RESPONSES OF A 6-YEAR-OLD ATD RESTRAINED IN A BOOSTER CHILD SEAT ON THE FMVSS 213 TEST BENCH, PROPOSED UPGRADED TEST BENCH AND A VEHICLE SEAT IN SIMULATED FRONTAL IMPACTS

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) is considering upgrades to the FMVSS No. 213 standard seat assembly and test parameters that better represent current vehicle conditions. A preliminary prototype for the test bench was released with upgraded seat cushion stiffness, geometry, seatbelt assembly, and anchorage locations. The objective of this study was to compare the responses of the Q6 ATD (Humanetics Inc., MI) restrained in booster child seats (CRS) on the current and proposed upgrade of the FMVSS 213 test bench, and a vehicle seat in frontal impacts.

Three child seating conditions were evaluated: no-CRS, lowback booster (LBB), and a highback booster (HBB) installed on validated finite element (FE) models of the current FMVSS 213 bench, upgraded bench, and a 2012 Toyota Camry vehicle seat. Simulations (N=9) were carried out using LS-DYNA ver.971 (LSTC, CA) on a 16-node double precision cluster. Kinematics and kinetic data were extracted and processed as per SAEJ211 metrics.

Head resultant accelerations (Hr) across conditions were comparable, however, for LBB the current bench over predicted Hr by 26G (72.1G) as compared to the upgraded bench (46.1G). For HBB, there was a difference of 13.5G in Hr between the upgraded bench (60.1G) and vehicle seat (46.6G). Similarly, chest resultant accelerations (Cr) showed a difference of 23.2G (No-CRS), 14.8G (LBB), and 22.5G (HBB) between the 213 bench [no-CRS (72.9G); LBB (62.5G); HBB (56.3G)] and upgraded bench [no-CRS (49.7G); LBB (47.7G); HBB (78.8G)]. HBB showed a difference of 19.2G in Cr between the upgraded bench (78.8G) and vehicle seat (59.6G).

HIC36 values for the no-CRS and HBB conditions were lower by 53.4 and 115.4 respectively for the 213 bench [no-CRS (258.7); HBB (443.2)] compared to the upgraded bench [no-CRS (312.1); HBB (558.6)]. Similarly, these values were lower for no-CRS and HBB conditions by 74.3 and 163.6 respectively for the vehicle seat [no-CRS (237.8); HBB (395.0)] compared to the upgraded bench. Chest displacements were higher on the 213 bench [no-CRS (16.6mm); LBB (24.2mm); HBB (29.2mm)] and vehicle seat [no-CRS (18.3mm); LBB (22.6mm); HBB (25.5mm)] as compared to the upgraded bench [no-CRS (6.6mm); LBB (14.8mm); HBB (17.3mm)]. Neck Forces (Fz) were higher for the LBB on the 213 bench (2637.3N) than on the upgraded bench (1982.3N).

All injury and excursion values were within IARV limits for all simulations. However, CRSs installed on the 213 bench have larger rotations (sagittal plane) [LBB (-10.2º); HBB (-12.9º)] as compared to the upgraded bench [LBB (1.5º); HBB (-3.6º)] and the vehicle seat [LBB (4.8º); HBB (-3.6º)]. The child seats on the 213 bench, first compress the foam and then rotate over the edge of the foam [Foam thickness (Ft) = 6 inches (4+2)] due to its inherent overhang from the edge of the base structure causing higher rotations as compared to the upgraded bench (Ft= 4 inches) or the vehicle seat, which are similar in construction.

Overall, the responses of the upgraded bench matched the vehicle seat more closely than the current bench and is a step towards emulating a real vehicle seat environment.

INTRODUCTION

Booster seats provide child occupants the appropriate belt fit that a traditional vehicle seat cannot offer due to the occupant being too small. There is ample evidence from real world crashes that belt-positioning booster seats reduce injury risk. The estimated odds of injury after adjusting for child, crash, driver and vehicle characteristics were 59%

lower (Durbin et. al. 2003) for 4 to 7-year-old children in belt-positioning boosters as compared to standard three-point lap-shoulder seat belts. Further, child-restraint systems reduced fatality risk by 28% for children 2 to 6-years old as compared to standard seat belts (Elliot et. al. 2007).

