial object. Finally, a "collision rollover" designates an accident in which the vehicle in question had collided with some object, in addition to overturning.

Figure 17 shows a distribution of fatalities among these categories. The source for this distribution was the accident data bank maintained by the Automotive Crash Injury Research (ACIR) activity of the Cornell Aeronautical Laboratory (CAL). This file consists of accident records on more than 50,000 rural, injury-producing accidents. Only the [illegible] records concerning passenger cars of model year 1960 or later were considered for use in the study, in an effort to select a sample more closely reflecting current design level. Among the completely unrestrained occupants

## FIGURE 17

### DISTRIBUTION OF ACIR FATALITIES BY FATALITY VEHICLE IMPACT TYPE

(Unrestrained occupants in
vehicles of model year
1960 and later.)

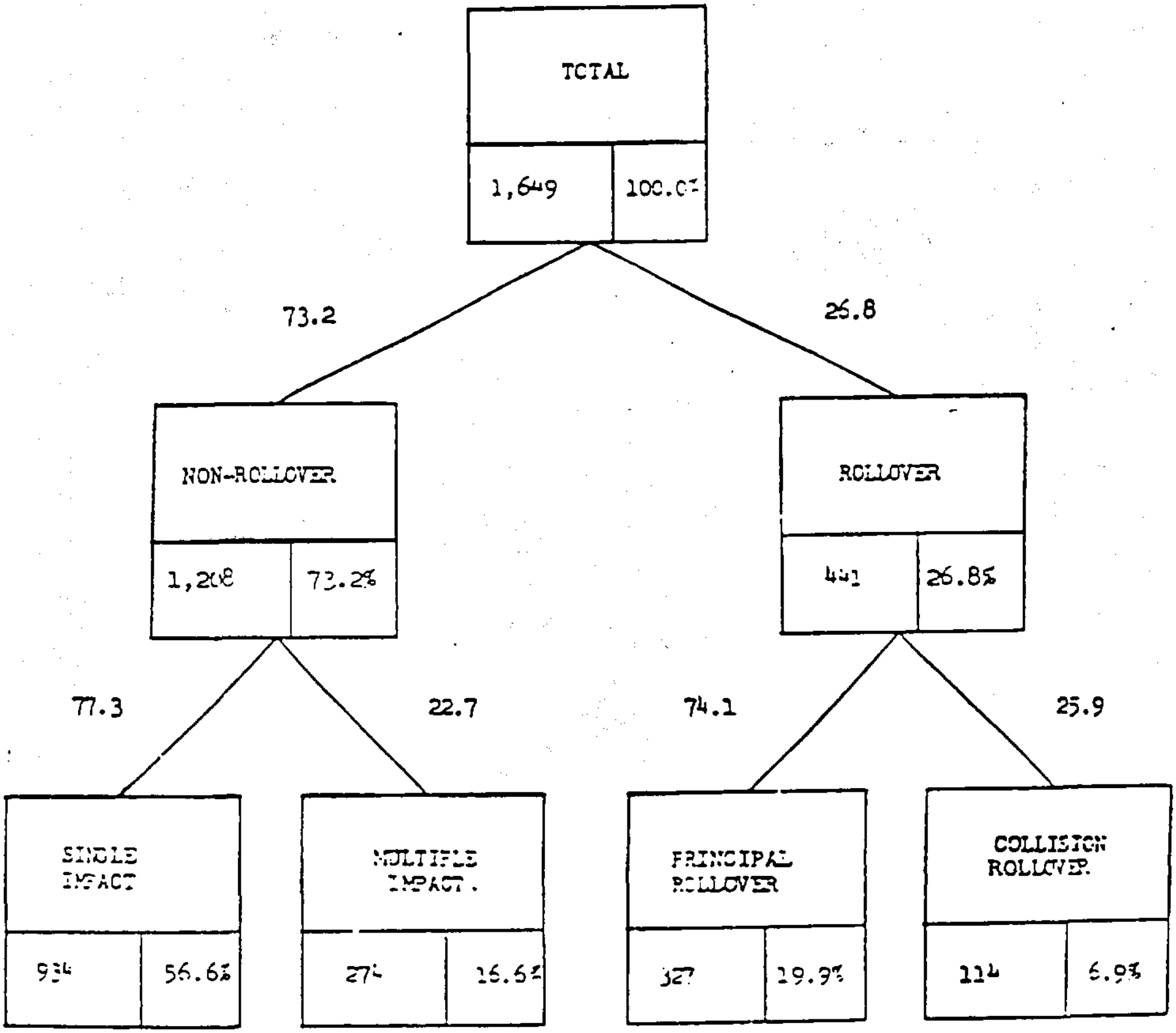
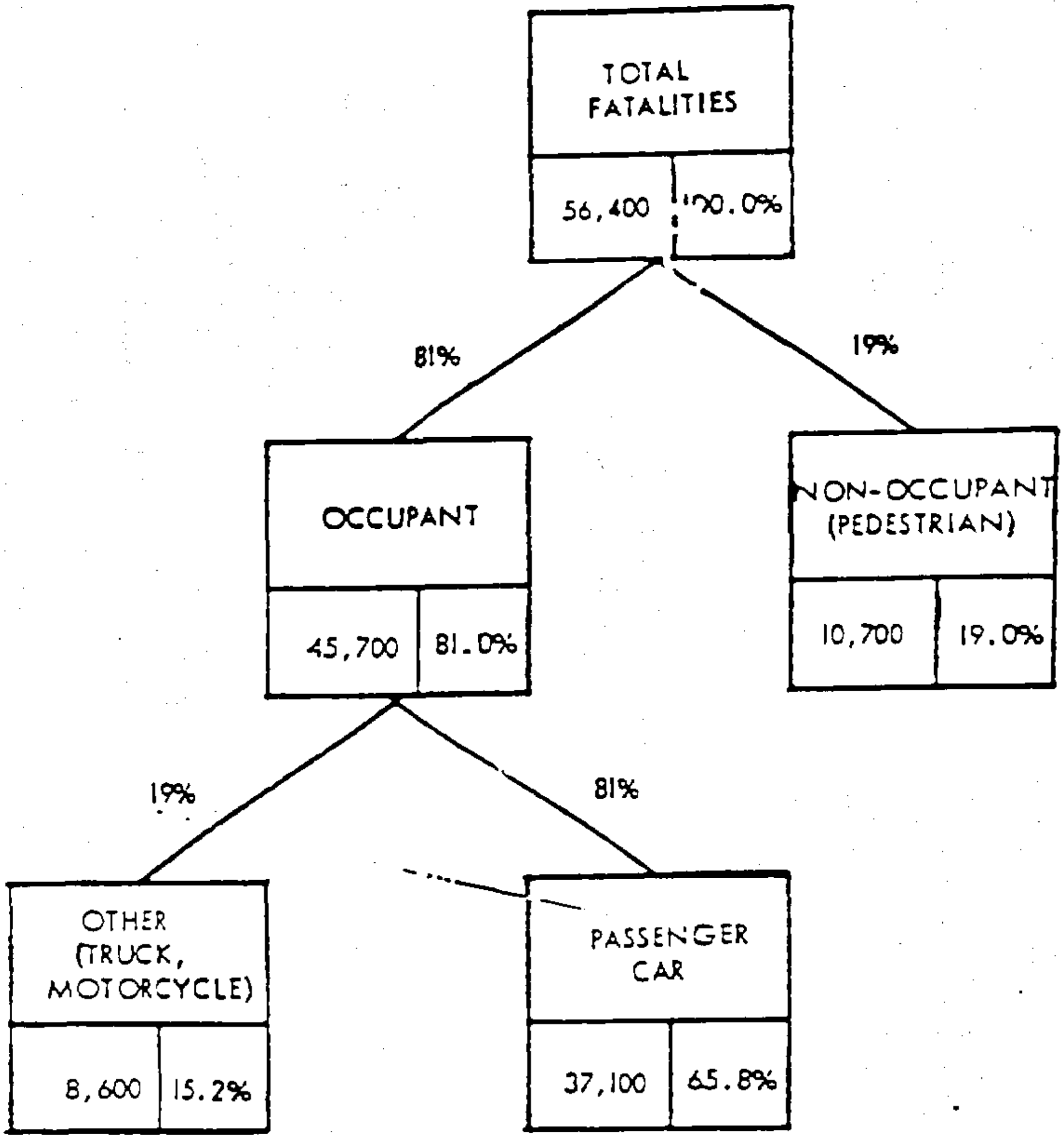


