EVALUATING THE PERFORMANCE OF INJURY PREVENTION EFFORTS:

THE CASE OF DRIVER-SIDE AIRBAGS

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This thesis is dedicated to José Manuel, who helped me find my wings

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Completing this thesis means the world to me. It has been a long trip (literally!), during which many, many people have served as sources of inspiration, valuable resources, and unforgettable friends. Their love and care made difficult times easier and good times even better. Their examples nurtured my desire to achieve a higher education and provided me with strength for the effort. Mentioning all of their names here would be impossible, but they know who they are, and most importantly, I know who they are -- they will always be near to my heart!

Special mention to my thesis committee members Drs. John D. Graham, Ellen J. Mackenzie, and Milton C. Weinstein. John has become the best mentor I ever could have dreamed of. I particularly thank him for his extremely generous intellectual, emotional and economic support during these years. Ellen is a constant reminder of how much I still have to learn and to do and has acted as my guardian angel since I first met her. Milt, with his methodological rigor and high professional standards, has undoubtedly helped me become a much better researcher. It will be my pleasure to continue to work with them in the forthcoming years.

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Finishing this thesis is the end of the beginning. I look forward to putting all that I have learned into good practice, giving myself generously to others, and contributing to lessening the burden of injuries among the population. These will be the best ways to prove to you my gratitude!

P.S. Papa, Mama and Ana: Thanks for letting me believe that I had wings.

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Gracias en especial a los miembros de mi comité de tesis, los doctores John D. Graham, Ellen J. Mackenzie y Milton C. Weinstein. John es el mejor mentor que yo pude nunca imaginar. Le agradezco en especial su extremadamente generoso y duradero apoyo tanto en el aspecto intelectual como en el emocional y el económico. Ellen me recuerda constantemente cuanto tengo todavía por aprender y por hacer en el área de la prevención de lesiones por causas externas y durante todo este tiempo ha actuado como mi ángel de la guarda. Milt, con su rigor metodológico y sus altísimos estándares profesionales ha contribuido, sin duda alguna, a que me convierta en una mejor investigadora. ¡Será un placer seguir trabajando con ellos en los años venideros!

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Completar esta tesis es el fin del principio. Confío utilizar el resto de mi vida en aplicar todo lo que he aprendido, en darme generosamente a los demás y en contribuir a disminuir el impacto de las lesiones por causas externas en la población. Estas serán las mejores maneras de demostrar mi agradecimiento.

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Introduction

Injuries are a major public health problem around the world. In the United States, injuries are the leading cause of death among persons age 1 to 43 years old. Approximately 140,000 people die every year as a consequence of an injury and 2.3 million people are injured seriously enough to require hospital admission. It is estimated that another 50 million people require some form of outpatient treatment (Robertson 1992). Injuries are also an important source of disabilities. Societal costs of injury in the U.S. have been estimated to amount to over $158 billion in 1985, which represents the third largest health-related cost in the country (Rice *et al.* 1989).

Motor vehicle crashes are the largest single cause of injuries, accounting for approximately one third of the problem. About half of all people involved in motor vehicle crashes are passenger-car drivers, constituting the single largest group of injury victims. In 1996 in the US alone there were 14,879 drivers of passenger cars who suffered fatal injuries, 611,00 who suffered moderate to severe nonfatal injuries, and more than 1,000,000 who suffered minor injuries (NHTSA 1997a). It is estimated that approximately 7% of the non-fatal injuries among front-seat occupants are severe enough to cause some degree of residual functional limitation one year or more after the crash (Segui-Gomez 1996).

Despite the magnitude of these injuries, it was not until the mid-1960s that they were regarded as a public health issue. In the past years, numerous studies have been conducted using descriptive and analytical epidemiological methods to characterize these injuries as well as to identify their incidence and prevalence. Quite a few additional studies have focused on the costs associated with these injuries (Faigin 1975, Blincoe 1996). Other studies have identified risk factors and evaluated the effectiveness of numerous interventions such as mandatory seat belt use laws, revised speed limits, vehicle crash-survivability standards, vehicle inspection laws, drunk-driving legislation and driver licensing restrictions (Graham 1988, pages 15-18). To date, very few studies have performed an economic evaluation (e.g., cost-benefit or cost-effectiveness analysis) that would determine the efficiency of different interventions (Segui-Gomez & Graham 1996, Graham *et al.* 1998).

As a result of former research and intervention activities, driving a passenger car is much safer now than in the past. The development and implementation of an impressive number of primary, secondary and tertiary preventive measures have both lowered injury rates as well as brought down injury severity from previous rates. Indeed, despite substantial increases in both the number of vehicles on the fleet and the amount of miles traveled, the rates of fatal injuries have been diminishing over the past years to the levels indicated above (NHTSA 1997a). Nevertheless, the problem is still huge and the need for "utilization of rigorous analytical methods in injury research" has been publicly raised (Committee on Injury Prevention and Control 1999)

One of the most controversial responses to the driver injury problem has been the installation of airbag systems (Graham 1989). Regulation initially passed in 1984, and modified in 1991, requires all passenger cars manufactured after September 1, 1997 to have a driver-side-frontal airbag system (NHTSA 1996). The U.S. is the only country in the world with such a mandate (Segui-Gomez & Graham 1996). This regulatory impetus, together with increased consumer interest in safety, has contributed to such a rapid introduction of airbag systems in the auto fleet that federal regulation was met ahead of time. Since 1989, more than 60 million driver-side airbag-equipped vehicles have been sold. It is estimated that as of 1999, 47% of the passenger cars in the U.S. fleet are equipped with such a system (Office for Communications, NHTSA, personal communication).

Driver-side frontal airbags are a safety device designed to protect occupants involved in frontal or front-angle crashes by providing a "soft" cushion that covers the vehicle's interior surfaces and reduces the likelihood of the driver being injured by hitting the steering wheel. The regulation set a performance criteria: an unbelted 50th percentile male dummy placed in the front seat of a vehicle that is crashed against a fixed barrier at 30 mph (19.7 km/h) cannot experience forces in the head and chest higher than a given level. A typical airbag system consists of sensors (which detect the severity of the crash), a central unit (which monitors the performance of the system and integrates the information from multiple sensors), and the bag itself. However, manufacturers have freedom in the design of the systems, which has led to some variability across passenger cars regarding issues such as the severity of the crash at which the airbag deploys, the airbag deployment speed, its size, shape or volume.

In its initial predictions based on experimental testing, the National Highway Traffic Safety Administration (NHTSA) determined that airbags would reduce the overall risk of fatal injuries by 40% among unbelted drivers and by 10% among belted drivers (Graham & Segui-Gomez 1996). U.S. government estimates from 1977 to 1987 indicated that between 6,000 and 9,000 lives could be saved each year if all passenger-cars were equipped with airbags (Thompson *et al.* 1999, NHTSA 1976 & 1984). At the time, there were few estimates regarding the impact of airbags on non-fatal injuries.

Extensive real-world crash data, now available, demonstrate the excessive optimism of prior estimates. Both statistical analyses of large population-based crash data and special crash investigations indicate that airbag systems have fewer benefits than previously thought and, in fact, can induce harm. To date, 52 drivers have died in minor crashes because of an airbag deployment (NHTSA, web page). The magnitude of the airbags' net life-saving effect for the unbelted driver is now estimated to be around 11% (NHTSA 1999).

Evaluations of the effect of airbags on non-fatal injuries have reported puzzling results. The risk of moderate to serious head injury appears to be reduced significantly (NHTSA 1996). However, an increased rate of moderate to serious injuries to other body regions have been documented in national crash surveillance data systems (NHTSA 1996), medical reports (Augenstein 1996), and special crash investigations (Huelke 1995).

Overall, it appears that 40% of airbag deployments result in at least one injury to the driver, although most of these injuries are reportedly minor (Werner *et al.* 1996).

A variety of strategies are being adopted to improve the performance of airbag systems. Some of them target current owners of airbag-equipped vehicles whereas others are aimed at enhancing future airbag systems. As an example of the former, NHTSA now allows drivers who meet certain conditions to apply for a permit that will allow them to temporarily or permanently disconnect their airbag system (NTHSA 1997b & c). Vehicle manufacturers have persuaded NHTSA to allow "depowering" of the airbags as a temporary measure while they develop more sophisticated airbag systems. Depowering entails decreasing the speed of deployment and/or the volume of the deploying airbag (NTHSA 1997d). Both of these solutions stem from the belief that most airbag-induced injuries occur when the driver interacts with a deploying airbag (NHTSA 1997b). Other solutions now under consideration include raising the crash severity threshold that triggers airbag deployment, changing the design of the bags themselves (type of fabric, shape, folding patterns, etc), or installing sensors that will suppress the inflation of the bag if the driver is within the airbag deployment area.

The three chapters that comprise this thesis use the driver-side frontal airbag systems example to illustrate three points: (1) the need to think of potential negative consequences when designing or implementing much needed injury prevention interventions; (2) the need for continuous monitoring of the performance of such strategies; and (3) the need to use the most up-to-date methodologies to allow for better characterization of the efficacy and efficiency of those strategies.

The first chapter "Driver Distance from the Steering wheel: Perception and Objective Measurement" emphasizes the need to be cautious when devising solutions to emerging injuries as well as the need for continuous monitoring. In light of the airbag-induced deaths and the surrounding media blitz (Haas 1997), NHTSA agreed to relax its policy regarding disablement of airbags. The agency developed a mechanism that allows drivers who meet some criteria to disconnect their systems. One criterion is sitting too close to the steering wheel while driving. As the research summarized in the chapter and presented in the *New England Journal of Medicine* and *the American Journal of Public Health* suggests, the self-reported nature of the permit process allows for driver misclassification which may constitute an additional source of harm among drivers.

The second chapter " Driver Airbag Effectiveness by Severity of the Crash" proves the need for continuous monitoring of the implemented interventions and the use of advanced methodologies in its evaluation. In this chapter, the effectiveness of airbags on (predominantly) non-fatal injuries is documented. A representative sample of police-reported crashes were analyzed using multivariable ordinal, linear and logistic methods. The research presented in this chapter is under review at *the American Journal of Public Health*.

The last chapter illustrates the application of state-of-the art methods widely used in other health-related fields to injury prevention. The cost-effectiveness analysis presented in this chapter constitutes one of the few applications of this technique to the injury control field in which both fatal and non-fatal consequences of the intervention are taken into consideration together with their impact on the quality of life of the subjects (Graham *et al.* 1998). The specific issue under evaluation is the choice of crash severity that warrants airbag deployment.

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Chapter 1

Driver Distance from the Steering Wheel: Perception and Objective Measurement

Airbag Safety and the Distance of the Driver from the Steering Wheel

Maria Segui-Gomez, Jonathan Levy, and John D. Graham

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Driver Distance from the Steering Wheel: Perception and Objective Measurement

Maria Segui-Gomez, Jonathan Levy, Henry Roman, Kimberly Thompson, Kathleen MacCabe, and John D. Graham

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may be a cause of spurious thrombocytopenia, the presence of polymorphonuclear neutrophils may also lead to a decrease in free platelets in vivo, and this will not be detected by standard methods of platelet enumeration. Platelet–leukocyte interactions are important in modulating inflammation and hemostasis and should not be confused with the image presented by Drs. Shahab and Evans.

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The authors reply:

To the Editor: We agree with the comment of Peters et al. regarding platelet–neutrophil interactions in vivo and their importance in modulating inflammation and hemostasis. However, platelet satellitism as we described it is a different phenomenon. It is observed solely after blood treated with an anticoagulant is incubated at room temperature.[1] It is not reproduced if blood is incubated at body temperature or smears are made immediately from either blood treated with EDTA as an anticoagulant or capillary blood.[1,2] We agree with Peters et al. that under similar conditions, both heparin-treated blood and citrated blood have occasionally been observed to produce the same phenomenon.[1] However, others have not observed this effect with anticoagulants other than EDTA.[2]

The underlying mechanism of platelet satellitism is not fully understood. IgG autoantibodies have been implicated,[3] and more recent studies have indicated that these autoantibodies are directed against the glycoprotein IIb/IIIa complex of the platelet membrane and the neutrophil Fcγ receptor III (CD16).[4] It was postulated that at low temperatures, the chelation of calcium ions by EDTA alters the conformation of the glycoprotein IIb/IIIa complex of platelets and the Fcγ receptor III of neutrophils. This change may unmask epitopes for the IgG autoantibody, which forms a bridge between platelets and neutrophils, and hence, reveal the hematologic picture.[4] An alternative, nonimmunologic mechanism has been proposed by Christopoulos and Mattock, who suggested that thrombospondin or some other alpha-granule platelet protein had a role after they observed that adherence to neutrophils involved only platelets that stained strongly for thrombospondin.[5]

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Airbag Safety and the Distance of the Driver from the Steering Wheel

To the Editor: Actuarial data indicate that driver-side airbags reduce the overall risk of death from a car accident by 11 percent,[1] but airbag-induced injuries (both fatal and nonfatal) have been reported.[2] The driver's proximity to the airbag is an important safety issue. Under a new government policy, drivers are being encouraged to maintain a safe distance from the steering wheel or, if that is not feasible, to obtain a manual cutoff switch for their airbags.[3] Yet drivers may not properly estimate their proximity to the steering wheel.

In order to evaluate the degree of misperception, we conducted a cross-sectional survey of 1000 drivers at gas stations in the Boston metropolitan area. Proximity was defined as the distance between the center of the steering wheel and the bridge of the driver's nose, as perceived by each driver and as measured with a tape measure by trained interviewers. We compared the perceived and actual distances, documenting the number of drivers who estimated that they were or who actually were sitting with the bridges of their noses within 12 in. (30 cm) of the steering wheel.

