Comparative Performance of Forward-Facing Child Restraint Systems on the C/FMVSS 213 Bench and Vehicle Seats

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Objective: The objective of this study was to evaluate the fidelity of the C/FMVSS 213 test bench, by comparing the dynamic performance of forward-facing child restraint systems (FFCRS) mounted on the C/FMVSS 213 sled bench versus mounted on a selection of production vehicle seats.

Methods: The C/FMVSS 213 bench or one of 3 second-row original equipment manufacturer vehicle seats was mounted to the deck of acceleration crash sled. An FFCRS with a restrained anthropomorphic test device (ATD) was secured by 3-point belt (3-PT) or LATCH lower anchor (LLA) on the C/FMVSS 213 bench or vehicle seat, with or without a tether. The sled was then exposed to a 48 km/h acceleration pulse. Three unique make and model vehicle seats and FFCRS were tested. Fifty-three sled tests were performed.

Results: When FFCRS were secured with LLA and no tether, little difference between the vehicle seats and 213 bench was observed. Similarly, when FFCRS were affixed with 3-PT and no tether, few kinematic variable differences achieved statistical significance; chest resultant acceleration was, on average, 9.1 g (SD = 6.6, P = .006) higher on the vehicle seats compared to the bench in 3-PT with tether condition. However, when the tether was added to either the 3-PT or LLA attachment methods, the difference between the bench and vehicle seats was more pronounced. ATD kinematic measures such as head resultant acceleration (Δ = 14.6 g, SD = 7.2, P < .001) and pelvis resultant acceleration (Δ = 8.6 g, SD = 6.0, P = .005) were higher on the vehicle seats compared to the bench, as were the injury metrics for head and chest injury: ΔHIC15 = 162.2 (SD = 87.4, P = .001) and ΔChest 3 ms clip = 5.5 g (SD = 6.2, P = .040). Of note, CRS (Δ = 62.8 mm, SD = 32.7, P = .000) and ATD head (Δ = 66.3 mm, SD = 30.9, P = .000) and knee (Δ = 46.9 mm, SD = 25.8, P = .001) forward excursion were all higher on the vehicle seats compared to the bench in 3-PT with tether condition.

Conclusions: Without the tether attached, we observed few kinematic and kinetic differences between the vehicle seat and the C/FMVSS 213 bench, suggesting that the bench is an adequate surrogate for the vehicle seat in this condition. With the tether attached, we found significant differences between the C/FMVSS 213 bench and vehicle seats, suggesting that the fidelity of the bench could be improved in the tethered mode. When differences were statistically significant, excursion and injury metrics were generally greater on the vehicle seats than on the C/FMVSS 213 bench.

Keywords: child passenger safety, sled testing, LATCH, child restraints, regulation

Introduction

Sled test regulations are in place worldwide to evaluate the dynamic crash performance of child restraint systems (CRS; ECE/R24 2008; NHTSA 2002). In the United States and Canada, 2 very similar CRS sled tests have been implemented in federal regulations: The Federal Motor Vehicle Safety Standard 213 and the Canadian Motor Vehicle Safety Standard 213 (C/FMVSS 213). The test bench that represents the vehicle seat in this regulation was developed in the 1970s by the Highway Safety Research Institute, based on a 1974 Chevrolet Impala. The most recent changes to the test bench occurred in 2002 when the NHTSA and Transport Canada revised the angles of the seat back and bottom of the C/FMVSS 213 bench (NHTSA 2002). Since that time, no regulatory changes to the C/FMVSS 213 bench have been made, but research on seat cushion material properties have revealed that the bench seat foam is softer than the vehicle seats at high displacements (Glass 2002) and that in some cases the CRS can contact the plywood cushion base and bench frame, creating artifacts in
the results (Manary et al. 2002). Component-level research on the effect of bench foam shape and stiffness has demonstrated that seat bottom foam shape is the most important factor (Prasad and Weston 2011), but no research to date has compared the fidelity of the C/FMVSS 213 bench to vehicle seats as a system.

Thus, the purpose of this line of research is to assess the system-level fidelity of the C/FMVSS 213 sled bench by comparing its dynamic response to that of real vehicle seats. Taking a matched-pair approach, we mounted either the C/FMVSS 213 bench or one of 3 vehicle seats to an acceleration sled and exposed each to an identical sled acceleration pulse. We placed a CRS and anthropomorphic test device (ATD) on the vehicle seat or the C/FMVSS 213 bench. To quantify the fidelity of the C/FMVSS 213 bench, we used paired t tests to compare the kinetic, kinematic, and injury criteria variables from the CRS and ATD on the C/FMVSS 213 bench with the same variables measured on the paired vehicle seat. For example, the head excursion in each vehicle seat test was subtracted from the head excursion from the corresponding test with the C/FMVSS 213 bench (these 2 tests make up the pair), and the mean differences in head excursions for all matched pairs of tests were then compared with tests of statistical significance.

