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RESTRAINT EFFECTIVENESS, OCCUPANT EJECTION FROM CARS, AND FATALITY REDUCTIONS

LEONARD EVANS
Operating Sciences Department, General Motors Research Laboratories,
Warren, Michigan 48090, U.S.A.

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Abstract—The effectiveness of air cushion restraint systems, or airbags, in preventing fatalities is estimated by assuming that they do not affect ejection probability, and protect only in frontal, or near frontal, crashes with impact-reducing effectiveness equal to that of lap/shoulder belts. In order to compute airbag effectiveness, lap/shoulder belt effectiveness and the fraction of fatalities preventable by eliminating ejection are estimated using Fatal Accident Reporting System (FARS) data. Ejection prevention is found to account for almost half of the effectiveness of lap/shoulder belts (essentially all for lap belts only). Airbag effectiveness is estimated as (18 ± 4)% in preventing fatalities to drivers and (13 ± 4)% to right front passengers. Drivers switching from lap/shoulder belt to airbag-only protection increase their fatality risk by 41%.

INTRODUCTION

Safety belts protect vehicle occupants in two ways: they prevent ejection, and they reduce the frequency and severity of occupant contact with the vehicle's interior. The purpose of the present work is to separate safety belt effectiveness into these two components, and thereby infer the effectiveness of air cushion restraint systems, or airbags. Airbags are designed primarily to reduce occupant contact with the vehicle's interior. There are presently insufficient field data to determine airbag effectiveness in the same way as was done for lap/shoulder safety belts and lap-only belts (Evans 1986a, 1988a). The study focuses exclusively on fatalities, so the results should not be generalized to other levels of injury.

METHOD

Two previously introduced quantities, E and F, are central to the present study.

E = effectiveness of safety belts, defined as the percentage reduction in fatalities an unbelted population of occupants would obtain by conversion to universal belt use, all other factors remaining unchanged (Evans 1986a, 1986b; 1988a).

F = percentage reduction in fatalities an unbelted population of occupants would obtain if ejection were eliminated, assuming that those prevented from ejecting would acquire the same fatality risk as those not ejected from similar crashes (Evans and Frick 1989).

By assuming (assumptions are discussed later) that safety belts eliminate ejection, we can infer how much of E is due to mechanisms other than ejection prevention. These other mechanisms are preventing the occupant from impacting the interior structure of the vehicle and reducing the severity of such impact. Let us call these mechanisms "interior impact reduction," and represent the fraction of fatalities eliminated by them by I, giving

$$I = E - F. \tag{1}$$

We use values of E and F from the literature (Evans 1986a, 1986b; Evans and Frick 1989) and from new analyses using Fatal Accident Reporting System (FARS) data (National Highway Safety Administration 1988a). Values of E are determined vs principal impact point using 1975–1983 FARS data and rollover status using 1978–1983 FARS data. Data only through 1983 [as in Evans (1986a)] were used to determine belt effectiveness because an examination of more recent FARS data indicated possible restraint-use reporting bias, possibly a consequence of mandatory wearing laws. Any tendency to code nonuser survivors as users will systematically bias effectiveness estimates upwards. Values of F are determined using FARS data through 1986 (Evans and Frick 1989).

RESULTS

Overall results

Table 1 shows estimates of E for lap/shoulder belts (Evans 1986a) and lap-only belts (Evans 1988a), together with estimates of F from Table 2 of Evans and Frick (1989). Applying eqn 1 gives that lap/shoulder belts reduce fatalities due to interior impact reduction by (23 ± 4)% for drivers and (22 ± 4)% for right front passengers. Taking the weighted average of these [and an error equal to that for the driver because the two E values are not based on independent data (Evans 1986a)], gives that lap/shoulder belts reduce interior impact fatalities by (23 ± 4)%. Thus, almost half of the effectiveness of the lap/shoulder belt in preventing fatalities results from preventing ejection.

