# PAIRED COMPARISON OF ATD RESPONSES FOR THE CMVSS 213 BENCH AND PROPOSED FMVSS 213 BENCH

**Suzanne Tylko**
Transport Canada
Canada

**Kathy Tang, Alain Bussières, Amanda Starr**
PMG Technologies
Canada

Paper Number 19-0331

## ABSTRACT

A controlled matched pair comparison of child ATD responses, installed in different models of child restraints was conducted to investigate differences between the current CMVSS 213 bench and the proposed FMVSS 213 bench. The effect of acceleration and deceleration pulses on ATD responses were also examined.

The CRABI 12-month-old and the Hybrid III 6-year-old were placed in rear facing and forward-facing child restraints installed on the current CMVSS 213 bench and the proposed FMVSS 213 bench. Repeatability of installation was verified with a 3D Faro measurement system. A total of 114 tests were conducted on the Seattle Safety acceleration sled and on the Messring HydroBrake deceleration sled.

Head, chest and pelvis acceleration responses were compared for pairs matched as a function of ATD, seat type, and installation method. Maximum head excursion, maximum knee excursion, and seat excursion at the time of maximum head excursion were estimated using video recordings.

Downward displacement of rear facing seats was reduced on the proposed bench when compared to the current CMVSS 213 bench. The Hybrid III 6-year-old head, chest, and pelvis responses on the two benches were similar (difference of ≤ 5g). One forward facing seat exhibited a higher chest response on the proposed bench. Maximum head excursions relative to both the bench and the seat tended to be greater on the proposed bench for all seats regardless of installation method. Paired responses on the acceleration and deceleration sleds were similar. Differences in paired responses were found to be more strongly linked to product design characteristics than to test bench characteristics or sled type.

The study contributes to an understanding of the influence of test configuration and is pertinent to the development of child restraint regulations or consumer evaluation programs.

## INTRODUCTION

The Canadian Motor Vehicle Safety Standard 213 and Federal Motor Vehicle Safety Standard 213 (C/FMVSS 213) are two very similar standards in place in Canada and the United States specifying performance requirements for child restraint systems (CRS). Both standards require dynamic testing on an acceleration or deceleration sled. The geometry and cushion stiffness of the test bench were originally based on the front seat of a 1974 Chevrolet Impala [1]. In 2003, the National Highway Traffic Safety Administration (NHTSA) introduced a new drawing package for the seat assembly which included changes to the seat bottom and seat back cushion angles, lap belt anchorage locations, and seat back rigidity [2], [3]. Changes to the seat cushion stiffness were not included in this revision [4].

In 2015, a new version of the bench was proposed by the NHTSA to replace the bench used in the FMVSS 213 standard [5], [6]. As part of a review of this proposal, Transport Canada fabricated the proposed bench and began a paired comparative study to quantify differences in the evaluation of seat performance attributable to the new seat assembly. Since the study was conducted between 2016 and 2018, the evaluation was based on the drawings that were shared by the NHTSA at that onset of the study, to ensure constancy. The intent of this paper is to present the results of paired comparisons of ATD responses obtained with the current CMVSS 213 bench and the proposed NHTSA bench. The principal objective is to provide a comparison of the regulatory measures used to determine compliance of bench belt-positioning booster seats, forward-facing CRS (FFCRS), and rear-facing CRS (RFCRS) in North America. Numerous ATD measures are included for the sake of completeness and for future analysis.

## METHODS

### Sled Testing

Sled tests were run in three different conditions: (1) using the proposed NHTSA bench on the acceleration sled (Fig. 1A); (2) using the CMVSS 213 bench on the acceleration sled (Fig. 1B); and (3) using the proposed bench on the deceleration sled (Fig. 1C). To assess CRS performance on the two benches or the two sleds, tests in condition (1) were respectively compared to those in condition (2) or (3).

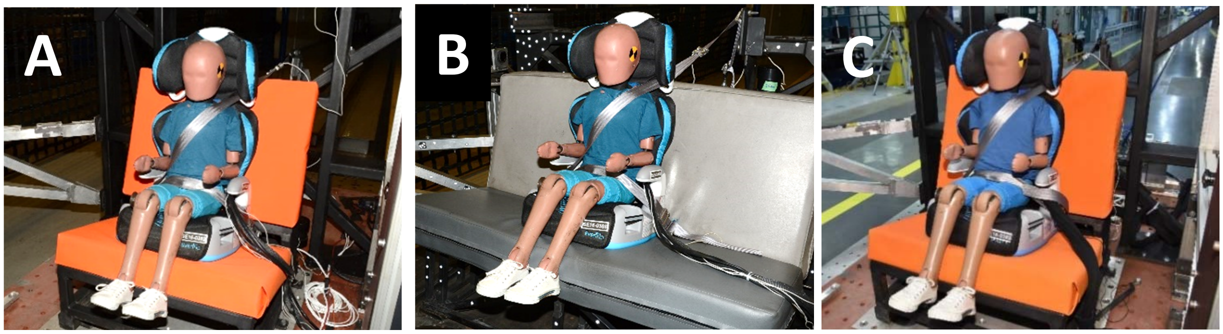

***Figure 1. The Hybrid III 6-year-old installed in a high-back booster seat on (A) the proposed FMVSS bench + accel sled, (B) the CMVSS bench + acceleration sled, and (C) the proposed FMVSS bench + deceleration sled.***

For each condition, child seats were installed in up to eight different configurations (Table 1), with each configuration varying by seat type (FFCRS, booster seat, or RFCRS with or without base) and attachment method (Type 2 belt or universal anchorage system (UAS)). FFCRS and booster seats were installed with the Hybrid III 6-year-old ATD, and RFCRS were installed with the CRABI 12-month-old. All tests with FFCRS included the use of a harness and the top tether. For each RFCRS, two targets were placed on the RFCRS shell to estimate RFCRS rotation.

A few minor changes, detailed in the Appendix were made to the proposed bench to increase durability. The sleds included a Seattle Safety 2 MN servo controlled pneumatic acceleration sled (Seattle Safety, Kent, WA, USA) and a MESSRING HydroBrake deceleration sled (MESSRING GmbH, Krailling, Germany). Figure 2 presents the pulses obtained. The pulses corresponding to the acceleration sled are shown in red while the deceleration pulses are presented in green.

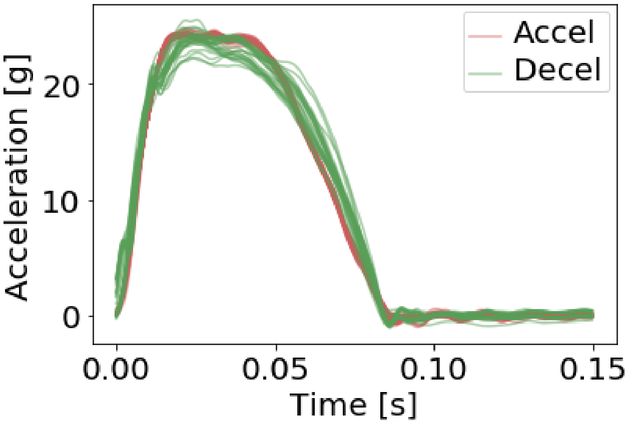

***Figure 2. Time-acceleration traces of the sled pulse on the acceleration (red) and deceleration (green) sleds.***

Installations of the child restraints and booster seats were carried out as per manufacturer instructions. The same Hybrid III 6-year-old and 12-month CRABI ATDs were used throughout the study. A FaroArm 3D metrology system (FARO, Lake Mary, Florida, USA) was used to precisely record placement and to reproduce the positioning of the ATDs between matched tests. Front, left, right, and top views of the tests were recorded using NAC high-speed cameras (NAC Image Technology, Simi Valley, CA, USA), Integrated Design Tools (IDT, Pasadena, CA, USA) at a rate of 1000 frames per second.

