A VIRTUALLY EXACT CALCULATION OF SAFETY BELT EFFECTIVENESS

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ABSTRACT

A number of analysts have attempted to determine the effectiveness of passenger vehicle safety belts over the past 25 years. One of the more widely used is the double pair comparison (DPC) method. This note looks at the larger picture of motor vehicle crash data to show the limitations of DPC and to present a more general method. The author organizes crash data according to whether occupants were restrained or not, whether their crashes were potentially survivable only with belt use, and whether the occupants were actually killed. Based on this model, the author develops a virtually exact means of calculating restraint use and effectiveness in preventing fatalities. Calculations using data from the Fatal Accident Reporting System (FARS) show that safety belts may be more effective in preventing fatalities than previously thought. However, part of the reason for the higher calculated effectiveness is that belt use appears to be over reported in FARS. Finally, the author discusses the origin of uncertainties and errors in the results, and shows how the data can be adjusted to give more reasonable results.

INTRODUCTION

A number of analysts have attempted to determine the effectiveness of passenger car occupant restraints such as safety belts. One of the more widely used is the double pair comparison (DPC) method. It was developed and used primarily by Evans (1986) although he gives credit to Park (1984) for its original conception.

This paper takes a new look at accident data to illustrate how we can learn more from it. To do so, we develop a more sophisticated formalism and provide results for passenger car and light truck occupants. The technique permits exploring the effect of correcting data to account for misreporting belt use. This technique may have applicability to other epidemiologic problems.

The Universe of Crashes

Let us imagine that we have perfect knowledge of all crashes involving light motor vehicles that occur in the U.S. each year. Our unit is a passenger car, light truck, or van involved in a crash.

Figure 1 (see next page) shows a classification of those vehicles according whether a driver, a right front passenger, or both were killed, whether one or both would have survived only if they had been restrained, and whether either or both were actually wearing a seat belt. Columns in this figure, which define driver characteristics, are identified by capital letters and rows – passenger characteristics – by Roman numerals. Specific cells contain the number of vehicles in which there were an actual or potential driver or passenger fatality, or both (as indicated by the headings). Cells are identified by a capital letter indicating the column with a subscript identifying the row: E_{IV}, for example.

We have only limited knowledge of the potential consequences of accidents. We can uniquely identify the cases in only four of the cells of the resulting matrix: those in which both restrained occupants were killed (F_{VI}), those where a restrained driver was killed and there was no right front passenger (F_{VII}), and those in which a restrained occupant was killed and an unrestrained occupant survived (A_{VI} and F_I).

Effectiveness of Occupant Restraints

The traditional definition of effectiveness is:

$$E = \left(1 - \frac{R_t}{R_u}\right) \times 100\% \qquad (1)$$

Where: R_t = rate of loss or injury for the treated population, and

R_u = rate of loss or injury for the untreated population.

This applies to a situation where we measure a characteristic (driver crash fatality rates, for example) in two randomly parts of a population, one of which is treated and one is not. In an ideal experiment, the population would be randomly selected, all other factors would be equivalent, and there would be no confounding issues.

<table>
<tr><td colspan="3"></td><td colspan="3">all drivers who survived</td><td colspan="3">all drivers who were killed</td><td></td></tr>
<tr><td colspan="3"></td><td colspan="2">survivable</td><td colspan="2">survivable if restrained</td><td colspan="2">not survivable</td><td></td></tr>
<tr><td colspan="3"></td><td>unrestraind</td><td colspan="2">restrained</td><td colspan="2">unrestrained</td><td>restrained</td><td>i =</td></tr>
<tr><td rowspan="3">right front passengers who survived</td><td rowspan="2">survivable</td><td>unrestrained</td><td colspan="3" rowspan="3">no driver or right front seat passenger fatalities</td><td>D_I</td><td>E_I</td><td>F_I</td><td>I</td></tr>
<tr><td>restrained</td><td>D_{II}</td><td>E_{II}</td><td>F_{II}</td><td>II</td></tr>
<tr><td rowspan="2">survivable if restrained</td><td>restrained</td><td>D_{III}</td><td>E_{III}</td><td>F_{III}</td><td>III</td></tr>
<tr><td rowspan="3">right front passengers who were killed</td><td>unrestrained</td><td>A_{IV}</td><td>B_{IV}</td><td>C_{IV}</td><td>D_{IV}</td><td>E_{IV}</td><td>F_{IV}</td><td>IV</td></tr>
<tr><td rowspan="2">not survivable</td><td>unrestrained</td><td>A_V</td><td>B_V</td><td>C_V</td><td>D_V</td><td>E_V</td><td>F_V</td><td>V</td></tr>
<tr><td>restrained</td><td>A_{VI}</td><td>B_{VI}</td><td>C_{VI}</td><td>D_{VI}</td><td>E_{VI}</td><td>F_{VI}</td><td>VI</td></tr>
<tr><td colspan="3">no right front passenger</td><td colspan="3">no driver fatalities</td><td>D_{VII}</td><td>E_{VII}</td><td>F_{VII}</td><td>VII</td></tr>
<tr><td colspan="3"></td><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td><td>F</td><td></td></tr>
</table>

Figure 1. A taxonomy of passenger car crashes.

With vehicle crashes, we cannot conduct an experiment in this fashion. We are only passive and imperfect observers of what happens on the road. We don't have two randomly selected groups with only one wearing restraints. Rather, the treated population is the group that chooses to wear restraints while the untreated do not. Thus, we must have a more pragmatic definition of effectiveness.

Within the universe of crashes that occur, considering what happens to drivers only, crashes can be classified according to severity and restraint performance in the following classes:

1. Crashes in which restraint use has no effect because an occupant would survive in any case (i.e. a fender-bender that an unrestrained person would survive as would a restrained person). These are not included in the rates, R_r and R_u, used in determining effectiveness because a restraint system could have no actual or potential effect on the outcome of any of these crashes. In Figure 1, these crashes are in column A for unrestrained drivers and in column B for restrained drivers.

2. Crashes in which restraint use makes the difference between death and survival (i.e. a serious crash that an occupant would survive *only* if restrained). These are important because they are the cases where this particular restraint system actually makes a difference. These crashes are in column C for restrained drivers (who survive as a consequence of using restraints) and column D (unrestrained drivers who are killed).

