MADYMO SIMULATION STUDY TO OPTIMIZE THE SEATING ANGLES AND BELT POSITIONING OF HIGH BACK BOOSTER SEATS

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Paper Number 07-0091

ABSTRACT

Data from the Partners for Child Passenger Study shows that booster seat use among children ages 4-7 years has increased and its use is beneficial in terms of injury risk when compared to vehicle seat belts. However, results from sled tests with a 6-year-old Hybrid III ATD in four different high back booster seats (HBB) at a speed (56 km/h) higher than current compliance requirements (48 km/h) did not show corresponding benefits in some designs. Potential hypothesis for the apparent differences are 1) the lack of biofidelity of the ATD spine and neck 2) lack of high severity crash data from the field and 3) the possible differential performance of different HBB due to their design. A number of studies aimed at improving the biofidelity of the ATD have been done, but no study has looked at the differential performance of the HBB due to their design.

The study objective was to use mathematical models to investigate and assess the Hybrid III 6-year-old ATD performance due to the variation in seating angles of a HBB and seat belt positioning across the ATD. Mathematical models of the HBB and FMVSS 213 bench seat were developed using the multi-body MADYMO software. The standard MADYMO 6-year-old ATD model was used to assess the performance. This model was validated against a sled test and further parametric analyses were conducted. Parameters changed were the overall angle and the base angle of the HBB and the seat belt routing angle. The standard injury metrics (HIC, head and chest accelerations, Nij, and excursions) were used to quantify the ATD performance.

The study demonstrated that by optimizing the ATD seating posture and the belt positioning across its chest, improved ATD performance is achieved. An optimized angle of 5 degrees for base angle and 100 degrees for overall angle of the HBB, in combination with a belt angle of 40 degrees achieved better performance than the validated baseline model.

INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA)[1] and American Academy of Pediatrics (AAP)[2] currently recommends that children over 40 lbs and approximately between 4 and 8 years of age (unless the child is 57 inches tall) should be restrained using a belt positioning booster seat. A belt-positioning booster improves the fit of both the lap and shoulder portions of the vehicle seat belt. A poorly positioned vehicle seat belt may lead to rapid, "jack-knife" and/or "submarining" effect, which increases the risk of intra-abdominal and spinal cord injuries, also known as "seat belt syndrome". Poorly positioned belt may also lead to injuries to the face and brain due to impact of the head with the child's knees or the vehicle interior[3-8], in the event of crash.

Epidemiological data from the Partners for Child Passenger Safety (PCPS)[9], a national data source of children in crashes, collected over a period of 5 years, shows that the belt-positioning booster seats provide added safety benefits over seat belts to children through age 7 years, including the reduction of injuries classically associated with improper seat belt fit in children.[10-12] This data also shows that there is an increase in the use of these belt positioning booster seats among children ages 4-7 years[13]. It is estimated that currently there are about 30 different types of belt positioning booster seats available to use for children who have outgrown child seats, but are yet not tall enough for adult seat belts[14].

Studies done in the laboratory[15-17] however, did not show corresponding benefits that were seen in the epidemiological studies. The study by Menon, et al.[15] looked at the performance of the various child restraint systems by conducting a series of sled tests with the Hybrid III 3 and 6-year-old child Anthropomorphic Test Devices (ATD) at a range of speeds namely 24, 40 and 56 km/h. It was observed in this study that the Hybrid III 6-year-old ATD, in the high back belt positioning booster seat at 56 km/h experienced, a significant neck flexion resulting in the chin and face contacting the chest of the ATD.

This phenomenon was also observed by Sherwood, et al.[16] who used the same make and model belt positioning booster seat to test at a speed of 48 km/h. The study attributed the unusual response to the stiff upper spine of the Hybrid III 6-year-old ATD. In order to better understand this phenomenon Menon, et al., conducted another study with a Hybrid III 6-year-old ATD in four different HBB seats at a speed of 56 km/h.[17] Although the biofidelity of the ATD has been questioned, the extreme behavior of the ATD was not observed at lower speeds and even at 56 km/h speed the extreme flexion of the neck was observed only in two of the four high back booster seats. The primary purpose of this study was two folds. The first purpose was to ascertain if the high back booster design had an effect on the ATD kinematics and secondly to evaluate the performance of these individual high back booster seats against the Injury Assessment Reference Values (IARV)[18] as measured by the Hybrid III 6-year-old ATD. In the study by Menon, et al. it was noted that the seating angles differed for the different high back booster seats, thus changing the ATD posture. The seat base inclination ranged from 0^o to 10^o, the seat back inclination had a variation of only 5^o, from 105^o to 110^o and the overall seat angle varied from 90^o to 100^o. It was also seen that although the upper anchorage of the shoulder belt was the same, the angle of the belt across the ATD differed in the different high back booster seats due to the attachment point of the shoulder belt on the booster seats. The angle of the belt varied from 45^o to 100^o.