For lap-only belts in rear seats, I is (3 ± 10)% for the left rear passenger and (−1 ± 9)% for the right rear passenger, for a weighted average of (1 ± 9)%. This result suggests that the (18 ± 9)% effectiveness of lap belts in preventing fatalities in rear seats (Evans 1988a) flows mainly from ejection prevention, though the high level of uncertainty in the rear results precludes any more definitive conclusion.

Direction of impact

Figure 1 shows driver fatalities by principal impact point, defined as the impact judged to have produced the greatest personal injury or property damage for a particular

Table 1. Fatality reductions from belt use and from eliminating ejection for driver and outboard passengers

	Fatality reducing source*	Fatality reduction, %	
		Driver(top) Left Pssngr	Right Passenger
Front	E	42.1 ± 3.8	39.2 ± 4.3
	F	18.7 ± 0.5	16.9 ± 0.6
	I = E - F	23.4 ± 3.8	22.3 ± 4.3
Rear	E	19.4 ± 10.0	17.3 ± 8.7
	F	16.1 ± 0.8	17.7 ± 0.7
	I = E - F	3.3 ± 10.0	-0.6 ± 8.7

* E is safety belt effectiveness (lap/shoulder in front, lap only in rear)
F is fatality reduction from preventing ejection
I is fatality reduction from reducing impacts with vehicle interior

Table 2. Comparison of lap/shoulder belt effectiveness, *E*, with fatality reductions from ejection elimination, *F*, according to principal impact point. Plus or minus one standard error is indicated under each estimate

Principal impact points	Description	Driver		Right front passenger	
		E, %	F, %	E, %	F, %
12	Front	43 ± 8	9 ± 1	39 ± 9	8 ± 1
1,2	Front right	41 ± 18	21 ± 1	30 ± 20	14 ± 1
3	Right	39 ± 15	17 ± 1	27 ± 19	6 ± 1
4,5,6,7,8	Rear	49 ± 14	22 ± 1	45 ± 20	21 ± 2
9	Left	27 ± 17	8 ± 1	19 ± 20	16 ± 1
10,11	Front left	38 ± 15	12 ± 1	23 ± 20	16 ± 1
13	Top	59 ± 10	41 ± 1	46 ± 15	41 ± 1
0	Non-collision	77 ± 6	63 ± 1	69 ± 8	61 ± 1
All principal impact points combined		42 ± 4	19 ± 1	39 ± 4	17 ± 1

vehicle. The preponderance of left- over right-side deaths follows because impacts on the left occur closer to the driver (Evans and Frick 1988); the pattern for right front passengers is essentially the mirror image of Fig. 1. The specific estimates of belt effectiveness for drivers and right front passengers vs. principal impact point shown in Table 2 have not been previously reported; they are similar to those obtained (Park 1987; Partyka 1988) applying a similar method to FARS data, but with various differences in detail. The values of *F* are calculated as in Evans and Frick (1989).

Impact directions for fatally injured unbelted car drivers

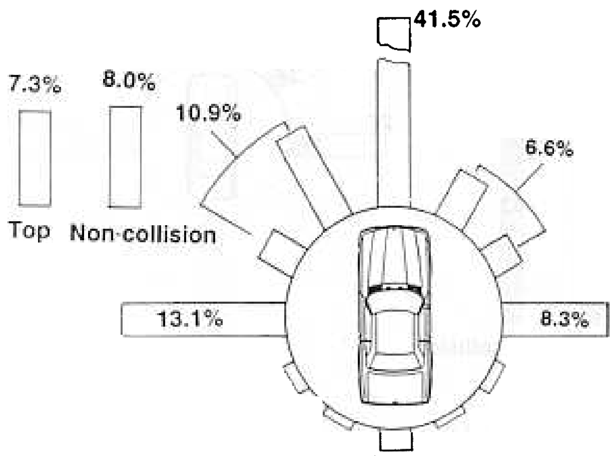

Fig. 1. Distribution of driver deaths by principal impact point, based on 170,298 driver fatalities coded in FARS data for 1975 through 1986. None of the rear clock positions (4, 5, 6, 7 and 8) contributed more than 2% of driver fatalities; combined, these contributed 4.2% of driver fatalities.

