Driver Air Bag Effectiveness by Severity of the Crash

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ABSTRACT

Objectives. This analysis provided effectiveness estimates of the driver-side air bag while controlling for severity of the crash and other potential confounders.

Methods. Data were from the National Automotive Sampling System (1993–1996). Injury severity was described on the basis of the Abbreviated Injury Scale, Injury Severity Score, Functional Capacity Index, and survival. Ordinal, linear, and logistic multivariate regression methods were used.

Results. Air bag deployment in frontal or near-frontal crashes decreases the probability of having severe and fatal injuries (e.g., Abbreviated Injury Scale score of 4–6), including those causing a long-lasting high degree of functional limitation. However, air bag deployment in low-severity crashes increases the probability that a driver (particularly a woman) will sustain injuries of Abbreviated Injury Scale level 1 to 3. Air bag deployment exerts a net injurious effect in low-severity crashes and a net protective effect in high-severity crashes. The level of crash severity at which air bags are protective is higher for female than for male drivers.

Conclusions. Air bag improvement should minimize the injuries induced by their deployment. One possibility is to raise their deployment level so that they deploy only in more severe crashes. (*Am J Public Health.* 2000;90:1575–1581)

Air bags have existed for more than 40 years and have always been surrounded by controversy.[1,2] Unlike most safety devices, a deploying air bag increases the amount of energy being released during the crash and, hence, potentially increases the frequency and severity of injuries sustained by the driver.[3,4] Frontal driver-side air bags, which have been mandated in all new passenger vehicles sold in the United States since model year 1997,[5] were available in many automobile makes and models before regulation took effect. (Note that this article refers to frontal driver-side air bags only, not to frontal passenger-side air bags or to side air bags for either the driver or any other occupant.) In fact, in 1999, almost half of all passenger cars in the US fleet were equipped with a frontal driver-side air bag (National Highway Traffic Safety Administration, written communication, May 1998), and over the next 15 years or so, this ratio will increase to nearly 100%.

Air bags (also called *supplemental restraint systems*) are supposed to protect the occupants in combination with lap and shoulder safety belts. Yet, the air bag systems sold in the United States were designed to meet a federal performance standard that requires that in an experimental frontal crash at approximately 48 km/h, the forces on an unbelted 50th percentile male dummy's head, chest, and thighs do not exceed a specified level.[5] A typical air bag system consists of one or more sensors that detect the longitudinal velocity change of the vehicle during the crash, an electronic unit that monitors the system, and a module that houses the inflator and the bag,[6] but the design varies across makes, models, and years.[7]

Since the early 1970s, researchers have evaluated the performance of air bag systems. Most evaluations have focused on the air bag's effect on preventing fatalities. Initial estimates of the percentage reduction in fatalities due to air bags plus safety belts, based on expert judgment or experimental data or both, ranged from 18% to 55%.[5,8–15] More recent effectiveness estimates, computed with real-world fatal crash data (and in some cases computed with the double pair comparison method[16]), suggest an approximately 19% reduction in fatality risk among belted drivers.[17–19] The only estimates available to date regarding air bag effectiveness in nonfatal injuries indicate reductions in moderate to serious nonfatal injuries to the head, face, and upper torso among occupants in frontal crashes,[18,20–23] but the magnitude of these benefits varies greatly from study to study. More complete reviews of the reported effectiveness estimates are available elsewhere.[24,25]

In contrast to these encouraging findings, several studies have linked air bags to the causation of injuries. To date, air bags have been linked to the deaths of 57 drivers (National Highway Traffic Safety Association, National Center for Statistics and Analysis [NCSA] online. Available at: http://www.nhtsa.dot.gov. Accessed December 1, 1999) and to numerous nonfatal injuries of varying degrees of severity, including corneal abrasions, aortic rupture, lung contusions, abdominal injuries, and open fractures of the forearm.[26–35]

It has been suggested that air bag–related injuries may be associated with specific design features, such as the amount of energy released by the deploying air bag; the speed of inflation; and the volume, shape, or folding pattern of the bag.[36,37] It has also been suggested that these air bag–induced injuries are more likely in female drivers.[21] In addition, air bag–induced injuries are the most serious injuries reported in relatively low-speed crashes,[22]