There are primarily two types of booster seats used extensively by parents, namely highback (HBB), lowback or backless boosters (LBB. A typical booster seat raises a child relative to the vehicle seat, by about 100mm (Reed et. al. 2006). This improves the belt angle, making it more vertical, thus, making it less likely for the belt to slide off the pelvis and onto the abdomen during a crash. It also reduces the likelihood of the shoulder belt interacting uncomfortably with the neck, a situation that can lead to a child leaning away from the belt or tucking the belt under an arm or behind the back. Booster seats include features like belt routing guides which improve the routing of the belt around the child (Reed et. al. 2006; 2009).

The Federal Motor Vehicle Safety Standard (FMVSS) No. 213 test is a baseline test to assess the safety of child seats. The FMVSS No. 213 test bench represents a vehicle rear seat. The effective length and undeflected seat contour are representative of the rear seat in vehicles (Reed 2011). The last time the FMVSS 213 test bench was upgraded was in 2003, where anthropomorphic test devices (ATDs) were used and design changes were made to better represent a vehicle rear seat (Aram et al. 2012). However, no modifications were made to the seat cushion, which was found to be thicker and softer as compared to rear seats in vehicles at the time. Since then, there have been studies highlighting the discrepancy between the FMVSS 213 test bench and vehicle rear seats (Maltese et al. 2014).

The National Highway Traffic Safety Administration (NHTSA) released a preliminary prototype for the new 213-test bench with upgraded seat cushion stiffness, geometry, seatbelt assembly, and anchorage locations (Wietholter et. al. 2017). The new bench has a much stiffer foam and is supposed to represent a vehicle rear seat more accurately as compared to the current FMVSS 213 test bench (Wietholter et. al. 2016). Moreover, the new bench has a 2 inch thinner foam as compared to the current bench, which is 6 inches thick (4+2 inches, different foam stiffnesses).

The dynamic performance of the FMVSS 213 test bench as compared to a vehicle rear seat needs to be evaluated and quantified. Thus, this study aims to quantify responses of a 6-year-old ATD on the FMVSS 213 test bench, proposed upgraded prototype, and a vehicle seat in frontal crashes.

METHODS

A Q6 ATD (Humanetics Innovative Solutions, MI) child occupant finite element (FE) model was used for this study. The ATD was restrained in two types of booster seats on the FMVSS 213 test bench, the proposed upgraded bench, and a vehicle seat. Additionally, a no-CRS condition was also modeled.

FMVSS 213 Test Bench and Vehicle Seat Model

The CAD data for the FMVSS 213-test bench and the proposed upgraded bench was obtained from the National Highway Traffic Safety Administration (NHTSA) archives. Thereafter, an FE model for the bench was created using LS-DYNA v. 971. Foam load curves and properties were obtained from previous studies on the FMVSS 213 test bench (Wietholter et. al. 2016). The vehicle rear seat was extracted from a 2012 Toyota Camry model obtained from the National Crash Analysis Center (NCAC) archives.

Development of Booster Seat Models

Two booster child restraint seats available in the US market were used, namely a lowback or backless booster (LBB), and a highback booster (HBB). The CAD data for the booster seats were developed by scanning the seats using an Xbox Kinect Sensor (Belwadi et al. 2015) following which an FE model was developed.

FE Assembly Setup and Validation

The CRS and the Q6 ATD were gravity settled on the FMVSS 213 test bench, proposed upgrade, and vehicle seat after getting them into position. The seat belt was then routed around the child and the CRS. A full frontal, 0-degree, crash impact was simulated by applying the FMVSS No. 213 crash test pulse (24 G over 120 milliseconds) to the system. In order to validate the FE model, the resultant head and chest acceleration measured at the center of gravity of the head and at the chest potentiometer (Infra-Red Telescoping Rod for the Assessment of Chest

Compression - IRTRACC) respectively were compared with the physical sled test data for proposed upgrade test condition (Belwadi et al. 2017). The values were within ± 8% of maximum values.

