RESTRAINT-SYSTEM EFFECTIVENESS

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•IN THIS study, 3 passenger-car, occupant-restraint systems are compared as to their potential effectiveness in saving lives. The systems studied include both existing restraints, such as lap belts and shoulder harnesses, and proposed restraints, such as air bags. The potential number of lives that could be saved each year through the universal installation and use of each restraint system is calculated, and the estimates are then compared. 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 relative effectiveness of the systems.

For each of the restraint systems studied, it was assumed that the car was equipped with an advanced steering column incorporating improved energy-dissipating characteristics. The lap-belt system consisted of a lap belt for each occupant. The shoulder-harness system was the one currently installed in passenger cars—a lap belt for each occupant with a shoulder harness in addition for the driver and right-front passenger. The third system evaluated was the air-bag system that consisted of a dynamic air bag plus a lap belt for each occupant. This system was evaluated both with and without each occupant using his lap belt. The air bags simulated in this study exhibit occupant-protection characteristics that to our knowledge are not attainable with currently developed air-bag systems. The near-term development of a system with such properties is considered feasible, however.

METHOD

Two broad tasks were undertaken to obtain the lives-saved estimates. One of the tasks involved mathematical modeling of each occupant-restraint and vehicle system in order to establish potential occupant head and chest decelerations in each of a number of narrowly categorized crash situations. Human-tolerance formulations were then used to convert these decelerations into values reflecting the ability of the restraint to save lives in each given crash situation.

The second major effort in the study was an examination of traffic accident records to determine the relative frequency of fatalities occurring in each crash situation. Two major sources of accident data were used. Total motor vehicle accident fatality data were drawn from the annual report of the National Safety Council (NSC). Distribution of fatalities by type of accident was developed from data provided by the Automotive Crash Injury Research (ACIR) program of the Cornell Aeronautical Laboratory.

Distribution of Fatalities

Motor vehicle fatalities can be categorized in a number of ways; among these is classification by placement of the fatality, e. g., truck or car occupant or pedestrian. The distribution of the 56,400 fatalities reported by NSC for 1969 is given in the tabulation. About a fifth of the fatalities (10,700) were not occupants of motor vehicles; included are pedestrians and bicyclists. Among the occupants, about a fifth were in vehicles other than passenger cars; those 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,

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because of the nature of the safety systems being considered, strictly to these passenger-car occupants.

Category	Number	Percent
Vehicle occupant	45,700	81
Truck	8,600	15
Passenger car	37,100	66
Pedestrian	10,700	19
Total	56,400	100

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 the vehicle rolled over. Among non-roll-overs, a single impact designation means that the vehicle in which the fatality occurred (fatality vehicle) collided with exactly 1 other object (which may be another vehicle); the multiple impact category includes fatality vehicles that collided with more than one object. An accident is classified as a principal roll-over when the fatality vehicle overturns without striking any other substantial object. Finally, a collision roll-over designates an accident in which the fatality vehicle collided with some object in addition to overturning.

A distribution of fatalities among these categories is as follows:

Category	Number	Percent
Non-roll-over	1,208	73.2
Single impact	934	56.6
Multiple impact	274	16.6
Roll-over	441	26.8
Principal	327	19.9
Collision	114	6.9
Total	1,649	100.0

The source for this distribution was the accident data bank maintained by the ACIR. That file consists of accident records on more than 50,000 rural, injury-producing accidents. Only the 23,000 records concerning passenger cars of model year 1960 or later were considered for use in the study so that the sample selected would more closely reflect current design level. Among the completely unrestrained occupants in this sample of vehicles, 1,649 fatalities were found, and those fatalities constitute the sample distributed by vehicle impact type. Safety-system effectiveness was determined separately for each of those impact types.

Single-Impact Effectiveness

Because most fatalities are found in the single-impact category, it seems appropriate to concentrate most of the technique description on this impact type. The life-saving benefit analysis was initiated by developing a measure that might be considered as an index of effectiveness; this measure was an estimate of the proportion of fatalities in a given accident situation that would be eliminated through occupant use of a certain restraint system. An example may make this concept of an effectiveness factor more clear.

Consider, for example, an accident situation of striking an abutment at 40 mph. Because our defined criterion is fatality reduction, our interest in this situation is only in the occupants who were killed. Suppose that all the occupants who were killed in such crashes in 1 year are counted. The question is, How many of those occupants would survive if we could repeat all the crashes with all the occupants furnished with, say, air bags? The ratio of the number saved to the original number killed represents an index of the effectiveness of the particular restraint in the given crash situation. With a different restraint system, the effectiveness factor for this accident situation may be different. In addition, varying one of the parameters determining the accident situation would lead to a separate effectiveness factor determination.

