The Blue Ribbon Panel for the Evaluation of Advanced Technology Airbags

An overview of Frontal Airbag Performance with Changes in Frontal Crash-Test Requirements: Findings of the Blue Ribbon Panel for the Evaluation of Advanced Technology Airbags

Susan A. Ferguson, Ph.D.

Ferguson International LLC

Lawrence W. Schneider, Ph.D.

University of Michigan Traffic Research Institute

Contact: **Susan A. Ferguson, Ph.D.**

Ferguson International LLC

1328 Lancia Drive

McLean, VA 22102, USA

fergsusan@gmail.com

703-847-5317

ABSTRACT

Objective In the mid 1990s evidence emerged that airbag deployments could result in deaths to vulnerable vehicle occupants who were very close to airbag modules when they deployed. In 1997, federal frontal crash test requirements were modified to allow crash testing with unbelted dummies to be performed using sled tests. As a result, vehicle manufacturers were able to redesign airbags to deploy with less force and energy, thereby reducing the toll of airbag-induced deaths. However, there was concern that depowered airbags may not provide the same level of protection to unbelted occupants in severe frontal crashes, particularly occupants of large stature and body mass. This paper provides a summary of recent studies addressing this issue.

Methods To expedite the accrual of data regarding airbag performance, the collection of additional crash data was funded by the Alliance of Automobile Manufacturers. A panel of experts was commissioned to oversee the process and evaluate the data. During the past 6 years, a series of studies has been undertaken by panel members and others to evaluate the performance of redesigned airbags and the data are summarized here.

Results There is now convincing evidence that the combination of airbag redesign and public education have resulted in dramatic reductions in airbag-induced infant and child deaths. In addition, the frontal crash fatality risks among children sitting in front seats have been reduced by as much as half, with younger children showing the greatest benefits. Among adult drivers and right-front passengers, there is no evidence for the predicted overall loss of protection with sled-certified airbags and there are far fewer airbag-induced deaths among this population. However, despite exhaustive analyses of frontal-crash data, the possibility of a somewhat elevated fatality risk among a subset of unbelted drivers in sled-certified 1998-99 model vehicles cannot be ruled out. There also is some evidence that the risks of serious chest injury may be higher among unbelted drivers in frontal crashes in sled-certified vehicles with redesigned airbags. Further research is warranted to determine whether these differences remain in newer model vehicles designed to the advanced airbag rule which took effect in 2003.

INTRODUCTION

Frontal airbags were first seriously considered as a protective device in the United States in the late 1960s in response to the very low seat belt use rates among motor vehicle occupants (O'Neill, 2006). At that time frontal airbags were seen by many as an alternative to seat belts – a passive restraint technology that could protect people in frontal crashes without any actions from the vehicle occupants. Frontal airbags were first included as original equipment in about ten thousand General Motors cars in the mid 1970s but, when other manufacturers did not follow suit, it was recognized that more widespread use would require government regulation. A highly contentious debate ensued that culminated many years later in a congressional mandate to require driver and passenger frontal airbags in all passenger vehicles by September 1998 (O'Neill, 2006). However, by the early to mid 1990s the marketplace was already getting ahead of regulation with airbags being touted by some manufacturers as a "must have" safety feature (O'Neill, 2006).

With the growing number of vehicles with frontal airbags in the fleet by the mid 1990s, evaluations of their effectiveness in frontal crashes confirmed their lifesaving benefits (Braver et al., 1997; Ferguson et al., 1995; Lund and Ferguson, 1995; National Highway Traffic Safety Administration (NHTSA), 1997; Zador and Ciccone, 1993). However, it also was becoming apparent that both driver and passenger airbags were causing serious and fatal injuries in low-severity crashes -- crashes in which only minor or no injuries would be expected from the crash itself (Ferguson, 1996; Ferguson, 1998). The results of NHTSA's in-depth Special Crash Investigations determined that many of these deaths involved young children in right-front passenger seats who were very close to the airbag module at the time of deployment. In many cases, this was because they were unbelted or improperly belted and had moved close to the airbag, primarily as a result of pre-impact braking (Kleinberger et al., 1997). Also at high risk were infants in rear-facing restraints being transported in front seats, such that the backs of the restraints were very close to, or against, the airbag modules when they deployed (Ferguson, 1998; Kleinberger et al., 1997). Small, female drivers who sat close to the steering wheel also were at risk of airbag-deployment injuries to the chest and neck (see Kahane, 2006).

As a result of these rare but serious side effects of airbags, a national education campaign funded by the NHTSA, automakers, and insurers, was launched in October 1995 to publicize the dangers to children riding in the front seats of vehicles equipped with passenger airbags, and to advise parents to place them in back seats. Drivers were advised to sit at least ten inches from the steering wheel. Letters were sent to existing owners of vehicles equipped with frontal airbags with instructions to affix labels to the dashboards or sun visors of their vehicles to warn of the dangers of being too close to deploying airbags. Permanent airbag warning labels also were required in all new vehicles.

Concern about the increasing number of airbag-induced deaths prompted a call for changes to the regulations governing airbag performance, particularly regarding the conditions used for crash testing with unbelted dummies, which were believed to be largely responsible for the injury potential of deploying airbags. In 1997, NHTSA amended its requirements for frontal crash performance under Federal Motor Vehicle Safety Standard (FMVSS) 208 to temporarily allow use of a 30 mph (48 kph) sled test with unbelted dummies as an alternative to the 30 mph head-on rigid-barrier vehicle tests. This was considered an interim step as NHTSA considered more comprehensive changes to the standard. Vehicles with frontal airbags tested to this interim rule are hereafter referred to as sled-certified vehicles; vehicles tested prior to this time are referred to as first-generation barrier-certified or just barrier-certified vehicles. Because the 30 mph sled deceleration pulse had a more gradual or slower rise to peak deceleration (i.e., was “softer”) than the 30 mph barrier crash pulse of most vehicles, automakers were able to reduce airbag inflation rates and thereby reduce the likelihood of airbag-deployment injuries to occupants who were close to airbag modules when they deployed.

