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16. Abstract

A general methodology is developed for estimating the change in the number of injuries and fatalities expected as a result of a change in vehicle crashworthiness design. It is assumed that crash tests have provided information on dummy response measurements, such as the maximum chest acceleration in a crash, and that based on these test results a conclusion has been reached as to the most likely effect of the design change on the response measurements. Cadaver injury risk curves, which give the probability of injury in terms of test crash and crash data injury risk curves, which give the probability of injury in terms of crash characteristics available in actual crash data (such as delta-v in the NASS database), are used to translate the conclusions expressed in terms the test crash measurements to conclusions expressed in terms of the crash characteristics available in the crash database. The crash database is then used to estimate the injuries and fatalities expected on the road. Detailed calculations are presented for the case of estimating the expected increase in chest injuries and the related as a result of the depowering of air bags.

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EXECUTIVE SUMMARY

The objective of this report is to present a general methodology for determining the benefits (or disbenefits) of a change in vehicle design in terms of injuries prevented (or incurred) and lives saved (or lost) on the basis of the results of crash tests in which dummy responses are measured before and after the change is implemented. The information on dummy responses is typically available for several test crashes and contains specialized measurements such as maximum chest acceleration or arm bending moment during the crash. Using this information, engineering and biomechanical judgements may be formed as to the likely effects of the design change in the measured physical responses. The problem is to translate these assessments on the change in the physical response into changes in the numbers of injuries and fatalities expected to be observed on the road if the design change is implemented in the fleet of vehicles.

The solution is based on the observation that the probability of injury (of a given severity on the AIS scale) can be expressed in two ways: 1) as a function of the physical response measured in test crashes using the cadaver test crash data; and 2) as a function of a measure of crash severity such as speed at the time of impact (or delta-v) as recorded in a crash database. The idea is to relate the crash severity measure and the physical response level corresponding to it based on the probability of injury. Then a change in the physical response can be translated to a change in the crash severity measure and the new probabilities of injury can be determined. Given the numbers of motor vehicle occupants involved in crashes at various crash severity levels in the crash database**,** the information on new probabilities of injury at those crash severity levels is used to predict the numbers of injuries after the vehicle design change is implemented. By comparing the predicted numbers of injuries based on the probabilities of injury before and after the change is implemented, the effect of the change can now be assessed.

The calculation of the change in the number of fatalities is based on a relationship between the probability of fatality and the injury severities of a motor vehicle occupant. This relationship is established empirically using crash data. The predicted number of fatalities is calculated using the estimated probability of injury at various severity levels before and after the vehicle design change.

The original motivation for developing this methodology was the problem of estimating the effect of changing the Motor Vehicle Occupant Protection Standard No. 208 to allow the depowering of air bags. The methodology was then implemented to estimate the expected increases in the numbers of chest injuries and related fatalities as a result of depowering. A refined version of these calculations is presented in this report to illustrate the use of the methodology in a practical example. The numbers presented are based on the assumption of a 33 percent increase in chest acceleration across all crash severities and occupants. This assumption is not based on actual experience with air bag depowering and consequently the results represent a purely hypothetical case. However, apart from the assumption about the increase in chest acceleration, the calculations presented are based on actual cadaver data and crash data. They show how to establish a statistically significant increase in chest injuries when the actual information on chest acceleration change due to depowering is used.

1. Introduction and outline of general methodology.

Vehicle safety research involves crash tests of cars with dummies or cadavers in place of living occupants. Specialized instruments are used to measure various physical responses of the dummies during the crash, such as chest acceleration, chest deflection, neck shear, tension, compression, flexion, extension, etc. It is also possible with cadaver testing to determine the types and severities of injuries that an occupant may experience in the crash. This information allows construction of injury risk curves relating the probability of injury of a given type and severity level to the physical responses measured. The injury risk curve is often constructed by fitting a cumulative distribution curve such as normal or logistic to the observation points representing injury rates at the measured physical response levels.

When a change in the automobile design is contemplated and the change is expected to affect the safety of vehicle occupants in crashes, the problem arises of estimating the effect of the change in terms of changes in the number of injuries and fatalities. We can determine, using crash tests, how the contemplated crashworthiness design change alters the occupant's physical responses from those observed before the design change was implemented in the experimental vehicle. The question then is how to utilize this information to estimate the effect of the change on injuries and fatalities if the change were actually implemented in the fleet of vehicles on the road.

The information on real-world crashes is available from crash databases, such as the NASS-CDS (National Automotive Sampling System - Crashworthiness Data System) database, maintained by the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety Administration (NHTSA). This database does not contain information on the physical responses of the occupants as measured in crash tests. Instead, it contains information on a number of crash characteristics, such as a measure of crash severity (delta-v), the principal direction of force of the impact, area of vehicle damage, as well as information on individual characteristics of the occupants, including age, sex, weight, height, and the type, location, and severity of all injuries.

Assuming that the database is representative of all crashes occurring in the country and that the proposed vehicle design change will not affect the number and the type of crashes occurring on the road, the effect of the design change can be estimated by its effect on the injuries and fatalities of the crashes represented in the database. That is, one wishes to compare the currently observed numbers of injuries and fatalities with the hypothetical numbers that are predicted if the design change were implemented.

To achieve this, the following approach is proposed. For a given crash type, it is possible to relate the probability of the occurrence of an injury of a given type and severity to the delta-v reported for the crash. This can be accomplished using any of the standard statistical techniques for modeling a binary or ordinal response variable as a function of explanatory variables, such as the logistic regression. The result is a smooth injury risk curve giving the probability of the injury as a function of delta-v. The probability of injury typically increases monotonically in delta-v.

The idea now is to determine what change in injury probabilities would occur for given crash severity categories (determined by delta-v) when the vehicle design changes are implemented. Then, to estimate the effect a particular design change would have on the number of injuries, one multiplies these new injury rates by their respective exposure numbers to calculate the expected number of injuries for each severity level and delta-v stratum. The issue that remains is how to estimate the change in injury probabilities that would occur if the proposed design changes were implemented.

Biomechanical impact trauma research studies and models relationships between physical responses observed on the individual and the probability of the occurrence of injury of a particular severity. Given such a model, one could estimate the effect of the vehicle design changes on injury probabilities if one could estimate the effect the design change has on the individual responses through experimental means. Fortunately, vehicle crash testing and sled testing offer such means by allowing testing of the design both before and after the proposed changes and observing how the particular body response changes on a test dummy.

To relate the observed effects the design changes have on a biomechanical response to the effects the design changes have on injuries and fatalities in a particular delta-v category, one determines the biomechanical response level associated with the injury rate of the delta-v category. This physical response level is then changed to the new level suggested by the vehicle tests implementing the new design. This, in turn, indicates what the new injury probability for the modified design would be for the given injury severity and delta-v category. These modified probabilities are then multiplied by their respective exposure numbers to determine the expected numbers of injuries at each severity level and delta-v.

Although it is assumed that the actual delta-v in crashes will not change with the design change, it is possible to think of the effect of the design change as an equivalent of a change in delta-v as far as occupant injuries and fatalities are concerned. This provides the following alternative description of the above outlined methodology. In order to determine the delta-v shift equivalent to the vehicle design change, one looks at the injury risk curve obtained from crash tests to find what value of the physical response corresponds to a given probability of injury. This is possible because of the one-to-one correspondence between the physical response measurement level and the probability of injury as given by the injury risk curve. The probability of injury corresponding to a shift in the physical response due to design change is then found. The delta-v corresponding to this probability of injury on crash injury risk curve represents the hypothetical delta-v of a crash equivalent to a crash with the original delta-v but for a vehicle with the new design. In this way, a new injury risk curve is constructed. Once the injury risk curves have been found, they are used to predict the numbers of injuries corresponding to the original and the new conditions. This is accomplished in the same manner as described above, by multiplying the total numbers of crash-involved individuals in various delta-v categories by the corresponding probabilities of injury from the injury risk curves.

Note that the change from the original delta-v to the hypothetical delta-v may be positive, when the probability of a particular type of injury under the new design of vehicle increases, or negative, when the new vehicle design results in a decrease in the injuries. Also, the change may be positive or zero for some range of delta-v, and negative for another range. Although the concept of modified delta-v is not required to complete the calculation, it appears useful as a theoretical device.

The methodology outlined above can be used to estimate the change in the number of injuries at a given severity level associated with a change in the vehicle design. The problem of estimating the change in the number of fatalities requires additional effort since examination of the dummy responses or cadavers in crash tests can provide information about injury severities, but in most cases it cannot be directly determined whether the injuries would have resulted in death. Consequently, no fatality risk curves can be constructed directly from crash test data. However, it is possible to estimate the probability of fatality based on the severities of the injuries received. The estimated probability of fatality can be used to predict the number of fatalities in the same way the probability of injury was used to predict the number of injuries.