Table 2 (also see Fig. 2) shows that lap/shoulder belts reduce fatalities for all principal impact points, and that much of this effectiveness is due to ejection prevention. Even for rear impacts, lap/shoulder belts substantially reduce fatalities to drivers and right front passengers, although the effectiveness estimate has large uncertainty, the estimate that over 20% of fatalities from rear impact would be eliminated by ejection elimination is more precise. For side impacts, ejection elimination would prevent 17% of driver fatalities in far-side impacts (16% for right front passengers); for the near-side the corresponding reductions of 6% and 8% are less because of the greater number of in-vehicle near-side fatalities (Evans and Frick 1988).

Lap/shoulder belts are (77 ± 6)% effective in preventing driver fatalities in "non-collisions." When the 63% ejection prevention component is subtracted from this effectiveness, a value of I = (14 ± 6)% remains; for the right front passenger the corresponding value is I = (8 ± 8)%. As noncollisions normally imply rollover not initiated by striking a clearly identifiable object, such as a tree or another vehicle, we now examine rollover in more detail.

Rollover

From 1978 onwards vehicles in FARS have been coded according to whether the first event was rollover, whether rollover was an event subsequent to striking some other vehicle or object, or whether no rollover was involved. The results in Table 3 use FARS data for 1978 through 1983 for the estimates of lap/shoulder safety belt effectiveness, E, and FARS data for 1978 through 1986 for the ejection estimates, F.

Note the high effectiveness of safety belts when rollover is the first event (82% for the driver and 77% for the right front passenger), and that 64% is due to preventing ejection. Such high effectiveness results from altering occupant dynamics in a discrete way, and consequently is not subject to the considerations (Evans 1987a; Horsch 1987) which make high effectiveness so difficult to achieve in the more normal situation in which forces on occupants increase as crash severity increases. The high effectiveness of belts in crashes in which ejection is likely, as reflected in Tables 2 and 3, contributes to their higher effectiveness in single vehicle than multiple vehicle crashes (Evans and Frick 1986). Recent detailed field examinations of individual crashes provided examples of lap/shoulder belted occupants surviving severe rollover crashes without serious injury (National Transportation Safety Board 1988).

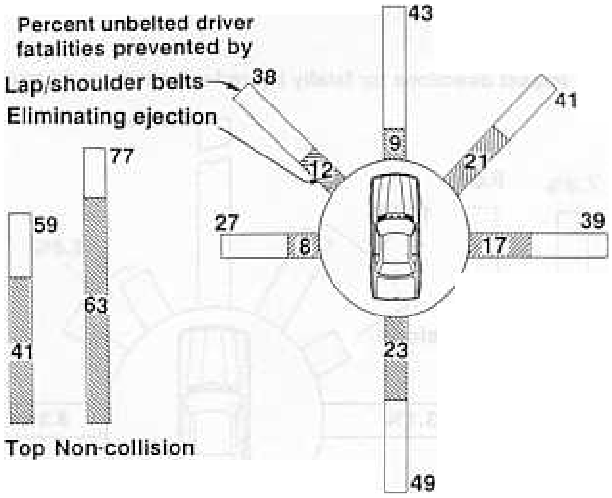

Fig. 2. Effectiveness of lap/shoulder belts in preventing driver fatalities, and the fraction of fatalities prevented by eliminated ejection according to impact direction. For example, in frontal (12 o'clock) crashes, lap/shoulder belts prevent 43% of driver fatalities; 9% of this is due to eliminating ejection, so that 34% is due to interior impact reduction.

Table 3. Results according to rollover status

Rollover status (Distn)[a]	Fatality reducing source	Fatality redns, %	
		Driver	Right front passenger
Rollover is first event (8.5%)[a]	E	82 ± 5	77 ± 7
	F	64 ± 1	64 ± 1
	I = E - F	18 ± 5	13 ± 7
Rollover is subsequent event (16.4%)	E	55 ± 10	57 ± 11
	F	42 ± 1	43 ± 1
	I = E - F	13 ± 10	14 ± 11
All rollovers[b] (24.9%)	E	69 ± 6	67 ± 6
	F	50 ± 1	50 ± 1
	I = E - F	19 ± 6	17 ± 6
No rollover (75.1%)	E	31 ± 8	23 ± 9
	F	7 ± 1	6 ± 1
	I = E - F	24 ± 8	17 ± 9

[a] Distribution of driver fatalities by rollover status based on same data used to determine F; distribution for right front passengers is similar.