Our previous paper (Tylko et al. 2013) reports on this matched-pair sled test approach with rear-facing child restraint systems (RFCRS). In that study, we examined the difference in RFCRS kinematics when installed via LATCH versus installed with the 3-PT belt (3-point or lap–shoulder belt) with a CRS base. On the C/FMVSS 213 bench, across the range of RFCRS models tested, the difference in RFCRS forward excursion between the LATCH and 3-PT belt ranged from 1% to 7%, suggesting that the 2 attachment methods would yield similar field excursion performance for the subset of vehicle seat and CRS we evaluated. However, when these same RFCRS were tested on the vehicle seats, the difference in RFCRS forward excursion between LATCH and 3-PT belt with base installations was much larger (22% to 76%), highlighting limitations of the C/FMVSS 213 bench to distinguish between LATCH and belt-attached RFCRS. This current article expands on our prior publication by now focusing on forward-facing child restraint systems (FFCRS).

Methods

The second-row vehicle seats from a 2010 Toyota Corolla (sedan), 2009 Dodge Caravan bench-type seat (minivan), and 2007 Ford Edge captain’s chair (SUV) were mounted to an acceleration sled. These vehicles were selected based upon a NASS query that revealed that these vehicles commonly carried children in the rear rows (Tylko et al. 2013). Testing was performed on a Seattle Safety 2 MN servocontrolled pneumatic acceleration sled (Seattle Safety, Kent, WA) that has been shown to produce a highly repeatable acceleration pulse (Tylko et al. 2013). We used a 48 km/h sled pulse that fell within the corridor specified by C/FMVSS 213. In the case of the sedan, the entire occupant compartment was mounted to the sled; the SUV and minivan seats were removed from the vehicle and installed directly on the sled. Vehicle seats were structurally reinforced to improve durability. For the minivan seat, we reinforced the legs to prevent collapse. For the sedan, we reinforced the B-pillar, seat pan, and tether anchorage. No modifications were made to the SUV seat. All seats were inspected for damage after each test and repeat tests conducted periodically throughout the test series ensured the repeatability of the vehicle seats (Tylko et al. 2013).

For the SUV and minivan seats, with the seats still installed in their respective vehicles, the 3D locations of belt and tether anchors and D-ring relative to the vehicle seat were determined. In the vehicle, the D-ring was adjusted to mid-height for these measurements. Then, a custom frame was built on the sled to allow for the reproduction of these 3D belt anchor locations on the sled, thus ensuring that the in-vehicle belt and tether geometry was reproduced on the sled. For the sedan, no such measurements were required, because the entire occupant compartment was mounted to the sled. On the vehicle seats, we used original equipment manufacturer retractor, belt, and buckle stalk components. On the bench, we used the belt and associated hardware that is typically used in the regulatory test procedure (further described below).

The C/FMVSS 213 bench was attached to the sled base plate in accordance with the regulatory drawing package. There are differences between the FMVSS 213 and CMVSS 213 regulations. For example, for head injury assessment the Canadian standard uses maximum resultant acceleration and excludes maxima that occur when the ATD head contacts other parts of the ATD or during rebound, but the United States uses the head injury criterion (HIC) with no time periods or impact events excluded. In addition, the Canadian standard always tests with the tether attached, but the U.S. tests both with and without the tether. As a result, Canada has only one excursion limit (720 mm), which is tested with the tether attached. Regardless of these procedural differences, our testing used a bench that is compliant with the regulatory text of both FMVSS 213 and CMVSS 213. The belt was secured with a standard buckle at the inboard location on the bench; the belt webbing was wound on a locking webbing spool and then threaded through a D-ring, the buckle, and looped through a locking clamp that was anchored to the frame of the bench at the right. The buckle anchor was rigidly attached to the frame of the bench. The LATCH lower anchors (LLAs) were rigidly mounted to the frame and were located between the 3-point seat belt anchors. In-line load cells (Denton 9191 FL; Humanetics ATD, Plymouth, MI) were used to attach the LLA webbing to the LLA anchorages.