It is proposed to estimate the effect of a vehicle design change on fatalities by taking the difference between the number of fatalities predicted from injury severities in the population of occupants in crashes under the current conditions and the number of fatalities predicted from injury severities expected in the same population after the design change is implemented. The estimated number of fatalities rather than the actual count in the population are used, but the difference between the two numbers is small if the model for predicting fatality numbers is valid. Although the actual number of fatalities in the population is available, the number of fatalities in the hypothetical, post-design-change population has to be estimated from injury severities, and it appears appropriate to use the estimated number of fatalities also for the original population for consistency.

A simple model for estimating the probability of fatality from injury severities using only the severity of the two most serious injuries was developed. Additional characteristics, such as injury locations, as well as an individual’s age, weight or height were not incorporated in the model. Although the statistical model assumes that the probability of dying is a function of the severities of the two most serious injuries irrespective of their type or location, it is necessary to distinguish between injuries affected by the design change and injuries which are assumed not to be affected by the design change. All the injuries of the type assumed to be affected by the design change are modeled as random severity injuries with a distribution of severities determined by the delta-v of the crash, while all other injuries are those found in the original data file. Only one injury of the type assumed to be affected by the design change is modeled for each individual. This injury is supposed to be the most severe injury of this type, but the possibility of zero severity is allowed, corresponding to the possibility of no injury. Because the injuries assumed to be affected by the design change are replaced with the random severity injury, the actual injuries and their severity as recorded in the data file are discarded to the extent that they are of the type assumed to be affected by the design change.

The model can be visualized as a two-step process. First, for each occupant recorded in the data file, an injury severity is generated as a random variable with a distribution depending on the delta-v of the crash in which the occupant was involved. This distribution is obtained from the injury risk curves giving the probabilities of injury of the type under consideration in terms of delta-v. The possibility that no injury of the type under consideration occurs is allowed and it corresponds to zero severity injury. Then, an injury of this statistically generated severity replaces all actual injuries of the type under consideration in the data file for this individual. The resulting set of injuries is used in the second step when hypothetical death or survival of the individual is determined as an outcome of a random trial with the probability of death determined by the highest two injury severities among the set of injuries determined in the first step.

The total number of fatalities in the population is estimated as the expected value of the number of deaths for all individuals under the above model. The procedure allows one to express the number of fatalities as a function of injury probabilities. Although this expression is only an estimate and is subject to error, it has the advantage that changes in the number of fatalities can now be studied through changes in the probabilities of injuries. Once this is accomplished, the results of crash tests can be applied to determine the effect of proposed design changes on fatalities.

The question arises of how good is the above procedure in estimating the number of fatalities. This can be gleaned by comparing the estimated number and the actual number of fatalities in the data file. But it should also be noted that inasmuch as the objective in developing the above procedure is to study the change in the number of fatalities as the injury probabilities change, the question of accuracy in estimating the fatality number is secondary to the question of whether the model accurately reflects the sensitivity of fatality probability to changes in injury severities.

The general methodology outlined above is illustrated by a practical application to the problem of estimating the effect of changing the speed of air bag deployment on chest injuries and fatalities.

2. An implementation of the methodology in a study of the effect of change in air bag deployment speed on chest injury and fatality rates.

A. Background.

Motivated by concerns about injuries and fatalities that were reported to have been caused by deploying air bags in certain types of crashes, the National Highway Traffic Safety Administration undertook a research program designed to study the effect of allowing the air bag to deploy with less force (depowering of the air bag). It was reasoned that although a depowered air bag may be less likely to cause injuries in lower speed crashes, it may also be less effective in protecting occupants in high speed crashes. The problem was to estimate the effect of depowering of the air bags in terms of changes in the number of injuries and fatalities.

In order to obtain experimental evidence of the effect of depowering, a number of crash tests were performed at NHTSA'a Vehicle Research Test Center (VRTC) in East Liberty, Ohio. In these tests specialized instrumentation, including accelerometers, was used to take measurements of various physical responses of dummies during crashes at various speeds and with air bags deploying at the current and reduced mass flow rates. It was observed that depending on the degree of reduction in the rate of deployment, the type of crash and the type of occupant, depowering of an air bag would result in an increase in the maximum chest acceleration during the crash of between 4 percent and 41 percent. The results of VRTC's tests are reported in NHTSA's Final Regulatory Evaluation (1997). The question then became what do these changes in chest acceleration mean in terms of changes in the number of chest injuries and fatalities. In order to answer this question, the previously outlined methodology was applied.

It should be noted that the results presented in the Final Regulatory Evaluation are based on different data than the results presented in this report, because since the publication of the Final Regulatory Evaluation, the 1996 NASS-CDS data became available. Also, the Final Regulatory Evaluation takes the analysis a step further than this report, because it considers different changes in the chest acceleration due to air bag depowering for drivers and passengers, for restrained and unrestrained occupants, and for different crash severity categories. The analysis presented in this report is restricted to the case of unbelted air bag restrained occupants, and assumes that the effect of air bag depowering is an across-the-board 33 percent increase in chest acceleration for all those occupants and crash severities. These assumptions may be unrealistic, but the objective of the report is not an examination of the actual problem of the effect of the depowering of air bags, which is a complex problem involving engineering judgments in addition to statistical analysis. Rather, the focus of the present report is to present a general methodology, which is applicable to problems beyond the evaluation of the effects of air bags depowering. A somewhat more refined version of the methodology is presented compared with the Final Regulatory Evaluation, although it uses the same basic approach. In particular, the calculations presented here allow a straightforward derivation of the confidence intervals for the estimates obtained.

B. Estimation of the change in the number of chest injuries.

NHTSA has data on probabilities of chest injury at various chest accelerations. These data were obtained from cadaveric tests conducted at the University of Virginia, the Medical College of Wisconsin, the University of Heidelberg, as well as from various previously published studies (Walsh et al., 1978, Cheng et al, 1982, Kallieris et al., 1982). A total of 35 unbelted air bag restrained tests were used in the analysis. The tests were frontal impacts at various speeds and for male and female cadavers covering a range of cadaver ages and sizes. In each of these tests, the maximum thoracic injury was recorded using the Abbreviated Injury Scale (AIS), and a valid chest acceleration measurement was available. The data are reproduced in Appendix 1.

Based on the information from these tests, injury risk curves were constructed which give the probability of injury at a given severity level as a function of chest acceleration in g (9.81 m/s^2) units. The severity levels considered were AIS 3+ injuries (injuries of AIS 3 or greater severity), AIS 4+ injuries, and AIS 5+ injuries. Injury risk curves were constructed using the multivariate logistic regression model. In addition to chest acceleration, age, gender, and weight were entered into the model. It was determined that a linear combination of age and chest acceleration was the best discriminator of AIS 3+, AIS 4+, and AIS 5+ chest injury severities. The model was then transformed to be independent of age by setting the age to 32.67, which is the mean age of the air bag restrained population in the NASS-CDS data. Thus, the general form of the model for chest injury probability P at chest acceleration a is

(1) $$P(a)=1/(1+\exp(-c_0-c_1a)),$$

where c_0 and c_1 are estimated regression coefficients. These coefficient are subject to estimation error, and standard statistical software provides the variances, and the covariance between c_0 and c_1. From this, one determines the variance of the expression $-c_0-c_1a$, viz., $\boldsymbol{\sigma_c}^{\mathbf{2}}=\mathrm{var}(c_0)+a^2\mathrm{var}(c_1)+2a\ \mathrm{cov}(c_0,c_1)$. Under the standard assumption of joint normality of the estimates of the regression coefficients, one then obtains lower and upper confidence bounds for $-c_0-c_1a$ as $-c_0-c_1a\pm z_{1-\ /2}\boldsymbol{\sigma_c}$, where z is the 100 -th percentile of the standard normal distribution, and 1− is the confidence level. It follows that a (1−)-level confidence interval for P(a) is $(1/(1+\exp(-c_0-c_1a-z_{1-\ /2}\boldsymbol{\sigma_c})),1/(1+\exp(-c_0-c_1a+z_{1-\ /2}\boldsymbol{\sigma_c})))$.

The resulting relationships between the probability of injury of severities AIS 3+, AIS 4+, and AIS 5+ are the cadaver chest injury risk curves used in this study. Table 1 presents the estimated probabilities of injuries as a function of acceleration at 20 g intervals, and Figure 1, Figure 2 and Figure 3 show graphs of the injury risk curves together with 95 percent confidence bounds for AIS 3+, AIS 4+ and AIS 5+ injuries, respectively.