According to Kahane (2006), 84 percent of 1998 model year vehicles sold in the U.S. were “depowered” as a result of this interim rule. Peak tank-inflation pressure was 16 percent lower and average pressure rise rate was reduced by about 30 percent. Other airbag design changes incorporated during the next few years included reductions in airbag volume and reductions in rearward deployment distance through the use of tethering. Other changes included driver airbags that were recessed below the steering-wheel rim, improved folding techniques that reduced airbag fabric deployment speeds, and a shift from pyrotechnic inflators to hybrids including stored gas (Hinch et al., 2001; Kahane, 2006).

In 2001, NHTSA issued the advanced airbag final rule which took effect in September 2003. The purpose of this much more demanding set of test requirements was to make airbags safer for out-of-position occupants while increasing their lifesaving benefits. In addition to expanding high-speed rigid barrier crash tests to include the 5th percentile (small) female dummy, the new rule included requirements to minimize harm to people close to airbags when they deployed by mandating out-of-position airbag deployment tests using crash dummies representing children and small females. Additionally, the 30 mph sled test or 30 mph rigid-barrier test with unbelted crash dummies was replaced by a 25 mph (40 kph) rigid-barrier test. The aim of the lower speed for tests with unbelted dummies was to continue to allow airbags to deploy with less energy than airbags produced before the 1997 interim rule.

Frontal airbags have always been viewed outside of the U.S. as supplemental restraints, and it is now widely agreed in the U.S. that frontal-impact airbags are most effective when used together with seat belts (Kahane, 2006, O'Neill, 2006). With this approach, manufacturers have been able to optimize seat-belt performance using belt load limiters so that seat-belt forces on the chest in high-speed crashes can be reduced. Also, reflecting the need to optimize protection for belt-restrained occupants, the top speed for the FMVSS 208 barrier tests with belt-restrained midsize-male dummies was recently increased from 30 mph to 35 mph (NHTSA, 2001).

NHTSA's initial decision to allow a 30 mph sled test and subsequently to require rigid-barrier testing with unbelted dummies at 25 mph instead of 30 mph met with considerable controversy (NHTSA, 1997; Public Citizen, 2003). When issuing the advanced airbag rules, NHTSA expressed concern that sled-certified airbags would provide insufficient protection for heavier unbelted occupants in higher speed frontal crashes (NHTSA, 2001) and estimated that as many as 1,500 lives could be lost as a result (NHTSA, 1997).

Prior to the publication of the final advanced airbag rule in 2003, organizations including the American Automobile Association, the American Trauma Association, the Governors Highway Safety Association, the Insurance Institute for Highway Safety, the National Safety Council, and the National Transportation Safety Board argued that lowering the unbelted-dummy rigid-barrier test speed to 25 mph would reduce airbag-induced injury risks without decreasing the protection afforded by frontal airbags. This was based on real-world evidence of how drivers were dying in frontal crashes (Cammisa et al., 2000; Lund et al., 1996; Zuby et al., 2001). The researchers found no evidence that people were dying because airbags were insufficiently protective; that is there was no evidence that unbelted drivers were overpowering the airbags and sustaining fatal injuries from steering wheels or instrument panels. There were, however, a number of deaths in high-speed crashes that were judged to have been caused by airbag-deployment forces rather than the crash energy. Taken together, these findings suggested that a reduction in deployment energy might reduce the incidence of airbag-related deaths without compromising protection in high-speed crashes.

With new regulations and test methods in place, there were concerns about the long lag time before real-world data would be available to indicate the benefits or negative consequences of the new rules. To expedite data collection and the ability to monitor airbag performance in new vehicles as promptly as possible, the above named organizations sent a letter to the Secretary of Transportation recommending that the automobile industry commit to funding additional data collection and establish a panel of experts to oversee the process and evaluate the data (http://brpadvancedairbags.org/wp-content/uploads/misc/ntsb_joint_letter.pdf). In response, the Alliance of Automobile Manufacturers (the Alliance) committed to funding a three-year program of data collection with a focus on frontal crashes to be managed by an independent third party. A panel of experts was established as the Blue Ribbon Panel (BRP) for the Evaluation of Advanced Technology Airbags.

After deliberation, the BRP decided that the Alliance-funded study should utilize the existing National Automotive Sampling System/Crashworthiness Data System program (NASS/CDS) and investigations of frontal crashes began at three new NASS sites in April of 2002. Procedures for these separate sites were consistent with the other NASS/CDS sites, including procedures for quality control, so that the cases could be incorporated into the NASS/CDS database. These additional cases, amounting to about 350-400 frontal crash investigations per year, accelerated the pace at which information on the frontal crash performance of vehicles equipped with depowered and advanced airbag systems was amassed.

Since the inception of the BRP, a number of studies have been undertaken to determine whether the protection afforded by frontal airbags has been affected by the changes in frontal crash test requirements. These studies have focused on three basic questions: 1) Are vehicles equipped with depowered/redesigned and advanced airbag systems as effective as vehicles equipped with first-generation airbags in reducing overall injury and death in frontal crashes? 2) Are these newer vehicles offering reduced protection in higher severity crashes, particularly for unbelted occupants? 3) Is the incidence of airbag-induced injuries and fatalities to children and other vulnerable occupants reduced in vehicles with depowered and advanced airbags, particularly in low-speed frontal impacts? Most studies have addressed the first question but some have also looked at airbag performance among more vulnerable occupants, including the elderly, small women, and children.