The correlation between perceived and actual distances

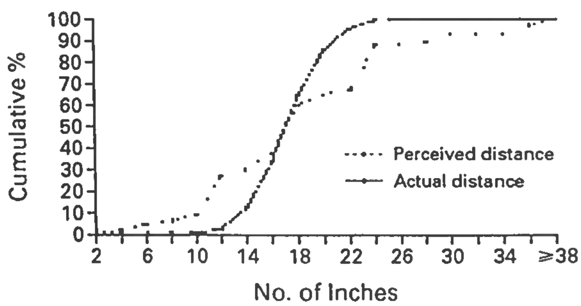

Figure 1. Perceived and Actual Distances from the Driver's Nose to the Steering Wheel.

was very low (r=0.24), with some drivers underestimating and others overestimating their proximity (Fig. 1). Although 234 of the drivers (mostly women) thought that they sat within 12 in. of the steering wheel, only 22 drivers (19 women and 3 men) actually did. Of these 22 drivers, only 8 correctly perceived that they sat within 12 in.

A limitation of our study is that the new regulation defines the safe distance as 10 in. (25 cm) from the breastbone to the steering wheel. We suspect that a considerable number of drivers will also misperceive their risk according to this alternative definition of safe distance.

Drivers who think they sit too close to the wheel but actually do not may be inappropriately concerned about their safety and disconnect their airbag systems, thus losing safety benefits. In contrast, drivers who actually sit too close but do not think they do may not be concerned enough. Since a petition for airbag disconnection must be submitted by the owner of the vehicle and the driver's risk status cannot be corroborated, physicians and policy makers should be aware of this problem of misperception and take a proactive approach to help identify the people truly at risk for injury from airbags. Drivers should be encouraged to measure objectively their distance from the airbag in a normal driving situation.

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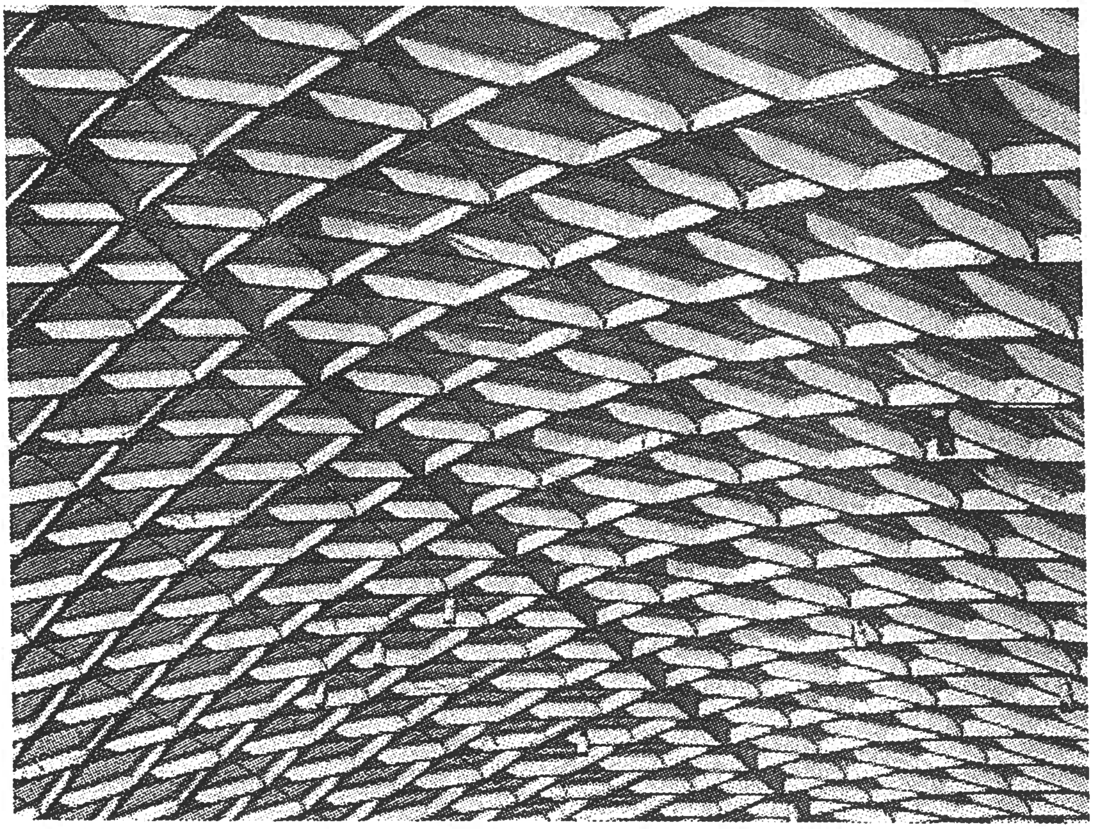

Vanishing Point — Jacob I. Hirsch, M.D.

ABSTRACT

Objectives. This study assessed the accuracy of driver perceptions of the distance between the driver's nose and the steering wheel of the vehicle as a factor in considering driver disconnection of an airbag contained in the steering wheel for preventing injury to the driver in an accident.

Methods. A cross-sectional survey of 1000 drivers was done to obtain perceived and objective measurements of the distance between the driver's nose and the steering wheel of the vehicle.

Results. Of 234 drivers who believed that they sat within 12 inches of the steering wheel, only 8 (3%) actually did so, whereas of 658 drivers who did not believe that they sat within 12 inches of the wheel, 14 (2%) did so. Shorter drivers were more likely than taller ones to both underestimate and overestimate their seating distance.

Conclusions. Considerable misperception of drivers' distance from the wheel indicates that drivers should objectively measure this distance. (*Am J Public Health.* 1999;89:1109–1111)

Driver Distance From the Steering Wheel: Perception and Objective Measurement

Maria Segui-Gomez, MD, MPH, Jonathan Levy, BA, Henry Roman, MS, Kimberly M. Thompson, ScD, Kathleen McCabe, MPH, and John D. Graham, PhD

Driver-side airbags, mandatory in the United States since 1984,[1] are designed to mitigate head and upper torso injuries to the driver in frontal crashes of motor vehicles. Despite the overall protective effect of airbags,[2] they can cause fatal and nonfatal injuries if the driver's head, neck, chest, or arms are too close to the deploying airbag.[3–6] As of November 1, 1998, 48 driver deaths in the United States had been attributed to airbags.[7] Of these deaths, 26 were of females and 2 were of males whose height was 64 inches or less.[7] Although some data indicate that women of small stature are more likely to be injured by airbag systems,[3] evidence suggests that such systems reduce their overall risk of death by 9.5%.[2]

Widely publicized information about these airbag-induced injuries has led to significant public concern.[8–9] A new US government regulation allows drivers who are at risk of airbag-induced injuries to disconnect their airbags. Eligibility criteria for airbag disconnection via an on–off switch include driver-attested inability to operate a vehicle while maintaining a 10-inch distance from the center of the steering wheel to the center of the driver's chest.[10] Eligibility criteria for airbag deactivation in the absence of a switch include a driver body height of 54 inches or less.[11]

Both the decision to disconnect an airbag and the burden of assessing the eligibility to do so fall on the driver. Studies reporting measured distances between the driver and the steering wheel indicate that 0% to 14% of men and 0% to 30% of women sit within 12 inches of the steering wheel when driving a vehicle and that 0% of men and 5% of women sit within 10 inches.[12–15] In contrast, a telephone survey found that 32% of women and 16% of men believed that they sat within 12 inches of the steering wheel.[16] These studies used different definitions of distance from the steering wheel, and none compared perceived and measured distances. However, the studies collectively suggest that drivers may misperceive their distance from the steering wheel.[17–20]

We investigated the frequency of such misperception and explored the factors that characterize drivers who are more likely to misperceive their seating distance from the steering wheel. In doing this, we put special emphasis on shorter drivers (including women) because they were thought likely to represent the largest proportion of individuals who sit too close to the wheel.[15]

Methods

During the summer of 1997, trained interviewers asked drivers refueling at 15 randomly selected gasoline stations in the Boston metropolitan area to participate in the study. Criteria for participation included completion of a survey instrument and measurement of the driver's nose–to–steering wheel seating distance during the refueling stop.

The survey instrument contained questions about driver and vehicle characteristics as well as about the driver's perceptions regarding airbags. Drivers participating in the survey were asked, "When driving, how far do you think you sit from the steering wheel (in inches measured from the bridge of your nose to the wheel)?" After instructing the driver to take his or her normal driving posture, the interviewer made manual measurements of the distance from the bridge of the driver's nose to the center of the steering wheel (in accordance with the measurements reported in the then-current literature[12–14,16]). The interviewer also collected information about airbag equipment and driver seat-belt use.

For statistical analysis, drivers were categorized as short (<64 inches), medium (>64–<70 inches), and tall (≥70 inches) on the basis of the height quartiles of the survey sample. Proximity of a seated driver to the steering wheel was defined as a distance of 12 inches or less,[12–14,16] although we conducted a sensitivity analysis with alternative definitions of proximity as 14 and 16 inches.

To compare perceived and measured distances of drivers from the steering wheel, we computed the Pearson correlation coefficient and the diagnostic test values of perceived distances, consisting of sensitivity (and false-negative results, defined as a real

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distance that was less than the perceived distance from the steering wheel), specificity (and false-positive results, defined as a real distance that was more than the perceived distance from the steering wheel), and positive and negative predictive values. Multivariate logistic regression analysis was used to determine the factors that predicted false-positive and false-negative results. Those factors evaluated included age, sex, height, seat-belt use, presence of a driver-side airbag in the vehicle, perception of an airbag as safe or not, year of the driver's vehicle, transmission type of the vehicle, and the interactions between sex and height, sex and perception of airbag safety, and height and perception of airbag safety.

Results

Of 1400 drivers who were approached for the survey, 1000 agreed to participate. Table 1 shows, by sex, the following characteristics of the survey population: age, height, seat belt use, perception of airbag safety, and presence of driver-side airbag.

Among the 892 subjects who estimated their seating distance from the steering wheel, the mean perceived distances were 18 inches (SD = 10) for women and 21 inches (SD = 9) for men. The mean measured distances from the wheel were 17 inches (SD = 2) for women and 19 inches (SD = 2) for men. The correlation between perceived and measured distance was 0.24 for the overall sample and varied between 0.2 and 0.3 after stratification by sex and height category.[21]

The percentage of drivers who sat within 12 inches of the steering wheel and perceived themselves as doing so (positive predictive value) was 3%, ranging from 0% for short and tall men and tall women to 6% for short women. The probability that drivers who sat within 12 inches of the wheel perceived themselves as doing so (sensitivity) was 53%, ranging from 45% for short women to 100% for women of medium height (Table 2).

The multivariate logistic regression models showed that only height and negative perceptions of airbags as safety devices had statistically significant ($P<.05$) effects on the rates of false-positive and false-negative results. Shorter individuals (both men and women) were more likely to have both false-positive and false-negative results (odds ratios [ORs] = 1.5 and 1.9, and 95% confidence intervals [CIs] = 1.2, 2.0 and 1.3, 2.9, respectively). Drivers who did not perceive airbags as safe were much less likely to have false-positive results (OR < 0.001; 95% CI = 0.0005, 0.03). Sensitivity analyses for distances of 14 or 16 inches from the steering wheel did not change the results. The results of these analyses are not shown.

TABLE 1—Selected Characteristics of the Study Population by Sex: Boston, Summer 1997

	Men (n = 476), %	Women (n = 523), %
Age, y		
15–24	11.8	16.0
25–64	81.3	81.1
65+	6.9	2.9
Height, inches		
≥56–≤64	2.9	52.4
>64–<70	43.7	42.8
≥70–≤79	53.4	4.8
Driver belted	62.2	65.6
Airbag not perceived as safe	32.0	41.9
Driver-side airbag	49.0	48.8

Note. The sex of one driver was not reported.

TABLE 2—Perceived and Measured Distances to the Steering Wheel and Diagnostic Test Values by Sex and Height Categories (n = 892): Boston, Summer 1997

	Measured Distance,ᵃ n		Diagnostic Test, %			
Distance,ᵃ by Height	≤12	>12	Sensitivity	Specificity	Positive Predictive Value	Negative Predictive Value
≤64						
Women						
≤12	5	81	45	64.0	6.0	96.0
>12	6	141				
Men						
≤12	0	4	NA	69.0	0.0	100.0
>12	0	9				
>64–<70						
Women						
≤12	2	55	100.0	72.0	4.0	100.0
>12	0	143				
Men						
≤12	1	35	50.0	81.0	3.0	99.0
>12	1	153				
≥70						
Women						
≤12	0	3	NA	86.0	0.0	100.0
>12	0	19				
Men						
≤12	0	49	NA	79.0	0.0	100.0
>12	0	185				

Note. The sex of one driver was not reported. NA = not applicable.
ᵃDistance, both perceived and measured, given in inches.

Discussion

Drivers' misperceptions of their nose–to–steering wheel distance during operation of a motor vehicle are a potentially serious public health problem. Drivers with false-positive results for this variable may put themselves at greater risk of injury by inappropriately seeking permission to disconnect their airbags, while those with false-negative results may not be aware of their risk of injury.

The main limitation of our study was that the definition of distance from the steering wheel in our survey differed from the current definition of a safe distance of 10 inches between the center of the driver's chest and the center of the steering wheel.[10] Although we cannot quantify the relationship between these definitions, they may be roughly equivalent. We believe that the current definition of a safe distance from the wheel would yield rates of misperception similar to those that we observed.

Drivers (and especially shorter ones, regardless of their sex) can easily, and should be encouraged to, measure the distance between themselves and an airbag contained in the steering wheel of their vehicle. Our findings should be helpful to drivers contemplating disconnecting an airbag, to health and safety professionals who are asked about airbags, and to the federal agency granting permits to disconnect these devices. □

Contributors

M. Segui-Gomez planned and supervised the data collection, performed the primary analysis of the data, and wrote the paper. J. Levy and H. Roman conducted a pilot study to test the survey questionnaire and assisted in the training of the interviewers. K. McCabe contributed to the data analysis. K. M. Thompson suggested the comparison of perceived and objective distances of seated drivers from the steering wheels of their vehicles. J. D. Graham planned and supervised the study. All of the authors contributed to the writing of the paper and are guarantors of the integrity of the study.

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Chapter 2

Driver Airbag Effectiveness by Severity of the Crash

Maria Segui-Gomez

ABSTRACT

Objectives. To provide effectiveness estimates of the driver-side airbag while controlling for the severity of the crash and other potential confounders.