A number of variables were used to identify the accident situation for each fatality. One of these was the seated position of the occupant. Six different seated position values were used, corresponding to the 6 normal occupant locations within the vehicle. A second factor used to describe the accident situation was the impact direction applied to the fatality vehicle. The 12 o'clock positions were used as values for this descriptor, with 12 o'clock representing a direct frontal collision. The third measure used in describing the accident situation was the impact severity, measured in terms of vehicle speed into a fixed barrier. The possible barrier speeds were partitioned into 6 ranges in a manner discussed below.

Now that the parameters indicative of the accident situation have been defined, effectiveness of each restraint within each seated position by impact direction by impact severity category can be evaluated. With 6 seated positions, 12 impact directions, and 6 impact severity levels, there are potentially $6 \times 12 \times 6 = 432$ tabular cells for which restraint-effectiveness factors could be determined. In this study, potential life-saving benefits were determined only for the 108 cells associated with frontal (11, 12, and 1 o'clock) impacts. Because most impact dynamics research, both empirical and theoretical, has been conducted with frontal impacts, comparatively little is known about dynamics in side and rear impacts, particularly when restraints are involved. The purpose of this study was to evaluate restraint systems; therefore, we feel it was justified to limit the calculations to those conditions in which the restraints would be significantly operative, the frontal impacts.

Head and Chest Decelerations

For each restraint, an effectiveness factor associated with each accident situation cell was developed. The effectiveness evaluations were based on occupant head and chest decelerations obtained from the application of computer models simulating the physical dynamics of the crash.

The Computer Simulation of the Automobile Crash Victim(1), developed at the Cornell Aeronautical Laboratory, was used for all simulations except the air bag. This is an 11-deg-of-freedom planar model of an occupant and a vehicle interior during a frontal collision. Because the Cornell model does not currently include a dynamic air-bag simulation, another model developed at Ford Motor Company especially for air-bag simulation was used. That model considers the air bag as functionally analogous to a piston, with the energy of an impacting upper torso dissipated by compressing the gas in the bag and forcing the compressed gas through an exit orifice. Tests have shown that chest decelerations are the limiting factor in predicting survival for air-bag-restrained occupants; therefore, only chest loads are measured in this simulation.

The 3 systems studied consist of a number of basic restraint components. The peak head decelerations that were obtained for each component at each speed are shown in Figure 1, and chest decelerations are shown in Figure 2.

It was more convenient to use the peak deceleration level rather than some average or "effective" level, although the latter may be more appropriate. This use of peak values seemed justified because all the measured deceleration pulses tended toward a skewed-bell shape, yielding a relatively constant relation between peak and effective deceleration values. This idealized condition is not always found in real crashes, where the waves are more irregular and sometimes have thin "spikes"—of doubtful significance—superimposed on the basic pulse shape.

Small, medium, and large occupants were simulated for each restraint component, corresponding to the 5th percentile female, 50th percentile male, and 95th percentile male. From decelerations measured for each of the 3 occupant sizes, a resultant value representing an "average"-sized occupant was determined, and those are the values shown in Figures 1 and 2.

Human Tolerance to Deceleration

As the peak decelerations increase, the likelihood of an occupant surviving the blow decreases. The relation between the deceleration measures and the likelihood of survival is shown in Figure 3. The relation is based on extensive impact tolerance research conducted at the University of Michigan Highway Safety Research Institute (HSRI) and elsewhere and is appropriate for deceleration pulse durations at the indicated level of longer than 20 milliseconds. The head impact tolerance curve was developed at HSRI itself, while the HSRI representatives concurred with the chest tolerance curve following its development at Ford Motor Company.

Combining the impact tolerance relation shown in Figure 3 with the decelerations shown in Figures 1 and 2 allows the life-saving potential of each restraint system to be assessed. For example, a driver using the harness system will sustain, in a 40-mph barrier-equivalent crash, a peak deceleration of about 95 head g's (Fig. 1) and 58 chest g's (Fig. 2). These values are referred to the relation shown in Figure 3, and the lower of the 2 associated survival likelihoods, 0.75 in this case, is taken to represent the effectiveness factor in this situation.

Now that a method for assessing restraint-system effectiveness in each accident situation has been developed, the question becomes, How many fatalities occurred in that situation to start with? The source for determining the proportion of fatalities that occur in each accident situation was the 934 single-impact fatalities contained in the ACIR sample.

