DIFFERENCES IN AIR BAG PERFORMANCE WITH CHILDREN IN VARIOUS RESTRAINT CONFIGURATIONS AND VEHICLE TYPES

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ABSTRACT

Previous studies have identified a fatality risk for children exposed to air bags, particularly in the presence of non-restraint or inadequate restraint of the child and pre-impact braking, conditions that place the child out-of-position. Consequently, many manufacturers are opting to suppress the air bag when an out-of-position child, particularly one who is unrestrained, is detected. This study provides current estimates of injury risk for children exposed to airbags based on the large experience of children in crashes from the Partners for Child Passenger Safety (PCPS) project; describes the most common scenarios for these injuries; and attempts to replicate and extend the field data through sled testing and simulations. This study was conducted to enhance the scientific base on which decisions to suppress airbags can be made on restrained children. The results of this study suggest that more investigation must be conducted before air bag suppression for restrained children is chosen as the option for future air bags. Surveillance data suggest that restrained children are not at as high a fatality risk as previously reported for predominantly unrestrained children and that injuries that restrained children exposed to airbags receive are mostly not life-threatening. However, the performance of air bags for children varies widely among vehicle types. Of particular concern are sport utility vehicles (SUV) and passenger vans: children in the front seat of these vehicles and not exposed to an air bag were at a very low risk of injury but children in similar severity crashes in these vehicles who were exposed to airbags were at a considerable increased risk of injury. In addition, consideration should be given to the evaluation of the risk of upper extremity fractures, as this is one of the most common injuries for children exposed to airbags. Dynamic sled tests (29kph pulse) were conducted in both a mid-sized car and sport utility vehicle buck. Results were extended using validated MADYMO models. Both sled testing and simulation results suggest a possible beneficial role of the air bag for certain crash scenarios involving children. Implications of the data for current child dummy design and airbag suppression considerations will be discussed.

INTRODUCTION

As of March 1, 2000, an estimated 5,303 lives have been saved by passenger and driver side air bags [National Highway Traffic Safety Administration 2001]. However, if the passenger comes into contact with an air bag during deployment or during the inflation phase, serious or fatal injuries may result [Winston and Reed 1996]. This increased risk has been shown to be particularly high in children under age 11 years. In 1997, Braver reported a 34% increased risk of fatality for children 10 years and younger in vehicles equipped with passenger air bags as compared with vehicles without passenger air bags [Braver et al. 1997]. In-depth crash investigations have identified the typical mechanisms of these pediatric air bag-associated passenger fatalities [Winston and Reed 1996; National Transportation Safety Board 1997] and have highlighted the importance of suboptimal or non-restraint in this fatality risk [Arbogast et al. 1999]. In a study of children exposed to airbags, Arbogast *et al* found 90% restraint non-use or suboptimal use among children who were fatally injured by airbags and only 10% restraint non-use/suboptimal use among children who survived airbag exposure [Arbogast et al. 1999]. These results suggest that airbag fatality risk for children is greatly influenced by restraint status.

In an effort to improve the performance of air bags for a wide range of occupants, in 2002, the National Highway Traffic Safety Administration issued a change in the FMVSS 208, *Frontal Occupant*

Protection [National Highway Traffic Safety Administration 2001]. Specifically, the new regulation requires the testing of air bags using child anthropometric dummies (ATD's) and allows for either a low risk deployment or suppression option for these passengers. With limited access to real world data regarding children exposed to airbags, manufacturers have needed to rely on laboratory testing utilizing the current Hybrid III family of ATD's to inform this vital decision. These ATD's, while state-of-the-art in child dummy design, are limited in their predictive ability in that a direct relationship between dummy responses and injuries sustained in real world crashes has not been established.

To evaluate the benefits of new air bag designs based on laboratory testing, an understanding of the current real world experience of children exposed to airbags and the relationship of this experience to laboratory data is crucial. Therefore, the purpose of the current study was to enhance the scientific base on which decisions to suppress airbags could be made. Further, since little is known about the potential benefits of airbags for restrained children, a focus of this study was directed towards understanding how a restrained child occupant interacts with a deploying air bag.

Specific aims of this study included: 1) providing population-based estimates of the risk of both minor and more consequential nonfatal injuries to children in frontal impact collisions exposed to passenger side air bags; 2) identifying typical injury mechanisms from the real world data; and 3) replicating these field data in the laboratory in order to evaluate the relative benefit or risk associated with suppression with various restraint configurations.

METHODS

Surveillance and Crash Investigation

Data were collected from December 1, 1998 to November 30, 2001 as part of the Partners for Child Safety (PCPS) project, in which State Farm Insurance Companies identifies claims for crashes in 15 states and the District of Columbia involving children and The Children's Hospital of Philadelphia conducts in-depth telephone interviews and on-site crash investigations. The methods for the telephone interview-based surveillance data crash investigation have been published previously [Winston, 2000; Durbin, 2001; Arbogast et al. 1999]. For this study, telephone surveillance data were analyzed for a probability sample of crashes in which the first impact was reported as frontal with a child occupant in the right front seat of a vehicle equipped with either a driver only or driver and passenger side airbags. This study sample included 9,779 vehicles with 15,341 child occupants, representing 115,729 vehicles with 178,769 child occupants in the study population. For the purposes of this study, "consequential injuries" were defined as all injuries with AIS scores of 2 or greater including concussions and more serious brain injuries, facial bone fractures, spinal cord injuries, internal organ injuries, and extremity fractures, as well as those injuries with potential for disfigurement (facial and scalp lacerations). "Minor injuries" were defined as all other lacerations, abrasions, and contusions. The risks of both minor and consequential injuries among children exposed to passenger side airbag (PAB) were compared to children occupying the front passenger seat in a vehicle equipped only with a driver air bag (DAB) in which the DAB deployed. In this way, PAB children could be compared to children in the same seating position in crashes of comparable severity. Because very few children under 3 years of age were exposed to a PAB, the two groups were restricted to children 3 to 15 years of age.

Detailed crash investigation of a subset of these cases yielded test parameters for the sled testing and simulation components of the study, i.e. the different restraint conditions, seat track position, position of the occupants, and crash severity (calculated Delta-v). Review of the surveillance and crash investigation results revealed the typical crash scenarios that resulted in the identified age-specific patterns of air bag-associated injury.

Sled Testing and Simulations

Typical crash scenarios were replicated on a HyGe sled with the Hybrid III 3- and 6-year old ATDs and served as the baseline tests. Validation of the baseline tests involved comparison of the injuries predicted by these tests with the injury patterns identified in the field data. An extensive sled test and simulation program followed to examine restraint conditions not covered by the field data. For this study, experimental vehicle platforms of a passenger car and sport utility vehicle were used in conjunction with the high output of a dual stage, airbag restraint system.

Baseline Testing - Initial baseline sled testing was conducted with the Hybrid III 3-year-old and 6-year-old ATD's placed in the right front seat of a mid-sized passenger vehicle with a pulse equivalent to 29 kph (18 mph) 0° full frontal impact. This 29 kph (18 mph) 0° full frontal impact represents the average equivalent impact velocity reported in cases in the

National Accident Sampling System (NASS) between 1995 and 1998 [Atkinson et al. 2000].
Review of the field data identified two test conditions appropriate as a baseline condition. Most children were reported as restrained, although children between 3 and 9 years old were not optimally seated in a child safety seat or booster seat and, when wearing seat belts, were often restrained by only the lap portion of the three-point restraint. To represent the real world risk scenarios, a Hybrid III 3-year-old ATD was placed sitting fully back in the passenger seat with the shoulder segment of the seatbelt system placed behind the ATD's back (Figure 1) and a Hybrid III 6-year-old ATD on the front edge of the seat, restrained by both parts of the lap shoulder belt system (Figure 2). Two sled tests were conducted with each ATD position and the seat in the rear track position, one with an airbag restraint system and one without.