***Table 1.***
***Test matrix.***

| Model | Configuration | ATD | Proposed FMVSS + accel sled | CMVSS + accel sled | Proposed FMVSS + decel sled |
|---|---|---|---|---|---|
| A | FF + Belt + tether | Hybrid II 6YO | 3 | 3 | 0 |
| B | FF + Belt+ tether | | 2 | 2 | 0 |
| | FF + UAS+ tether | | 2 | 2 | 0 |
| | HB | | 1 | 1 | 1 |
| C | FF + Belt+ tether | | 1 | 1 | 0 |
| D | FF + Belt+ tether | | 3 | 4 | 0 |
| | FF + UAS+ tether | | 1 | 1 | 0 |
| | Conv. RF + Belt | CRABI 12MO | 1 | 1 | 1 |
| E | HB | Hybrid II 6YO | 1 | 1 | 1 |
| F | HB | | 3 | 1 | 3 |
| G | HB | | 2 | 2 | 1 |
| | LB | | 3 | 3 | 1 |
| H | HB | | 1 | 1 | 1 |
| | LB | | 1 | 1 | 1 |
| I | LB | | 4 | 4 | 2 |
| J | Conv. RF + Belt | CRABI 12MO | 1 | 1 | 2 |
| K | RF + Belt | | 1 | 1 | 1 |
| | RF + Base + Belt | | 2 | 2 | 2 |
| | RF + Base + UAS | | 3 | 1 | 3 |
| L | RF + Belt | | 1 | 1 | 1 |
| | RF + Base + Belt | | 1 | 1 | 1 |
| | RF + Base + UAS | | 1 | 1 | 1 |
| M | RF + Base + Belt | | 1 | 1 | 1 |
| N | RF + Base + Belt | | 1 | 2 | 1 |
| | RF + Base + UAS | | 1 | 1 | 1 |
| O | RF + Base + UAS | | 1 | 1 | 0 |
| P | RF + Base + Belt | | 1 | 1 | 1 |

FF = forward-facing, HB = high-back booster, LB = low-back booster, RF = rear-facing, UAS = universal anchorage system

**Data Analysis**

High-speed videos were used to visually compare ATD and CRS movements. The vertical displacements, rotations and excursions of the two targets on each RFCRS were tracked using TEMA 3.5 (Image Systems Motion Analysis, Linköping, Sweden). RFCRS rotation was calculated as the angle from the vertical (12 o'clock) of the line drawn between the two targets, measured in degrees. The absolute values of the x, y, and z accelerations were determined at the time of peak resultant acceleration.

To compare ATD responses on the two benches or the two sleds, linear mixed effects models were constructed for each comparison. This allowed us to compute configuration-specific differences in mean responses and test for their significance while accounting for the variation in responses resulting from differences between specific child seat models. Linear mixed effects models were favoured over paired tests because they allowed for the inclusion of replicate tests. For each comparison, linear mixed effects models were constructed as

$$X = \beta_0 + \beta_1 + \gamma + \epsilon \qquad \text{Equation (1)}$$

where

$X$: Response (e.g. maximum head excursion) observed for either condition (2) or (3), depending on the comparison of interest

$\beta_0$: Response observed for condition (1)

$\beta_1$: Difference between the responses in the two conditions

$\gamma$: Random effect describing variance attributed to differences between CRS models; follows a normal distribution with mean 0

$\epsilon$: Residual term; follows a normal distribution with mean 0

The difference between the responses either on the two benches or on the two sleds is thus given by $\beta_1$. To test for the significance of this difference, Eq. (1) was tested against a model which assumed no difference in responses under the two different conditions, i.e. $\beta_1$=0 and $X = \beta_0 + \gamma + \epsilon$. Significance testing was conducted using p-values determined by the likelihood ratio test (implementation using the anova function in R) and a 5% significance level. Linear mixed effects models were constructed in R using the lme4 package [7].

## RESULTS

### Comparison of FFCRS and Booster Seats Between Benches Using the Hybrid III 6-Year-Old

**Aggregate comparisons of the Hybrid III 6-year-old response on the two benches** In a number of tests with the FF + belt configuration, the path of the shoulder belt was altered by contact with the seat back foam on the proposed FMVSS bench (Fig. 3A). The shoulder belt path was straighter on the CMVSS bench (Fig. 3B).

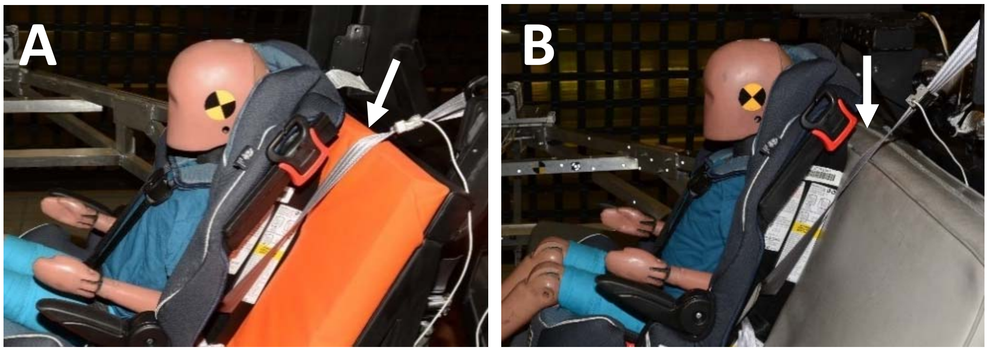

***Figure 3. Example of a FFCRS installed with the Type 2 belt on (A) the proposed bench and (B) the CMVSS bench. White arrows indicate the point on the shoulder belt where differences in contact with the bench were observed.***

Figure 4 compares the means and standard deviations of ATD responses on the two benches for each configuration, and Table A1 specifies the differences in mean response (i.e. $\beta_1$ in Eq. (1)) and p-values for each comparison. While all excursions were well below the compliance limits, head excursions tended to be slightly greater on the proposed bench. The difference was statistically significant for only the FF + belt and LB configurations (Fig. 4A). Knee excursions were significantly greater on the proposed bench for all configurations (Fig. 4B). Head and chest 3ms clips were not significantly different on the two benches (Fig. 4C-D). The difference between mean peak chest deflections was only significant for the FF + UAS (Fig. 4E).

Statistically significant differences in the responses on the two benches were found for peak shoulder belt loads, upper neck axial loads, and lumbar spine moments about z. Shoulder belt loads were significantly greater on the CMVSS bench than on the proposed bench for all configurations using a Type 2 belt (Fig. 4F). For tests with booster seats, upper neck loads tended to be greater on the proposed bench, although the difference was statistically significant for only high-back boosters. Conversely, peak (maximum) lumbar spine moments about z for booster seats were lower on the proposed bench than on the CMVSS bench.

