SIDE IMPACT AIR BAG EFFICACY, INJURY MITIGATION PERFORMANCE IN VEHICLE MODELS WITH AND WITHOUT SIDE IMPACT AIR BAGS AND INFLATABLE HEAD PROTECTION

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ABSTRACT

New injury control technologies are continually emerging in the automotive marketplace. Insertion mechanisms and rates vary based on the complexity and stability of the technology, the cycle of new vehicle and platform introductions, and consumer acceptance. The injury control effectiveness of newly emerging technologies is assessed based upon changes recorded in collision related injury and fatality data from US Federal and State motor vehicle collision databases. This analysis provides an assessment of side impact air bag (SIAB) effectiveness based upon data from the Fatality Analysis Reporting System (FARS). The study considers vehicle models over the time period 1998 to 2008 that converted from having no side impact air bags available to having side impact air bags as standard equipment. Distinctions are made between two types of side impact air bags: torso (or thorax) side air bags and roof rail mounted head curtain air bags. Estimates of effectiveness are based on comparisons of fatality rates for the 2 years prior to insertion of the injury control technology and 2 years following insertion in each model pair.

SIDE IMPACT AIR BAG INSERTION HISTORY

Coincident with the near ubiquitous installation of driver frontal air bags and the increasing density of passenger front air bags into the light vehicle fleet during the late 1990s, motor vehicle manufacturers began to engineer and install air bag restraints for side impact. Initial side impact air bag applications were intended to provide supplemental energy absorption to driver and passenger torso exposure to near side (same side of the vehicle) impact insult. Some early side impact air bags were mounted in the outboard seat back bolster and some were mounted in the door above the arm rest. As the technology has matured, seat mounted torso air bags have become the predominant location.

Side impact air bag systems were developed in an extra-regulatory environment; that is the first, and several subsequent generation side impact air bag systems were developed and inserted into the stream of commerce without a governing regulation. Therefore motor vehicle manufacturers themselves were responsible to establish the performance parameters, deployment characteristics, and acceptance criteria that each individually developed and applied to side impact air bag systems. Air bag systems were thereby validated to each manufacturers' own test standards and criteria without the regulatory overlay requiring certification.

Nearly at the same time side impact air bags were being developed for production applications, the adverse unintended consequences of frontal air bag inflation induced injuries became evident. Many manufacturers were able to adopt side impact air bags and simultaneously generate internal standards and acceptance criteria for side impact air bag deployment characteristics so as to control the risk of injury to out of position occupants. Eventually, with the assistance of the Insurance Institute for Highway Safety (IIHS) and the Canadian Ministry of Transportation (MOT), manufacturers developed a voluntary industry standard to control side impact air bag inflation induced injury risk. The resultant test conditions and acceptance criteria for out of position occupant considerations and the sponsoring manufacturers' commitment to the procedures and criteria were documented in a transmittal letter from the IIHS, the "Alliance of Automobile Manufacturers", and the "Association of Import Automobile Manufacturers" to The Administrator of the National Highway Traffic Safety Administration (NHTSA) dated August 8, 2000 [1].

Since early side impact air bag systems were first introduced into the stream of commerce in the late 1990s, motor vehicle collision injury control has greatly advanced and the penetration of side impact air bags for torso protection deepened into the new car and light duty truck fleet (herein after for simplicity, the "new car fleet") and additional design features have been added to improve side impact restraint effectiveness in side collisions including the emergence of technologies to provide inflatable head protection in near side impacts.

This paper builds upon work performed by Exponent and described in "Installation Patterns for Emerging Injury Mitigation Technologies," paper 11–0088 presented at the 2011 ESV Conference [2]. Exponent compiled data regarding the application of multiple safety technologies by manufacturer, vehicle make, vehicle model and vehicle model year. That data matrix was used to identify the paired models and model years in which a given vehicle model converted from not having a safety technology to having the safety technology installed as standard equipment in the model year immediately following.

By studying paired populations of like make/model vehicles without and with side impact air bags, we can calculate the side impact injury likelihood for each of the paired populations individually, and thereby also compare the likelihood of injury in near side impacted vehicles without side impact air bags and with side impact air bags. The reduction in injury likelihood compared to the original probability of injury in the paired models that are not equipped with side air bag technology is a measure of efficacy in side impact injury reduction.

Table 1 is a sample of the make/model/model year matrix for head curtain side air bags in model year 2003. A clear or white cell indicates that the base model of that vehicle make/model in 2003 had no head curtain air bag available. A yellow cell indicates that the make/model combination had the head curtain air bag available as an option in 2003. A green cell indicates that the make/model had the head curtain air bag installed as standard equipment for the 2003 model year.

The penetration growth of a new injury mitigation technology into the new car fleet can be tracked and illustrated by counting the number of unique make/models in a given model year with the technology of interest as standard or optional equipment and calculating the proportion of the entire new vehicle fleet (based upon an aggregate count of unique make/models). The resulting plot then provides a history of new technology penetration into the new vehicle fleet. Figure 1 illustrates the insertion history for head curtain air bags. Figure 2 illustrates the same for torso air bags.