Figure 1. Hybrid III 3-year-old – Baseline HyGe sled position.

Figure 2. Hybrid III 6-year-old – Baseline HyGe sled position.

Simulations - The HyGe sled test conditions were used as baseline inputs for a series of simulation validations. MADYMO [TNO, The Netherlands, 1999] models were generated for all four test conditions and subsequently validated against the HyGe test data. Quantitative levels of correlation were achieved using a method called the 'Validation Statistic' [Cooper et al. 1999] to evaluate and control the level of simulation correlation. This method evaluates the correlation achieved for each individual output response and subsequently indicates the overall correlation for each simulated case. A validation statistic of 0.0 indicates a perfect correlation. Previous work has shown that the validation statistic numbers below 0.5 suggest that the simulation models can be used to predict a range of events [Cooper et al. 1999].
To evaluate the full range of real world conditions suggested by the surveillance data and other relevant literature, a detailed simulation matrix was defined, (Appendix A.1). This simulation matrix was analyzed using a full factorial Design of Experiment Method (DOE). Two hundred and eighty eight simulations were required to complete the matrix with AutoDOE [Breed Technologies and Quest, 2002] being used to complete the DOE analysis using MADYMO as the crash simulation solver. Simulation variables, which were varied, included the ATD size, seat track position, impact speed, specifics of seat belt restraint, ATD position in the seat and the use of an airbag.
Both the testing and simulation results were compared to current Injury Criteria and Injury Performance Levels (ICPL's) for FMVSS 208 [National Highway Traffic Safety Administration 2001] as shown in Table 1.

Table 1. Injury Criteria and Injury Performance Levels (ICPL's) for FMVSS No 208.

	Head	Neck			Chest	
	HIC (15ms)	N_{IJ}	Tension (N)	Compression (N)	3ms (g)	Deflection (mm)
6yr	700	1.0	1490	1820	60	40
3yr	570	1.0	1130	1380	55	34

Secondary Testing - In order to confirm the numerical simulation results, HyGe sled testing was completed at the key conditions highlighted by the numerical simulation. To minimize the number of sled tests needed only the Hybrid III 6-year-old ATD was tested. This ATD choice was based upon findings from the surveillance data that suggested that majority of the children seated in the front passenger seat were above 5 years of age. A total of twelve sled tests at 42 kph (26mph) were completed using the same passenger car platform and restraint system as in the baseline sled series. Although not previously simulated, an unbelted condition was added in order to further explore the role of restraint in injury and probable effects of airbag suppression.

An additional 10 HyGe sled tests were also conducted using a generic sport utility vehicle (SUV) platform to explore the role of vehicle type in air bag risks. This testing replicated the passenger vehicle tests, however, two tests were eliminated due to a lack of available parts. The test matrix for the secondary HyGe sled tests is shown in Table 2.

Table 2. Secondary HyGe Sled Test Matrix for Passenger Vehicle and SUV

ATD	Child Position in Seat	Seat Track Position	Seat Belt Restraint	Airbag
Hybrid III 6 yr ***	Sitting Back	Full Rear	Lap and Shoulder	With and Without
Hybrid III 6 yr	Sitting Back	Full Forward	Lap Only	With and Without
Hybrid III 6 yr	Sitting Forward	Middle	Lap and Shoulder	With and Without
Hybrid III 6 yr	Sitting Forward	Middle	Shoulder Under Arm	With and Without
Hybrid III 6 yr	Sitting Forward	Middle	Lap Only	With and Without
Hybrid III 6 yr	Sitting Back	Middle	Unbelted	With and Without

*** - Test not conducted in SUV due to part availability

RESULTS

Surveillance

Between December 1, 1998, and November 30, 2001 interviews were completed for 852 children 3 to 15 years of age who were exposed to passenger airbags (PAB). These data were then weighted, based on their probability of selection, to represent 1,377 children. For this analysis a weighted comparison group was chosen representing 642 children in the right front passenger seat of vehicles where the driver airbag (DAB) deployed, but the vehicle did not have a passenger airbag. 90.3% of the children exposed to the PAB were restrained and less than 4% of these were in child/booster seats, whereas only 85.1% of the children in vehicles where the DAB deployed were restrained and none were in a car/booster seat. Analysis was further broken down by vehicle type to examine the influence of this parameter on injury rates.

<u>All Vehicle Types</u> - For all vehicle types, the overall risk of any level of severity of injury (both minor and consequential) was 87.0% (1,198 /1,377) among children exposed to PAB compared to 52.5% (337/642) among the DAB exposed comparison group (referred to below as the "comparison non-exposed group") (OR=6.06, 95% CI 2.63-13.93, p<0.001) (Figure 3). Minor injuries (facial abrasions,

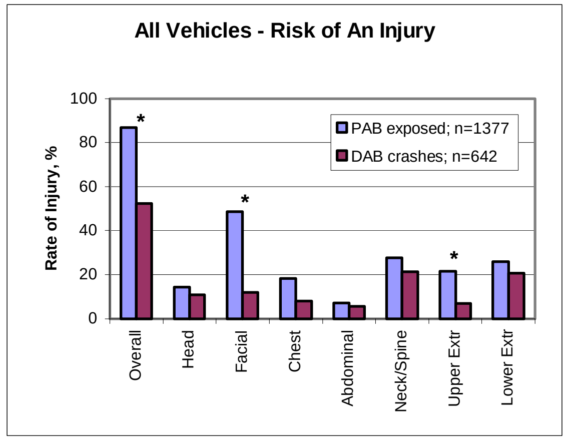

Figure 3. Risk of any injury (both minor and consequential) by body region for all vehicle types. *Represents statistically significant differences.

chest abrasions, arm abrasions) account for approximately 85% of all injuries recorded in this sample. The child exposed to a PAB was almost twice as likely to suffer a consequential injury (includes serious facial lacerations, concussion and more severe head/brain injuries, intra-abdominal organ injuries, spinal cord injuries and extremity fractures) compared to the child in the comparison non-exposed group (OR=1.84; 95% CI 1.07-3.15, p=0.020). Head injuries, including concussions and more serious brain injuries, were the most common consequential injury among both the PAB exposed children and the comparison non-exposed group, as shown in Figure 4. There was a trend toward a higher risk of consequential head injury to the PAB exposed child in comparison to the comparison non-exposed group (OR=1.67; 95% CI 0.90-3.10, p=0.10). The difference in consequential injury risk

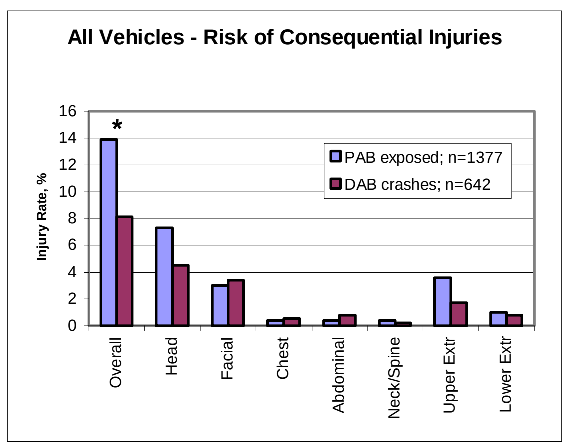

Figure 4. Risk of consequential injuries by body region for all vehicle types.
*** Represents statistically significant differences.**

was primarily due to an increase in upper extremity fracture (OR=2.12, 95% CI 0.97-4.60, p=0.06) with exposure to PAB compared to the comparison non-exposed group. Among all children in the study, children ages 3-8 years had the highest absolute risk of consequential injuries when exposed to a PAB (17.5%) and the highest risk difference when compared to the age-specific comparison non-exposed group (17.5% in the PAB group versus 8.1% in the comparison non-exposed group). No deaths due to airbag deployment were found in this study.

