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The Roles of Vehicle Seat Cushion Stiffness and Length in Child Restraint System (CRS) Performance

Julie Mansfield Ohio State University

HyunJung Kwon Transportation Research Center Inc.

Yun-Seok Kang Ohio State University

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Abstract

The objective is to determine whether responses and injury risks for pediatric occupants in child restraint systems (CRS) are affected by vehicle seat cushion stiffness and fore/aft cushion length. Eighteen sled tests were conducted using the Federal Motor Vehicles Safety Standard (FMVSS) 213 frontal pulse (48 km/h). Seats from a recent model year vehicle were customized by the manufacturer with three different levels of cushion stiffness: compliant, mid-range, and stiff. Each stiffness level was quantified using ASTM D 3574-08 and all were within the realistic range of modern production seats. The usable length of each seat cushion was manipulated using foam spacers provided by the manufacturer. Two different seat lengths were examined: short (34.0 cm) and long (43.5 cm). Three different types of CRS were tested with size-appropriate anthropomorphic test devices (ATDs): rear-facing (RF) CRS with 12-month-old CRABI, forward-facing (FF) CRS with Hybrid III 3-year-old, and high-back booster with Hybrid III 6-year-old. Each CRS, vehicle seat (including cushion and frame), seat belt webbing and buckle were replaced after every test. ATD kinematic and kinetic data were compared across seat cushion lengths and cushion stiffness levels to determine which seat configurations were the most beneficial for each type of CRS. For RF CRS, short vehicle seats allowed more y-axis rotation (SAE J211) but reduced several injury metrics including HIC36. For FF CRS, long and short seats resulted in similar injury metrics across matched conditions. For boosters, short seats increased chest resultant acceleration but did not have a noticeable effect on other injury metrics. The range of cushion stiffness examined in this study did not have a consistent or relevant effect on any of the CRS or occupant responses.

Introduction

Best practice recommendations from the American Academy of Pediatrics (AAP) advise that children ride in the rear row of a vehicle until at least age 13 [1]. However, data indicate that rear seat lengths are too long compared to the thigh length of many rear row occupants, including both children who have outgrown boosters and many small adults [2, 3]. Long seats can force an occupant into a slouched posture, which induces poor belt fit [4]. Studies have questioned whether rear row seat lengths should be shortened to better accommodate the leg lengths of younger, smaller occupants [5, 6]. Physical testing and a computer simulation study suggest that shorter seats provide improved responses for children 6 to 10 years old who are not restrained in boosters [7, 8]. Further sled testing revealed that shorter seats do not negatively affect the kinematics and kinetics of an adult anthropomorphic test device (ATD) in frontal crashes [5].

Shorter seats may pose a problem when installing child restraint systems (CRS) with large bases. Some CRS manufacturers require the entire base to be supported by the vehicle seat, while others state that up to 20% of the length of the base may protrude past the edge of the vehicle seat [9]. Short vehicle seats may not be able to meet these installation criteria. Currently, very limited data exist to determine the consequences of CRS installations on short vehicle seats.

Klinich et al. performed frontal impacts with four forward-facing (FF) CRS models and several rear-facing (RF) CRS models [5, 6]. Vehicle seat lengths were varied among 35.0 cm, 40.0 cm, and 45.0 cm, and baseline testing was also completed on the Federal Motor Vehicles Safety Standard (FMVSS) 213 bench. The results indicate that shortening the seat lengths resulted in only minimal detrimental effects to CRS performance. Rotation of RF CRS was slightly greater for shorter vehicle seats, although was often less than the rotation observed on the FMVSS 213 bench itself, and always within the FMVSS 213 limit of 70°. A few "worst case scenario" trials occurred when the front "foot" of FF CRS slipped off the front edge of the shortened vehicle seat. However, even these trials passed all relevant FMVSS 213 injury limits [10]. Overall, these studies indicate that shorter seats do not adversely affect the performance of most harnessed child restraints. However, occupants in boosters were not fully examined in these series.

