Analysis of the interaction between child occupants and deploying frontal passenger airbag in simulated frontal crashes

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ABSTRACT

Objective: Since the 1990s there has been an emphasis on designing the vehicle airbag system to depower the front passenger airbag to improve the safety of child occupants in the front seat. Recommendations based on first-generation airbag designs varied from switching off PAB to having children less than 13 years of age to be seated in the rear seat. Airbags have evolved over the years and there have been changes to the intensities and deployment characteristics of modern airbags. The aim of the study was to quantify the responses of the 6-year-old ATD installed in child restraint systems seated in the front passenger seating position exposed to a deploying modern front passenger airbag.

Methods: Finite element (FE) models of a 2012 Toyota Camry model (National Crash Analysis Center archives), child seat models (developed internally), a tuned modern front passenger airbag (PAB) (Takata Inc., MI), a Q6 anthropomorphic test device (ATD) model (Humanetics Inc., MI), and a tuned 3-point lap-shoulder belt with pretensioner/retractor (developed internally) were used for the simulations. Seating conditions consisted of a convertible seat in forward-facing harness mode (FFC) with and without a top tether, a highback booster (HBB) and a baseline condition without any child restraint system (No-CRS) in normal seating and a misuse condition with seatbelt behind the back. Models were simulated (N = 12) for NCAP frontal test at 35mph.

Results: Head contact was observed with the instrument panel (IP) in all misuse conditions without PAB (HBB and No-CRS condition with seatbelt behind the back, and FFC without top tether). This contact was eliminated for HBB and FFC seats by the deployment of a PAB. PAB and no-PAB conditions for HBB in normal seating resulted in HIC15 values of 390 and 359 respectively, and resultant head acceleration of 72G and 71G respectively. For FFC with top tether, deployment of PAB resulted in 24.4% reduction in HIC15 (754 to 570) and 12.9% reduction in resultant head acceleration (93G to 81G) as compared to no-PAB condition. For FFC, utilization of top tether resulted in 15.6% reduction in head excursion in the no-PAB condition (471mm to 397mm) and 5.2% reduction (324mm to 307mm) in the case with PAB. In the No-CRS normal usage condition, there was minimal head interaction with the PAB. The PAB and no-PAB conditions showed similar HIC15 (204 and 188 respectively) and resultant head acceleration values (51G for both). In the misuse condition, the Q6 head slid under the deployed PAB and contacted the IP.

Conclusions: In all situations, deployment of PAB provided similar or a relative positive effect as compared to no-PAB condition. There was a clear benefit of using a PAB in all the misuse conditions as it eliminated head contact with the IP. Even in cases where there was no contact with IP (no PAB), usage of PAB resulted in reduced head excursion and comparable or lesser values of HIC. Additional simulation conditions and testing are necessary to explore crash pulses, directions and vehicle/airbag models.

Keywords: Child restraints, Crash dummies, Finite Elements, Front airbags, Front impact, Occupant kinematics

INTRODUCTION

Historically, much attention has been devoted to the interaction between children and frontal passenger airbags. Since the 1990s there has been an emphasis on designing the vehicle airbag system to disable the passenger airbag (PAB) to improve the safety of child occupants. Recommendations vary from switching off passenger airbags to varying airbag deployment intensities based on seating weight. Another initiative in the US was to have all children less than 13 years of age sit in the rear seat. However, these recommendations were based on the designs of first-generation airbags. In the last decade, there have been advancements in airbag inflators and folding techniques with changes in the deployment characteristics of PABs. Additionally, there have been developments in seatbelt restraint systems with the inclusion of pretensioners and load limiters which are designed to work as an integrated system in conjunction with the airbag to further help position the occupant and manage the crash energy. There is a need to explore and quantify the injury potential for children due to a deploying modern front passenger airbag for those in forward-facing child restraints and booster seats in a frontal impact across a range of normal seating and misuse conditions.