FIGURE 16

DISTRIBUTION OF 1969 MOTOR VEHICLE FATALITIES BY PLACEMENT OF FATALITY



in this sample of vehicles, 1649 fatalities were found and these fatalities constitute the sample distributed by vehicle impact type. Safety system effectiveness was determined separately for each of these impact types.

## Distribution Of Accident Situations

The source for determining the proportion of fatalities which occur in each accident situation was the 934 single-impact fatalities contained in the ACIR sample (Figure 17). Three variables were used to identify the accident situation for each fatality. One of these was the *seated position* of the occupant. Six different values were used for seated position, corresponding to the six normal occupant locations within the vehicle.

Another factor used to describe the accident situation was the *direction of force* applied to the fatality vehicle. The 12 clock positions were used as values for this descriptor, with 12 o'clock representing a direct frontal collision. Figure 18 illustrates the placement of values for seated position and direction of force.

Potential life-saving benefits were determined only for frontal (11 to 1 o'clock) impacts, in this study. Most impact dynamics research, both empirical and theoretical, has been conducted with frontal impacts. Thus, comparatively little is known about dynamics in side and rear impacts, particularly when restraints are involved. Although research in these areas is now under way, the present state of knowledge dictates that benefit estimates for side and rear impacts would be more speculative than estimates concerning vehicles impacted at the front. The elimination of side and rear impacts from consideration has at least one effect, an underestimation of overall belt effectiveness relative to air bags. Belts have an obvious advantage, not possessed by air bags in side impacts. However, the results may not be quite so distorted as would appear at first, since about two-thirds of single impact fatalities occur in frontal impacts.

The third measure used in describing the accident situation was the *severity*. This index is coded by ACIR personnel on the basis of vehicle deformation and frame damage shown in vehicle photographs. Six different severity levels, ranging from "minor" to "extreme", are used by ACIR.