Cushion stiffness is another characteristic of vehicle seats which has not been fully quantified with respect to CRS performance. Prasad and Weston modified the foam stiffness and thickness on the FMVSS 213 test bench frame [11]. The Hybrid III 5th percentile female showed less desirable kinematic outcomes on thicker cushions compared to thinner cushions, with no significant differences between stiff or soft foams. Testing of a Hybrid III 3-year-old in a FF CRS did not result in any appreciable performance differences due to cushion thickness or stiffness variation. However, it is unclear whether these results would hold true if testing were completed on a realistic vehicle seat or with different CRS models. A series of computer simulations with 6- and 10-year-old ATD models suggested that the location of the underlying structure of the vehicle seat plays a larger role in occupant outcomes rather than the stiffness properties of the cushion itself [8]. A six-trial sled series performed varied seat stiffness by inserting an aluminum plate into the front edge of the underlying vehicle seat structure [5]. The authors report no appreciable changes in RF CRS or adult ATD response due to variation of the seat stiffness properties in this manner. However, the stiffness properties of the seat cushions themselves were not modified in that study.

This study investigates whether injury risks to pediatric occupants in harness CRS and boosters are affected by the length or stiffness of vehicle seat cushions, so that the rear seat environment can be optimized for all occupants.

Methods

Vehicle Seats

An automotive seating company provided custom-modified second row captain's chairs from a full-size, recent model year sport utility vehicle (SUV). The stiffness of the seat cushions was modified by adjusting the density of the foam material injected into the seat mold. Cushions with three different stiffness levels were provided: compliant, mid-range, and stiff. All stiffness levels were within the realistic range of modern production seats. The stiffness of each cushion was quantified using ASTM D 3574-08 [12]. An 8-inch round, flat plate was placed over the center of the seating area. The plate was pressed into the cushion at 50 mm/minute until the cushion was compressed by 50% of its thickness. The side bolsters of each seat were compressed using 50 mm hemispherical indenters at the same speed and compression targets. Results of the compression tests for the compliant and stiff cushions used in this study are shown in Table 1. The mid-range seats were not tested as these were standard production seats, but were held to the production range of this vehicle: 162.5 ± 2.5 N.

The SUV seats used in this study have a length of 49.0 cm, which is longer than most seats on the current market [13, 14]. To shorten the usable length of the seats, foam "spacers" were

TABLE 1 Stiffness range of vehicle seats

	Center section (N)	Side Bolsters (N)
Compliant	148.3 ± 1.7	15.9 ± 0.7
Mid-range	Typically 162.5 ± 2.5	N/A
Stiff	181.7 ± 1.2	19.0 ± 0.9

attached to the seat backs (Figure 1). The spacers were made of mid-range level foam supplied by the seating company, and were contoured to match the actual seat backs. The final lengths of the vehicle seats with spacer modifications were 34.0 cm ("short" condition) and 43.5 cm ("long" condition). These lengths correspond to approximately the 2nd and 70th percentiles of vehicle seats on the current market [13, 14].

Each CRS only interacted with the spacers during installation and setup, then pulled away from the spacers during the frontal crash event. Thus, the presence of the spacers was not expected to affect responses during the main crash event (rebound kinematics were not analyzed in this study). The spacer method was used to ensure consistent and realistic properties of the front edge of the vehicle seat cushion and underlying seat frame. Adding or removing length from the front edge of the vehicle seat might interfere with the critical interactions between the CRS and this area of the vehicle seat. Thus, the spacer method manipulates the length of the vehicle seat by reducing the length near the seat bight.

All CRS were installing using seat belts attached with a clamp to the anchor points (i.e., no seat belt retractors were used). This method was selected because seat belt retractors are not used in FMVSS 213 test procedures. The belts were adjusted to the pre-test tensions specified by FMVSS 213 for each type of CRS [10]. All three seat belt anchor points were manipulated in the x- and z-directions such that the modified

FIGURE 1 The wider spacer created the "short" seat length (foreground) and a narrow spacer created the "long" seat length (background). The spacers were held in place by Velcro between the surfaces, duct tape wrapped horizontally and a ratchet strap wrapped vertically around the seat back.

seat bight was always in the same relative location with respect to the belt anchor points across all conditions. Each vehicle seat was replaced after every test (including cushion, frame, belt webbing, and belt buckle).

Child Restraint Systems (CRS)

CRS models with long base lengths were chosen so that the bases would overhang the front edge of the short vehicle seat conditions. Published literature was used as a guide for selecting CRS with long bases [13, 14]. The Combi Shuttle (RF infant seat), Safety 1st Alpha Elite 65 (FF convertible mode), and Eddie Bauer Deluxe High Back 65 (high back booster mode) were selected. None of the CRS instruction manuals specified how much of the base should be supported by the vehicle seat. Table 2 summarizes the mass of each CRS and the length of each CRS base that protruded past the front edge of the vehicle seat when installed in each seat length condition.