[b] Calculated from combined raw data for first event and subsequent event cases

Frontal crashes and airbag effectiveness

In order to estimate airbag effectiveness in preventing fatalities we make two additional assumptions: first, that airbags provide protection only in frontal, or "near frontal" crashes, which we define as those with principal impact points at 10, 11, 12, 1 or 2 o'clock; second, that the airbag effectiveness is due exclusively to reducing occupant impact with the vehicle's interior, and it achieves this with the same effectiveness as the lap/shoulder belt, that is, we assume that the airbag does not influence ejection rates.

From these assumptions, effectiveness is calculated from Table 4 as $0.415 \times 34 + 0.175 \times 24 = 18.3$, with a standard error of 4.2; that is, we find that airbags are $(18 \pm 4)\%$ effective in reducing driver fatalities. From Table 5 we similarly calculated that airbags are $(13 \pm 4)\%$ effective in reducing right front passenger fatalities. These estimates assume nonuse of safety belts. In conjunction with a lap-only belt, the airbag has been estimated in the literature to have effectiveness similar to that of the lap/shoulder belt (National Highway Traffic Safety Administration 1984); if used in conjunction with a lap/shoulder belt, overall effectiveness is estimated to be about five percentage points higher than for the lap/shoulder belt alone. Drivers who cease wearing lap/shoulder belts because they have an airbag increase their fatality risk by $(1 - 0.18)/(1 - 0.42) - 1 = 41\%$; the corresponding calculation for right front passengers associates a 43% fatality risk increase with switching from lap/shoulder belt use to airbag only protection.

DISCUSSION

Assumptions, possible biases, and errors

The assumption that safety belts eliminate ejection is more than adequately correct for the present study, even though some belted occupants may be ejected. For example,

Table 4. Summary of driver results for frontal and near frontal crashes

Principal impact (clock points)	Distribution	Fatality reductions, %		
		E	F	I
Frontal (12 o'clock)	41.5%	43 ± 8	9 ± 1	34 ± 8
Near frontal (10+11+1+2 o'clock)	17.5%	39 ± 11	15 ± 1	24 ± 11

a study (Green et al. 1987) of 919 crashes in the United Kingdom found 2 cases of completely ejected belted occupants among a predominantly belted population; Green et al. (1987) concluded that belt use reduces the rate of ejection by a factor of 39. Our own examination of FARS data revealed that only 0.2% of fatally injured ejected occupants were coded as using any type of restraint.

The assumption that airbags do not materially affect ejection risk for otherwise unrestrained occupants is based on the absence of any clear mechanism of ejection prevention. Intuition can conjure up mechanisms by which airbag could either hinder or facilitate ejection. Eliminating all ejection in frontal crashes reduces driver fatalities by 9% (Table 2), so that if, for example, airbags prevented 10% of such ejections, this would increase the overall effectiveness by $0.41 \times 0.1 \times 0.9 = 0.4\%$. Ejection plays a larger role in near frontals; as most such ejections are through side glass, it seems implausible that airbag could contribute much to ejection prevention.

The assumption that an occupant prevented from ejecting will acquire the same probability of surviving as a presently nonejected occupant in a similar crash is discussed by Evans and Frick (1989).

The assumption that the airbag provides protection only in frontal or near frontal crashes is based on the design goals of the device. Deployment may occur in some unknown fraction of nonfrontal crashes, with safety consequences that are difficult to estimate even approximately. In some cases airbags may provide some ejection protection. The uncertainties are too great to justify any more complex assumption than the one made, which does probably bias effectiveness estimates downwards. On the other hand, the "near frontal" definition used probably includes crashes in which the device would not deploy, and assumes associated risk reduction that may be too large; these biases would increase the effectiveness estimate.