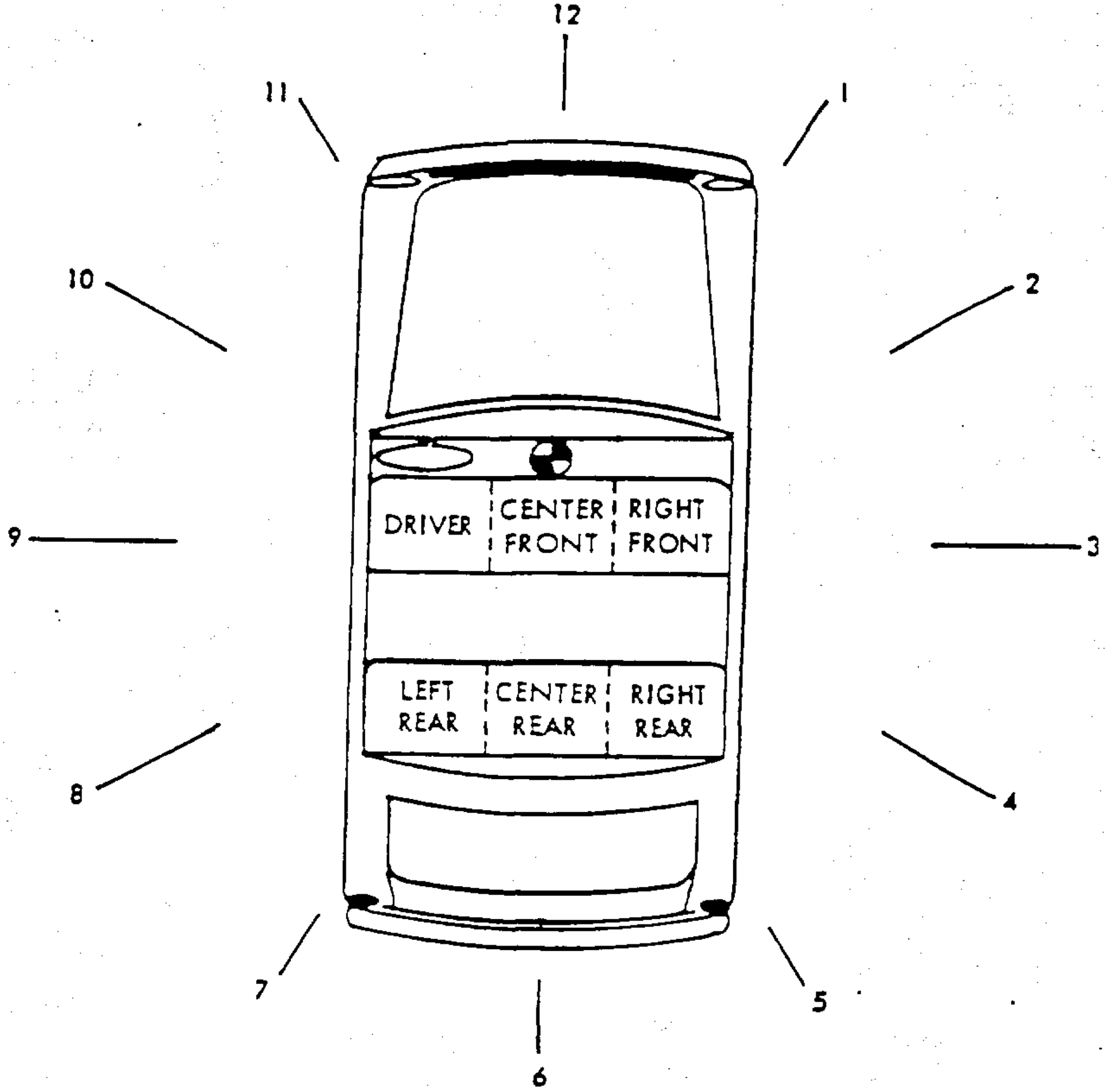
## Barrier-Equivalent Impact Speed

For the calculation of lives saved by each restraint it was necessary to establish a distribution of barrier-equivalent speeds in fatal accidents.

The simplest approach would be to accept the collision speed reported by [redacted] the investigator for each fatal accident case in the ACIR file, and then to convert that reported speed to a barrier-equivalent value. The following factors were considered in the conversion: the relative closing speed between the fatality vehicle and the object struck; the weight differential; a center of gravity adjustment and an accident location adjustment, both of which are described below. The adjustments used in arriving at these speeds are discussed in more detail in Appendix C.

FIGURE 18

IDENTIFICATION OF SEATED POSITION AND DIRECTION OF FORCE



A second method of relating barrier-equivalent speed to fatal accidents was investigated, based on the accident severity as reflected in the vehicle damage. This relationship was established by a careful matching of photographs (furnished by ACIR) for each accident severity level with photographs of barrier crashes conducted by Ford Motor Company at known impact speeds. This procedure is illustrated in Figure 19. The first column shows the ACIR severity levels, and the second column associated reference photographs used by the ACIR accident coding experts for determining the various severity levels. These photographs were then reviewed and a range of speeds into a fixed barrier (column 3) producing the same damage was estimated for each photograph. Each reported severity rating was thus assigned an associated fixed-barrier speed.

Two minor adjustments were made in the speeds to obtain the final barrier-equivalent speed distribution. The first of these, the center of gravity adjustment, attempted to isolate the proportion of crash energy dissipated along the direction-of-force line. That is, in some cases, such as striking a fender in a 12 o'clock direction, only a portion of the crash energy is lost along the 12 o'clock line. The remainder is dissipated through "spin-out." It was assumed that only the initial crash forces, along the designated direction-of-force line, contributed to occupant trauma, and that fatal injury was not directly associated with rotational forces. Thus, in identifying a collision severity level in a certain direction for each fatality vehicle in the ACIR case history file, only the energy level associated with that direction of force was of interest; the rotational energy was eliminated as a contributor to severity level. Both the direction-of-force and the area of impact were used to determine the extent (if any) to which the line of force in each case missed the vehicle center of gravity and thus induced spin. A more complete discussion of this correction, including the adjustment factors used in each direction and area of force combination, may be found in Appendix D.

A second adjustment in vehicle speed was performed to correct the rural bias of the data source. The National Safety Council had once estimated impact speed distribution for fatal accidents occurring both in rural and in urban areas. Although these distributions are not definitive enough for use as the actual speed estimates for purposes of this study, the difference between the rural speeds and the overall (urban and rural) speeds was taken as an indication of the amount by which rural estimates may be misrepresentative of the overall situation. If these overall vs. rural differences are applied uniformly for each direction of impact to the rural-oriented center-of-gravity-adjusted speeds previously obtained, the resultant distributions should be free of accident location bias. Appendix E illustrates this procedure in detail.

Figure 20 shows the consequence of each adjustment on the speeds of the fatality vehicles impacted from the front. The accident-location adjustment was made subsequent to and includes the center-of-gravity adjustment. The accident-location-adjusted impact speeds should be interpreted as approximating an equivalent speed into a fixed barrier. Thus, the median barrier-equivalent speed for fatality vehicles in frontal collisions is about 35 mph. It bears emphasizing that this distribution is for the speed of the vehicle in which the fatality occurred. Had all injury-producing accidents been taken, the distribution would have shifted downward, and even more-so had property damage cases been included.