Table 1. Probability of chest injury as a function of chest acceleration from cadaver data (95 percent confidence intervals given in parenthesis).

Acceleration (in g units)	Probability of AIS 3+ injury	Probability of AIS 4+ injury	Probability of AIS 5+ injury
10	0.004 (0.000,0.070)	0.002 (0.000,0.041)	0.000 (0.000,0.009)
30	0.015 (0.002,0.128)	0.007 (0.000,0.078)	0.001 (0.000,0.018)
50	0.060 (0.013,0.233)	0.027 (0.005,0.147)	0.002 (0.000,0.038)
70	0.206 (0.085,0.422)	0.103 (0.032,0.284)	0.010 (0.001,0.081)
90	0.513 (0.287,0.735)	0.318 (0.144,0.564)	0.040 (0.007,0.189)
110	0.811 (0.509,0.947)	0.655 (0.335,0.877)	0.144 (0.033,0.453)
130	0.946 (0.685,0.993)	0.885 (0.530,0.981)	0.406 (0.100,0.808)
150	0.986 (0.811,0.999)	0.969 (0.695,0.998)	0.736 (0.218,0.965)

Figure 1

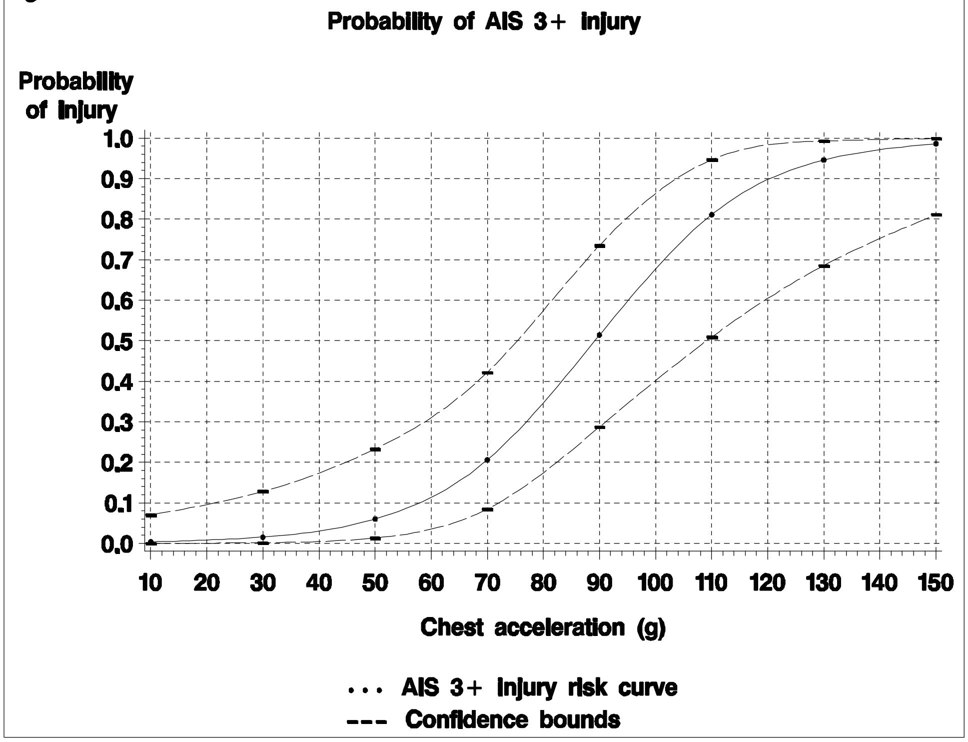
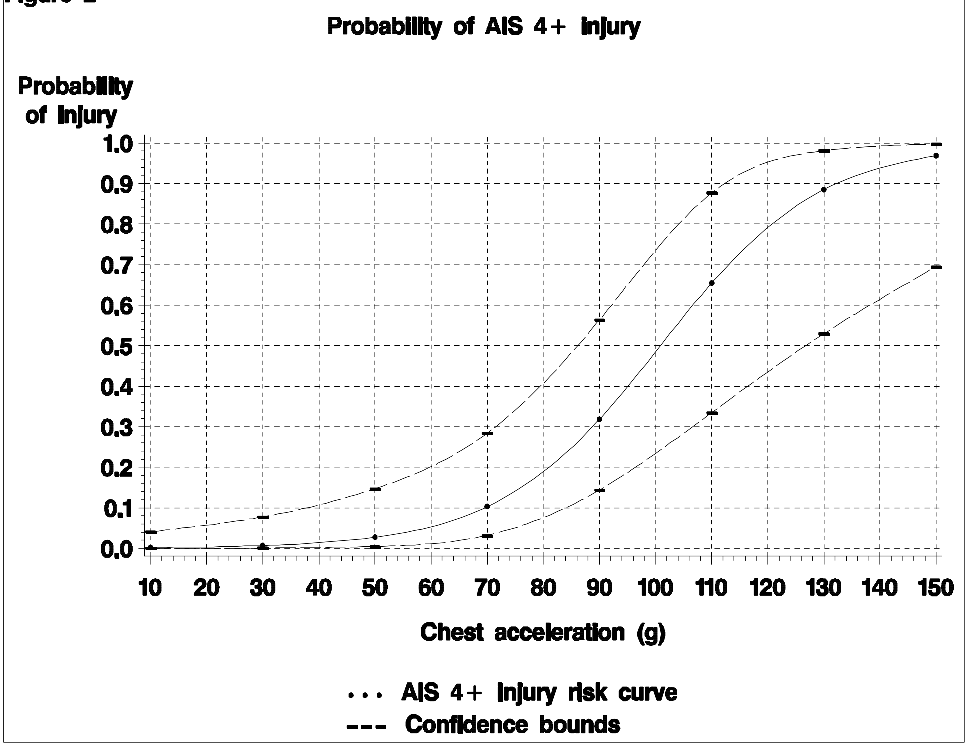
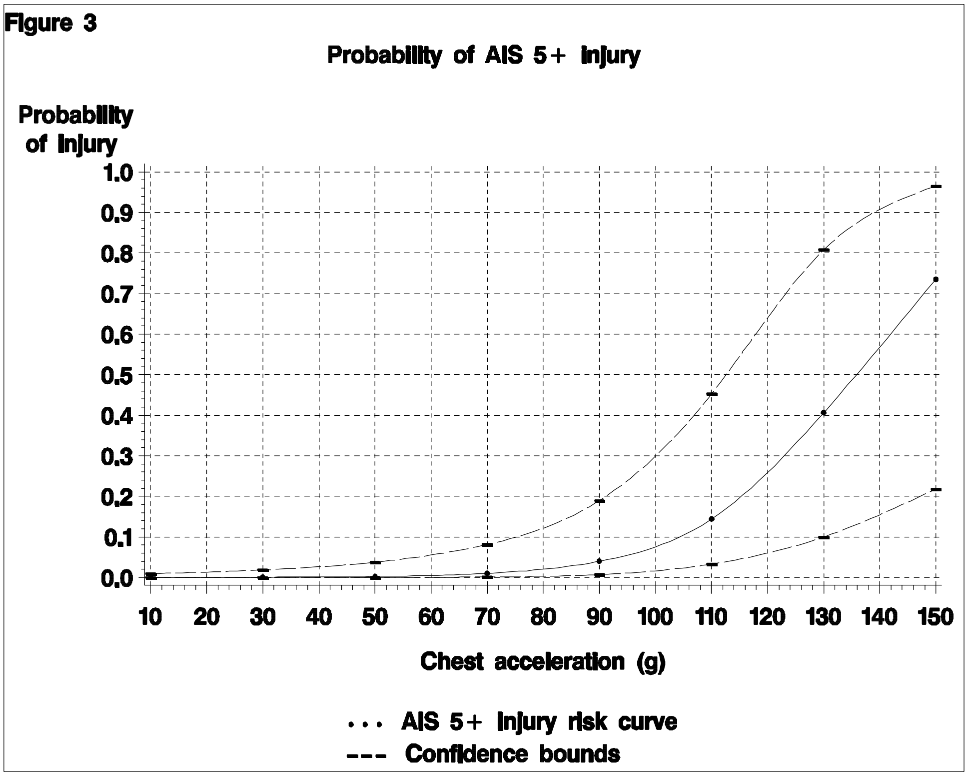


Figure 2





It is possible to use these curves to assess the change in the probability of injury corresponding to a change in the chest acceleration. For example, at 60g the probability of an AIS 3+ chest injury is about 0.145 according to the cadaver injury risk curve. If the acceleration is increased by 33.33 percent to 80g, the probability of AIS 3+ chest injury increases to 0.354. However, these injury risk curves do not give a clue as to the effect of increasing the chest acceleration in all the various crashes actually occurring on the road. That is, the injury risk curves cannot be directly used to tell how many additional AIS 3+, AIS 4+ and AIS 5+ injuries would occur in frontal crashes in cars currently equipped with air bags if the design of the air bag were changed to allow an across-the-board 33.33 percent increase in chest acceleration. The reason is that it is not known what the chest acceleration levels are in crashes occurring on the road.