Three off-the-shelf, 5-point harness FFCRS were selected for testing, designated FFCRS1, FFCRS2, and FFCRS3. We selected FFCRS from across the retail price range. The least expensive CRS retained for less than US$100 and the most expensive for approximately US$250. All FFCRS had 5-point harnesses, but their weights range from 8 to 25 lb without the ATD. Two had single-web tethers with no load limiting, and one had a dual-web tether with rip stitch load limiting. The most restrictive weight range was 22 to 40 lb and the most generous was 25 to 80 lbs (all ranges for forward-facing harness mode). Two of the CRS were convertibles (use in harness mode both rear and forward facing) and one was a 3-in-1 (harness mode both rear and forward facing and with vehicle belts in forward facing). Fifty-three tests were conducted on the C/FMVSS 213 bench or one of the 3 vehicle seats, including...
periodic repeat tests. With this study design, each unique combination of attachment method and FFCRS model is tested in a matched pair of the C/FMVSS bench and one of the 3 vehicle seats. Thirty-six matched pairs were possible, but one test was omitted (no tether, 3-point belt, FFCRS3 on SUV), reducing the number of actual tested matched pairs to 35 (Table 1).

### Installation Procedure

All FFCRS were installed per manufacturer instructions and the C/FMVSS 213 test procedure. The FFCRS was placed in the designated seating position on the bench or vehicle seat being evaluated. The designated seating positions were as follows: bench = center seat position, sedan = left position, SUV = right position, minivan = right position. The LLA, seat belt, or tether webbing was threaded through the required paths and secured to the bench or vehicle seat. When applicable, LLA webbing was pulled taught until the in-line LLA load cells recorded a value of 53.5 to 67 N. Note that C/FMVSS 213 does not stipulate a pretest webbing tension for the LLA; however, we chose to prescribe a target range here, based upon C/FMVSS 213 procedure for 3-PT preloads, to increase test-to-test repeatability. For 3-point belt attachment, preloads ranged from 53.5 to 67 N for the lap belt portion of the 3-point belt and 9 to 18 N for the shoulder belt. Seat belt load cells were used to measure belt preload. For the seats installed with the tether (both LLA+TETHER and 3-PT+TETHER), the tether was pulled taught until the in-line load cells recorded a value of between 53.5 and 67 N. Adjustment of the FFCRS required alternate tightening of the lower LATCH webbing and tether webbing to achieve the aforementioned preload ranges. A multicamera 3D metrology system (TraceCam Aicon, 3D Systems, Germany) was used to ensure repeatability of FFCRS initial position from test to test and FFCRS alignment with the centerline of the seating position along the direction of sled travel. All CRS used in the study were new and underwent a single test.

Child restraints FFCRS1 and FFCRS2 were tested with the Hybrid III 6-year-old, and FFCRS3 was tested with the Hybrid III 3-year-old. The 6-year-old ATD was selected unless it exceeded the maximum allowable weight range for the CRS, in which case the 3-year-old ATD was selected. After being placed in the FFCRS, the arms and legs of the ATD were successively raised to settle the ATD in the seat. Using a flat square surface with an area of 2,580 mm², a force of 178 N was applied to the crotch and then to the thorax of the ATD. A webbing tension pull device was used to ensure that a 9 N force was applied to the top of each shoulder harness and the pelvis harness (50 mm from the centerline), resulting in a 7 mm clearance between the ATD and the belt webbing at the point of application of the webbing tension pull device.

Optical targets were placed at regular intervals along the structural members of the bench and vehicle seat. Targets were also placed in the plane defining the excursion limits defined by C/FMVSS 213. The seat anchorages, cushions, and belts were visually inspected after each test. Video footage was closely monitored to detect signs of fatigue and damage. Tests completed at the beginning of a series were repeated at the end to ensure that any undetected seat degradation did not contribute to a variation in response.

The Hybrid III 3-year-old and 6-year-old ATDs were instrumented with triaxial accelerometers in the head, chest, and pelvis (62-2000, Endevco, CA) in addition to a 6-axis load cell in the upper neck (Humanetics ATD, Plymouth, MI). Data processing followed SAE J-211 (Society of Automotive Engineers 1995). FFRCS and ATD motion were captured at 1,000 frames per second with 4 NAC video cameras (NAC Image Technology, Simi Valley, CA). The views included a close-up of the left side of the child restraint, a frontal view, the right side of the bench or vehicle seat to capture forward excursion, and a rear view. Optical tracking targets were placed on the lateral aspect of the head in line with the center of gravity of the head of the ATD, on the knee of the ATD, and on the lateral aspect of the FFCRS. Head and CRS marker motion in the upper neck (Humanetics ATD, Plymouth, MI) was quantified using video tracking software (Tema Automotive Motion Analysis software, version 3.5-012, Photo Sonics, Burbank, CA). Head and CRS excursion was defined as the maximum forward (x) motion of the head or CRS marker relative to the initial position of the head or CRS marker.