Although these speeds are shown as continuous in Figure 20, it is well to remember that the distributions were based originally on a discrete partition of the

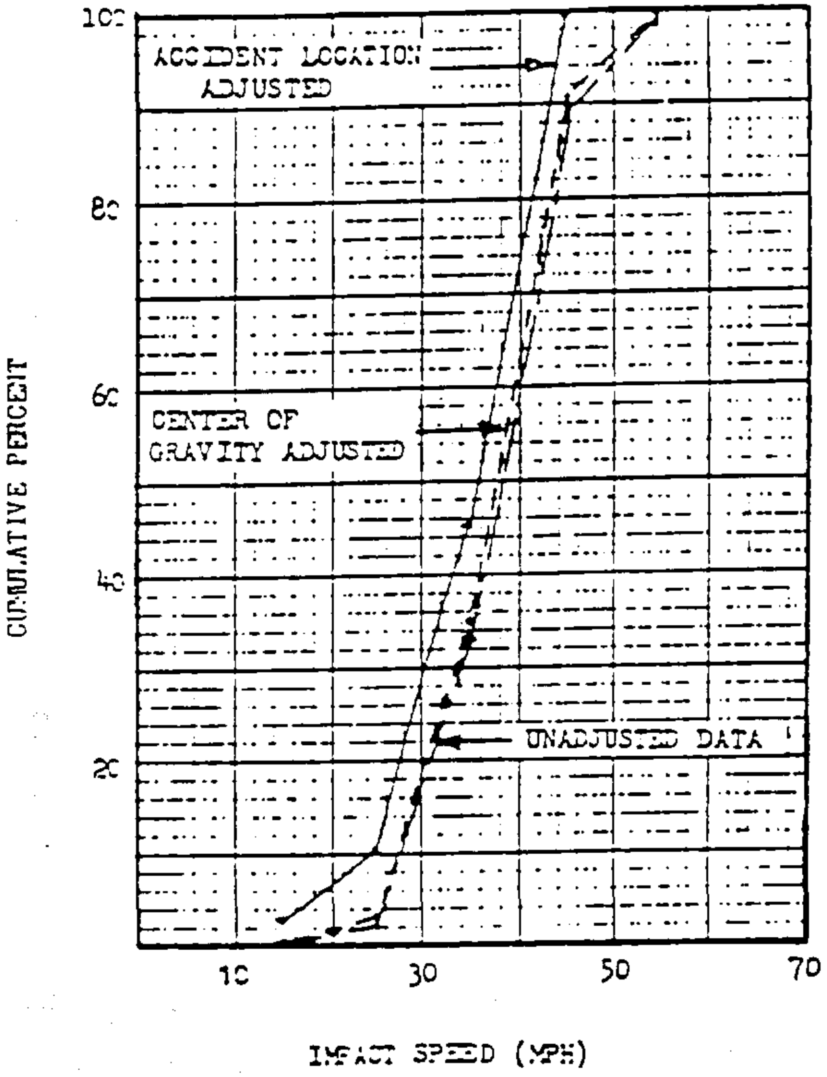
FIGURE 19

## RELATIONSHIP BETWEEN ACIR ACCIDENT SEVERITY RATING AND CORRESPONDING FIXED-BARRIER SPEED

| CAL RATING | ASSOCIATED PICTURE | CORRESPONDING SPEED (MPH) |
|---|---|---|
| MINOR |  | 0 - 15 |
| MODERATE | | 16 - 25 |
| MODERATELY SEVERE | | 26 - 35 |
| SEVERE | | 36 - 45 |
| EXTREMELY SEVERE | | 46 - 55 |
| EXTREME | | 56 + |

FIGURE 20

PERCENTAGE DISTRIBUTION OF IMPACT SPEEDS FOR SINGLE COLLISION FRONTAL FATALITY VEHICLES BY TYPE OF DATA ADJUSTMENT (*)



* Speeds based on vehicle damage ratings; adjustments lead to barrier-equivalent speed, as discussed in text.

data into six coded severity levels. The severity levels were transformed to speeds to facilitate the making of these adjustments and to allow calculation of the effectiveness value, a calculation which required analytical inputs to a dynamics model.

The appropriateness of reducing all crashes to a barrier-equivalent speed can be questioned, inasmuch as cars collide with various fixed and movable objects of various weight and stiffness. The nature of the object struck in a collision has a lot to do with the severity of the collision and the level of hazard to the occupants. Light weight, soft objects can be struck at higher speeds than heavy, rigid or fixed objects, with the same degree of hazard to occupants of the striking vehicle.

Therefore, to study automobile collision fatalities, it is necessary to identify collisions which present roughly the same hazard to the occupants. This can be done most conveniently by expressing the severity of all collisions in terms of a common scale. However, this can never be done exactly since collisions which are equivalent in one dynamic parameter are seldom equivalent in others. For example, if we base collision severity on speed change we find that peak vehicle accelerations and absorbed energy vary considerably, due to the varying dynamic characteristics of objects involved in collisions.

It thus becomes necessary to select a scale for comparing collisions and examine the consequences of assumptions made. In this study, collision severity has been expressed in terms of fixed barrier-equivalent impact speed. That is, the collision severity is expressed by the speed that a vehicle would impact a fixed barrier to produce the same vehicle crush that was observed in the actual accident. Thus, the hazard to the occupant is assumed to be related to the amount of energy absorbed by his vehicle. Expressing collision severity in terms of a fixed barrier-equivalent collision is also convenient since most available test data and mathematical simulations are for this type collision.

However, as stated above, all collisions with the same energy absorption do not involve the same vehicle speed change. Calculations show, for example, that for collisions involving vehicles of the same weight but with a 2 to 1 stiffness ratio, the stiffer vehicle may have undergone a velocity change 22 percent greater than the barrier equivalent while the weaker vehicle would have undergone a velocity change 14 percent less than the barrier equivalent. The net result is that the actual velocity changes of vehicles may be slightly higher than the barrier equivalent velocity changes. However, the maximum vehicle deceleration will be the same.

The extent to which the above situation actually occurs is not known, but the difference between the barrier-equivalent speed distribution and the speed-change distribution is believed to be small compared to the uncertainty inherent in determining the distributions.

Furthermore, it is known from dynamic simulations that increasing the vehicle speed change at a fixed peak vehicle deceleration will not necessarily increase the loads on the occupant and in some cases may decrease them. Since it is the eventual effect on the occupant that is of interest, it is believed that vehicle energy absorption expressed in terms of barrier-equivalent impact speed is a sufficiently accurate measure of collision severity.