NHTSA's Crashworthiness Data System (CDS) is a probability sample of police-reported crashes occurring in the United States. It contains detailed information on occupant and vehicle characteristics in crashes, and can be used to estimate national totals. In particular, CDS contains information about delta-v for vehicles in crashes, as well as information about the occupant's injury type, location and severity. For the purposes of this analysis, the population of interest is unbelted individuals experiencing air bag deployment during the crash. Appendix 2 shows the unweighted sample sizes for each delta-v and chest injury severity in the data used. Table 2 presents the estimated national totals of crash-involved occupants, injured occupants, and the injury rates for chest injuries at AIS 3+, AIS 4+, and AIS 5+ levels based on these data for each of the specified delta-v ranges, which were chosen to be 0-10, 11-20, 21-30, 31-40, 41-50, and over 51 mph.

Table 2. Estimated Chest Injuries (unbelted occupants, age 16 to 76, air bag deployed) NASS-CDS weighted data, 1991-1996, cases with missing data elements omitted.

ΔV	Estimated Number of Individuals	AIS 3 +		AIS 4 +		AIS 5 +	
		Number	Rate	Number	Rate	Number	Rate
0-10	18,557	40	0.002	40	0.002	0	0.000
11-20	47,701	286	0.006	51	0.001	0	0.000
21-30	7,165	1116	0.156	361	0.050	11	0.002
31-40	2,218	723	0.326	428	0.193	101	0.046
41-50	580	252	0.434	210	0.363	126	0.218
51 and up	443	0	0.000	0	0.000	0	0.000

The logistic regression model was used to develop chest injury risk curves for these crash data for each of the three injury severity levels AIS 3+, AIS 4+ and AIS 5+. The injury risk curves give the probability of chest injury as a function of delta-v. The logistic regression model assumes that the probability of injury at a given delta-v is

(2) $$P(\Delta v)=1/(1+\exp(-b_0-b_1\Delta v)),$$

where b_0 and b_1 are regression coefficients estimated using the maximum likelihood method. This is the same type of model as the one used to construct the cadaver injury risk curves, and the same method can be used to obtain the confidence intervals for the estimated probabilities. Thus, a (1−)-level confidence interval for $P(\Delta v)$ is $(1/(1+\exp(-b_0-b_1\Delta v-z_{1-\ /2}\boldsymbol{\sigma_b})),1/(1+\exp(-b_0-b_1\Delta v+z_{1-\ /2}\boldsymbol{\sigma_b})))$, where $\boldsymbol{\sigma_b}^2=var(b_0)+\Delta v^2\, var(b_1)+2\Delta v\, cov(b_0,b_1)$. The resulting estimated probabilities, evaluated at the mid-point of each delta-v range, together with the corresponding confidence intervals, are presented in Table 3.

Table 3. Probability of chest injury as a function of delta-v from crash data (95 percent confidence intervals given in parenthesis).

Delta-v (in mph)	Probability of AIS 3+ injury	Probability of AIS 4+ injury	Probability of AIS 5+ injury
5	0.005 (0.002,0.012)	0.002 (0.001,0.007)	0.000 (0.000,0.002)
15	0.019 (0.011,0.031)	0.008 (0.004,0.015)	0.002 (0.001,0.003)
25	0.068 (0.021,0.197)	0.029 (0.010,0.085)	0.006 (0.003,0.012)
35	0.218 (0.033,0.697)	0.103 (0.016,0.452)	0.022 (0.005,0.098)
45	0.516 (0.049,0.957)	0.305 (0.024,0.886)	0.079 (0.007,0.505)
55	0.803 (0.072,0.995)	0.626 (0.036,0.987)	0.246 (0.011,0.908)