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TABLE 1—Selected Driver, Vehicle, and Crash Characteristics in Frontal and Near-Frontal Crashes With Known Longitudinal Delta V: National Automotive Sampling System Crashworthiness Data System Calendar Years 1993–1996, Passenger Cars of Model Years 1986–1997

	All (N = 5003), %	Air Bag Deployed (n = 1095), %	Air Bag Not Deployed (n = 3908), %
Driver			
Age, y			
13–24	30.6	28.5	31.1
25–54	51.8	53.5	51.3
55–64	6.2	7.1	6.0
≥65	10.8	10.2	11.0
Missing	0.6	0.7	0.6
Sex			
Male	49.3	50.9	48.8
Female	50.6	49.0	51.0
Missing	0.1	0.1	0.2
Injury severity[a]			
MAIS			
0	40.4	37.0	41.4
1	32.9	34.4	32.5
2	11.3	12.2	11.1
3	8.4	10.9	7.7
4	1.7	1.5	1.8
5	1.1	1.2	1.0
6	4.2	2.8	4.5
ISS			
0	40.4	37.0	41.4
1–3	32.9	34.4	32.5
4–8	9.3	10.6	8.8
9–15	8.1	10.0	7.6
16–24	3.1	2.9	3.1
25–75	6.2	5.1	6.6
MFCI			
0	83.7	79.6	84.9
1–20	4.1	6.5	3.4
21–40	2.8	3.9	2.5
41–60	3.7	6.2	3.0
61–80	1.1	0.6	1.2
81–100	4.6	3.2	5.0
Vehicle			
Air bag present	34.0	100.0	15.5
Crash			
Air bag deployed	21.9	100.0	0.0
Delta V, km/h			
<12	17.5	10.6	19.4
12–23	42.8	45.6	42.0
24–31	19.2	21.5	18.6
32–39	9.7	10.8	9.4
≥40	10.8	11.5	10.6
Seat belt used			
Yes	66.0	69.9	64.9
Missing	5.6	5.5	5.7

Note. MAIS = Maximum Abbreviated Injury Scale; ISS = Injury Severity Score; MFCI = Maximum Functional Capacity Index.

[a]Injuries selected for analyses include up to 14 of the most severe injuries per driver reported from autopsy, hospital, emergency room, and medical records. Fatalities were considered as MAIS = 6, ISS = 75, and MFCI = 100 (excludes drivers who died of causes unrelated to the crash). Drivers with no injuries were coded as MAIS = 0, ISS = 0, and MFCI = 0.

which raises the question of whether these air bags are deploying unnecessarily in some crashes.

When is the crash serious enough to warrant air bag deployment? Current air bags are designed to deploy at crashes between 12 and 26 km/h, although the precise threshold varies by make, model, and, in some cases, the restraint use of the occupant.[7] Lower deployment levels imply higher air bag deployment rates, which have been associated with a higher incidence of air bag–related injuries.[38,39] In low-speed crashes, the injuries induced by the deploying air bag may be more serious than injuries that would otherwise have occurred, whereas in higher-speed crashes, air bag deployment may actually prevent the driver from sustaining more severe injuries.

The goal of this analysis is to provide net effectiveness estimates of the driver-side air bag in preventing fatal and nonfatal injuries in frontal and near-frontal crashes by severity of the crash, while controlling for characteristics known to influence the frequency and severity of injuries, such as age and sex of the driver,[17,40–43] vehicle size and mass,[44,45] and safety belt use.[46–48]

Methods

Outcome Measures

The effectiveness of air bags in reducing injury severity was evaluated with the Abbreviated Injury Scale, the Injury Severity Score, the Functional Capacity Index, and survival.

The Abbreviated Injury Scale is a consensus-derived, anatomically based system that classifies each injury on an ordinal scale that ranges from 1 (minor injury) to 6 (virtually unsurvivable).[49] The most severe injury sustained by an occupant is referred to as the maximum Abbreviated Injury Scale score. Drivers who died were assigned a maximum Abbreviated Injury Scale score of 6, and those with no injuries were assigned a maximum Abbreviated Injury Scale score of 0.