Braver et al. (2005) compared frontal-crash deaths per registered vehicle in a matched set of pre-1998 and 1998 and newer model vehicles (with the same essential designs or platforms) and found no evidence of reduced protection for drivers in cars, minivans, and SUVs with the redesigned airbags. However, the authors reported an increased risk of death among pickup truck drivers. Olsen et al. (2006) estimated frontal airbag effectiveness among front-seat occupants for pre-1998 cars and for 1998 and newer cars. They used matched-pair cohort analyses to control for potential differences in vehicle and crash characteristics, and Poisson regression models to control for other confounding factors. They found that, across all crash types, death rates both in pre-1998 models cars and 1998 and newer model cars were about 10 percent lower than in cars without airbags. Thus, their results showed that there was no loss of overall protection among front-seat occupants in 1998 and newer cars for all crashes combined. Because frontal airbags are designed to protect occupants in frontal crashes, Olsen et al. looked specifically at this sub group of crashes. Frontal crash performance was no different for cars with frontal airbags in 1998 and newer model cars compared with pre-1998 models.

Olsen et al. also found that the risk of death for younger front-seat occupants six years and younger) in pre-1998 model cars with frontal airbags was higher than for the same age occupants in cars without airbags. However, the risk was not elevated for children in the front seats of 1998 and newer model cars.

Arbogast et al. (2003) examined injury risk to children in frontal crashes in pre-1998 vehicles with frontal airbags versus 1998 and newer vehicles. Using a database of insurance company-reported crashes the authors reported much lower airbag deployment rates for 1998 and newer model vehicles, with the exception of SUVs. Furthermore, the risk of serious injury to children in the right-front seats of newer model vehicles in which airbags had deployed was 41 percent lower than in the pre-1998 vehicles.

While overseeing the collection of additional data on frontal crashes of 1998 and later model-year vehicles at the three new NASS PSUs, the BRP hosted three public meetings in 2003, 2004, and 2007 in which the latest information concerning frontal airbag performance was presented. Analyses utilized data from a wide range of sources including NHTSA’s Special Crash Investigation (SCI) program, the Fatality Analysis Reporting System (FARS), NASS/CDS, the

University of Michigan Transportation Research Institute database of in-depth crash investigations, the William Lehman Injury Research Center Crash Injury Research and Engineering Network program, and the Partners for Child Passenger Safety, Children's Hospital of Philadelphia data. In a paper summarizing the 2004 BRP meeting, Ferguson (2004) concluded that the combination of consumer education and redesigned airbag systems in 1998 and newer vehicles had dramatically reduced the harm to out-of-position occupants. At the same time, there was no evidence that frontal crash protection in higher severity crashes had been reduced.

The purpose of this paper is to provide a summary of the most recent analyses regarding the frontal-crash performance of vehicles equipped with depowered and advanced airbag systems in comparison to that of vehicles equipped with first-generation airbags. Several of the studies reported here (Braver et al., 2007, 2008 and Bahouth et al. 2007) were proposed by the BRP and funded by the Alliance. The results of these studies were presented at the final public meeting of the BRP convened in May, 2007.

When interpreting the results of these studies, it should be noted that other restraint system and vehicle design changes were being implemented by manufacturers around the same time that airbags were being redesigned to meet the sled-test requirements. For example, seat-belt load limiters and pretensioners, and a myriad of changes to the airbag module, were beginning to be implemented in vehicles in about model year 1998. Because of concurrent changes in seat-belt and airbag design, other changes in vehicle crashworthiness, and the fact that manufacturers began implementing advanced airbag features such as dual or multi-level inflators and automatic airbag suppression systems before the advanced airbag rule was in place, it generally has not been possible to separate out the effects of these technologies from the effects of airbag deployment due to changes in rulemaking.

RESULTS

Driver Airbag Performance

Airbag-induced driver deaths -- SCI Data The purpose of the NHTSA's SCI program is to examine the safety effects of new, emerging, and rapidly changing vehicle technologies (such as airbags) and to explore alleged or potential vehicle safety defects. SCI cases are not chosen through any statistical sampling and cannot, therefore, provide a complete picture of airbag system performance or occupant injury risk. However, they are useful for examining special crash circumstances or outcomes. Because SCI investigations are undertaken and reported in a timely manner, they can provide evidence of newly emerging problems such as airbag-induced injuries..

Recent data from NHTSA's SCI program indicate that airbag-induced driver deaths in low-speed crashes are down substantially from previous levels (Chidester, 2007). Airbag-induced driver fatalities per 100-million registered vehicle years declined from 80 during 1990-91 to 1 during 2002-03. This decline is thought to be due to several factors, including changes in airbag system designs, such as depowering, and to increased seat-belt use and changes in behavior (e.g., sitting farther away from the steering wheel) due to public information about airbag-inflation injury risk (Chidester, 2007; Kahane, 2006).

Kahane (2006) examined the separate contributions of these factors to reductions in airbag-induced SCI death rates. To estimate the effects of airbag redesign as a result of sled-certification testing with unbelted crash dummies, he compared SCI driver fatality rates per registered vehicle for 1995 and older model-year vehicles that were not sled certified, with fatality rates for sled-certified vehicles in the same calendar years (1998-2003). By comparing these two vehicle groups in the same calendar years, Kahane assumed that any changes in driver behavior during that period would be similar for both groups. To estimate the effects of behavioral changes, vehicles that were not sled certified (MY 1989-94) were examined over a number of calendar year periods (1990-94, 1995-97, 1998-2003). A change in fatality rates across calendar years in the same set of vehicles could be due to a change in behavior, such as sitting farther away from the steering wheel or increased belt use. Airbag redesign was estimated to have reduced SCI airbag-induced fatality rates by 70 percent and behavioral changes were estimated to have reduced fatality rates by 62 percent.