Two of the parameters used to characterize the accident situation, seated position and impact direction, are coded directly by ACIR. The third parameter, accident severity as measured by barrier-equivalent speed, was developed from an accident severity rating assigned to each case by the ACIR coders.

Barrier-Equivalent Speed Distribution

This severity level is coded by ACIR personnel on the basis of deformation and frame damage shown in vehicle photographs. The relation between severity and barrier-equivalent speed was established by a careful matching of reference photographs (used by the ACIR coding experts in determining the severity level) with photographs of crashes conducted by Ford Motor Company at known impact speeds. This matching allowed an estimation of a range of speeds into a fixed barrier producing about the same damage as shown in each reference 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. One of those adjustments was applied to each of the crashes in the sample to isolate the proportion of crash energy dissipated along the impact direction line, thus discounting the portion of energy associated with rotation or "spin-out." A second adjustment was made to the overall speed distribution to correct the rural bias of the ACIR data source. The cumulative effect of these 2 alterations was rather minor.

Figure 4 shows that the median barrier-equivalent speed for fatality vehicles in frontal collisions was less than 40 mph. This distribution concerns only vehicles in which a fatality occurred; if vehicles in lesser or no-injury accidents had been considered, the distribution would be shifted downward considerably.

Also shown in Figure 4 is an impact-speed 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 Trauma Research Group at the University of California, Los Angeles, and by the accident investigation group at the University of Michigan. The distribution of barrier-equivalent speeds for the 42 fatality vehicles impacted from the front in the AMA in-depth file, along with the distribution based on the ACIR data, is shown in Figure 4. Although these AMA cases are inappropriate as source data for this paper because of their small number and the lack of appropriate sampling

Figure 1. Maximum head decelerations for various restraints.

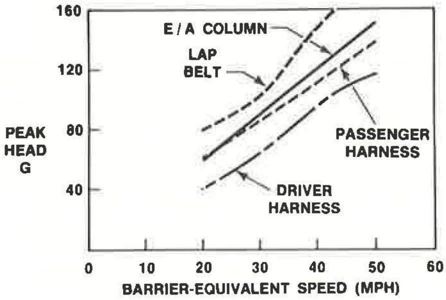

Figure 2. Maximum chest decelerations for various restraints.

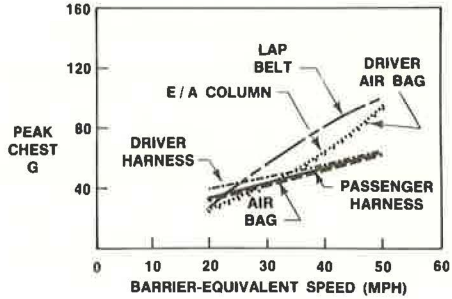

Figure 3. Probability of survival as a function of maximum deceleration.

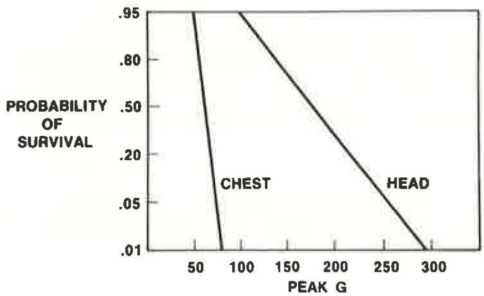

Figure 4. Barrier-equivalent speeds for single-impact frontal fatality vehicles.

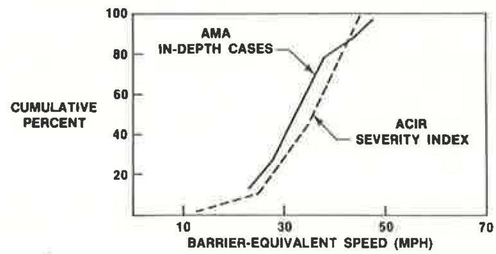

Table 1. Estimated passenger car occupant lives saved in 1969 with complete use of each safety system.

	Non-Roll-Over		Roll-Over		
Restraint System	Single Impact	Multiple Impact	Without Collision	With Collision	Total
Shoulder harness for driver and right-front occupant and lap belts for all other occupants	11,700	2,300	6,500	1,100	21,600
Lap belt for all occupants	7,400	1,600	5,900	1,000	15,900
Air bag only for all occupants	9,700	900	200	100	10,900
Air bag with lap belt for all occupants	9,900	2,000	6,100	1,000	19,000

Figure 5. Lives saved as a function of active restraint system used.