A CRABI 12-month-old (12mo) was positioned in the RF CRS, a Hybrid III 3-year-old (3yo) in the FF CRS, and a Hybrid III 6-year-old (6yo) in the booster. FMVSS 213 seating procedures were followed along with CRS manufacturers' instructions. The RF CRS (Combi Shuttle) was always installed with the base, using the seat belt lock-off feature as recommended. Each CRS was replaced after every test. See Appendix A for setup photos.

Test Matrix

The full test matrix is shown in Table 3. Tests were run two at a time in symmetrical left and right side vehicle seats. The FMVSS 213 frontal pulse was used [10] (see Appendix B).

Data Analysis

The ATDs were instrumented with head and T4 chest accelerometers (Endevco/Meggitt Sensing Systems, Irvine, CA), head angular rate sensors (Diversified Technical Systems (DTS), Seal Beach, CA), six-axis upper neck load cells (Denton, now Humanetics Innovative Solutions, Plymouth, MI), and chest linear potentiometers in the 3yo and 6yo

TABLE 2 Masses and lengths of CRS bases compared to vehicle seat cushion

	CRS mass (kg)	Base length, cm	Overhang, cm (% base length)	
			Long cushion	Short cushion
RF infant seat	7.6	52.3	5.9 (11%)	14.5 (28%)
FF convertible	7.3	44.4	No overhang (0.1 cm extra)	9.3 (21%)
Booster	5.2	43.5	No overhang (3.7 cm extra)	4.9 (11%)

TABLE 3 Test matrix

Test	Seat length	Cushion stiffness	CRS	ATD
1	Short	Compliant	RF	CRABI 12mo
2	Short	Mid-range	RF	CRABI 12mo
3	Short	Stiff	RF	CRABI 12mo
4	Long	Compliant	RF	CRABI 12mo
5	Long	Mid-range	RF	CRABI 12mo
6	Long	Stiff	RF	CRABI 12mo
7	Short	Compliant	FF	Hybrid III 3yo
8	Short	Mid-range	FF	Hybrid III 3yo
9	Short	Stiff	FF	Hybrid III 3yo
10	Long	Compliant	FF	Hybrid III 3yo
11	Long	Mid-range	FF	Hybrid III 3yo
12	Long	Stiff	FF	Hybrid III 3yo
13	Short	Compliant	Booster	Hybrid III 6yo
14	Short	Mid-range	Booster	Hybrid III 6yo
15	Short	Stiff	Booster	Hybrid III 6yo
16	Long	Compliant	Booster	Hybrid III 6yo
17	Long	Mid-range	Booster	Hybrid III 6yo
18	Long	Stiff	Booster	Hybrid III 6yo

(Servo Instrument Corporation, Baraboo, WI). All signals were processed per SAE J211 guidelines [15]. The following injury metrics are reported: Head Injury Criterion over 36 ms (HIC36), chest resultant acceleration over a 3ms clip (Chest Accel, 3ms), and neck tension force (along the z-axis). CRS kinematics were recorded with high speed video at 1,000 fps. CRS rotation about the y-axis was analyzed for RF CRS and head displacements along the x-axis were analyzed for FF CRS and boosters. TEMA Motion Analysis software (v3.8, Image Systems Motion Analysis) was used to analyze these metrics, and each is reported as displacement from initial position. Injury metrics were compared across vehicle seat length and stiffness conditions, and also compared to current pediatric injury assessment reference values (IARVs) from Mertz et al. [16] and US regulatory limits in FMVSS 213 [10]. Tabular data are presented in this paper, with bar graphs included in Appendix C for improved visualization.

Results

RF CRS With CRABI 12mo

The base pieces of some of the RF CRS experienced minor bending and/or cracking where they interacted with the edge of the vehicle seat (see Appendix D for photos). The damage did not correlate with any particular seat length or cushion stiffness.

Seat length: The RF CRS on the long vehicle seats rotated less than those on the short seat (Table 4; mean difference of 2.7°), but had higher HIC36, chest accelerations, and neck tension (mean differences of 278, 1.5 g, and 113 N, respectively).

TABLE 4 Results for RF CRS with CRABI 12mo. CRS rotation was measured from initial position.