The Injury Severity Score constitutes the most common method of computing overall severity when a patient has multiple injuries. It is defined as the sum of the squares of the highest Abbreviated Injury Scale scores in 3 different body regions (or is assigned the value of 75 if at least 1 Abbreviated Injury Scale score of 6 is reported).[50] Thus, the Injury Severity Score is an ordinal scale that ranges from 0 to 75, although it is often treated by data analysts as a continuous scale.

The Functional Capacity Index is the first preference-based multiattribute score system that reflects the predicted extent of functional limitation 1 year postinjury.[51] Each injury has its own Functional Capacity Index. The Functional Capacity Index is a continuous score that ranges from 0 (no limitation) to 100 (maximum limitation). For our analyses, patients with no injuries were coded as having a Functional Capacity Index of 0, fatalities were coded as a Functional Capacity Index of 100, and the remaining patients were classified by the functional limitation of the injury leading to the maximum (i.e., worst) functional limitation.

The scores from these severity measures generated the outcome (or dependent) vari-

TABLE 2—Multivariate Regression Models—Adjusted[a] Air Bag Deployment–Related Coefficients, Variances, and Covariances in Frontal and Near-Frontal Crashes With Known Longitudinal Delta V (n = 4697): National Automotive Sampling System Crashworthiness Data System Calendar Years 1993–1996, Passenger Cars of Model Years 1986–1997

		Coefficients			Variances			Covariances		
Regression Technique	Outcome Variable	Air Bag Deployment (Main Term)	Air Bag Deployment × Sex (Interaction Term)	Air Bag Deployment × Delta V (Interaction Term)	Air Bag Deployment	Air Bag Deployment × Sex	Air Bag Deployment × Delta V	Air Bag Deployment, and Air Bag Deployment × Sex	Air Bag Deployment and Air Bag Deployment × Delta V	Air Bag Deployment × Sex and Air Bag Deployment × Delta V
Logistic	Fatality	–0.54	NA	NA	0.051	. . .	. . .	. . .	. . .	. . .
Ordinal	3-level MAIS	0.56	–0.47	–0.01	0.022	0.017	0.00003	–0.0069	–0.0006	–0.00005
	7-level MAIS	0.58	–0.44	–0.01	0.027	0.020	0.00003	–0.0089	–0.0007	–0.00005
Linear	ISS	2.83	–2.29	–0.10	1.220	0.955	0.0014	–0.423	–0.032	–0.0023
	MFCI	5.32	–4.18	–0.13	2.875	2.251	0.0032	–0.996	–0.075	–0.0055

Note. Three-level Maximum Abbreviated Injury Scale (MAIS) categorizes injuries into "none" (MAIS = 0), "minor" (MAIS = 1–3), and "severe" (MAIS = 4–6); 7-level MAIS uses the entire Abbreviated Injury Scale (AIS) for severity categorization (i.e., 0, 1, 2, 3, 4, 5, and 6). ISS = Injury Severity Score; MFCI = Maximum Functional Capacity Index. Injuries selected for analyses include up to 14 injuries with the highest AIS reported from autopsy, hospital, emergency room, and medical records. Fatalities were considered as MAIS = 6, ISS = 75, and MFCI = 100 (excludes drivers who died of causes unrelated to the crash). Drivers with no injuries were considered as MAIS = 0, ISS = 0, and MFCI = 0. NA = not applicable (i.e., the term did not reach statistical significance).
[a]Controlling for longitudinal Delta V, safety belt use, age, and sex of driver.

ables: a dichotomous variable indicating whether the driver died (i.e., maximum Abbreviated Injury Scale score of 6), 2 ordinal variables indicating the maximum Abbreviated Injury Scale level of the driver, and 2 continuous variables with the Injury Severity Score and the maximum Functional Capacity Index. The 2 maximum Abbreviated Injury Scale–related ordinal variables were a 3-level maximum Abbreviated Injury Scale that categorized the drivers' injuries into "none" (Maximum Abbreviated Injury Scale score of 0); "minor" (maximum Abbreviated Injury Scale score of 1, 2, or 3); and "severe" (Maximum Abbreviated Injury Scale score of 4 or 6) and a 7-level maximum Abbreviated Injury Scale (i.e., 0, 1, 2, 3, 4, 5, and 6). The use of these ordinal variables allowed for a more comprehensive evaluation of the air bag effect on each injury severity level.