Passenger Cars Only - Passenger cars accounted for over half the vehicles equipped with PAB for crashes in the PCPS study meeting the study criteria (Figure 5). Figure 6 shows the injury rates for the passenger car only with the overall injury rates in both the PAB airbag exposure subgroup as well as the comparison non-exposed group (including both minor and consequential) similar to that for all vehicles. The likelihood of any severity facial injury (OR=5.59, 95% CI 2.39-13.07, p<0.001) or upper extremity injury (OR=3.93, 95% CI 1.79-8.60, p=0.001) was significantly greater in the PAB exposed group when compared to the comparison non-exposed group. There was a trend toward increased risk of consequential injury to the child in a passenger car PAB deployed crash as compared with a child in a passenger car in the comparison non-exposed, however the result was no longer statistically significant (OR=1.50; 95% CI 0.76-2.96, p=0.24), Figure 7.

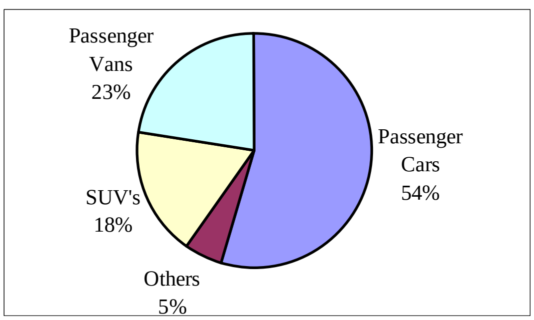

Figure 5. Distribution of vehicle types involved in frontal crashes with air bag deployment in the PCPS surveillance system.

Sport Utility Vehicles (SUV) Only - The overall injury rate in the children exposed to PAB as passengers in SUV (Figure 6) was similar to that for children exposed to PAB for all vehicles combined (SUV: 89.9% versus all vehicles: 87%) and the rate in the comparison non-exposed group (children in SUV with DAB deployment without a PAB) was much lower than that for children in the whole comparison non-exposed group (SUV: 13.9% versus all vehicles: 52.5%). The risk of consequential injury to the child in a SUV PAB

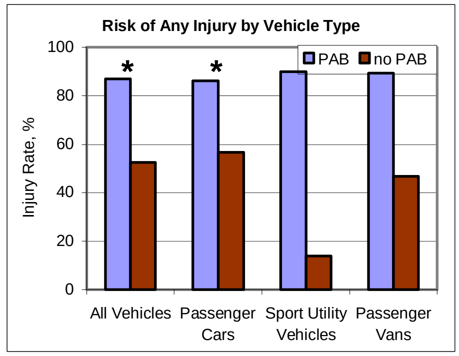

Figure 6. Risk of any injury (both minor and consequential) by vehicle type.
*** Represents statistically significant differences.**

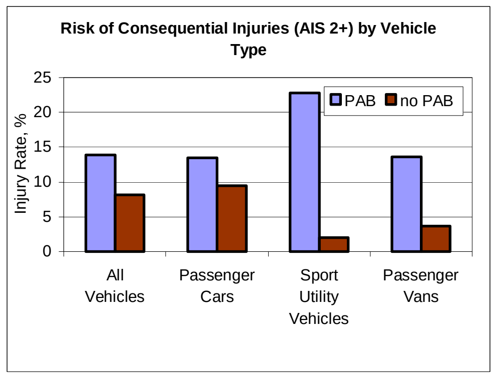

Figure 7. Risk of any consequential injuries by vehicle type.

deployment crash was over 14 times greater than a child in the front seat of an SUV DAB deployment crash (OR=14.56, 95% CI 1.18-178.90, p=0.037), Figure 7. Injury rates for SUV children seated in the front seat of DAB deployment frontal crashes was the lowest among all vehicle types, but injury rates were highest for children seated in the front seat of SUV PAB deployment crashes. There were too few counts of injuries in the DAB group to perform meaningful statistical tests comparing body region specific and age group injury rates.

Passenger Vans Only - The overall injury rate in the children exposed to PAB (Figure 6) was similar to that for other vehicle types (vans: 89.5% versus all other vehicles: 87%) and the rate in the passenger van comparison non-exposed group was similar to that for all vehicles combined (vans: 46.8% versus all other vehicles: 52.5%). The risk of consequential injury to the child in a passenger van PAB deployment crash was more than 4 times greater than that for a child in the front seat of a passenger van DAB deployment crash (OR=4.06, 95% CI 1.09-15.11, p=0.037), Figure 7. There were too few counts of injuries in the DAB group to perform meaningful statistical tests comparing body region specific and age group injury rates.

Testing and Simulations

Baseline Testing - The baseline test results for the Hybrid III 3-year-old and 6-year-old ATD demonstrated similar biomechanical performance with and without the airbag restraint. In both ATD types, the injury values were below the latest FMVSS 208 (Final Rule Making) ICPL's. Figures 8 and 9 show the normalized results of the four tests with the two types of ATD's respectively.

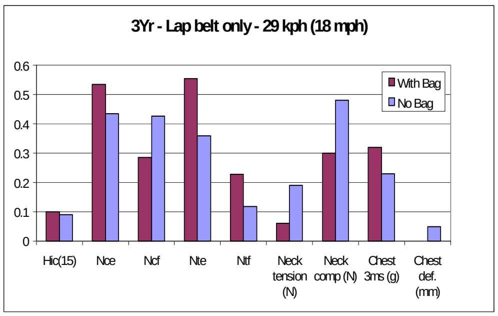

Figure 8. Normalized results of the Hybrid III 3-year-old baseline HyGe sled test.

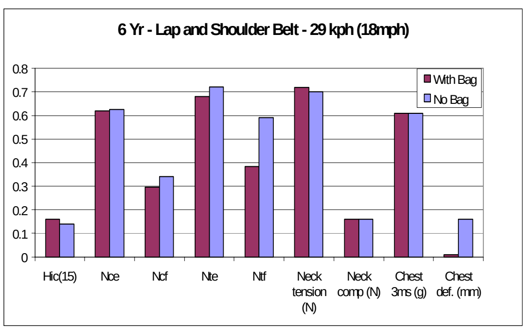

Figure 9. Normalized results of the Hybrid III 6-year-old baseline HyGe sled test.

Simulation Validation - MADYMO models were validated against the baseline HyGe sled tests for the 3- and 6-year-old ATD's, with and without an airbag. The level of validation statistic achieved between the injury measures obtained during the simulation and those obtained during the baseline HyGe testing are shown in APPENDIX A.2. For the head, chest and pelvis body regions, the correlation results meet the criteria of 0.5 required for predictive models. A higher level of correlation was achieved with the Hybrid III 6-year-old condition than with the Hybrid III 3-year-old. In particular the neck responses for the Hybrid III 3-year-old show unsatisfactory correlation values suggesting that any predicted responses from the neck should be treated with extreme caution. Head impact did not occur with the instrument panel in any of the baseline sled test cases. As a result the simulation model validation did not include the development of a head to instrument panel contact interaction function. Therefore, great care was taken when using the simulations results produced where head to instrument contact had occurred.

Simulation Results - The simulation results for each injury criterion was plotted against impact speed and seat track position with and without the airbag restraint. A typical set of injury results is shown in APPENDIX B for the Hybrid III 3-year-old, with and without the airbag restraint, using the lap shoulder belt sitting fully back and in APPENDIX C for the corresponding Hybrid III 6-year-old. For both types of ATD, in the case of the correctly positioned seat belt and the ATD seated fully back in the seat, the injury values increase with impact speed and increasing distance between the child and the instrument panel. However, for each ATD, as the effective level of seat belt restraint and the proximity to the instrument panel is reduced the injury values typically increase for any given speed in comparison to the ATD with the lap shoulder belt restraint.