Seat length	Seat stiffness	CRS Rotation (deg)	HIC36	Chest Accel, 3 ms (g)	Neck Tension (N)
Short	Comp	24.2	686	50.7	1580
Short	Mid	24.6	709	53.2	1790
Short	Stiff	23.2	600	49.8	1620
Long	Comp	21.0	924	52.8	1770
Long	Mid	21.4	1004	55.5	1870
Long	Stiff	21.6	901	50.0	1690
IARV [10, 16]			**1000**	**60.0**	**990**

Seat stiffness: The RF CRS installed on mid-range stiffness seats appear to have slightly higher injury metrics than either the compliant or stiff seats, despite the CRS rotation being similar among all stiffness levels within each seat length group.

FF CRS With Hybrid III 3yo

The FF CRS showed evidence of minor damage near the belt paths, such as scuff marks or friction burns from the seat belt (see Appendix D). No other CRS damage was visible.

Seat length: No clear injury metric patterns are visible between the short and long seat conditions for the FF CRS (Table 5).

Seat stiffness: Chest deflection is the only injury metric with a distinct pattern with respect to vehicle seat cushion stiffness. Stiff cushions produced an average of 2.6 mm less chest deflection than corresponding compliant seats, with mid-range seats producing levels in between. All chest deflections were below the current IARV of 28 mm [16], so these small differences might not be significant from an injury prediction standpoint.

Booster With Hybrid III 6yo

All booster trials showed evidence of chin-to-chest contact via chalk impressions of the ATD's chin on the shoulder belt and/or shirt. In the trial with the long/stiff seat, the shoulder belt guide broke away from the shell of the booster approximately 50 ms into the trial. Photos of the failed shoulder belt guide and a plot of the seat belt load cell data are provided in Appendix D. The break occurred while the belt was being loaded, and appears to have affected the kinematics and kinetics of the ATD. No other damage to the boosters was visible. In the trial with the long/compliant seat, the shoulder belt slipped out of the shoulder guide. The slip occurred after the belt was at its peak load and during the rebound, so the kinematics and kinetics of the ATD were not affected.

Seat length: Chest resultant acceleration was higher on the short seats compared to the long seats (Table 6; mean difference of 3.9 g). Neck tension appears to be higher for the short seats (mean difference of 680 N), but this metric had high levels of variation across trials.

Seat stiffness: No visual trends or statistical significance could be determined across vehicle seats with different cushion stiffness levels in the booster trials.

TABLE 5 Results for FF CRS with Hybrid III 3yo. Head displacement was measured from initial position. HIC36 was not available for one trial due to the loss of a head accelerometer. The connection was repaired and testing proceeded.

Seat length	Seat stiffness	Head Displacement, x (mm)	HIC36	Chest Accel, 3 ms (g)	Chest Deflection (mm)	Neck Tension (N)
Short	Comp	419	982	53.1	18.6	1980
Short	Mid	418	N/A	53.3	17.9	2000
Short	Stiff	418	492	55.2	16.1	1910
Long	Comp	434	581	54.4	18.9	2090
Long	Mid	419	714	51.5	17.8	2000
Long	Stiff	431	673	50.3	16.3	1850
IARV [10, 16]			**1000**	**60.0**	**28.0**	**1430**

TABLE 6 Results for booster with Hybrid III 6yo. The shoulder belt guide broke on the trial shaded in gray, which may have affected the outcomes. Head displacement was measured from initial position.

Seat length	Seat stiffness	Head Displacement, x (mm)	HIC36	Chest Accel, 3 ms (g)	Chest Deflection (mm)	Neck Tension (N)
Short	Comp	301	664	59.5	32.4	2820
Short	Mid	290	675	59.1	31.5	2300
Short	Stiff	311	875	59.9	35.8	3300
Long	Comp	300	674	56.3	37.4	2330
Long	Mid	311	603	54.1	34.5	2010
Long	Stiff	353	524	56.2	24.7	2040
IARV [10, 16]			**1000**	**60.0**	**31.0**	**1890**

Discussion

Seat Length

For RF CRS, the length of the vehicle seats presented a trade-off. The shorter seats allowed more rotation but reduced several injury metrics such as HIC36, chest acceleration, and neck tension. The longer vehicle seats interacted more aggressively with the base of the RF CRS, preventing rotation but driving HIC36 and other injury metrics values up slightly. Previous studies have reported similar kinematic outcomes [5, 6]. The HIC36 value for the long seat with mid-range stiffness was slightly over the FMVSS 213 limit of 1000, and the other long seat HIC36 values were in the 900-range.