Examination of model year matrices as illustrated in Table 1 permit comparisons among one model year to the immediately following model year and were used to identify paired couplings of make/model/model year vehicle combinations wherein the first year of the pair did not have the technology and the second year of the pair did have the technology as standard equipment. To capture more injury data for the paired comparisons, the last two model years without the technology were compared to vehicles in the first and second model years in which the technology was applied as standard equipment.

METHODOLOGY

Injury data was obtained for each make/model pair from the FARS [4]. Because FARS reports fatal injuries for whole calendar years, injuries for a particular vehicle model were tallied through 2008 beginning with the calendar year equal to the model year "+1." For example the injury count for a 1998 Buick LeSabre would be the sum of all fatal injuries in fatal crashes for which the main impact was a side impact for calendar years 1999 through 2008.

Injury rates were calculated using years of vehicle registration for denominator data. For example, vehicle registration years for a 1998 Buick LeSabre would be tallied by adding up the counts of U.S. registrations for 1999 to 2008 Buick LeSabres.

The resultant injury rates for a particular model were thus calculated as fatal injuries per registered vehicle year as shown in Equation 1.

$$injury\ rate = \frac{\begin{matrix} driver\ \ right\ front\ passenger \\ fatal\ injuries\ in\ near\ side\ impacts \end{matrix}}{\begin{matrix} registered\ vehicle\ counts\ for\ calendar \\ years\ corresponding\ to \\ injuries\ represented\ in\ the\ numerator \end{matrix}} \qquad (1).$$

In making paired comparisons, the numerator and denominator in Equation 1 would include counts for two successive vehicle model years—the first rate in the pair accounting for the last two model years without the technology under consideration and the second rate in the pair accounting for the first and second years in which the technology was applied.

The measured improvement is an efficacy calculation:

$$efficacy = \frac{\begin{matrix} (rate\ without\ SIAB) - \\ (rate\ with\ SIAB) \end{matrix}}{rate\ without\ SIAB}\ x\ 100\% \qquad (2).$$

Table 1.
2003 head curtain air bag availability

Model Year 2003

Safety Technology: Head Curtain Availability

Ford	Mazda	Mercury	Lincoln	Volvo	Land Rover	Jaguar	Buick	Cadillac	Chevrolet	GMC	Hummer	Oldsmobile	Pontiac	Saab	Saturn	Hyundai	Kia
									Cavalier								
Crown Victoria									Corvette								
Focus									Impala								
Mustang									Malibu								
Taurus									Monte Carlo								
Thunderbird									Astro								
ZX-2									Avalanche								
E-Series Van									Blazer								
Escape									Express								
Excursion									S10 Pickup	Envoy							
Expedition				C70					Silverado	Safari			Aztek				
Explorer	Mazda6			S40/V40				CTS	Silverado	Savana			Bonneville			Accent	
Explorer Sport Trac	Miata			S60			Century	DeVille	Suburban	Sierra			Grand Am			Elantra	Optima
F-150	Protégé	Grand	Aviator	S80		XJ-	LeSabre	Seville	Tahoe	Sierra HD		Alero	Grand Prix			Sonata	Rio
F-250/350	B-Series	Sable	LS	V70	Discovery	XK-	Park Avenue	Escalade	Trailblazer	Sonoma		Aurora	Montana		Ion	Tiburon	Sedona
Ranger	MPV	Mountaineer	Navigator	XC70	Freelander	S-Type	Regal	Escalade	Tracker	Yukon	H1	Bravada	Sunfire	9-3	L-Series	Santa Fe	Spectra
Windstar	Tribute	Marauder	Town Car	XC90	Range Rover	X-Type	Rendezvous	Escalade	Venture	Yukon XL	H2	Silhouette	Vibe	9-5	Vue	XG350	Sorento
Ford	**Mazda**	**Mercury**	**Lincoln**	**Volvo**	**Land Rover**	**Jaguar**	**Buick**	**Cadillac**	**Chevrolet**	**GMC**	**Hummer**	**Oldsmobile**	**Pontiac**	**Saab**	**Saturn**	**Hyundai**	**Kia**
Ford							GM									Hyundai	
US																South Korea	