### Data Analysis

Unique vehicle seat tests were compared directly to the equivalent C/FMVSS 213 tests using a matched-pair analysis. The

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Table 1. Matched-pair test matrix. Each test in the "C/FMVSS bench" column forms a matched pair with any single test in the same row under the "Vehicle seat" column heading.

| Attachment method | C/FMVSS 213 bench | Vehicle seat |
|-------------------|-------------------|--------------|
|                   | Sedan             | Minivan      | SUV          |
| No tether         | 6YO/FFCRS1        | 6YO/FFCRS1   | 6YO/FFCRS1   |
|                   | 6YO/FFCRS2        | 6YO/FFCRS2   | 6YO/FFCRS2   |
|                   | 3YO/FFCRS3        | 3YO/FFCRS3   | 3YO/FFCRS3   |
| 3-PT              | 6YO/FFCRS1        | 6YO/FFCRS1   | 6YO/FFCRS1   |
|                   | 6YO/FFCRS2        | 6YO/FFCRS2   | 6YO/FFCRS2   |
|                   | 3YO/FFCRS3        | 3YO/FFCRS3   | 3YO/FFCRS3   |
| Tether            | 6YO/FFCRS1        | 6YO/FFCRS1   | 6YO/FFCRS1   |
|                   | 6YO/FFCRS2        | 6YO/FFCRS2   | 6YO/FFCRS2   |
|                   | 3YO/FFCRS3        | 3YO/FFCRS3   | 3YO/FFCRS3   |

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3YO = Hybrid III 3-year-old ATD; 6YO = Hybrid III 6-year-old ATD.
—Test omitted due to logistical problems.
following variables were analyzed: maximum head resultant acceleration, neck (upper) resultant force, maximum chest resultant acceleration, chest displacement, maximum pelvis resultant acceleration, maximum LATCH lower anchor reaction force, maximum shoulder harness force, upper and lower CRS seatback and CRS seat bottom forward (x) excursion, and forward (x) head and knee excursion relative to initial position. The outcomes of each C/FMVSS 213 bench tests were subtracted from the corresponding vehicle seat test and analyzed for significance (difference from zero) using a homoscedastic t test with 2-tailed distribution. The differences between the bench and vehicle seats were considered statistically significant if the P value was less than .05.

Results

No-tether Test Results

Differences between vehicle seats and the bench were few in the FFCRS secured by LLA only (i.e., LLA no tether; Table 2). Left LLA anchor force was 356 N (SD = 385, P = .024) lower on the vehicles compared to the bench and was the sole variable (of 19 total) that was statistically significant in this restraint group. The difference between the matched pairs for the FFCRS secured with a 3-point belt and no tether resulted in 5 of 19 variables with differences that were statistically significant (Table 3). Differences in chest resultant acceleration and 3 ms clip chest acceleration (Δ = 9.1 g, SD = 6.6, P = .006 and Δ = 8.8 g, SD = 5.9, P = .004, respectively) were higher on the vehicles compared to the bench. Measures of CRS and ATD excursion were also higher for the vehicles compared to the bench: upper CRS seatback excursion (Δ = 39.8 mm, SD = 32.7, P = .011), lower CRS seatback excursion (Δ = 19.9 mm, SD = 18.9, P = .021), and knee excursion (Δ = 36.4 mm, SD = 12.0, P = .000) were all higher on the vehicles as compared to the bench.