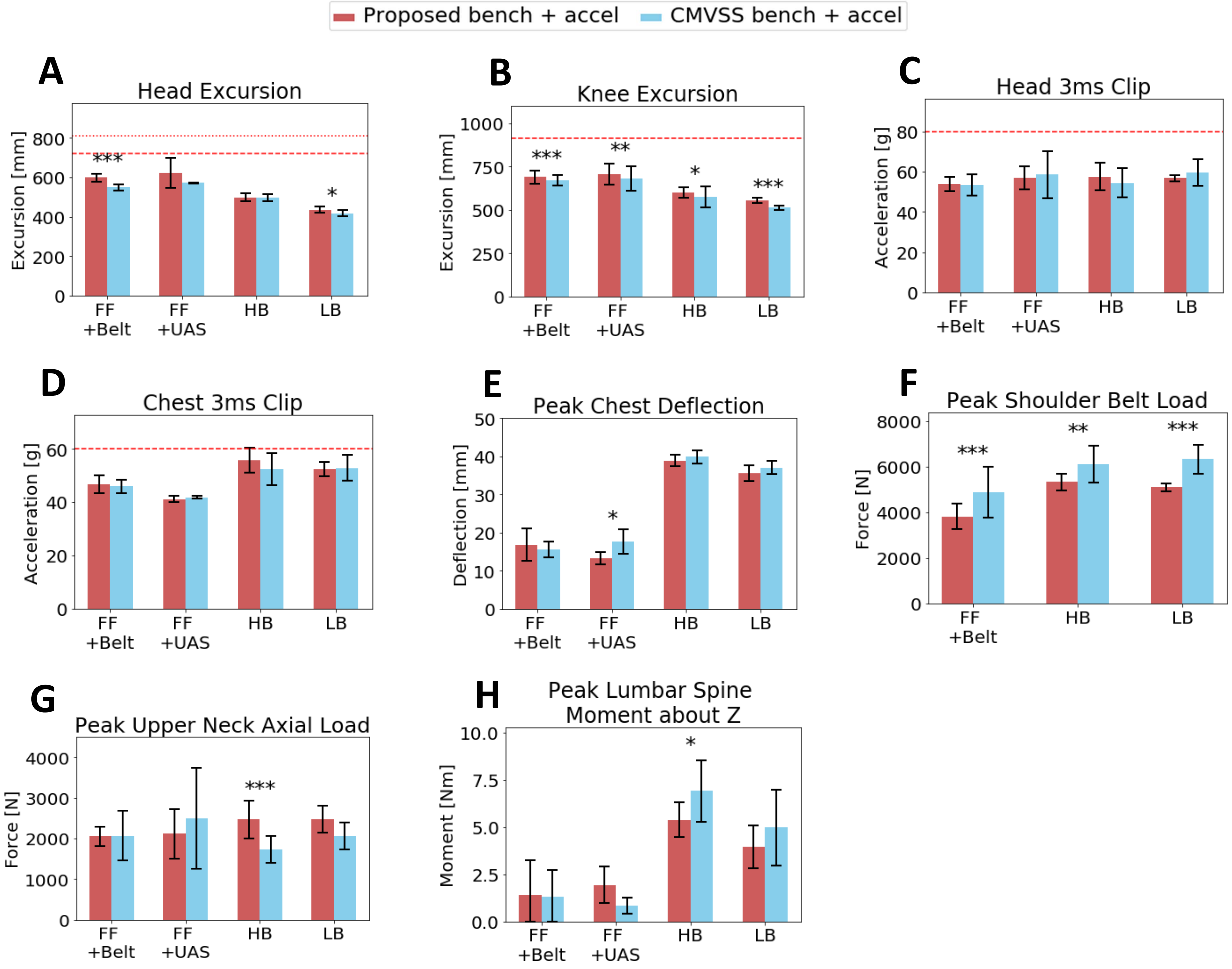

***Figure 4. Differences in responses of the 6-year-old on the proposed (red bars) and CMVSS (blue bars) benches for each configuration[1].***

**<u>Matched comparisons of the Hybrid III 6-year-old response on the two benches</u>** Paired tests[2] were carried out to investigate the responses associated with specific CRS models. To this end, we found large differences in head excursion for Model B when installed with the UAS. The mean head excursion in this seat installed on the proposed bench (n=2) exceeded the mean head excursion on the CMVSS bench (n=2) by 92 mm. At peak head excursion, the ATD torso and the CRS backrest appeared to be more upright on the proposed bench compared to the CMVSS bench (Fig. 5). Mean knee excursions were 33 mm greater on the proposed bench than on the CMVSS bench. The differences in mean head and chest 3ms clips, chest deflections, and upper neck axial loads were all relatively small (Table A2).

---

[1] Bars in all charts represent the mean ± standard deviation of each response. Statistical significance is indicated by the asterisks above pairs of bars (* for p<0.05, ** for p < 0.01, *** for p < 0.001).

[2] Refers to tests matched by model and configuration

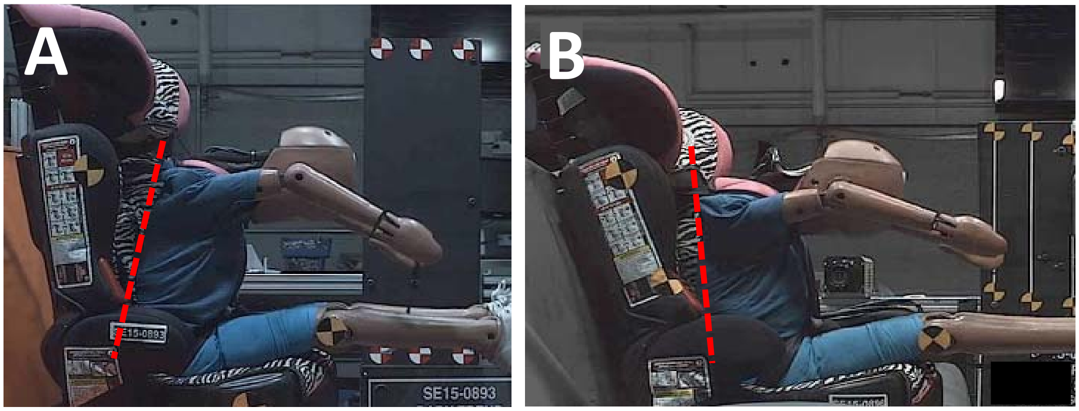

***Figure 5. Freeze frames at maximum head excursion of the 6-year-old on Model B FFCRS installed with tether + UAS on the (A) proposed bench and (B) CMVSS bench.***

### Comparison of FFCRS and Booster Seats Between Sleds Using the Hybrid III 6-Year-Old

**Aggregate comparisons of the Hybrid III 6-year-old response on the two sleds** Assessments of CRS performance on the acceleration and deceleration sleds using the Hybrid III 6-year-old were limited to comparisons of booster seats only. In general, the responses seen on the two sleds were not significantly different from each other (Fig. 6A-D, F-H). We did observe, slightly greater peak chest deflections (2.7 mm and 2.5 mm for high-back and low-back boosters, respectively) on the acceleration sled compared to the deceleration sled (Fig. 6E).