### Validation Of Barrier-Equivalent Impact Speed Distribution

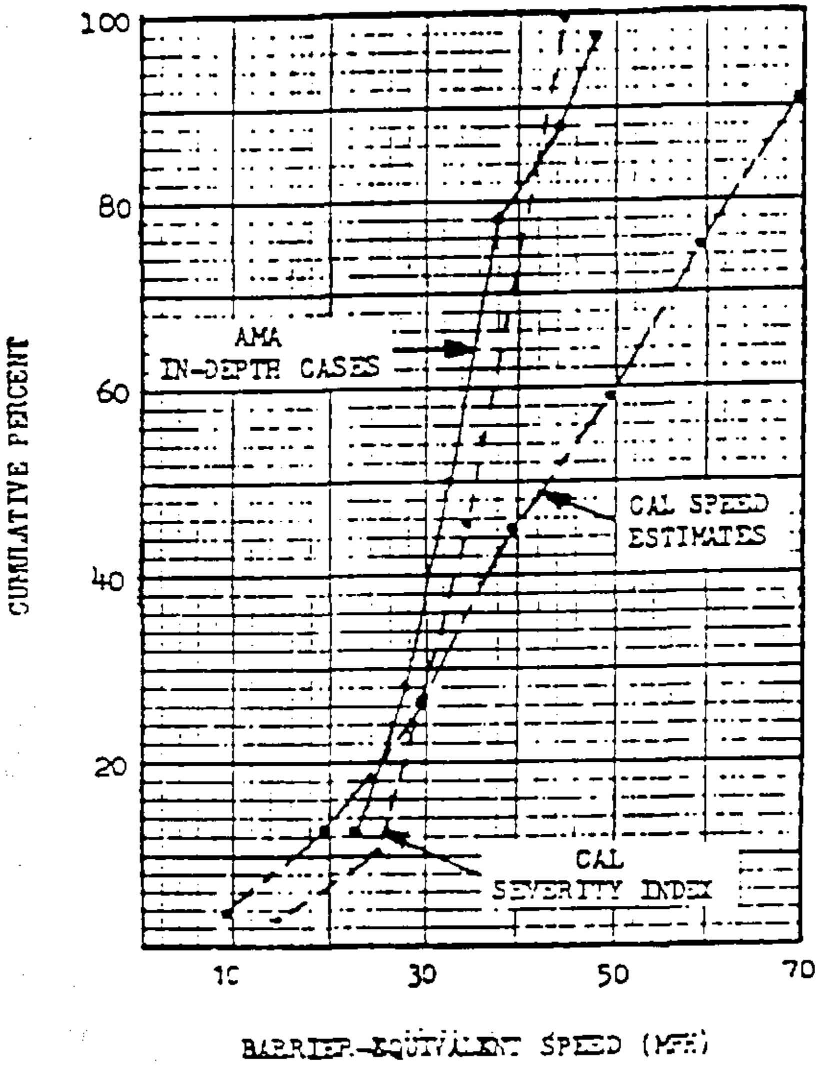
Barrier-equivalent impact speed distributions as derived from both approaches discussed in the preceding section are shown in Figure 21. The wide divergence between the two distributions, particularly at the higher speeds, indicates a major derivation problem associated with at least one of the distributions. This divergence is of concern because the two distributions are based on the same data file. Thus, an attempt was made to validate one of the impact speed distributions by comparing these two sets of barrier-equivalent speeds from the ACIR data with a similar distribution based on in-depth, or "clinical," accident investigations conducted under the sponsorship of the Automobile Manufacturers Association (AMA). Each of these rigorous investigations leads to a detailed report concerning a large number of accident-related vehicle and occupant parameters; about 800 such cases were contained in the data file. This file consists of investigations conducted by the UCLA Trauma Research Group, Mr. A. Siegel, Principal Investigator; and by the UM accident investigation group, Dr. D. Huelke, Principal Investigator. While these AMA cases are inappropriate as source data for this paper due to their small number and the lack of appropriate sampling techniques in their collection, similarity between the AMA and either of the ACIR impact speed distributions would tend to verify that distribution as being representative of the actual "real-world" speeds. The distribution of barrier-equivalent speeds for the 42 fatality vehicles impacted from the front in the AMA in-depth file, along with the two barrier-equivalent speed distributions based upon the ACIR data, are shown in Figure 21. The close resemblance of the AMA and the ACIR severity-rating-based distributions at least partially validates the severity-rating-based speed estimates actually used in this study.

Figure 21 suggests that the ACIR state trooper speed reports are grossly overestimated at the higher speeds. One possible explanation for this misrepresentation concerns the general manner in which the estimates are obtained by police organizations. The estimates are determined by means of reports of witnesses, on-scene interviews with vehicle occupants, and personal evaluation by the investigating officer. The personal evaluation may be influenced by the outcome, in terms of injury, of the accident--that is, speed may be overestimated in accidents resulting in serious injury, and underestimated in minor or no-injury accidents. The reports of witnesses and accident-involved vehicle occupants may be considered suspect in some cases--these people often have a vested interest in the speed reported by the trooper. In addition, the consistency of the estimates may be open to question due to the large number of evaluators (patrolmen) making estimates.

Even if the trooper errors in estimation are non-systematic, an overestimate of high-speed frequency would be found. That is because any error of measurement always serves to inflate the variance of the distribution of reported values, regardless of the nature of the data. Thus, reported variance (i.e., the mean-square deviation from the mean) is equal to the sum of "true" variance and "error" variance. White and Nelson(6) point this out, in suggesting that high speed estimates would tend to be exaggerated. They state that "errors in estimating speeds of accident-involved vehicles causes the involvement rate, when plotted as a function of the speed deviation, to be U-shaped—overestimated for large deviations (from the mean) and underestimated for small deviations." White and Nelson refer to traveling, not impact, speed, but the principle is the

FIGURE 21

PERCENTAGE DISTRIBUTION OF BARRIER-EQUIVALENT
SPEEDS FOR SINGLE COLLISION
FRONTAL FATALITY VEHICLES BY SOURCE OF DATA



same in either case. Furthermore, Wolf et al, (7) in an ACIR report, indicate that the reported ACIR traveling and impact speeds are somewhat allied. This close correspondence between the two was confirmed in a Ford study (8); in fact, a recent Department of Transportation study (9) assumed an exact one-to-one relationship between traveling and impact speed.