The findings from the above mentioned study confirmed that the high back booster seat design had an effect on the ATD kinematics and also showed that there is a difference in the injury measures obtained from the ATD, when measured in different high back seat designs. These observed results not only highlighted the need to conduct research for improving the biofidelity of the Hybrid III 6-year-old ATD neck, but also called for dedicating research to understand the effect of variation of the high back booster seat design on the 6-year-old ATD responses, especially at higher speeds. Since all the tests conducted with high back booster seats used the same Hybrid III ATD, and showed a difference in the performance, this study examined this hypothesis of possible differential performance of different high back booster seat designs using mathematical models. Also with the increase in the number of children using high back booster seats, it is only reasonable to conduct studies to understand the differential performance of the different high back booster seat designs to anticipate any problems in future and to avoid them from occurring.

OBJECTIVE

The objective of this study was to use mathematical models to investigate the effects of

1) ATD posture by varying the seating angles of a high back booster seat
2) Seat belt positioning across the ATD
3) Environment change by replacing old FMVSS 213 bench seat with the new FMVSS 213 bench seat and a vehicle seat
4) Use of a top tether

This would identify key design characteristics of the high back booster seats that reduce injury metrics in a sled test environment and lead to possible design guidelines for high back booster seats.

In order to achieve the above objectives a mathematical model of an Evenflo Express high back booster seat was developed along with the sled environment and validated against the sled test, performed in the study by Menon, et al.[17], of the high back booster seats at 56 km/h. The Evenflo Express was chosen among the four high back booster seats tested. This validated model served as the baseline model and allowed parametric studies to be conducted on it. The parametric studies included changing the angle of the seat base and overall angle of the high back booster seat, which in turn changed the posture of the ATD, and changing the angle of the shoulder belt routing from the point of attachment on the booster seat over the ATD's chest. Additionally as part of the parametric study top tethers were included and the old FMVSS 213 bench seat model was replaced with the new FMVSS 213 bench model and a vehicle seat model.

METHODOLOGY

Model Development

These model simulations were performed in the multibody simulation environment Mathematical and DYnamic MOdel (MADYMO) v.6.2.[19]**.** MADYMO is a computer program that simulates the dynamic behavior of physical systems with an emphasis on the analysis of vehicle collisions and assessing injuries sustained by the occupants. The study involved developing of the HBB and FMVSS 213 Sled model. The HBB model seat was modeled using the facet elements along with the planes and ellipsoids. The HBB model was considered rigid with defined mass and inertia. The facet elements were used mainly to define the geometry of the HBB. The model of the HBB was considered rigid to have a computationally efficient model in conducting the parametric study.

Bench and Vehicle Seat Models Two FMVSS 213 benches were modeled in this study i.e. old FMVSS 213 bench and new FMVSS 213 bench. The old FMVSS 213 bench was based on the dimensions of the actual FMVSS 213 test bench seat as outlined in the standard[18]. This modeled bench was represented by ellipsoids and the material properties for these ellipsoids were based on the materials specified in the standard (Figure 1). The seat cushion properties were derived from foam tests that were conducted as part of the sled test performed by Menon, et al.,[17] which is also used as the baseline sled test for this project and for the validation of the developed model.

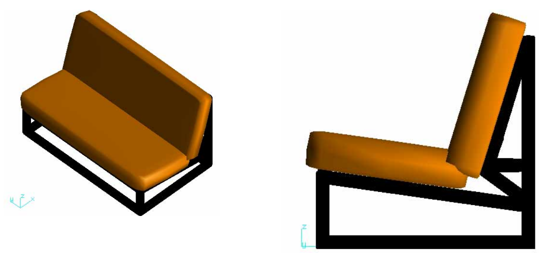

Figure 1. MADYMO model of FMVSS 213 bench seat

The new bench seat model was based on the new FMVSS 213 standards in a similar manner as described above. The difference between the new and old standards of the FMVSS 213 bench was that in the old 213 bench the seat back assembly was flexible whereas for the new 213 bench the seat back assembly was fixed and not allowed to move during the test and both the seat back and seat cushion angles have been changed as shown in Table 1.

Table 1.
Differences between the new and old FMVSS 213 bench seats

	Old 213 Bench	**New 213 Bench**
Seat Cushion angle	8°	15°
Seat Back Angle	15°	22°
Seat Back Assembly	Flexible	Fixed

For the vehicle seat model the backseat of a Ford Windstar was modeled as ellipsoid structures with dimensions approximating the actual seat. The seat bottom was tilted rearward 16° from horizontal and the seat back was reclined 24° from vertical (Figure 2). This model was based on Sherwood et al.[18].