Methods. Data are from the National Automotive Sampling System from 1993 through 1996. Injury severity was described using the Abbreviated Injury Scale (AIS), Injury Severity Score, Functional Capacity Index, and survival. Ordinal, logistic and linear multivariable regression methods were employed.

Results. Airbag deployment in frontal or near frontal crashes decreases the probability of suffering severe and fatal injuries (e.g., AIS 4-6), including those causing a long-lasting high degree of functional limitation. However, airbag deployment increases the probability that a driver (particularly a woman driver) will sustain injuries of AIS level 1-3. Airbag deployment in low-severity crashes exerts a net injurious effect whereas in high-severity crashes it exerts a net protective effect. The severity of the crash above which the airbag net effect is protective is higher for women than for men.

Conclusions. Airbag improvement should minimize the injuries currently being induced by their deployment. One possible strategy is to raise their deployment level so that airbags only deploy in more severe crashes.

INTRODUCTION

Airbags have been around for more than 40 years and they have always been surrounded by controversy.[1-2] Unlike most safety devices, a deploying airbag 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[a] driver-side airbags, which have been mandated in all passenger vehicles sold in the US since model year 1997,[5] were available in many makes and models before regulation took effect. In fact, in 1999 almost half of all passenger cars in the US fleet are equipped with a frontal driver-side airbag (NHTSA, personal communication) and over the next years this ratio will increase to nearly 100%.

Airbags are supposed to protect the occupants in combination with lap and shoulder safety belts (they are called "Supplemental Restraint Systems"). Yet, the airbag systems sold in the US were designed to meet a federal performance standard that requires that in an experimental frontal crash at approximately 19 km/h the forces on an unbelted 50th percentile men dummy's face, head, and chest do not exceed some level.[5] A typical airbag system consists of one or more sensors that detect the longitudinal deceleration rate of the vehicle during the crash, an electronic unit that monitors the operation of the system, and an airbag module that houses the inflator and the bag,[6] but there is some design variability across makes, models and years.[7]

Since the early 1970s, researchers have evaluated the performance of airbag systems. Most existing evaluations focus on the airbag's impact in reducing fatalities. Initial estimates of the percent reduction in fatalities due to airbags plus safety belts, based on expert judgment and/or experimental data, ranged from 18% to 55%.[5, 8-15] The most recent effectiveness estimates for driver-side airbags in frontal or near frontal crashes, using the double pair-comparison method[16] and real-world fatal crash data, suggest a reduction of approximately 19% reduction in fatality risk among belted drivers.[17-19] The only estimates available to date regarding airbag effectiveness in non-fatal injuries indicate reductions in moderate to serious non-fatal 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 airbags with the causation of a variety of injuries. To date, airbags have been linked with the deaths of 52 drivers (NHTSA, NCSA online on 3/26/1999, http://www.nhtsa.dot.gov) and numerous non-fatal injuries of varying degrees of severity, including corneal abrasions, aortic rupture, lung contusions, abdominal injuries, and open fractures of the forearm.[26-30] Using real-world crash data, researchers have also associated airbags with an increased risk of

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[a] This paper refers to frontal driver-side airbags only (as opposed to frontal passenger-side airbags or side airbags for either the driver or the front right passenger).

serious upper extremity injuries[31] and an overall increased risk of minor and moderate injuries.[22, 32-35]

It has been suggested that airbag-related injuries may be associated with specific design features, such as the amount of energy released by the deploying airbag, the speed of inflation, and the volume, shape and folding pattern of the bag.[36-37] It has also been suggested that women are more likely to suffer these airbag-induced injuries.[21] In addition, the fact that airbag-induced injuries are the most serious injuries reported in relatively low-speed crashes[22] raises the question of whether these airbags are deploying unnecessarily in some crashes.

When is the crash serious enough to warrant deployment of the bag? Current airbags are designed to deploy at crashes between 11-26 km/h --although the precise threshold varies by make, model, and in some cases, by the restraint use of the occupant.[7] Lower deployment levels imply higher airbag deployment rates (i.e., airbags deploying in more crashes), which in turn, has been associated with a higher incidence of airbag-related injuries.[38-39] In low-speed crashes, the injuries induced by the deploying airbag may be more serious than injuries that would otherwise have occurred, whereas in higher speed crashes airbag deployment may actually prevent the driver from sustaining more severe injuries.

The goal of this paper is to provide net effectiveness estimates of the driver-side airbag in preventing fatal and non-fatal 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 gender of the driver,[17, 40-43] vehicle size and mass,[44-45] and safety belt use.[46-48]

DATA & METHODS

a) Outcome Measures

The effectiveness of airbags was evaluated using the following injury severity measures: the Abbreviated Injury Scale, the Injury Severity Score, the Functional Capacity Index, and survival.

The *Abbreviated Injury Scale* (AIS) is a consensus derived, anatomically based system that classifies each injury on a 6-point ordinal scale that ranges from 1 (minor) to 6 (virtually unsurvivable).[49] The most severe injury sustained by an occupant is referred to as the maximum AIS (or MAIS). Drivers who died were assigned a MAIS of 6.

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

The *Functional Capacity Index* (FCI) is the first preference-based multi-attribute score system that reflects the predicted extent of functional limitation one-year post-injury.[51] Each injury has its own FCI. The FCI 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 FCI=0, fatalities were coded as FCI=100, and the remaining patients were classified by the functional limitation of the injury leading to the maximum (i.e., worst) functional limitation (MFCI).

The scores from these severity measures generated ten outcome (or dependent) variables. Six of these outcome variables were dichotomous variables indicating whether the most severe injury that a driver sustained was of some severity level or higher (e.g., MAIS3+) or whether the driver had died (e.g., MAIS6). The seventh and eighth outcome measures were ordinal variables indicating the MAIS level of the driver: MAIS0-6 indicates the value of the MAIS using the full AIS scale (i.e., 0 through 6); MAISnms indicates the level of the most severe injury categorized into: none (or MAIS=0), "minor" (or MAIS=1, 2, or 3) or "severe" (MAIS=4,5,or 6). The two remaining dependent variables were continuous variables: the ISS and the MFCI.

As an example of the assignment of values to dependent variables, a driver who survived the crash and sustained a unique injury of AIS level 3 with no functional limitation would be categorized as: MAIS1+=1, MAIS2+=1, MAIS3+=1, MAIS4+=0, MAIS5+=0,MAIS6=0, MAIS0-6=3, MAISnms=1, ISS=9, and MFCI=0.

b) Data

The National Automotive Sampling System Crashworthiness Data System, formerly National Accident Sampling System, (NASS CDS), for calendar years 1993-1996 was used. NASS CDS is a stratified sample of police-reported crashes involving passenger vehicles in which at least one of the vehicles was towed away from the scene due to 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 5,000 crashes are investigated per year.

Inclusion criteria for the analysis entailed being the operator of a passenger car of model years 1986 through 1997 in a frontal or near-frontal crash during 1993-1996 for which the severity of the crash was known. For each driver, we analyzed injuries reported either in the autopsy, hospital, emergency room, or medical records. Some drivers were not injured, while others experience one or more injuries. For each driver, we included up to his/her 14 injuries with the highest AIS (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 excluded from further analyses.

The NASS CDS data used in the analyses included driver characteristics (age, gender, and height), crash consequences (number, type, and severity of the injuries), crash circumstances (severity of the crash, direction of crash, airbag deployment, safety belt use), and vehicle characteristics (airbag presence, wheelbase, curb weight, and the Vehicle Identification Number --VIN). In our analyses, the severity of the crash was defined using the longitudinal component of the maximum velocity change incurred by the vehicle during the crash (the so-called longitudinal delta V –herein delta V). The delta V is calculated by crash investigators using a computerized algorithm that is solely based on vehicle deformation as measured in the post-crash investigation. The VIN was decoded using VINDICATOR(R) to corroborate the information regarding airbag presence and restraint systems.[52] A vehicle was characterized as equipped with a frontal driver-side airbag 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 were within the 10:00-2:00 range. [17,31] A computerized mapping algorithm (M. Waltz, National Center for Statistical Analysis, NHTSA, personal communication) was used to assign FCI scores to the injuries sustained by the drivers. Stata® and Excel® were used for data management and statistical analysis.[53-54]

c) Analyses

We conducted a descriptive analysis of driver demographics, injuries, vehicles, and crash characteristics. Univariable and multivariable regression techniques were then used to evaluate: 1) the effect of airbag 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 airbag deployment and personal, vehicle, and crash characteristics.

Logistic regression techniques were used with the six dichotomous outcome variables. These logistic regressions were performed to be able to compare our findings to previously reported airbag effectiveness estimates. The seventh and eighth outcome measures (MAIS0-6 and MAISnms) required the use of ordinal regression techniques. The use of these ordinal variables allows for a more comprehensive evaluation of the airbag effect over each injury severity level. Linear regression techniques were used with the two continuous outcome variables (i.e., ISS and MFCI). The ISS was used to evaluate the impact of airbag deployment on the severity of the driver (particularly interesting for those drivers suffering multiple injuries). The FCI was used to evaluate the impact of airbag deployment on injuries that lead into long-term functional limitations.

Independent variables for inclusion in the multivariable regression were those that had significant or quasi-significant coefficients ($p<0.25$) in the univariable regressions (i.e., drivers' gender, age, and height, seatbelt use, vehicles' wheelbase, and severity of the crash) and a dummy variable indicating whether the airbag deployed. For each dependent variable, models were built systematically including two, three, and more independent variables and the interaction terms between airbag deployment and each of the covariates (e.g., airbag deployment and severity of the crash). More complex models were evaluated using Log Likelihood Ratios[55] or the Residuals Sum of Square Test.[56] The independent variables that retained statistical significance ($p<0.1$) in most (if not all) of the ten regression models were: airbag deployment, severity of the crash, and the driver's gender, age, and safety belt use. These variables were selected for the final models. In the final models we also included the two terms reflecting the interaction between airbag deployment and gender and airbag deployment and delta V when these terms achieved statistical significance ($p<0.1$).

The airbag deployment coefficients in the final multivariable regression models reflect the point estimates of airbag deployment effectiveness while controlling for severity of the crash, age and gender or the driver and his/her seatbelt use. "Effectiveness" is defined as a decrease or increase in: (a) the probability of sustaining injuries of different severity levels (i.e., when evaluating MAIS), (b) the severity of the injuries sustained (i.e., when evaluating ISS), and (c) the functional limitations associated with those injuries (i.e., when evaluating MFCI). Statistically significant interaction coefficients indicate whether the airbag effectiveness varies across circumstances. For example, airbags could be more protective for men than for women drivers and/or airbags could be more protective in more severe crashes than in less severe crashes. In the models in which there is a significant interaction term, the airbag effectiveness estimates must be reported for the different categories that were used in creating the interaction term.[55,57]

RESULTS

Of the 13,092 drivers in the NASS CDS 1993-1996 in passenger cars of model year no older than 1986, 6,409 (49.0%) had a known delta V. A comparison of drivers with and without delta V revealed differences both in the proportion of cases with missing data and in the proportion of frontal crashes. Drivers with unknown delta V were more likely than drivers with known delta V to have missing information for variables such as age, gender, airbag presence, airbag deployment, seat belt use, vehicle size or mass, and direction of crash. (For example, direction of the crash was missing in 52.2% of the cases with unknown delta V compared to 10.2% of cases with known delta V ($p<0.0001$).) For those cases with known direction of crash, frontal crashes were more common among drivers with known delta V (86.9%) than for drivers with unknown delta V (81.5%) ($p=0.0005$). There were no statistically significant differences regarding the distribution of any other variables, including injury severity (MAIS or ISS) and functional limitations (MFCI) (Data not shown).

Of the 6,409 drivers with known delta V, 11 died of no crash-related causes, 655 had missing information regarding the direction of crash, and 740 were in non-frontal crashes (23.8% right, 33.8% left, and 42.4% rear). Hence, 5,003 drivers met our study's inclusion criteria; their personal, vehicle, and crash characteristics are summarized in Table 1.

Among these 5,003 drivers, 208 (4.2%) died as a consequence of the crash. No injuries were reported for 2,023 drivers (40.4%). Among the remaining drivers for whom at least one injury was indicated, 518 sustained only one injury each and the other 2,441 drivers presented a total of 10,055 injuries.

The NASS CDS indicated that 1,545 vehicles were equipped with a frontal driver-side airbag whereas the decoding of the VIN identified 1,580 such vehicles. Agreement between the two sources occurred in 1,424 cases, whereas at least one of the data sources indicated the presence of an airbag in 1,701 cases (34.0%). Airbag deployment occurred in 1,095 cases (64.4%).

The logistic multivariable regression models confirm that airbag deployment is associated with a statistically significant decrease in the probability of suffering injuries MAIS4+ (OR 0.72 95% CI 0.52-0.99) or fatal injuries (MAIS 6 OR 0.58 95%CI 0.37-0.90). This protective effect is not different by gender of the driver. In contrast, airbag deployment in frontal or near-frontal crashes is associated with a statistically significant ($p<0.05$) increase in the probability that women drivers will sustain at least one injury (MAIS1+ OR 1.54, 95%CI 1.23-1.92) and injuries MAIS2+ or MAIS3+ (both ORs approximately 1.5 95%CI 1.2-1.9). The effect of airbag deployment on men driver regarding injuries of AIS level 1 through 3 does not reach statistical significance, although the point estimates indicate protective effects (ORs 0.93, 0.81, and 0.78 respectively) (Table 2).