Thus, the involvement rate at high speeds (representing large deviations from the mean speed for all accident-involved vehicles) would tend to be overestimated, according to White and Nelson; in addition, the higher the speed, the greater this overestimate would tend to be. Other evidence that there is also some longrun exaggeration of the high speeds would compound the error.

## Single-Impact Fatality Distributions

Now that the parameters indicative of the accident situation have been defined, each single-impact fatality can be uniquely placed in a seated position by direction of force by accident severity category. With 6 seated positions, 12 directions of force, and 6 severity levels, there are potentially 6 x 12 x 6 = 432 tabular cells into which a fatality may be placed. In this study only the 108 cells associated with frontal (11, 12 and 1 o'clock) collisions were used. The placement of fatalities within such a table allows the proportion of fatalities in each cell to be determined. The percentage distribution of fatalities in frontal collisions is shown in Figure 22.

Certain marginal distributions may be derived from the data shown in Figure 22. The percentage distribution of seated position by direction-of-force is depicted in Figure 23. For the sake of completeness, the distribution is shown for all directions of force, even though only 11, 12 and 1 o'clock directions were used in determining potential restraint benefits. (These frontal directions account for about two-thirds of the fatalities.) Figure 23 also indicates that the driver and the right-front passenger constitute about 84 percent of all fatalities.

## Calculation Of Effectiveness In Single Impacts

Knowing the distribution of real-world accident situations and the effectiveness values provided by each occupant restraint system, one can calculate the number of lives that would be saved by each restraint in each accident situation. Summing all accident situations leads to the number of lives which would be saved through use of a given restraint system. Since each restraint has a different set of effectiveness values, combining this different set with the unaltered accident situation distribution yields a different number of lives saved for each restraint. (An example of a complete single-impact effectiveness calculation was presented earlier on page 20.)

## FIGURE 22

## PERCENTAGE DISTRIBUTION OF FATALITIES IN SINGLE-IMPACT ACCIDENTS

| | DRIVER | | | CENTER FRONT | | | RIGHT FRONT | | |
|---|---|---|---|---|---|---|---|---|---|
| | DIRECTION OF FORCE | | | DIRECTION OF FORCE | | | DIRECTION OF FORCE | | |
| CAL ACCIDENT SEVERITY RATING | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor | 0.19 | 0.83 | 0.11 | 0.02 | 0.07 | 0.01 | 0.08 | 0.39 | 0.09 |
| Moderate | 0.49 | 1.79 | 0.57 | 0.05 | 0.14 | 0.04 | 0.22 | 0.84 | 0.47 |
| Moderately Severe | 2.21 | 9.56 | 1.72 | 0.23 | 0.76 | 0.13 | 0.98 | 4.48 | 1.42 |
| Severe | 4.53 | 14.18 | 2.06 | 0.47 | 1.13 | 0.15 | 2.01 | 6.65 | 1.70 |
| Extremely Severe | 0.00 | 0.14 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.06 | 0.00 |
| Extreme | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00. | 0.00 |

| | LEFT REAR | | | CENTER REAR | | | RIGHT REAR | | |
|---|---|---|---|---|---|---|---|---|---|
| | DIRECTION OF FORCE | | | DIRECTION OF FORCE | | | DIRECTION OF FORCE | | |
| CAL ACCIDENT SEVERITY RATING | 11 | 12 | 1 | 11 | 12 | 1 | 11 | 12 | 1 |
| Minor | 0.02 | 0.04 | 0.01 | 0.01 | 0.02 | 0.00 | 0.01 | 0.04 | 0.01 |
| Moderate | 0.05 | 0.08 | 0.04 | 0.02 | 0.04 | 0.01 | 0.03 | 0.08 | 0.05 |
| Moderately Severe | 0.21 | 0.41 | 0.11 | 0.10 | 0.24 | 0.04 | 0.14 | 0.44 | 0.14 |
| Severe | 0.42 | 0.61 | 0.13 | 0.20 | 0.35 | 0.05 | 0.29 | 0.65 | 0.17 |
| Extremely Severe | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Extreme | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

FIGURE 23

## PERCENTAGE DISTRIBUTION OF FATALITIES IN SINGLE-IMPACT ACCIDENTS, BY SEATED POSITION AND DIRECTION OF FORCE

| DIRECTION OF FORCE (O'CLOCK) | SEATED POSITION | | | | | | |
|---|---|---|---|---|---|---|---|
| | DRIVER | CENTER FRONT | RIGHT FRONT | LEFT REAR | CENTER REAR | RIGHT REAR | TOTAL |
| 1 | 4.5 | 0.3 | 3.7 | 0.3 | 0.1 | 0.4 | 9.2 |
| 2 | 1.8 | 0.4 | 2.4 | 0.2 | 0.3 | 0.5 | 5.6 |
| 3 | 4.2 | 0.7 | 3.8 | 0.5 | 0.1 | 0.9 | 10.3 |
| 4 | 0.8 | 0.0 | 0.8 | 0.0 | 0.0 | 0.2 | 1.9 |
| 5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.3 |
| 6 | 0.8 | 0.1 | 0.4 | 0.1 | 0.0 | 0.3 | 1.7 |
| 7 | 0.4 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.7 |
| 8 | 0.8 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 1.3 |
| 9 | 4.4 | 0.3 | 0.9 | 0.6 | 0.2 | 0.4 | 6.7 |
| 10 | 3.4 | 0.3 | 0.6 | 0.5 | 0.0 | 0.4 | 5.2 |
| 11 | 7.4 | 0.8 | 3.3 | 0.7 | 0.3 | 0.5 | 13.0 |
| 12 | 26.5 | 2.1 | 12.4 | 1.1 | 0.7 | 1.2 | 44.0 |
| TOTAL | 55.1 | 5.0 | 29.0 | 4.2 | 1.9 | 4.8 | 100.0 |

## Multiple Impact Effectiveness

Each multiple impact consists, by definition, of an initial impact followed by one or more additional collisions; these ensuing crashes will collectively be termed, "the subsequent impact." The sample of multiple impact fatalities can thus be divided: one portion consisting of occupants killed in the initial impact, and the remaining portion composed of occupants killed in the subsequent impact. Since the restraint benefit will be different in each of these portions, an estimate of the relative portion of the total sample in each division must b. obtained.