Figure 2. MADYMO model of vehicle seat[18]

Child ATD The Hybrid III 6-year-old child ATD model from the MADYMO database was used (Figure 3) to simulate the child occupant. The standard Hybrid III 6-year-old ATD model is a representation of the physical ATD. It constitutes the same basic geometry, inertial properties, joints and stiffness functions. It is represented in a multibody environment with rigid bodies, interconnected by kinematic joints and an ellipsoid geometry. Forces and moments are recorded at the same position as the measurement capabilities of the physical ATD.

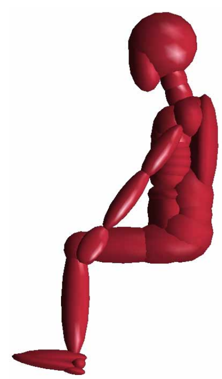

Figure 3. MADYMO models of a HYBRID III 6-year-old ATD

Belt Model The belt model, which is representative of the three point sled/seat belt, was modeled in MADYMO by means of a hybrid belt system, which uses a multibody belt model combined with a finite element mesh. This hybrid belt system consists of a multibody belt, which was attached to the vehicle anchor points, and a finite element belt for contact with the ATD. In the actual sled test, the ATD and booster seat were restrained to the FMVSS 213 test bench by a three-point belt and hence in the developed model, finite element belt was wrapped around the booster seat as well.

High Back Booster Seat Model The high back booster (Evenflo Express Booster) seat was modeled as one rigid body with geometry described by facets, ellipsoids and planes. This geometry sufficiently described both the frame and the seating surface. The geometry was obtained by taking actual measurements from the booster seat and then incorporating into the model building.

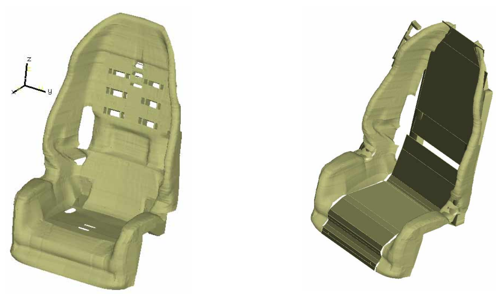

Figure 4. High back booster seat model

Model Validation

The model was validated according to the standard procedure against the sled test performed by Menon, et al.,[17] with the high back booster (Evenflo Express Booster) seat. The pulse used in the test was a 56 km/h FMVSS 213 type pulse (Figure 5). The developed model consisted of a 6-year-old ATD model from the MADYMO database seated in a HBB seat and restrained with a three-point belt to the standard FMVSS 213 test bench. The ATD kinematics from the model was matched with that of

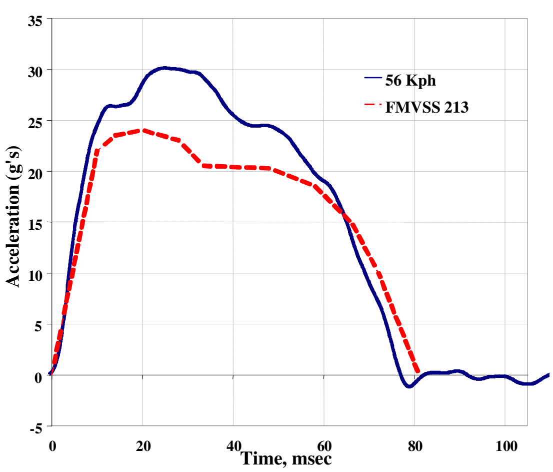

Figure 5. 56 km/h and standard FMVSS 213 48 km/h acceleration pulse

the Hybrid III 6-year-old ATD in the sled test. The other output parameters compared for the injury measures included the HIC, head accelerations, Nij, chest deflections, chest acceleration, head and knee excursions. Validation of the model was quantified using a statistical approach based on Pipkorn, B. et al. [20], where the standard deviation, peak values and coefficient of correlations between the two curves were calculated.

Parametric Study

Parametric studies were conducted at 48 km/hr on the validated model of the HBB with the 6-year-old ATD model as the baseline model. The acceleration pulse used as input for the model was a standard FMVSS 213 48 km/h acceleration pulse shown in Figure 5. The parametric studies included

1) Changing the angle of the booster seat base angle and overall booster angle which in turn changed the posture of the ATD (Figure 6)
2) Changing seat belt routing angle across the ATD (Figure 6)
3) Conducting simulations with the best seating angle and the best belt angle from both the parametric studies based on overall ATD responses.
4) Conducting simulations with the new FMVSS 213 bench seat and vehicle seat
5) Simulation with the top tether

The detailed matrix for the parametric study is given in Table 2

Table 2.
Matrix for Parametric Studies

Parameter		Top Tether use
HBB angle in degrees (Base angle/ Overall angle) Best angle	0 / 100	No
	0 / 90	No
	5 / 100	No
	5 / 90	No
	10 / 100	No (Baseline)
	10 / 90	No
Belt angles in degrees	40	No
	60	No
	70	No
Best angle	Old 213 bench	No
		Yes
	New 213 bench	No
		Yes
	Vehicle seat	No
		Yes