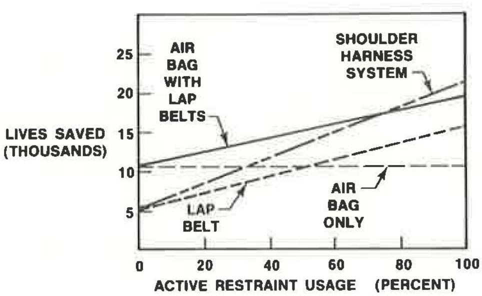

Table 2. Estimated baboon and human head-on crash survivability as a function of restraint system used.

Restraint System	Baboon Test LD-50 Speed[a] (mph)	Scaled Human LD-50 Speed[a] (mph)	Assumed Cumulative Crash Fatalities Saved With 100 Percent Usage of Restraint[b]: Percent	Lives/Year
Lap belt only	31	21	<10	<3,700
Lap and shoulder belt	45-57[c] (52)	30-38[c] (35)	27-70[c] (46)	10,000-26,000[c] (17,000)
Air bag and lap belt	59	40	74	27,500
Air bag only	>60[c]	>41	>76	>28,200

[a]LD-50 speed refers to the estimated barrier equivalent speed at which the deceleration experienced by the user of the given restraint system would be lethal to half of the healthy population.

[b]This assumes that LD-50 speed approximates the median fatal speed for the population. Savings are taken from Figure 4, ACIR curve.

[c]57 mph with elaborate Air Force double shoulder harness system [12]. Single diagonal belt is probably 10 to 20 percent less effective.

techniques in their collection, the close resemblance of the AMA and the ACIR distributions at least partially validates the severity-rating-based speed estimates used in this study.

Calculation of Single-Impact Effectiveness

Each single-impact fatality can be uniquely placed in an accident category, according to seated position by impact direction by barrier-equivalent speed. Knowing the distribution of real-world accident situations and the associated effectiveness provided by each occupant-restraint system, one can calculate the number of lives that would be saved by each restraint in each accident situation.

For example, consider all the driver fatalities that resulted from a 12 o'clock or direct (frontal) crash at a barrier-equivalent speed between 36 and 45 mph. The deceleration and human-tolerance formulations discussed earlier predict that, if all drivers used the shoulder-harness system, 75 percent of the fatalities would be eliminated. The distribution of ACIR fatalities places about 14 percent of all single-impact fatalities in the designated accident situation. The product of an effectiveness factor indicative of the fatalites eliminated (0.75 in this example) times the corresponding actual proportion of total fatalities (0.14 here) gives the proportion of the total existing fatalities that would be eliminated in the particular accident situation.

The sum of these proportional lives-saved estimates across the 3 accident situation variables (seated position, impact direction, and barrier-equivalent speed) yields the percentage of existing fatalities that would no longer occur as a result of usage of the given restraint system. For example, for 100 percent usage of the shoulder-harness system, these proportions sum to 0.49. 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. The procedure for determining single-impact 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 remains unchanged.

Multiple-Impact Effectiveness

Each multiple impact consists, by definition, of an initial impact followed by one or more additional collisions; those ensuing crashes will collectively be termed the subsequent impact. The sample of multiple-impact fatalities can thus be divided into 1 portion consisting of occupants killed in the initial impact and 1 portion consisting of occupants killed in the subsequent impact. Because the restraint benefit will be different in each of these portions, and estimate of the relative portion of the total sample in each division must be obtained.

The source of information on the division of lethality consisted in part of the AMA in-depth data file, which was discussed earlier in connection with the barrier-equivalent speed validation. 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. Those investigations are conducted in a manner similar to that described above for the AMA investigations. From these 2 sources, 30 multiple-impact fatality cases were discovered. The narrative account of each of the 30 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 percent) resulted from the first impact, while the remaining 21 deaths (70 percent) were caused by the subsequent impact. These values, 30 and 70 percent, were thus taken to be the likelihoods of each impact, initial or subsequent, producing the fatality in a multiple-impact accident.

Initial-impact proportional effectiveness was determined in the same way as single-impact effectiveness. For the 30 percent portion of the multiple-impact fatalities assumed to occur in the first impact, no further calculation was made of effects from the following impacts. In fact, however, it is possible that the subsequent impact could also be of life-threatening severity.

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 that impact had occurred first.

It was assumed that completely passive air-bag systems would furnish no subsequent-impact protection at all. The reason is that air bags rapidly deflate upon occupant loading, a necessity for appropriate energy absorption. Therefore, a functioning air bag would not be available for subsequent impacts. Even if the bag did not inflate in the initial impact, the unbelted occupant would tend to be severely displaced in that impact and would be poorly positioned to receive any benefit in the subsequent impact.