Nine simulations were set up (three seating conditions, three benches) using Hypermesh v17.0 (Altair Inc., MI) as the pre-processor. The simulations were run and post-processed using LS-DYNA v. 971 and LS-PrePost v. 4.5 (LSTC, CA) respectively. Models were solved on a 4-node computing cluster on a double-precision explicit solver. HIC36, head and chest acceleration, chest and IR-TRACC displacement were extracted. Maximum head excursion, Nij and head trajectories were calculated. All simulations were carried out and data filtered as per SAEJ211 sign convention and filtering classes respectively.

RESULTS

Table 1.
Injury metrics across simulations

No.	Seat	Booster Condition	HIC36	Hr	Cr	Pr	IR-TRACC Chest Displacement	Neck Force Fz	Neck Moment My	Maximum Head Excursion	CRS Max Delta Angle
				(G)	(G)	(G)	(mm)	(N)	(N.m)	(mm)	(degrees)
1	Upgraded FMVSS 213 Test Bench	No CRS	312.1	49.4	49.7	47.7	6.6	1722.4	30.0	211.5	---
2		LBB	334.7	46.1	47.7	44.1	14.8	1982.3	34.2	298.2	1.5
3		HBB	558.6	60.1	78.8	52.7	17.3	2545.1	36.1	317.3	-3.6
4	Current FMVSS 213 Test Bench	No CRS	258.7	50.6	72.9	45.5	16.6	1866.0	32.0	237.0	---
5		LBB	352.6	72.1	62.5	45.7	24.2	2637.3	31.1	321.1	-10.2
6		HBB	443.2	57.5	56.3	49.1	29.2	2855.6	34.9	314.9	-12.9
7	Vehicle Seat	No CRS	237.8	50.9	49.1	51.1	18.3	2021.9	28.8	240.1	---
8		LBB	313.3	45.6	46.6	41.5	22.6	2014.9	35.8	280.1	4.8
9		HBB	395.0	46.6	59.6	53.5	25.5	1711.5	34.5	321.9	-3.6

Table 1 lists all the injury metrics across the nine simulations. Head resultant acceleration (Hr) values were mostly comparable across the benches and vehicle seat. However, compared to the upgraded bench, the child on LBB showed a 56.3% higher Hr on the current bench [LBB-Hr: Current (72.1G); Upgrade (46.1G); Vehicle (45.6G)]. Consequently, the Q6 on HBB showed a 22.4% lower Hr on the vehicle seat compared to the proposed upgrade [HBB-Hr: Current (57.5G); Upgrade (60.1G); Vehicle (46.6G)]. HIC36 values were 17.1% and 23.8% lower for the current bench and vehicle seat respectively for the no-CRS condition as compared to the upgrade bench [no-CRS-HIC36: Current (258.7); Upgrade (312.1); Vehicle (237.8)]. Similarly, HIC36 values were 20.7% and 29.3% lower for the current bench and vehicle seat respectively for the child on HBB as compared to the upgrade bench [HBB-HIC36: Current (443.2); Upgrade (558.6); Vehicle (395.0)]. Figure 1 shows the variation in HIC36 across the simulations. Figure 2 shows variation in head, chest, and pelvis acceleration across all simulated cases.