3. Crashes that are so severe that a driver would not survive even using this restraint. Some restraint system might have been effective here, but this one (safety belts) was not. If we had a 100 percent effective restraint system, there would be no crashes in this class. Here, column E in Figure 1 contains the unrestrained drivers (who are killed), and F those who are restrained (and are also killed despite the restraint).

Looking at crashes this way also points up the fact that restraint effectiveness and use determines how crashes are distributed in Figure 1. That is, if a restraint system is more effective, the result will be that some of the crashes that would have been in column E or F move to column D or C, respectively, in this figure. The spectrum of crashes, by severity, appears to be different for belted drivers than for unbelted drivers. This suggests that belted drivers may be involved in fewer severe crashes. (If the way in which crashes are distributed and characterized in this paper is still mysterious, see Appendix A for a more detailed discussion.)

Using the nomenclature of Figure 1 in equation 1 (that is, A is the sum of all cases in which an unrestrained driver survived), we define the effectiveness of this restraint system as:

$$E = \left(1 - \frac{\dfrac{E+F}{A+B+C+D+E+F}}{\dfrac{C+D+E+F}{A+B+C+D+E+F}} \right) \times 100\%$$

$$= \left(1 - \frac{E+F}{C+D+E+F} \right) \times 100\%$$

$$= \left(\frac{C+D}{C+D+E+F} \right) \times 100\% \qquad (2)$$

In other words, if all drivers had been restrained (treated), only those in columns C and D would have survived, while if none had been restrained, all drivers in columns C, D, E, and F would have died. See Appendix B for a discussion of this equation.

Let us define the ratio of restrained to unrestrained occupants within the two most serious classes of crashes: $\alpha = F/E$, and $\beta = C/D$. We can now write equation 2:

$$E = \left(1 - \frac{(1+\alpha)E}{(1+\beta)D + (1+\alpha)E} \right) \times 100\% \qquad (3)$$

If $\alpha = \beta$ we get:

$$E = \left(1 - \frac{K_B \times \dfrac{D_U}{D_B}}{(K_U)} \right) \times 100\% \qquad (4)$$

where K is killed drivers, D is total drivers, and the subscripts indicate belt use: B = belted, U = unbelted.

This equation is essentially the double pair comparison (DPC) method. The DPC restraint use ratio is taken from restraint use in a subset of crashes that killed the right front passenger all of whom had the same restraint status. Within that stratum, this ratio is the sum of A, D, and E divided by the sum of B, C, and F as defined above. This is approximate both because it depends on the equality of α and β, and because it does not use all of the available data included in equation 2 (see Appendix C).

Limitations of Input Data and Other Problems

The data generally used for estimating fatality-prevention effectiveness of safety belts comes from the Fatal Accident Reporting System (FARS). FARS provides a file of all fatal motor vehicle crashes on U.S. public roads. It is based primarily on police accident reports. Within Figure 1, solid lines enclose groups of crashes that can be differentiated using information in FARS. Figure 2 (below) which is in the same format at Figure 1, shows the data as it is available in FARS. Note that in this figure, the data in column K is equivalent to the data in column A of Figure 1, the data in column L is equivalent to the sum of the data in columns B and C in Figure 1, M is the sum of the data in columns D and E, and N is equivalent to column F. Similarly, the data in row 1 is equivalent to the data in row I in Figure 1, row 2 is the sum of II and III, row 3 is the sum of IV and V, and 6 is equivalent to row VI in Figure 1.

		all drivers who survived		all drivers who were killed		
		unbelted	belted	unbelted	belted	i =
right front passengers who survived	unbelted	Not in FARS		*j*	*a*	1
	belted					2
right front passengers who were killed	unbelted	*k*	*b*	*l*	*c*	3
	belted					4
no right front passenger		Not in FARS				5
		K	L	M	N	

Figure 2. Passenger car crashes in the Fatal Accident Reporting System (FARS).

The validity of FARS data can be no better than the validity of its source data. Many data elements in FARS -- whether a person lived or died, the descriptions of vehicles, age and sex of people involved, and type of roadway, for example -- are both reasonably complete and accurate. Belt use information in FARS is less so.

Police officers are almost never at the scene of a crash when it happens. Therefore, they must determine belt use for occupants from their investigation of physical evidence, claims by vehicle occupants, and information from emergency medical personnel or others who were first at the scene. Belt use information is obviously better for occupants who are killed in the crash or who are still in the car when police or emergency personnel arrive. That introduces a further bias in the data. Some police officers lack adequate training for judging belt use on the basis of secondary evidence.

For states that have belt use laws, or where belt use may be a factor in insurance payments, occupants may claim they were using a belt even when they were not. Specific evidence of bias in belt use reporting came from states that passed belt use laws. After belt use laws took effect, there was a greater increase in belt use reported in FARS than was observed in roadside surveys in such states. This suggests that errors in belt use are not random: there is probably a bias toward reporting higher belt than was actually the case, particularly in data from more recent years. Such reporting would affect any calculation of effectiveness from FARS.

The determination of safety belt effectiveness may also strongly depend on the size or type of vehicle, the age and sex of the occupant, and other factors. If this were so, the way in which the data is selected from FARS, or differing use rates among the range of people by age and sex in various types of cars would bias the determination of effectiveness.

Despite these limitations, FARS is one of the few data bases that can be used for evaluating safety belt effectiveness in preventing fatalities in serious crashes. Therefore, it is worth the effort to develop analytic methods that minimize or deal with the problems with FARS data.

A NEW SOLUTION TO THE EFFECTIVENESS PROBLEM

There is a highly accurate formulation of the problem that overcomes the limitations of the DPC. Consider again Figure 1 and the definition of effectiveness in equation 2. Writing out the full summations this is:

$$E = \left(\frac{\sum_{i=I}^{VII} (C_i + D_i)}{\sum_{i=I}^{VII} (C_i + D_i + E_i + F_i)} \right) \times 100\% \qquad (5)$$

This equation can be used by limiting the summations i = I through VI to get the effectiveness for drivers who are in crashes while traveling with right front passengers, or to i = VII for the effectiveness for drivers who are traveling without a right front passenger. The effectiveness is likely to be different in the two cases because the types or severities of the crashes may depend upon whether a passenger is in the vehicle.