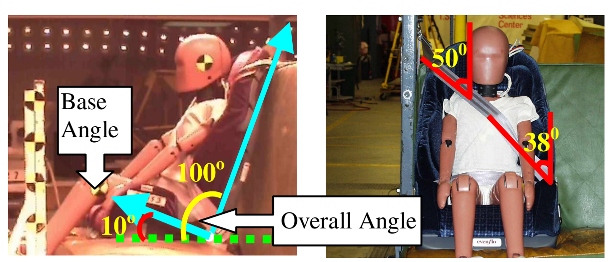

Figure 6. Booster seat base inclination and overall booster angle and shoulder belt angle

RESULTS

Validation Results

The model was validated based on the experimental sled test at 56 km/h. The kinematics of the model matched well with the sled test and is show in Appendix A - Figure A.1 along with the validation results in Figures A.2. Overall both the kinematics and the statistical tests showed a good correlation between the model and actual sled test. Thus the model was considered robust for further parametric analyses.

Parametric Analyses

Baseline For all parametric studies the pulse used was a 48 km/h standard FMVSS 213 acceleration pulse (Figure 5). The baseline model was simulated with the HBB in the original setup (Figure 6) with the FMVSS 213 pulse and was used for all the comparisons for the parametric analyses. Responses of the ATD with the baseline setup are shown in Table 3

Table 3.
High back booster baseline results

	Units	IARV	Baseline
Head Acceleration	m/s^2	-	828
HIC	-	1000	813
Chest Acceleration 3MS	m/s^2	600	505
Pelvic Acceleration	m/s^2	-	479
Neck Forces	N	-	3453
Neck Moments	N.m	-	41
Chest Deflection	m	0.040	0.032
Head Displacement	m	0.813	0.439
Knee Displacement	m	0.915	0.606
Belt Forces	N	-	3747
NIJ	-	1	1.46

Change in High Back Booster Angles The parametric analysis of the model was conducted by varying the base angle and the overall angle of the HBB. The combination of the changes in the base angle and overall angle are as shown in Table 4 and Figure 9. The angles for the baseline model were 10^o base angle with an overall angle of 100^o (Figure 6).

Table 4.
High back booster angle changes for parametric study

	Base Angle (degrees)	Overall Angle (degrees)
HBB Angle	0	100
		90
	5	100
		90
	10	100
		90

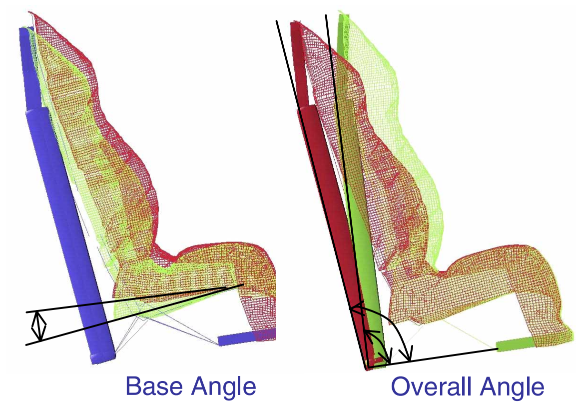

Figure 9. High back booster change in angles

The outcomes of the paparemetric analysis with varying angles are as shown in Figure 10. The results in the figure are expressed as the change in the percentage of the various parameters, measured for the ATD model, in comparison to the baseline model. All values above zero or positive indicate that the values were higher than the corresponding baseline values. While the decrease in the parameter as compared to the baseline configuration is shown with the negative percentage values. Based on the parametric study with angle changes the simulation with a base angle of 5^o in combination with the overall angle of 100^o showed the best performance based on kinematics and peak response values and is highlighted in Figure 10.

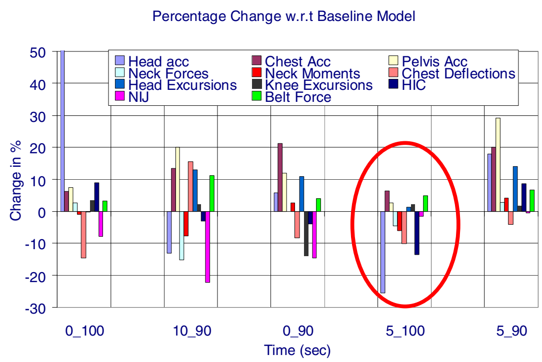

Figure 10 Percentage change from the baseline (10_100) with the change in HBB angles

<u>Change in Seat Belt Angle</u> The baseline seat belt angle was 50° (Figure 6). Parametric analyses were conducted by changing the angle of the belt as shown in Table 4 and Figure 12. These simulations were run with the standard and the modified ATD.

Table 4.
Belt angle changes for parametric study

	Belt Angles (degrees)
Belt Angle	40
	60
	70

Figure 12. Change in belt angle

Figure 13 show the change in percentage from the baseline model for the ATD responses. The simulation with the belt angle of 40° showed the best performance based on the kinematics and peak response values. This is highlighted in Figure 13.