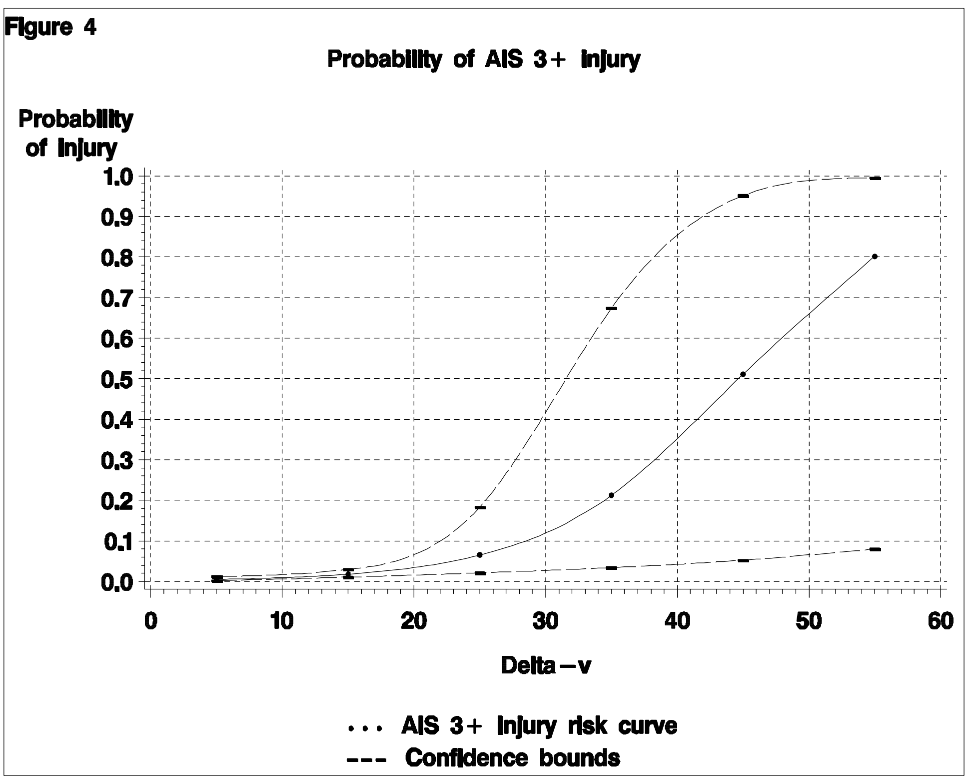


Figure 5

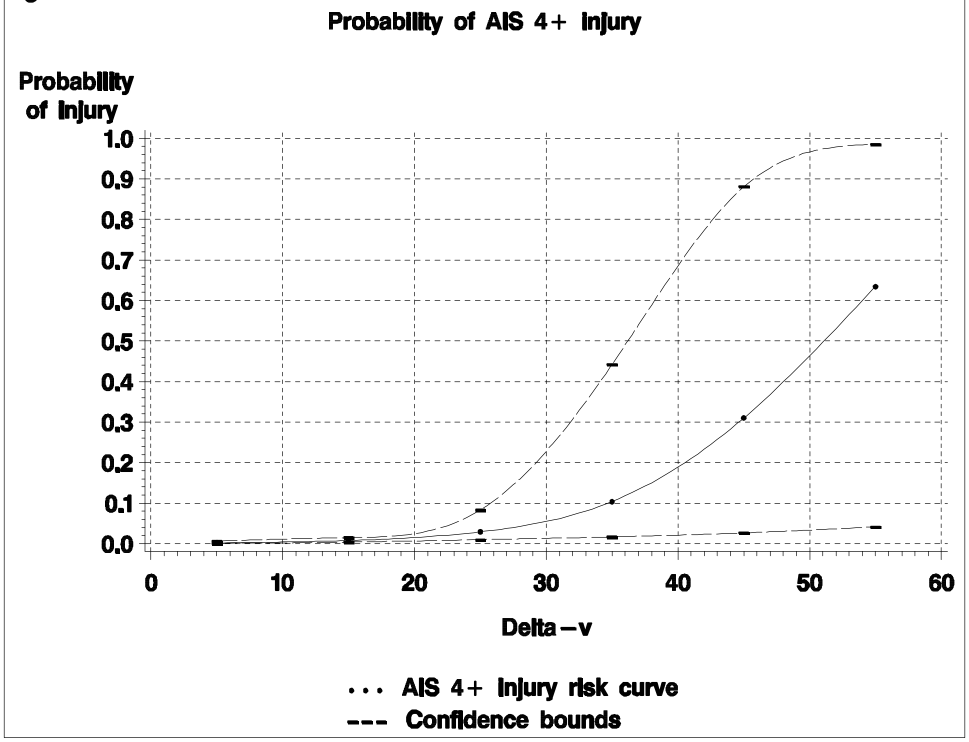
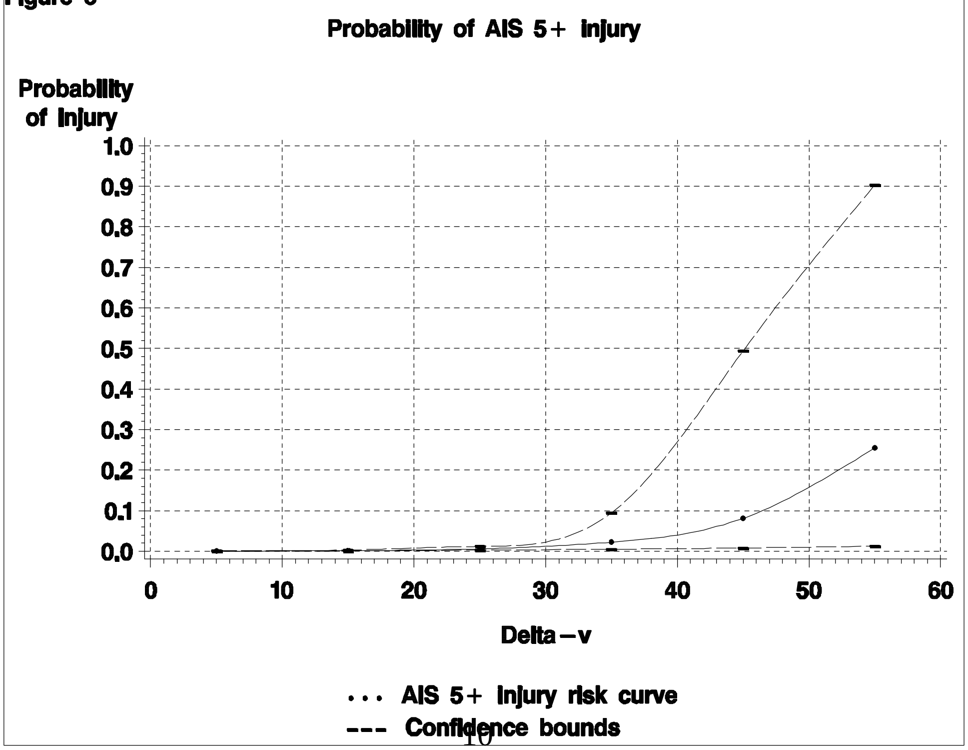


Figure 6



Once the injury risk curves for both the laboratory data and the field data are constructed, the key step is to relate the two. The cadaver injury risk curve (1) gives a probability of injury at a given severity level (AIS 3+, AIS 4+, AIS 5+) as a function of chest acceleration measured in g units. On the other hand, the crash injury risk curve (2) gives the same probability of injury as a function of delta-v. Equating the expressions for probability of injury (1) and (2) gives the relationship between chest acceleration and delta-v. Specifically, the relationship is

(3) $$c_0+c_1a=b_0+b_1\Delta v.$$

In this way, delta-v levels representing a measure of crash severity can be related to chest accelerations. This correspondence can be established for each of the three curves for injury probability at AIS 3+, AIS 4+ and AIS 5+ severities.

This relationship between chest acceleration and delta-v allows one to construct modified crash injury risk curves which represent the probabilities of AIS 3+, AIS 4+ and AIS 5+ injuries when chest accelerations in crashes are increased due to air bag depowering. For example, suppose that depowering results in a certain percentage increase in chest acceleration, say 33.33 percent, across all crash severities. In order to find the modified injury probabilities under this scenario, one first determines the new delta-v level, say $\Delta v'$, corresponding to the new chest acceleration level, say $a'=1.333a$. From (3), one obtains

$$\Delta v'=(c_0-b_0+c_1a')/b_1=(c_0-b_0+c_1a)/b_1+0.333a/b_1=1.333\Delta v+0.333(c_0-b_0)/b_1.$$

The resulting modified delta-v levels for the mid-points of the delta-v ranges for the three injury risk curves (AIS 3+, AIS 4+, AIS 5+) are shown in Table 4.

Table 4. Delta-v levels corresponding to increase in injury due to a 33.33% increase in chest acceleration

Original Δv	Modified Δv AIS 3+	Modified Δv AIS 4+	Modified Δv AIS 5+
5	7.38	7.21	9.16
15	20.71	20.54	22.49
25	34.04	33.87	35.82
35	47.37	47.20	49.15
45	60.70	60.53	62.48
55	74.03	73.86	75.81

The modified injury probabilities are determined using crash injury risk curves, i.e. equation (2), with $\Delta v'$ in place of the original Δv. Thus, the chest injury probability under the new conditions is

(4) $$P(\Delta v')=1/(1+\exp(-b_0-b_1\Delta v'))=1/(1+\exp(-1.333(b_0+b_1\Delta v)+0.333c_0)).$$

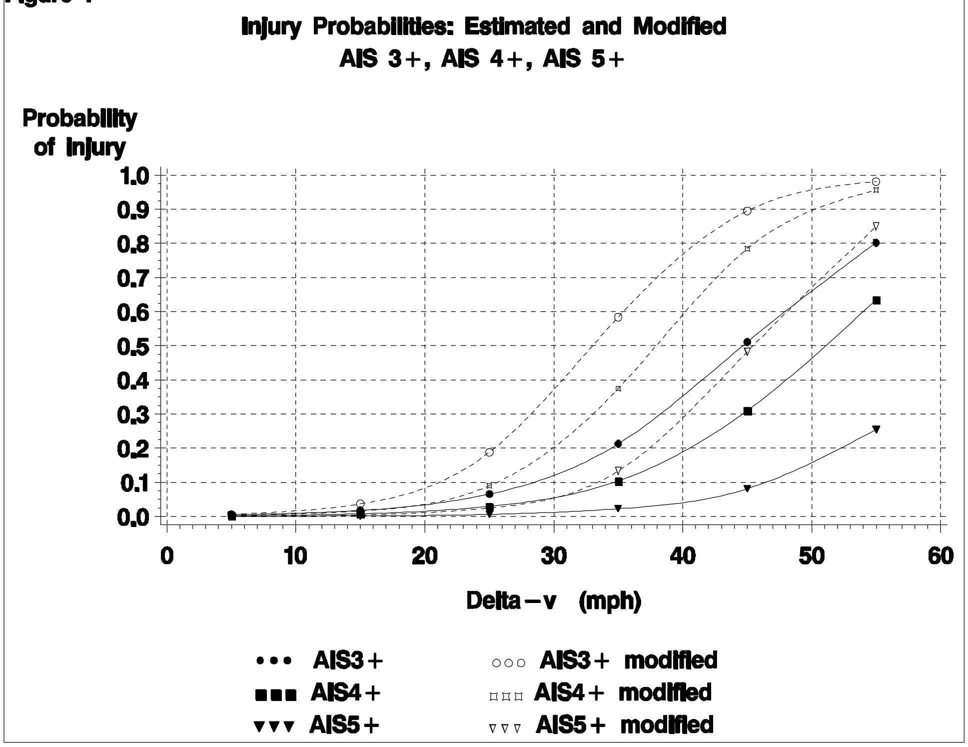
The modified probabilities of AIS 3+, AIS 4+, and AIS 5+ injuries are presented in Table 5.

Table 5. Modified Injury Probabilities (assuming 33.33% increase in chest acceleration).

△V	AIS 3 +		AIS 4 +		AIS 5 +	
	Baseline Probability	Modified Probability	Baseline Probability	Modified Probability	Baseline Probability	Modified Probability
0-10	0.005	0.007	0.002	0.003	0.000	0.001
11-20	0.019	0.039	0.008	0.016	0.002	0.004
21-30	0.068	0.197	0.029	0.090	0.006	0.024
31-40	0.218	0.595	0.103	0.371	0.022	0.130
41-50	0.516	0.898	0.305	0.779	0.079	0.472
51 and up	0.803	0.981	0.626	0.955	0.246	0.842

The modified injury risk curves are shown in Figure 7.