Data

The National Automotive Sampling System Crashworthiness Data System (NASS CDS), formerly the National Accident Sampling System, for calendar years 1993 through 1996 was used. The NASS CDS is a stratified sample of police-reported crashes involving passenger vehicles in which at least 1 of the vehicles is towed away from the scene because of damage from the crash. Trained crash investigators complete an extensive questionnaire of data elements that describe the crash, the vehicles, the occupants, and their injuries. About 5000 crashes are investigated per year.

Inclusion criteria for this analysis entailed being the operator of a passenger car of model years 1986 through 1997 in a frontal or near-frontal crash during 1993 through 1996 for which the severity of the crash was known. For each driver, we analyzed injuries reported in the autopsy, the hospital, the emergency room, or the medical records. Some drivers were not injured, whereas others had 1 or more injuries. For each driver, we included up to 14 injuries with the highest Abbreviated Injury Scale scores (these 14 injuries accounted for 97% of all reported injuries and included the most severe ones). Drivers who died because of causes not related to the crash were not included.

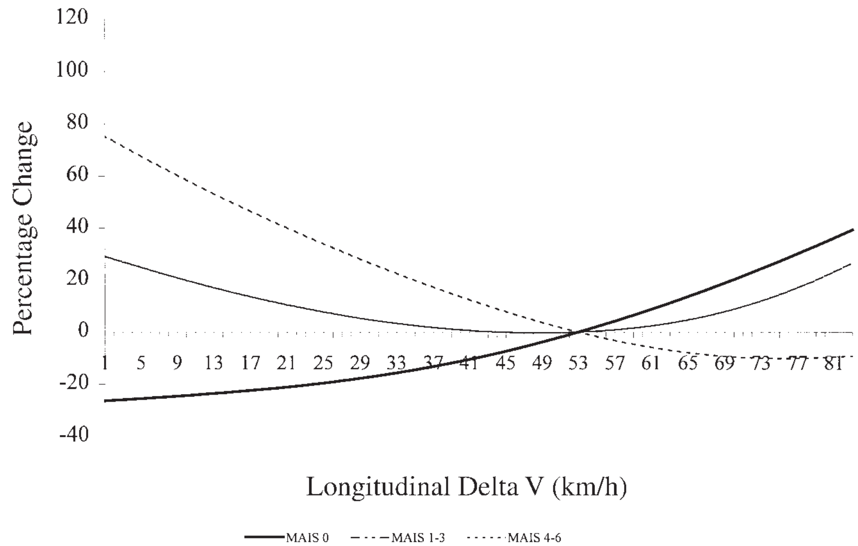
The analyzed NASS CDS data included driver characteristics (age, sex, and height), crash consequences (number, type, and severity of the injuries), crash circumstances (severity of the crash, direction of crash, air bag deployment, safety belt use), and vehicle characteristics (air bag presence, wheelbase, curb weight, and the Vehicle Identification Number [VIN]). The severity of the crash was defined on the basis of the longitudinal component of the maximum velocity change incurred by the vehicle during the crash (the so-called longitudinal Delta V—herein, Delta V). Crash investigators calculate the Delta V with a computerized algorithm that is solely based on vehicle deformation as measured in the post-crash investigation. The vehicle identification number was decoded with VINDICATOR[52] to corroborate the information about air bag presence and restraint systems. Vehicles were characterized as equipped with a frontal driver-side air bag when either the VIN or the NASS CDS data indicated so. Crashes were classified as frontal or near-frontal if the direction of force of the primary or secondary impacts was within the 10:00 to 2:00 range.[17,31] A computerized mapping algorithm (M. Waltz, MS, National Center for Statistics and Analysis, National Highway Traffic Safety Administration, written communication, November 1997) was used to assign Functional Capacity Index scores to the injuries sustained by the drivers. Stata[53] and Microsoft Excel[54] were used for data management and statistical analysis.