One might hypothesize that more RF CRS rotation may lead to increases in neck tension due to a more horizontal position of the occupant. Previous studies have shown this trend when RF CRS rotation is drastically modified by the use of tethers, front row seat interference, and load legs [17, 18]. However, in the current study, Table 4 shows a trend toward slightly less neck tension during the trials with greater CRS rotation. It appears that the small increase in rotation angle (2.7 degrees) is not enough to detrimentally affect neck tension. Considering all the RF CRS data presented here, it appears that shorter vehicle seats may actually be beneficial for RF CRS occupants because they allow for more rotation, extended energy absorption, and decreased injury metrics. However, in a real vehicle, the RF CRS may interact with the front row seat before traveling through its full rotational arc. Front seat interaction might be especially possible for larger RF convertible seats. The sled setup did not have a front row seat or any vehicle interior structures. Additionally, the test conditions all utilized proper harness tension and proper CRS installation. Real-world CRS misuse such as loose installations or loose harness adjustments may result in poorer outcomes, and it is unclear how vehicle seat length and stiffness parameters may influence the outcomes in misuse scenarios. Future work should investigate how vehicle seat characteristics might affect installations with CRS misuse.

For FF CRS, the key injury metrics were similar between the two seat length conditions. All the FF CRS in this study were secured snugly to the seat with the seat belt and top tether. It is hypothesized that the secure connection reduced the system's sensitivity to vehicle seat length, especially compared to RF CRS which have fewer attachment points. Klinich et al. report that the use of the top tether plays a larger role in reducing head excursion on shorter seats compared to longer seats [6]. In the current study, there is a weak trend for greater head displacements on the long seats compared to the short seats for FF CRS. However, the trend was not consistent across all conditions and the overall differences were small (20 mm or less).

Previous work suggests that shorter seats are not detrimental to younger occupants in harnessed CRS. The authors of those studies also recognize the benefits of shorter seats for older children and small adults whose legs do not fit well on longer seats [5, 6, 8]. The results of the current study also conclude that shorter vehicle seats are not detrimental to RF and FF CRS performance, and may even be beneficial for some injury metrics.

Most of the injury metrics examined in the booster trials did not correlate strongly with seat length. There is evidence of reduced chest resultant acceleration in the trials with the long seats compared to the short seats (mean difference of 3.9 g). The mean chest acceleration on the short seat was 59.5, which is near the FMVSS 213 limit of 60.0 g [10]. Thus, careful control of this injury metric may be important to the safety of the occupant. Chest deflection values were typically beyond the published IARV for the booster trials. However, this metric is not addressed by FMVSS 213 so few conclusions can be drawn regarding its consequence. The result might be unique to this vehicle seat and booster setup combination. The data showed a possible trend for lower neck tension on the long seats, although this metric was variable across trials. Thus, while neither seat length produced clearly favorable results over the other, there is a small amount of evidence that longer seats may be beneficial for boosters. The exception appears to be the head displacement metric: there is a weak trend for greater head displacement on long seats compared to short seats. However, these data are limited and the literature on this topic is scarce. Further investigation might reveal differences in different booster models' performances.

Neck tension metrics were beyond the reported IARVs for all CRS types in all conditions in this study. The neck tension values are similar to those reported in the literature for other CRS tested under similar conditions [18, 19]. This may be an artefact of poor biofidelity in the pediatric neck [17, 19] and/or the use of scaling and non-human surrogates in determining pediatric neck IARVs [16]. Non-contact cervical spine injuries are not common in properly restrained children.

Seat Stiffness

The trials on the seats with mid-range stiffness resulted in the highest injury metrics for the RF CRS. Due to the small sample size, it is unclear whether this is a significant outcome or due to random variability in the data. For the FF CRS, the stiff seats appeared to produce less chest resultant acceleration than the mid-range or compliant seats. The booster trials did not exhibit any apparent trends for the injury metrics studied.