These advancements question the validity of the guidelines, based on first-generation airbags, for modern airbag designs. Menon et al. (2003) performed real-world surveillance studies, sled tests, and simulations to explore the interaction of PAB and restrained child occupants in front passenger seat. Their analysis showed that the fatality risk for restrained children was not as high as previously reported for unrestrained children, and that the injuries sustained by restrained children exposed to airbags were mostly not life-threatening. Both sled testing and simulation results suggested a possible benefit of the passenger airbag for restrained children.

Several studies (Winston et al. 2007) have suggested that for certain subgroups of occupants, the front seat is actually safer. These include older adults (Kuppa et al. 2005) and may even extend to young adolescents (Durbin et al. 2015).

Volvo (Heurlin et al. 2016) studied forward-facing pediatric ATDs (Q series dummies - 3YO, 6YO, 10YO) in the front passenger seat exposed to a modern deploying PAB. The hypothesis of the Volvo study was to explore the validity of the front passenger airbag disabling strategy for modern airbag designs and restrained forward-facing children. There was a concern in regard to countries where the airbag deployment was switched off for children, and if forgotten to be turned back on for adults, may compromise the safety of the occupant. The restrained ATDs were positioned in various seat track positions, booster types and sled tests were conducted for three different crash pulses. Typical misuse conditions such as seatbelt behind the back or under the arm were also considered. The study demonstrated relative positive or comparable effect for activated airbag compared to no airbag. The positive influence of the PAB was relatively more pronounced in the forward seat adjustment positions. In the misuse conditions, the airbag appeared to provide clear benefits to the child. In part based on this work, Volvo changed its recommendation for the use of the airbag cut-off switch (in Europe) for restrained children as front seat passengers in car models with airbag designs as tested in the study. Previously, they recommended switching the airbag off for children less than a height of 140 cm. Now, they recommend the airbag to be switched on (in certain newer model year vehicles with this airbag design) for all forward-facing children.

However, the Volvo study evaluated only children restrained in booster seats. Further exploration across a broader range of child restraints, occupant positioning, and test conditions is required to understand how these findings influence our comprehensive understanding of child occupant protection and the role a frontal airbag can play.

The aim of this study was to quantify the injury potential for restrained children in front of a deploying modern front passenger airbag for frontal impacts. Computational finite element (FE) modeling were used to evaluate the kinetics and kinematics of the pediatric occupant restrained in a forward-facing child restraint and a booster seat (CRSs) installed in the front passenger seating position exposed to a modern passenger airbag.

METHODS

This study utilized a validated Q6 ATD FE model as the occupant. The test environment used was a 2012 Toyota Camry model. The ATD was positioned on booster CRSs and restrained using a 3-point lap-shoulder belt modeled with a retractor and pretensioner in the front passenger seat of the vehicle. Normal seating condition and a misuse condition with the seatbelt behind the back were tested for the study. The models were subjected to a NCAP (New Car Assessment Program) full-frontal barrier impact at 35mph.

The test matrix for this study consisted of a high-back booster CRS (HBB) and a forward-facing convertible seat (FFC). In addition to this, a No-CRS condition was also modeled to simulate a baseline seating condition.

A total of 12 simulations were carried out using an explicit solver in LS-DYNA ver. 971 (LSTC, Livermore, CA) and HyperMesh v17.0 (Altair Inc., MI) as the pre-processor. The simulations were solved on a 16-node computing cluster using a double-precision solver. All post-processing of data was carried out using LS-PrePost v4.5 (LSTC, Livermore, CA).

HIC (Head Injury Criterion), resultant head, chest, and pelvis accelerations, chest displacement, neck forces and moments were extracted and plotted. Head excursion and Nij (Neck Injury) were calculated. All data was filtered as per SAE J211 sign convention and class filter.

Vehicle and Barrier FE Model

The full vehicle FE model chosen for the simulations was the 2012 Toyota Camry obtained from the National Crash Analysis Center (NCAC) archives. The front passenger seat was setup in the foremost possible position to test the extreme condition of the child head impacting the instrument panel (IP). The barrier model used was a rigid wall. This full vehicle model was simulated for a NCAP frontal test at 35mph for a duration of 120ms.