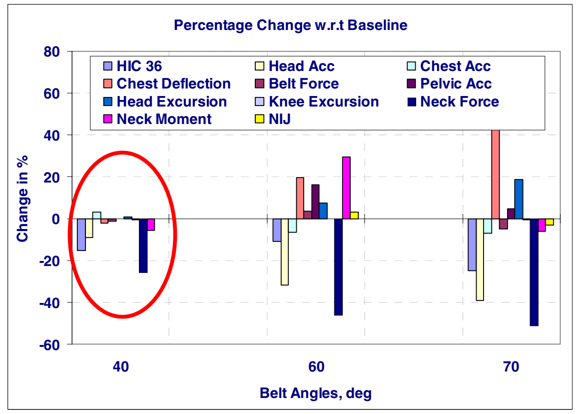

Figure 13. Percentage change from the baseline (50°) with the change in belt angles

<u>Parametric Analysis of Different Environment with Best High Back Booster Seat and Belt Angles</u>
From the above parametric studies for the high back booster a base angle of 5° in combination with the overall angle of 100° and with a belt angle of 40° showed the best performance based on injury metrics measured from the ATD. Using these angles as the optimized angles for best performance, analyses were conducted by changing the environment. For the environment the variables were the new FMVSS 213 bench seat and a vehicle seat.

Response of the ATD is tabulated in Appendix B Table B.1. In general it can be seen that with the change in environment from the old FMVSS 213 bench to the new FMVSS 213 bench the injury parameters like the head and chest acceleration reduced but the pelvic accelerations increased. This was also observed when the vehicle seat was used. Although there are increases in the HIC values, chest deflections, etc., it must be noted that the higher values did not cross their respective threshold values.

<u>Parametric Analysis with Top Tether</u> In order to see if there would be any benefit from using a top tether, simulations were conducted on the optimized models. The tether properties used is shown in Figure 15.

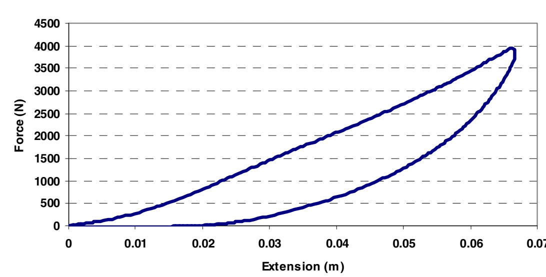

Figure 15 Force-deflection curve for Top Tether

From the kinematics of the simulations it was seen that excursion of the high back booster seat in the vehicle seat has been restricted with the use of a top tether. Table B.1 in Appendix B shows the comparison of the response values with and without top tether use for the three different environments with the standard ATD. It can be seen that in general the head and chest accelerations, knee excursions and neck forces have been reduced with the use of top tether. For the injury values that exceed with the use of top tether none exceeded the IARV. Use of the top tether improved the performance notably in the new FMVSS 213 bench seat of the neck forces and NIJ by around 20 percent.

SUMMARY

Models of the old and FMVSS 213 bench seats, a vehicle seat and high back booster seat were developed using the multi-body MADYMO software. The initial model was validated against a sled test which was run at 56 km/h. The validated model was considered robust for further parametric analyses. Parametric studies were conducted at 48 km/h by changing the overall and base angle of the high back booster seat and the belt angle. These changes resulted in an optimized solution where the best angles from the high back booster in combination with the best belt angle improved the performance of the ATD based on injury metrics measured on the ATD. This is shown in Figures 15.

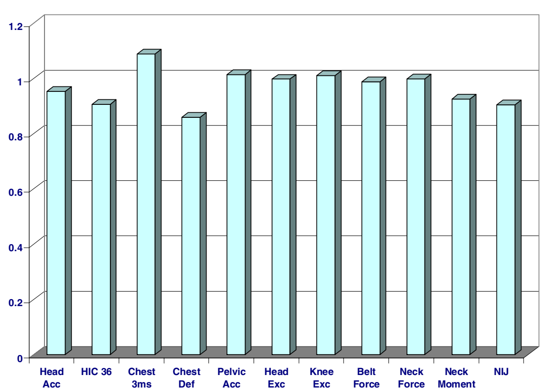

Fig 15. Comparison between the baseline and the optimized model (normalized by the baseline model)

It should be noted that different injury parameters of the ATD in the optimized seat was normalized by the ATD injury parameters of the baseline seat. A value of 1 would show that the ATD in the baseline and optimized high back booster seat had the same response, where as a value less than 1 would show better response from the ATD in the optimized seat.

From Figure 16 it can be seen that all response values, except for the chest acceleration, were lower than that of the baseline model. Although the chest acceleration for the ATD in the optimized seat was greater than that of the baseline model, it did not exceed the IARV limit.