The results with the airbag restraint were compared to those without for each ATD tested in each seat track position and seat belt condition. In most cases maximum airbag injury occurred at a speed of 56 kph (35 mph). This speed was considered too extreme when considering the surveillance data and was not considered further. As a result, the simulation data were presented for the 42 kph (26 mph) case, (APPENDIX D) as this was considered the worst-case scenario representative of the surveillance field data. In all cases the HIC, Chest G, Chest Deflection, and Neck forces, moments, and Nij were compared.

With the Hybrid III 3-year-old ATD, the injury results in general were seen to decrease as the level of seat belt restraint increased, i.e. from shoulder belt behind the back to under the arm to in front of the chest. In general for all cases, except for the ATD with both portions of the seat belt in front of the torso, the injury measures were lower with the airbag restraint than without the airbag. HIC levels for the less optimal level of restraint with and without airbag are shown in APPENDIX E.1. In the case of the Hybrid III 3-year-old ATD sitting fully back, with the seat track in the rear position, and using both parts of the lap shoulder belt, the airbag did not influence the injury measures, especially HIC, regardless of the fore–aft seat track location, Figure 10.

In the case of the 3-year-old ATD sitting fully forward at the edge of the seat and using both parts of the lap shoulder belt, the HIC measures were much higher with the air bag than without with the seat in

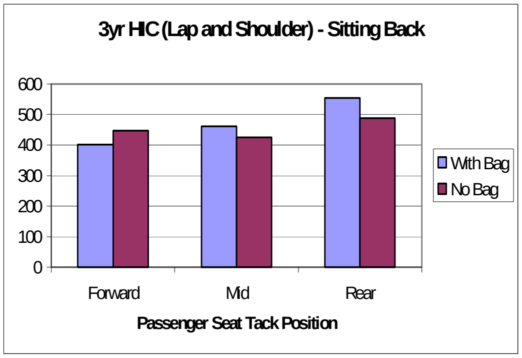

Figure 10. 3-year-old HIC injury with Lap and Shoulder Belt, sitting back at 42 kph (26 mph)

the mid position, Figure 11. When the seat was full forward the HIC results were lower with the airbag. When the seat was full rear, the HIC results with and without the airbag were almost identical. In all other cases where a less optimal level of seat belt restraint was used, regardless of the fore-aft seat track position, in general, the injury measures were lower with the airbag than without, especially the HIC. Although the N_{IJ} values were seen to decrease with the addition of the airbag there was generally an increase in neck compression, which was compensated by a larger decrease in neck tension to produce the reduction in N_{IJ}.

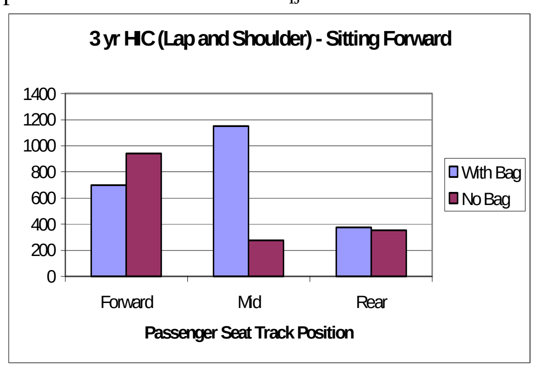

Figure 11. 3-year-old HIC injury with Lap and Shoulder Belt, sitting forward at 42 kph (26 mph)

The Hybrid III 6-year-old ATD simulation results produced similar results to the 3-year-old ATD results. In general, the injury measures decreased as the level of seat belt restraint increased. HIC levels for the less optimal levels of restraint with and without airbag are shown in APPENDIX E.2. In all cases, except for the ATD using both portions of the lap shoulder belt, the injury measures with the airbag restraint were lower than without. In the case of the ATD sitting fully back, with the seat in the rear position, and using both portions of the lap shoulder belt, the airbag did not seem to influence the injury measures, regardless of the fore–aft seat track location (Figure 12).

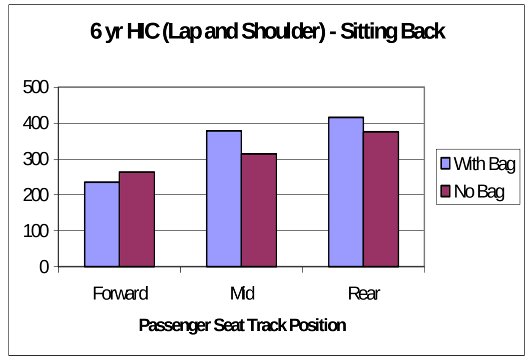

Figure 12. 6-year-old HIC injury with Lap and Shoulder Belt, Sitting Back at 42 kph (26 mph)

In the case of the 6-year-old ATD sitting fully forward on the edge of the seat and using both portions of the lap shoulder belt, the injury measures were higher with the air bag than without regardless of the fore aft seat track position. In the case of the seat in the full forward position the HIC measures with the airbag were much higher than without as shown in Figure 13. In all other cases where a less optimal level of seat belt restraint was used, regardless of the fore-aft seat position the HIC measures were lower with the airbag than without, except in the one case with the ATD sat fully back, with the shoulder belt placed under the arm, with the seat in the middle track position. In this case the HIC result was comparatively higher with the airbag than without.

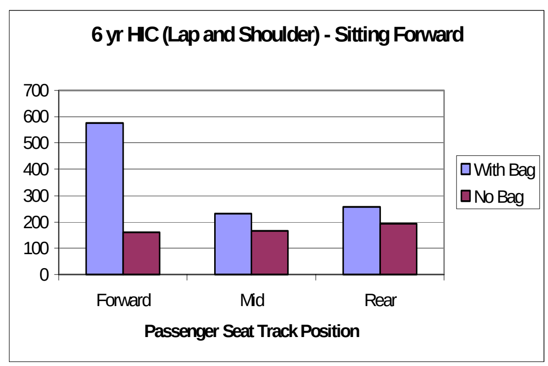

Figure 13. 6-year-old HIC injury with Lap and Shoulder Belt, Sitting Forward at 42 kph (26 mph)

Secondary Testing - The simulation results were further explored through HyGe testing and the injury trends obtained were similar to the simulation. For the passenger car sled testing, APPENDIX F summarizes the normalized results showing the injury comparison between airbag restraint and no airbag restraint. In the case of the shoulder belt in front of the chest with the ATD sitting fully back and the seat track in the full rear position, the test results with and without the airbag restraint were very comparable for the ATD positions and fore-aft seat track positions tested.

In all the other restraint scenarios tested, the 6-year-old ATD injury measures were collectively lower with an airbag restraint system than without. This was especially true of the unbelted test where there was significant reduction in all injury measures when exposed to an airbag except for HIC where the values were similar. For the positions and ATD tested, the HyGe sled test results confirm the simulation results.

The SUV sled tests replicated the same setup and dummy conditions as the passenger car. Two tests, with and without an airbag, where the dummy is seated full rear and wearing the lap and shoulder belt in front, were omitted from the SUV tests due to lack of available vehicle parts. This omission is not considered critical since in the passenger car tests, the bag/no bag comparison of this ATD position and belt use pair yielded nearly identical results.