These results suggest that the responses of the pediatric occupants were not sensitive to the range of vehicle seat cushion stiffness levels examined in this study. The cushion stiffness range examined here is within the range of production seats currently on the market. It is possible that a wider range of cushion stiffness levels (i.e., more extreme variation) could have produced more relevant differences in injury metrics across conditions. However, the applicability of these data would have been less, because the ranges would not reflect realistic vehicle properties. Vehicle seat stiffness is a topic currently being investigated in regards to FMVSS 213 updates. Several studies have reported that the stiffness of the bench foam currently used in FMVSS 213 is more compliant than that found in the rear seats of the modern vehicle fleet [20, 21]. Proposed FMVSS 213 bench updates include a stiffer foam to better reflect realistic vehicle environments [21].

It is important to note that the underlying structures of the front edge of all vehicle seats used in this study were identical to one another. Computer simulation studies have suggested that pediatric occupant outcomes are more sensitive to the underlying seat structure than the stiffness of the cushion itself [8]. Klinich et al. tested one RF CRS on vehicle seats with the stiffness modified by adding an extra support plate underneath the cushion [5]. The reinforced seat produced slightly higher chest accelerations in the RF CRS compared to the standard (more compliant) cushion condition, but other injury metrics were not affected by the modifications. To our knowledge, the current study is the first to present data from production vehicle seats produced with varying seat cushion stiffnesses. The current study concludes that seat cushion stiffness did not play a significant role in CRS performance within the ranges tested.

Limitations

This study is limited by small sample size. Only one RF CRS, one FF CRS, and one booster model were tested. Different models may react differently to changes in vehicle seat length and stiffness, especially those with different base geometries or additional features such as load legs, RF tethers, ISOFIX, etc. The RF CRS selected in this study was an infant seat. An infant RF CRS was selected instead of a RF convertible seat because infant bases tend to be longer [6, 13] and encounter more issues with front edge seat overhang compared to RF convertibles. However, using an infant RF CRS inherently limited the size of the RF occupant to a 12 month old. Convertible seats can often accommodate children up to 3 years old or more in RF mode. It is unclear whether the greater size and mass of an older RF child would have affected the outcomes of this study.

To partially address the question of system mass, the Klinich et al. study can be examined [6]. The authors used the 12mo CRABI ATD in all of their RF trials, but some RF CRS had much higher masses than others. One convertible RF CRS with an unusually high mass produced the highest chest resultant acceleration values and slightly greater rotation angles compared to the other convertible RF CRS. These outcomes support the inclusion of a higher-mass ATD (such as the 3yo) when the RF CRS are able to accommodate them, since some injury metrics might be worse with heavier occupants and/or heavier CRS. The CRS tested in this study were in the lighter range (see Table 2) compared to those reported in literature [6].

Only one vehicle seat model was included in this study. Vehicle seat models with different underlying structures may affect the sensitivity of CRS performance to length and stiffness differently than the one examined here. Only one repetition of each trial was conducted, so it was difficult to identify changes in response due to the independent variables versus normal sled testing variation. The sled setup did not have front row seats, so the CRS and ATDs were free to rotate forward without obstacles. The kinematics in a real vehicle might be limited by front row seat interactions. The sled system also did not introduce any z-axis acceleration. Realistic z-axis acceleration might have changed the responses between the CRS and the vehicle seats.

The amount of front edge overhang on the short seat varied between CRS types, with 28%, 21%, and 11% of the RF CRS, FF CRS, and booster bases protruding past the edge of the vehicle seat, respectively. Thus, the effects of the short seat on RF CRS might have been magnified compared to the booster, because the booster was better supported by the short seat. Additionally, the short vehicle seat length fell near the 2nd percentile of the US market [13], so these tests may be considered extreme cases. No seat belt retractors were used, but the seat belts were clamped at the FMVSS 213 pre-test tension during setup.

Summary/Conclusions

- For RF CRS, short vehicle seats allowed more y-axis rotation but reduced several injury metrics including HIC36.
- For FF CRS, long and short seats resulted in similar injury metrics across matched conditions.
- For boosters, short seats increased chest resultant acceleration slightly but did not have a noticeable effect on other injury metrics.
- Considering the pre-established benefits of shorter seats for non-booster children and small adults, this study supports shorter seat usage for other rear seat occupants, i.e. CRS users.
- The range of cushion stiffness examined in this study did not have a consistent or relevant effect on any of the CRS or occupant responses.