Further analyses were conducted by changing the environment by replacing the old FMVSS 213 bench seat model with the new FMVSS bench seat model and a vehicle seat model. These analyses compared the response of the ATD in these different environments and in general it was seen that for the change in environment from the old FMVSS 213 bench to the new FMVSS 213 bench the injury parameters like the head and chest acceleration reduced but the pelvic accelerations increased. This was also observed when the vehicle seat was used. Analyses were also conducted to understand the effects of top tether use. This analysis showed that that there was a benefit in using the top tether with the high back booster seat and benefited most in the vehicle seat environment.

CONCLUSIONS

- This study showed that by optimizing the seating posture of the ATD and by optimizing the belt positioning over the ATD better performance can be achieved from the ATD
- An optimized angle for high back booster seat base angle of 5^{o} in combination with the overall angle of 100^{o} and with a belt angle of 40^{o} achieved better performance from the ATD when compared to the baseline model.
- Also achieved as part of this study was a comparison of the ATD in different environments, old FMVSS 213 bench seat, new FMVSS 213 bench seat and a vehicle seat.
- This study also showed that it was beneficial to a use of a top tether with a high back booster.

ACKNOWLEDGEMENT

This research was conducted at The Center for Child Injury Prevention Studies (CChIPS), an NSF Industry/University Cooperative Research Center at the Children's Hospital of Philadelphia. The authors thank all the Industry Advisory Board members of the Center for their input and support for this research.

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APPENDIX A - Validation Results