Changes in Risk of Driver Death: Analyses of FARS data Several recent studies have examined the effects of redesigned airbags on drivers' overall fatality risk in frontal crashes. As previously noted, there are many potential confounding factors to consider when evaluating the independent effects of airbag redesign on passenger vehicle crashes. When comparing the fatal crash rates of drivers in sled-certified vehicles with redesigned frontal airbags and vehicles with first-generation airbags, there may be differences in vehicle crashworthiness features and designs as well as vehicle age, driver gender and age distributions, and in where and how much the vehicles are driven. Outcomes also can be affected by calendar year differences in for example, seat-belt use rates, speed limits, rates of alcohol-impaired driving, and changes in annual vehicle mileage due to economic conditions. Researchers have controlled for these factors using different approaches.

After controlling to the extent possible for other vehicle design changes by using a matched set of vehicles, Kahane (2006) used the induced exposure, or case-control method to control for other potential confounding factors. The total number of fatal crashes in which frontal airbags are expected to be effective (frontals) are divided by the total of crashes where frontal airbag technology is expected to have no effect (non-frontals). This rate ratio is derived for both sets of vehicles and compared. The basic premise is that the fatality risk for control crashes will vary with changes in vehicle miles traveled, driver characteristics, and numbers of vehicles on the road, among other factors. However, fatality risk in these non-frontal control crashes should be unaffected by the presence of frontal airbags. A separate set of analyses controlled directly for driver exposure by comparing the fatality risks in frontal crashes per registered vehicle for matched sets of barrier- and sled-certified vehicles.

Barrier-certified vehicles included in the analyses were up to three model years before sled testing was allowed; sled-certified vehicles included the model year in which sled certification began plus the two following model years. For example, if a vehicle model was sled-certified starting in 1998, barrier-certified model years would include 1995-97 and sled certified would include 1998-2000 model years. Kahane compared vehicles that were sled-certified (whether or not the airbag was redesigned) with a matched set of barrier-certified vehicles, matching on make/models, eliminating vehicles with dual-stage airbags, and including only vehicles that were homogeneous with regard to safety features such as seat-belt pretensioners, side airbags, and electronic stability control. No attempt was made to control for model-year effects, but the range of model years was small.

Regardless of the analysis methodology used, Kahane found that the overall fatality risk of drivers in frontal crashes was essentially no different in sled-certified vehicles than in barrier-certified vehicles. A second set of analyses, including only the vehicles for which it was known that airbag depowering had occurred provided similar results. Additional stratified analyses to examine fatality risk by driver belt use, gender, and age were conducted using the induced-exposure, frontal/non-frontal methodology. The fatality risk for belted drivers was found to be 5 percent lower in sled-certified vehicles, and that of unbelted drivers was 5 percent higher, but neither difference was statistically significant. There was, however, a statistically significant interaction between belt use, sled certification, and the probability that a crash is frontal, suggesting that the effect of sled certification is different for belted than unbelted drivers. There was little interaction of driver age with airbag type, but somewhat lower protection was seen in vehicles with sled-certified airbags among female drivers, shorter drivers (less than 5’3”), and lighter drivers (125 pounds or less) as well as tall drivers (over 6’), although none of these differences was statistically significant.

When examining frontal crashes with unbelted drivers separately, these differences tended to be larger. In particular, small unbelted drivers (less than 125 pounds) were 25 percent more likely to die in sled-certified vehicles. The reason for this is unclear, but this finding does not support the concern that unbelted drivers would be “overpowering” sled-certified airbags since that problem should be more evident for taller and heavier drivers.

Braver et al. (2008a) looked at changes in driver fatality risk in vehicles with barrier- and sled-certified airbags by comparing deaths per police-reported crash as a control for exposure. The authors included a wider range of model years than Kahane for both barrier-certified (MYs 1994-97) and sled-certified vehicles (MYs 1998-2004) and also tried to examine model-year effects by analyzing different model-year groupings. The authors (Braver et al., 2008b) also conducted matched-pair cohort analyses to control for potential differences in vehicle and crash characteristics, and used Poisson regression models to control for other confounding factors such as vehicle type, driver age, belt use, and car size. They compared fatality rates in two-vehicle head-on crashes resulting in death to at least one driver. The pairs consisted of head-on collisions between a barrier- and a sled-certified vehicle.

From their first analysis examining frontal crash deaths per crash, Braver et al. reported that drivers in sled-certified vehicles were 11 percent less likely to die in frontal crashes than drivers in barrier-certified vehicles; however, this difference was not statistically significant. Estimates of fatality rates by driver age were suggestive of a larger reduction for drivers younger than 75 than among drivers 75 and older, but these differences also were not statistically significant. Driver death rates in sled-certified vehicles were lower than those for barrier-certified vehicles for all vehicle types. There were indications that drivers of newer-model sled-certified vehicles (2002-04) had a lower risk of death than for early model sled-certified vehicles (18 percent lower for 2002-04 MY vehicles vs. 2 percent for 1998-99 MY vehicles), but this difference was not statistically significant. The only difference that reached statistical significance was the reduction in driver fatality rates for 2002-04 sled-certified vehicles compared to barrier-certified vehicles.

In the matched-pair study, Braver et al (2008b) compared driver death rates in sled- versus barrier-certified vehicles when both vehicle types were involved in the same head-on crash and at least one driver died. Conditional Poisson regression analyses were used to calculate risk ratios while adjusting for driver and vehicle factors. Adjusted risk ratios for all passenger vehicles combined indicated that drivers in sled-certified vehicles were 13 percent less likely to die than those in barrier-certified vehicles. In contrast to Kahane's findings, there was no significant interaction between belt use and airbag generation, suggesting no differential effects among belted and unbelted drivers. However, there was an interaction between sled-certification and vehicle type. This was due to a significantly lower death rate for drivers in sled-certified pickup trucks than in pickups certified to the barrier test. Separate analyses examining death rates for car-to-car collisions revealed no difference in adjusted driver death rates for these barrier-certified and sled-certified passenger cars.