Tethered Tests

Adding tether restraint to both the LLA and 3-PT conditions yielded a greater number of variable differences that were statistically significant. FFCRS secured with LLA and tether yielded 8 of 20 variable differences that were statistically significant—head resultant acceleration, HIC, HIC15, HIC36, left and right LLA, and CRS seat bottom excursion (Table 4). FFCRS secured via 3-PT and tether yielded 15 of 20 variables that were statistically significant (Table 5). ATD kinematic measures such as head resultant acceleration (Δ = 14.6 g, SD = 7.2, P < .001) and pelvis resultant acceleration (Δ = 8.6 g, SD = 6.0, P = .005) were higher on the vehicle seats compared to the bench, as were the injury metrics for head and chest injury: ΔHIC = 220.1 (SD = 160.3, P = .003), ΔHIC15 = 162.2 (SD = 87.4, P = .001), ΔHIC36 = 213.1 (SD = 132.2, P = .01), ΔHead 3 ms clip = 14.8 g (SD = 8.5, P = .01) and ΔChest 3 ms clip = 5.5 g (SD = 6.2, P = .040). Measures of restraint load were also higher on the vehicle seats compared to the bench: ΔLeftLap belt force was 1,100 N (SD = 757, P = .002), ΔRight harness force was 325 N (SD = 260.4, P = .028), and ΔLeft harness force was 276 N (SD = 110, P = .002) higher on the vehicle seat compared to the bench. In addition, CRS and ATD excursions were higher for the vehicle seats compared to the bench: ΔCRS upper seatback excursion was 62.8 mm (SD = 32.7, P < .001), ΔCRS lower seatback excursion was 29.3 mm (SD = 23.8, P = .006). ΔCRS seat bottom excursion was 23.2 mm (SD = 17.0, P < .003), ΔATD head excursion was 66.3 mm (SD = 30.9, P < .001), and ΔATD knee excursion was 46.9 mm (SD = 25.8, P = .001).

Figure 1 shows exemplar kinematics of an FFCRS secured via LLA and tether on the C/FMVSS 213 bench and vehicle seat. Of note, CRS rotation on the bench was counterclockwise (rearward) and CRS rotation of the vehicle seat was clockwise (forward). This finding was observed in all but one FFCRS secured via LLA and tether (Figure 2). Additional plots of all of the kinematic and kinetic variables, and all of the injury criteria, are shown in the Appendix (see online supplement).

Table 2. Matched-pair analysis results for forward-facing CRS secured to the vehicle/bench with LLA and no tether. “Mean diff” is the difference between the vehicle minus the bench for the “Variable,” averaged over the N matched pairs.

| Variable                                | N  | Mean diff | SD  | SE   | Min | Max | t    | P value |
|-----------------------------------------|----|-----------|-----|------|-----|-----|------|---------|
| Head resultant acceleration (g)         | 9  | 1.9       | 7.5 | 2.5  | -6.0| 15.0| 0.8  | .474    |
| Neck resultant force (N)                | 8  | 182.1     | 335.6| 118.7| -331.0| 591.0| 1.5  | .169    |
| Chest resultant acceleration (g)        | 9  | 1.1       | 6.5 | 2.2  | -7.0| 15.0| 0.5  | .623    |
| Chest displacement (mm)                 | 9  | -0.2      | 3.3 | 1.1  | -5.0| 5.0 | -0.2 | .847    |
| Pelvis resultant acceleration (g)       | 6  | 7.5       | 9.1 | 3.7  | -3.0| 21.0| 2.0  | .099    |
| HIC                                     | 8  | 46.8      | 79.0| 27.9 | -108.0| 170.0| 1.7  | .138    |
| HIC15                                   | 8  | 59.5      | 106.0| 37.5 | -81.0| 190.0| 1.6  | .156    |
| HIC36                                   | 8  | 38.9      | 74.2| 26.2 | -112.0| 130.0| 1.5  | .182    |
| Head 3 ms clip (g)                      | 8  | 3.9       | 8.5 | 3.0  | -8.0| 17.0| 1.3  | .239    |
| Chest 3 ms clip (g)                     | 9  | 0.7       | 6.3 | 2.1  | -8.0| 14.0| 0.3  | .761    |
| Left LLA anchor force (N)               | 9  | -356.2    | 384.9| 128.3| -983.0| -33.0| -2.8 | .024    |
| Right LLA anchor force (N)              | 9  | -223.4    | 322.4| 107.5| -802.0| 165.0| -2.1 | .071    |
| Right harness force (N)                 | 9  | 116.3     | 208.1| 69.4 | -404.0| 338.0| 1.7  | .132    |
| Left harness force (N)                  | 9  | 32.7      | 169.3| 56.4 | -282.0| 246.0| 0.6  | .579    |
| CRS up seatback excursion (mm)          | 9  | 0.6       | 88.4| 29.5 | -92.3| 123.5| 0.0  | .985    |
| CRS low seatback excursion (mm)         | 9  | -15.0     | 33.5| 11.2 | -67.5| 27.2 | -1.3 | .217    |
| CRS seat bottom excursion (mm)          | 6  | -3.8      | 45.8| 18.7 | -64.5| 46.6 | -0.2 | .849    |
| Head excursion (mm)                     | 9  | 27.0      | 110.4| 36.8 | -88.1| 195.0| 0.7  | .484    |
| Knee excursion (mm)                     | 9  | 16.9      | 50.1| 16.7 | -29.4| 89.7 | 1.0  | .340    |