Roll-over Effectiveness

Saving lives in automobile roll-overs is dependent on reducing the incidence of ejection and its associated high risk of fatality. A certain proportion of the occupants of overturned passenger cars are killed, whether or not they are ejected. If an occupant is ejected, however, his risk of fatality increases significantly.

The consequences of roll-over involvement for the 1,486 principal-roll-over and 362 collision-roll-over occupants found in the ACIR data file are as follows:

Category	Number	Percent
Principal roll-over	1,486	
Not ejected	1,031	69.4
Not fatal	1,017	98.6
Fatal	14	1.4
Ejected	455	30.6
Not fatal	373	82.0
Fatal	82	18.0
Collision roll-over	362	
Not ejected	281	77.6
Not fatal	258	91.8
Fatal	23	8.2
Ejected	81	22.4
Not fatal	55	67.9
Fatal	26	32.1

Only occupants of 1964 model year or later cars were selected for this sample. These figures indicate that 30.6 percent of the principal-roll-over occupants and 22.4 percent of the collision-roll-over occupants are ejected. They also show that 1.4 percent of the nonejected occupants of principal roll-overs were killed, while 18.0 percent of the ejectees were killed. For collision roll-overs, 8.2 percent of the nonejected and 32.1 percent of the ejected occupants were killed. It is clear from these data that being ejected from the vehicle increases considerably the likelihood of being killed.

It was assumed that, whatever the restraint in question, the risk of fatality for each ejection condition was the same as that indicated in the preceding data. This means, for example, that in a principal roll-over accident an ejected occupant was killed 18 percent of the time and a nonejected occupant was killed 1.4 percent of the time, no matter which restraint was used, if any.

What differentiated the restraint systems was the proportion of occupants who were ejected. It was assumed on the basis of a Cornell Aeronautical Laboratory study (2) that a lap belt reduced the ejection probability to about 3 percent and that a shoulder harness essentially precluded ejection completely. On the other hand, an air bag all by itself had a very negligible effect (a 1 percent reduction) on the proportion of occupants ejected. Adjusting this ratio of occupants ejected to those not ejected from the values for unrestrained occupants allowed us to estimate a number of lives saved that would result from use of each of the occupant restraint systems in roll-over crashes.

Actual Restraint Usage Adjustment

Some modification in the number of passenger car fatalities given earlier 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 ACIR impact type of distribution, 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 the total car population in 1969 was taken to be 30 percent lap-belt usage, plus 1 percent shoulder-harness usage. Using the effectiveness-calculation procedures described above, it was determined that 41,700 passenger car occupants would have been killed in 1969 if no one had used restraints. The difference between this number and the actual number of 37,100 given earlier represents lives saved in 1969 by existing restraint usage.

RESULTS

Table 1 gives the lives saved by the restraint systems considered in this study, assuming that all cars are so equipped and that there is complete usage of active restraints in those configurations where they are provided.

The current production harness system (lap belts for all occupants and harness for driver and right-front occupant), if it had been installed in all vehicles and been universally used, would have saved 21,000 lives in 1969. Most of the savings is in the single-impact category, where most of the fatalities themselves occur. A substantial saving of lives is found in the roll-over categories, however.

Usage by all passenger car occupants of the lap-belt-only system in 1969 would have saved 15,900 lives. Lap belts by themselves are nearly as effective as the harness system in preventing roll-over fatalities. In the non-roll-over situation, however, a large difference in benefit is found between lap-belted occupants with and without harnesses.

Universal installation of the air-bag system, with no usage of the available lap belts (a completely passive arrangement), would have saved 10,900 lives in 1969. Although the non-roll-over performance of this system is quite good (better than the lap belt alone, for example), the roll-over savings are negligible. Utilization of the lap belts in this air-bag system, while not affecting non-roll-over performance appreciably, has a large roll-over benefit, and thus increases the total savings substantially to 19,000 lives.

Figure 5 shows the lives saved for a number of restraint systems as a function of the percentage of occupants using the system. With no restraint "usage," the air-bag system saves 10,900 lives. The intersection of the dashed lines drawn across the figure at this level of savings with the lines for the other restraint systems indicates the active restraint usage rate needed to equal this purely passive system in benefit. The 5,700 lives saved with no lap-belt or harness-system usage consists of drivers saved by the advanced steering column.

Figure 5 shows that lap-belt use of 51 percent would save as many lives as the air-bag system with no-belt usage (10,900 lives). A 32 percent usage rate of the harness system would produce equivalent savings. Greater usage of either active system would, of course, produce greater benefit.