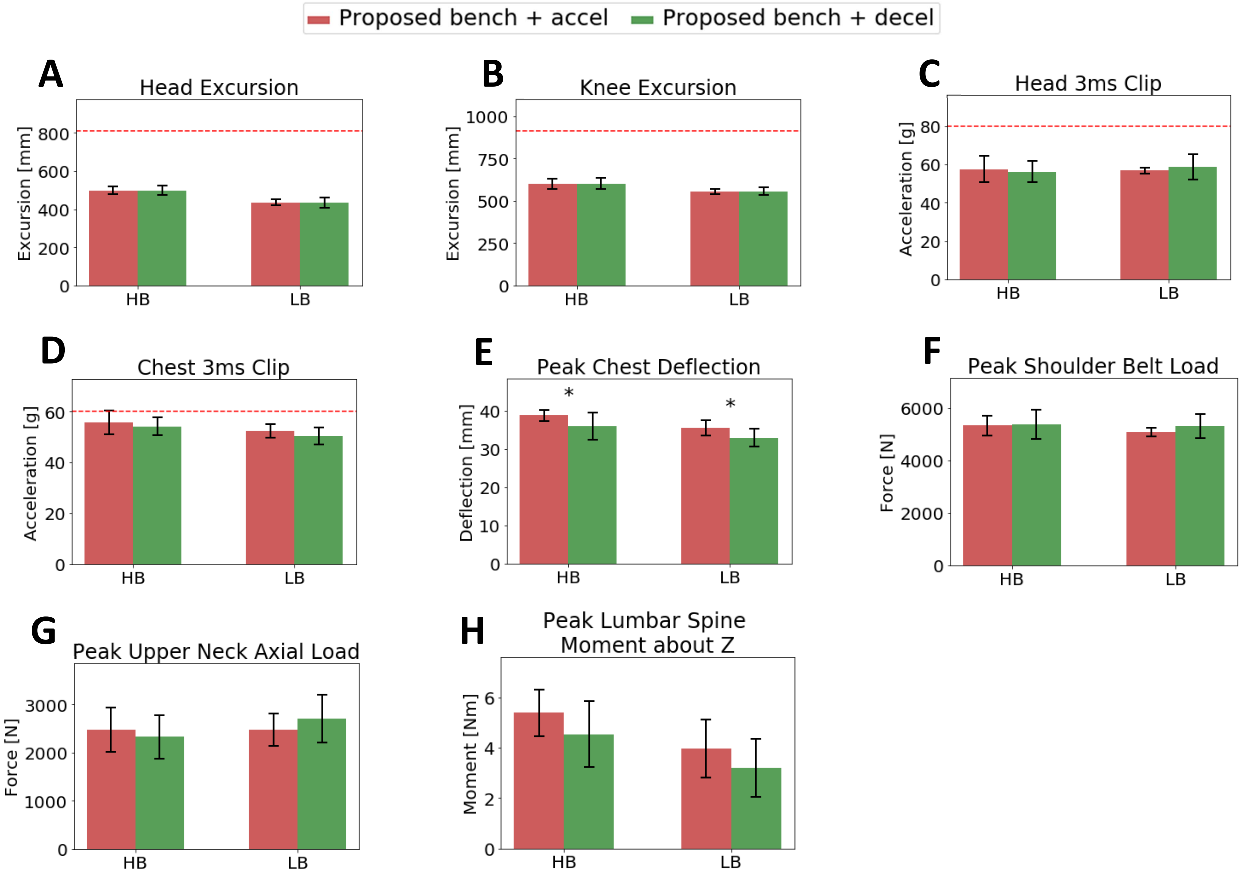

***Figure 6. Differences in responses of the 6-year-old on the acceleration (red bars) and deceleration (blue bars) sleds for HB and LB booster seats. Dashed red lines in panels A-D indicate the regulatory limits of each response.***

**Matched comparisons of the Hybrid III 6-year-old response on the two sleds** Comparisons of responses seen for specific booster seat models showed that for tests with Model F, one of the three tests conducted on the acceleration sled resulted in a chest 3ms clip exceeding 60g (Table 2). In the three matched tests conducted on the deceleration sled, all chest 3ms clips were below 60 g.

***Table 2.***

***Chest 3ms clips for six tests with Model F installed on the proposed bench.***

| Sled | Acceleration | | | Deceleration | | |
|---|---|---|---|---|---|---|
| Test no. | 1 | 2 | 3 | 4 | 5 | 6 |
| Chest 3ms clip [g] | 63.2 | 58.9 | 57.5 | 57.7 | 56.5 | 52.9 |
| Mean (Stand dev.) | 59.9 ± 3.0 | | | 55.7 ± 2.5 | | |

### Comparison of RFCRS Performance Between Benches Using the CRABI 12-Month-Old ATD

**Aggregate comparisons of the CRABI 12-month-old response on the two benches** The CRABI 12-month-old responses were compared for four different configurations. Additionally, tracking of the targets on the RFCRS shell allowed for comparison of RFCRS motions. The differences in mean responses seen on the two benches (i.e. $\beta_1$ in Eq. (1)) and their associated p-values are summarized in Table A4.

Visual comparisons of the two benches showed that the path of the shoulder belt was altered by contact with the seat back foam on the proposed NHTSA bench (Fig. 7A, white arrow). The shoulder belt path was straighter on the CMVSS bench (Fig. 7B, white arrow). This difference was consistently seen for all tests where the Type 2 belt was used.

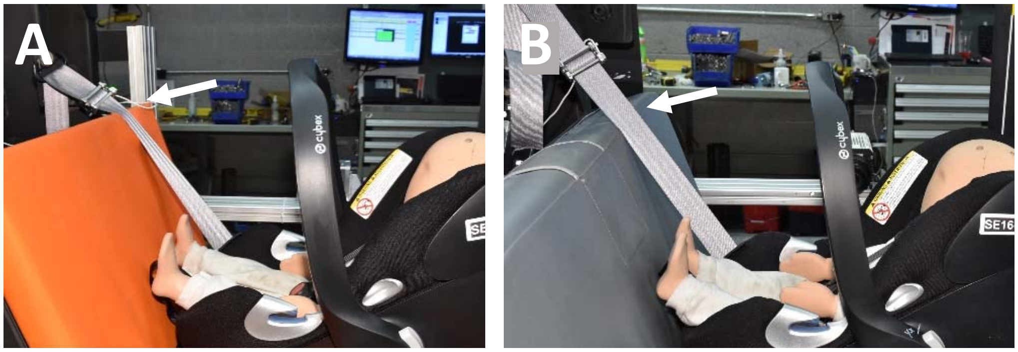

***Figure 7. Example of an installation of the RF + base + belt configuration on the (A) proposed bench and (B) CMVSS 213 benches. White arrows indicate the point on the shoulder belt where differences were observed.***

Comparisons of RFCRS motions on the two benches showed significantly greater peak angle changes and vertical displacements on the CMVSS bench compared to the proposed bench (Fig. 8A-B). Differences in peak excursion varied by configuration (Fig. 8C). For the non-convertible RF + belt configuration, mean excursion on the proposed bench was slightly greater than the mean excursion on the CMVSS bench. Conversely, for both configurations where the RFCRS was installed with a base, mean excursions were lower on the proposed bench. Peak shoulder belt loads were significantly greater on the CMVSS bench than on the proposed bench (Fig. 8D). Differences in head and chest 3ms clips on the two benches also varied by configuration (Fig. 8E-F). The only significant difference in head 3ms clip occurred for the RF + base + belt configuration, where responses were greater on the proposed bench. The chest 3ms clips were generally slightly greater on the proposed bench for both the convertible RF + belt and RF + base + UAS configurations. In contrast, the chest 3ms clip for the RF + base + belt configuration was less on the proposed bench.