Shaded values are statistically significant (p < 0.05).
Table 3. Matched-pair analysis results for forward-facing CRS secured to the vehicle/bench with a 3-point belt and no tether. “Mean diff” is the difference between the vehicle minus the bench for the “Variable,” averaged over the N matched pairs.

| Variable                        | N  | Mean diff | SD  | SE  | Min | Max | t    | P value |
|---------------------------------|----|-----------|-----|-----|-----|-----|------|---------|
| Head resultant acceleration (g) | 8  | −6.4      | 13.2| 4.7 | −35.0| 9.0 | −1.4 | .214    |
| Neck resultant force (N)        | 8  | 55.8      | 247.1| 87.4| −242.0| 555.0| 0.6 | .544    |
| Chest resultant acceleration (g)| 8  | 9.1       | 6.6 | 2.3 | −1.0 | 18.0 | 3.9 | .006    |
| Chest displacement (mm)         | 8  | 1.88      | 3.9 | 1.4 | −3   | 9    | −1.3 | .221    |
| Pelvis resultant acceleration (g)| 6  | −6.5      | 20.5| 8.4 | −29.0 | 22.0 | −0.8 | .473    |
| HIC                             | 8  | −20.6     | 97.2| 34.4| −196.0| 119.0| −0.6 | .567    |
| HIC15                           | 8  | −35.4     | 83.0| 29.3| −148.0| 93.0 | −1.2 | .267    |
| HIC36                           | 8  | −27.5     | 108.4| 38.3| −170.0| 165.0| −0.7 | .496    |
| Head 3 ms clip (g)              | 8  | 4.4       | 11.1| 3.9 | −6.0 | 29.0 | 1.1  | .301    |
| Chest 3 ms clip (g)             | 8  | 8.8       | 5.9 | 2.1 | −1.0 | 16.0 | 4.2  | .004    |
| Shoulder belt force (N)         | 8  | −39.4     | 1,040.3| 367.8| −1,554| 1,347.0| −0.1 | .918    |
| Lap belt force (N)              | 7  | 483.6     | 884.1| 334.2| −1,069| 1,380.0| 1.4  | .198    |
| Right harness force (N)         | 8  | 73.4      | 323.3| 114.3| −477.0| 519.0 | 0.6  | .541    |
| Left harness force (N)          | 8  | −166.4    | 382.0| 135.0| −890.0| 237.0| −1.2 | .258    |
| CRS up seatback excursion (mm)  | 8  | 39.8      | 32.7| 11.6| −16.2| 74.3 | 3.4  | .011    |
| CRS low seatback excursion (mm) | 8  | 19.9      | 18.9| 6.7 | −0.1 | 58.9 | 3.0  | .021    |
| CRS seat bottom excursion (mm)  | 3  | 5.4       | 9.6 | 5.5 | −1.3 | 16.4 | 1.0  | .429    |
| Head excursion (mm)             | 8  | 17.3      | 36.4| 12.9| −30.7| 69.3 | 1.3  | .221    |
| Knee excursion (mm)             | 8  | 36.4      | 12.0| 4.2 | 20.6 | 57.3 | 8.6  | .000    |

Shaded values are statistically significant (p < 0.05).

Discussion

This is the first system-level quantification of the fidelity of the C/FMVSS 213 test bench in representing the response of FFCRS on production motor vehicle seats. We formed matched-pair sled tests by with the C/FMVSS 213 bench and one of three vehicle seats, while holding constant the ATD, FFCRS make/model and attachment method, crash pulse and direction, and pretest restraint webbing and ATD positioning loads. To evaluate the difference between matched pairs, we compared the kinematic, kinetic and injury metrics between the 2 sled tests in the matched pair. The fidelity of the C/FMVSS 213 bench was highly dependent on method of attachment of the FFCRS to the vehicle seat/bench. When evaluating FFCRS attached via the LLA without a tether, only one of the measured responses from the C/FMVSS 213 bench was statistically significantly different from those on the vehicle seats, suggesting that the C/FMVSS 213 bench is a good surrogate for vehicle seats in this particular CRS attachment mode.