Division of Lethality. The source of information on the division of lethality consisted in part of the AMA in-depth data file, discussed earlier on page 36. In addition, about 450 Multidisciplinary Accident Investigations conducted by a number of groups under the sponsorship of the National Highway Traffic Safety Administration (NHTSA) were examined for relevant information. These investigations are conducted in a manner similar to that described above for the AMA investigations. From these two sources, 30 multiple impact fatality cases were discovered. The narrative account of each of these thirty cases was examined to determine which of the impacts, the initial or the subsequent, produced the fatal injury. It was found that 9 of the 30 fatalities (30%) resulted from the first impact, while the remaining 21 deaths (70%) were caused by the subsequent impact. These values, 30 percent and 70 percent, were thus taken to be the likelihoods of each impact, initial or subsequent, producing the fatality in a multiple impact accident.

Although the sample upon which this division is based is rather small (30 cases), it is well to remember that well over 1000 in-depth investigations were examined to yield the sample, and that no other comparable source of information is known to exist.

Initial-Impact Effectiveness. Initial-impact proportional effectiveness was determined in the same way as single-impact effectiveness. For each restraint system, the appropriate table of effectiveness values is multiplied, cell-by-cell, by an accident situation matrix for multiple-impact fatality occurrences. The sum of the resultant products represents the proportional life savings appropriate for the 30 percent portion of the multiple-impact fatalities assumed to occur in the first impact.

For these occupants, it was assumed that no further protection is required in the following impacts. In fact, however, it is possible that the subsequent impact could also be life-threatening. Ignoring this possibility, as we have in this study, artifactually enhances the effectiveness of passive restraints, and air bag systems in particular.

Once an air bag is deployed, no residual benefit remains for any subsequent collision; belt systems, on the other hand, maintain a high level of protection throughout the sequence of collisions.

Subsequent Impact Effectiveness - The benefit assigned to restraint systems for those occupants killed in the subsequent collision depended on the positioning afforded by a lap belt. For those occupants whose restraint included a lap belt, the entire restraint was assumed to be fully operational in the subsequent impact. It was presumed that the lap belt would retain the occupant reasonably in place through the initial impact and hence allow the complete restraint to perform its designed function. The actual proportional effectiveness was thus calculated exactly as if the impact had occurred first.

This postulation produces an overestimate of lives saved for the air bag plus lap belt restraint. Assuming that the air bag is always operable in the subsequent collision is inaccurate for all instances in which the air bag deployed on a previous impact -- probably at least half the time. This overestimate very likely occurs, to a much lesser degree, for other active-passive hybrid restraint systems.

It was assumed that completely passive restraints would furnish no subsequent impact protection at all. The unbelted occupant would tend to be severely displaced by the initial impact, and would not be positioned to receive benefit in the subsequent lethal impact. On the contrary, Ford impact tests have shown that air bag deployment itself can impart seriously high decelerations to a mispositioned occupant, and thereby possibly jeopardize occupants previously not imperiled.

Assigning no subsequent impact benefit to the high-impact panel by itself probably leads to an underestimate of the overall protection offered by this restraint. Impact-induced mispositioning in some situations could actually improve the protection of the panel, since the occupant might "ride-down" the otherwise lethal subsequent impact, thus receiving lower decelerations.

### Rollover Effectiveness

Life savings in both principal and collision rollovers is related to the reduction in the incidence of ejection resulting from the use of a restraint system. Among occupants of overturned vehicles, ejectees are killed much more frequently than are non-ejectees in both types of rollovers. Reducing the incidence of ejection would thus reduce the proportion of occupants killed. Preventing ejection would not (by itself) completely eliminate rollover fatality, however, since a portion of the non-ejected occupants are still killed in each rollover type.

The life savings potential in rollovers was determined by placing a portion of the previously ejected occupants inside the vehicle; some of these previously ejected occupants who were formerly fatalities are no longer killed. As explained in Appendix F, each restraint system has its own characteristic estimated ratio of ejectees to total occupants. The percentage of lives saved with each system represents the overall effectiveness of that system in the rollover situation. For each rollover type a seperate, but analogous, life savings analysis was performed.

The very conservative assumption was made that no benefit from restraints would accrue to non-ejected occupants in rollovers. While this assumption is rather pessimistic, other studies also have indicated that the primary benefit of restraints is in ejection control; restraints inhibit ejection and its increased risk of serious injury.

Even if some benefit does accrue to non-ejected occupants in rollovers, it would be overshadowed by ejection prevention anyway. Furthermore, assessing the extent of this benefit would be difficult, particularly for collision rollovers. An attempt was made in this report to present benefits only when the derivation could be reasonably well substantiated. The detailed procedure with which effectiveness in each rollover type was determined may be found in Appendix F.

### Application of Effectiveness Values Derived from this Study To Nationwide Fatalities in 1969

A procedure has been developed for assessing restraint system effectiveness within each of the impact types. Summing the effectiveness for each impact type, weighted by the proportion of that type shown in Figure 22 produces the overall life savings potential of each system. These effectiveness measures may then be compared with each other to establish the relative benefit of each restraint.