To satisfy this equation, one needs the values for each individual cell in Figure 1. Unfortunately, we cannot readily separate the crashes in column D from those in column E, nor those in column C from those in column B. That is, we do not have good information on which individual crashes are potentially survivable only if an occupant is restrained.

We have particularly limited knowledge of those crashes in which there was no fatality, but in which there would have been one had an occupant been unrestrained. Whether an otherwise fatal crash would have been survivable if restraints had been worn implies a knowledge of the restraint's effectiveness. However, as will be seen, the FARS data set itself contains sufficient information to get around this apparent circularity.

Let us partition the data in a way that makes use of information about restraint use. First, we link restraint use within groups of cells of Figure 1. Figure 3 (see below), for example, shows the relationship between driver and passenger restraint use for the four cells at the lower center portion of Figure 1, C_V, C_{VI}, D_V, and D_{VI}. All of these crashes that are counted in these cells posed the same threat to the lives of the drivers involved: they would have been killed unless they were restrained. In all of these crashes, the right front passengers were killed regardless of restraint use.

C_V Driver Restrained, Passenger Unrestrained $u(1\text{-}w)$	D_V Neither Driver Nor Passenger Restrained $(1\text{-}u)(1\text{-}v)$	V
C_{VI} Driver and Passenger Restrained uw	D_{VI} Driver Unrestrained, Passenger Restrained $(1\text{-}u)v$	VI
C	D	

Figure 3. Relationships between driver and passenger restraint use for four cells in Figure 1. Formulae within each box give the proportion of vehicles with drivers and passengers restrained as indicated.

The cells on the left side of Figure 3 contain counts of the number of restrained drivers and the cells on the right count unrestrained drivers. The proportion of all drivers in the four cells who were restrained is u (the sum of the numbers in the two left cells divided by the sum of the number in all four cells). The lower two cells count restrained passengers. The proportion of passengers who were restrained is w when they are riding with restrained drivers (the count in the lower left cell divided by the counts in both left cells in Figure 3) and v when riding with unrestrained drivers (the cells on the right side of Figure 3). This representation can be made of any set of four adjacent cells for which the risk to all drivers is the same and the risk to all passengers is the same but not necessarily the same as to the drivers. Note that because u, v, and w are proportions, the sum of the proportions in each cell: $u(1\text{-}w) + uw + (1\text{-}u)(1\text{-}v) + (1\text{-}u)v = 1$.

If the values of u, v, and w were known, they could be used to determine the partition of data between crashes that have the same restraint use characteristics but that differ in the severity of the crash, such as D_{IV}, D_V, E_{IV}, and E_V. We could, for example, partition $D_{VI}+E_{VI}$ by noting that $E_{VI}/F_{VI} = (1\text{-}u)v/(uw)$.

From this point on, we shall use the nomenclature of Figure 2 -- K_1, L_2, and so on -- to indicate known values from FARS. Since the sum $(D_{VI}+E_{VI})$ is a known quantity (M_4 from Figure 2), we can express $D_{VI} = M_4 - E_{VI}$. The same type of relationship can be used for $F_V = N_4\, u(1\text{-}w)/uw$ and $F_{IV} = N_3 - F_V$. Similarly, D_V, E_V, and E_{IV} can be expressed using the values of M_4, N_4, and N_3, respectively by using the appropriate ratios of the numbers of people using and not using restraints. Then, D_{IV} is the difference between the total of the four cells $(D_{IV}+D_V+E_{IV}+E_V) = M_3$ and the values of the three of these cells that have been determined. In this way, values for all nine cells in the lower right section of Figure 1 can be expressed as a function of known FARS data and values of restraint use u, v, and w.

This bootstrapping technique can be used beginning at $A_{VI} = K_4$ to develop expressions for the values in the nine cells at the lower left of Figure 1 and from $F_I = N_1$ to obtain expressions for the nine cells at the upper right. Next, A_{III}, B_{III}, C_I, and C_{II} can be expressed in terms of their neighbors, A_{IV}, B_{IV}, D_I, and D_{II}, respectively, and u, v, and w. C_{III} can be expressed in terms of either C_{IV} or D_{III}. In this way, we can express values for all of the individual cells in Figure 1 except A_I, A_{II}, B_I, and B_{II}, which are not fatal to even unbelted front seat occupants.

Thus far, we have assumed that u, v, and w are the same for all sections of four cells in Figure 1 that have the same outcome severity. There is evidence that safety belt use is lower for crashes of increasing severity. In particular, we assume the following:

Since the behavior of the driver has a substantial effect on the severity of a crash, driver restraint use may take on different values depending on the severity of the crash as it affects the driver: u_o if the driver survives regardless of restraint use (columns A and B), u_i if the driver survives only if restrained (columns C and D), and u if the driver is killed regardless of restraint use (columns E and F). Let us further assume that the value u_i is the harmonic average[1] of the restraint use value u_o, and the value u.

[1] We use the harmonic average: $2/u_i = 1/u_o + 1/u$, because it has computational advantages (see below). The difference between the average and the harmonic average is very small as long as u_o and u are reasonably close in value. The results are not sensitive to this difference.

- The values of v and w are assumed to be the same throughout the Figure. Note that since passenger restraint use is dependent on driver restraint use, so that restraint use by passengers will actually vary proportionally to driver use by crash severity.

These assumptions give five unknowns requiring five equations for solution. These five equations come from the intersections between quadrants of Figure 1 and the relationship for driver restraint use. Specifically, four of the cell groups, $(C_{IV}+C_V)/(D_{IV}+D_V)$, C_{VI}/D_{VI}, $D_{III}+E_{III})/(D_{IV}+E_{IV})$, F_{III}/F_{IV} can be compared using values of restraint use independently from their derivation. The five equations are:

$$\frac{C_{IV}+C_V}{D_{IV}+D_V} = \frac{u_i(1-w)}{(1-u_i)(1-v)} \tag{6}$$

$$\frac{C_{VI}}{D_{VI}} = \frac{u_i w}{(1-u_i)v} \tag{7}$$

$$\frac{D_{III}+E_{III}}{D_{IV}+E_{IV}} = \frac{v}{1-v} \tag{8}$$

$$\frac{F_{III}}{F_{IV}} = \frac{uw}{u(1-w)} = \frac{w}{1-w} \tag{9}$$

$$u_i = \frac{2u_o u}{u_o+u} \tag{10}$$

For equation 8, $E_{III}/E_{IV} = (1-u)v/(1-u)(1-v) = v/(1-v)$, leading to the above result. The solution of these equations gives the three values of u and of v and w. The complete expressions come from substituting for $(C_{IV}+C_V)$, $(D_{IV}+D_V)$, C_{VI}, D_{VI}, $(D_{III}+E_{III})$, $(D_{IV}+E_{IV})$, F_{III} and F_{IV}. For example:

$$\begin{aligned} C_{IV}+C_V &= L_3 - \frac{u_o(1-w)}{(1-u_o)v} K_4 \\ &\quad - \frac{u_o(1-w)}{(1-u_o)(1-v)} [K_3 - \frac{1-v}{v} K_4] \\ &= L_3 - \frac{u_o(1-w)}{(1-u_o)(1-v)} K_3 \end{aligned} \tag{11}$$

and:

$$C_{VI} = L_4 - \frac{u_o w}{(1-u_o)v} K_4 \tag{12}$$

Similar expressions can be developed for the values in the remaining cells to substitute into equations 6 through 10. The four equations that result are:

$$\begin{aligned} &\frac{1-u_i}{u_i} [L_3 - \frac{u_o}{1-u_o} \frac{1-w}{1-v} K_3] \\ &= \frac{1-w}{1-v} M_3 - \frac{1-u}{u} N_3 \end{aligned} \tag{13}$$

$$\begin{aligned} &\frac{1-u_i}{u_i} [L_4 - \frac{u_o}{1-u_o} \frac{w}{v} K_4] \\ &= \frac{w}{v} M_4 - \frac{1-u}{u} N_4 \end{aligned} \tag{14}$$

$$(1-v)M_2 - vM_1 = vM_3 - (1-v)M_4 \tag{15}$$

$$wN_1 - (1-w)N_2 = (1-w)N_4 - wN_3 \tag{16}$$

One can solve for v in equation 15 and for w in equation 16:

$$v = \frac{M_2+M_4}{M_1+M_2+M_3+M_4} \tag{17}$$

$$v = \frac{M_2 + M_4}{M_1 + M_2 + M_3 + M_4} \tag{17}$$

$$w = \frac{N_2 + N_4}{N_1 + N_2 + N_3 + N_4} \tag{18}$$

In equations 13 and 14, the variables representing driver restraint use, u_o, u_i, and u all appear in the form: $(1-u)/u$. Now define two new variables, $x = (1-u_o)/u_o$ and $y = (1-u)/u$, so that $(1-u_i)/u_i = (x+y)/2$. Equations 13 and 14 can then be restated by incorporating values for x and y giving two equations in two unknowns. Equation 14 can be solved for y in terms of x:

$$y = \frac{x^2 L_4 - \frac{w}{v} x (K_4 + 2M_4)}{\frac{w}{v} K_4 - x (L_4 + 2N_4)} \tag{19}$$

The result can be substituted into equation 13 giving a quadratic equation in x:

$$\begin{aligned} &x^2 (L_3N_4 - L_4N_3) \\ &- x \left[\frac{1-w}{1-v}(M_3(N_4+L_4)+N_4(M_3+K_3)) \right. \\ &\left. - \frac{w}{v}(M_4(N_3+L_3)+N_3(M_4+K_4))\right] \\ &- \frac{w}{v}\frac{1-w}{1-v}(K_3M_4 - K_4M_3) = 0 \end{aligned} \tag{20}$$

This equation is easily solved for x using FARS data. One of the roots is negative giving a meaningless value of restraint use. The remaining root gives unique values for driver restraint use. From the solution both driver and passenger restraint use can be determined. Using the relationships developed from Figure 3, the specific values in all cells of Figure 1 can be found, and equation 5 will give restraint effectiveness.

Somewhat the same procedure can be used for drivers who are traveling alone. The problem is that we have no equations similar to equations 6 through 10 above for this case. If restraint use is dependent on crash severity, we have two unknowns: u and u_i, using the nomenclature developed above. Note, however, that $E_{VII} = F_{VII}(1-u)/u$, $D_{VII} = M_7 - E_{VII}$, and $C_{VII} = D_{VII}u_i/(1-u_i)$. Making these substitutions in equation 5 and assuming that usage is the same for all drivers who are traveling alone when they are involved in fatal crashes gives:

$$E = 1 - \frac{(1-u_i)N_5}{uM_5 + (u-u_i)N_5} \approx 1 - \frac{(1-u)}{uM} \tag{21}$$

The second expression is exact if restraint use is independent of the severity of the crash (i.e. $u_i = u$). However, we must still obtain restraint use from other sources. This equation shows that the higher the observed use rate, the higher the derived effectiveness.

RESULTS

Table 1 (see following page), taken from FARS, shows the number of passenger cars in which a driver or right front occupant was killed in the U.S. from 1985 through 1992. It is in the same format as Figure 2. It includes all cases for which safety belt use is known. Within each cell, the numbers are listed with 1985 data at the top and 1992 data at the bottom. Note that for those cells where both a driver and a right front passenger were killed, M_3, M_4, N_3, and N_4, each count represents two fatalities. Table 2 (see second following page) provides the same data for 1985 through 1992 for cases involving light trucks in which belt use is known. Belt use is unknown for about 15% of all cases. Ignoring the unknown cases is equivalent to assuming that belt use among cases in which it is unknown is the same as in the known cases. This may slightly overestimate belt use.