Figure 7



Using the original injury risk curves and the modified injury risk curves, it is now possible to estimate the change in the number of chest injuries (at AIS 3+, AIS 4+, and AIS 5+ levels) due to the change in chest acceleration by 33.33 percent. For each delta-v category, the number of individuals with a given level of injury under the original conditions is predicted using the original injury risk curve by multiplying the total number of individuals in that delta-v category by the estimated probability of injury. The predicted number of chest injuries under the modified conditions is obtained by multiplying the same total by the modified probability. For example, for delta-v range 0-10 the estimated number of crash-involved individuals is 18,557 (Table 2), and the estimated injury probability is 0.00497 under the baseline conditions, and it is 0.00648 under the modified conditions (Table 6, where the numbers are rounded to three decimal places). So the predicted number of injuries is 18,557×0.00497 under the original conditions, which is approximately 92, and it is 18,557×0.00648 under the modified conditions, which is approximately 127. The difference between the baseline number and the modified number represents the change in the number of injuries at the given level due to the expected change in chest acceleration numbers, and a percent change can be calculated by dividing this difference by the baseline number.

In order to find confidence bounds for these estimates, the following argument can be made. In calculating the percent increase in injuries at a given delta-v level, the baseline injury probabilities should to be considered as fixed, and the modified probabilities of injuries are determined relative to these fixed baseline probabilities. Although the baseline probabilities are in fact estimates subject to substantial uncertainty (as shown by their confidence intervals in Table 2), for the purposes of calculating percent change under modified conditions they have to be treated as fixed and known. It is natural to fix them at the values given by formula (2), but other values, such as the end-points of their confidence intervals, can also be considered. This means that the coefficients b_0 and b_1 in formula (2) are to be treated as known rather than estimated. Consequently, in the formula for modified injury probabilities (4) these coefficients should also be treated as fixed, and the only coefficient subject to estimation error is c_0. Thus, (1−)-level confidence bounds for the modified injury probabilities when we assume a fixed level of baseline probabilities as determined by b_0 and b_1 are $1/(1+\exp(-1.333(b_0+b_1\Delta v)+0.333c_0 \pm z_{1-\ /2}\ 0.333\,\sigma_{c0}))$, where σ_{c0} is the standard deviation of c_0.

Table 6 shows the expected numbers of injuries under the original (baseline) conditions, the modified numbers, and 95 percent confidence intervals for the modified numbers calculated under the assumption that the baseline conditions are fixed and known.

Table 6. Estimated numbers of injuries and modified numbers of injuries assuming a 33.33% increase in chest acceleration. The 95% confidence intervals for modified numbers given in parenthesis are calculated for fixed baseline conditions.

ΔV	AIS 3 +		AIS 4 +		AIS 5 +	
	Baseline Number	Modified Number	Baseline Number	Modified Number	Baseline Number	Modified Number
0-10	92	127 (42,381)	38	51 (15,169)	7	13 (3,58)
11-21	894	1884 (635,5309)	372	775 (236,2476)	73	199 (45,876)
21-30	488	1413 (535,3066)	209	643 (207,1766)	42	175 (40,720)
31-40	484	1319 (721,1812)	228	822 (335,1467)	49	288 (72,888)
41-50	299	521 (430,559)	177	451 (298,533)	46	273 (96,463)
51 and up	356	435 (419,440)	278	423 (383,437)	109	373 (421,425)

Table 7 shows the percent increase in injuries and the associated confidence intervals based on the numbers found in Table 6.

Table 7. Percentage increase in chest injuries (95 percent confidence intervals given in parenthesis).

ΔV	Increase in AIS 3+ injuries	Increase in AIS 4+ injuries	Increase in AIS 5+ injuries
0-10	38% (-54%,314%)	34% (-61%,345%)	86% (-57%,729%)
11-21	111% (-29%,494%)	108% (-37%,566%)	173% (-38%,1100%)
21-30	190% (10%,528%)	208% (-1%,745%)	317% (-5%,1614%)
31-40	173% (49%,274%)	261% (50%,543%)	488% (47%,1712%)
41-50	74% (44%,87%)	155% (68%,201%)	493% (109%,907%)
51 and up	22% (18%,24%)	52% (38%,57%)	242% (121%,290%)

These results show that there is a statistically significant increase in injuries at 95 percent level for AIS 3+ chest injuries in delta-v categories 21 mph and above, and a statistically significant increase in AIS 4+ and AIS 5+ chest injuries in delta-v categories 31 mph and above. For crashes in delta-v range 21 to 30 mph, the increase in AIS 4+ and AIS 5+ injuries appears close to being statistically significant (at 95 percent level).

The estimated and modified numbers of injuries at AIS 3 and AIS 4 are obtained by subtracting the number of AIS 4+ injuries from the number of AIS 3+ injuries, and the number of AIS 5+ injuries from the number of AIS 4+ injuries. These numbers are presented in Table 8.

Table 8. Estimated numbers of chest injuries and modified numbers of chest injuries (assuming 33.33% increase in chest acceleration).

ΔV	AIS 3		AIS 4		AIS 5+	
	Baseline Number	Modified Number	Baseline Number	Modified Number	Baseline Number	Modified Number
0-10	54	76	31	38	7	13
11-21	532	1109	299	576	73	199
21-30	279	769	167	468	42	175
31-40	256	497	180	534	49	288
41 -50	123	69	131	178	46	273
51 and up	78	12	168	50	109	373

By summing the estimated and modified numbers of injuries across delta-v categories the total increases in AIS 3, AIS 4, and AIS 5+ injuries are calculated. In this example, the percentage increases are 93 percent for AIS 3, 89 percent for AIS 4, and 305 percent for AIS 5+ injuries.

C. Estimation of the change in the number of fatalities.

Although crash test data do not provide information about probability of fatality as a function of chest acceleration, it is possible to utilize the information about the relationship between the chest acceleration and the probabilities of injuries of various severities to infer the effect of increased chest acceleration on fatalities. This is accomplished by establishing a relationship between probability of death and injuries received. This relationship can be studied using the crash data. Clearly, more severe injuries are associated with greater probability of death. Also, multiple injuries should be associated with greater probability of death than a single injury of the same severity. There are many other factors that affect the probability of death, such as location of injuries and occupant’s age. However, for the purposes of this analysis, a simple model utilizing only the two highest AIS injury scores to estimate the probability of death is considered.

To develop this model, fatality rates are calculated for each possible combination of two highest AIS scores, that is (5,5), (5,4), (5,3), (5,2), (5,1), (5,0), (4,4), (4,3), . . . , (1,0), (0,0), by dividing the number of fatalities by the total number of individuals in each category. These rates are thought of as estimates of the probability of death given the two highest injury severities for an occupant. For any population of crash-involved individuals with known AIS scores, the number of fatalities can be estimated as the expected value of the number of fatalities given the AIS scores. In other words, the estimate is the weighted sum of the numbers of individuals in the AIS categories (5,5), (5,4), ... , (1,0), (0,0), with weights equal to the probabilities of death for the respective categories.

This would give the exact number of fatalities in the given population if the fatality rates used as the weights were based on the fatalities in this same population. However, in the present analysis, fatality rates in the above injury categories are calculated using larger population (all individuals in 1991-1995 NASS-CDS database age 16 to 76 with known injury levels). Since these rates are applied to the population of front-seat occupants with a deployed air bag, the predicted number of fatalities may differ from the actual number at this preliminary step of the analysis. However, it was concluded that these fatality rates were closer to the actual, hypothetical, fatality rates compared to fatality rates obtained using the smaller sub-population, and hence they would provide a better basis for estimating the change in fatalities due to changes in chest acceleration.

Because fatality rates corresponding to the highest two AIS injuries (2,0), (3,0), and (4,0) appear to be outliers (they are much higher than the fatality rates in the categories (2,1), (3,1), and (4,1), respectively) and are based on small numbers of observations, they were adjusted by combining these categories, i.e., categories (2,0) and (2,1) were combined and the rate for the combined categories was used for each of the categories (2,0) and (2,1), and similarly for categories (3,0) and (3,1), (4,0) and (4,1), and (5,0) and (5,1). The same was done for categories (1,0) and (1,1) for consistency.