The assumption that the airbags provide protection against impact with the vehicle interior equal to that provided by the lap/shoulder belt is made in the absence of firmer quantification. There are general considerations (Evans 1987a; Horsch 1987) why it is

Table 5. Summary of right front passenger results for frontal and near frontal crashes

Principal impact (clock points)	Distribution	Fatality reductions, %		
		E	F	I
Frontal (12 o'clock)	36.3%	39 ± 9	8 ± 1	31 ± 9
Near frontal (10+11+1+2 o'clock)	17.5%	26 ± 14	15 ± 1	11 ± 14

unlikely that any device can have very high effectiveness in impact protection over a wide range of crash severities. In particular, airbags and belts do not protect against intrusion into the occupant compartment, nor against crush of the occupant compartment so that it can no longer safely contain the occupant. If one made the substantially different assumption that airbags provided 50% more impact protection than lap/shoulder belts [so that frontal effectiveness would become 34% × 1.5 = 51% for the driver—a value higher than this seems highly implausible (Evans 1987a)], then the overall effectiveness values would similarly increase by 50%, to 27% for drivers and 19% for right front passengers.

Some occupants, especially older ones (Evans 1988b), may be fatally injured at crash severities below the threshold at which airbags deploy, typically designed to occur at a perpendicular barrier crash equivalent of about 12 mph (Passell 1987; Maugh 1986). There will be many just-below-threshold-severity crashes because the number of crashes at a given severity increases steeply with declining severity. On the other hand, deployment can cause or increase injury, especially to out-of-position occupants (Passell 1987). Assuming no additional fatalities from either of these effects biases effectiveness estimates upwards.

The standard errors in the (18 ± 4)% and (13 + 4)% effectiveness estimates for driver and right front passenger arise only from the errors in the quantities from which they are calculated. Violations of the above assumptions constitute additional sources of error. As it is not possible to quantify these, one has only judgment to rely on. I do not consider that the assumptions, collectively, generate any obvious systematic bias in the estimates, nor that the collective effect is to increase the stated errors substantially beyond those quoted.

The difference between the effectiveness estimate for drivers and for passengers has two sources. First, lower values of I for right front passengers (Table 4) compared to those for drivers (Table 3); these are probably spurious in origin, given the large uncertainties. If average (I = 33% for frontal and I = 18% for near-frontal) rather than seat-specific values were used, the effectiveness estimate for the driver would decrease to 17% and that for the passenger would increase to 15%. Second, a larger fraction of driver deaths (41.5%) than right front passenger deaths (36.3%) result from frontal crashes. This difference reflects different crash patterns for lone drivers (for drivers accompanied by right front passengers, the corresponding fraction, 37.1%, is similar to that for right front passengers).

Prior estimates

Of a number of prior studies of airbags, only one (Pursel et al. 1978) used field data and found an effectiveness in preventing severe injuries (AIS ≥ 3) of 9%. This was based on comparing injuries sustained by 180 occupants in a fleet of airbag-equipped cars introduced in the early 1970s with those sustained in matched crashes of nonequipped cars. Design approaches to increasing effectiveness beyond this value have been discussed recently (Mertz 1988). There are insufficient data to examine effectiveness in reducing fatalities as was done (Pursel et al. 1978) for injuries not restricted to fatalities. Seven fatalities were reported in airbag equipped cars (National Highway Traffic Safety Administration 1984), equal to the number expected based on the exposure. Although this implies a nominal effectiveness in preventing fatalities of 0%, the statistical uncertainty is too great to allow any useful inference.