In the ordinal and linear multivariable regression models, both the interaction between airbag deployment and delta V and between airbag deployment and gender are statistically significant. Airbag deployment *per se* increases both the overall injury severity as measured by the MAIS0-6, MAISnms, and ISS, and the resulting functional limitations as indicated by the MFCI (regression coefficients = 0.56, 0.58, 2.8, and 5.3, respectively). In contrast, the interaction terms have protective effects (Appendix A). As a consequence: (a) airbag deployment induces fewer (and less severe) injuries among men drivers than among women drivers, (b) at higher delta Vs, the airbag protective effect becomes large enough to offset its injurious effect, and the airbag deployment net effect becomes protective, and (c) the delta V at which the net effect of airbag deployment becomes protective differs between women and men. Figures 1a&b illustrate net airbag effectiveness at each crash severity level as the percent change in the probability of women and men drivers to sustain no injury (i.e., MAIS0) or injuries of different severity (MAIS1-3 or MAIS4-6) while controlling for age and seat belt use. For example, the net airbag effect on injuries of MAIS 4, 5 or 6 among women drivers ranged from a 10% protective effect in crashes with longitudinal delta Vs around 70 km/h to a 70% increase in crashes with delta Vs below 3 km/h. Its effect on MAIS 4, 5 or 6 among men drivers ranged between a 35% protective effect in crashes with delta Vs around 64 km/h to a 10+% increase in crashes with delta Vs below 5km/h. Overall, the delta V at which the airbag deployment changes from injurious to protective occurs at 52.0 km/h for women and 12.9 km/h for men.

The effect of airbag deployment evaluated using the alternative outcomes measures (i.e., the full MAIS range, ISS or FCI) produced results consistent with the findings just described (data not shown) although the precise delta V at which airbag deployment becomes protective varied depending on the outcome measure evaluated. As summarized in Table 3, airbag deployment among men drivers has a net protective effect in crashes with delta V at or above 5.2 km/h whereas the protective effects for women drivers only has occur in more severe crashes --crashes at or above 27.5 km/h (Table 3).

All other covariates included in the final multivariable 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 seatbelt use) (Data not shown).

CONCLUSION & DISCUSSION

Our analyses show that in crashes at low longitudinal deceleration rates there is an overall injurious effect of airbags, largely due to an increase in injuries affecting women drivers. Among women, airbag deployment increases in a statistically significant manner: (1) the probability of sustaining MAIS1+, 2+, 3+ and MAIS 1 through 3, (2) the overall severity of their injuries (as indicated by the ISS), and (3) the functional limitations associated with their injuries (as indicated by the MFCI).

This airbag's detrimental effect is offset in crashes at higher delta Vs when airbags become protective and prevent all drivers from suffering more severe injuries (e.g., MAIS 4+, ISS), injuries associated with more functional limitations, and death.

This analysis presents the first evaluation of airbag effectiveness to include minor injuries and an important strength of it is the breadth of dependent variables evaluated. We used 10 different outcome measures that represent a wide range of ways to characterize injury severity (for both fatal and non-fatal injuries) and long-term consequences. No previous research that we are aware of has evaluated shifts in injury severity by using all injury levels in one analysis (e.g., ordinal regression using MAIS0-6), used severity measures than integrate multiple injuries (i.e., ISS), or evaluated the long term consequences of those injuries. Previous researchers evaluated only fatality reduction effectiveness or the effectiveness on reducing the most serious non-fatal injuries (e.g., MAIS3+).[17,18,31] Our estimates are consistent with those presented in the technical literature. For example, the reported 19% fatality reduction estimate generated using fatal crash data[17] is within the 95%CI of our 40% fatality reduction estimate and the 8% non-statistically significant increase in MAIS 3+ in frontal crashes for all drivers[31] is very similar to the 9% increase we identified when an airbag effectiveness estimate is computed for both men and women together (OR 1.09 95%CI 0.88-1.33) (Table 2).

Another interesting finding is the differential effectiveness of airbags by severity of the crash. Although the interaction terms between airbag deployment and delta Vs are statistically significant only in the ordinal and linear multivariable regression models, that is most likely due to the larger variability of the dependent variables in these models. Our interaction results confirm the hypothesis that airbags (in vehicles model year 1997 or older) are deploying in low severity crashes were the risk of incurring any injuries is actually exacerbated by the deployment of the bag.[22, 58] These induced injuries (more frequently MAIS1,2, or 3s) are disproportionally borne by women, although men are also at a higher risk of suffering injuries. The longitudinal delta Vs above which airbag deployment is beneficial is above the deployment levels reported by most manufacturers (well above in the case of women drivers). The confidence estimates around the delta Vs above which airbag deployment has a net protective effect are very large due to the limited sample size of real world crashes available for analysis. Most likely, analysis of future years of NASS data will not permit greater precision in these switchpoints given the current changes in airbag design.

There are some peculiarities of our analyses that are worth noting. For example, research conducted to date has evaluated the effectiveness of airbag presence (regardless of actual deployment) instead of the effectiveness of airbag deployment.[17-23, 31] In our data, 606 additional drivers had an airbag in their vehicle which did not deploy during the crash. To evaluate the robustness of our findings, we ran the final regression models with airbag presence instead of airbag 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, our findings describe the aggregate effects of airbags available in all makes, models and years included in the data set. Obviously, design and performance differences exist among airbag systems, which may change the effectiveness of any particular system. As an example, the recent federal regulation allowing for depowering of the airbags (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 airbag systems: a) specific airbag design parameters across models and years are proprietary information that has not been made available to researchers, and b) even if these proprietary data were available, the NASS CDS may lack enough sample size to allow statistically significant findings in analyses by airbag design.

Second, our airbag effectiveness estimates are based on crashes for which the delta Vs of the crashed passenger car was known, but there are about half as many crashes in the real world for which we do not have information on their delta V. Missing delta Vs are most frequently due to the fact that the algorithm used by crash investigators to compute the deceleration rates (which does not involve information on airbag deployment) does not allow for such computations when the crash involves a rollover, other non-horizontal forces, sideswipe, severe override, overlapping damage, or there is insufficient data at the crash scene and/or in the vehicle.[59] Indeed, direction of impact was the only statistically significant difference between drivers with known and unknown longitudinal delta Vs. Thus, the external validity of our findings is limited.

Finally, the NASS CDS data are subject to some measurement error, particularly regarding the severity of the crash. Several researchers have reported that the validity of the estimates for delta V values lower than 40km/h is questionable since the algorithm is calibrated at approximately 48.3 km/h (M. Finkelstein, personal communication) and it tends to underestimate the actual impact speed, especially in non-frontal crashes.[60-61]

Although the exact degree of error present in the NASS CDS data is unknown, evaluation of the reported delta V estimates by researchers from NHTSA reveals that for 3,777 (75.5%) of the crashes, the computed delta Vs fit the crash description, 846 (16.9%) delta Vs appear reasonable, and 186 (3.7%) and 194 (3.9%) delta Vs appear high and low. The impact of these measurement errors on our estimates is hard to evaluate, but most probably our estimates of deceleration rates at which airbags become protective are underestimates of the actual deceleration rates at which this happens. However imperfect this measure might be, it provides us the only proxy for crash severity that is available for this type of analysis.

In conclusion, our results show that in frontal or near-frontal crashes, airbag deployment is effective in reducing the most severe and fatal injuries whereas in low severity crashes airbag deployment induces injuries of AIS level 1-3 (predominantly among women). Raising the crash severity level at which airbags are designed to deploy should be considered an injury prevention strategy in conjunction with other changes in airbag design. However, one should be cautious in interpreting this recommendation. With imperfect sensor technology, raising the airbag deployment threshold means that (in some crashes) it will take longer for the airbag system to recognize that a crash is severe enough to justify airbag deployment. This may be a particular problem in off-frontal crashes (also called "late pulse" crashes) where the sensor(s) might take longer to acknowledge the existence of a crash due to their positioning.[62-63] Late deployment may injure drivers who have moved forward into the airbag's deployment zone. Use of crush-zone sensors and/or more advanced sensor technology may help alleviate this problem.

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Table 1. Selected Driver, Crash, and Vehicle Characteristics. NASS CDS Calendar Years 1993-1996, Passenger Cars Model Year ≥1986. Frontal and Near-Frontal Crashes with Known Longitudinal Delta V.

		All (n=5,003) %	Airbag Deployed (n=1,095) %	Airbag Not Deployed (n=3,908) %
Driver				
Age	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
Gender	Men	49.3	50.9	48.8
	Women	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	84.8
	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				
Airbag present		34.0	100.0	15.5
Crash				
Airbag deployed		21.9	100.0	0.0
Delta V (km/h)	<24	60.3	56.2	61.4
	24-31	19.2	21.5	18.6
	32-39	9.7	10.8	9.4
	40+	10.8	11.5	10.6
	Missing	0.0	0.0	0.0
Seatbelt used		66.0	69.9	64.9
	Missing	5.6	5.5	5.7

MAIS: Maximum Abbreviated Injury Scale; ISS: Injury Severity Score; MFCI: Maximum Functional Capacity Index Score. Excludes drivers who did not die of crash-related causes.

[a] Injuries selected for analyses include the up to 14 most severe injuries per driver reported from autopsy, hospital, emergency rooms, and medical records. Fatalities considered as MAIS = 6, ISS = 75, and MFCI = 100.

Table 2. Airbag Deployment Effectiveness (Adjusted[a] Odds Ratios and 95% Confidence Intervals). NASS CDS Calendar Years 1993-1996, Passenger Cars Model Year ≥1986. Frontal and Near-Frontal Crashes with Known Longitudinal Delta V (n=4,697).

Variable	Women & Men		Women		Men	
	OR	95%CI	OR	95%CI	OR	95%CI
MAIS1+	1.20	1.03-1.40	1.54	1.23-1.92	0.95	0.77-1.17
MAIS2+	1.09	0.92-1.30	1.46	1.16-1.84	0.81	0.63-1.05
MAIS3+	1.08	0.88-1.33	1.49	1.13-1.96	0.78	0.57-1.06
MAIS4+	0.72	0.52-0.99	N/A		N/A	
MAIS5+	0.71	0.49-1.02	N/A		N/A	
MAIS6	0.58	0.37-0.90	N/A		N/A	

MAIS = Maximum Abbreviated Injury Scale; Fatalities considered as MAIS = 6; Injuries selected for analyses include the up to 14 injuries with the highest AIS reported from autopsy, hospital, emergency rooms, and medical records; Excludes drivers who died of not crash-related causes. N/A = The effect of airbags did not differ by gender.

[a] Controlling for severity of crash, safety belt use, age, and gender of driver.

Table 3. Severity of Crash Above Which Airbag Deployment Exerts a Net Protective Effect (Adjusted[a] Point Estimates and 95% Confidence Intervals). NASS CDS Calendar Years 1993-1996, Passenger Cars Model Year ≥1986. Frontal and Near-Frontal Crashes with Known Longitudinal Delta V (n=4,697).

	Women & Men		Women		Men	
Outcome	Point Estimate (km/h)	95%CI	Point Estimate (km/h)	95%CI	Point Estimate (km/h)	95%CI
MAISnms	32.8	0-74.8	52.0	0-127.6	12.9	0-53.9
MAIS0-6	36.5	0-85.6	62.2	0-157.8	9.7	0-53.5
ISS	16.6	0-39.2	27.5	0-65.6	5.2	0-30.2
MFCI	25.3	0-58.2	41.1	0-98.8	8.8	0-41.9

MAIS: Maximum Abbreviated Injury Scale [MAISnms categorizes MAIS into no injuries (MAIS 0), "minor injuries (MAIS1-3), and "severe" (MAIS4-6), whereas MAIS0-6 uses each of the AIS levels for severity categorization]; ISS: Injury Severity Score; MFCI: Maximum Functional Capacity Index Score; 95% CI truncated at 0 km/h. Excludes drivers who died of not crash-related causes

[a] Controlling for safety belt use, age, and gender of the driver.

Figures 1a & b. Percent Change in the Probability of Sustaining Injuries by Injury Severity Level (as Defined by MAIS) and Gender in Frontal or Near-Frontal Crashes. NASS CDS Calendar Years 1993-1996, Passenger Cars Model Year ≥1986. Cases with Known Delta V.

N=4,697

Note: MAIS categorized into no injuries (MAIS 0), "minor injuries (MAIS1-3), and "severe" –including fatalities - (MAIS4-6); Controlling for age and seatbelt use; Excludes drivers who died of not crash-related causes.