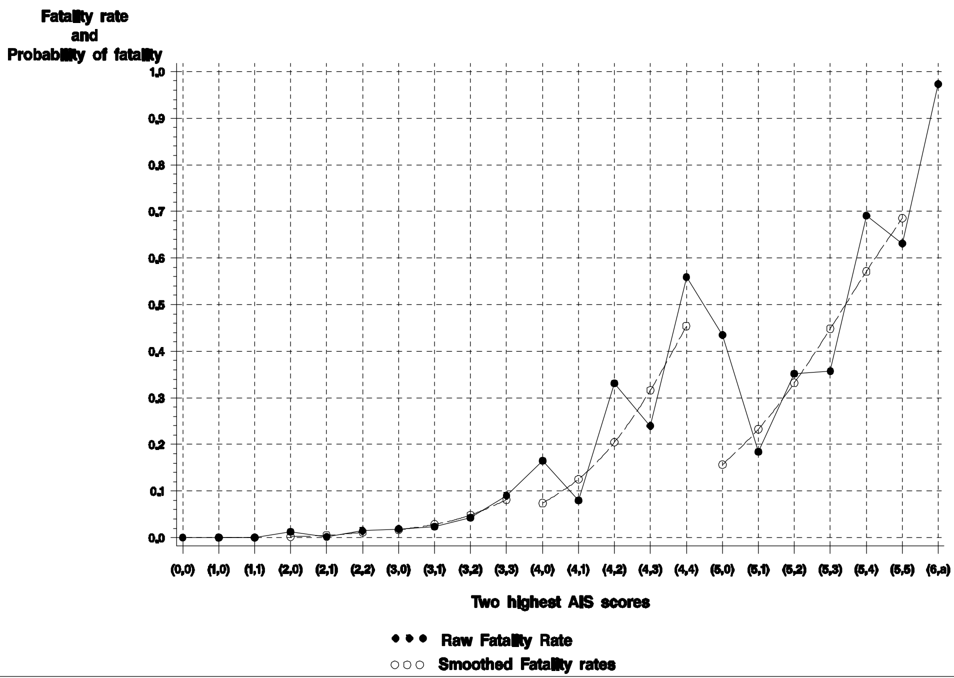
Furthermore, the raw fatality rates were smoothed. The smoothing was done in groups determined by the highest AIS; that is (0,0) was treated as one group, (1,0),(1,1) was the second group, (2,0),(2,1),(2,2) was the third group, (3,0),(3,1),(3,2),(3,3) was the fourth group, (4,0),(4,1),(4,2),(4,3),(4,4) was the fifth group, and (5,0),(5,1),(5,2),(5,3),(5,4),(5,5) was the last group. It was observed that within each of these groups, the raw fatality rates were not monotonic, and it was concluded that smoothed, monotonically increasing fatality rates within each group would be more realistic. For each of the groups, a probit curve was fit, using the same procedure as that utilized to smooth the injury risk curves above. Both the raw and the smoothed fatality rates developed are presented in Table 9 and illustrated in Figure 8.

Table 9. Fatality Rates (original and smoothed).

Two highest AIS	Raw Fatality Rate	Smoothed Fatality Rate
(0,0)	0.00000	0.00000
(1,0)	0.00015	0.00021
(1,1)	0.00024	0.00021
(2,0)	0.01150	0.00202
(2,1)	0.00186	0.00480
(2,2)	0.01479	0.01134
(3,0)	0.01789	0.01650
(3,1)	0.02385	0.02851
(3,2)	0.04290	0.04883
(3,3)	0.09096	0.08241
(4,0)	0.16459	0.06566
(4,1)	0.07823	0.11608
(4,2)	0.29565	0.19705
(4,3)	0.24655	0.31440
(4,4)	0.56161	0.46147
(5,0)	0.43512	0.15359
(5,1)	0.18168	0.23074
(5,2)	0.34192	0.33148
(5,3)	0.35999	0.45044
(5,4)	0.69466	0.57535
(5,5)	0.63696	0.69133

Figure 8

Fatality Rates and Estimated Fatality Probabilities



These smoothed fatality rates were used as the estimates of fatality probabilities in their respective injury severity categories. The actual and predicted numbers of fatalities in the sub-population of front-seat occupants where an air bag deployed are shown in Table 10. As explained above, the predicted numbers are the expected values of the numbers of fatalities with the smoothed fatality rates used as fatality probabilities in their respective AIS-category.

Table 10. Baseline fatality numbers: actual and predicted from fatality rates.

ΔV	Actual number of fatalities	Predicted number of fatalities based on fatality rates
0-10	0	36
11-20	68	165
21-30	100	346
31-40	515	365
41 -50	138	125
51 and up	8	2
Total	829	1039

The above method allows one to estimate the number of fatalities in the population of crash-involved motor vehicle occupants given their AIS scores. However, when estimating the number of fatalities under the hypothetical conditions of increased chest accelerations due to air bag depowering, the AIS scores for chest injuries were not available. It was assumed that non-chest injuries are not affected by the change, so they will be the same before and after the modification. But all that is known about chest injuries after the modification is a probability distribution of their severities. This distribution was estimated in section 2.B above (see Table 5). The baseline probability distribution of chest injuries was also estimated. The idea now is to develop a model for predicting the number of fatalities in the population based on actual non-chest injuries and a probability distribution of chest injuries. To accomplish this, the actual chest injuries in the population (as recorded in the database) were disregarded, and random variables with severities distributed according to a probability distribution were substituted in their place. This probability distribution can be specified as either the one under the original (baseline) conditions, or the one under the modified conditions.

In the simplest case, only one, the most severe chest injury is modeled. The probability distribution of chest injury severities depends in general on a number of factors (just like the probabilities of fatality), including crash characteristics and individual's characteristics, but here only the simplest case is treated, one where the distribution is assumed to depend only on the delta-v of the crash. Note that Table 5 gives the baseline probabilities of AIS 3+, AIS 4+ and AIS 5+ injuries estimated from the data and the same probabilities under the assumption that the design modification has increased the chest acceleration by 33.33 percent. To obtain the probabilities of AIS 3 injuries, the probability of AIS 4+ injury is subtracted from the probability of AIS 3+ injury. Similarly, the probability of AIS 4 injury is obtained by subtracting the probability of AIS 5+ injury from the probability of AIS 4+ injury. Using a standard procedure based on the Bonferroni inequality, the confidence intervals for the probabilities of AIS 3 injuries were obtained by combining the confidence intervals for AIS 3+ and AIS 4+ injuries, and similarly for AIS 4 injury probabilities, confidence intervals for AIS 4+ and AIS 5+ were combined. The resulting confidence intervals are rather conservative, and quite wide. In fact, the combined intervals often extend to a range of negative numbers, in which case they were truncated at zero. As is well-known, the Bonferroni confidence intervals obtained from two 95 percent level confidence intervals result in a 90 percent level interval. The results are presented in Table 11.

Table 11. Probability of chest injury as a function of delta-v from crash data (90 percent confidence intervals given in parenthesis).

Delta-v (in mph)	Probability of AIS 3 injury	Probability of AIS 4 injury	Probability of AIS 5+ injury
5	0.003 (0.000,0.012)	0.002 (0.000,0.006)	0.000 (0.000,0.002)
15	0.011 (0.000,0.027)	0.006 (0.001,0.014)	0.002 (0.001,0.003)
25	0.039 (0.000,0.188)	0.023 (0.000,0.082)	0.006 (0.003,0.012)
35	0.115 (0.000,0.682)	0.081 (0.000,0.448)	0.022 (0.005,0.098)
45	0.211 (0.000,0.933)	0.226 (0.000,0.879)	0.079 (0.007,0.505)
55	0.176 (0.000,0.959)	0.380 (0.000,0.976)	0.246 (0.011,0.908)

Rows of Table 11 represent probability distributions of injury severities (restricted to AIS 3, AIS 4 and AIS 5+ injuries) at various delta-v levels. It was assumed that only these chest injuries are material in producing fatalities. Thus, the probability distribution of injury severities for a given delta-v level consists of the probabilities of AIS 3, AIS 4, and AIS 5+ injuries represented in the rows of Table 11 supplemented by the probability of 'AIS 0-2 injury', i.e. one minus the sum of AIS 3, AIS 4 and AIS 5+ injury probabilities. The AIS 0-2 injury in this context can be thought of as a completely non-life-threatening injury. Although the fatality rates associated with AIS 1 and AIS 2 injuries are non-zero (cf., Table 9), fatal AIS 1 or AIS 2 chest injuries are very rare so that the analysis is not much affected by disregarding them.

Using this probability distribution, the hypothetical chest injuries replacing the actual chest injuries can be generated for each individual. Such generation procedure is unbiased in the sense that the generated distribution of maximum chest injuries is on the average the same as the distribution estimated from the actual data.