Honda	Acura	Isuzu	Nissan	Infiniti	Suzuki	Subaru	Toyota	Lexus	BMW	Mini	Chrysler	Dodge	Jeep	Mitsubishi	Mercedes	Porsche	VW	Audi
							Avalon											
							Camry											
							Camry Solara											
							Celica											
							Corolla											
							Matrix											
							Echo					Intrepid						
							MR2 Spyder					Neon						
							Prius					Stratus			C-Class			
Accord			Altima				Highlander	ES 300				Viper			CL-Class			
Civic			Maxima				Land Cruiser	IS 300				Grand Caravan		Diamante	CLK			
CR-V	3.2CL		Sentra	G35			4Runner	GS 300/430	3-Series			Dakota		Eclipse	E-Class			
Element	RSX		350Z	I35		Baja	RAV4	LS 430	5-Series		Concorde	Durango		Galant	G-Class		Beetle	Allroad
Insight	MDX	Ascender	Frontier	M45	Aerio	Forester	Sienna	RX 300	7-Series		300M	Ram 1500		Lancer	M-Class		Golf/Gti	A4
Odyssey	NSX	Axiom	Murano	Q45	Grand Vitara	Impreza	Sequoia	GX470	X5		PT Cruiser	Ram 2500/3500	Liberty	Outlander	S-Class	Boxster	Jetta	A6
Pilot	3.5RL	Rodeo	Pathfinder	FX35/FX	XL-7	Legacy	Tacoma	LX 470	Z4		Sebring	Ram Van Cargo	Grand	Montero	SL	911	Passat	A8
S2000	3.2TL	Rodeo Sport	Xterra	QX4	Vitara	Outback	Tundra	SC 430	Z8	Cooper	Town &	Sprinter	Wrangler	Montero	SLK	Cayenne	EuroVan	TT
Honda	**Acura**	**Isuzu**	**Nissan**	**Infiniti**	**Suzuki**	**Subaru**	**Toyota**	**Lexus**	**BMW**	**Mini**	**Chrysler**	**Dodge**	**Jeep**	**Mitsubishi**	**Mercedes**	**Porsche**	**VW**	**Audi**
Honda		Isuzu	Nissan		Suzuki	Subaru	Toyota		BMW		Daimler AG					Porsche	VW	
Japan									Germany									

Green=Standard | Yellow=Optional

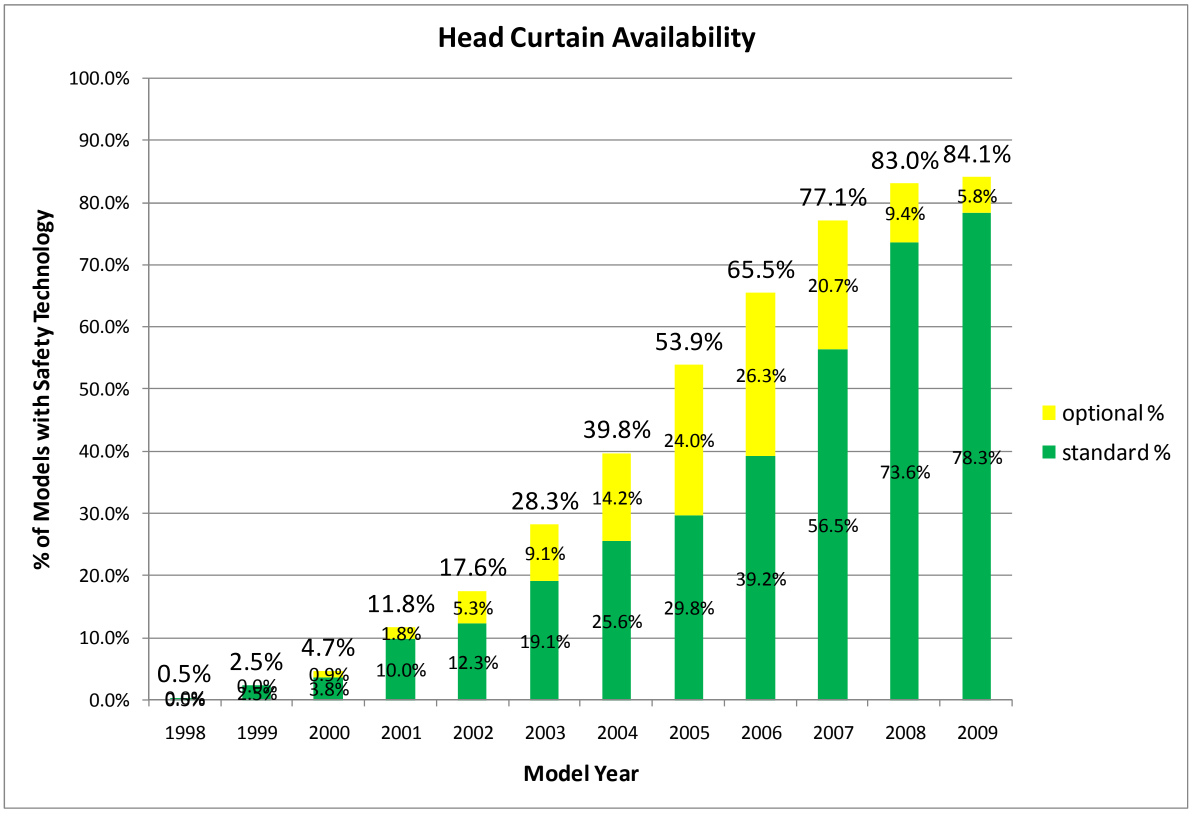

Figure 1. Head curtain air bag availability by model year [3].