In summary, research conducted using a wide range of different methodologies has failed to find an overall increase in risk of driver death in frontal crashes in sled- versus earlier model barrier-certified vehicles. In fact, Braver et al. (2008a,b) reported a reduced risk of driver death ranging from 11-13 percent. This reduction was significant when the authors used a matched-pair cohort design in which the mortality outcome from crashes involving both a barrier-certified and a sled-certified vehicle were compared. Braver et al. used a wider range of vehicle years than Kahane and there was some limited evidence that drivers of newer model sled-certified vehicles have a lower risk of death compared to drivers of older sled-certified vehicles. Effectiveness did not appear to change as a function of driver age, although Braver found a tendency for older drivers in sled-certified vehicles to have a higher risk ratio than younger drivers (i.e., less reduction in risk for older drivers in sled-certified vehicles). However, the risk of death still was lower relative to barrier-certified vehicles.

Kahane found little change in frontal crash protection for either belted or unbelted drivers as a group but he did find elevated risks among some other subsets of drivers, especially smaller drivers. However, these findings do not support the predicted concern for reduced airbag protection because of occupants overpowering airbags. This is because injury risk for depowered airbags should increase primarily for larger, heavier, unbelted occupants if the airbags failed to absorb sufficient crash energy. There was some indication (though estimates were not significant) that taller unbelted occupants might be less well protected by sled-certified airbags, particularly when considering car drivers. However, heavier occupants did not seem to be disadvantaged. Furthermore, in the matched-pair analyses Braver et al. failed to find different effects for belted and unbelted drivers.

Changes in risk of driver injury: Analyses of NASS/CDS data Bahouth et al. (2007) examined changes in injury risk in non-fatal and fatal crashes of barrier-certified and sled-certified vehicles using the NASS/CDS database. This database contains detailed data on a nationally representative sample of tow-away crashes with oversampling of recent model vehicles (less than 5 years old) and more severe injury crashes. The data can be weighted based on the probability of sampling to provide national estimates of injury and fatality risk. Information is collected by crash investigators on crash circumstances, including pre-crash maneuvers and scene information, such as other involved vehicles or objects. Vehicles are examined to provide information on vehicle crush and intrusion of components into the occupant space, and evidence of occupant interior contacts, airbag deployment, and belt use. Also provided is detailed information on occupant injuries and sources of those injuries.

Data from 1994-2005 model vehicles in frontal crashes occurring during the period 1997-2005 were included in the analyses. The authors used logistic regression techniques to compute odds ratios (ORs) of the likelihood of being injured in frontal crashes (excluding crashes with a subsequent rollover) comparing results for barrier-certified and sled-certified vehicles. ORs for drivers and right-front passengers were computed separately. Cases were weighted to represent national numbers, but cases with exceptionally high case weights (>3,272) were excluded to reduce the potential bias from possible outliers. Injury in NASS/CDS is coded according to the

Abbreviated Injury Severity (AIS) coding system. Injury severities range from 1 to 6, with 1 representing minor injuries and 6 representing injuries that are not currently treatable. Injury risks were calculated for three injury groups; Maximum Injury Severity (MAIS) 1, MAIS 2 or higher, and MAIS 3 and higher, and for different body regions. The analyses were stratified by seat-belt use and low versus medium/high crash severities. Analyses were not conducted if fewer than 30 cases were available for these comparisons. Additional confounding factors controlled for included occupant age, gender, occupants' height and weight, vehicle body type, occupant compartment intrusion, and multiple impact events.

Among belted drivers of sled-certified vehicles, for all crash severities combined, the risk of sustaining an MAIS 1 injury was 22 percent lower, the risk of an MAIS 2+ injury was 14 percent lower and an MAIS 3+ injury 3 percent lower than in barrier-certified vehicles. However, only the MAIS 1 difference was statistically significant. When stratified by low-versus medium/high crash severity, results were similar.

Among unbelted drivers, for all crash severities combined, injury risks were elevated by about 20 percent for MAIS 2+ and MAIS 3+ injuries. However, neither result was statistically significant. When broken out by crash-severity category, injury risks were not elevated at low crash severities but were elevated at medium/high crash severities in sled-certified vehicles. The higher risks ranged from 13 to 66 percent but these differences were not statistically significant.

Driver injury risk also was examined separately for six body regions: head, face, chest, abdomen, upper and lower extremities. Many comparisons were not possible because of small sample sizes and in many cases when analyses were conducted it was often not possible to reach statistical significance. The odds of sustaining upper and lower limb injuries (AIS 1+ and AIS 2+) generally were lower in sled-certified vehicles regardless of belt use or crash severity, although many of these differences was not significant. There was a non-significant increase in the risk of lower-limb injury among unbelted drivers at higher crash severities. Generally, the risk of AIS 2+

abdominal injuries was lower in sled-certified vehicles regardless of belt use or crash severity, but none of these differences was statistically significant.

At low crash severities, the risks of head injury among belted and unbelted drivers were lower in sled certified vehicles, but differences were not statistically significant. At medium/high crash severities, there were indications that the risk of AIS 2+ head injuries may be elevated in sled-certified vehicles although again estimates were not significant. The estimated risk of AIS 1+ facial injury tended to be lower among belted drivers and higher among unbelted drivers in sled-certified vehicles, but none of the differences was statistically significant.

When chest injuries were examined, the risk of sustaining AIS2+ injuries was elevated in sled-certified vehicles, especially at higher crash severities, but only among unbelted drivers in the medium/high crash-severity category did the increase in injury risk reach statistical significance. In this instance the odds of sustaining an AIS 2+ chest injury was found to be twice as high among unbelted drivers in sled-certified vehicles as those in barrier-certified vehicles.

To summarize the analyses by Bahouth et al., overall injury risk does not seem to be compromised among belted drivers in sled-certified vehicles regardless of crash severity. However, among unbelted drivers there are indications that overall injury risks may be slightly elevated ay higher crash severities, though the estimates did not approach statistical significance. When examining body regions separately, small sample sizes often precluded significant findings. The risks of drivers sustaining lower or upper extremity injuries generally were lower in sled-certified vehicles, as was the incidence of minor facial injuries among belted drivers. However, the risks of minor facial injuries appeared elevated among unbelted drivers. Of greatest concern is the finding that AIS 2 and higher chest injury was found to be twice as high among unbelted drivers in higher severity crashes.