Table 1.
Numbers of fatally injured passenger car occupants according to the characteristics of the crash.
Data in each cell is shown for 1985 (at the top) through 1992 (at the bottom).

			all drivers who survived		all drivers who were killed		
			survivable	survivable if belted	survivable if belted	not survivable	
			unbelted	belted	unbelted	belted	i =
right front passengers who survived	survivable	unbelted	Not in FARS	Not in FARS	1813 1843 1871 1864 1779 1683 1412 1273	50 58 95 102 82 89 98 100	1
right front passengers who survived	survivable / survivable if belted	belted	Not in FARS	Not in FARS	112 188 154 327 319 356 304 303	218 404 588 657 691 727 786 788	2
right front passengers who were killed	survivable if belted / not survivable	unbelted	1780 1849 1801 1834 1733 1581 1437 1320	164 254 319 384 341 378 388 388	805 884 818 844 812 801 706 648	31 45 37 70 62 64 59 87	3
right front passengers who were killed	not survivable	belted	44 63 89 107 96 78 90 97	286 505 663 804 884 913 946 960	29 37 44 69 71 56 60 69	98 169 215 327 304 303 351 359	4
no right front passenger			Not in FARS	Not in FARS	6400 6713 6985 7368 7212 6745 6059 5586	828 1450 1810 2155 2339 2501 2699 2861	5
			K	L	M	N	

Table 2.
Numbers of fatally injured light truck occupants according to the characteristics of the crash. Data in each cell is shown for 1985 (at the top) through 1992 (at the bottom).

			all drivers who survived		all drivers who were killed		
			survivable	survivable if belted		not survivable	
			unbelted	belted	unbelted	belted	i =
right front passengers who survived	survivable	unbelted	Not in FARS		567 569 596 678 681 702 630 555	4 10 11 21 18 17 20 29	1
	survivable	belted			28 36 54 87 100 101 104 107	28 43 68 78 94 113 108 109	2
right front passengers who were killed	survivable if belted	unbelted	463 508 613 641 595 648 562 523	23 43 75 106 107 101 126 126	166 171 206 190 165 224 203 175	4 8 13 10 12 10 20 15	3
	not survivable	belted	4 3 8 17 11 19 20 16	28 47 62 90 93 101 124 120	2 6 7 12 18 6 12 14	8 12 39 15 38 21 33 33	4
no right front passenger			Not in FARS		1858 2071 2394 2626 2676 2661 2597 2509	102 198 287 355 412 441 475 519	5
			K	L	M	N	

Table 3 (see below) shows the data on all passenger car fatalities for the years 1985 through 1992 fully partitioned according to the procedure outlined above. The effectiveness calculated for drivers traveling with right front passengers, the sum of columns C and D divided by the sum of columns C through F, is 63 percent. For right front passengers, the effectiveness is the sum of rows III and IV divided by the sum of rows III through VI which is 57 percent. This calculation found that, when traveling together, reported belt use averaged 49 percent for drivers and right front passengers, was 86 percent for right front passengers riding with belted drivers, and was 12 percent for right front passengers riding with unbelted drivers. According to this calculation, for the eight year period, 14,000 drivers and 12,400 right front passengers were saved by wearing safety belts. However, an additional 14,100 drivers and 13,000 right front passengers could have been saved if they had been belted.

Table 4 (see following page) shows the same partition of data for light trucks. The effectiveness calculated for drivers is 76 percent and for right front passengers is 73 percent. Belt use, according to this calculation, averaged 37 percent for drivers and right front passengers, 80 percent for passengers with restrained drivers, and 10 percent for passengers with unrestrained drivers. We calculated that belts saved 3,300 light truck drivers and 2,800 right front passengers, and could have saved an additional 5,500 drivers and 5,000 passengers.

For drivers who were alone in passenger cars and in light trucks, we have no independent way to estimate belt use. According to the 19 Cities Study, the average passenger car driver belt use for 1985 through 1994 was about 40 percent. Using a more conservative figure of 35 percent would give an effectiveness of 42 percent for passenger cars according to equation 21. We have no equivalent observations for light truck drivers. Belt effectiveness may be as high as 69 percent for light truck drivers traveling alone if their belt use was only 30 percent for this period. Using a more conservative figures of 25 percent for belt use of drivers alone in light trucks, their belt effectiveness would be 60 percent.

Table 3.
Numbers of passenger car occupants in fatal crashes from 1985 through 1992 partitioned according to the severity of the crash and restraint use by occupants.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if belted		not survivable		
			unbelted	belted		unbelted		belted	i =
right front passengers who survived	survivable	unbelted			1,448	9,174	4,364	674	I
		belted			8,960	1,200	571	4,170	II
	survivable if belted	belted	1,081	8,068	2,156	295	96	689	III
right front passengers who were killed		unbelted	8,260	1,304	348	2,257	737	111	IV
	not survivable	unbelted	5,075	801	162	1,051	2,173	344	V
		belted	664	4,957	1,004	138	297	2,126	VI
no right front passenger					11,932	22,160	30,908	16,643	VII
			A	B	C	D	E	F	

Table 4.
Numbers of light truck occupants in fatal crashes from 1985 through 1992 partitioned according to the severity of the crash and restraint use by occupants.

			all drivers who survived	all drivers who survived	all drivers who survived	all drivers who were killed	all drivers who were killed	all drivers who were killed	
			survivable	survivable	survivable if belted	survivable if belted	not survivable	not survivable	
			unbelted	belted	belted	unbelted	unbelted	belted	i =
right front passengers who survived	survivable	unbelted			537	4,038	940	130	I
right front passengers who survived	survivable	belted			2,161	433	101	523	II
right front passengers who survived	survivable if belted	belted	390	1,876	304	61	23	119	III
right front passengers who were killed	survivable if belted	unbelted	3,638	466	76	568	214	30	IV
right front passengers who were killed	not survivable	unbelted	915	117	48	361	358	49	V
right front passengers who were killed	not survivable	belted	98	472	193	39	38	199	VI
no right front passenger					3,342	10,025	8,376	2,789	VII
			A	B	C	D	E	F	

These belt use figures show that approximately 11,900 passenger car drivers traveling alone, and 3,300 solo light truck drivers were saved. An added 22,100 passenger car drivers and 10,000 light truck drivers traveling alone could have been saved had they been wearing belts.

The grand total indicates that more than 47,000 people were saved by wearing safety belts in the eight years from 1985 through 1992. It is unfortunate that more than 69,000 were killed who could have been saved by buckling up.

Two surprising results come from this procedure. The first is that we found driver belt use to be somewhat higher than was observed in the 19 cities observations. The second is that the effectiveness found for safety belts is significantly higher than has been found by previous methods: nearly 60 percent for passenger car occupants and over 70 percent for light truck occupants.