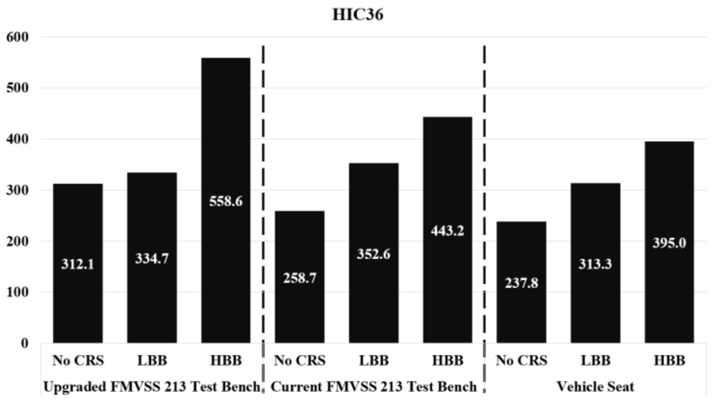

Figure 1: Variation in HIC36 across simulations

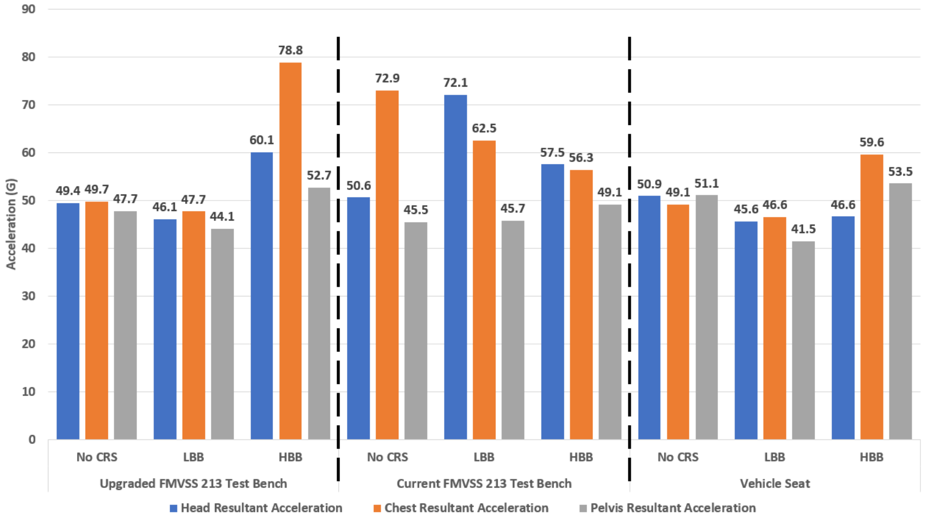

Figure 2: Variation in head, chest, and pelvis acceleration across simulations

Chest resultant acceleration (Cr) values showed greater variation in the current bench as compared to the upgraded bench, with values being 46.6% and 31.0% higher for no-CRS and LBB conditions, and 28.5% lower for HBB condition. Although the Q6 on the vehicle seat showed similar chest resultant acceleration values, for the child on the HBB, Cr was 24.4% lower on the vehicle seat as compared to the upgraded bench.

Chest displacements were consistently higher on the current bench and the vehicle seat as compared to the upgraded bench. The Q6 on the current bench showed 150.9%, 63.7%, and 68.9% higher chest displacements for the no-CRS, LBB, and HBB conditions respectively. Similarly, the Q6 on the vehicle seat showed 177.1%, 53.0%, and 47.6% higher chest displacements for the no-CRS, LBB, and HBB conditions.

Pelvis resultant accelerations (Pr) were within ± 7% for the current bench and vehicle seat as compared to the upgraded bench. Pr was 4.7% and 6.8% lower on the current bench for no-CRS and HBB, and was 3.6% higher for LBB. Contrarily, Pr was 7% and 1.6% higher on the vehicle seat for no-CRS and HBB, and was 5.9% lower for LBB.

The Q6 ATD showed a 33.0% higher neck force (Fz) on the current bench as compared to the upgraded bench for the LBB case. However, it showed a 32.8% lower Fz on the vehicle seat for the HBB case. Neck moment (My) was within ± 9% for the current bench, and ± 4.7% for the vehicle seat as compared to the upgraded bench.

The ATD experienced a 12.0% and 13.5% higher head excursion for the current bench and vehicle seat respectively for the no-CRS condition. Head excursion was 7.7% higher and 6.0% lower for the current bench and vehicle seat respectively for the LBB condition. Minimal variation in head excursion was seen for the HBB case, with 0.8% lower, and 1.5% higher values for the current bench and vehicle seat respectively.