Figure 1a. Women Drivers

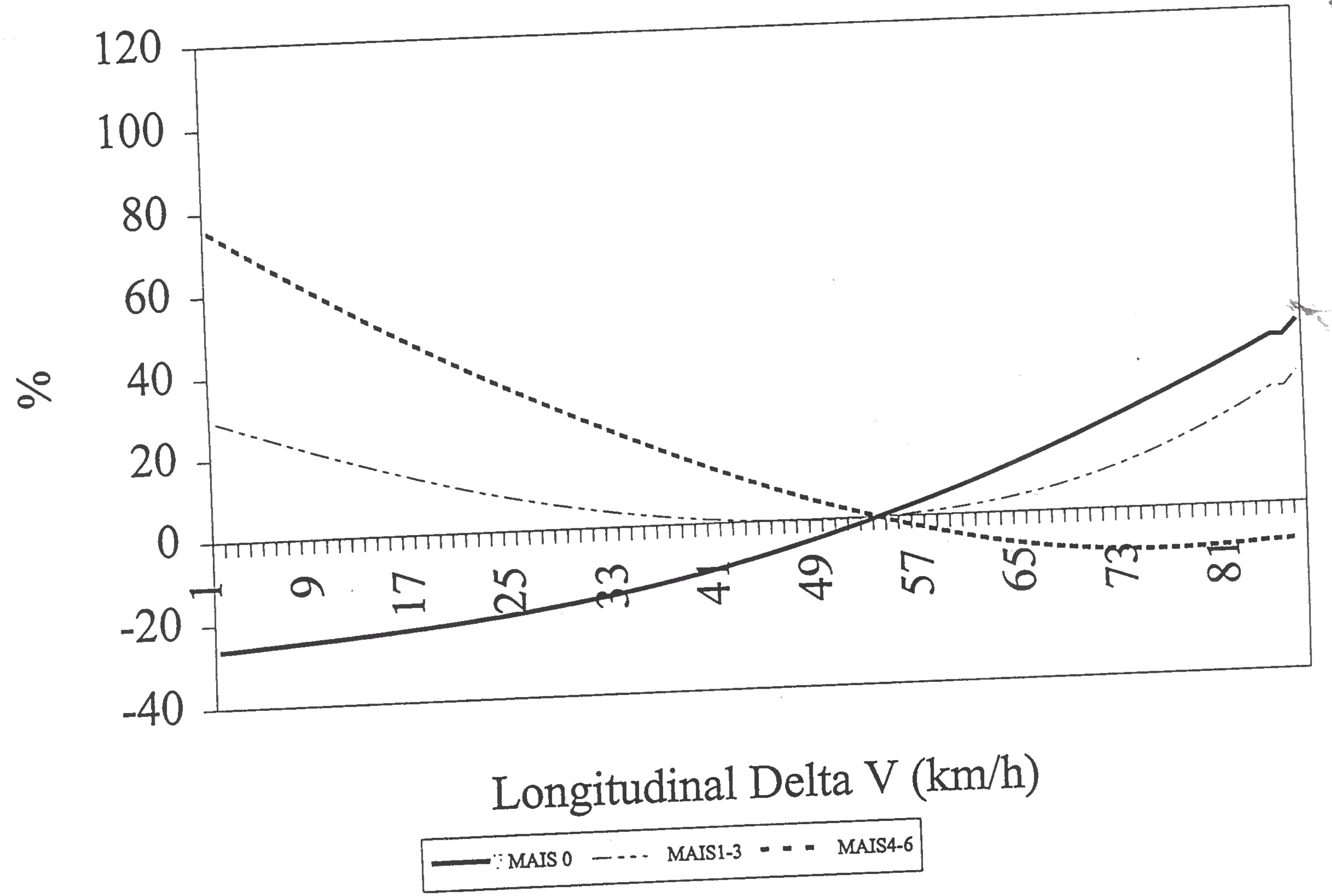
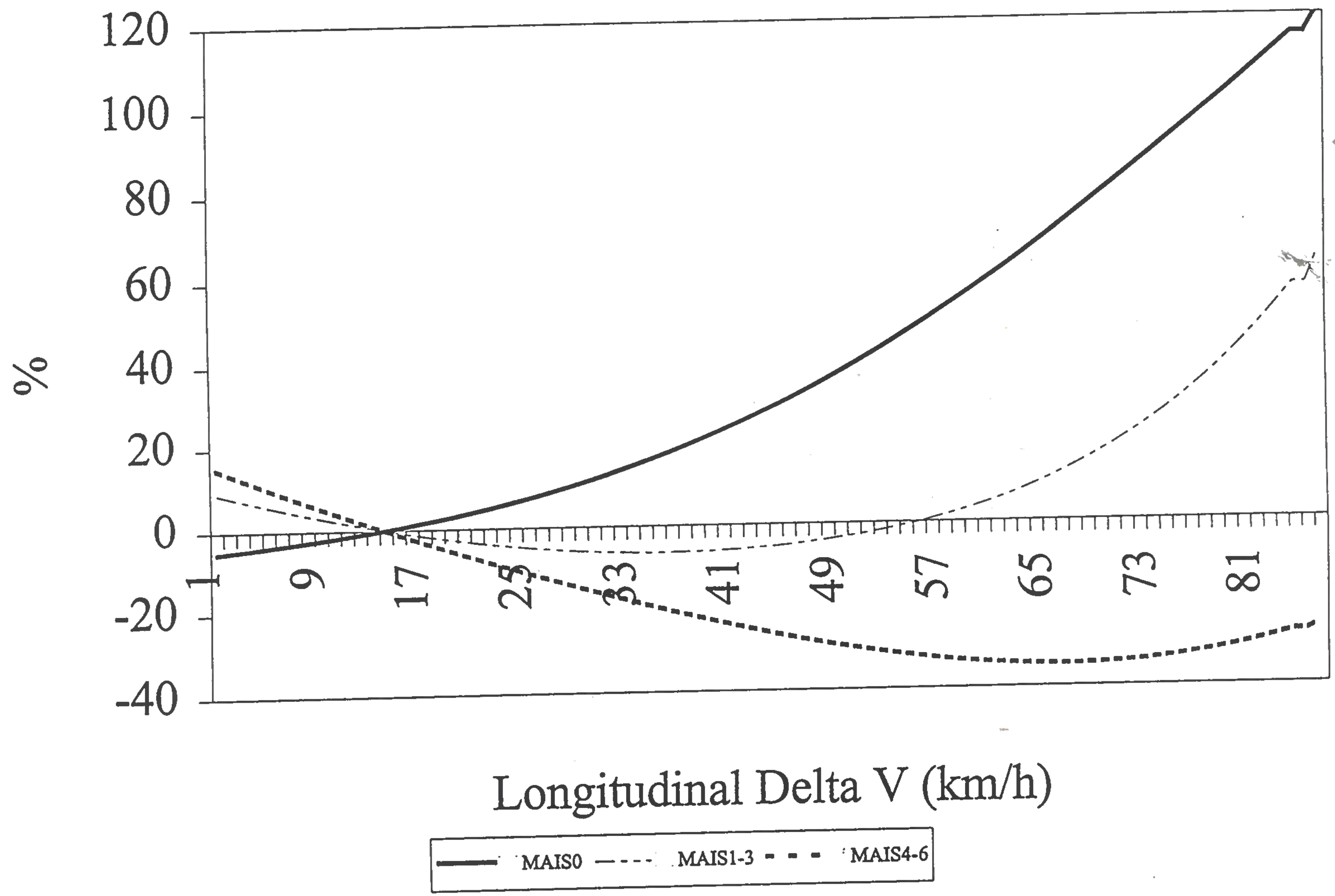


Figure 1b. Men Drivers



Appendix A. Multivariable Regression Models. Adjusted[a] Airbag Deployment-Related Coefficients, Variances and Covariances. NASS CDS Calendar Years 1993-1996, Passenger Cars Model Year ≥1986. Frontal and Near-Frontal Crashes with Known Delta V (n=4,697).

								Airbag Deployment &		Airbag Deployment*
		Airbag Deployment		Airbag Deployment *				Interaction Terms (Airbag Deployment *		Gender &
				Gender		Delta V		Gender)	Delta V)	Airbag Deployment * Delta V
Regression Technique	Dependent Variable	Point Estimate	Variance	Point Estimate	Variance	Point Estimate	Variance	Covariance	Covariance	Covariance
Logistic	MAIS1+	0.43	0.013	-0.48	0.024	N/A	--	-0.013	N/A	N/A
	MAIS2+	0.38	0.014	-0.59	0.030	N/A	--	-0.014	N/A	N/A
	MAIS3+	0.40	0.020	-0.65	0.045	N/A	--	-0.019	N/A	N/A
	MAIS4+	-0.32	0.027	N/A	--	N/A	--	N/A	N/A	N/A
	MAIS5+	-0.35	0.036	N/A	--	N/A	--	N/A	N/A	N/A
	MAIS6	-0.54	0.051	N/A	--	N/A	--	N/A	N/A	N/A
Ordinal	MAISnms	0.56	0.022	-0.47	0.017	-0.01	0.00003	-0.0069	-0.0006	-0.00005
	MAIS0-6	0.58	0.027	-0.44	0.020	-0.01	0.00003	-0.0089	-0.0007	-0.00005
Linear	ISS	2.83	1.220	-2.29	0.955	-0.10	0.0014	-0.423	-0.032	-0.0023
	MFCI	5.32	2.875	-4.18	2.251	-0.13	0.0032	-0.996	-0.075	-0.0055

MAIS: Maximum Abbreviated Injury Scale [MAISnms categorizes MAIS into no injuries (MAIS 0), "minor injuries (MAIS1-3), and "severe" (MAIS4-6), whereas MAIS0-6 uses each of the AIS levels for severity categorization]; ISS: Injury Severity Score; MFCI: Maximum Functional Capacity Index Score. Injuries selected for analyses include the up to 14 injuries with the highest AIS reported from autopsy, hospital, emergency rooms, and medical records. Fatalities considered as MAIS = 6, ISS = 75, and MFCI = 100. Excludes drivers who died of not crash-related causes.

[a] Controlling for longitudinal delta V of crash, safety belt use, age, and gender of driver.

Chapter 3

Using Cost-Effectiveness to Evaluate Alternative Airbag Deployment Levels

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ABSTRACT

Introduction: In designing airbag systems, engineers must decide which crashes are severe enough to warrant airbag deployment. Frontal airbags sold in the U.S. are set to deploy in crashes around 11-26 km/h and above.

Objective: To conduct a cost-effectiveness analysis of alternative deployment settings for driver-side frontal airbag systems, assuming no other changes in vehicle or airbag design.

Methods: We used a deterministic state transition model to track a hypothetical cohort of new vehicles over a 20-year period with airbag systems designed to deploy in crash severities ranging from 85 km/h to 0 km/h. Crash severity was defined by the maximum longitudinal deceleration of the vehicles during the crash. Model outcomes included total lifetime costs (in 1993 U.S. $), quality-adjusted life years (QALYs) gained, and incremental cost-effectiveness ratios. Data were obtained from the National Highway Traffic Safety Administration, automobile manufacturers and insurers.

Results: Deployment levels between ≥34 km/h and ≥26 km/h provided incremental gains in QALYs for incremental costs and could therefore be considered cost-effective options. The incremental cost-effectiveness ratios for these non-dominated strategies ranged from $500/QALY gained (≥34km/h) to $50,000/QALY gained (≥26 km/h). Deployment levels above ≥34 km/h or below <26 km/h were associated with both losses of QALYs and added costs compared to the ≥26-≥34 km/h range.

Conclusions: Depending on the willingness to pay for a QALY, the optimal deployment threshold ranges from 26 km/h to 34 km/h, although this finding is sensitive to plausible estimates of airbag effectiveness that are consistent with available data.

Keywords: Cost-effectiveness, airbag effectiveness

INTRODUCTION

Frontal airbags are a safety device designed to protect occupants involved in frontal or front-angle crashes by providing a "soft" cushion that covers the vehicle's interior surfaces, thereby reducing the likelihood of the driver being injured by hitting the steering wheel. Frontal airbags are intended to complement, not replace, lap and shoulder belts. A typical airbag system consists of three parts: (1) sensors to detect the vehicle's longitudinal deceleration rate (a measure of crash severity); (2) a central unit to monitor the performance of the system, integrate the information from multiple sensors, and decide whether the crash is above the preset deployment level; and (3) the airbag itself. Once the central unit detects a deceleration rate equal or higher than its deployment level, the bag deploys fully within approximately 0.05 seconds. The deployed airbag then begins to deflate immediately after inflation. Once deployed, the bag cannot be reused and requires replacement.[1-2]

The effectiveness of airbags was initially evaluated using fatal crash data and the "double-pair" comparison method.[3] Overall, studies demonstrated that current frontal airbag systems reduce fatal injuries to drivers in frontal crashes by approximately 19%.[4-6] We previously conducted a cost-effectiveness analysis of driver-side frontal airbag systems and found that the addition of a driver-side frontal airbag to standard safety belts had an incremental cost-effectiveness ratio of $24,000 per QALY gained.[7] In that study we assumed that the net airbag effectiveness was a 13% reduction in fatalities and severe injuries in frontal and non-frontal crashes. A limitation of that study was that the impact of airbags on less severe non-fatal injuries was not considered.

Regrettably, airbags also induce fatal and non-fatal injuries. In fact, as of March 1999, airbags had caused the death of at least 52 drivers.[8] The high energy generated for fast deployment has the potential to injure a driver whose hands, arms, chest or face are in the path of the deploying bag.[9-10] The results of government analyses of the effect of airbags on moderate and severe injuries, using real-world crash data and multivariable regression methods, initially showed an overall injurious effect,[11] and later a non-statistically significant 10% protective effect.[6] Other recent estimates suggest that in less severe crashes airbag deployment increases the probability of sustaining minor and moderately severe injuries, particularly among women, whereas in more severe crashes there is a net protective effect for the most severe and fatal injuries.[12]

Fatal and non-fatal airbag-induced injuries have triggered the interest of regulators, manufacturers, researchers, attorneys and the media in the technical design and performance of airbag systems.[13] In response to airbag-induced injuries manufacturers have proposed several modifications to the system. These modifications include: (1) depowering (i.e., airbags deploy with less force);[14] (2) higher deployment levels (i.e., a more severe crash is required for deployment); and/or (3) sensors that detect out-of-position occupants (i.e., prevent airbag deployment when the occupant is too close to the bag). Alternative design issues, for example how large the bag is, its shape, or how it is folded while stored, may impact the effectiveness of the airbag system,[15] but little real-world evidence is available with regard to these specific airbag design features.

The analysis presented here focuses on the *deployment level,* i.e., the choice of deceleration rate, at which the crash is considered severe enough to warrant airbag deployment. Due to the imprecision of currently used crash sensors, airbag systems have a deployment interval or threshold rather than a single deployment level. The higher limit of that interval (referred to as the *deployment always* threshold) is set such that in all crashes above this higher level airbags must deploy. In vehicles sold in the U.S. it is set at approximately 26 km/h. The lower limit of the deployment interval (referred to as the *absolutely no deployment* threshold) is set such that in all crashes of severity below that level airbags will never deploy. In vehicles sold in the U.S. this absolutely no deployment threshold is set at approximately 11 km/h.[16]

The choice of which crash severity is high enough to warrant airbag deployment is a discretionary design choice that implies implicit and important tradeoffs. Consider the extremes: If the deployment level is set very low, airbags will deploy in relatively minor crashes where the probability of crash-related injuries, much less fatal injuries, would be very low. In such low severity crashes airbag deployment may actually induce more injuries than they prevent. Furthermore, deployed airbags will need to be replaced, resulting in additional costs. Alternatively, if the severity of the crash needed for airbag deployment is set very high, airbags will deploy only in the most severe crashes and may not sufficiently protect drivers who may incur nonfatal and fatal injuries that might have been prevented.

In this paper, we use a decision-analytic model to project the costs and consequences resulting from different deployment levels. By explicitly acknowledging the tradeoff between lower and higher deployment thresholds decision makers can use these results to help determine the optimal deployment level consistent with their willingness to pay for a quality-adjusted life year (QALY), sometimes called the "threshold" cost-effectiveness ratio.