Analyses

We conducted a descriptive analysis of driver demographics, injuries, vehicles, and crash characteristics. Univariate and multivariate regression techniques were then used to evaluate (1) the effect of air bag deployment on injury frequency and severity; (2) the association between injury severity and several personal, vehicle, and crash characteristics; and (3) the possible confounding and effect modification between air bag deployment and personal, vehicle, and crash characteristics.

Independent variables for inclusion in the multivariate regression were those that had significant or quasi-significant coefficients ($P<.25$) in the univariate regressions (i.e., driver's sex, age, and height; seat belt use; vehicles' wheelbase; and crash severity) and a dummy variable indicating whether the air bag deployed. For each dependent variable, models were built systematically and included 2, 3, or more independent variables and the interaction terms between air bag deployment and each of the covariates (e.g., air bag deployment and crash severity). More complex models were evaluated with log likelihood ratios[55] or the residuals sum of square test.[56] The independent variables that retained statistical significance ($P<.1$) in most (if not all) of the regression models (and thus were included in the final models) were air bag deployment, crash severity, the driver's sex and age, and safety belt use. In the final models, we also included the 2 terms reflecting the interaction between air bag deployment and driver's sex and air bag deployment and Delta V when these terms achieved statistical significance ($P<.1$).

The air bag deployment coefficients in the final multivariate regression models reflected the point estimates of air bag deployment effectiveness, while controlling for severity of the crash, age and sex of the driver, and his or her seat belt use. "Effectiveness" was defined as a decrease or increase in (1) the probability of sustaining injuries of different severity levels (i.e., when evaluating maximum Abbreviated Injury Scale), (2) the overall severity of the injuries sustained (i.e., when evaluating Injury Severity Score), and (3) the functional limitations associated with those injuries (i.e., when evaluating maximum Functional Capacity Index). Statistically significant interaction coefficients indicate whether the air bag effectiveness varies across circumstances. For example, air bags could be more protective for male than for female drivers or for more severe than for less severe crashes. In the models that have a significant interaction term, the air bag effectiveness estimates must be reported for the different circumstances that were used in defining the interaction term.[55,57]



Note. Maximum Abbreviated Injury Scale (MAIS) categorizes injuries into "none" (MAIS = 0), "minor" (MAIS = 1–3), and "severe" (MAIS = 4–6). Fatalities were considered as MAIS = 6 (excludes drivers who died of causes not related to the crash).

FIGURE 1A—Percentage change (with control for age and seat belt use) in the probability of female drivers' (n = 2532) sustaining injuries, by injury severity level (as defined by maximum Abbreviated Injury Scale) in frontal or near-frontal crashes (with known longitudinal Delta V): National Automotive Sampling System Crashworthiness Data System calendar years 1993–1996, passenger cars of model years 1986–1997.

Results

Of the 13 092 drivers in the NASS CDS from 1993 to 1996 in passenger cars of model years no earlier than 1986, 6409 (49.0%) had a known Delta V. A comparison of drivers with and without known Delta Vs found differences both in the proportion of cases with missing data and in the proportion of (near) frontal crashes. Drivers with unknown Delta Vs were more likely than drivers with known Delta Vs to have missing information for variables such as age, sex, air bag presence, air bag deployment, seat belt use, vehicle size or mass, and direction of crash. For those cases with known direction of crash, frontal crashes were more common among drivers with known Delta Vs (86.9%) than among drivers with unknown Delta Vs (81.5%) ($P=.0005$). However, no statistically significant differences were found regarding the distribution of any other variables, including the maximum Abbreviated Injury Scale, Injury Severity Score, and maximum Functional Capacity Index (data not shown).

