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A model for the objective assessment of automobile restraint systems

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Abstract

A model was presented to demonstrate how one could objectively evaluate the alternatives of occupant restraint systems (air bags, passive seat belts, and active seat belts) in passenger vehicles. The effectiveness of each alternative was computed as a function of the vehicle collision characteristics. Cost was computed as a function of the possibility of injury and death attributed to the characteristics of the restraint system. Both the effectiveness and the cost functions were converted into a person-years of life index for comparison purposes. Passive lap and shoulder belts were found to be a preferable alternative to air bags in their potential for saving lives.

Relevance to industry

The paper represents a methodology that can be used as a manufacturing and design safety assessment tool for the incorporation of seated restraint systems in vehicles.

Keywords

Seating, impact, restraint systems, safety, vehicle crashes.

Introduction

Casualties in motor vehicle crashes continue to be a major public health problem of epidemic proportions. Today's death rate in motor vehicles is comparable to the typhoid and diphtheria death rates of the early 1900's.

The current toll is nearly 46,000 deaths and 4 million injuries each year (FARS, 1989). The monetary cost of these deaths and injuries has been estimated at $50 billion each year.

One of the few technological advancements which might modify these grim statistics is the Air Bag Restraint System. This consists of an air cushion which inflates during frontal collisions of over 12 miles per hour (mph) and protects front seat occupants from contact with the dashboard steering wheel and windshield.

The purpose of this paper is to present a model that can objectively evaluate whether the benefits of mandatory airbags outweigh the costs. The objective of the analysis (benefits and costs) is stated in terms of the only ethical issue which should play a part in this type of decision: that of saving human lives. A dollar value will not be placed upon a human life, but a life index will be utilized throughout the analysis.

The approach taken in this analysis consists of evaluating the effectiveness of the occupant restraint devices as defined by relative reduction in severe injury and death for restrained passengers compared to unrestrained passengers. Further-

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more, the analysis shall be divided into the components of a crash, and the effectiveness shall be a function of these components.

The collision

First, let us investigate the mechanism of a crash so we may identify those variables which we could consider in the restraint effectiveness analysis.

In an automobile crash there are actually two collisions. One collision involves the vehicle itself. If the vehicle hits a solid barrier, the vehicle deforms and absorbs some of the force. At 30 mph it takes about $\frac{1}{10}$ of a second to come to a complete stop. The vehicle is often crushed but the passenger compartment usually remains undamaged. The second collision is the human collision. In a 30 mph collision, the vehicle stops but the occupant continues traveling at 30 mph until he is stopped by the interior of the passenger compartment. The human stops ten times faster than the vehicle (in about $\frac{1}{100}$ of a second) since he cannot deform and absorb the force as does the vehicle. In such a collision, a mechanism is needed to slow down the human and prevent him from traveling at the vehicle speed during the collision.

Let us examine some of the factors involved in the human collision which may be helpful in the evaluation of restraint effectiveness. First, the human is always thrown in the direction opposite that of the force. Therefore, the direction of impact should be a consideration in evaluating the effectiveness of occupant restraint alternatives. This type of data has been compiled for fatal crashes (U.S. Dept of Transportation, 1980)). Figure 1 shows this distribution of initial impact in vehicle collisions resulting in fatalities.

The velocity change of the vehicle at time of impact is also a factor that should be considered, since the human is travelling at the same speed as the vehicle. However, to be useful in an analysis, this velocity information should be collected as a function of the direction of impact. These data are very difficult to collect, since only estimates of speeds by witnesses and deformation characteristics of the vehicle are used to estimate the speed of the crash. Therefore, in this analysis we shall assume the effectiveness is computed as a function of the entire range of speeds. This is a realistic assumption if the number of crashes investigated is large.

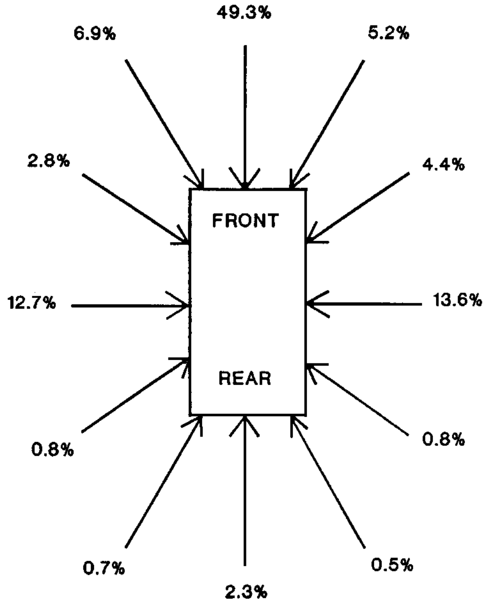

Fig. 1. Distribution of fatalities by direction of impact.