The results of the 10 tests demonstrated the same trends as the passenger car tests relative to the effect of the airbag. APPENDIX G summarizes the normalized results showing an injury comparison between airbag restraint and no airbag restraint for the SUV environment. In all seatbelt restraint scenarios for the PAB deployment, the 6-year-old ATD injury values were consistently lower or equal to the comparable test without an airbag. HIC was dramatically lower in 3 of 5 positions with an airbag than without and well below the tolerance values in the other 2 positions for both bag and no bag. Neck tension was always less when an airbag was present and other neck values remained lower in most tests when an airbag was present as the head shows less tendency to strike hard objects or to have more violent motions. The most striking difference was the unbelted case where the injury values for the no airbag case were at or exceeded the threshold value (normalized value greater than 1) while the airbag case for this position with no belt use were all less than threshold.

DISCUSSION

This study provides real world, sled test, and simulation data regarding restrained children in frontal crashes. The results can be used to aid in decision-making regarding the low-risk or suppression options for passenger airbags when children are seated in the front seat.

Surveillance

Based on a large experience of children in crashes, this study found that restrained children in frontal crashes who were exposed to airbags were at a 6-fold increased risk of injury as compared with children, in similar severity frontal crashes, who were not exposed to airbags, but that the vast majority of these injuries were minor. Consequential injuries of particular concern were upper extremity fractures and head injuries in that children exposed to PAB were more likely to suffer these injuries than children who were in similar severity crashes but were not exposed to PAB.

Across vehicle types, a similar pattern of injury was found. However, there appeared to be an increased risk of injury to children exposed to air bags in SUV and passenger vans when compared with children in passenger cars despite the fact that children in SUV and passenger vans who were not exposed to air bags were at lower risk of injury as compared with children in passenger cars. This result should be interpreted with caution because the study sample for both groups consisted of low number of children within each of these SUV exposures to airbag groups – PAB (n=79) and DAB (n=50).

Testing and Simulations

Tests with the Hybrid III 3- and 6-year-old ATD at 29 kph (18 mph) in frontal impacts without pre-impact braking showed that the risk of head injury was very low based on the current ICPL's. These results suggest a less than 10% chance of an AIS 1 head injury [Prasad and Mertz 1984]. Chest g's were slightly higher for the 3-year-old ATD exposed to the PAB but injury values were well below the thresholds. Extension of the baseline testing by simulation further demonstrated that the air bag is potentially injurious only for the lap and shoulder belt restrained child sitting fully forward on the seat – otherwise the airbag appeared to mitigate injuries, especially to the head for children sub-optimally restrained. The simulations also suggest that the airbag restraint offered a level of protection to both the Hybrid III 3- and 6-year-old except where the ATD has the seat belt correctly placed in the front of the chest and lap. In any case, the risk of injury did not appear to increase with the addition of the airbag restraint regardless of the level of seat belt restraint used or seat position of the ATD. As these results were predicted using numerical simulation models that were validated over a limited restraint range of test conditions, the conclusions were deemed interesting but not necessarily conclusive. Additionally, the neck responses for the Hybrid III 3-year-old show unsatisfactory correlation values suggesting that any predicted responses from the neck were treated with extreme caution. In this simulation study no account for upper extremity injury was considered due, specifically, to the limitation of the simulation modeling capability and the absence of recognized injury criteria for the upper extremity. From the surveillance data results, the upper extremity injury appears to be a significant factor when considering an airbag restraint performance. Therefore, the simulation analysis results should carefully consider the omission of the upper extremity results before reaching any significant conclusion. From the secondary sled tests it was confirmed that in the restrained cases (both lap and shoulder belt) that the PAB was neither harmful nor beneficial in the rear seat track position and had higher head injury values (HIC) for the ATD's in the middle seat track positions. These values from the middle seat track position, although not higher than the ICPL's, could be interpreted using the AIS scores [Prasad and Mertz 1984] as having between 11 and 25 % chance of an AIS 2 head injury and between 5 and 11% chance of AIS 3 head injury. The HIC values obtained from the SUV environment tests were slightly higher than that obtained for the passenger car. Both the simulations and the testing show that in all the other restraint scenarios, the Hybrid III 6-year-old ATD injury measures are collectively lower with an airbag restraint system than without. This is especially true of the unbelted test where there was significant reduction in all injury measures except for HIC where the values were similar.

LIMITATIONS

Surveillance

Nearly all of the data for the surveillance system were obtained via telephone interview with the driver/ parent of the child and is, therefore, subject to potential misclassification. On-going comparison of driver-reported child restraint use and seating position to evidence from crash investigations has demonstrated a high degree of agreement. In addition, our results on age-specific restraint use and seating position are similar to those of other recently reported population-based studies of child occupants [Edwards, 1997; Wittenberg, 1999].

The surveillance study sample represents the entire spectrum of crashes reported to an insurance company including property damage only, as well as bodily injury crashes. While the sample included a significant number of vehicles with intrusion into the occupant compartment, it is possible that we do not have a representative sample of the most severe crashes.

Although the contemporary nature of our data collection system allowed for injury estimates of the current vehicle fleet (model years 1990 – 2002), a small portion of the study sample involved second generation airbags (MY 1998 or newer vehicles). Our current data can provide a suitable baseline to which future air bags may be compared in order to assess the real world effectiveness of future air bags development. Future work will explore the effect of second generation airbags on injury risk.

Serious injuries as defined for this study included injuries ranging in severity from concussions to severe brain injuries. Our surveillance results suggest that, on average, airbags confer no safety advantage to children in crashes. There might be specific conditions, as identified in the sled test results, in which the airbag does confer a safety advantage, however these could not be detected in our surveillance data. If airbags are actually beneficial in the most severe crashes, such as modifying the severity of head injuries in serious crashes from potentially life-threatening injuries to concussions, the current study may not be able to detect this.

Surveillance data of the nature presented in this study are crucial for identifying the magnitude and nature of risk for injury to children from passenger airbags. While the pattern of injuries noted among children exposed to PAB is consistent with the injuries being caused by interaction with the airbag, we cannot determine this with certainty. In order to elucidate the specific mechanisms by which children are injured in these crashes, more detailed information on the nature and severity of the injuries, occupant kinematics, and characteristics of airbags is needed.

Testing and Simulations

Previous studies have demonstrated the importance of pre-impact braking combined with restraint non-use or misuse in child air bag-associated fatalities. [Arbogast et al. 1999]. The laboratory testing and simulations in the current study that demonstrated a safety benefit to some children did not take into account pre-impact braking. Further consideration of the option of suppression or non-deployment of airbags should take into account the effect of pre-impact braking. In addition, the current ATD's neck has been suggested to be lacking in biofidelity and tends to show a higher degree of injury than is reflected in the real-world data. In addition, there is no instrumentation or injury tolerances for the upper extremity to help evaluate the risk of this injury in the simulation or testing data.

CONCLUSIONS

The results of this study suggest that more investigation must be conducted before air bag suppression for restrained children is chosen as the option for future air bags. Surveillance data suggest that restrained children are not at as high a fatality risk as previously reported for predominantly unrestrained children and that injuries that restrained children exposed to airbags receive are mostly not life threatening. The study further demonstrated that the performance of air bags for children varies widely among vehicle types. Of particular concern are SUVs and passenger vans: children in these vehicle types in the front seat and not exposed to an air bag were at a very low risk of injury but children in similar severity crashes who were exposed to airbags were at a slightly increased risk of injury. In addition, consideration should be given to the evaluation of the risk of upper extremity fractures, as this is one of the most common injuries for children exposed to airbags. Sled and simulation testing results suggest a possible beneficial role of the air bag for certain crash scenarios involving children.

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REFERENCES

Arbogast K, Durbin, D, Resh, B and Winston, F. (1999) The Influence of Occupant Characteristics on Risk of Pediatric Air Bag Injury. *43rd Stapp Car Crash Conference*. San Diego, CA.