DISCUSSION

The various equations and relationships developed here are exact and are derived using only algebra with which a good high school student would be familiar. This is in no way a statistical calculation, and no statistical approximations are involved. The approximations and sources of error involved in solving the equations are as follows:

- The FARS data on restraint use is not necessarily accurate as discussed above. Some people who survive fatal crashes may be out of their vehicles by the time the police officer arrives. Those who are interviewed by the officer may claim that they were using belts when they were not. Injured victims may have been unbuckled or removed from the vehicle by rescue personnel before the officer had an opportunity to determine belt use.
- Cases with unknown belt use have been ignored. If belt use in these cases is significantly different from belt use that was observed, it might skew the results.
- To a more limited extent than in the DPC method, we assumed that safety belt use is similar in crashes of differing risk. For example, the values of v and of w (passenger belt use with belted and unbelted drivers, respectively) were assumed to be the same in all eight sets of four cells. The values of u (driver belt use) vary with the seriousness of the crash as indicated by the risk to the driver.
- When this methodology is applied to small data sets, such as one year of data on light trucks, it is likely to give spurious results because uncertainties and inaccuracies in the data become much more important for such sets. The

result may be that none of the roots of equation 22 are valid, that values for the individual cells in Figure 1 may be negative, or that the effectiveness values derived may be completely unrealistic. See Appendix D for a discussion of this uncertainty.

The higher safety belt use found in the calculations probably comes from over-reporting of safety belt use to police officers, particularly in an era of safety belt use laws in many states. The higher effectiveness value may be due to the fact that this is the first attempt to define safety belt use from first principles that include all available real world data.

It is possible that safety belt effectiveness has improved over time as a consequence of improved design of both vehicles and belt systems. However, when the effectiveness of safety belts was calculated for the individual years from 1985 through 1992, there were no trends toward improved effectiveness in later years, indicating that this is not the case.

This analysis was not carried out beyond 1992 both because cars with air bags and automatic belts were becoming a significant fraction of the fleet by that time.

Adjustments to FARS Data

A criticism of the preliminary results of this work was that the effectiveness values that were found were unrealistically high. Belt use reported in FARS, particularly by people who survive fatal crashes, is also thought to be unrealistically high. As a consequence, some analysts have adjusted the effectiveness calculated using the DPC method downward to compensate. The present method offers a more direct means of addressing this question.

To better understand the consequences of over-reporting of belt use, we arbitrarily reclassified some of the FARS cases to reflect more realistic values of belt use. First, 30 percent of the passenger car cases indicating that both driver and right front passenger were wearing belts and where one or the other was killed were reclassified: 25 percent became cases in which neither driver nor right front passenger were wearing belts, and the remainder were classified as either driver or right front passenger only wearing belts. Fifteen percent of the cases where both driver and right front passenger were belted and killed were reclassified with ten percent becoming both unbelted and the remainder becoming cases in which one or the other was belted.

Table 5 (see next page) shows the redistribution of cases from the new solution of equation 22. The result of this change was to decrease overall belt use to a more realistic 39 percent and to decrease the calculated effectiveness for drivers from 63 to 57 percent, and for right front passengers from 57 to 54 percent. For drivers traveling alone, belt use can still be assumed to be 35 percent regardless of this process of redistribution. At this use rate, the calculated belt effectiveness rises substantially from 42 percent to 56 percent (which is consistent with effectiveness when there is a driver and right front passenger) with the reclassification.

For light trucks, the same procedure reduces belt use to 29 percent and effectiveness to 73 percent for drivers and 71 percent for right front passengers. For light truck drivers traveling alone, at 25 percent belt use the effectiveness would be 60 percent.

There is no formal basis for this reclassification of cases. A general justification is that the belt use calculated from this methodology is higher than observed belt use. The reclassification resulted in much more realistic overall belt use (the 19 Cities Study gives average driver usage of somewhat over 40 percent for this period). It also resulted in a modest reduction in the calculated safety belt effectiveness of roughly 5 percentage points. This gives some confidence that the effectiveness of safety belts is at least 55 percent for passenger car occupants and 65 percent for light truck occupants.

The error from misclassification of belt use is probably less than 10 percent, indicating that misclassification was not primarily responsible for these present results being higher than previous estimates. There is no error due to approximations (there are no significant approximations) nor are there any statistical errors (FARS is a census). This gives strong evidence that previous methods of determining safety belt effectiveness, such as those used in the 1984 decision by the Department of Transportation on occupant crash protection, may have underestimated it.

Table 5.

A recalculation of the numbers of fatally injured passenger car occupants for 1985 through 1992, completely partitioned according to the characteristics of the crash and the state of restraint of driver and right front passenger. For this calculation, the numbers of unrestrained drivers and right front passengers were reduced by 30 percent where only one was killed, 15 percent where both were killed, and ten percent for drivers alone who were killed. These were reclassified as neither being restrained except that 5 percent were reclassified as only driver or right front passenger restrained.

			all drivers who survived			all drivers who were killed			
			survivable		survivable if belted		not survivable		
			unbelted	belted		unbelted		belted	i =
right front passengers who survived	survivable	unbelted			1,474	9,223	5,529	795	I
right front passengers who survived	survivable	belted			5,768	1,196	717	3,113	II
right front passengers who survived	survivable if belted	belted	1,109	5,349	1,300	299	73	288	III
right front passengers who were killed	survivable if belted	unbelted	8,553	1,367	332	2,309	562	74	IV
right front passengers who were killed	not survivable	unbelted	6,272	1,002	64	444	3,322	435	V
right front passengers who were killed	not survivable	belted	813	3,923	250	58	431	1,701	VI
no right front passenger					17,053	31,670	24,727	13,314	VII
			A	B	C	D	E	F	

Statistical Validity

Although this paper uses no statistical techniques and does not develop any statistical formalism, it raises a problem that must be addressed with statistical techniques. The problem is that although FARS is a census of crashes, there is clearly a smallest FARS data file that will provide reliable results. For example, if one were attempting to determine the effectiveness of safety belts in Rolls Royces, there would be at most only a handful of cases in FARS from which to make that determination. They would not permit a meaningful calculation of effectiveness using the technique developed above.

In performing these calculations, the author found data sets that were too small to provide meaningful results, such as one year of data on light trucks. Appendix D is a pragmatic attempt to define the smallest data sets that can be accurately analyzed using this formalism. It shows that FARS data sets must have at least 30,000 vehicles with both a driver and right front passenger in order to provide reasonably accurate results.