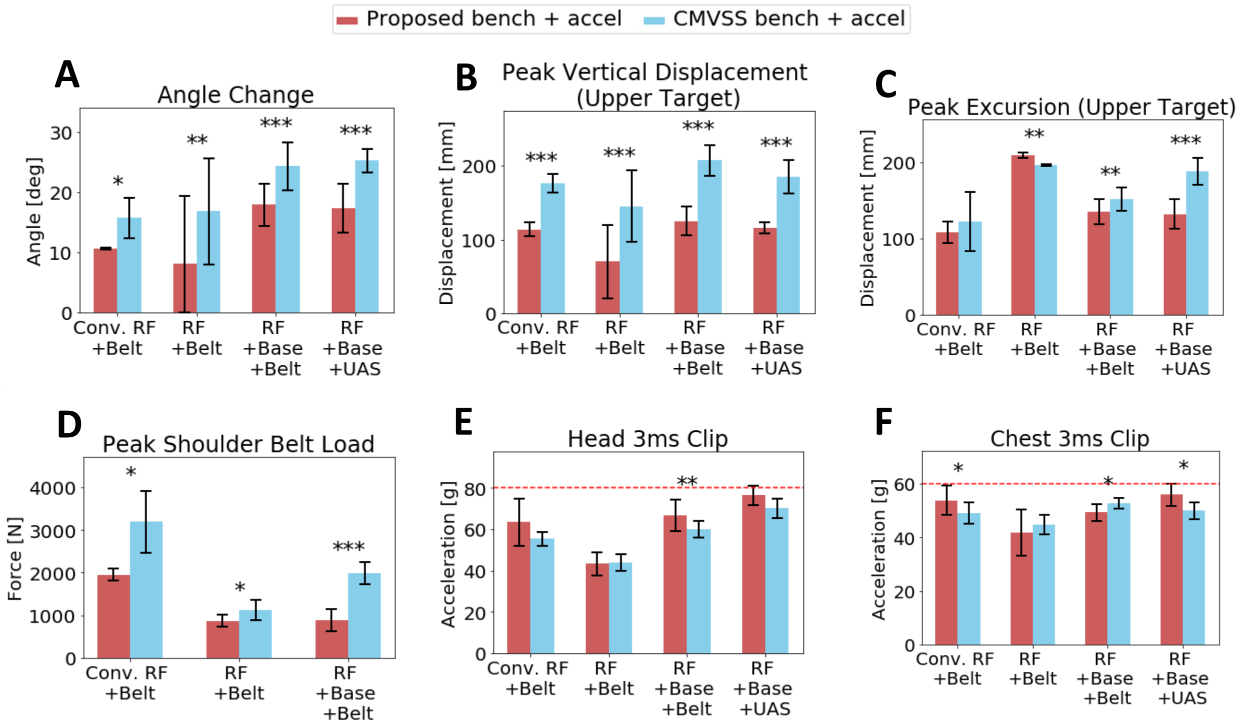

*Figure 8. Differences in responses of the 12-month-old on the proposed FMVSS (red bars) and CMVSS (blue bars) benches for each configuration. Thick dashed red lines in panels E-F indicate the regulatory limits of each response.*

In order to better understand the chest clip differences, the chest acceleration components were examined. At the time of peak resultant acceleration, the x components in the tests for the two RF + Base configurations were greater in magnitude for the proposed bench (Fig. 9A) compared to the CMVSS bench. The z components in contrast, were much lower in magnitude for the proposed bench compared to the CMVSS bench (Fig. 9B). For these two test configurations, the differences in the z component associated with the proposed bench were comparable (Fig. 9B) but the difference in the magnitude of the x component associated with the proposed bench was smaller and much less significant for the RF + base + belt installation (Fig. 9A).

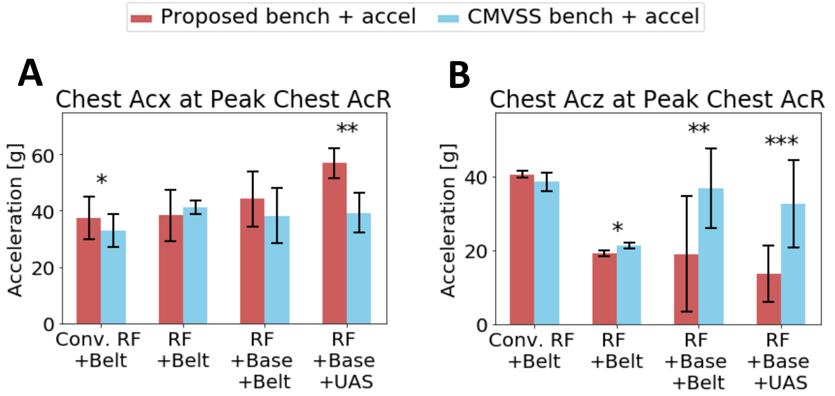

*Figure 9. Differences in (A) Chest Acx and (B) Chest Acz at the time of peak chest resultant acceleration on the proposed FMVSS (red bars) and CMVSS (blue bars) benches for each configuration.*

In addition to the differences in chest responses shown in Fig. 9, we also found differences in the relationship between the chest 3ms clip and RFCRS motion for the belt and UAS installations. For tests in the RF + base + belt configuration, chest 3ms clips were lower when the peak angle change was reached before the lower visual target on the CRS attained its peak vertical displacement; but the chest 3ms clips were greater when the peak angle change occurred at or after peak vertical displacement was attained (Fig. 10A). On the other hand, for tests with the RF +

base + UAS configuration, the correlation between chest 3ms clip and the timing of peak angle change relative to peak vertical displacement was weak. Instead, tests with this configuration showed a stronger relationship between chest 3ms clip and peak (lower target) excursion, where greater peak excursions were associated with lower chest 3ms clips (Fig. 10B). R values shown are Pearson correlation coefficients.

Multiple linear regression using all of the tests on the proposed bench suggested that both the peak excursion and the timing of peak angle change relative to peak vertical displacement were significant predictors of chest 3ms clip values (Table 3).

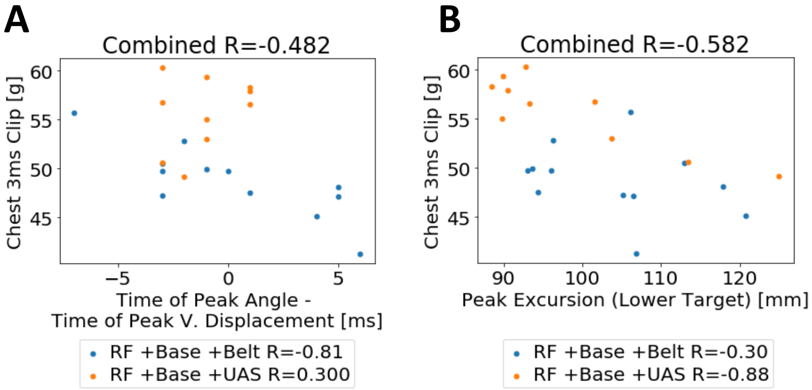

***Figure 10. Correlations between chest 3ms clips and (A) the time of peak angle change relative to the time of peak vertical displacement and (B) peak lower target excursion in RFCRS installed in the RF + base + belt (blue points) and RF + base + UAS (orange points) configurations.***

***Table 3.***

***Coefficients and associated p-values of each predictor of the multiple regression model.***

| | Coefficient | p |
|---|---|---|
| Intercept | 67.0 | < 0.001 |
| Time of peak angle change – time of peak vertical displacement | 0.2 | < 0.001 |
| Peak excursion | -0.7 | 0.011 |

**Matched comparisons of the CRABI 12-month-old response on the two benches** Matched comparisons of responses seen with specific RFCRS models on the two benches revealed that in tests using Model K with a base and UAS, the chest 3ms clips seen on the proposed bench across three tests ranged from 56.6-60.3g. Testing the same RFCRS model on the CMVSS bench yielded a chest 3ms clip of 53.5 g, which was 3.1 g lower than the lower bound of the range obtained on the proposed bench and 1.6 standard deviations lower than the mean.