With 68 percent usage of the shoulder-harness system, a few more than 16,000 lives would be saved. This same percentage of lap-belt use in cars furnished with the air-bag system (with the remaining 32 percent of the occupants protected by the air bag alone) produces corresponding savings. If the usage rate of the active components in each system is the same, and this rate is greater than 68 percent, more lives are saved with the harness than with the air-bag system.

In conclusion, it seems as though the shoulder-harness system could potentially save more lives than could the simulated air-bag system. The harness system is valuable, however, only if used. A passive-restraint system, such as the air-bag system, is assumed to be beneficial in many situations regardless of the actions of the occupants.

Either system, the harness or the air bag, requires the use of the lap belt to be fully effective.

It is estimated that at the present time in cars so equipped some 40 percent of the occupants avail themselves of their lap-belt protection but only 4 percent of the drivers use their shoulder harnesses. If suitable air bags were developed and were in all cars in the population today, more lives would be saved by them than would be saved with the current 40 percent lap-belt usage. However, no suitable air-bag system has yet been developed; therefore, no cars today are equipped with air bags, and their installation in the total car population is still many years away, at best. In contrast, most cars on the road today are equipped with lap belts and many with shoulder belts. Thus, it seems that some way of increasing belt usage would unquestionably be extremely beneficial in saving lives and would surely be the most cost-effective way of increasing substantially the number of lives saved.

REFERENCES

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DISCUSSION

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One is required, in the study of many-faceted problems such as this one, to make some simplifying assumptions that stand or fall based on the judgment of the reader. Some of these assumptions deserve discussion.

Let us first examine the conclusion reached in the final sentence of the paper, which states that some way of increasing usage of active restraints would surely be more cost-effective than passive restraint systems but suggests neither how it would be accomplished nor what it would cost. The conclusion is unsupported. The magnitude of the task of increasing restraint-system usage is underestimated by the authors, who imply that the group composed of more than 60 percent of all car occupants who do not habitually wear belts can be induced to do so without appreciable cost. One very recent occupant motivation study concludes that only gradual, limited success will be seen (2). Reliable data on cost and effectiveness of systems designed to improve belt usage are not available. In the absence of specified alternatives and cost data, conclusions about the "most cost-effective" alternative are not justified.

USAGE

The 40 percent lap-belt usage figure is probably based on a very optimistic estimate by the National Safety Council and should be referenced. Actually, belt usage is highly variable with geography and other factors. Some estimates have been made based on interviews and questionnaires, but actual observations show lower usage. Many studies, some very recent ones, indicate an actual lap-belt usage below 20 percent (3, 4, 5). Further, among those who can be induced to wear the belt systems, many are unable to realize full benefits for they cannot (because of anatomy and belt design) or do not (because of personal preferences or ignorance) wear the belts properly. Belts can cause serious injury if improperly worn (6).

TOLERANCES

Another source that should be better referenced is the human tolerance data shown in Figure 3. The data and assumptions used in the preparation of this figure have not yet been published in complete form. The data, based on extrapolation from experiments with rhesus monkeys and other small primates, are a pivotal part of the study and should certainly be available for public examination. The chest injury data are particularly suspect (7). [The head-impact curve shown in Figure 3 is based on an extrapolation from primate experiments. The chest curve was not produced by HSRI (7).]

EJECTION

In their discussion of ejection, the authors omitted the effect of recent automotive innovations that are certainly important. The ACIR data bank includes primarily vehicles produced before 1970. The authors have used only that portion of the data that deals with cars of model year 1960 or later. In 1968 new door locks were required on passenger vehicles, and in 1970 windshield retention requirements were introduced, reducing the probability of ejection (8, 9). Thus, the ejection fatality rates used in the study are not fully representative of the substantially improved ejection behavior of modern vehicles (10). (The CAL study shows a 70 percent reduction in door-opening frequency by late model cars.)

MODELING

The techniques used for modeling the restraint systems should also be compared. Whereas the elaborate 11-deg-of-freedom Cornell Automobile Crash Victim Simulator was used for the belt systems, a simple, 1-deg model was assumed for the air-bag occupant. The improved distribution of force over the head and torso that is afforded by the air bag was thus ignored. Perhaps more important, both models ignored the effects of localized force on human tolerance. Both are purely kinematic analyses. The differences in method of application of deceleration forces cannot be overlooked: certainly the broad distribution of the air-bag forces will lead to smaller local pressures on the occupant and, consequently, to decreased likelihood of injury and fatality.