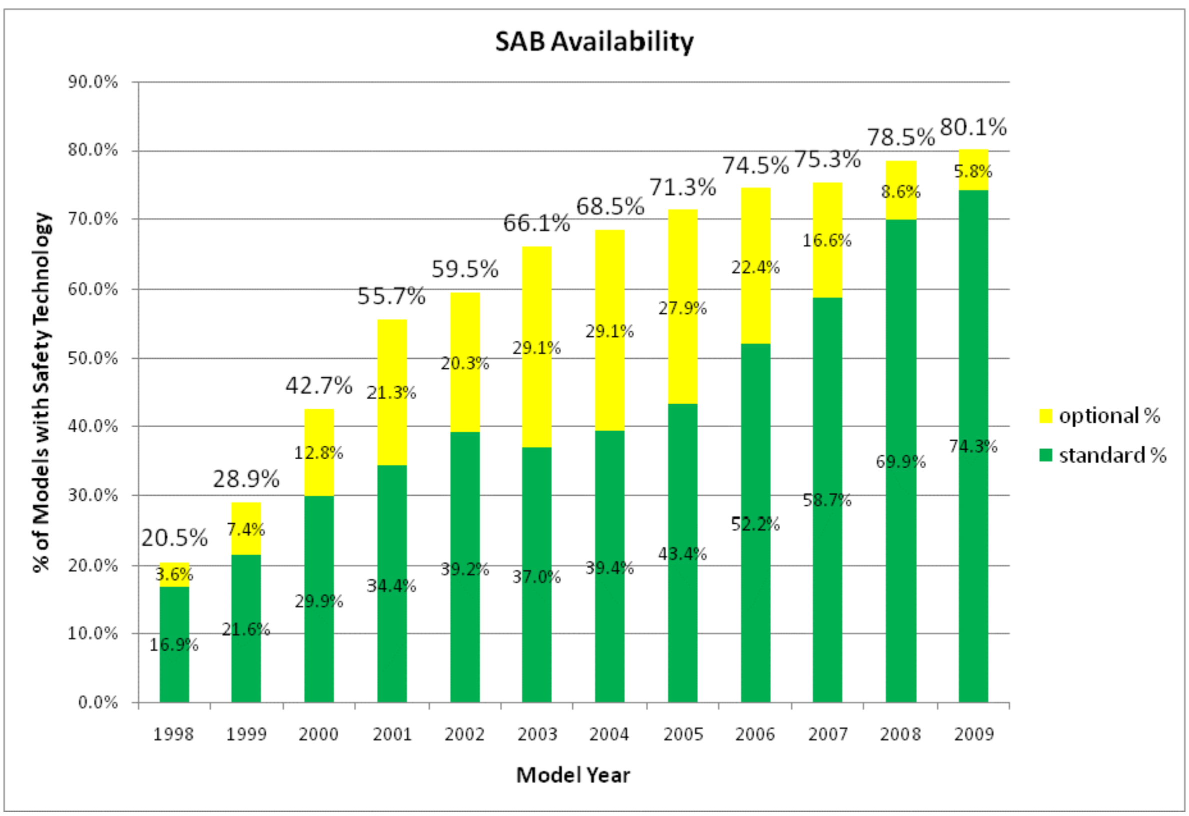

Figure 2. Seat or door deployed side air bag availability by model year [3].

SIDE IMPACT AIR BAG TECHNOLOGY MATCHED PAIRS

The matched pairs that fit these selection criteria are: (1) torso side air bag insertion from not available to standard equipment in immediately successive model years and (2) head curtain air bags insertion from not available to standard equipment in immediately successive model years. Table 2 lists the pair matches for torso side air bags. Group 1 in Table 2 are pair vehicles not equipped with torso side air bags and Group 2 are pair vehicles that have torso side air bags as standard equipment.

Table 3 lists the pair matches for head curtain air bags. Group 1 are pair vehicles that were not equipped with head curtain air bags; some models may have been equipped with torso side air bags as standard equipment. Group 2 are pair vehicles that have head curtain air bags as standard equipment; some models may also have torso side air bags as standard equipment. See the bottom of Table 3 for an exact definition of Group 1 and Group 2.

For each vehicle matched pair we assume as a null hypothesis that the fatal injury rate in vehicle models with the side air bag is not different than the fatal injury rate in vehicle models without side impact air bags. For each matched pair of vehicle models we calculated a p-value test statistic: the probability that the number of fatal injuries occurring in the model population with side impact air bags is less than or equal to the actual observed value. If the p-value is sufficiently small, commonly taken as 5%, the null hypothesis is rejected and we conclude that the reason the observed value of fatalities is smaller than expected when assuming the null hypothesis is that the fatality rate for the model population with side air bags is lower than that for the model population without side airbags.

For several vehicle models, even though the calculated efficacy measure is fairly high, the p-value is not low enough to provide statistical significance for an improvement. Larger vehicle sample sizes or longer time periods would be required to obtain more statistical certainty for individual models.

For the specific set of vehicle models under study, we also aggregated data over the two populations, those not having side air bags and those having side air bags. For the aggregated data, we totaled the number of fatal injuries for all of the vehicle model population with side air bags and totaled the number of fatal injuries for all of the population without side air bags; these aggregate values then become numerator data for rate calculations. The aggregate vehicle registration-based rate calculation is exact in that the numerator and denominator data are straight counts of events and registrations for the set of vehicles under study.