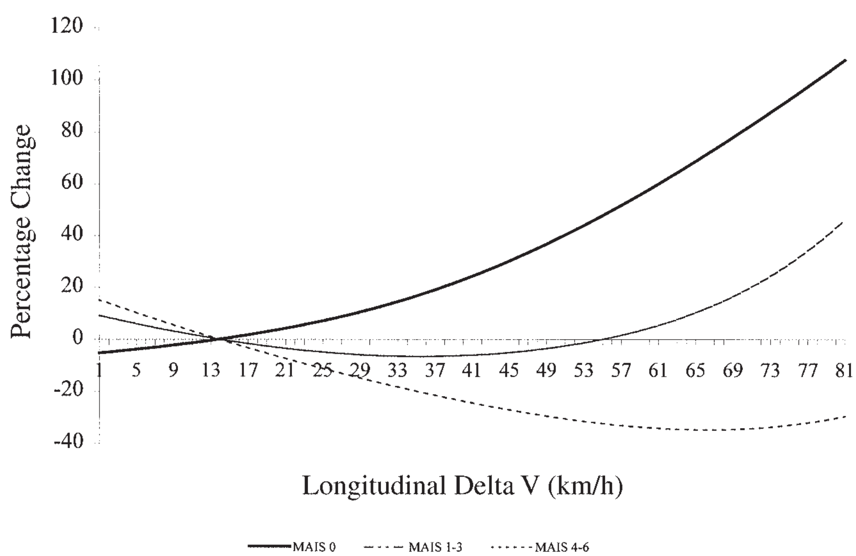
Of the 6409 drivers with known Delta Vs, 11 died of causes unrelated to the crash, 655 had missing information about the direction of crash, and 740 were in nonfrontal crashes. Hence, 5003 drivers met the study's inclusion criteria; their personal, vehicle, and crash characteristics are summarized in Table 1.

Among these 5003 drivers, 208 (4.2%) died as a consequence of the crash. No injuries were reported for 2023 drivers, including 187 of the drivers who died. Among the drivers who had at least 1 injury, 518 sustained only 1 injury each, and the other 2441 drivers had a total of 10 055 injuries.

The NASS CDS indicated that 1545 vehicles were equipped with a frontal driver-side air bag, whereas the decoding of the vehicle identification number identified 1580 such vehicles. Agreement between the 2 sources occurred in 1424 cases, whereas at least 1 of the data sources indicated the presence of an air bag in 1701 cases (34.0%). Air bag deployment occurred in 1095 cases (21.9% of the total or 64.4% of the air bag–equipped vehicles).

The logistic multivariate regression confirmed that air bag deployment was associated with a statistically significant decrease in the probability of fatal injuries (odds ratio [OR] = 0.58, 95% confidence interval [CI] = 0.37, 0.90). This protective effect did not differ by sex of the driver (Table 2).

In the ordinal and linear multivariate regression models, both the interaction between air bag deployment and Delta V and the interaction between air bag deployment and driver's sex were statistically significant (Table 2). Air bag deployment per se *increases* the overall injury severity and functional limitations as measured by the 3- and 7-level Maximum Abbreviated Injury Scale, the Injury Severity Score, and the maximum Functional Capacity Index. In contrast, the interaction terms have *protective* effects. As a consequence, (1) air bag deployment at low Delta V induces (more severe) injuries, particularly among female drivers; (2)



Note. Maximum Abbreviated Injury Scale (MAIS) categorizes injuries into "none" (MAIS = 0), "minor" (MAIS = 1–3), and "severe" (MAIS = 4–6). Fatalities were considered as MAIS = 6 (excludes drivers who died of causes not related to the crash).

FIGURE 1B—Percentage change (controlling for age and seat belt use) in the probability of male drivers' (n = 2466) sustaining injuries, by injury severity level (as defined by Maximum Abbreviated Injury Scale) in frontal or near-frontal crashes (with known longitudinal Delta V): National Automotive Sampling System Crashworthiness Data System calendar years 1993–1996, passenger cars of model years 1986–1997.

at higher Delta Vs, the air bag's protective effect becomes large enough to offset its injurious effect, and the air bag deployment net effect becomes protective; and (3) the Delta V at which the net effect of air bag deployment becomes protective differs between female and male drivers.

Figures 1A and 1B illustrate net air bag effectiveness at each crash severity level as the percentage change in the probability that female and male drivers will sustain no injury (i.e., Maximum Abbreviated Injury Scale score of 0) or injuries of different severity (Maximum Abbreviated Injury Scale score of 1–3 or 4–6), after controlling for age and seat belt use. For example, the net air bag effect on "severe" injuries among female drivers ranged from a 10% protective effect in crashes with Delta Vs around 70 km/h to a 70% increase in crashes with Delta Vs below 3 km/h. The effect on "severe" injuries among male drivers ranged from a 35% protective effect in crashes with Delta Vs around 64 km/h to a 10% increase in crashes with Delta Vs below 5 km/h. Overall, the Delta V at which the air bag deployment changes from injurious to protective occurs at 52.0 km/h for female and 12.9 km/h for male drivers.