### Comparison of RFCRS Performance Between Sleds Using the CRABI 12-Month-Old ATD

**Aggregate comparisons of the CRABI 12-month-old response on the two sleds** For all installations except the RF + belt configuration, tests on the two sleds showed no significant differences in RFCRS movement. For the RF + belt configuration, the angle change, peak upper target excursion, and peak upper target vertical displacement were statistically significantly greater on the deceleration sled, although the differences were small (Fig. 11A-C, mean differences of 2°, 4 mm, and 10 mm, respectively). Lower target excursions for tests in this configuration were not significantly different on the two sleds (Fig. A1), suggesting that the differences shown in Fig. 11A-C are related to differences in the peak CRS angle change. Head and chest 3ms clips on the two sleds tended to be similar, except in tests with convertible RF + belt, for which they were greater on the acceleration sled than on the deceleration sled (Fig. 11F).

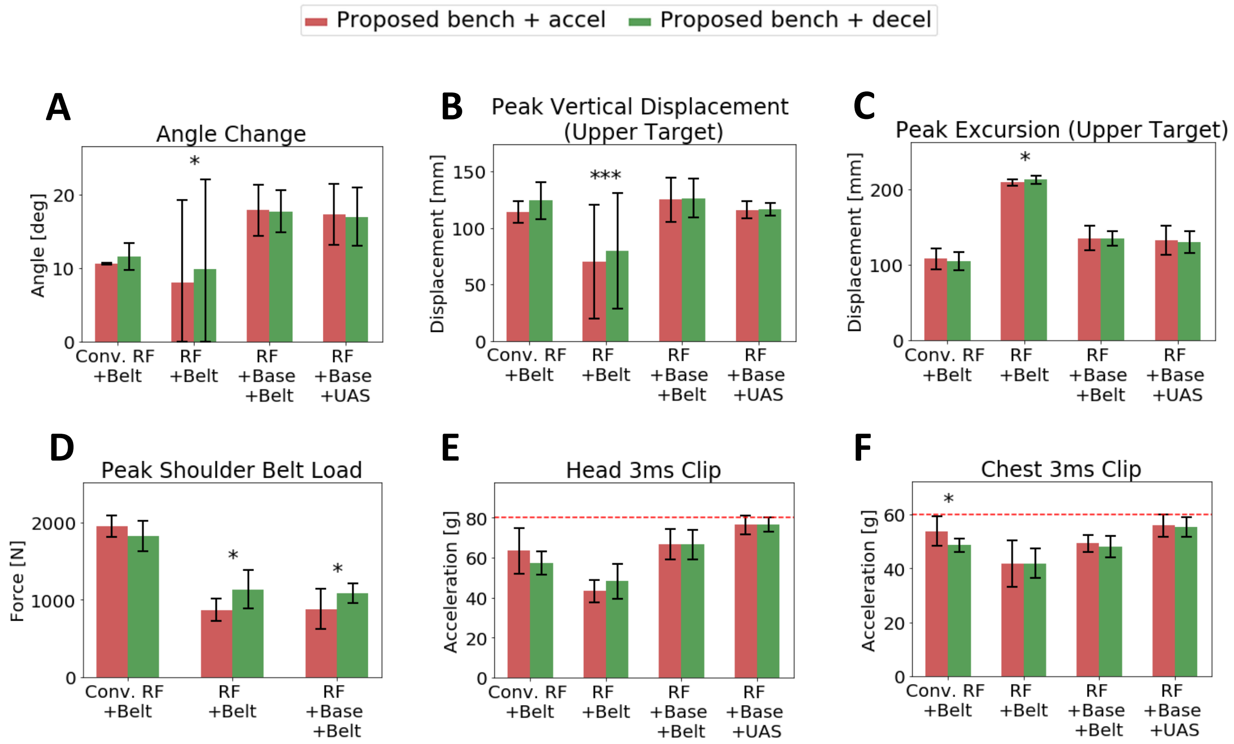

***Figure 11. Differences in responses for the 12-month-old on the acceleration (red bars) and deceleration (green bars) benches for each configuration. Dashed red lines in panels E-F indicate the regulatory limits of each response.***

**Matched comparisons of the CRABI 12-month-old response on the two sleds** For both models tested in the convertible RF + belt tested configuration, chest accelerations in x at peak resultant acceleration were higher on the acceleration sled (Fig. 12A) while z was comparable (Fig. 12B). The time of peak angle change on the acceleration sled was within 1ms of that of peak vertical CRS displacement, whereas on the deceleration sled, the peak angle change preceded the peak vertical displacement by up to 4 ms.

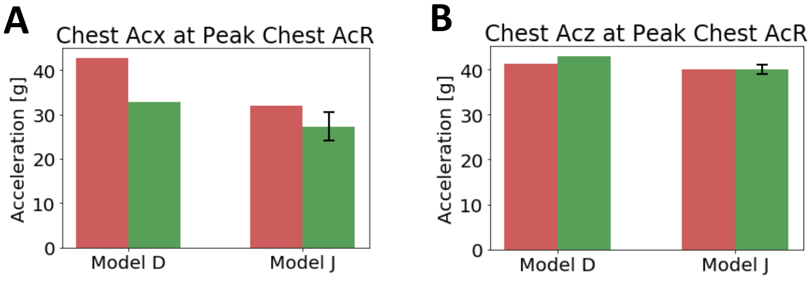

***Figure 12. Differences in (A) Chest Acx and (B) Chest Acz at the time of peak chest resultant acceleration on the acceleration (red bars) and deceleration (green bars) sleds for each configuration.***

## SUMMARY & DISCUSSION

Results from 114 tests that included belt-positioning booster seats, forward-facing CRS (FFCRS), and rear-facing CRS (RFCRS) installed on the proposed NHTSA and current CMVSS benches were presented. In tests with the 6-year-old, differences in responses on the two benches, if any, were minor. Forward facing child restraints and booster seats installed on the proposed bench were associated with slightly greater head and knee excursions for the 6-year-old however, all remained well below the established compliance limits. There was no significant difference in the head and chest acceleration clips. Chest deflections were not significantly different with the exception of the

FF + UAS configuration which resulted in a very small decrease (4.3 mm, $p<0.05$) in chest deflection on the proposed bench. Paired testing of a specific FFCRS installed with the UAS demonstrated that certain CRS designs can produce results that are different from the average response of the sample. In this pair, the upper torso of the ATD was more upright on the proposed bench. This difference in motion is likely the effect of the increased seat cushion stiffness and bench geometry. The influence of the bench characteristics was much more apparent with this CRS model. Previous comparisons of Hybrid III 6-year-old responses in FFCRS showed that head and knee excursions were greater on vehicle seats than on the CMVSS bench, and that CRS rotated forward on vehicle seats and rearward on the CMVSS bench [8]. The differences observed here between the two benches may be indicative that the proposed bench is more representative of modern vehicle seats than the CMVSS bench.

No significant difference in responses were observed for the proposed bench as a function of sled type with the single exception of the chest deflection responses which were approximately 2.5 mm greater on the acceleration sled. Analysis of the matched pair comparison of a specific seat model produced a chest acceleration response that was on average 4 g greater on the acceleration sled. The cause of this difference is being investigated in a separate study.

Comparisons of RFCRS movements on the two benches showed significantly lower mean RFCRS angle changes and vertical displacements on the proposed bench. In a previous study [9] comparing RFCRS performance on the CMVSS bench and on vehicle seats, RFCRS vertical displacements were lower in magnitude on vehicle seats than on the bench. The similarities between the comparisons made in the current study and those made between the CMVSS bench and vehicle seats in [9] suggest that the proposed bench reproduces RFCRS motions as seen on a vehicle seat better than the CMVSS bench.

Head and chest responses of the 12-month-old that were statistically significantly different were higher on the proposed bench. The only exception was the chest 3ms clip for the RF + base + belt configuration. We suspect that this exception is due to a difference in the x and z contributions of the resultant acceleration which are in turn the result of differences in the timing and magnitude of CRS rotations.