Isolating the front passenger seating compartment

All parts of the vehicle that could potentially come in contact with the occupant seated in the front passenger seating compartment, such as instrument panel (IP), side door trims and window, A-pillar, and the center console, were identified. Interface definitions were used to define surfaces and nodal points of the mentioned components. The displacement and velocity time history data for these components was extracted from the full vehicle crash simulation using Interface cards in LS-DYNA to generate a sub-simulation interface file. The data was saved at a specific frequency (5ms) using the *INTERFACE_COMPONENT option. The subsequent sub-simulations involved only the extracted front passenger seating compartment along with the ATD and CRS. The interface file generated in the main full vehicle crash simulation was then used as a master file to provide the appropriate motion to the extracted components using the *INTERFACE_LINKING option. This technique significantly reduced the computation time as the simulations involving the ATD were carried out using just the extracted front passenger compartment instead of the entire vehicle.

Child Restraint Seats

The CRS models chosen were a high-back booster (HBB) seat and a forward-facing convertible seat (FFC). The CAD data for the CRSs were developed by scanning the seats using an Xbox Kinect Sensor (Belwadi et al. 2015). The FE models for the CRSs were subsequently developed. The HBB was modeled as a rigid material and setup in normal usage conditions as well a misuse condition with the seatbelt behind the ATD's back. The FFC was modeled as a deformable polypropylene plastic material and was used with and without top tether conditions. The child seats were positioned on the front passenger vehicle seat by applying a small force on the CRS and positioning it firmly on the vehicle seat. The FFC was attached to the vehicle seat via a 3-point lap-shoulder belt. Additionally, a No-CRS case was run with normal and misuse conditions. The misuse condition involved the seatbelt behind the ATD's back.

Child Model Positioning

A validated Q6 ATD FE model from (Humanetics Inc., MI) was used for the simulations. The child model was positioned by adjusting the limbs to appropriate positions to get it to fit in the child seat. Further, the ATD was positioned on the CRS by gravity settling. The ATD was installed on the FFC using a 5-point harness, while a 3-point lap-shoulder belt was used for the HBB and No-CRS conditions as per the Federal Motor Vehicle Safety Standard (FMVSS) No. 213 recommendations for ATD positioning.

Seatbelts with Pretensioner and Load-Limiter

After obtaining the most naturalistic ATD placement on the CRS, the lap and shoulder seatbelts were routed over the ATD. A setup of retractor and pretensioner was used along with a load-limiter of 4kN. Sensor models in LS-DYNA were used to trigger the retractor and pretensioner at a specific time to simulate the effect of the vehicle crash.

Front Passenger Airbag (PAB)

Front passenger airbag used for the simulations was provided by Takata Inc. and was modeled as per a 2012 Toyota Camry specifications. All the simulations were carried out with two conditions, with and without PAB.

Final Simulations

After routing the seatbelt, the ATD and the CRS were given an initial velocity of 35mph and the interface file generated from the full vehicle simulation (containing the data for the motion of the components) was assigned to the front passenger seating compartment using interface definitions.

RESULTS

Table 1 lists all injury metrics across all 12 simulations. Head contact was observed with the IP in all misuse seating conditions (seatbelt behind the back for HBB and No-CRS conditions, and convertible seat without top tether). For HBB, this was eliminated when the PAB was deployed. For the convertible seat the head contact was eliminated either by using the CRS with a top tether or deploying the front passenger airbag, or both. However, for the misuse seating condition for No-CRS with PAB, it was observed that the ATD's head slid under the deployed airbag and made contact with the IP. This indicates the potential effectiveness of booster seats.

For the ATD in normal seating condition on a HBB, using a PAB resulted in 13% reduction in HIC36 (from 540 to 471) and 37% reduction in Nij (from 1.2 to 0.75). The upper neck forces and moments saw a reduction of 31% (2790N to 1935N) and 15% (29.2Nm to 24.7Nm) respectively. The values observed for maximum resultant head acceleration and chest displacement were similar in the cases with and without PAB. When seated in misuse condition with the seatbelt behind the back, the PAB provided a clear benefit as it eliminated the head impact with the IP.