Passenger airbag performance

Right-front passenger airbag-induced deaths -- SCI Cases: Children Airbag-induced fatalities involving children and infants have decreased substantially since they were first noted in the early 1990s, especially in 1998 and newer vehicles. As of December 2007, the SCI program has not yet identified an airbag-induced fatality or life-threatening injury to a child or infant in a low-severity crash of a vehicle certified to the advanced passenger-airbag test requirements that became effective in September 2003. Airbag-induced child fatalities per 100 million registered vehicle years declined from 80 during 1996-97 to an extremely low rate in 2006-07 (Chidester, 2007). The airbag-induced death rates among children in sled-certified vehicles were lower in all calendar year groupings compared with passenger airbag vehicles certified to the rigid-barrier unbelted-dummy test. These reductions are believed to be due both to educational programs aimed at getting children in rear seats and to changes in passenger airbag designs and deployment characteristics. NHTSA researchers analyzed the seating position of child passengers who were in police-reported crashes (using crash data from Florida, Maryland, and Utah) and found far fewer children sitting in the front seat in 2001 compared to 1995. Among children 0-3 years, only 8 percent were seated in the front in 2001 compared to 26 percent in 1995; among 4-7 year-olds rates fell from 33 percent in the front seat in 1995 to 19 percent in 2001 (Kindelberger et al., 2003).

Using SCI cases for which it was determined that the passenger airbag was responsible for the child deaths, Kahane (2006) examined the effects of airbag design changes on child fatality rates among first generation, barrier-certified and sled-certified vehicles in the same calendar years (1998-2003), as well as the effects of behavioral changes by looking at rates among the same model year vehicles (barrier-certified) across different calendar years (1990-97, 1998-2003). He estimated that behavioral changes reduced the overall child airbag-induced fatality rate per registered vehicle by 60 percent, and that sled-certification reduced it by 83 percent.

Kahane also analyzed SCI fatality rate changes as a function of child age. He found that the largest reductions attributed to behavioral changes were among the youngest children; 71 percent reduction among infants (less than 1 year), 60 percent among 1-5 year-olds, and 53 percent among 6-10 year-olds. Estimated reductions attributed to airbag design changes were around 80 percent for 0-10 year-olds. Furthermore, during the study period there were no airbag-related deaths of infants in rear-facing child safety seats in vehicles with redesigned airbags.

Teenagers and adults The risk of death from deploying passenger airbags among teenage and adult right-front passengers also was found to be much lower than before (Kahane, 2006). Although far fewer cases of airbag-induced deaths among this population have been identified, deaths were about 82 percent lower in barrier-certified vehicles during 1998-2003 compared with barrier-certified vehicles during 1990-97, suggesting that behavioral factors played a major role. However, the airbag-induced fatality rate in sled-certified vehicles during the 1998-2003 was 42 percent lower than for barrier-certified vehicles during the same period, pointing to a positive effect of airbag and other restraint system design changes.

Changes in passenger fatality risk: Analyses of FARS data Kahane (2006) examined the effects of sled-certification on frontal-crash fatality risk among adult and teen right-front passengers (ages 13 and older) as well as for child right-front passengers (ages 0-12). Similar to the analyses that examined potential changes in driver airbag performance, steps were taken to match vehicle characteristics and safety features, including whether the vehicles were equipped with factory installed manual on-off airbag switches. Model years of vehicles used in these analyses were similar to those used in the driver airbag analyses.

Using the induced-exposure method with non-frontal crashes as controls, the overall fatality risk to right-front passengers ages 13 and older was 5 percent lower in sled-certified vehicles. The fatality risk was 9 percent lower in sled-certified versus barrier-certified vehicles when comparing rates per registered vehicle. However, neither difference was statistically significant. Further analyses found no evidence of loss of protection for adult and teen belted or unbelted passengers, or for male or female passengers. A couple of other findings are also worthy of note. For example, vehicles with sled-certified passenger airbags were found to be significantly more effective in preventing fatalities to adult right-front passengers in single-vehicle frontal crashes than vehicles with first-generation barrier-certified airbags. However, they were less effective among passengers 70 years and older. Occupants in this age group had a consistently higher fatality risk in vehicles with sled-certified airbags whether belted or unbelted, although in most analyses these differences were not statistically significant.

Kahane also examined changes in fatality rates among front-seat child passengers. Prior to airbag redesign, the fatality risk for child passengers ages 0-10 seated in the right-front passenger seat was consistently higher in airbag-equipped vehicles than in vehicles without airbags, and the increased risk was incrementally greater with decreasing child age. For example, compared to vehicles without frontal airbags, children in barrier-certified vehicles with frontal airbags had a 47 percent higher risk of fatality in frontal crashes (Kahane, 2006). To evaluate the performance of sled-certified airbags versus first-generation airbags, Kahane used a double-pair comparison method in which driver fatality risk was compared with the fatality risk for children in the right-front passenger seat. (Note that previous analyses have determined that the effect of sled-certification for drivers was negligible so Kahane assumed that the performance of driver airbags was essentially unchanged).

Overall fatality risk in frontal crashes was 45 percent lower for children ages 0-12 years in sled- versus barrier-certified vehicles. Effects also varied as a function of child age, with larger reductions in fatality risk among younger children. There were too few fatalities involving infants in rear-facing child safety seats in the right-front passenger seat to determine whether there was a change in effectiveness, but, among children 1- 5 years-old, there was a significantly lower (58 percent) likelihood of dying in a frontal crash in sled-certified vehicles. Children ages 6-10 were 31 percent less likely to be killed, and fatality risk among 11-12 year-olds was 8 percent lower, although neither of these differences was statistically significant. Additional analyses using registration-based rates also found reduced fatality risk among child front-seat passengers with generally increasing benefits with decreasing age.