The effect of air bag deployment evaluated with the 7-level Maximum Abbreviated Injury Scale, Injury Severity Score, and Functional Capacity Index as the outcome measures produced results consistent with the findings just described, although the precise Delta V at which air bag deployment became protective varied depending on the outcome measure evaluated (Table 3). The lowest crossover points occurred when Injury Severity Score was the analyzed outcome. Air bag deployment among male drivers had a net protective effect in crashes with Delta Vs at or above 5.2 km/h, whereas the protective effects for female drivers occurred only in more severe crashes (at or above 27.5 km/h).

All other covariates included in the final multivariate regression models had statistically significant effects in the anticipated directions (e.g., more severe injuries were associated with higher Delta Vs, older drivers, and no seat belt use) (data not shown).

Discussion

The results show that crashes with low Delta V result in an overall injurious effect of air bags largely caused by an increase in injuries of female drivers. The air bag's detrimental effect is offset in crashes at higher Delta Vs, when air bags become protective and prevent all drivers from having more severe injuries (e.g., Maximum Abbreviated Injury Scale score of 4 or higher), from having injuries associated with more functional limitations, and from dying.

Among female drivers, air bag deployment in low-severity crashes increases the probability of "minor" injury (i.e., Maximum Abbreviated Injury Scale score of 1, 2, or 3), the

TABLE 3—Severity of Crash Above Which Air Bag Deployment Exerts a Net Protective Effect (Adjusted[a] Point Estimates and 95% Confidence Intervals [CIs]) in Frontal and Near-Frontal Crashes With Known Longitudinal Delta V (n = 4697): National Automotive Sampling System Crashworthiness Data System Calendar Years 1993–1996, Passenger Cars of Model Years 1986–1997

	All Drivers		Female Drivers		Male Drivers	
Outcome Variable	Point Estimate, km/h	95% CI	Point Estimate, km/h	95% CI	Point Estimate, km/h	95% CI
3-level MAIS	32.8	0.0, 74.8	52.0	0.0, 127.6	12.9	0.0, 53.9
7-level MAIS	36.5	0.0, 85.6	62.2	0.0, 157.8	9.7	0.0, 53.5
ISS	16.6	0.0, 39.2	27.5	0.0, 65.6	5.2	0.0, 30.2
MFCI	25.3	0.0, 58.2	41.1	0.0, 98.8	8.8	0.0, 41.9

Note. MAIS = Maximum Abbreviated Injury Scale: 3-level MAIS categorizes injuries into "none" (MAIS = 0), "minor" (MAIS = 1–3), and "severe" (MAIS = 4–6), whereas 7-level MAIS uses each of the Abbreviated Injury Scale levels for severity categorization (i.e., 0, 1, 2, 3, 4, 5, and 6); ISS = Injury Severity Score; MFCI = maximum Functional Capacity Index. 95% confidence interval truncated at 0 km/h.
[a]Controlling for safety belt use, age, and sex of driver.

overall injury severity (as indicated by the Injury Severity Score), and the functional limitations (as indicated by the maximum Functional Capacity Index score).

The strength of these findings resides in the breadth of dependent variables evaluated, which includes minor injuries. Previous researchers predominantly evaluated fatality reduction effectiveness or the effectiveness in reducing the most serious nonfatal injuries (e.g., Maximum Abbreviated Injury Scale score of 3 or higher).[17,18,31,58,59] The estimates are consistent with those presented in the technical literature, including the often reported 19% fatality reduction estimate,[17] which is within the 95% confidence interval of the fatality reduction estimate reported here.