METHODS

Analytic Overview

The analysis presented here follows, to the maximum extent feasible, the recommended practices of the Panel on Cost-Effectiveness in Health and Medicine of the U.S. Department of Health and Human Services.[17] The practices recommended by the Panel are a set of methods and assumptions that serve to facilitate the comparison of cost-effectiveness (CE) ratios across interventions. We adopted a societal perspective and incorporated information on all costs, risks, and benefits resulting from airbag deployment, regardless of who incurs them. All changes in resource use due to the implementation of a given intervention are captured in the numerator of the cost-effectiveness ratio and expressed in monetary terms. All long-term health consequences of the intervention (including changes in productivity due to functional limitations) are captured in the denominator and expressed as QALYs.

We developed a deterministic state transition model, based in part on one previously reported,[7] to track a hypothetical fleet of 10 million new passenger cars. The model estimated the net resources associated with the installation, maintenance, and replacement of driver-side frontal airbags, and the health-related costs and changes in QALYs of the drivers involved in crashes for the maximum 20-year period that the passenger cars were expected to last. The number of vehicles in the fleet decreased over time due to scrappage related to normal use and accident-related damage. As in our previous analysis, we assumed that 15%, 50%, 65% and 100% of the vehicles would be scrapped at years 5, 10, 15, and 20 respectively.[18] In addition, if the cost of replacing an airbag approached the residual value of the vehicle, then the deployed airbags were not replaced and the vehicle was assumed to be scrapped. Based on limited experience, the replacement rates for airbags were assumed to be 70% during the first year of the vehicle's life, 59% during year 2, 56% during year 3, 40% during year 4, 21% during year 5, 10% during years 6 through 10, and 0% during years 11 through 20.[7,19]

The incremental costs and health effects of alternative deployment levels were used to evaluate the impact of airbag deployment in progressively less-severe crashes. We assumed that airbags could be set to deploy at any crash severity ranging from ≥85 km/h to ≥0 km/h, in 1 km/h decrements.

For each deployment level evaluated we computed: (1) the number of airbags deployed over 20 years, which required summing the number of airbags deployed each year, which in turn was a function of the number of vehicles in the fleet for that year, the crash rate, and the crash severity distribution; (2) the costs of installing, replacing, and maintaining the airbag systems as well as the changes in medical costs due to injury reduction or induction secondary to deployment; and (3) the changes in health consequences, as measured in QALYs, due to airbag deployment associated with the reduction or induction of fatal and non-fatal injuries. We controlled for inflation by computing constant 1993 U.S. dollars using the Consumer Price Index and accounted for consumer time preference by discounting all costs and consequences at a real rate of 3%. We conducted univariate and multivariate sensitivity analyses on parameter uncertainty.

We assumed that drivers did not disarm their airbags and that driver behavior was not affected by the presence of an airbag (i.e., there were no changes in the crash rate or crash severity distribution due to the presence of an airbag). We also assumed constant crash severity, injury severity distributions, and changes in quality of life across vehicles' and drivers' ages. Finally, we assumed that the gross long-term marginal cost of setting the airbag deployment at any particular level was zero.

Data

Selected values used in the base case and plausible and arbitrary ranges used for sensitivity analysis are presented in Table 1 and Figures 1 and 2.

Injury and crash rate

Rates of fatal and non-fatal injuries among drivers vary by severity of the crash. Figure 1 shows the baseline distribution of injury severity among drivers in frontal crashes* when no airbags were available, based on data from the 1993-1996 National Automotive Sampling System Crashworthiness Data System (NASS CDS). The NASS CDS is a probabilistic sample of U.S. police-reported crashes maintained by the National Highway Traffic Safety Administration in which at least one of the vehicles needed to be towed away from the crash scene. In this dataset the severity of each injury was summarized using the 1990 version of the Abbreviated Injury Severity (AIS) score.[20] The AIS is a commonly used 7-point ordinal scale where 0 indicates no injury, 6 indicates almost fatal or fatal injuries, and 1 to 5 indicates progressively more life-threatening injuries.

We categorized drivers according to their maximum AIS score across all injuries sustained: MAIS 0 (no injury), MAIS 1-3 (minor, moderate, and serious injuries), and MAIS 4-6 (severe, critical, and fatal injuries). Since the only injury cost estimates available in the literature refer to injuries coded using the 1985 version of the AIS,[21] we adjusted the baseline injury severity distribution to reflect this version of the scale.[7,22]

In the NASS CDS data, crash severity is indicated by the longitudinal component of the deceleration rate of the most severe impact that the vehicle suffered, referred to as "longitudinal delta V." Federal crash investigators, using a computerized algorithm based on vehicle deformation,[23] calculate this deceleration rate in order to express the maximum velocity (an integer in km/h) at which the vehicle crashed. The cumulative distribution of crash severity for frontal crashes is shown in Figure 2.

Costs

Driver-side airbag installation, maintenance, and replacement costs were estimated to be $278, $25, and $664, respectively. The average present value of lifetime injury-related costs included the medical costs (including pre-hospital and rehabilitation) as well as the legal and insurance administrative costs.[21] These have been estimated by NHTSA to be $87 for MAIS 0, $4,160 for MAIS 1-3, and $146,302 for MAIS 4-6 (Table 1).

Effectiveness of airbags

Airbag effectiveness was defined as the percent change in the probability of sustaining a particular level of injury in a frontal crash when an airbag deployed compared to the probability of sustaining that same level of injury in the absence of airbag deployment.[12] Figure 3 shows the predicted reduction (or increase) and the 95% confidence intervals (CIs) in the probabilities that a driver sustained no injury (MAIS 0) or that his/her most severe injury was of levels MAIS 1-3 or MAIS 4-6 by severity of the crash. For example, airbag deployment in crashes with a longitudinal delta V of 17 km/h increased the probability of a driver sustaining a MAIS 4-6 injury by 17% (95%CI 13%-21%) when compared to no airbag deployment. In contrast, airbag deployment in crashes at 67 km/h

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• Frontal crashes are defined as crashes in the 10 o'clock-2 o'clock range using the diagram adopted decreased the probability of a driver sustaining such injury by 21% (95%CI 15%-29%) when compared to no airbag deployment. Overall, in crashes with longitudinal deceleration rates below 33 km/h, airbag deployment increased the probability that drivers would sustain injuries, whereas in crashes with deceleration rates above 33 km/h airbag deployment decreased the probability that drivers would sustain any injuries (including the most severe and fatal injuries). Thus, 33 km/h represents the MAIS "turn over" severity of the crash. Below this "turn over" point airbag deployment has a net injurious effect, and above it airbag deployment has a net protective effect.

Quality of life

Changes in quality of life due to the prevention or inducement of fatal and non-fatal injuries resulting from airbag deployment were quantified using the Functional Capacity Index (FCI) score. The FCI incorporates rating-scale preferences that reflect the quality of life associated with reduced capacity to perform daily activities after sustaining particular injuries lasting at least one year after the crash.[24] The scores used in this analysis range from 0.0 (total loss of function or death) to 1.0 (no functional loss or perfect health). We derived the maximum FCI (or MFCI) of each driver using a computerized algorithm which mapped all his or her injuries as described in the NASS CDS using the AIS scores into their corresponding FCI value and then choosing the score reflecting the greatest functional limitation (M. Waltz, NCSA, NHTSA personal communication). The airbag's average impact on the driver's quality of life is shown in

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by the National Highway Traffic Safety Administration to classify direction of impact [6] (Appendix A)

Figure 4.[12] Airbag deployment in crashes with longitudinal deceleration rates below 25 km/h induced net losses in the driver's quality of life whereas deployment in crashes above 25 km/h resulted in net gains in quality of life. Thus, 25 km/h represents the MFCI "turn over" crash severity. For example, in crashes at 17 km/h airbag deployment induced a loss of 0.01 QALY per year in a 0 to 1 scale (95%CI 0.002-0.02) when compared to no airbag deployment, whereas in crashes at 35 km/h airbag deployment increased by 0.01 QALY per year (95% CI 0.006-0.02).

Changes in quality of life as reflected in changes in the MFCI score were added over the average remaining years that drivers were anticipated to live after the crash and discounted back to the year when the crash occurred. The QALYs gained (or lost) per driver were then multiplied by the total number of drivers who suffered a crash with airbag deployment in any particular year. The discounted QALYs gained (or lost) during the 20-year life of the hypothetical fleet were further discounted to compute the present value of QALYs at the beginning of our cohort's life.

The average remaining life expectancy per driver used in the above calculations (or "pre-crash" life expectancy) represented the average quality-adjusted remaining life expectancy. This "pre-crash" life expectancy was computed using the driver's age distribution as indicated in the NASS CDS data, their remaining life expectancy according to the U.S. Life Tables,[25] and the age-adjusted quality-of-life weights reported in the Beaver Dam Health Outcomes Study.[26] These population-based quality-of-life weights were 1.0 per each year of life lived below age 45, 0.92 for years lived between the ages of 45 and 54, 0.87 for years lived between 55 and 64, 0.84 for years between 65 and 74, 0.82 for years between 75 and 84, and 0.81 for each year lived thereafter. This computation rendered an average of 44.3 remaining quality-adjusted life years per driver "pre-crash" or prior to his/her involvement in a frontal crash (Table 1).

RESULTS

Base Case

Costs

Changes in expected costs associated with different deployment levels are shown in Figure 5. The higher the severity of the crash required to allow airbag deployment (i.e., the higher the deployment level is set), the fewer airbags actually deploy and fewer cars are scrapped because of the airbag replacement cost, allowing more cars to reach their 10th year of life when maintenance service is due.[27] Thus, maintenance costs increase when airbags are set to deploy only in more severe crashes. For example, if airbags were to deploy in all crashes (because deployment thresholds were set above 0 km/h), maintenance costs would be $62 million, whereas if airbags were set to deploy only in crashes at or above 50 km/h, maintenance costs would be $79 million.

The lower the severity of the crash required to allow airbag deployment (i.e., the lower the deployment level is set), the more airbags actually deploy, resulting in high airbag replacement costs. For example, when airbags deploy in all crashes, replacement costs amount to approximately $777 million, whereas if airbags deploy only in crashes equal to or more severe than 50 km/h, the replacement costs are approximately $6 million.

With a low deployment level, the net health effect resulting from airbag deployment is an increase in total injuries, accompanied by increased total health-related costs. For example, when airbags deploy in all crashes net health-related costs approximate $2.7 billion. As the deployment level is raised, injury-related costs decrease. For example, when airbags are set to deploy in crashes at or above 24 km/h the net effect on health costs is approximately $350,000 in savings, compared to no airbag deployment. This occurs because the number of injuries prevented by airbag deployment in crashes at or above 33 km/h exceeds the number of airbag-induced injuries that occur in crashes between 24 and 33 km/h. When airbags are set to deploy in crashes at or above 33 km/h, the health-related savings peak at $332 million. At deployment levels higher than 33 km/h, the magnitude of savings decrease, since fewer injuries are prevented. When airbags are set to deploy only in crashes at or above 85 km/h the savings reach their nadir at $600,000.

Quality-adjusted life years

Quality-adjusted life years are gained if and only if the deployment level is set at or above ≥18 km/h. The lower the deployment level below 18 km/h, the greater the net total loss of QALYs (Figure 6). At the extreme, when airbags deploy in all crashes, there is a net loss of 720,000 QALYs when compared to no airbag deployment. In contrast, at deployment levels equal to or higher than 18 km/h, airbag deployment has a net positive impact on total QALYs gained. This occurs because the quality of life gains that occur when airbags deploy in crashes at or above 25 km/h exceed the quality of life lost in crashes between 18 and 25 km/h. The gain in QALYs is maximized when deployment levels are set at or above 26 km/h. If airbags are set to deploy in crashes at or above 26 km/h, 147,000 QALYs are gained, when compared to no airbag deployment.

Incremental cost-effectiveness ratios

Strategies using deployment levels between ≥85km/h and ≥35 km/h were associated with both gains in incremental QALYs and cost savings compared to higher deployment levels. Therefore, all deployment levels above ≥35km/h were dominated and could be eliminated as cost-effective options. For example, a deployment level at or above 35 km/h dominated a deployment level at or above 36 km/h since it provided an incremental gain of 7,000 QALYs and saved an additional $3.0 million. Deployment levels from ≥34 km/h through ≥26 km/h provided incremental gains in QALYs for incremental costs. The incremental cost-effectiveness ratios for these non-dominated strategies ranged from $500/QALY gained (≥34km/h) to $50,000/QALY gained (≥26 km/h) (Table 2). Deployment levels below 26 km/h were associated with an incremental loss of QALYs and incremental costs when compared to the next prior deployment level, and were thus eliminated by dominance.

Sensitivity Analysis

Results were most sensitive to changes in the airbag effectiveness on quality of life (as measured by the MFCI) and to changes in the severity of the crash at which airbags had net protective effects regarding MAIS and MFCI (i.e., the "turn over" points). Results were less sensitive to univariate and multivariate changes in crash rates, discount rates, airbag costs, injury costs and airbag effectiveness on MAIS. (Table 3.)

Using the upper or lower 95% CI airbag effectiveness estimates for MFCI was associated with "non-dominated" deployment levels between ≥ 21km/h and ≥ 34 km/h (compared to ≥26 km/h - ≥34km/h in the base case). Multivariate sensitivity analysis using the upper or lower 95% CI airbag effectiveness estimates for MAIS and MFCI generated similar "non-dominated" deployment levels between ≥21 and ≥36 km/h. Using the upper or lower 95% CI or upper or lower 70% CI (i.e., ± 1 standard deviation) of the "turn over" crash severities, below which airbag deployment had a net negative impact on MAIS and/or MFCI, radically changed the range of "non-dominated" deployment levels as well as the incremental cost-effectiveness ratios. For example, setting the "turn over" points for MAIS and MFCI two standard deviations below their base case value (i.e., lower 95%CI) resulted in "non-dominated" deployment levels between ≥2 and ≥12 km/h. Setting the "turn over" points two standard deviations above their base case value (i.e., higher 95%CI) was associated into "non-dominated" deployment levels between ≥59 and ≥75 km/h.