For the convertible seat when used with top tether, the deploying PAB resulted in 24% reduction in HIC15 (754 to 570) and 48% reduction in HIC36 (1548 to 805). The resultant head acceleration was reduced by 13% (93G to 81G). The upper neck forces and moments showed reduction of 49% (3347N to 1717N) and 20% (57Nm to 45Nm) respectively. Similarly, the head excursion and IR-TRACC (Infra-Red Telescoping Rod for the Assessment of Chest Compression) chest displacement reduced by 23% (397mm to 307mm) and 40% (17mm to 10mm) respectively when the PAB was deployed. When the convertible seat was used without top tether, there was head impact with the IP in the situation without airbag. This was eliminated when the PAB was deployed.

For normal usage conditions without any CRS, minimal interaction was observed between the ATD and the airbag and thus, the injury metrics were very similar in the cases with and without PAB. However, when the ATD was seated in the misuse condition with the seatbelt behind the back, there was head impact in both the conditions, i.e., with and without PAB. In the case without PAB, there was direct impact of the ATD's head with the IP, while in the case where the PAB was deployed it was observed that the ATD's head slid under the deployed PAB and made contact with the IP.

In all the conditions, all the injury metrics for the convertible seat were lower for the condition with top tether. For the Q6 seated on a convertible seat without top tether there was contact of the ATD's head with the IP when simulated without PAB. This contact was eliminated when the ATD was restrained on the convertible seat with top tether. When these cases were run with the front passenger airbag, the kinetics and kinematics of the Q6 were very similar (with variation less than 5% for all injury metrics) for the cases of convertible seat with and without top tether.

DISCUSSION

The study is an important step towards understanding kinetics and kinematics of a restrained pediatric occupant in the front passenger seating position across a wide variety of crash, vehicle, and occupant conditions. The conditions simulated in the study were chosen to examine the extreme conditions when a restrained forward-facing pediatric occupant is seated in the front passenger seat. The front passenger seat was modeled in the foremost position to ensure maximum interaction with the deployed PAB, or potential impact with the IP when simulated for conditions without PAB. Additionally, misuse conditions were simulated to examine if the injury risk to the pediatric occupant is increased due to the activation of the front passenger airbag.

In all the misuse cases (the seatbelt behind the back for HBB and No-CRS condition, and FFC without top tether) without airbag where there was head contact with the IP, resulting in extremely high values for HIC and head acceleration (Figure 1). The deployment of PAB eliminated this head contact indicating a clear benefit of airbag where there is contact with the vehicle interiors. In addition to this, the deploying passenger airbag supported in controlling the kinematics of the head and neck as well as the arms of the ATD.

For the scenarios where there was no head contact with IP without the usage of airbag, the kinetics and kinematics of the ATD were comparable to or lesser for the case where the airbag was deployed. The HIC and resultant head acceleration values were similar or lesser for the cases with airbag, while the head excursion was reduced in all the situation when using the PAB.

The airbag also provided support for the head-neck complex of the ATD. In the misuse conditions, the airbag eliminated the head contact with the IP. For the other situations, the deployment of airbag resulted in significant reduction in Nij values (37% reduction for HBB, 7% reduction for convertible seat with top tether, and 17% reduction for the No-CRS condition).

In the No-CRS misuse seating condition with the seatbelt behind the back, head contact was observed with the IP. However, unlike other conditions for HBB and forward-facing CRS, this contact was not eliminated even with the deployment of the front passenger airbag. The ATD's head was observed to slide under the deployed airbag and make contact with the IP. This suggests the usage of booster seats proves to be significantly more effective than not using a booster seat at all.