In an attempt to characterize average efficacy in some way, we calculated the average z-score for comparisons between the population without side air bags and the population with side air bags for the aggregated sets. The z-score for a particular model is the difference between the observed value and the expected value expressed as a proportion of the standard deviation for that model. The observed values are taken for the vehicle model group equipped with side air bags. The expected values for comparison are calculated as the product of the exposure values for the population with side air bags and the fatality rate for the population equipped without side air bags.

$$z - score = \frac{(observed\ fatalities) - (expected\ fatalities)}{standard\ deviation} \quad (3).$$

The z-score is a standardized score indicating the difference from expected value in units of standard deviation; the standardization allows scores to be averaged across cases with different standard deviations. A negative value of the average z-score would indicate an improvement (reduction) in fatality rate has been realized for the population with side air bags as compared to the population without side air bags.

Finally, we also applied Fisher's combined probability test to the aggregated data. This method combines p-values from individual vehicle hypothesis tests into a single test statistic. The null hypothesis for this "meta-analysis" is that all of the separate null hypotheses are true (i.e., all fatality rates are the same before and after air bag implementation). This hypothesis is rejected when p is small (< 5-10%). The alternative hypothesis is that at least one of the separate alternative hypotheses is true (at least one of the model specific rates is different following implementation).

STUDY RESULTS

Figure 3 shows the proportional change (improvement or increase) for the torso air bag (SIAB) vehicle pairs. The rate calculations are for near side fatal injuries per registered vehicle year for the fleets equipped with torso side air bags and not so equipped. The chart plots data for all of the vehicle pairs for which there was at least one fatal injury over

Table 2.
SIAB matched pairs

Vehicle	Group 1		Group 2	Vehicle	Group 1		Group 2
Acura CL	1998-1999	vs.	2001-2002	Hyundai Sonata	1997-1998	vs.	1999-2000
Acura TL	1998-1999	vs.	2000-2001	Infiniti I30	1996-1997	vs.	1998-1999
Acura RL	1997-1998	vs.	1999-2000	Jaguar XJ-Series	1996-1997	vs.	1998-1999
Acura Integra/RSX	2000-2001	vs.	2002-2003	Land Rover Range Rover	1997-1998	vs.	2000-2001
Audi A4	1996-1997	vs.	1998-1999	Lexus ES	1996-1997	vs.	1998-1999
Audi A6	1996-1997	vs.	1998-1999	Lexus GS	1996-1997	vs.	1998-1999
Buick LeSabre	1998-1999	vs.	2000-2001	Lexus LS	1995-1996	vs.	1997-1998
Buick Park Avenue	1998-1999	vs.	2000-2001	Lexus SC	1999-2000	vs.	2002-2003
Cadillac Catera	1997-1998	vs.	2000-2001	Mitsubishi Montero	1999-2000	vs.	2001-2002
Cadillac DeVille	1995-1996	vs.	1997-1998	Oldsmobile Aurora	1998-1999	vs.	2001-2002
Cadillac Escalade	1999-2000	vs.	2002-2003	Oldsmobile Bravada	2000-2001	vs.	2002
Cadillac Seville	1996-1997	vs.	1998-1999	Oldsmobile Silhouette	1996-1997	vs.	1998-1999
Chevrolet Suburban	1998-1999	vs.	2000-2001	Pontiac Bonneville	1998-1999	vs.	2000-2001
Chevrolet Tahoe	1998-1999	vs.	2000-2001	Pontiac TransSport/Montana	1996-1997	vs.	1998-1999
Chevrolet Blazer/Trailblazer	2000-2001	vs.	2002	Porsche 911	1997-1998	vs.	1999
Chevrolet Venture	1997	vs.	1998-1999	Porsche Boxster	1997	vs.	1998-1999
GMC Jimmy/Envoy	2000-2001	vs.	2002	Suzuki Aerio	2003-2004	vs.	2005-2006
GMC Suburban/YukonXL	1998-1999	vs.	2000-2001	Toyota Avalon	1996-1997	vs.	1998-1999
GMC Yukon	1998-1999	vs.	2000-2001	VW Passat	1996-1997	vs.	1998-1999
Honda Odyssey	2000-2001	vs.	2002-2003	Volvo 850	1994-1995	vs.	1996-1997
Honda Pilot	2001-2002	vs.	2003-2004	Volvo 960	1994-1995	vs.	1996-1997