Multiple linear regression suggested that the peak excursion and the timing of peak angle change relative to peak vertical displacement were significant predictors of chest 3ms clip values. Contact with the bench frame, which may interrupt RFCRS rotation, was suspected in tests where peak angle change and vertical displacement coincided. The likelihood of contact with the seat frame was reduced if peak angle change occurred much earlier than peak vertical displacement. Contact with the frame may contribute to an increased chest response.

Comparisons of RFCRS performance on the two sleds did not generally show statistically significant differences in RFCRS movement or ATD response. Where statistical significance was identified, the differences were relatively small.

## CONCLUSION

Results of paired tests conducted with forward-facing child restraints and booster seats that were installed on the proposed NHTSA and current CMVSS benches suggest that the differences in responses were generally small. Though excursions of the head and knees tended to be greater on the proposed bench these were all well below the regulatory limits. No significant difference in responses were observed for the proposed bench as a function of sled type with the single exception of the chest deflection responses which were greater on the acceleration sled.

Differences in the angle changes and vertical displacements of rear-facing child restraints suggest that the proposed bench may produce a better representation of motions produced on a contemporary vehicle seat than the current CMVSS bench. Small differences in the timing of the CRS motion and small differences in chest acceleration were observed for rear facing installations on the proposed bench as a function of sled type.

Certain differences appeared to be more strongly linked to product design characteristics than to test bench characteristics or sled type and will be investigated in future studies.

## LIMITATIONS AND FUTURE WORK

- The sample size of child seats tested in this study allowed for evaluation of aggregate responses as well as statistical testing. For most configurations, at least three tests were conducted in each of the three conditions (proposed NHTSA bench + accel, CMVSS bench + accel, and proposed bench + decel). However, for the FF + UAS and convertible RF + belt configurations, only two tests were conducted in each condition. The low sample size for tests in each of these two configurations limits our knowledge of how well the samples represent the typical behaviours of other child seats in those configurations.
- In 2018, NHTSA published a revised drawing of the proposed bench [10] which included new drawings of the lap belt anchorages, rear locking belt anchor, and D-ring. Given these changes, further testing should be conducted to quantify the differences in ATD responses on the original and revised versions of the proposed bench.
- Although the current CMVSS and FMVSS 213 benches are very similar, differences exist between the two benches, such as the height of the lower anchorages [9]. Differences in the ATD responses as a function of CMVSS/ FMVSS benches were not included in this analysis.
- Qualitative video analysis of the tests was limited by differences between camera positioning, especially in comparisons of the two sleds, where the top and frontal views were not identical.
- A study is currently underway to examine the influence of sled pulse, seat design, belt path, and arm position on the 6-year-old chest response.

## DISCLAIMER

This paper shall not be construed as an endorsement, warranty, or guarantee, expressed or implied, on the part of Transport Canada for any evaluated material, product, system or service described herein. Readers should not infer that Transport Canada's evaluation is for any purpose or characteristic other than as stated herein. All information in this document is for information purposes, only and is not intended to provide any specific advice. Any reliance on or use of the information contained in this document is at the user's sole risk and expense.

## ACKNOWLEDGMENTS

The authors are grateful to the child seat manufacturers who graciously provided child restraints and booster seats for this study and the excellent sled team at PMG Technologies for conducting the tests.

## REFERENCES

[1] Glass, W. 2002 "Technical Report on the FMVSS 213 Crash Pulse and Test Bench Analysis" Naval Air Warfare Center (NAVAIR) Report No. NAWCADPAX/TR-2001/184

[2] 67 FR 21836.

[3] 68 FR 37619.

[4] Wietholter, K., Echemendia, C., Louden, A.E. 2017. "Development of a Representative Seat Assembly for FMVSS No. 213." In Proceedings of the 2017 Enhanced Safety of Vehicles Conference. (Detroit, MI, Jun. 5-8). 17-0431.

[5] NHTSA. 2015. Federal Register Docket Number NHTSA-2013-0055-0002.

[6] NHTSA. 2015. Federal Register Docket Number NHTSA-2013-0055-0008.

[7] Bates, D., Maechler, M., Bolker, B. and Walker, S. 2015. "Fitting Linear Mixed-Effects Models Using lme4." Journal of Statistical Software 67, No. 1, October: 1-48.

[8] Maltese, M.R., Tylko, S., Belwadi, A., et al. 2014. "Comparative Performance of Forward-Facing Child Restraint Systems on the C/FMVSS 213 Bench and Vehicle Seats." Traffic Injury Prevention 15, S103-S110.

[9] Tylko, S., Locey, C. M., Garcia-Espana, J. F., et al. 2013. "Comparative Performance of Rear Facing Child Restraint Systems on the CMVSS 213 Bench and Vehicle Seats." Annals of Advances in Automotive Medicine 57, September 2013: 311-328.

[10] NHTSA. 2018. Federal Register Docket Number NHTSA-2013-0055-0014.

## APPENDIX

### Modification of the Proposed FMVSS 213 Bench

The proposed FMVSS bench was constructed according to the drawings provided by NHTSA in the Federal Docket (Docket No. NHTSA-2013-0055-0002) with the modifications specified in Docket No. NHTSA-2013-0055-0008 as well as the following modifications to improve durability:

1. Two legs were attached to the back of the bench (Fig. 1A, labeled as 1);
2. Braces were added behind the lower anchorages (Fig. 1A, labeled as 2) and D-ring (Fig. 1B); and
3. The D-ring was secured to a plate attached to the bench (Fig. 1B).

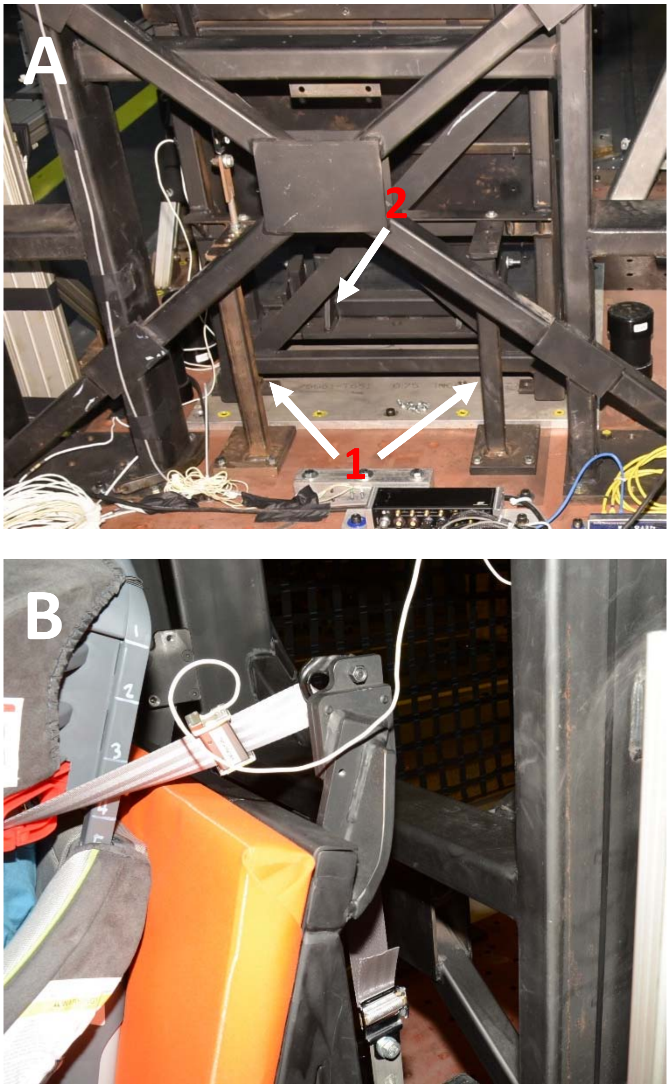

**Figure A1. (A) Rear view of the proposed NHTSA bench showing (1) legs added to the back of the bench and (2) braces added behind lower anchorages. (B) D-ring on the proposed NHTSA bench.**