We conducted an analysis for a "best case" and "worst case" with the parameters shown in Table 3. In the "best case" scenario, all deployment setting were associated with a quality of life gains and non-dominated deployment levels ranged from ≥17 to ≥32 km/h. In the "worst case" scenario, the non-dominated deployment levels ranged from ≥30 to ≥39 km/h.

Finally, we evaluated the impact of assuming that MAIS 1, MAIS ≤2, or MAIS ≤3 injuries were not associated with quality of life decrements. The range of non-dominated deployment levels widened from ≥26-≥34 km/h to ≥17km/h ($34,000/QALY) to ≥34 km/h ($160/QALY).

DISCUSSION

The base case results of our analysis indicate that airbag deployment in passenger cars provided a net protective effect on the driver's quality of life only when the crash severity equaled or exceeded a longitudinal deceleration rate of 18 km/h, when compared to no airbag deployment. "Non-dominated" deployment levels ranged from ≥26 to ≥34 km/h, which are above the deployment levels reported by manufacturers. However, the sensitivity analyses indicate that this conclusion is not robust with respect to changes in the effectiveness inputs or changes in the impact of less serious injuries on quality of life. Neither of these uncertainties are likely to be clarified in the foreseeable future and yet airbag design decisions are being made. Under these circumstances, we recommend that airbag suppliers and vehicle manufacturers give serious consideration to raising the airbag deployment levels. Airbags in model years prior to 1997 were reportedly set to deploy in crashes above 11 km/h. However, according to real world crash data, approximately 10% of airbag deployments occurred in crashes with estimated longitudinal delta Vs below 11 km/h.

Changing the deployment level such that airbags deploy only in crashes at or above 18km/h would prevent airbag deployment in 48% of frontal crashes. Raising the deployment level to crashes at or above 26 km/h would further eliminate airbag deployment in an additional 35% of frontal crashes. Finally, setting deployment levels at ≥34 km/h would eliminate deployment in an additional 10% of frontal crashes, allowing airbags to deploy only in the 7% of crashes that are the most severe crashes.

In choosing the actual deployment level, engineers may be advised to consider the following factors. First, the incremental cost-effectiveness ratio of the chosen deployment level should be equal to or less than the chosen maximum willingness to pay per QALY; second, the chosen level should reflect the fact that current crash sensing technology does not allow for reliable discrimination of crash severities within approximately 3 km/h.[28] In our base case analysis and over the range of non-dominated deployment settings, the incremental CE ratios were below or equal to $50,000 per QALY gained. From among these alternative strategies, one would choose a deployment level based on the willingness to pay for a QALY or the cost-effectiveness ratio threshold

(Table 3). However, given the low reliability of sensors, engineers may want to choose a slightly higher deployment level to avoid the possibility of airbag deployment in lower severity crashes where either the incremental cost-effectiveness ratio exceeds that of the chosen willingness to pay or in which airbag deployment is associated with an incremental loss is QALYs. Yet, liability concerns are also likely to influence these decisions.

There are several limitations to be aware of resulting from the use of the FCI as a method to generate injury-specific QALY values. First, the FCI ignores impairments and utility losses of injuries that resolve before one-year post injury. Second, the current scale measures "predicted" changes in the quality of life. A validation study currently underway may change the values and result in different airbag effectiveness estimates. Third, the specific elicitation technique used in the development of the scale to derive preferences, the so-called "rating scale," may have driven the utility weights to be too low for minor injuries.[29] Finally, the FCI-preference values were elicited from middle-aged adults (our study applies the scale to all drivers), and during the elicitation of the preference values no effort was made to include descriptions of the emotional, psychological, psycho-social or productivity-related consequences of the injuries. Despite these limitations, the FCI constitutes the only injury-specific quality of life measure available and when compared to other preference-based scores, is a relatively sophisticated and well-developed scale.[30]

Due to the lack of reliable real-world data suggesting alternative values, we also made several simplifying assumptions. We assumed that the crash severity distribution was constant throughout the life of the vehicles. We further presumed that crash severity and injury severity distributions were constant over the age distribution of drivers. Also, in our sensitivity analysis we considered only the role of parameter uncertainty in airbag effectiveness. We did not evaluate alternative estimates of airbag effectiveness by severity of the crash nor did we explore the potential impact of measurement error or model uncertainty on our cost-effectiveness ratios. Finally, readers should be cautioned against presuming that the incremental CE ratios reported here are valid for newly designed airbags. Our analysis relied on airbag effectiveness estimates derived from airbags in passenger cars model year 1986 through 1997. We did not incorporate other changes in airbag design or vehicle regulation which have taken place since 1997 (e.g., depowering of the systems). Reliable and valid data on the performance of these designs may be available in several years, at which point this analysis should be repeated.

To the best of our knowledge, the research summarized here is the first application of cost-effectiveness techniques to the assessment of the optimal airbag deployment level. It constitutes one of the few examples of cost-effectiveness methodology applied to the field of injury control that follows the recommendations by the U.S. Panel in Cost-Effectiveness in Medicine of the U.S. Department of Health and Human Services.[31-32] The results of this analysis provide information which can assist decision makers (e.g., regulators, motor vehicle manufacturers, and airbag suppliers) in choosing an optimal deployment level given the resources available.[33] This should prove particularly helpful since several vehicle manufacturers have already indicated that they intend to raise airbag deployment levels (M. Finkelstein, personal communication).

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Table 1. Base Case Values and Plausible Ranges Used in Sensitivity Analysis.

Selected Variables		Base Case	Plausible Range	References
Cohort size		10,000,000	N/A	--
Crash rate (%)		3.4	2.4-4.4⁺	34
Airbag replacement rate (%)		y1 70, y2 59, y3 56, y4 40, y5 21, y6-10 10, y11-20 0	N/A	18
Discount Rate (%)		3	0,5,7	--
Driver age (%)	<45 years old	75.7	N/A	NASS CDS 1993-1996
	45-54 "	10.5	"	"
	55-64 "	5.8	"	"
	65-74 "	5.1	"	"
	75-84 "	2.4	"	"
	85+ "	0.5		"
Quality-adjusted life-years (undiscounted), "pre-crash"		44.3	"	", 25,26
Airbag costs ($)	Installation	278	236-319⁺	19
	Maintenance	25	0-50	
	Replacement	664	240-1,800⁺	"
Lifetime average Injury costs ($)	MAIS 0	87	31-113⁺	21
	MAIS 1-3	4,160	2,912-5,408⁺	"
	MAIS 4-6	146,302	102,411-190,193⁺	"

⁺ Reflects changes by 30% in base case values.
MAIS = Maximum Abbreviated Injury Severity. Costs are in 1993 U.S.$. See methods section for vehicle survival data, and population-based age-specific quality of life. See Figure 1 for baseline injury severity rates and Figures 2a and 2b for airbag effectiveness estimates. Driver's age distribution based on NASS CDS 1993-1996 passenger cars model year ≥1986 with known longitudinal delta V.

Table 2. Base Case Results.

Deployment level	Net Cost (1993 U.S.)	Net Effectiveness	Incremental Cost	Incremental Effectiveness	Incremental CE ratio
km/h	Billion $	Thousand QALYs	Million $	Thousand QALYs	$ per QALY
≥ 18	4.032	11	---	---	dominated
≥ 19	3.895	38	---	---	dominated
≥ 20	3.697	71	---	---	dominated
≥ 21	3.516	94	---	---	dominated
≥ 22	3.324	116	---	---	dominated
≥ 23	3.160	132	---	---	dominated
≥ 24	3.042	140	---	---	dominated
≥ 25	2.915	145	---	---	dominated
≥ 26	2.808	147	82	2	50,000
≥ 27	2.726	145	35	2	19,000
≥ 28	2.691	143	39	5	8,000
≥ 29	2.652	138	21	3	6,000
≥ 30	2.631	135	19	4	5,000
≥ 31	2.612	131	15	5	3,000
≥ 32	2.597	125	14	9	1,000
≥ 33	2.583	116	5	5	900
≥ 34	2.578	111	6	12	500
≥ 35	2.572	99	*	*	*

QALY = Quality-Adjusted Life Years; Costs are in 1993 U.S.$; Numbers Rounded. (*) The deployment level of ≥35 km/h dominates all higher deployment levels, i.e., has lower cost and saves more QALYs.

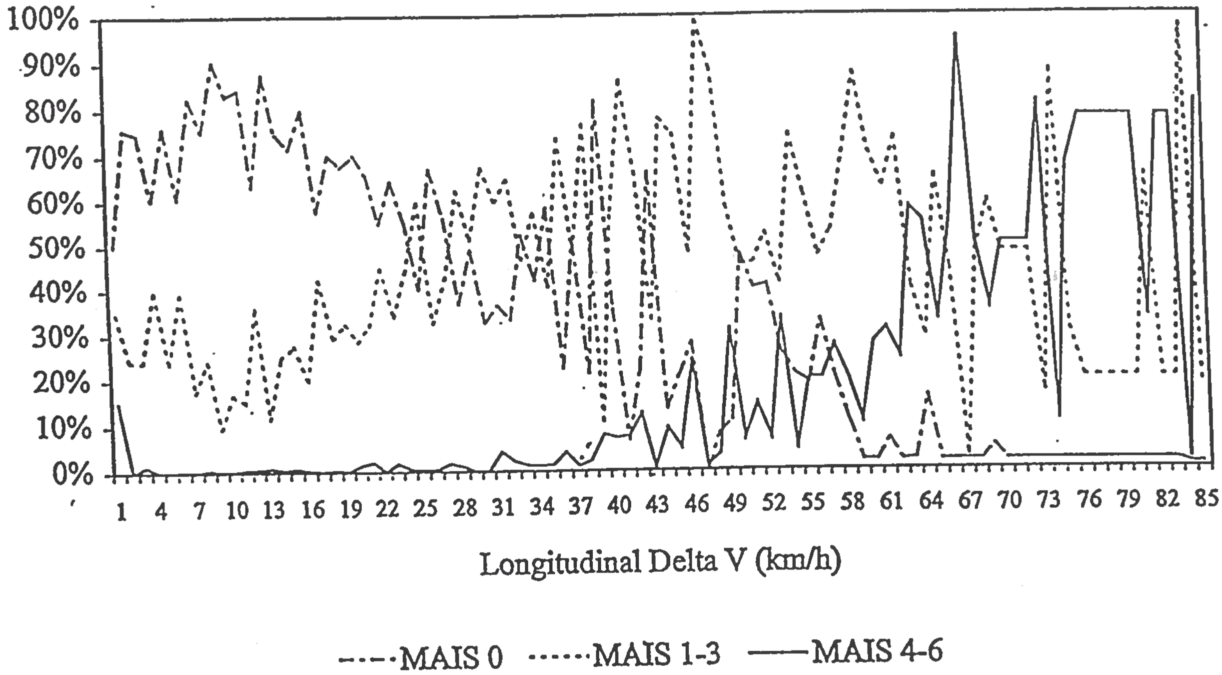
Table 3. Sensitivity Analysis. Range of Non-Dominated Deployment Levels and Choice of Deployment Level (≥ km/h) by Willingness to Pay.

		Non-Dominated deployment levels	Preferred Deployment Level Assuming Willingness to Pay Equal to ($/QALY)			
	Values Used*	Km/h	20,000	50,000	100,000	250,000
Base Case		26-34	27	26	26	26
Costs-related inputs						
I) Airbag-related						
Installation	+30%	26-34	27	26	26	26
	-30%	"	27	26	26	26
Maintenance	$50	"	27	26	26	26
	$0	"	27	27	26	26
Replacement	+30%	26-38	28	27	26	26
	-30%	26-33	27	26	26	26
All airbag costs	+30%	26-38	28	27	26	26
	-30%	26-33	27	26	26	26
II) Health-related						
MAIS 0	+30%	26-34	27	26	26	26
	-30%	"	27	26	26	26
MAIS 1-3	+30%	"	27	27	26	26
	-30%	"	27	26	26	26
MAIS4-6	+30%	"	28	27	26	26
	-30%	26-36	27	26	26	26
All MAIS costs	+30%	26-34	28	27	26	26
	-30%	26-36	27	26	26	26
Airbag effectiveness on:						
MAIS 0	-2 sd.	26-34	27	27	26	26
	+2 sd.	"	27	26	26	26
MAIS 1-3	-2 sd.	"	27	27	26	26
	+2 sd.	"	27	26	26	26
MAIS 4-6	-2 sd.	"	27	26	26	26
	+2 sd.	26-36	28	27	26	26
MAIS 0-6	-2 sd.	26-34	27	26	26	26
	+2 sd.	26-36	28	27	26	26
All costs	+30%	"	28	27	26	26
	-30%	26-34	27	26	26	26
Quality of life-related						
MFCI	-2 sd.	21-34	23	22	22	21
	+2 sd.	30-34	31	30	30	30
MFCI	W/o MAIS ≤1	26-34	27	26	26	26

W/o MAIS ≤2		20-34	22	21	21	20
W/o MAIS ≤3		17-34	18	17	17	17
Cost- and Quality of life-related						
Discount rate	0%	26-34	27	26	26	26
	5%	"	28	27	26	26
	7%	"	28	27	26	26
Crash Rate	+30%	"	27	27	26	26
	-30%	"	27	26	26	26
MAIS0-6 & MFCI	-2 sd.	21-34	23	22	22	21
	+2 sd.	30-36	31	31	30	30
MAIS & MFCI turn over points:						
	-2 sd.	2-12	2	2	2	2
	-1 sd.	11-15	11	11	11	11
	+1 sd.	43-54	46	44	44	43
	+2 sd.	59-75	67	64	61	60
Best Case**		17-32	18	17	17	17
Worst Case***		30-39	33	31	31	30