Atkinson, P., et al, (2000) Analysis of Rollover and Frontal-Side-Rear Impact Accidents in the United States, Breed Technologies Internal Report Number, E5689100-00

AutoDOE, Copyright 2002 Breed Technologies and Quest, Distributed by TNO Automotive, Delft, The Netherlands.

Braver E, Ferguson S, Greene M, Lund A. (1997) Reductions in death in frontal crashes among right front passengers in vehicles equipped with passenger air bags. *Journal of the American Medical Association*. v278:1437-1439.

Cooper, J., et al., (1999) Qualitative Methods for Comparison of Analytical Models to Empirical Data, Conference: 3rd Annual North American Madymo Users Meeting, October 13th, 1999.

Durbin, D., et al. (2001) Partners for Child Passenger Safety: A unique child-specific crash surveillance system. *Accid. Anal. Prev.*, **33**: p. 407-412

Edwards J, Sullivan K. (1997) Where are the children seated and how are they restrained? Presented at the Society of Automotive Engineers, Government/Industry Meeting; Washington, D.C. SAE 971550; May 5-7.

King A, Yang K (1994) Research in biomechanics of occupant protection. *Journal of Trauma*. 261:11.

MADYMO Crash Victim Simulator, Version 5.4.1, Copyright 1999, TNO Automotive, Delft, The Netherlands.

National Transportation Safety Board (1996) The performance and use of child restraint systems, seatbelts, and airbags for children in passenger vehicles. Washington.

National Highway Traffic Safety Administration, (2001) 49 CFR Part 571, [Docket No. 01-11110; Notice1], RIN 2127-Al10, Federal Motor Vehicle Safety Standards; Occupant Crash Protection; Final Rule, Tuesday December 18th 2001

National Highway Traffic Safety Administration – Special Crash Investigation, (2001) Counts of Air Bag Related Fatalities and Seriously Injured Persons. http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/SCI/3Q_2001/ABFSISR.html.

Prasad, P. and Mertz, H. (1984) The position of the United States delegation to the ISO working group 6 on the use of HIC in the automotive environment, SAE Government/Industry Meeting and Exposition, SAE # 851246.

Winston F, Reed R. (1996) Airbags and Children: Results of a National Highway Traffic Administration special investigation into actual crashes. *40th Stapp Car Crash Conference*. Albuquerque, NM;pp:383-389

Winston, F., et al. (2000) The danger of premature graduation to seat belts for young children. *Pediatrics*, 105: p. 1179-1183.

Wittenberg E, Nelson TF, Graham JD. (1999) The effect of passenger airbags on child seating behavior in motor vehicles. *Pediatrics*, 104(6):1247-1250.

APPENDIX A

A.1 Simulation DOE Matrix

3Yr Old - Sitting fully back	3Yr Old - Sitting forward with knees at edge of the seat
6Yr Old - Sitting fully back	6Yr Old - Sitting forward with knees at edge of the seat

Total number of simulation runs for each ATD was 288

3 seat positions
- Full Forward
- Middle
- Full back

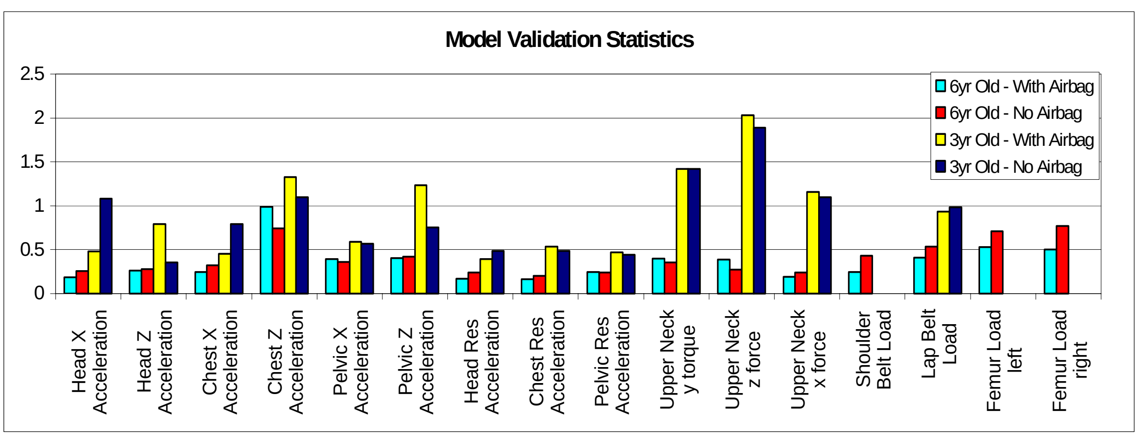
4 impact speeds
- 12 MPH
- 18 MPH
- 26 MPH
- 35 MPH

2 ATD positions
- Back in the seat
- At the edge of the seat

4 firing scenarios
- With Airbag (high output, + 20 % and - 20 %)
- no Airbag

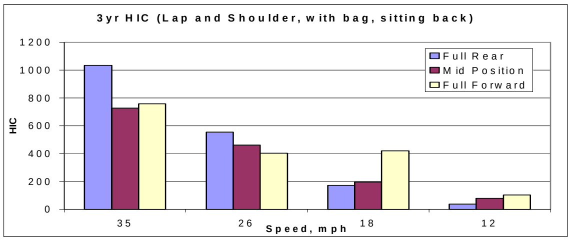
3 belting scenarios
- Lap and shoulder,
- Lap and shoulder belt behind back
- Lap and shoulder belt under arm

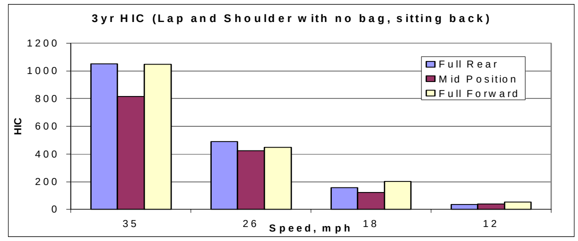
A.2 Level of correlation achieved with the simulations as compared to the baseline testing.

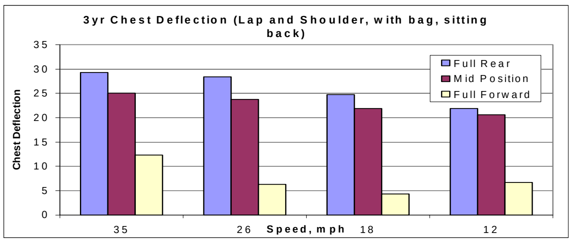


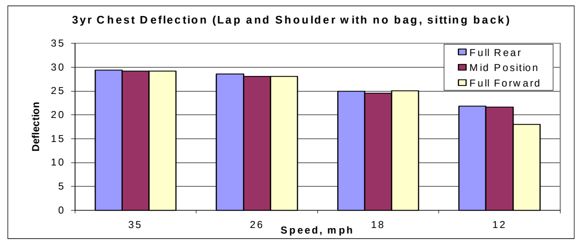
APPENDIX B

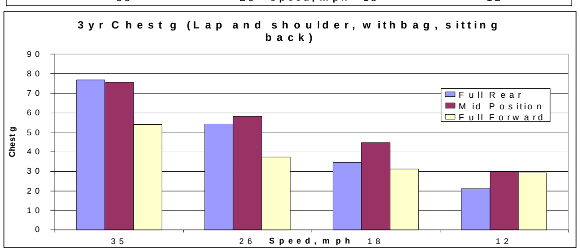
Head and Chest Injury Results for the Hybrid III 3 Year Old with and without the airbag restraint system .