Several factors relating to the effectiveness of lap-belt-only restraints have not been made clear in the paper. Although the use of the lap belt alone can prevent total ejection and limit the range of interior targets that the occupant head and chest may strike, the head and upper torso are only grossly restrained. The lap-belt-only restraint causes the head and upper torso to rotate about the hip and can cause an increase in head tangential velocity. Eventually, the total momentum of the body must be removed by force impulses experienced in contact with vehicle interior surfaces. These force interactions are not easy to model. It is not clear from the paper how the upper torso of any modeled occupant, other than the driver, was brought to rest, i.e., cushion thickness, energy absorption, or windshield impacts.

A second belt-effectiveness factor that requires proper consideration in belt-restraint system performance is the effective slack in the belts. Slack may be allowed by a careless user, or it may be caused by seat softness and geometry. The presence of slack in the belt system can cause overshoot in the acceleration response of as much as 30 percent (11). What is probably more important, the presence of excess belt slack in an actual use situation can introduce fatal abdominal injury resulting from improper load transfer to the body. The actual seriousness of such abdominal injuries cannot be assessed by the peak acceleration terms used for the chest (Fig. 3).

MULTIPLE IMPACTS

The implication that passive restraints offer no protection for subsequent impacts deserves a more detailed analysis than was given in the paper. It is largely a matter of the relative severity and time phasing of the multiple impacts. Proper air-bag deployment and deflation characteristics allow satisfactory air-bag performance for most multiple-impact situations. Moreover, the effectivess of belt systems may also be expected to deteriorate in multiple impacts, particularly if one of the impacts is a side impact.

Although the lap belt does offer protection from ejection, the direct addition of lap belt and air-bag effectiveness as shown in Figure 5 is not justified. The lap belt-air bag combination may actually cause more injury than the air bag alone in some crash modes, particularly if the belt is improperly worn.

AN EMPIRICAL APPROACH

As an alternative prediction of restraint performance and injury by mathematical models, one may take an empirical approach. Experimental determination of the lethal dose levels for primates can be combined with the ACIR statistical experience to give a realistic indication of relative effectiveness. A summary of this type of investigation is given in Table 2. Data relating to human tolerance have been derived by scaling the results of primate tests in situations designed to simulate various vehicle restraint crash environments. In the case of the lap-belt, lap-shoulder belt, and lap-belt plus air-bag systems, impact tests have determined approximate 50 percent lethal doses for baboons (12, 13). In the case of air-bag-only restraints, impacts of baboons at equivalent barrier speeds of more than 60 mph have not yet resulted in a fatality (13). Also, air-bag tests with human volunteers at barrier-equivalent speeds of more than 30 mph have not yet resulted in serious injury (11, 12, 14).

Table 2 gives distinctly different results from those given in the first column of Table 1 for 100 percent usage. The empirical technique predicts annual fatality reductions of 3,700, 17,000, 27,500, and 28,200 for lap-belt, lap-shoulder, lap-air bag, and air-bag-only systems respectively as compared to 7,400, 11,700, 9,900, and 9,700 for the same respective systems in the computer model approach. The picture of relative effectiveness shown in Figure 5 is thus significantly changed when the empirical approach is used.

SUMMARY

The paper has introduced an analytical approach to the comparative rating of automotive restraint systems. However, the employment of some questionable modeling assumptions and poorly substantiated biomechanical survivability data, together with very optimistic estimates of belt-system effectiveness and usage, siginificantly cloud the accuracy of the conclusions regarding relative effectiveness. The conclusion regarding cost-effectiveness is definitely not supported by any cost data contained in the paper and avoids the ultimate question of societal cost versus societal benefit. The true answer to this question requires more reliable data.

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AUTHORS' CLOSURE

COST EFFECTIVENESS

Methods other than general publicity campaigns are available to motivate usage of restraints. Results of an NHTSA study (15), concerning vehicles with systems that prevent the engine from starting if belts are not fastened, indicated that 95 percent of the sample surveyed kept lap belts fastened while in such cars. A study sponsored by Ford (16) showed that 72 percent of a sample of habitual nonusers of belts became consistent users when exposed to a system incorporating warning devices to remind occupants to fasten their belts. Furthermore, legislation in Victoria, Australia, requiring restraint usage has substantially increased usage rate in that state (17). Thus, it appears possible to raise belt-usage rates to very high levels by technological or legislative means. Yet harness systems incorporating advancements such as suggested here have been estimated (18) to be much less costly than air-bag systems. Therefore, belt systems are estimated to be 6 times as cost effective as air bags.