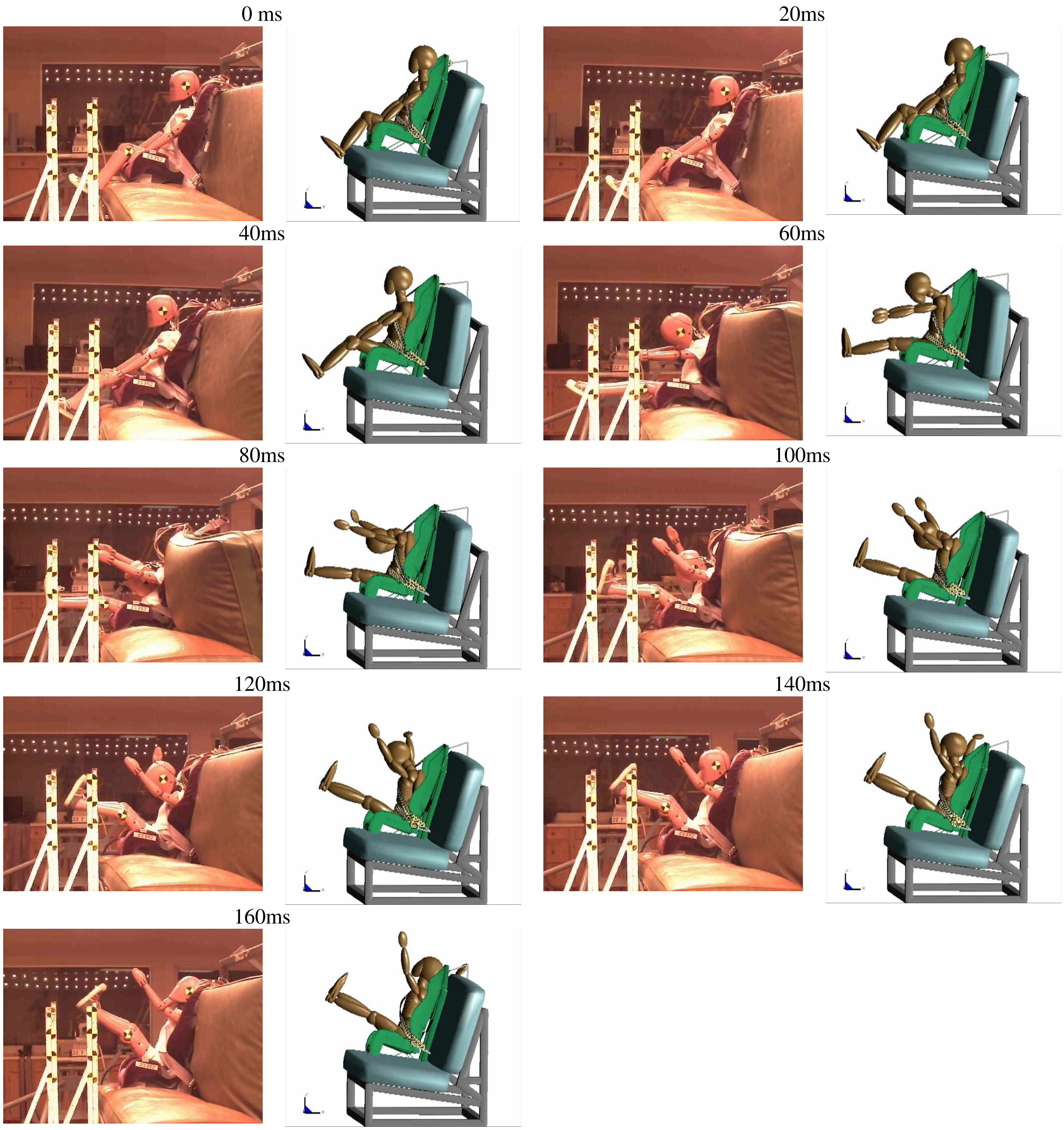

Figure A.1 Kinematic comparison between experimental sled test and model

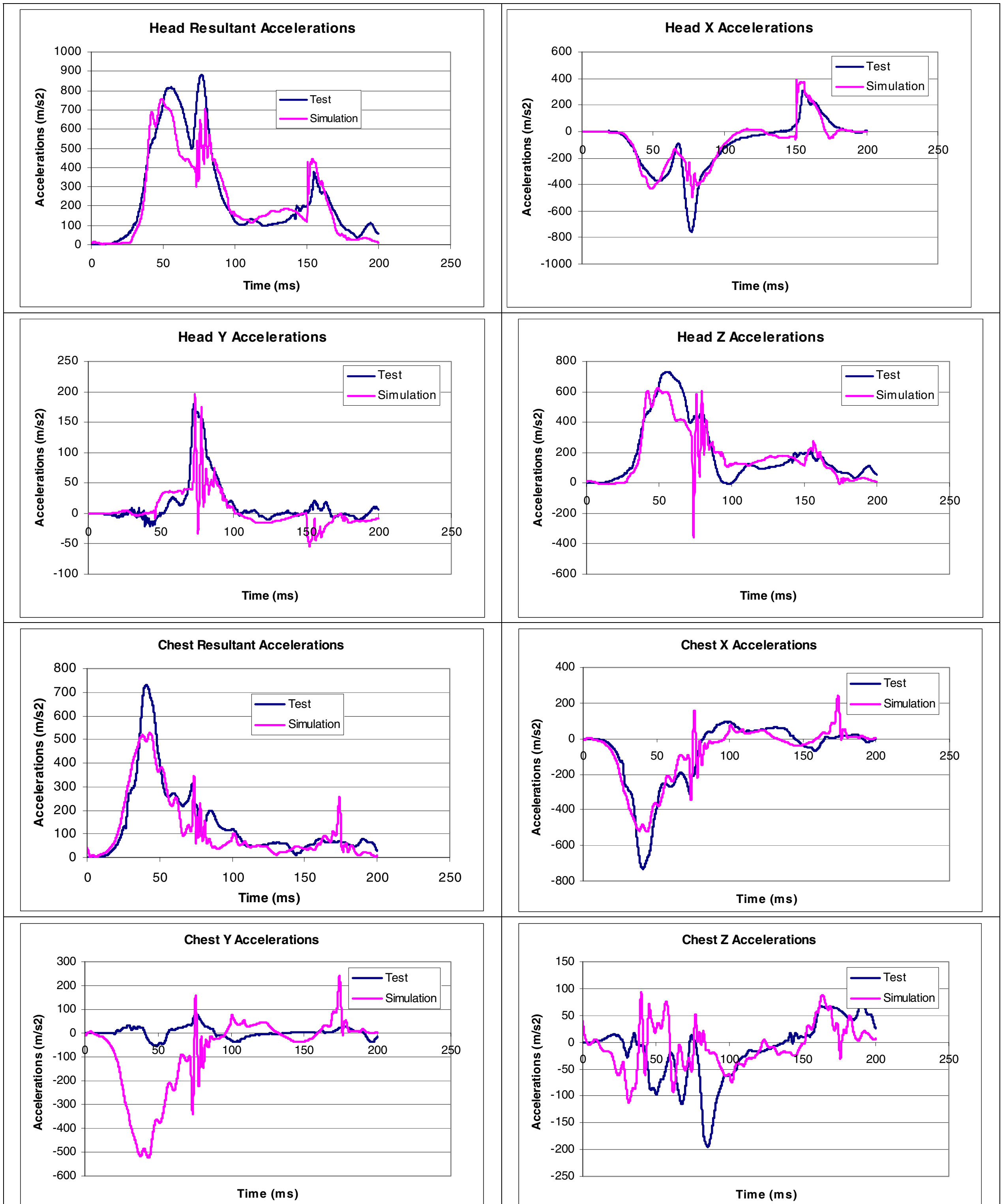

Figure A.2 Response curves from test and simulation

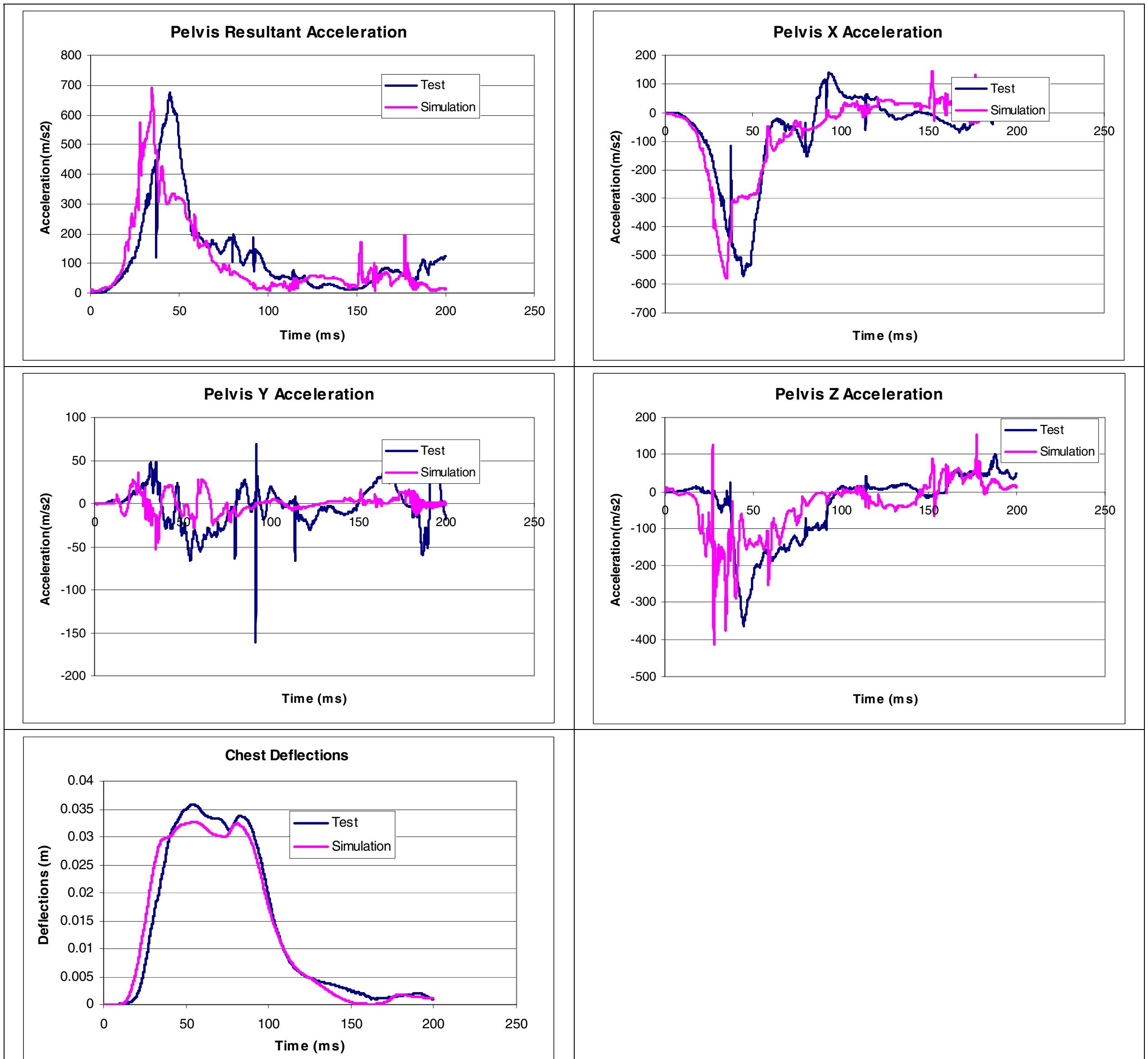

Figure A.2 (cont) Response curves from test and simulation

APPENDIX B

Table B.1.
Comparison of the injury values with and without top tether use for the three different environments

	Units	IARV	Old FMVSS 213 Bench		New FMVSS 213 Bench		Vehicle Seat	
			No Top Tether	With Top Tether	No Top Tether	With Top Tether	No Top Tether	With Top Tether
Head Acceleration	**m/s²**	**-**	789	740	792	772	595	597
HIC	**-**	**1000**	623	648	796	768	526	586
Chest Acceleration 3MS	**m/s²**	**600**	550	521	453	456	493	473
Pelvic Acceleration	**m/s²**	**-**	486	502	606	687	860	860
Neck Forces	**N**	**-**	3446	3299	3822	3026	2720	2534
Neck Moments	**N.m**	**-**	38	41	45	48	35	33
Chest Deflection	**m**	**0.040**	0.027	0.029	0.034	0.034	0.027	0.026
Head Excursion	**m**	**0.813**	0.438	0.443	0.460	0.463	0.429	0.433
Knee Excursion	**m**	**0.915**	0.612	0.598	0.585	0.579	0.604	0.597
Belt Forces	**N**	**-**	3701	3556	3987	3759	5105	5285
NIJ	**-**	**1**	1.32	1.13	1.56	1.28	0.98	1.09