DISCUSSION

All injury metrics were within injury assessment reference value (IARV) limits for all simulated cases. To further evaluate the differences between the current FMVSS 213 test bench, the upgraded bench, and the vehicle seat, the change in CRS angle was calculated in the sagittal plane. The maximum change in CRS angle for the upgraded bench [LBB: 1.5deg; HBB: -3.6deg], current bench [LBB: -10.2deg; HBB: -12.9deg], and vehicle seat [LBB: 4.8deg; HBB: -3.6deg] were calculated from the CRSs initial position.

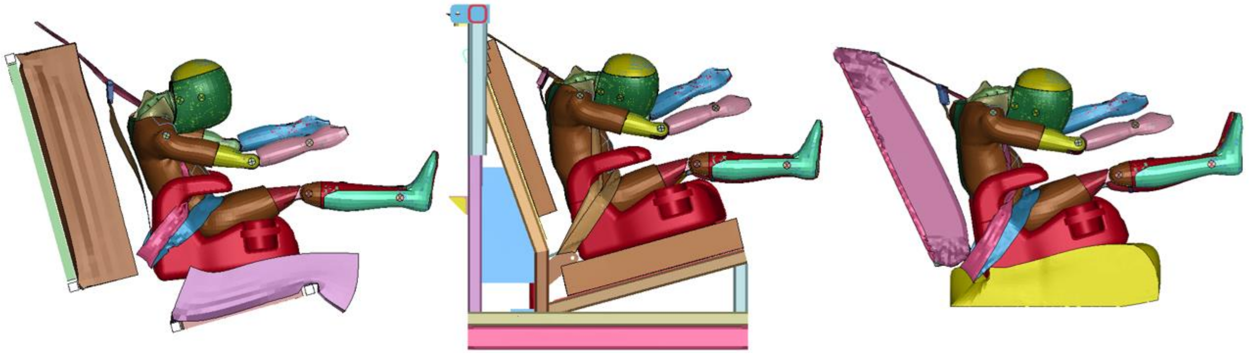

Figure 3: Foam compression in current FMVSS 213 test bench, upgraded bench, and vehicle seat

The large negative CRS angles represent the fact that the CRS pushes down on the seat cushion. Figure 3 depicts the behavior of the foams across the seating conditions for the current FMVSS 213 test bench, upgraded bench, and vehicle seat. Due to the softer foam and the inherent overhang on the current FMVSS 213 test bench, the CRSs rotate extensively by compressing the foam, and then rotating about the overhang. However, this situation is not represented in the upgraded bench and the vehicle seat, where the CRS behavior is similar. The LBB shows a positive CRS rotation for the upgraded bench and vehicle seat, while the HBB shows a slight negative rotation of the seat. This could also be due to the inertia of the HBB and slightly higher center of mass as compared to the LBB.

Limitations

There are a few important limitations to the study. The study only accounts for one make and model of a LBB and HBB. There could be variation due to the design of the CRS which could affect the ATDs kinematics and performance across these different seating structures. Further, the Q6 ATD is a mechanical device, thereby resulting in stiffer responses as opposed to an actual human being in the same crash condition. To evaluate the efficacy of the FMVSS 213 test bench, human body models can be used to provide a complete estimate into the limitations and possible upgrades to the test bench. Moreover, newer vehicle makes and models have rear seats equipped with retractors and pre-tensioners. The dynamic response of a pediatric occupant due to the presence and absence of a retractor and pre-tensioner could be a useful analysis into upgrading the current FMVSS protocols.

CONCLUSIONS

The upgrade to the current FMVSS 213 test bench better represents a vehicle rear seat under dynamic crash scenarios for a frontal impact. Due to the absence of the overhang and a much stiffer foam, ATDs in CRSs on the upgraded bench perform similar to vehicle seats.

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