Braver et al. (2008a) also examined the performance of passenger airbag performance in sled-certified vehicles compared to barrier-certified vehicles using the FARS database. The fatality rate per police-reported crash among right-front passengers of all ages in sled-certified vehicles was 11 percent lower than that for barrier certified vehicles but this difference was not statistically significant. No significant differences in effects of sled-certification testing on passenger airbag performance were observed as a function of age. As was the case for drivers, right-front passengers ages 75 and older had a slightly higher risk of death in sled-certified vehicles, but this was not significantly different than that for other adult age groups. Passengers in newer model year sled-certified vehicles (2000-2004) generally had reduced fatality risks compared with those in 1998-99 model vehicles.

Among front-seat child passengers of all ages, Braver et al. reported significant reductions in fatality risk in sled-certified versus barrier-certified vehicles. Children ages 0-4 were 65 percent less likely to die in a frontal crash, and fatality risk among 5-9 year-olds was 46 percent lower. Non-significant decreases were observed among 10-12 and 13-14 year-olds.

Because of shortcomings in the NASS/GES database, whereby police-reported belt-restraint use rates in NASS/GES are overestimated, it was not possible to accurately control for higher seatbelt use rates among occupants in newer model vehicles. These higher belt-use rates may, in part, account for the reduced risk of death in sled-certified vehicles. Braver et al. attempted to estimate the possible effects of different belt use rates based on police-reports, assuming that the magnitude of these differences for right-front passengers killed in crashes is representative of those involved in crashes. Accounting for differences in restraint use led to modest changes in the estimates of reduced mortality among children in sled-certified vehicles. For example, adjusting for the higher belt use in newer model vehicles, fatally-injured children ages 5-9 (the age group with the greatest belt use differential) had an estimated reduction in risk of death of 39 percent compared to 46 percent without such adjustments.

In summary, there is clear evidence that the fatality risk for young children in front seats of sled-certified vehicles with passenger airbags is much lower than the fatality risk in barrier-certified vehicles. Furthermore, the greatest benefits were seen among the youngest children. Fatality risks among adult front-seat passengers generally were lower in sled-certified vehicles, with reductions ranging from 5-11 percent across different analyses. However, none of these reductions was statistically significant. There is some evidence of reduced frontal-crash protection in sled-certified passenger vehicles among elderly passengers, but none of these differences was statistically significant.

Changes in risk of passenger injuries: Analyses of NASS/CDS data Bahouth et al. (2007) examined changes in injury risk among right-front adult passengers in sled-certified vehicles compared to earlier barrier-certified vehicles. Because of small sample sizes, their analyses combined injuries across all body regions. Findings were mixed but generally indicate a reduced injury risk at lower crash severities for sled-certified vehicles, and a higher injury risk at higher crash severities. However, none of the differences reached statistical significance. The authors cautioned that the results are based on small sample sizes and therefore should not be used to draw any firm conclusions.

DISCUSSION

In 1997, NHTSA enacted the first of a series of modifications to the rules governing frontal airbag performance. This interim rule allowed manufacturers to conduct sled tests rather than barrier tests with unbelted crash dummies, thereby allowing airbags to deploy less aggressively. At the time, concern was raised that the use of sled-testing to meet the unbelted dummy requirement would significantly reduce occupant protection in high-speed frontal crashes, particularly for heavier unbelted occupants. Initial findings regarding the frontal crash performance of vehicles equipped with depowered or redesigned airbags indicated that the combination of consumer education and redesigned airbag systems had dramatically reduced the harm to out-of-position occupants while still maintaining the airbags' lifesaving benefits (Ferguson, 2004). Three years later, further studies using the additional frontal crash data that have accrued provide a more complete understanding of the impacts of these changes in frontal-crash test methods.

There is now an abundance of evidence that infant and child deaths from deploying airbags in low-speed crashes are greatly diminished. A combination of public education to put children in back seats and airbag system redesigns have resulted in dramatic reductions in airbag-related child and infant fatalities investigated by NHTSA's Special Crash Investigations (Kahane, 2006). While this is very positive news, the evidence from the SCI cases is not comprehensive since this database does not provide a complete picture of airbag performance across all frontal crashes. However, additional analyses utilizing the FARS database, which is a census of fatalities on U.S. public roads, have confirmed that the fatality risk among children who are sitting in vehicle front seats of sled-certified vehicles has been dramatically reduced (Braver et al., 2008a; Kahane, 2006). Furthermore, these reductions are largest among the youngest children for whom the risk of airbag-induced fatalities had been the greatest. Some of the reductions in the risk of fatality may be due to increases in restraint use, but according to Braver et al., (2008a) it is unlikely that these increases account for the majority of the benefits. In spite of these improvements, parents still are advised to put children in back seats because the rear is the safest place for them to ride, regardless of restraint status. There is reliable evidence that sitting in the back seat substantially reduces fatality risk (Braver et al., 1998), and the latest available data also confirm that injury risk is reduced by a factor of about two by placing children in the rear versus front seats (Durbin et al., 2005). Further research is needed to determine whether additional benefits might accrue in vehicles that can suppress or modify airbag deployments when sensors determine small children are riding in right-front passenger seats.

There also is evidence that airbag-induced deaths of adult passengers and drivers, although far fewer than the deaths among children, have been significantly reduced in vehicles with sled-certified airbags (Kahane, 2006). According to Kahane, educational efforts advising people to sit further away from steering wheels and always to buckle up, as well as improvements in airbag design and performance have contributed to the decline in adult deaths due to deploying airbags.