Table 4. Matched-pair analysis results for forward-facing CRS secured to the vehicle with LLA and tether. “Mean diff” is the difference between the vehicle minus the bench for the “Variable,” averaged over the N matched pairs.

| Variable                        | N  | Mean diff | SD  | SE  | Min | Max | t    | P value |
|---------------------------------|----|-----------|-----|-----|-----|-----|------|---------|
| Head resultant acceleration (g) | 9  | 9.2       | 9.9 | 3.3 | −8.0| 23.0| 2.8  | .023    |
| Neck resultant force (N)        | 9  | −81.6     | 619.0| 206.3| −678.0| 1,196.0| −0.4 | .703    |
| Chest resultant acceleration (g)| 9  | 3.6       | 5.4 | 1.8 | −6.0| 11.0| 2.0  | .084    |
| Chest displacement (mm)         | 9  | −0.89     | 3.79| 1.26| −6.0| 7   | −0.7 | .502    |
| Pelvis resultant acceleration (g)| 9 | 0.6       | 11.7| 3.9 | −16.0| 23.0| 0.1  | .890    |
| HIC                             | 9  | 164.2     | 172.3| 57.4| −52.0| 483.0| 2.9  | .021    |
| HIC15                           | 9  | 133.6     | 104.3| 34.8| −50.0| 250.0| 3.8  | .005    |
| HIC36                           | 9  | 174.1     | 171.6| 57.2| −42.0| 488.0| 3.0  | .016    |
| Head 3 ms clip (g)              | 9  | 10.8      | 8.2 | 2.7 | −7.0| 21.0| 4.0  | .004    |
| Chest 3 ms clip (g)             | 9  | 3.7       | 5.8 | 1.9 | −6.0| 12.0| 1.9  | .093    |
| Left LLA anchor force (N)       | 9  | 796.7     | 593.3| 197.8| −458.0| 1,679.0| 4.0  | .004    |
| Right LLA anchor force (N)      | 9  | 780.4     | 590.4| 196.8| −216.0| 1,912.0| 4.0  | .004    |
| Tether force (N)                | 9  | −1,362.9  | 1,919.5| 639.8| −3,822| 2,204.0| −2.1 | .066    |
| Right harness force (N)         | 8  | 131.6     | 248.6| 87.9| −140.0| 475.0| 1.5  | .178    |
| Left harness force (N)          | 8  | 113.5     | 220.4| 77.9| −208.0| 450.0| 1.5  | .189    |
| CRS up seatback excursion (mm)  | 9  | 14.1      | 38.9| 13.0| −40.0| 71.4| 1.1  | .309    |
| CRS low seatback excursion (mm) | 9  | −17.9     | 31.8| 10.6| −64.7| 32.0| −1.7 | .131    |
| CRS seat bottom excursion (mm)  | 9  | −29.9     | 24.8| 8.3 | −62.4| 11.6| −3.6 | .007    |
| Head excursion (mm)             | 9  | 17.0      | 37.3| 12.4| −39.8| 76.5| 1.4  | .299    |
| Knee excursion (mm)             | 9  | −1.3      | 33.5| 11.2| −38.4| 66.2| −0.1 | .912    |

Shaded values are statistically significant (p < 0.05).
The foam of the C/FMVSS 213 bench has been the topic of much research. Glass (2002) developed a protocol to test the compressive stiffness of the 213 bench foam and any vehicle seat cushion. In that protocol, a 6-in.-diameter indentor was slowly (0.5 in. per minute) pushed into the seat cushion, and applied force and indentor displacement was measured. The indentation stiffness was assessed in 3 locations: near the front edge of the seat bottom cushion, at the middle of the seat bottom cushion, and on the seat back. The authors found that the cushion stiffness of the FMVSS 213 bench was comparable to the average vehicle seat up to 80 mm of displacement, but from 80 to 120 mm of displacement the average vehicle seat cushion was substantially stiffer than the bench. In our data, the LLA without tether condition showed that the C/FMVSS 213 bench was an adequate representation of the vehicle seats we tested. In those sled tests, video analysis showed that the maximum bench seat cushion foam compression at the front edge of the FFCRS base was ≤78.1 mm (slightly greater than 50% of the foam thickness), which is in the range where the bench seat cushion foam stiffness matches the vehicle seat cushion stiffness according to Glass’s (2002) report. Note also that the LLA without tether condition had the largest seat cushion compressions of any of the other test conditions (LLA with tether, 3-PT with and without tether) and so for all tests reported herein seat cushion compression was within the range where bench seat cushion force-displacement properties are similar to the vehicle, as reported by Glass (2002). However, though the foam stiffness may be vehicle seat-like over certain ranges of compression, reports of high C/FMVSS 213 bench foam compression leading to nonfidelic CRS contact with the plywood base or frame of the bench is common (Manary et al. 2002). This may not be an issue of seat cushion stiffness but rather that the fundamental construction approach of the bench (steel frame atop plywood base atop thick foam) is different than that of vehicle seats (steel frame supporting springs encapsulated in thin or thick foam). This matter requires further research.