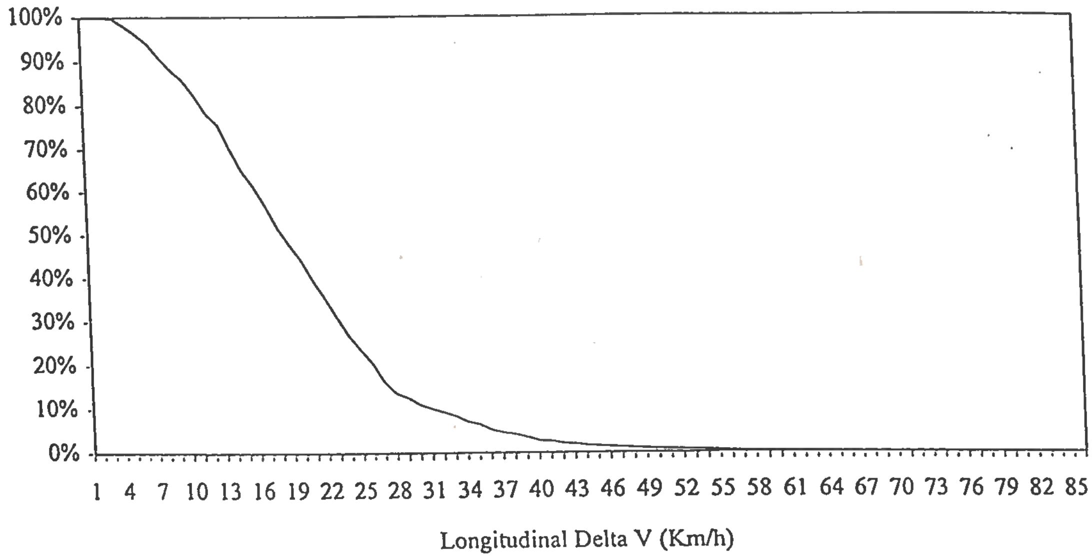
(*) Values used were arbitrarily chosen to be either ±30% or ±2 or ±1 standard deviations (sd) from the base case value (unless otherwise indicated). (**) Best scenario input values included interest rate 0%, crash rate +30%, airbag costs –30%, injury costs +30%, airbag effectiveness on MAIS0 in its higher 95%CI, airbag effectiveness on MAIS1-6 in its lowest 95%CI, and MFCI w/o MAIS≤3. (***) Worst scenario input values included interest rate 7%, crash rate -30%, airbag costs +30%, injury costs -30%, airbag effectiveness on MAIS0 in its lowest 95%CI, airbag effectiveness on MAIS1-6 in its highest 95%CI, and MFCI upper 95%CI. QALY = Quality-Adjusted Life Years; MAIS = Maximum Abbreviated Injury Scale (MAIS 0 = no injury; MAIS 1-3 = minor, moderate, and serious injuries; MAIS 4-6 = severe, critical, and fatal injuries); MFCI = Maximum Functional Capacity Index; W/o = without.

Figure 1. Baseline Driver Injury Severity by Severity of the Crash.



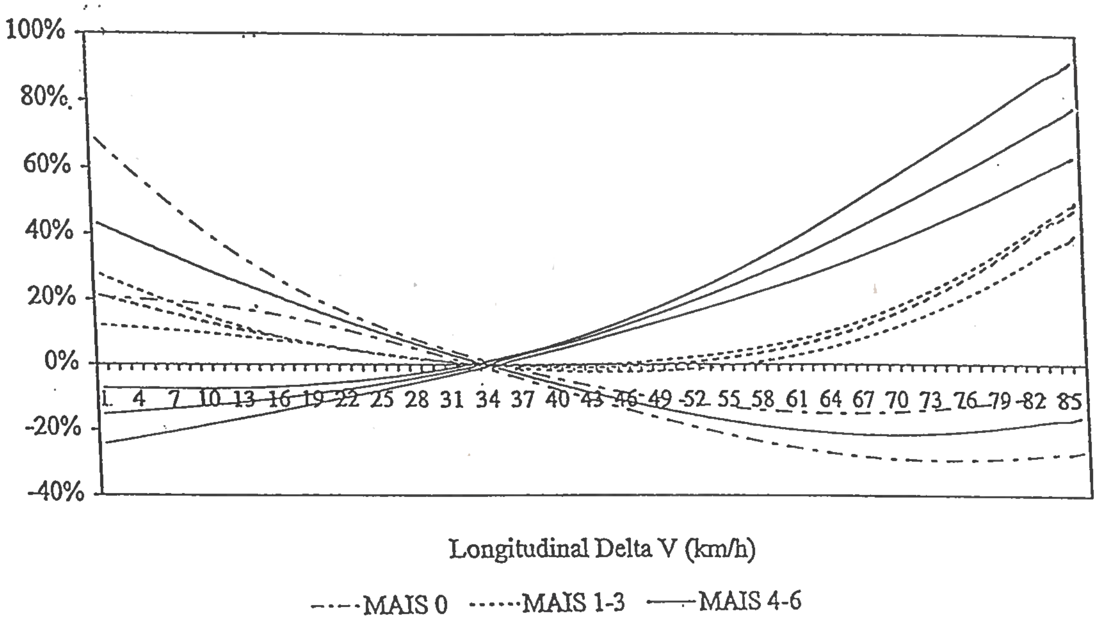
MAIS = maximum Abbreviated Injury Severity; MAIS 0 = no injury; MAIS 1-3 = minor, moderate, and serious injuries; MAIS 4-6 = severe, critical, and fatal injuries. (AIS version 1990.) Source: NASS CDS 1993-1996 drivers in passenger cars model year ≥1986 in frontal crashes with known longitudinal delta V (N = 2,138,892)

Figure 2. Crash Severity Distribution



Source: National Accident Sampling System Crashworthiness Data System 1993-1996 drivers of passenger cars model year ≥1986 in frontal crashes with known longitudinal delta V (N = 2,138,892)

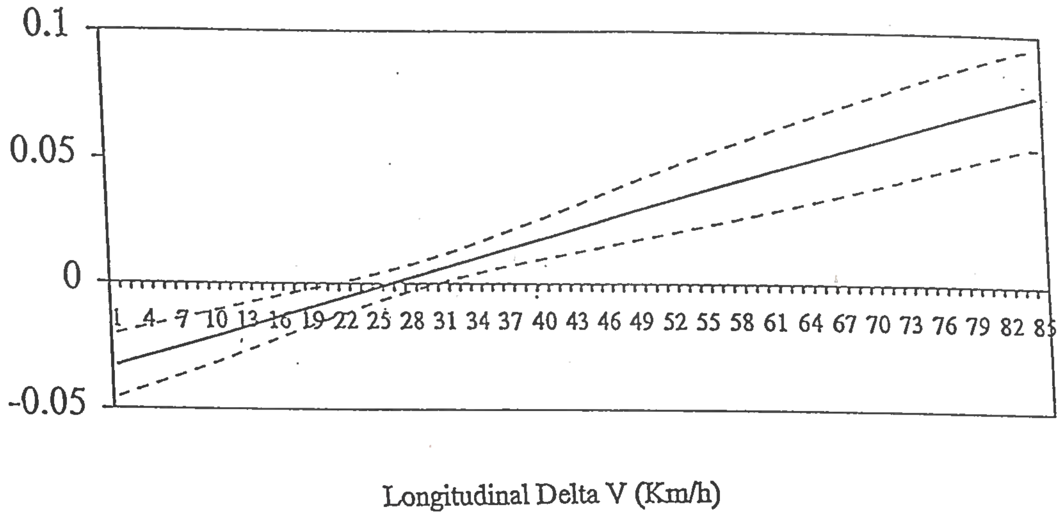
Figure 3. Predicted Percent Change in MAIS (mean and ± 2 standard deviations) due to Airbag Deployment by Severity of Crash.



The "turn over" severity of crash above which net airbag effect is protective regarding MAIS is 33 km/h (standard deviation 21 km/h). The effectiveness of airbag deployment at each severity of crash was computed compared to no airbag deployment.

MAIS = maximum Abbreviated Injury Severity; MAIS 0 = no injury; MAIS 1-3 = minor, moderate, and serious injuries; MAIS 4-6 = severe, critical, and fatal injuries. (AIS version 1990.) Source: Segui-Gomez, under review

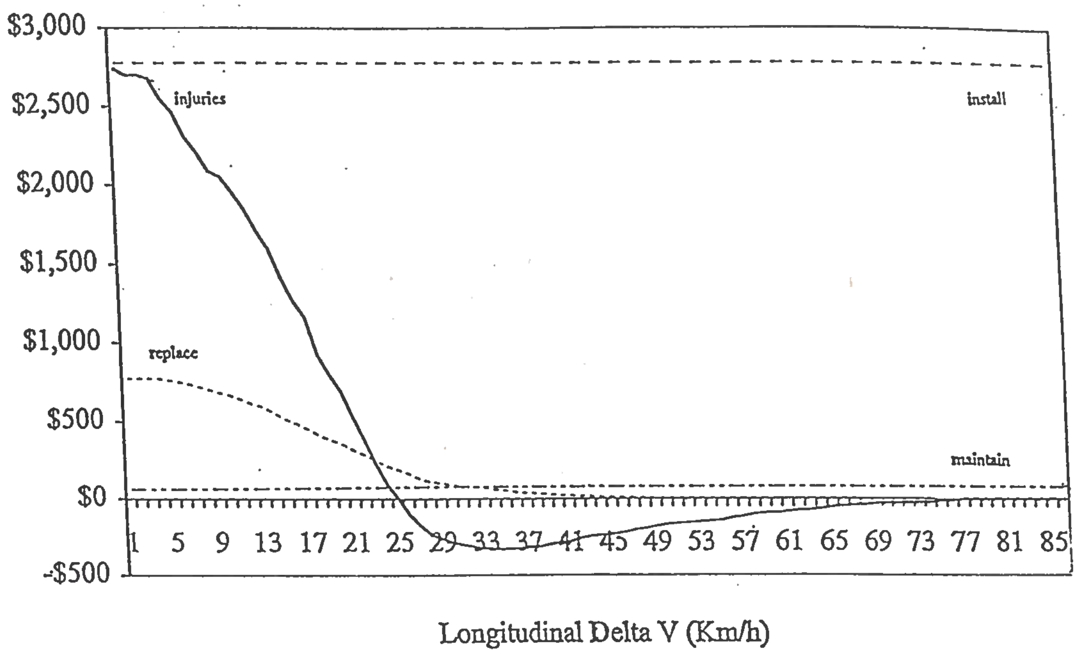
Figure 4. Predicted Changes in MFCI (mean and ± 2 standard deviations) due to Airbag Deployment by Severity of Crash.



The "turn over" severity of crash above which net airbag effect is protective regarding MFCI is 25 km/h (standard deviation 17 km/h). The effectiveness of airbag deployment at each severity of crash was computed compared to no airbag deployment.

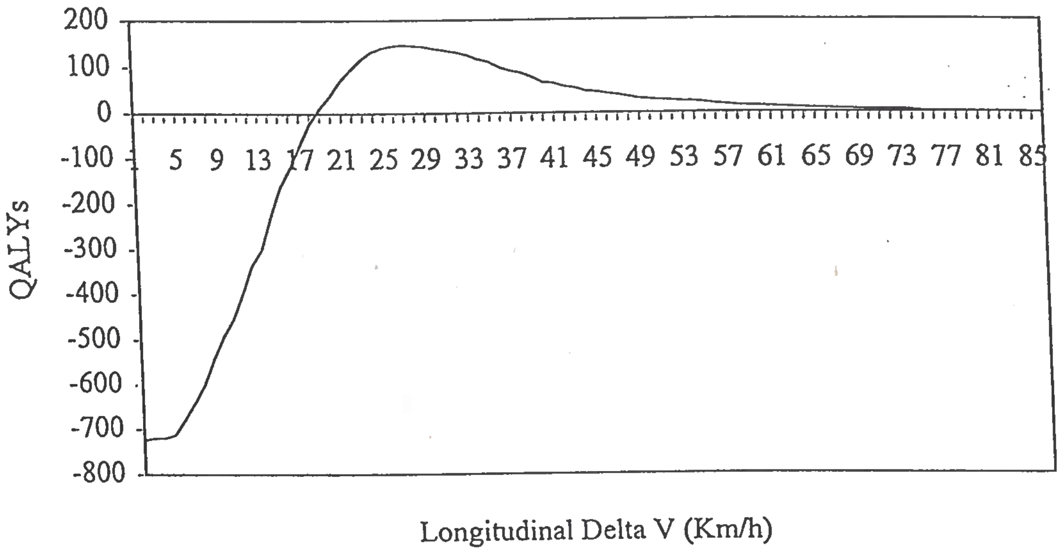
MFCI = maximum Functional Capacity Index. FCI ranges from 0.0 –death- to 1.0-perfect health. Source: Segui-Gomez, Under Review

Figure 5. Discounted Net Installation, Maintenance, Replacement, and Health-related Costs by Deployment Level (1993 Million U.S.$).



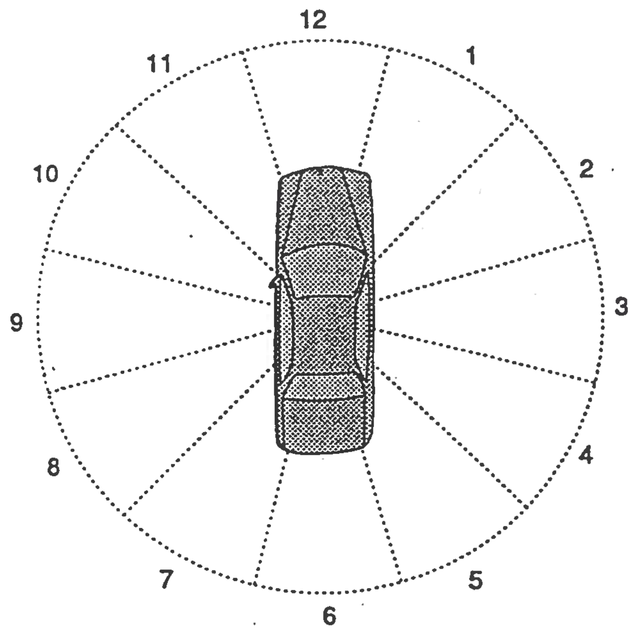
Notes: Each deployment level compared to no airbag deployment. Maintenance costs only occur if car lives through its 10th year of life.

Figure 6. Discounted Net Quality-Adjusted Life Years by Deployment Level (in Thousands).



Note: Each deployment level compared to no airbag deployment.

Appendix A. Categorization of Direction of Impact.



Source: National Highway Traffic Safety Administration