Some modification in the number of passenger car fatalities shown in Figure 16 must be made before these data can be used as a basis for estimating an actual number of lives saved. These adjustments are necessary because the impact type distribution shown in Figure 17, as well as the effectiveness measures for each type, assumes that each occupant is unrestrained; this does not describe the 1969 situation. Restraint system usage in 1969 was taken to be 30 percent lap belt usage, plus 1 percent harness system usage. (Any change in these usage estimates would change the actual estimates of lives saved slightly, but would not affect the relative contribution of different systems). It was assumed that benefit was uniformly distributed among all users and that no differential accident-proneness existed among wearers and non-wearers. Although this may be a questionable assumption, no quantitative grounds for an alternative formulation was evident. Using the effectiveness percentages discussed above, an estimate of the number of fatalities which would have occurred had no restraints been used was established. The algebraic procedure by which this was accomplished is found in Appendix G. This anticipated fatality distribution (Figure 24) becomes the foundation to which the effectiveness measures can be applied. The number of lives saved with use of each restraint system is then estimated by applying the percentage of lives saved within each impact type to the projected number of lives lost. Figure 25 is an extension of Figure 16 obtained from the anticipated fatality distribution by applying the effectiveness measures associated with actual 1969 restraint usage.

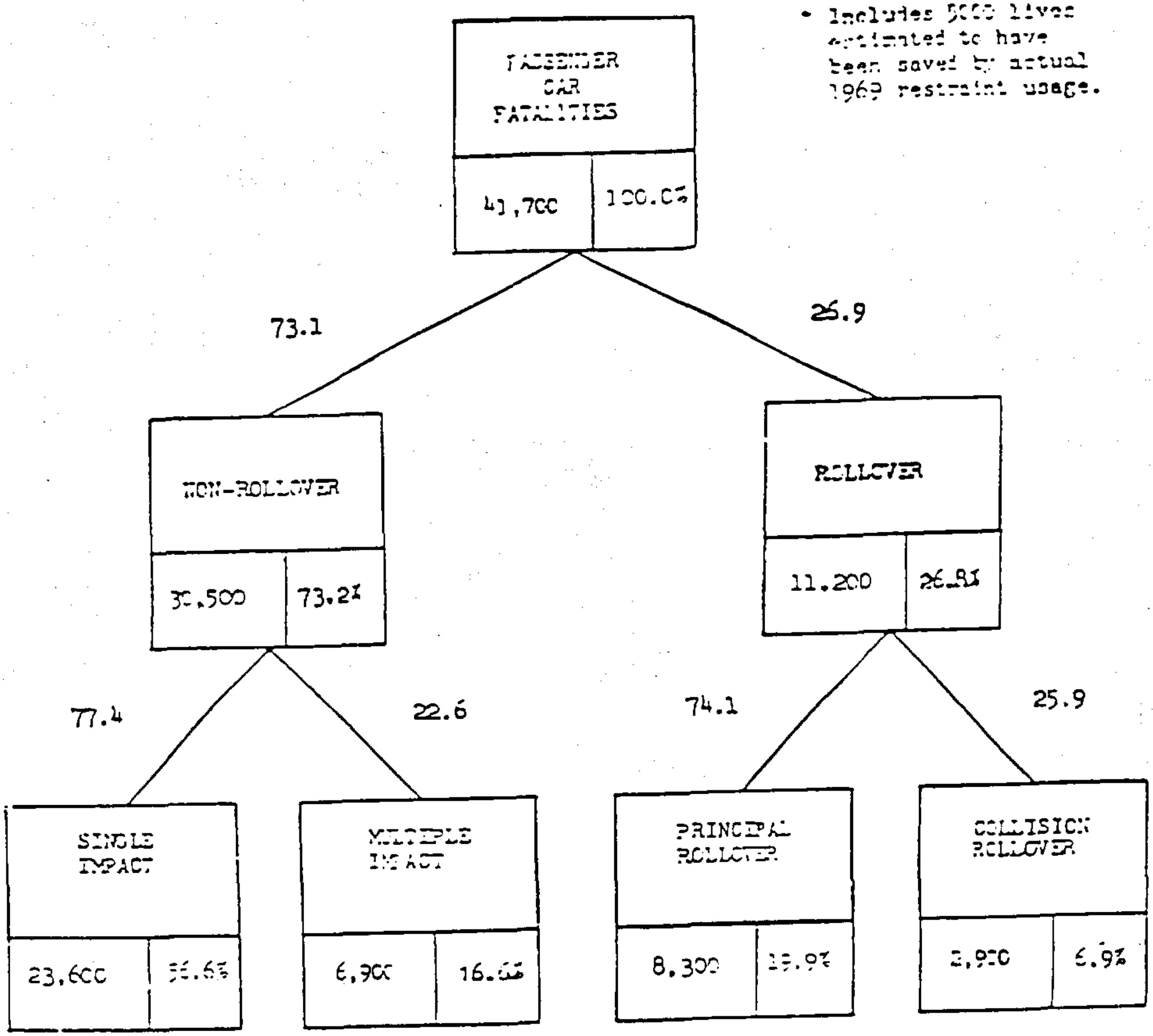
## RESULTS

Figure 26 presents the lives saved for each restraint component examined in this study. It indicates that the energy absorbing column by itself would save about one-fifth of all drivers. Adding a constant-force harness increases this protection to include about two-thirds of those drivers who would otherwise have been killed. For front passengers, lap belts and air bags each save about the same number of lives. As will be indicated in Figure 27, these savings are distributed quite differently into the various impact types. The high-impact panel simulated in this study does not exhibit the same degree of benefit as does each other system; this panel installed for all front and rear passengers would, by itself, have saved 6% of the total passenger car fatality population in 1969.

Fifteen alternative restraint system configurations, composed of the components in Figure 26, were evaluated for life-saving value. Those results are shown in the section that follows.

FIGURE 24

ANTICIPATED 1969 PASSENGER CAR FATALITY DISTRIBUTION WITH NO RESTRAINT USAGE*



* Includes 5000 lives estimated to have been saved by actual 1969 restraint usage.

FIGURE 25

1969 PASS [illegible] CAR FATALITY DISTRIBUTION:
ASSUMING 30 [illegible] T AND 1% HARNESS SYSTEM USE