The differences between the C/FMVSS 213 bench and vehicle seats were more pronounced with the tether attached than with the tether unattached (compare number of statistically significant differences in Tables 2 and 3 versus Tables 4 and 5). Interestingly, with the tether attached, we observed opposing FFCRS rotational kinematics on the C/FMVSS 213 bench compared to most of the vehicle seats (Figure 2), where CRS rotation on the bench was counterclockwise (rearward) and CRS rotation of the vehicle seat was clockwise (forward).
in the LLA and tether condition. Future research should examine how the kinematics of the CRS is influenced by variables such as tether anchor location, bench and cushion geometry, and cushion stiffness.

Two observations can be made based on the previous 2 paragraphs: (1) In our LLA without tether experiments, where the absence of a tether causes the seat foam to govern FFCRS rotation, the C/FMVSS 213 bench was found to match well with the vehicle seat and (b) work by Prasad and Weston (2011), where seat cushion foam shape and stiffness were parametrically examined with FFCRS in frontal sled tests, found that cushion foam shape, not stiffness, was the dominant factor in determining kinematic outcomes. Thus, our working hypothesis is that seat cushion shape and LATCH and belt anchorage geometry are the dominant factors that govern C/FMVSS 213 bench fidelity in FFCRS sled tests and that seat cushion stiffness is less important. More research is needed to parametrically examine all the C/FMVSS 213 bench design variables mentioned here to determine which C/FMVSS 213 bench variables have the most significant effect on bench fidelity.

We also note that for most variables, the mean difference between the vehicle seats and the C/FMVSS 213 bench was positive, indicating larger values on the vehicle seats. This finding is particularly important because the actual available interior excursion space for many vehicle and FFCRS combinations is less than the limits imposed by FMVSS 213 (Glass 2002; Sherwood et al. 2006), vehicle seats tend to position heads further forward at initial position than the FMVSS 213 bench (Sherwood et al. 2006), and current data herein shows that the C/FMVSS 213 test conditions underestimate head excursion in some CRS-to-vehicle conditions. These 3 factors combined may partially explain why head injuries are observed in FFCRS-restrained occupants in the field (Arbogast et al. 2002) but laboratory tests generally show low risk.

Over the past 10 years, great strides have been made in the reduction of child occupant fatalities and injuries due to motor vehicle crashes. According to the Fatality Analysis Reporting System, 1,168 child occupants aged 0–14 years died in motor vehicle crashes in the United States in 2012, representing a 45% decrease from 2003 (NHTSA 2014). Despite these reductions, in the United States motor vehicle crashes rank fourth in cause of death for 1- to 3-year-olds and second in cause of death for 4- to 8-year-olds, and for each fatality approximately 18 children are hospitalized and over 400 receive medical treatment for injuries sustained in a crash (Centers for Disease Control and Prevention, National Center for Injury Prevention and Control 2010). With these losses in mind, it is important to note that, compared to seat belts, child restraints that are not seriously misused are associated with a 28% reduction in risk of death (relative risk, 0.72; 95% confidence interval, 0.54–0.97) in children aged 2 through 6 years (Elliott et al. 2006). This finding suggests that the current CRS designs driven in part by the regulation are successful in mitigating injuries in a vast number of crash circumstances. Our line of research seeks to understand ways to further improve CRS effectiveness by examining one component of the occupant protection process—the vehicle surrogate (i.e., C/FMVSS 213 bench) used in FFCRS design in North America. As the safety community seeks to refine the regulations and gain insight into real-world interpretation of existing sled test data from analyses like those presented herein, we must be cognizant of the current effectiveness of CRS in reducing mortality and morbidity and ensure that the changes we make to safety systems will yield increased safety benefits for children in actual motor vehicle crashes.

Our study is subject to certain limitations. The test matrix was restricted to 3 common forward-facing child restraint models and 3 common second-row automotive seats. The results are therefore based on a relatively small sample of all possible combinations of child restraint, vehicle seats, and installation methods. The sled testing was conducted with an acceleration pulse that was within the corridor specified by the C/FMVSS 213 for purposes of repeatability and to provide reference to regulatory test results. The pulse was not intended to represent any actual passenger vehicle deceleration crash pulse, and results may differ with actual vehicle crash pulses.

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Supplemental Materials

Supplemental data for this article can be accessed on the publisher’s website.

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