Group 1: No Airbags Available
Group 2: Airbag is Standard Equipment

Table 3.
Head curtain matched pairs

Vehicle	Group 1		Group 2	Vehicle	Group 1		Group 2
Acura MDX	2002-2003	vs.	2004-2005	Honda Pilot	2004-2005	vs.	2006-2007
Acura RL	2003-2004	vs.	2005-2006	Jaguar XJ-Series	2002-2003	vs.	2004-2005
Acura TL	2002-2003	vs.	2004-2005	Land Rover Range Rover	2001-2002	vs.	2003-2004
Audi A4	1998-1999	vs.	2001-2002	Lexus ES	2000-2001	vs.	2002-2003
Audi A6	1998-1999	vs.	2001-2002	Lexus GS	1999-2000	vs.	2001-2002
Audi A8	1998-1999	vs.	2000-2001	Lexus LS	1999-2000	vs.	2001-2002
Cadillac Catera/CTS	2000-2001	vs.	2003-2004	Lexus RX	2002-2003	vs.	2004-2005
Cadillac Deville/DTS	2004-2005	vs.	2006-2007	Mercedes G-Class	2003-2004	vs.	2005-2006
Cadillac Escalade	2005-2006	vs.	2007	Mitsubishi Endeavor	2005-2006	vs.	2007
Cadillac Escalade ESV	2005-2006	vs.	2007	Mitsubishi Outlander	2006	vs.	2007
Cadillac Escalade EXT	2005-2006	vs.	2007	Suzuki XL7	2005-2006	vs.	2007
Cadillac STS[1]	2003-2004	vs.	2005-2006	Toyota Avalon	2003-2004	vs.	2005-2006
Chevrolet Impala[1]	2004-2005	vs.	2006-2007	VW Passat	1999-2000	vs.	2001-2002
Honda Odyssey	2003-2004	vs.	2005-2006				

Includes vehicles with the following configurations:
Group 1: No bags available; Group 2: Standard Curtain
Group 1: Seat Torso Bag Standard; Group 2: Seat Torso and Curtain Airbag Standard
Group 1: Seat Torso Bag Standard; Group 2: Curtain only Standard

1) Analysis for passenger side only

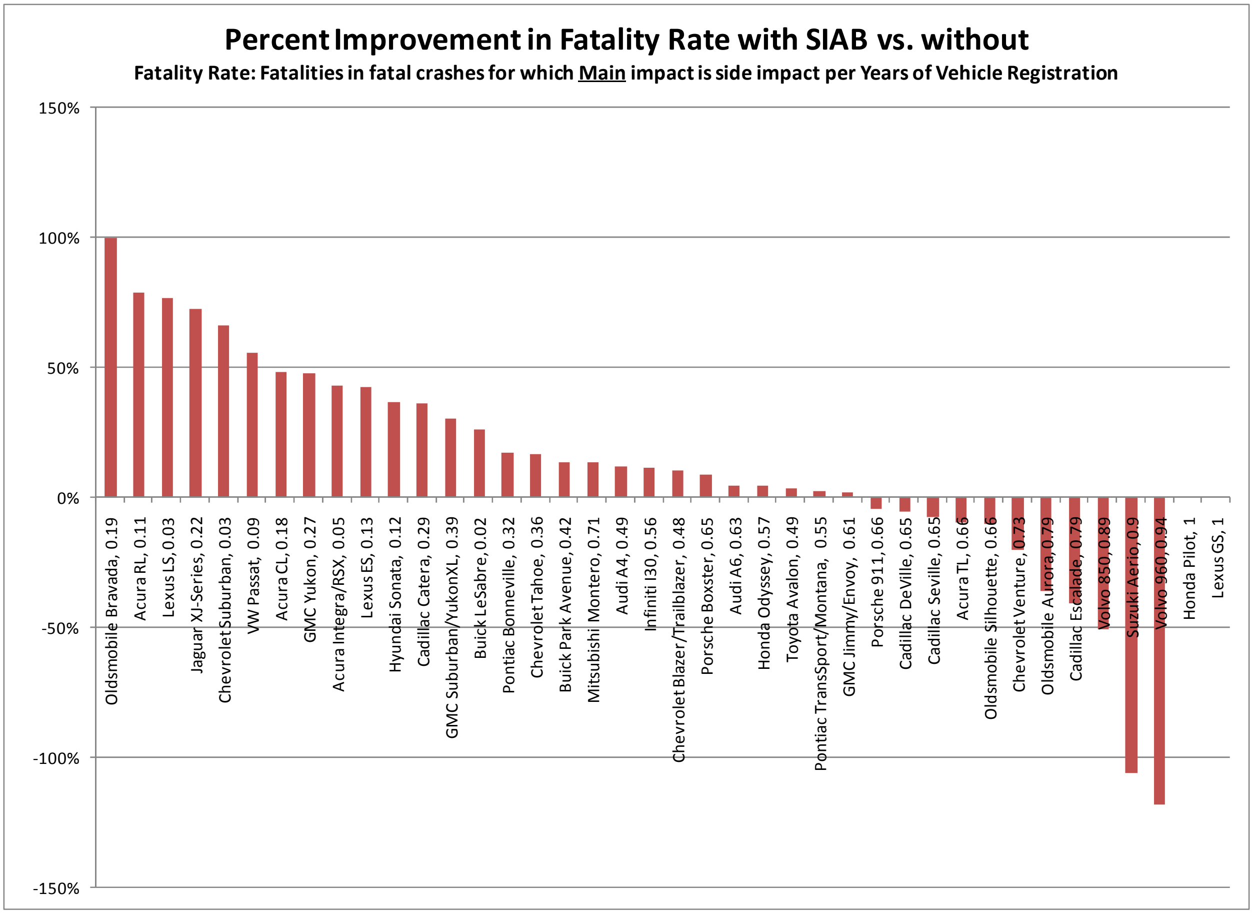

Figure 3. Fatal injury rate change for the torso side air bag matched fleet.