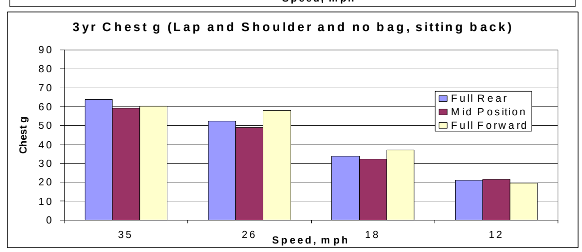






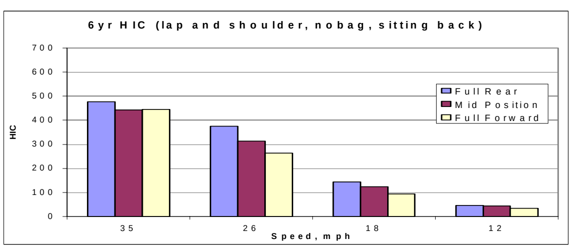


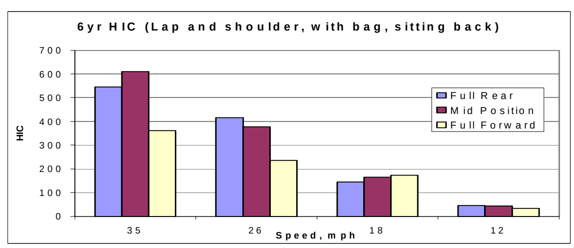


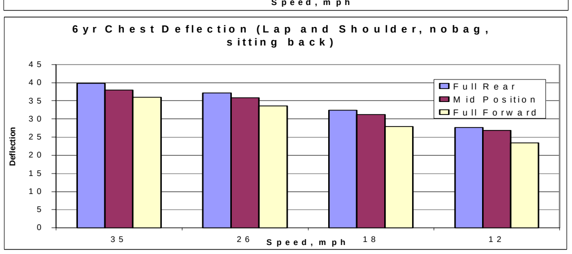


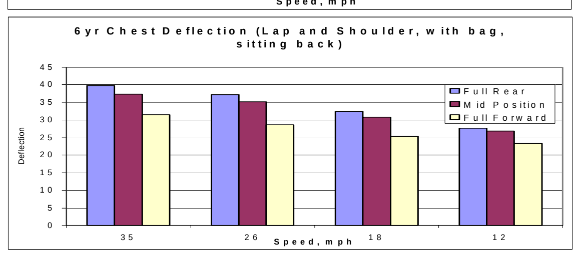
APPENDIX C

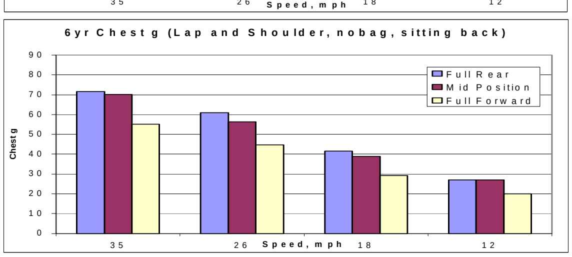
Head and Chest Injury Results for the Hybrid III 6-year-old with and without the airbag restraint system.

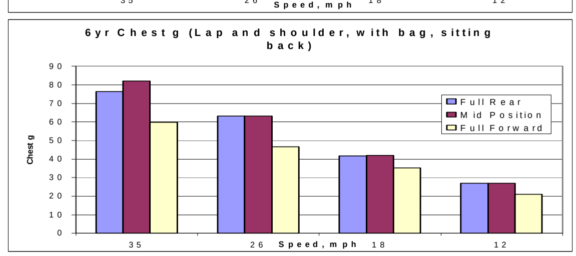






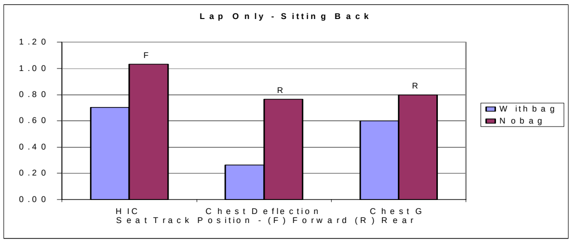


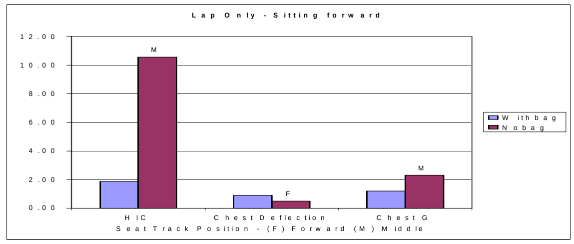


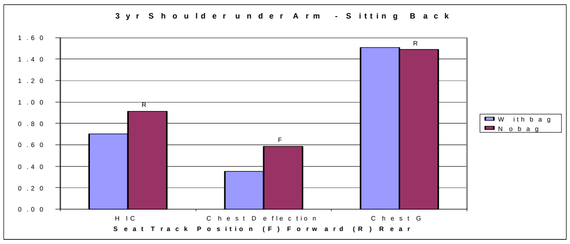


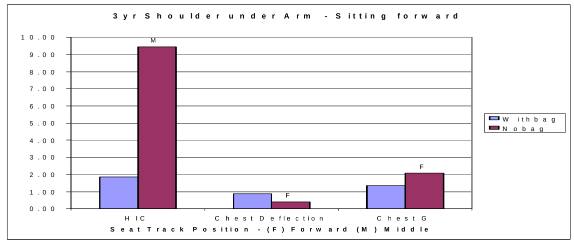
APPENDIX D

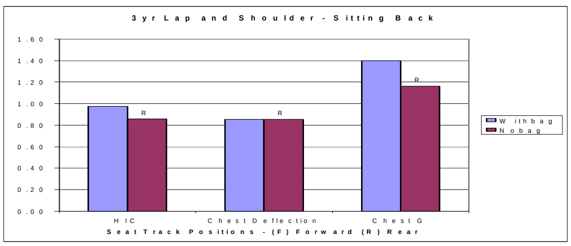
Hybrid III 3-year-old Results at 42 kph (26 mph) for Each Seat Track Position Considered.