CONCLUSION

The primary purpose of the research reported here was to develop a more exact and useful formalism for the determination of effectiveness. The fact that effectiveness values calculated using this formalism were found to be reasonable and consistent gives confidence that the formalism is valid.

One of the major contributions of this methodology is that it give a detailed picture of how many crashes were in each cell defined in Figure 1. Thus, for example, we can see the number of cases in which a crash would have been survivable if driver and passenger had both worn belts, and how many people actually survived.

It is the author's hope that this methodology will be used more extensively and that this work will stimulate refinements and further development of the formalism, and a striving to obtain better input data in FARS, restraint use, and other data sets. This would result in more refined values for restraint effectiveness, which is particularly important as the variety of systems increases. This approach might also prove useful for estimating the effectiveness of restraints in reducing non-fatal injury and of other safety equipment such as automatic safety belts and air bags when sufficient data are available.

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APPENDIX A: A Further Explanation of the Mathematical Formalism used in this Paper

The mathematical formalism used in this paper does not go beyond highschool algebra. What may be confusing to the reader is the nomenclature in which various variables are used to describe similar elements of the problem. The author apologizes for this complexity, but attempts to find simpler expressions failed. Thus, in this appendix, we shall attempt to clearly state what all of the variables stand for and the relationship between them.

All of the variables refer to the data and characteristics of drivers and right front passengers shown in figure 1. This figure introduces the names A_1 through F_7 to describe the driver (capital letter) and right front passenger (subscript). The six states of either a driver or passenger are:

- people who survived an actual crash which are listed in FARS only if someone else was killed in the crash (A, B and C for drivers and I, II and III for right front passengers)
- people who were killed in an actual crash, and therefore were listed in FARS (D, E and F for drivers and IV, V and VI for right front passengers)
- people who wore safety belt restraints when they were in a crash (B, C and F for drivers and II, III and VI for right front passengers)
- people who were unrestrained when they were in a crash (A, D and E for drivers and I, IV and V for right front passengers)
- people who were in crashes that could have been survived regardless of belt use (A and B for drivers and I and II for right front passengers)
- people who were in crashes that could only have been survived if the occupant was wearing a safety belt (C and D for drivers and III and IV for right front passengers)
- people who were in unsurvivable crashes regardless of restraint use (E and F for drivers and V and VI for right front passengers)

The number VII is used to indicate that there was no right front passenger in the vehicle at the time of a crash.

Since the FARS data does not indicate whether a crash was survivable or not, we cannot make the distinctions shown in the last three bullets above unless an unrestrained driver or right front passenger survived (A and I) or a restrained driver or right front passenger was killed (F and VI). FARS data can tell us whether an occupant was restrained or not, and whether he or she was killed or not. Thus, FARS tells us the sum of B and C (but not B or C individually), the sum of D and E, the sum of II and III, and the sum of VI and V. Therefore, we chose to rename the data elements as follows:

K = A	1 = I
L = B + C	2 = II + III
M = D + E	3 = IV + V
N = F	4 = VI
and	5 = VII

Next, the variables u, v, and w were introduced to provide further relationships that can be used to derive the data in the individual cells of the matrix shown in Figure 1. They take on values of 0 (if no one in a particular cell was wearing belts) to 1 (if everyone in a cell was wearing belts). In particular, u_o is used to designate the belt use rate of drivers in survivable crashes and u (without subscript) is used to designate the belt use rate of drivers in crashes that could not be survived regardless of belt use. For those drivers in crashes that are survivable only if the belts are used, we designated belt use as u_i and assumed that it is a harmonic average of u_o and u:

$$1/u_i = 2/u_o + 2/u \quad \text{or} \quad u_i = 2uu_o/(u_o + u)$$

The new variables v and w indicate the belt use rate of right front passengers when drivers are belted and unbelted, respectively. It is well known that passenger belt use tends to follow driver belt use, so that v is close to zero and w is close to unity.

The final transformation is made solely for mathematical purposes. We found that passenger belt use could be expressed in terms of known values from the FARS file, so no further specification was necessary for them. However, to transform the equations involving u_o and u into solvable equations, we defined new variables x and y so that:

$$x = (1 - u_o)/u_o \quad \text{and} \quad y = (1 - u)/u$$

That transformation put equations involving u_o, u, and the FARS data into quadratic form with the variables x and y that can be exactly solved. From values of x and y, we can derive values of u_o and u, and can determine values for all of the individual cells in Figure 1. This not only permits an exact calculation of safety belt effectiveness, it provides remarkably detailed information about what happened to the people involved in real world crashes. It is a far more powerful solution than the double pair comparison method which is only a special case of the present methodology.

More importantly, this method permits a kind of experimentation that can explore uncertainty in certain variables in the FARS file. FARS is virtually exact in showing whether occupants of a vehicle lived or died by seating position. It is less reliable in showing safety belt use, particularly for occupants who survived and were capable of getting out of the vehicle before emergency personnel arrive.

The experiments that can be performed are of the "what if" variety: what if safety belt use for surviving drivers is overestimated by 10 percent? We need only increase u by 10 percent and we can see the effect on the calculated effectiveness.

APPENDIX B. The Equation for Effectiveness

Equation 2 may seem inconsistent with equation 1 at first glance. One might be tempted to write equation 2 as:

$$E = \left(1 - \frac{\dfrac{B + C}{B + C + F}}{\dfrac{A}{A + D + E}} \right) \times 100\% \qquad (22)$$

The numerator represents the proportion of cases where drivers were wearing safety belts who survived. The denominator represents the proportion of cases where drivers who were not wearing belts survived.

The first problem with this expression is that we have no way of knowing how many people were in crashes where there were no fatalities and would not have been even if belts had been worn. The second problem with the expression is that it ignores the problem that belted drivers may have a substantially different spectrum of crashes by severity.

The expression of equation 2 is derived by assuming that we could determine how many drivers would have been killed if the entire population of vehicles involved in potentially fatal crashes even if all had been belted (columns E and F). This becomes the numerator in the expression. For the denominator, we assume that we could determine how many drivers would have been killed if none had been belted (columns C, D, E, and F). Thus, equation 2 is fully consistent with equation 1.