the period without torso side air bags and for which a p-value could be calculated. Aggregated data for the paired populations registered a fatality rate of 1.76 E-05 without torso side air bags and 1.47 E-05 with torso side air bags, a 16 % reduction in fatal injury rate for the population with torso side air bags as standard equipment. The average z-score is -0.39. The Fisher's p-value is 1.87 E-06. Each of these results support the conclusion that torso side air bags have a positive effect in reducing fatalities. It should be noted that in Figure 3, some vehicles show a reduction in efficacy. In general, sample sizes are quite small for those examples. For comparison, see Figure 4 which shows only vehicles in which there were 12 or more fatalities in the period without airbags. In this situation, with larger samples, all but one vehicle model showed an increase in efficacy.

Figure 5 shows the proportional change (improvement or increase) for the head curtain air bag vehicle pairs. The rate calculations are for near side fatal injuries per registered vehicle year for the fleets equipped with head curtain air bag and not so equipped. The chart plots data for all of the vehicle pairs for which there were at least six fatal injuries and for which a p-value could be calculated. Aggregated data for the paired populations registered a fatality rate of 9.23 E-06 without head curtain air bags and 6.19 E-06 with head curtain air bags, a 33 % reduction in fatal injury rate for the population with head curtain air bags as standard equipment. The average z-score is -0. 41. The Fisher's p-value is 1.11 E-06. Each of these results supports the conclusion that head curtain side air bags have a positive effect in reducing fatalities.

SUMMARY

The technology insertion patterns for both torso side air bags and for head curtain air bags follow a common pattern for injury control technology insertion: small or modest penetration in early years of adoption, a monotonic increase in fleet insertion proportion, a mix of optional and standard equipment availability throughout the insertion period, and relatively high penetration levels in later years.

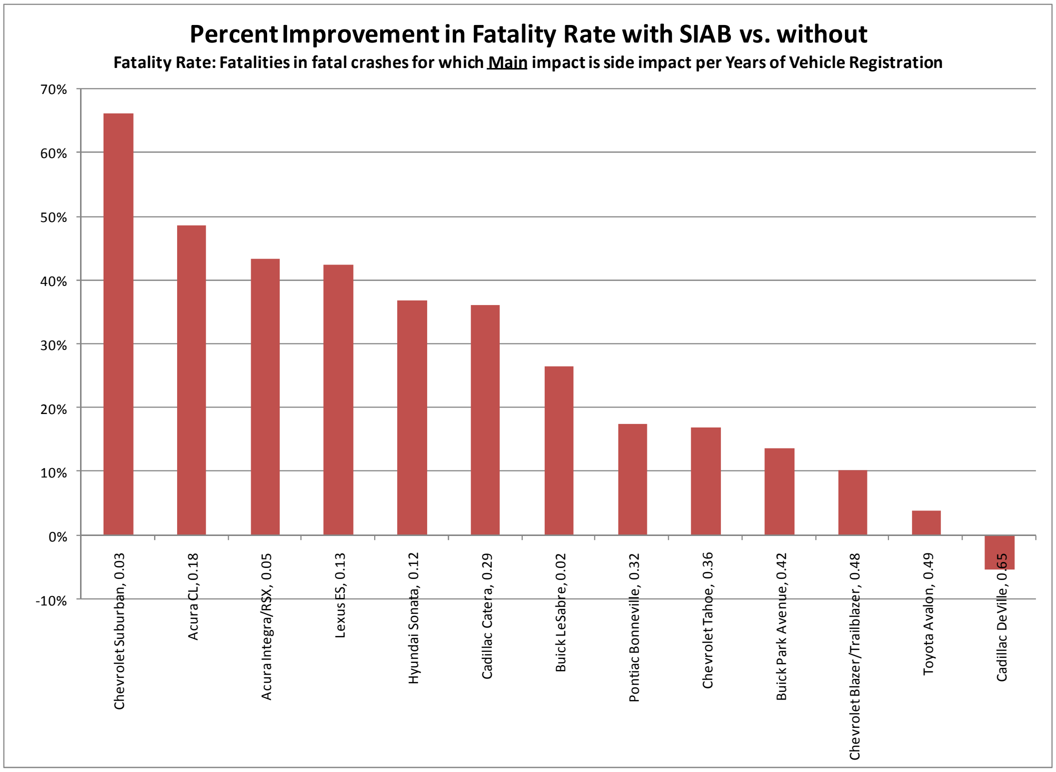

Figure 4. Fatal injury rate change for the torso side air bag matched fleet, cases with 12 or more fatalities during the period without torso side air bags.