This analysis offers new data on the differential effect of air bags across the severity of crashes. The statistical significance of the interaction terms between air bag deployment and Delta Vs confirms the hypothesis that air bags (in vehicles of model year 1997 or older) deploy in low-severity crashes in which the risk of incurring any injuries is actually exacerbated by the deployment of the bag.[22,60] These induced injuries (more frequently, Maximum Abbreviated Injury Scale score of 1, 2, or 3) are disproportionately borne by female drivers, although male drivers are also at higher risk for injuries. The Delta Vs above which air bag deployment is beneficial are higher than the deployment levels reported by most manufacturers (much higher in the case of female drivers). The confidence estimates around the Delta Vs above which air bag deployment has a net protective effect are very large because of the limited sample size of real-world crashes available for analysis. It is unlikely that analysis of future years of NASS CDS data will permit greater precision in these switch points because of the current changes in air bag design.

Our analyses had some peculiarities that are worth noting. Research conducted to date has evaluated the effectiveness of air bag presence (regardless of actual deployment), instead of the effectiveness of air bag deployment.[17–23,31] In our data, 606 additional drivers had an air bag that did not deploy during the crash. To evaluate the robustness of our findings, we ran the final regression models with air bag presence instead of air bag deployment as the variable of interest. The resulting effectiveness estimates were comparable (i.e., had the same direction and similar magnitude) to those reported here, although the statistical significance of some estimates was lost.

Despite the relevance of our findings, one should exercise caution when interpreting them for several reasons. First, the findings describe the aggregate effects of air bags available in all makes, models, and years included in the data set. Obviously, air bag systems have design and performance differences, which may change the effectiveness of any particular system. Furthermore, the recent federal regulation allowing for depowering of the air bags (i.e., reducing the speed and/or volume of inflation) may change the effectiveness of the system.[37] Two factors prevent us from performing a more refined analysis of specific air bag systems: (1) specific air bag design parameters across models and years are proprietary information not available to researchers, and (2) even if this information became available, the NASS CDS may not have enough cases to allow statistically significant findings in analyses by air bag design.

Second, our air bag effectiveness estimates were based on crashes for which the Delta Vs of the crashed passenger car were known. The NASS CDS data set has about half as many crashes without such information. This limits the external validity of the findings. Delta Vs are most often missing because the algorithm used by crash investigators in their computation cannot be used when the crash involves a rollover, other nonhorizontal forces, sideswipe, severe override, and overlapping damage or when data about the crash or vehicle are insufficient.[61] In fact, direction of impact was the only statistically significant difference between drivers with known and unknown Delta Vs in our sample.

Finally, the NASS CDS data are subject to some measurement error, particularly regarding the severity of the crash. The validity of the estimates for Delta V values lower than 40 km/h is questionable, because the algorithm is calibrated at approximately 48 km/h (M. Finkelstein, MA, oral communication, June 1998), and it tends to underestimate the actual impact speed, especially in nonfrontal crashes.[62,63] However imperfect this measure might be, it is the only proxy for crash severity that is available for this type of analysis. Although the exact degree of error present in the NASS CDS data is unknown, qualitative evaluations included in the NASS CDS data set indicate that for 75% of the 5003 crashes, the computed Delta Vs fit the crash description. In 17%, the Delta Vs appear reasonable, and in 8%, the Delta Vs appear high or low (4% of each). The effect of these measurement errors on our findings is difficult to evaluate, but our estimates of Delta Vs at which air bags become protective are probably underestimates of the actual Delta Vs at which this happens.

In conclusion, our results showed that in frontal or near-frontal crashes, air bag deployment is effective in reducing the most severe and fatal injuries, whereas in low-severity crashes, air bag deployment induces injuries of Maximum Abbreviated Injury Scale level 1 to 3 (predominantly among females). Raising the crash severity level at which air bags are designed to deploy should be considered an injury prevention strategy in conjunction with other changes in air bag design. However, one should be cautious in interpreting this recommendation. With imperfect sensor technology, raising the air bag deployment threshold means that (in some crashes) it will take longer for the air bag system to recognize that a crash is severe enough to justify air bag deployment. This may be a particular problem in off-frontal crashes, when the sensors might take longer to acknowledge the existence of a crash because of their positioning.[64,65] Late deployment may injure drivers who have moved forward into the air bag's deployment zone. Use of crush-zone sensors and/or more advanced sensor technology may help alleviate this problem.

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