BELT-USAGE RATES

Warner is quite correct in noting that belt usage is highly variable in different situations and that observational studies tend to be more reliable than interviews. Observations do not always lead to low-usage estimates, however. For example, a recent observational study (19) conducted by the Highway Safety Research Center of the University of North Carolina found a 1968 usage rate of 36 percent, much closer to our 40 percent than to the less than 20 percent proposed by Warner.

BELT-INDUCED INJURY

Twenty-six documents in the general references of NHTSA Docket 69-7 reported on accidents involving belt-restrained occupants of passenger cars. Of the 3,438 such occupants, only 67 (2 percent) sustained some degree of injury directly attributable to the belt-restraint system. No statistics are yet available for potential air bag-induced human injuries in vehicles; only air bag-baboon injuries have been reported for tests conducted at Holloman Air Force Base (discussed below).

HUMAN TOLERANCE

As mentioned in the text, the primary source of the tolerance to impact relations, which are indeed of central importance, was the Highway Safety Research Institute. Using data obtained for the most part from their own experiments (20) the HSRI personnel developed and furnished to Ford 2 curves showing the expected relation between probability of survival and peak triangular pulse head acceleration for both frontal and lateral head impacts. Human tolerance to chest impact was also determined as a function of peak triangular pulse chest acceleration. A properly restrained adult male should be capable of tolerating 30 to 45 g anterior-posterior acceleration without serious injury (21, 22); at the other extreme, we would expect very few to survive at more than 80 g. Assuming that there is a normal distribution of tolerance between these limits results in the postulated relation between lethality and peak chest acceleration shown in Figure 5 of our study.

EJECTION

As stated in the paper, the sample used for determining ejection and fatality rates for occupants of roll-overs included only vehicles of model year 1964 (not 1960) or later. This date was chosen in an effort to have the sample be representative of on-the-road condition in 1969, the base year considered.

EFFECTIVENESS ADDITION

Warner is correct in asserting that "direct addition of lap belt and air-bag effectiveness as shown in Figure 5 is not justified." It is an important point that the air bag-lap belt system requires separate analysis, and each curve shown in Figure 5 does in fact represent an individual calculation of lives saved through total system operation, not simply additive effectiveness.

AIR BAG-BABOON INJURIES

Specific baboon autopsy information pertaining to the test series at Holloman Air Force Base (13) may be found in general reference 7 of Docket 69-7 in 2 parts: "Baboon Lethal Tolerance Tests," June 1970, and DOT final report attachment to a letter from Robert Carter to the Office of Science and Technology, July 12, 1971. "Fatality" in this test series was defined as death within 3 hours following the test, and none of the 8 baboons subjected to crash tests using air bags alone died within the time period. However, all 8 animals were damaged, sustaining such injuries as aneurysm of the aorta at the abdominal bifurcation with an overlying thrombus, premaxillary fracture of the face, brain and spinal cord hemorrhaging, and rib fractures. In fact, one of the baboons was found dead in its cage the day following the test. How many of the remaining animals would have died from their injuries within a reasonable period (36 hours, say) is not known, for all save the one found dead were sacrificed within 24 hours of the test.

EMPIRICAL APPROACH

The unrealistic definition of fatality and the premature sacrifice of test animals precludes a meaningful comparison among the LD-50 speed estimates given by Warner in Table 2. Furthermore, as detailed in an affidavit submitted to Docket 69-7 by R. H. Fredericks on August 6, 1971, the Holloman baboon tests cannot be considered representative of the real-world crash situation because of certain characteristics of the air-bag system and crush distances that were employed. The unrealistic conditions specified at Holloman included an actuation time (20 ms) much shorter than that experienced in actual barrier crashes that use present technology (35 to 40 ms) and a bag volume of 7 ft^3. This bag volume scales to an equivalent bag size of 21 ft^3 for a human, which would be impossible to package in an automobile. The Holloman tests also employed a bag finely tuned to reduce injury at the specific conditions of these tests.

The comparisons given in Table 2 are also questionable because the speeds were calculated from an accelerometer mounted not on the occupant but on the sled; in addition, the sled was decelerated in only 2 ft, whereas an automobile exhibits crush proportional to impact velocity. Hence, the deceleration forces experienced by the baboons during the tests cannot be related to—but no doubt were much greater than—what would occur in an actual automobile. The Holloman report also indicates that the cause of some of the lap-belted baboon fatalities was head-neck trauma. Some of the primates' heads contacted the floor during deceleration, an impossible result in a lap-belted car occupant!

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