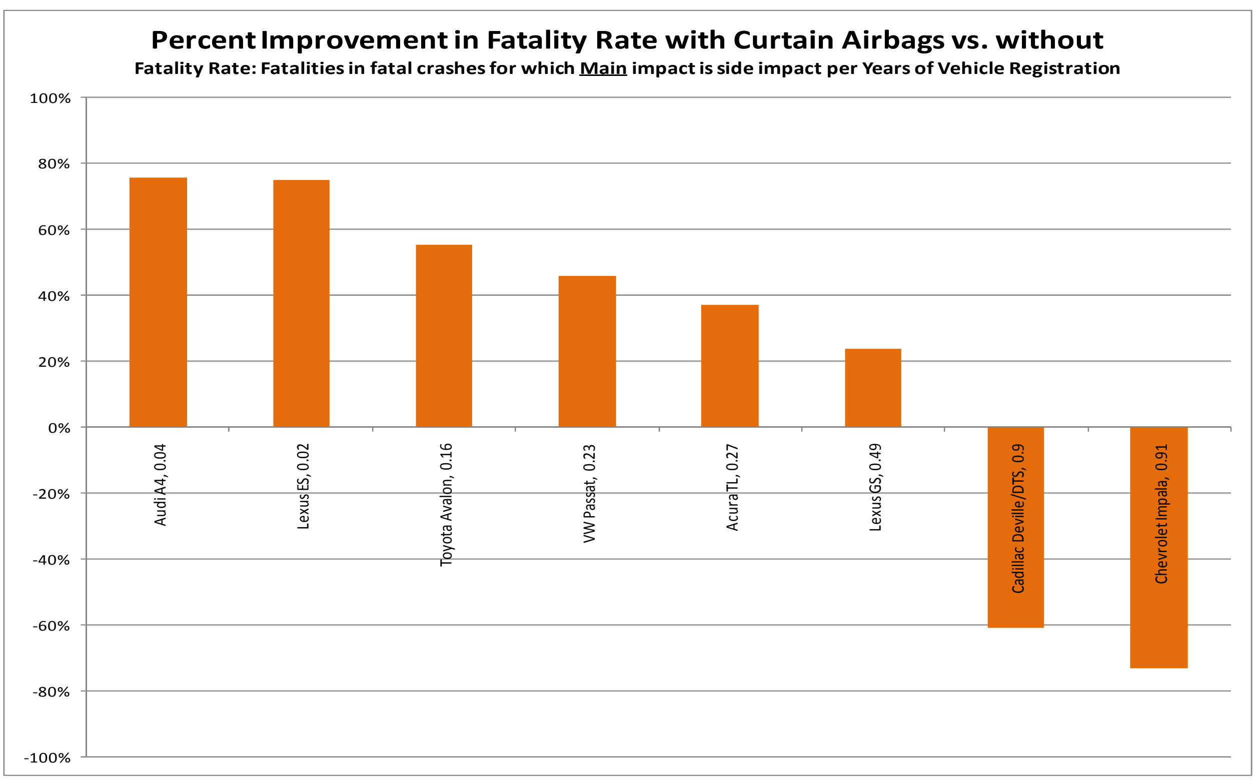

Figure 5. Fatal injury rate change for the head curtain air bag matched fleet.

Insertion of both of these technologies has been influenced somewhat by the industry voluntary agreement to improve vehicle to vehicle side impact compatibility [5] and both of these technologies will likely become ubiquitous consequent to Federal Motor Vehicle Safety Standard 214 finalized in September 2007 and now in the third year of its phase-in schedule.

With somewhat limited data for relative small vehicle fleets, an analysis was conducted of FARS data and national vehicle registration data from R.L. Polk. Only 42 vehicle model pairs were available for study of torso air bag effects and 27 pairs for study of head curtain air bags. Even so, the analysis registered a real occupant protection improvement in near side crashes for both technologies. In the vehicle population studied, torso side air bags were about 16% effective in reducing the probability of near side impact fatal injury and head curtain air bags were about 33% effective in reducing near side impact fatal injury.

A review of the technology improvements registered at the paired vehicle model level in Figures 3 and 5 show large variations. Variation at the vehicle model level would be expected as the values for fatal injury counts are all quite small; the chance inclusion or exclusion of an event will yield large rate variation. Additionally, individual comparisons among models would likely be affected by integrated vehicle design characteristics, base vehicle architectural changes (that often may enable installation of new technologies that present architectural challenges or unique architectural criteria), and the possible inclusion of other vehicle safety countermeasures. However, close examination shows that "sister" vehicles (those sharing common architectures and technology but sold under different make nameplates) exhibit variation over nearly the entire range of improvements. Compare, for example, the improvement for Oldsmobile Bravada to that for the Chevrolet Blazer/Trailblazer and the GMC Jimmy/Envoy or the Chevrolet Suburban to the Cadillac Escalade. This suggests perhaps the performance variations measured at the individual paired model level may be due to chance rather than performance variation among models identical save for name plates. Additionally, at the individual paired model level, many of the comparisons are themselves not statistically significant.

As noted, some negative improvement rates for individually paired vehicle models were calculated. The uncertainty placed on individual fatality rate improvement calculations are affected by a small sample size in addition to compounding influences such as crash severity exposure and vintage of technology.

A future improvement to this work could be to use numbers of police reported or tow-away crashes as exposure (denominator) data in the rate calculations. This would improve the estimate of rates for efficacy of performance in a crash rather than efficacy per years of vehicle registration. Differences in crash rates between vehicle types could have a large affect on the rates calculated in this paper.

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