Because of the absence of field fatality data, all prior estimates of fatality-reducing effectiveness have depended on indirect inference or judgment. A panel of experts (Wilson and Savage 1973) judged the potential of different occupant protection devices to prevent each of 706 unrestrained occupant fatalities that were examined in detail. They estimated airbag effectiveness to be 18%, in close agreement with the present finding. A thorough an comprehensive investigation (National Highway Traffic Safety Administration 1984) based on performing three new studies and evaluating earlier work in the literature led to an effectiveness estimate in the range 20% to 40%. Based on information not then available, this range now appears high. For example, the same study estimated lap-belt-only effectiveness to be 30% to 40%; that is, higher than for the airbag. More recent studies have estimated lap-belt-only effectiveness to be 18% (Evans 1988a) and 17% (Kahane 1987). Incidentally, the Wilson and Savage (1973) study which found airbags to be 18% effective found lap-only belts to be 17% effective.

Equation 5 of Evans (1986c) calculates that a 210 kg (460 pound) increase in car mass reduces fatality risk by 18% in single car crashes, and by more (depending on the other car) in two car crashes. Fatality reductions from increasing car mass arise from a different mix of crashes than the 18% reduction from airbags. For example, airbags offer no protection to occupants whose vehicles are struck on the side or rear by other vehicles, whereas increased car mass reduces fatality risk to all occupants in essentially all types of crashes. Such reductions far exceed fatality risk increases to other road users.

As car driver fatalities comprise 36.2% (1986 FARS) of all traffic fatalities, all drivers being protected by airbags compared to no drivers being protected by any restraint system will reduce traffic fatalities by $0.362 \times 18\% = 6.5\%$; if right front passenger fatalities (13.2% of all fatalities) are included, the overall reduction becomes 8.2%. This is a simplified calculation aimed only to indicate the magnitude of effects. In reality, all motorized populations start with some initial belt-use rate, so that any estimate of the actual reductions that would flow from universal installation of airbags would require a detailed calculation which goes beyond the scope of the present study. The same 18% reduction in driver fatalities associated with the airbag is achieved by a 54% lap/shoulder belt use rate (Evans 1987b). Although US rates are currently below this [recent data (National Highway Traffic Safety Administration 1988b) indicate 42%], many other countries have much higher rates (Campbell and Campbell 1988).

As the present estimates are not markedly different from others published in the last decade or so, it is remarkable how many statements have been made and publicized that are grossly beyond even the most flexible boundaries of plausible technical uncertainty. The following is but one of many examples: "For instance, if airbags were installed in all cars on American highways, it is estimated that the death toll would be reduced by about 80 percent without requiring any behavioral changes. In contrast, if every drunk driver could be permanently removed from the road—an ideal hypothesis at best—the wisest estimates suggest that the death toll would decline by only about one fourth." (Ross 1986). Our 8.2% estimate is based on changing from 0% to 100% installation. This would require a minimum phase-in period in excess of ten years. Complete conversion of one year's vehicle production would generate an approximate 0.8% reduction.

This paper has demonstrated the large role ejection plays in occupant fatalities. For crash types in which most fatalities are ejections, lap/shoulder belts were shown to have high effectiveness. For example, $(82 \pm 5)\%$ effective in preventing driver fatalities in crashes in which rollover was the first event; 64% of this effectiveness resulted from ejection prevention, with the remaining 18% attributed to reducing occupant impact with the vehicle interior. Lap/shoulder-belted drivers who stop wearing belts because airbags become available increase their fatality risk by over 40%; this underlines the importance of belt-wearing even when the additional supplemental protection of the airbag is available.

CONCLUSIONS

Almost half of the effectiveness of lap/shoulder belts is due to ejection prevention. When rollover is the first event in a crash, driver lap/shoulder belt effectiveness is $(82 \pm 5)\%$, 64% being due to ejection prevention. Lap-belt-only effectiveness, previously estimated at $(18 \pm 9)\%$, appears due mainly to preventing ejection.

Airbag effectiveness in preventing fatalities is estimated as $(18 \pm 4)\%$ for drivers and $(13 \pm 4)\%$ for right front passengers. Total U.S. traffic fatalities would decline if all cars had airbags (compared to all cars having no restraint systems) by 6.5% if installed for all drivers and 8.2% if installed for all drivers and right-front-seat passengers.

Lap/shoulder belted drivers who stop wearing belts because airbags are available increase their fatality risk by over 40%.

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