Finally, the vehicle size should be considered. Larger and heavier vehicles offer more protection to the passenger compartment than smaller vehicles since there is more vehicle mass to absorb the crash energy. However, this is not a reflection of the type of occupant restraint system. Therefore, we shall assume that the type of restraint system is independent of vehicle size and, therefore, a given restraint system would be equally likely to be found in any size vehicle.

Alternatives

Let us turn our attention to the various restraint systems that are available. Figure 2 shows various restraint systems that have been developed. Some of these systems are experimental and have not been road tested. As can be seen in the figure, restraint systems can be classified into two modes, active and passive. Active restraints are those which the occupant must fasten and secure himself. Passive restraints are those which operate automatically.

Of these alternatives, the only systems that have been road tested by the driving population and which have yielded any performance data are the active seat belts (lap and shoulder), passive seat belts (lap and shoulder), and air bags. The data available from these restraints would all be comparable and would not violate the assumptions of factors mentioned earlier.

Effectiveness analysis

In the following analysis, three more assumptions were made. First, it was assumed that the alternatives are mutually exclusive and operate independently of one another. That is, we shall opt for either active belts or passive belts or air bags, not a mixture. This assumption is probably not realistic since drivers are encouraged to use seat belts in conjunction with air bags. However, there are factors that would make any other assumption inappropriate. First, seat belt usage has varied tremendously over the years. It has varied from 14 to 47 percent in the past ten years alone. Second, psychological factors may come into play. For example, it is feasible that an owner of a vehicle with airbags might have a false sense of security and not feel it necessary to use seat belts also. There is no data available that show how many occupants with air bags also use the seat belts. Therefore, the mutually exclusive restraint system assumption was maintained.

Secondly, it is assumed that the crash data obtained involve only one collision and not multiple collisions.

Finally, it is assumed that the effectiveness data reflect only benefits of the restraint system over no restraint system. That is, costs are not imbedded in the effectiveness data. This is probably also an unrealistic assumption, but it is believed possible to collect data in this manner.

The criterion function of effectiveness is stated in terms of the utility effectiveness (U) of a restraint type (D) as a function of the angle of impact (i). Therefore, the expected utility of an alternative or $E(U, D)$ could be expressed as:

$$E(U, D) = \sum_{i=1}^{12} p_i U(I, D) \qquad (1)$$

where p represents the probability of impact from a particular direction (data from figure 1) and i corresponds to the direction of impact in terms of the numbers on the face of a clock.

$U(I, D)$ is the effectiveness utility of a restraint type D from direction I. U was derived from existing data but is an obtainable utility. The effectiveness as computed by the Department of Transportation (DOT) is:

$$E_I = 100(R_N - R_A)/R_N \qquad (2)$$

where R_N is the normal unrestrained injury rate and R_A is the alternative injury rate. The rates were computed as

$$R_{A\ or\ N} = 1000 I_x/e \qquad (3)$$

where I_x is the number of injured occupants classified according to an arbitrary severity rating (x), e is the exposure rate of the vehicle with the particular alternative.

The sources of these effectiveness values are shown in table 1. The Department of Transportation (DOT) data was derived from the Restraint System Evaluation Program (RSEP) and National Crash Severity Study (NCSS). The values in the table were derived according to equations (2) and (3). General Motors (GM) did not reveal exactly how they arrived at their values but reported they were derived from a 'matched comparison' of

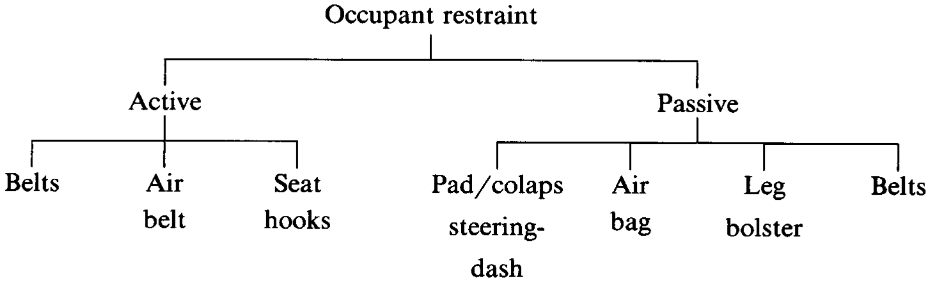

Fig. 2. Occupant restraint alternatives.

Table 1

Effectiveness comparison (matched studies).