LIMITATIONS

There are a few limitations to the study. The study only considers frontal impacts. Further, it is to be noted that only one make/model of highback booster seat and forward-facing CRS was examined in this study. Additional simulation and testing is necessary to explore crash pulses, directions, CRS and vehicle/airbag models.

CONCLUSIONS

The study shows that a deploying modern front passenger airbag provides improved protection to restrained forward-facing pediatric occupants. In all the situations, deployment of PAB provided similar or a relative positive effect as compared to a no-PAB condition. In the cases where there was head contact with the IP without the usage of airbag, the deployment of PAB avoided this head contact. This indicates a clear benefit of using a PAB in situations where there is contact with vehicle interiors. For the cases where there was no head contact with IP even without airbag deployment, the usage of PAB resulted in the reduction of maximum head excursion and comparable or lesser values of HIC. In the misuse condition (shoulder belt behind the back) without any CRS, there was head contact with IP even with airbag deployment. The ATD's head slid under the deployed airbag and impacted the IP. This situation was not observed in any of the studied child restraining seats. This clearly suggest the effectiveness of booster seats as compared to using No-CRS.

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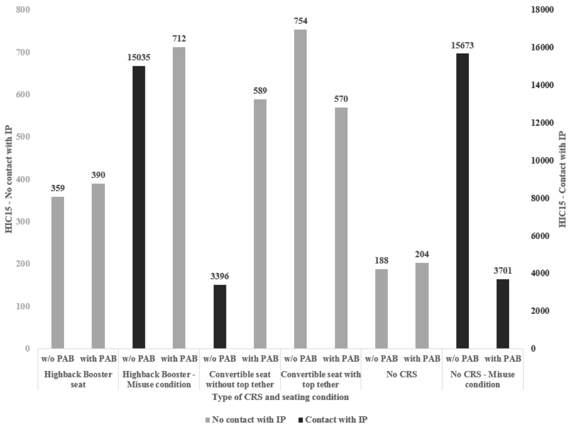
Table 1: Comparison of injury metrics across simulations

#	CRS	PAB	HIC15	HIC36	NIJ	Max Head Resultant Acc (G)	Max Chest Resultant Acc (G)	Max Upper Neck Forces Fz (N)	Max Head Excursion (mm)	Max Chest Displ (mm)
1	Highback Booster seat	without PAB	359	540	1.20	71.3	76.6	2790.1	303.9	16.8
2		with PAB	390	471	0.75	71.6	95.2	1935.1	243.3	17.0
3	Highback Booster - Misuse condition	without PAB	8508	15035	4.40	1499.5	385.4	8922.8	601.9	5.5
4		with PAB	712	1352	1.53	92.9	80.0	-1208.9	455.0	2.4
5	Convertible seat without top tether	without PAB	3125	3396	1.96	664.3	171.8	2629.7	470.7	11.6
6		with PAB	589	756	1.54	84.2	84.5	1713.4	323.6	11.8
7	Convertible seat with top tether	without PAB	754	1548	1.66	92.7	79.1	3347.0	397.3	16.6
8		with PAB	570	805	1.54	80.5	79.7	1717.3	306.9	10.0
9	No CRS	without PAB	188	323	0.82	51.3	55.6	1983.6	247.8	2.9
10		with PAB	204	314	0.68	50.7	56.2	1722.2	220.3	3.7
11	No CRS - Misuse condition	without PAB	7154	15673	3.78	1553.0	205.9	4095.5	497.9	1.7
12		with PAB	2377	3701	1.98	991.3	101.4	1817.1	496.9	1.8

Note: The simulations with grey markings indicate head contact of the ATD with the instrument panel.



HIC15 - No contact with IP
HIC15 - Contact with IP
800
700
600
500
400
300
200
100
0
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
359
390
15035
712
3396
589
754
570
188
204
15673
3701
w/o PAB
with PAB
Highback Booster seat
Highback Booster - Misuse condition
Convertible seat without top tether
Convertible seat with top tether
No CRS
No CRS - Misuse condition
Type of CRS and seating condition
No contact with IP
Contact with IP