### *Table A1.*

***Differences in mean responses of the Hybrid III 6-year-old on the two benches in four different configurations and associated p-values. A positive difference indicates that the response on the CMVSS bench was higher. Highlighted cells indicate responses that were statistically significantly different on the two benches.***

| | **FF + Belt** | | **FF + UAS** | | **HB** | | **LB** | |
|---|---|---|---|---|---|---|---|---|
| | **Difference** | **p** | **Difference** | **p** | **Difference** | **P** | **Difference** | **P** |
| Head Excursion | -49 mm | < 0.001 | -50 mm | 0.154 | -2 mm | 0.812 | -19 mm | 0.015 |
| Knee Excursion | -21 mm | < 0.001 | -26 mm | 0.006 | -32 mm | 0.011 | -43 mm | < 0.001 |
| Head 3ms clip | -1.0 g | 0.291 | 1.5 g | 0.671 | -0.8 g | 0.541 | 2.9 g | 0.183 |
| Chest 3ms clip | -0.9 g | 0.463 | 0.7 g | 0.306 | -1.9 g | 0.171 | 0.5 g | 0.669 |
| Peak chest deflection | -1.2 mm | 0.247 | 4.3 mm | 0.023 | 1.3 mm | 0.076 | 1.4 mm | 0.116 |
| Upper neck axial load | -62 N | 0.607 | 375 N | 0.206 | -696 N | <0.001 | -331 N | 0.051 |
| Lumbar spine moment about z | 0.2 Nm | 0.496 | -1.1 Nm | 0.057 | 1.4 Nm | 0.011 | 1.1 Nm | 0.132 |
| Peak shoulder belt load | 971 N | 0.001 | N/A | N/A | 836 N | 0.001 | 1242 N | < 0.001 |

### *Table A2.*

***Mean difference in response of the Hybrid III 6-year-old on the two benches installed with the Baby Trend + harness + tether + UAS.***

| | Difference (CMVSS-proposed) |
|---|---|
| Head Excursion | -92 mm |
| Knee Excursion | -33 mm |
| Head 3ms clip | -2.5 g |
| Chest 3ms clip | 0.1 g |
| Chest deflection | 3.6 mm |
| Upper neck axial force | 5 N |

***Table A3.***

***Differences in mean responses of the Hybrid III 6-year-old on the two sleds in two different configurations and associated p-values. A positive difference indicates that the response on the deceleration sled was higher. Highlighted cells indicate responses that were statistically significantly different on the two benches.***

| | **HB** | | **LB** | |
|---|---|---|---|---|
| | **Difference** | **P** | **Difference** | **P** |
| Head Excursion | -1 mm | 0.736 | -8 mm | 0.230 |
| Knee Excursion | -3 mm | 0.319 | -2 mm | 0.746 |
| Head 3ms clip | -2.4 g | 0.097 | 1.9 g | 0.351 |
| Chest 3ms clip | -2.2 g | 0.082 | -2.2 g | 0.131 |
| Peak chest deflection | -2.7 mm | 0.044 | -2.5 mm | 0.030 |
| Resultant upper neck load | -220 N | 0.135 | 237 | 0.291 |
| Lumbar spine moment about z | -0.9 Nm | 0.127 | -0.8 Nm | 0.256 |
| Peak shoulder belt load | 9 N | 0.927 | 230 N | 0.165 |

***Table A4.***

***Differences in mean responses of the CRABI 12-month-old on the two benches in four different configurations and associated p-values. A positive difference indicates that the response on the CMVSS bench was higher. Highlighted cells indicate responses that were statistically significantly different on the two benches.***

| | **Conv. RF + belt** | | **RF + belt** | | **RF + base + belt** | | **RF + base + UAS** | |
|---|---|---|---|---|---|---|---|---|
| | **Difference** | **p** | **Difference** | **p** | **Difference** | **p** | **Difference** | **p** |
| Angle Change | 5 ° | 0.030 | 9 ° | 0.010 | 6 ° | < 0.001 | 6 ° | < 0.001 |
| Excursion (upper target) | 14 mm | 0.330 | -13 mm | 0.002 | 16 mm | 0.009 | 48 mm | < 0.001 |
| Vertical Displacement (upper target) | 63 mm | < 0.001 | 75 mm | < 0.001 | 81 mm | < 0.001 | 73 mm | < 0.001 |
| Excursion (lower target) | 9 mm | 0.556 | -26 mm | 0.028 | 7 mm | 0.148 | 39 mm | < 0.001 |
| Vertical Displacement (lower target) | 44 mm | < 0.001 | 57 mm | < 0.001 | 66 mm | < 0.001 | 61 mm | < 0.001 |
| Shoulder Belt Load | 1235 N | 0.018 | 254 N | 0.019 | 1112 N | < 0.001 | N/A | N/A |
| Head 3ms clip | -8.1 g | 0.137 | 0.7 g | 0.457 | -7.1 g | 0.003 | -6.2 g | 0.068 |
| Chest 3ms clip | -4.8 g | 0.013 | 3.0 g | 0.304 | 3.5 g | 0.013 | -4.8 g | 0.017 |
| Chest Acx at peak chest resultant | -4.5 g | 0.021 | 2.8 g | 0.437 | -6.9 g | 0.068 | -17.7 g | 0.001 |
| Chest Acz at peak chest resultant | -2.0 g | 0.087 | 2.1 g | 0.014 | 19.3 g | 0.002 | 22.9 g | < 0.001 |

***Table A5.***

***Differences in mean responses of the CRABI 12-month-old on the two sleds in four different configurations and associated p-values. A positive difference indicates that the response on the deceleration sled was higher. Highlighted cells indicate responses that were statistically significantly different on the two benches.***

| | **Conv. RF + belt** | | **RF + belt** | | **RF + base + belt** | | **RF + base + UAS** | |
|---|---|---|---|---|---|---|---|---|
| | **Difference** | **p** | **Difference** | **p** | **Difference** | **p** | **Difference** | **p** |
| Angle Change | 1 ° | 0.378 | 2 ° | 0.046 | 0 ° | 0.780 | 0 ° | 0.457 |
| Excursion (upper target) | 0 mm | 0.850 | 4 mm | 0.031 | 0 mm | 0.976 | -2 mm | 0.494 |
| Vertical Displacement (upper target) | 7 mm | 0.199 | 10 mm | 0.001 | 1 mm | 0.705 | 0 mm | 0.818 |
| Excursion (lower target) | -1 mm | 0.625 | 0 mm | 0.763 | 0 mm | 0.919 | -1 mm | 0.551 |
| Vertical Displacement (lower target) | 6 mm | 0.066 | 6 mm | 0.007 | 2 mm | 0.357 | 1 mm | 0.215 |
| Shoulder Belt Load | -130 N | 0.341 | 266 | 0.022 | 170 N | 0.032 | N/A | N/A |
| Head 3ms clip | -4.1 g | 0.078 | 5.0 g | 0.060 | -1.3 g | 0.481 | 0.2 g | 0.938 |
| Chest 3ms clip | -4.5 g | 0.030 | 0.2 g | 0.902 | -1.2 g | 0.258 | 0.4 g | 0.731 |