Front collisions (AIS)		GM	DOT		Average for calculation
			NCSS	RSEP	
Air bag	(≥ 2)	42			
(front only)	(≥ 3)	11	(3 & 4) (56.2 ± 11)	N/A	33.6
	(≥ 5)	0	(5 & 6) (54.5 ± 21)	N/A	27.3
Active lap	(≥ 3)		60.5 ± 11	56.8 ± 9	58.6
& shoulder	(≥ 6)		47.6 ± 16.7	54.6 ± 2	51.1
Passive belts	(≥ 3)				55
(lap & shoulder)	(≥ 6)				50

crashes. The numbers in the left column refer to the abbreviated index of severity (AIS). An AIS of 5 or 6 represents a fatal or critical injury and 3 or 4 represents a serious or severe injury. All available sources were averaged to yield the average effectiveness (last column of table 1).

Using table 1 as a reference, the effectiveness by angle of impact was derived and appears in table 2 (for fatal and critical cases; the same can be done for other AIS's). These values (U_i) were the utility effectiveness values described in equation (1). As can be seen from table 2, the air bag is only effective for a 30-degree range (11 to 1 o'clock) of head-on collisions, otherwise it does not deploy, thus it has a zero effectiveness at these angles.

Using equation (1), the expected effectiveness for air bags (A), active belts (AB), and passive belts (PB) can be expressed as:

$$E(U, A) = 0.168$$

$$E(U, AB) = 0.508$$

$$E(U, PB) = 0.488$$

However, these values assume total usage of restraint systems. If we adjust these values by the probability of use or deployment of a restraint system, we would have the expected real world utility $E[RWU, D]$ of each restraint system. This equation is presented as equation 4.

$$E(RWU, D) = E[U, D] * p(\text{use}) \qquad (4)$$

The values for $p(\text{use})$ were obtained from the National Highway Traffic Safety Administration (NHTSA, 1990) as of April 1990. Using these values in equation (4) yields:

$$E(RWU, A) = (0.168)(0.99) = 0.166$$

$$E(RWU, AB) = (0.508)(0.47) = 0.239$$

$$E(RWU, PB) = (0.488)(0.81) = 0.395$$

These figures may be interpreted as the percentage effectiveness for AIS 5 or 6 (critical and fatal injury) and can be thought of as the percentage of lives saved.

At this point, it is interesting to perform a sensitivity analysis on the real world utility values. The effectiveness as a function of direction of impact (U_i) will not change but the $p(\text{use})$ variable can change. These statistics emphasize the fact that seat belts have the potential to be over twice as effective as air bags if people use them, whereas air bags (as they are today) cannot increase in

Table 2

Estimated effectiveness by angle of impact (roll overs not included).

Angle (i) (o'clock)	Air bag (A)	Active belts (AB) Lap & shoulder worn properly	Passive belts (PB)
1	0.25	0.52	0.52
2	0	0.48	0.46
3	0	0.47	0.40
4	0	0.48	0.46
5	0	0.52	0.52
6	0	0.53	0.53
7	0	0.52	0.52
8	0	0.48	0.46
9	0	0.47	0.40
10	0	0.48	0.46
11	0.25	0.52	0.52
12	0.28	0.53	0.53

effectiveness. This is due to the fact that air bags would not deploy in side or rear impact collisions which account for almost 40 percent of collisions.

Utility of restraint effectiveness

The $E(RWU, D)$ can be converted into a utility form which would allow for later cost–benefit analyses. One could assume that the reduction in the incidence of death for a restraint system is uniformly distributed for all automobile crashes and is approximately 46,000 lives per year (FARS, 1989). The savings in person-years due to the reduction of fatalities as a consequence of each restraint system can now be calculated.

If the death rate due to motor vehicles per age group is multiplied by the number of people in that age group and by the average number of expected years of life for each group, this yields approximately two million person-years (Dickerson and Robertshaw, 1975). This new utility of each restraint system can be expressed in terms of the saving of lives represented by $E(RWU, D)$ times the two million person-years lost per year given the expected utility in person-years $E(UPY)$. The results follow:

$E(UPY, A) = 332{,}000$ person-years

$E(UPY, AB) = 478{,}000$ person-years

$E(UPY, PB) = 790{,}000$ person-years

Cost analysis

Cost shall be defined as the antonym of effectiveness. That is, the probability of injury (classified according to the AIS index) that would not have occurred had the particular restraint system not been used. It is important to point out once again that we are assuming that cost data are not imbedded in the effectiveness data. Unfortunately, cost data due to the use of various restraint systems do not exist but there are factors which should be considered since they may have an impact on the lives saved during crashes. Therefore, we shall assume some data.

Let the expected cost of restraint type D be represented by the following equation:

$$E(C, D) = \sum_J P_J(D) \sum_K C(S_K) P(S_K \mid J, D) \quad (5)$$

where:

$P_J(D)$ = probability of a costly event which would not occur had restraint type D not been used;

$C(S_K)$ = cost in terms of severity level K (assumed);

$P(S_K \mid J, D)$ = probability of severity level K occurring given event J occurred and device D was used (assumed).