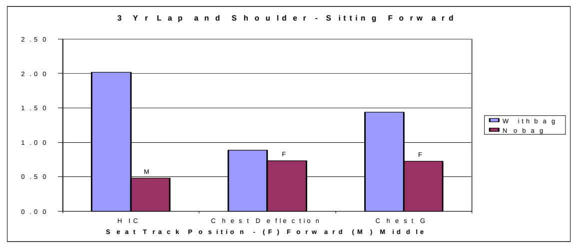






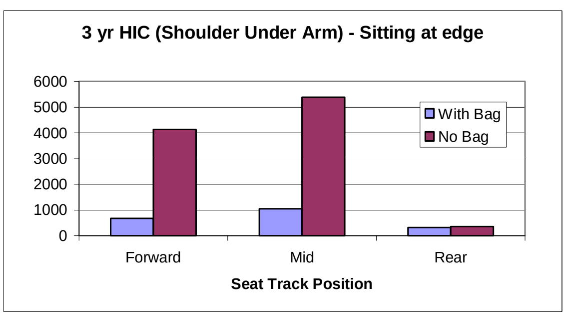


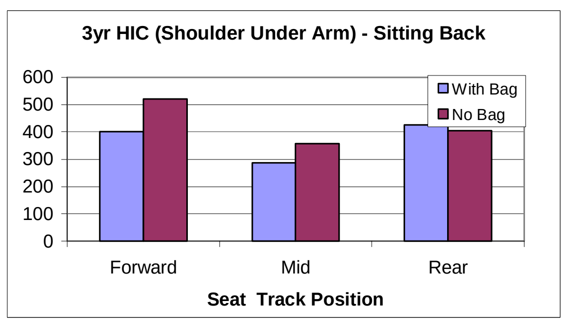


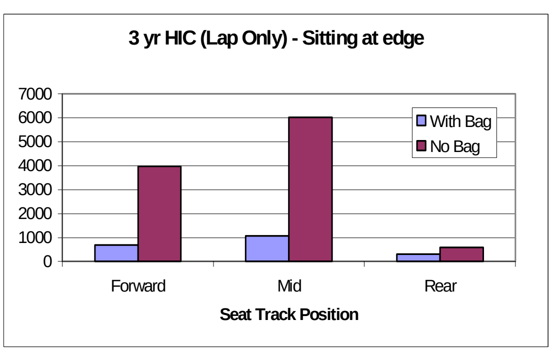


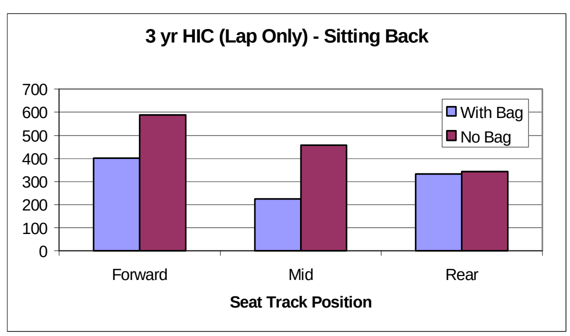
APPENDIX E

E.1. Hybrid III 3-yr-old HIC injury with Less Optimal Level of Restraint at 42 kph (26 mph)

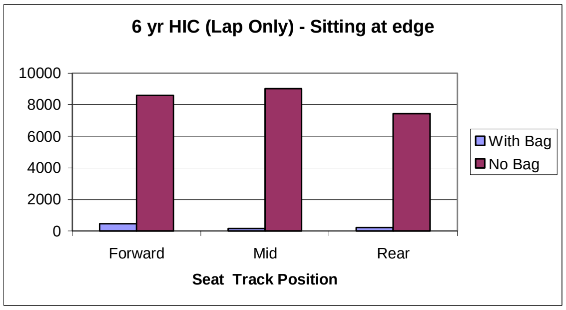


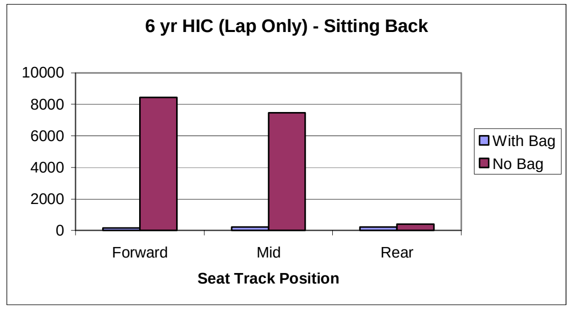


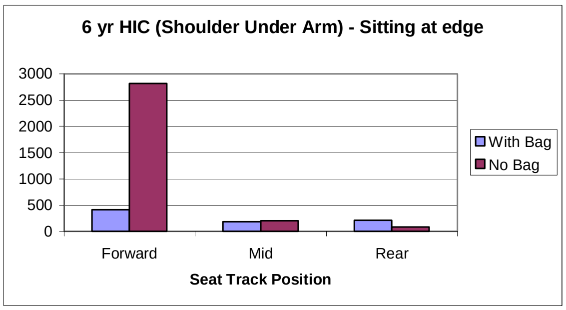


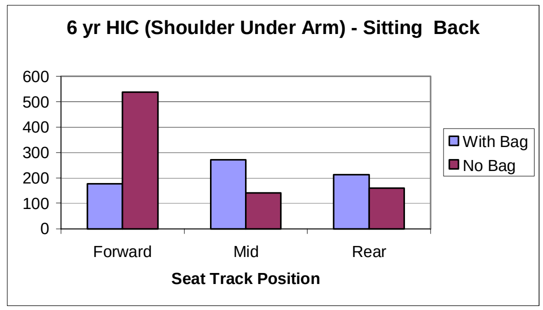


E.2. Hybrid III 6-yr-old HIC injury with Less Optimal Level of Restraint at 26 mph.



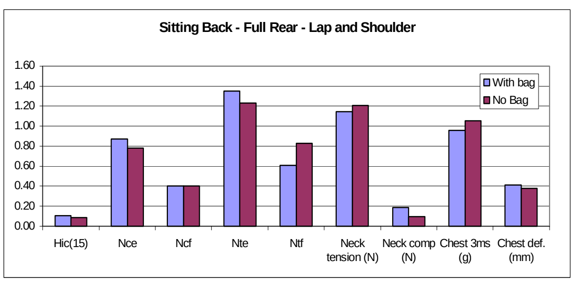


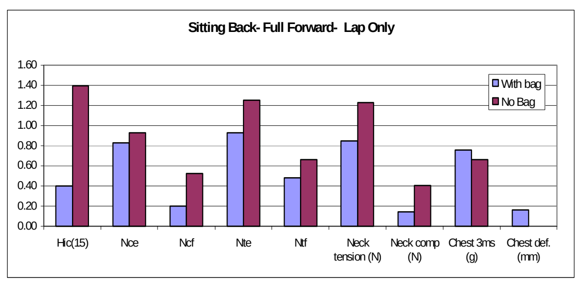


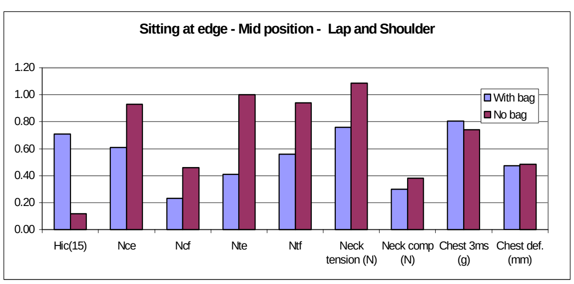


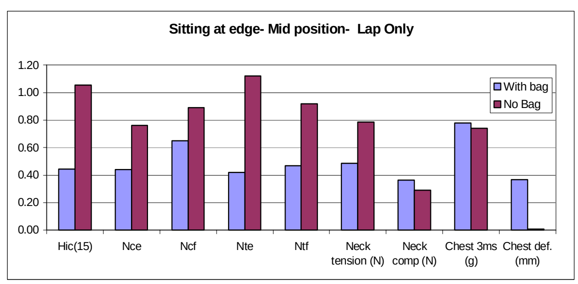
APPENDIX F

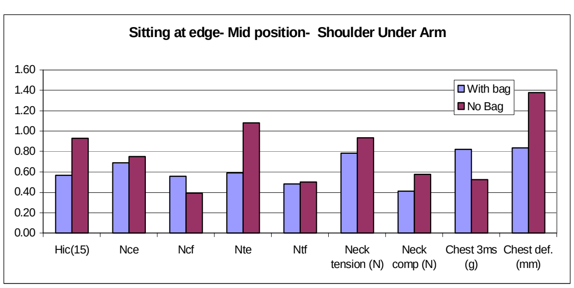
Normalized Sled Test Results for Secondary Tests in Passenger Car Environment with Hybrid III 6-year-old ATD.

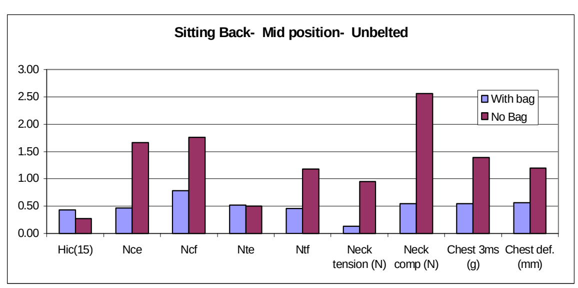












APPENDIX G

Normalized Sled Test Results for Secondary Tests in SUV environment with Hybrid III 6-year-old ATD.