APPENDIX C: The Double Pair Comparison Method

Evans defines what he calls the "true effectiveness" of belts for drivers as the ratio of the number of unbelted drivers who would have been saved had they been wearing belts to the total number of unbelted drivers who were actually killed. For drivers, referring to Figure 1, this is column D divided by the sum of columns D plus E. This is a more limited definition than the one described above (which is equivalent to columns C plus D divided by columns C plus D plus E plus F), so that Evans' label "true" is a substantial overstatement.

More importantly, Evans recognized that there is no direct way to measure which unbelted drivers would have been saved had they been wearing belts (or, as Evans formulated the problem, how many unbelted drivers would have been killed even if they had been wearing belts).

Evans procedure was to use known quantities from FARS to estimate what he called the "true effectiveness." Specifically, for belt effectiveness in protecting drivers, using the nomenclature of Figure 2, he proposed the equation:

$$\begin{aligned} E &= (1-R)\times 100\% \\ &= 1-\frac{(a+c)/(b+c)}{(j+l)/(k+l)}\times 100\% \end{aligned} \qquad (23)$$

where:

$a =$ number of crashes killing a belted driver but not an unbelted passenger,

$b =$ number of crashes killing an unbelted passenger but not a belted driver,

$c =$ number of crashes killing both a belted driver and an unbelted passenger,

$j =$ number of crashes killing an unbelted driver but not an unbelted passenger,

$k =$ number of crashes killing an unbelted passenger but not an unbelted driver, and

$l =$ number of crashes killing both an unbelted driver and an unbelted passenger.

Figure 2 shows what parts of the crash spectrum are defined by these letters. Note that $a+c$ and $j+l$ are all crashes killing a belted or unbelted driver, respectively, who was with any unbelted passenger. Similarly, $b+c$ and $k+l$ are all crashes involving any unbelted or belted driver, respectively, who is with an unbelted passenger who was killed. This is the belt use ratio defined as α or β above. (For completeness, similar relations can be developed involving only belted passengers in order to use more of the data available in FARS. One can also make the parameters relating to the right front passengers the dependent variables in such equations.)

In using this formulation, Evans is substituting the number of belted drivers who are killed (cells $F_1+F_3+F_4$ in Figure 1) for unbelted drivers who would have been killed even if they were belted (the part of $j+l$ that would have been killed even if they were belted or cells $E_1+E_3+E_4$ in Figure 1) in his "true effectiveness" equation. Since the ratio of these numbers is equal to the ratio of belted to unbelted drivers involved in unsurvivable crashes, he multiplies the number of belted drivers who are killed by the ratio of the total number of unbelted to belted drivers who are with passengers who are killed. To the extent that belt use is consistent in crashes that are sufficiently serious to kill either a driver or a right front passenger, this gives a reasonable approximation of Evans' "true effectiveness."

This substitution does not address the more fundamental limitation of Evans' definition of "true effectiveness," nor does it make complete use of the available data. The most general formulation of the DPC is as follows:

$$E = \left(1 - \frac{\sum_{i=1}^{6} (F_i) \frac{\sum_{i=4}^{6} (A_i + D_i + E_i)}{\sum_{i=4}^{6} (B_i + C_i + F_i)}}{\sum_{i=1}^{6} (D_i + E_i)} \right) \times 100 \qquad (24)$$

The elements of this equation are all known from FARS. While this is still an approximation, it can give a reasonable estimate of effectiveness.

APPENDIX D: Estimating The Minimum Data File Size for which this Method Provides Valid Results

The analysis developed in this paper does not use statistical methods in any way. However, the author recognizes that with small data files, uncertainties or variations in the input data -- the numbers of crashes in any one cell -- may introduce errors in the results of using this methodology. Because the numbers in the cells of Figure 1 are a complicated function of the numbers in the cells of Figure 2, the author has found no elegant method of analyzing how uncertainties in the numbers in each cell affect the answers provided by this methodology.

Fortunately, the computer provides a technique for experimentally exploring the effect of variation in the input data on the results of the analysis. First, let us assume that each of the numbers in each cell of Figure 2 is a Poisson distribution. That is, the injury consequences in each vehicle is effectively independent of all others. This is not strictly true because in a two vehicle collision, each vehicle may be in a different cell of Figure 2, and therefore the consequences for the occupants of one vehicle may be dependent on what happens in the other. Nevertheless, for our purposes, this is a reasonable assumption.

In a Poisson distribution, the standard deviation is defined as the square root of the mean. If we have 144 cases, the standard deviation of that number is 12. What this means is that we can assume that if we took a sample X times larger (where X is much larger than unity) and divided the number of cases in that larger sample by X, the result has a high probability of being between 132 and 156.

Let us now look at the figures in Tables 1 and 2. Note that the smallest numbers occur in the cells in which a driver was restrained and a passenger was not or vice versa: K_4, L_3, M_2, N_1, M_4, and N_3. In particular, if we look at the data in Tables 1 and 2, the smallest numbers are in just four cells, K_4, N_1, M_4, and N_3. Variations in any of the numbers in these four cells probably govern the validity of the results of the analysis.

We set up a spread sheet with data in the form of Figure 2 using the analysis of this paper to fill in results in Figure 1 and to provide driver and right front passenger restraint use (*u*, *v*, and *w*) and effectiveness. Next, we varied the values in the four cells with the smallest numbers to see the effect of such variation on the results.

Note that a standard deviation is larger for smaller numbers. For example, if the number of cases in a cell is 25, a standard deviation is 5 which is 20 percent of the value in the cell. If the number of cases is 100, the standard deviation is 10 which is 10 percent of the value.

The results were relatively insensitive to large variations in M_4 and N_3. Thus, variations in K_4 and N_1 govern the validity of the results. We found that a variation of 10 percent in these values substantially distorts the results, in some cases giving values of use that are either greater than one or less than zero which is clearly unrealistic, or values in cells of Figure 1 that are negative which is also unrealistic. We found that variations within 5 percent did not produce abnormal results, but that variations of 10 percent definitely did. From this, we conclude that the smallest numbers in cells K_4 and N_1 that produce reliable results are around 400 (standard deviation 20 which is 5 percent of the number of cases in the cell).

The files on which this analysis is based, this suggest that a minimum data file size of about 30,000 cases in which there is both a driver and right front passenger is necessary to provide accurate results.