Let us continue to compute our calculations with respect to AIS 5 and 6 (critical and fatal injuries) so that we may compare appropriate dimensions in later analyses.

If we compute the expected cost of air bags [$E(C, A)$], we should include several factors such as: (1) the event of not being thrown clear of the vehicle during accidental air bag deployment, (2) the event that the air bag propellant explodes, (3) the event that sodium azide (the active ingredient in the air bag system) would cause a toxic reaction, and (4) deaths due to the event of air bag deployment throws a small child standing on the seat out of the back window. There is not a sufficient body of data available to document these probabilities accurately. Therefore, for the purposes of demonstrating the model, data associated with the probabilities of these events have been assumed. Thus the $E(C, A)$ is:

$$\begin{aligned} E(C, A) &= (0.025)(0.001) + (0.0001)(0.001) \\ &\quad + (0.0001)(0.001) + (0.05)(0.001) \\ &\quad + (0.001)(0.45) \\ &= 0.0000752 + 0.00045\ ^{1} \end{aligned}$$

The expected cost of active belts can be based upon events such as not being thrown clear of the vehicle during explosion, the event of injury due to incorrect use of belts, and the event of fatal strangulation due to a person's sitting height being

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[1] Cost is separated here for later analyses.

at a level which would permit the belt to cross the neck. Thus, the $E(C, AB)$ is:

$$E(C, AB) = (0.025)(0.001) + (0.0065)(0.02) + (0.27)(0.05) = 0.01355$$

A similar argument can be made for passive belt costs, however the event values are adjusted due to the fact that the belts do not fit as well as active belts, therefore:

$$E(C, PB) = (0.025)(0.001) + (0.01)(0.02) + (0.27)(0.06) = 0.016425$$

The expected real world cost, $E(RWC, D)$, of each restraint system can also be computed by adjusting the cost by the probability of deployment or use. This results in the following:

$$E(RWC, A) = (0.99)(0.0000752) + (0.99)(0.00045)^{1}$$

$$E(RWC, AB) = (0.47)(0.01365) = 0.0064155$$

$$E(RWC, PB) = (0.81)(0.016425) = 0.0133042$$

Utility of restraint costs

The $E(RWC, D)$ can be converted into a utility cost similar to the utility effectiveness mentioned earlier. If we convert cost into person-years of lives risked, we can use the same procedure as for utility effectiveness, with the exception that the air bag cost must be adjusted for the probability that ejection of small children out of the vehicle will occur (small children have a longer life expectancy than the general distribution of adults). This is why $E(RWC, A)$ was expressed in two parts in the proceeding section. Therefore, the expected cost in person-years per year for the various alternatives becomes:

$E(CPY, A) = 2{,}754$ person-years

$E(CPY, AB) = 12{,}831$ person-years

$E(CPY, PB) = 26{,}608$ person-years

Effective-cost comparison

All values have now been converted into comparable units. Therefore, we can now make rational decisions as to whether or not to recommend air bags. First, let us look at the Net Public Worth (NPW) of our alternatives. If our objective was to save as many lives as possible regardless of how many are risked, we would use this criterion. The NPW can be computed as $E(UPY, D) - E(CPY, D)$, and a comparison of our alternatives yields:

$NPW, A = 329{,}246$ person-years

$NPW, AB = 465{,}169$ person-years

$NPW, PB = 763{,}392$ person-years

Under this criterion, we would clearly recommend the use of passive belts over the use of air bags and active belts.

Discussion

An attempt has been made to quantify as many factors as possible in this evaluation of restraint systems. However, there are certain factors which cannot be quantified, such as the psychological factors associated with the various restraint systems. For example, would a passive restraint system give a driver a false sense of security? If it did, would he take more driving risks (such as excessive speed), thereby altering the effectiveness distribution?

Another point which must be considered is that most of the data that have been published are biased toward the viewpoint of the organization performing the study. For example, some of the early air bag data were confounded by the fact that drivers also use lap belts. How could the effectiveness of the seat belt be filtered from that of the air bag? These data are in violation of the independence assumption.

Another problem with the data could be the inherent dangers of the critical incidence technique of data collection. Most of the information is derived by witnesses and estimated damage review. This is certainly a risky source of variability which has not been considered in the model. Perhaps confidence intervals should be constructed to indicate the assurance of the data and model.

These shortcomings need not detract from the merits of the model. The model is built upon objective weightings and should be sound if the inputs are reasonable. In order to ensure model accuracy, better data (especially with respect to the speed of collision and details of the crash) are needed.

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