The probability of fatality for each individual is now determined using the law of total probabilities. The following notation will be used. Suppose there are N individuals in the population under study, numbered 1, ... , N. For the I-th individual ($1 \leq I \leq N$), let q_{ik} denote the probability that the maximum chest injury of this individual is k, where the injury severity is measured on a scale from 1 to K. Actually, in the present example, k runs through 0,3,4,5, and q_{ik} is determined by the delta-v of the crash in which the I-th individual was involved. Let p_{ik} be the conditional probability that the I-th individual dies given that his maximum chest injury severity is k. Again, in the present example, p_{ik} is determined by the two most severe injuries suffered by the I-th individual, although in general it could depend on other individual and crash characteristics. Note that the non-chest injuries are considered as deterministic characteristics fixed for each individual. The chest injury may or may not be among the two most severe injuries of this individual. By the law of total probabilities, the probability of death for the i-th individual is

$$P_i(\text{death}) = \sum_{k=1}^{K} p_{ik}\, q_{ik},$$

or, in the present example,

$$P_i\,(\text{death}) = \sum_{k\in\{0,3,4,5\}} p_{ik}\, q_{ik}\,.$$

If F_i (i=1, ... , N) is a random variable indicating for the I-th individual death (F_i=1) or survival (F_i=0) in the crash, then the number of fatalities in the population is $\sum_{i=1}^{N} F_i$, and the expected number of fatalities in the population is

$$E\left(\sum_{i=1}^{N} F_i\right) = \sum_{i=1}^{N} P_i\,(\text{death}) = \sum_{i=1}^{N}\sum_{k=1}^{K} p_{ik}\, q_{ik} = \sum_{i=1}^{N}\sum_{k\in\{0,3,4,5\}} p_{ik}\, q_{ik}\,. \tag{5}$$

In the current example, the probabilities q_{ik} of chest injury of severity k (k=3,4,5) are given by Table 6, and $q_{i0}=1-q_{i3}-q_{i4}-q_{i5}$. The probabilities of fatality given the two highest injury scores p_{ik} are given in Table 9 (last column). In general, confidence bounds for the above estimate of the number of fatalities depend on the accuracy of the estimates of injury probabilities and fatality probabilities given two most severe injuries. However, for the purposes of this study, it is be assumed that the fatality rates are fixed and known. This is because the objective of the study is to determine the effect of design change (air bag depowering), and the fatality rates are the same before and after the change. Actually, the fatality rates are determined from the population of all occupants age 16 to 76 in the NASS-CDS database, and not from the subset of occupants experiencing air bag deployment. They are treated as given constants in the calculation. If a better source of injury were available, those rates would be used, regardless of their source. But if the fatality rates p_{ik} are treated as constants, then the only quantities in formula (5) subject to estimation error are injury probabilities q_{ik}, and within each delta-v category, these do not depend on individual, i.e., $q_{ik}=q_k$ does not depend on i. Hence, formula (5) can be rewritten as

$$q_0\sum_{i=1}^{N} p_{i0}+q_3\sum_{i=1}^{N} p_{i3}+q_4\sum_{i=1}^{N} p_{i4}+q_5\sum_{i=1}^{N} p_{i5}. \tag{6}$$

Confidence bounds for each of the injury probabilities given in Table 5 can now be used to obtain confidence bounds for the estimate in (6) by combining the confidence intervals. The results of this calculation, are given in Table 12. The table gives also the predicted numbers of fatalities based directly on the two highest injury severities in the crash file (from Table 10 above). The comparison of the estimates using the two methods indicates that the probabilistic imputation of chest injuries does not introduce much error.

Table 12. Baseline fatality numbers predicted from fatality rates and fatality numbers predicted using the imputed chest injuries (confidence intervals given in parenthesis).

ΔV	Predicted number of fatalities using the actual chest injury severities	Predicted number of fatalities using the imputed chest injury severities
0-10	36	34 (24,51)
11-21	165	212 (147,303)
21-30	346	258 (146,424)
31-40	365	344 (0,909)
41 -50	125	95 (0,358)
51 and up	2	72 (0,241)

In order to estimate the number of fatalities when the probabilities of chest injuries are increased due to depowering of the air bag, the probabilities of chest injuries q_{ik} are replaced by the modified injury probabilities q'_{ik}, k=3,4,5, obtained from Table 6 and set $q'_{i0}=1-q'_{i3}-q'_{i4}-q'_{i5}$, so that the

estimator becomes $\sum_{i=1}^{N} \sum_{k\in\{0,3,4,5\}} q'_{ik}\, p_{ik}$.

Confidence intervals for these estimates are obtained using a formula analogous to (6), with q_k replaced by q_k', i.e., the modified injury probabilities given in Table 5, with the same confidence intervals. The predicted numbers of fatalities for the case when chest accelerations are assumed to increase by 33.33 percent together with the baseline predicted fatality numbers are presented in Table 13.

Table 13. Fatality numbers predicted using the imputed chest injuries under the baseline conditions and assuming a 33.33% increase in chest acceleration (confidence intervals given in parenthesis).

ΔV	Predicted number of fatalities under baseline conditions	Predicted number of fatalities assuming 33.33% increase in chest acceleration	
0-10	34	37	(21,67)
11-21	212	294	(0,837)
21-30	258	356	(0,908)
31-40	344	482	(0,1241)
41-50	95	158	(0,329)
51 and up	72	134	(0,185)

These results suggest substantial increases in fatalities, particularly in the higher delta-v categories, but due to the fact that the confidence intervals obtained are very wide, no statistically significant increase can be shown. The confidence intervals for AIS 3+, AIS 4+ and AIS 5+ injuries are already quite wide, and when they are combined, first in Table 11 and then in the application of formula (6), the results are not satisfactory. However, the calculations illustrate a methodology which can lead to more satisfactory results when applied to other data sets.

The total fatalities are calculated by summing the estimated and modified numbers of fatalities across delta-v categories. In this example, there is a 44 percent increase in fatalities.

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Appendix 1. Cadaver data used to obtain crash test injury risk curves.

MAX CHEST AIS	AGE	CHEST ACCELERATION
0	29	44.04
0	31	35.47
0	57	31.00
0	58	59.66
0	25	48.54
0	76	18.40
0	38	45.65
0	63	97.00
0	67	62.00
0	66	39.00
0	26	67.00
0	26	75.00
0	37	63.00
0	18	45.00
0	31	47.00
1	55	44.00
1	61	42.00
2	81	20.61
2	67	43.96
2	64	43.27
2	62	51.00
2	61	25.00
2	43	54.00
2	57	38.00
3	64	26.85
3	75	45.55
3	65	76.00
4	66	66.99
4	71	53.71
4	58	111.54
4	68	95.00
4	56	67.00
4	66	93.00
5	66	88.17
5	67	70.42

Appendix 2. NASS-CDS data used to obtain crash injury risk curves. Unbelted individuals, air bag deployed, age 16 to 76, with reported delta-v and all injury locations and severities. Actual (unweighted) numbers of cases in 1991-1996 data files, classified by delta-v and maximum chest injury severity.

TABLE OF DELTA-V BY MAX CHEST AIS

MAX CHEST AIS

DELTA-V	0	1	2	3	4	5	6	Total
4	1	0	0	0	0	0	0	1
5	2	0	0	0	0	0	0	2
6	3	0	0	0	0	0	0	3
7	4	1	0	0	0	0	0	5
8	4	0	0	0	0	0	0	4
9	13	1	0	0	1	0	0	15
10	7	0	0	0	0	0	0	7
11	24	7	1	0	1	0	0	33
12	19	4	0	1	0	0	0	24
13	14	2	0	0	0	0	0	16
14	23	4	1	2	0	0	0	30
15	12	2	0	1	0	0	0	15
16	24	6	1	0	0	0	0	31
17	34	3	0	0	0	0	0	37
18	12	0	1	0	0	0	0	13
19	9	3	1	1	1	0	0	15
20	5	2	0	0	0	0	0	7
21	16	3	0	1	0	0	0	20
22	14	4	1	2	1	0	0	22
23	9	1	0	0	0	0	0	10
24	4	0	1	0	0	0	0	5
25	6	3	1	1	0	0	0	11
26	3	0	1	0	0	0	0	4
27	8	1	0	3	0	0	0	12
28	2	1	0	1	0	0	0	4

29	4	1	0	0	0	0	1	6
30	1	0	0	0	2	0	0	3
31	1	0	0	1	0	0	0	2
32	4	0	0	2	1	0	0	7
33	0	1	0	0	0	0	0	1
34	2	2	1	0	1	0	0	6
35	1	1	0	2	0	0	0	4
36	1	0	0	0	0	0	0	1
37	2	0	0	0	0	0	0	2
38	1	1	0	0	0	1	0	3
39	0	1	0	0	0	0	1	2
40	1	2	0	1	0	0	0	4
42	1	0	0	0	0	1	0	2
44	0	0	0	1	0	0	0	1
45	0	1	0	1	1	0	0	3
46	0	0	0	0	0	1	0	1
47	0	0	0	1	0	1	1	3
48	0	2	0	0	0	0	0	2
52	1	0	0	0	0	0	0	1
57	0	2	0	0	0	0	0	2
Total	292	62	10	22	9	4	3	402