Contrary to predictions, overall fatality risks in frontal crashes have not risen among adult drivers and passengers in vehicles with redesigned airbags. Using a variety of analytical approaches, Kahane (2006) and Braver et al. (2008a,b) found that the fatality risks among front-seat adult occupants in sled-certified vehicles are not higher than those in barrier-certified vehicles with first-generation airbags, and there are some indications that risks may have declined slightly. For example, passenger fatality risks were estimated to be 9-11 percent lower (Braver et al., 2008a,b; Kahane, 2006) and driver fatality risks were estimated to be 4-11 percent lower in the Braver studies, although Kahane did not find differences of this magnitude. The inclusion of newer model vehicles with advanced airbag and belt systems in the Braver et al. analyses may have contributed to these differences. Drivers and passengers in newer model vehicles (2000-04), some of which have more advanced airbag features, tended to have lower fatality risks than those in 1998-99 model vehicles for which airbags were primarily depowered. There is, however, one caveat to these findings. Because concurrent changes in vehicle crashworthiness design were not controlled for, it is possible that vehicle design changes rather than airbag design changes could have contributed to the positive results.

Although differences in frontal crash protection for barrier- and sled-certified vehicles do not appear to vary consistently as a function of occupant age, there are some indications in both the Kahane and Braver studies of somewhat lower protection among older right-front passengers (evidence among drivers is inconsistent). Although fatality risks are generally lower in sled-certified vehicles for all age groups, they are somewhat higher among older occupants (70 or 75 and older) who were in right-front passenger seats. It is not clear whether these age-related differences are reliable, but the findings are counter to the notion that the frailest occupants should benefit the most from less aggressive airbags.

One of the key questions addressed in these analyses is whether newer airbag-equipped vehicles certified using unbelted-dummy sled tests or 25-mph barrier tests are offering reduced protection in higher severity crashes for any subset of the population, particularly for larger, unbelted occupants. In the matched-pairs cohort study, arguably one of the best methods for controlling for confounding factors, Braver et al. did not find a significant interaction between airbag generation and belt use, suggesting that there were no differential effects among belted and unbelted occupants in fatal frontal crashes. In his analysis of fatal crashes, Kahane (2006) reported somewhat lower protection among female drivers, and smaller and lighter as well as taller drivers, although these differences were not statistically significant. Among unbelted drivers, these differences were larger. In particular, an elevated fatality risk was found among small drivers in sled-certified vehicles. This finding is contrary to expectations that less powerful airbags would be “overpowered" by heavier drivers in severe frontal crashes, thus putting them at greater risk of death. It should also be noted that Kahane’s analyses were restricted to vehicles manufactured in the first few years after sled-certification was permitted so further advances in airbag design are not accounted for.

Bahouth et al. (2007) examined injury risk, both fatal and non-fatal, among drivers and passengers in sled- versus barrier-certified vehicles. The effects differed by belt use and crash severity. Among belted drivers in sled-certified vehicles there were no indications of an increased risk of minor, moderate, or severe injuries. This was true regardless of crash severity. However, among unbelted drivers there are indications that minor, moderate, and severe injuries are elevated at higher crash severities, although the increases were not statistically significant. Among unbelted and belted passengers, a tendency was reported for elevated injury risks at higher crash severities, but the authors cautioned that these findings were not statistically significant due to small sample sizes.

Findings were mixed when individual body regions were examined, with a lower reported risk of lower or upper extremity injuries and minor facial injuries among belted drivers. There was one concerning finding that deserves further study. Chest injury was twice as high among unbelted drivers in sled-certified vehicles compared to first-generation barrier-certified vehicles for higher severity crashes. These findings are puzzling given the reports by Braver el al. and Kahane that driver fatality-risk did not rise significantly in sled-certified vehicles. Further analyses are needed to explain these inconsistencies.

CONCLUSIONS

There is now convincing evidence that redesigned airbags have been highly beneficial in reducing fatalities to children. Both improvements in airbag designs and public education have contributed to dramatic reductions in airbag-induced child deaths. Furthermore, the risk of fatality in frontal crashes among children who still are sitting in front seats has been reduced by as much as half, with the greatest benefits being among the youngest children. Despite these improvements in protection, parents still are advised to place their children in the back seats to avoid injuries from deploying airbags and reduce their likelihood of dying when involved in crashes.

There is no evidence of the predicted large-scale loss of protection in frontal crashes among adult drivers and passengers with sled-certified airbags. There are far fewer airbag-related deaths among front-seat adult occupants, and overall fatality risk in frontal crashes has not increased measurably relative to risks for vehicles with first-generation, barrier-certified airbags. However, despite the exhaustive analyses conducted in the last few years, the possibility remains of a somewhat elevated fatality risk in frontal crashes among a subset of unbelted drivers in 1998-2000 model year sled-certified vehicles. There also is some evidence that risks of serious chest injury may have increased among unbelted drivers in frontal crashes. Further research is needed to determine whether these differences are real and whether they are evident in newer model vehicles with advanced airbag and restraint systems. As more data accrue, additional analyses should be conducted to determine whether advanced airbag features, including dual stage inflators, seat and occupant position sensors, and improvements to belt systems, adopted in response to the advanced airbag rules have had any additional impact on the risks of injury and death to front-seat occupants.

ACKNOWLEDGEMENTS

The authors wish to thank the Blue Ribbon Panel members and observers, Jeff Augenstein, Don Bischoff, Tom Carr, Joseph Carra, Chip Chidester, Dainius Dalmotas, Ken Digges, Bella Dinh-Zarr, Dennis Durbin, Tim Hoyt, Kristin Poland, Vernon Roberts, Larry Schneider, Maria Segui-Gomez, and Bill Windsor, for all their hard work during the last several years in overseeing and evaluating frontal airbag performance. Thanks also are due to the Alliance of Automobile Manufacturers, without whose support this effort would not have been possible. We also wish to thank the Blue Ribbon Panel Members who took the time to review the draft paper and for their thoughtful responses.

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