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Contact Information

Julie Mansfield,
453 W. 10th Ave, Columbus, OH 43210.
Julie.Mansfield@osumc.edu

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Definitions/Abbreviations

AAP - American Academy of Pediatrics

ASTM - American Society for Testing and Materials (formerly)

ATD - Anthropomorphic test device

CRS - Child restraint system

FF - Forward facing

FMVSS - Federal Motor Vehicle Safety Standards

HIC36 - Head injury criterion, 36 milliseconds

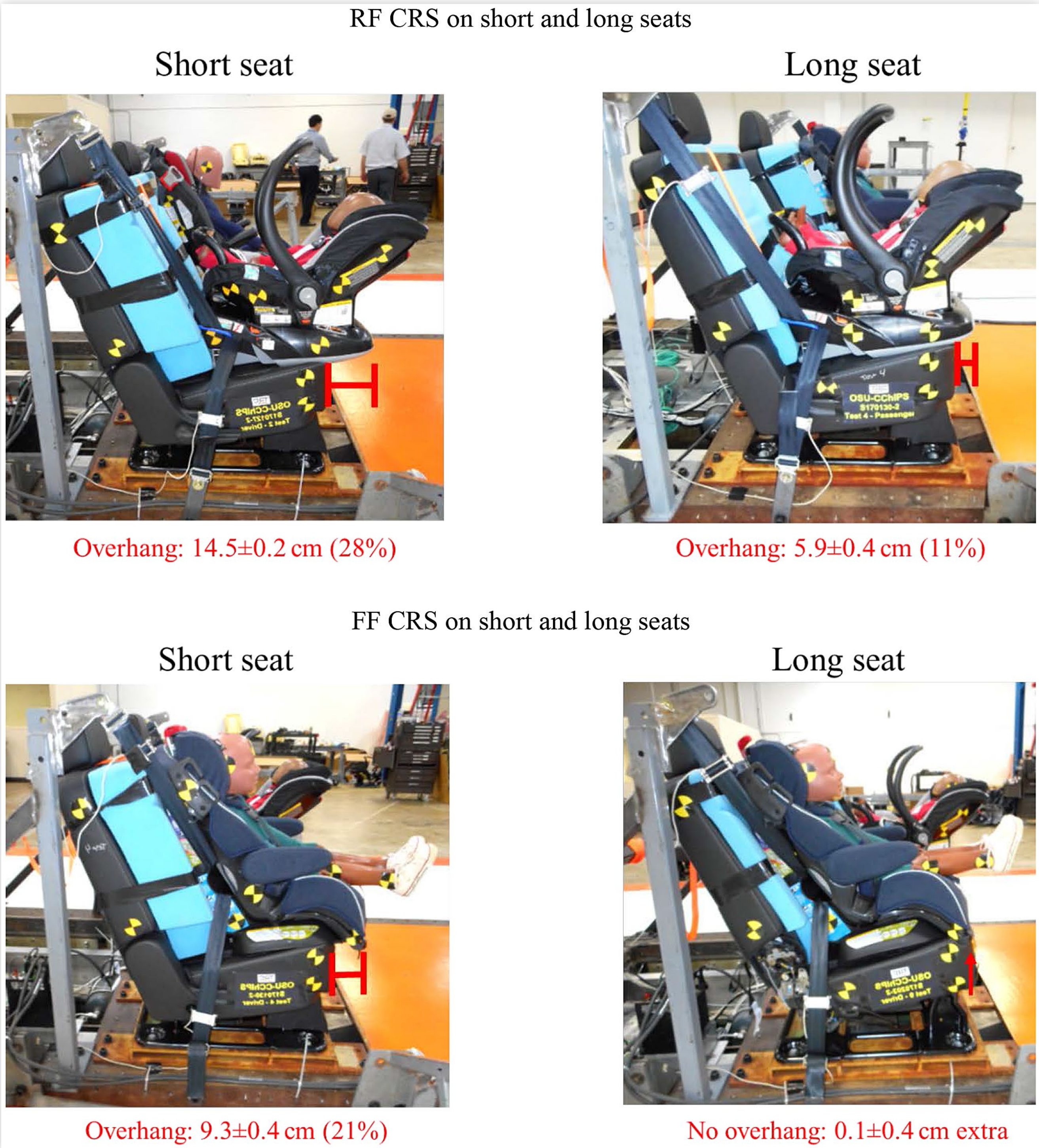
IARV - Injury assessment reference value

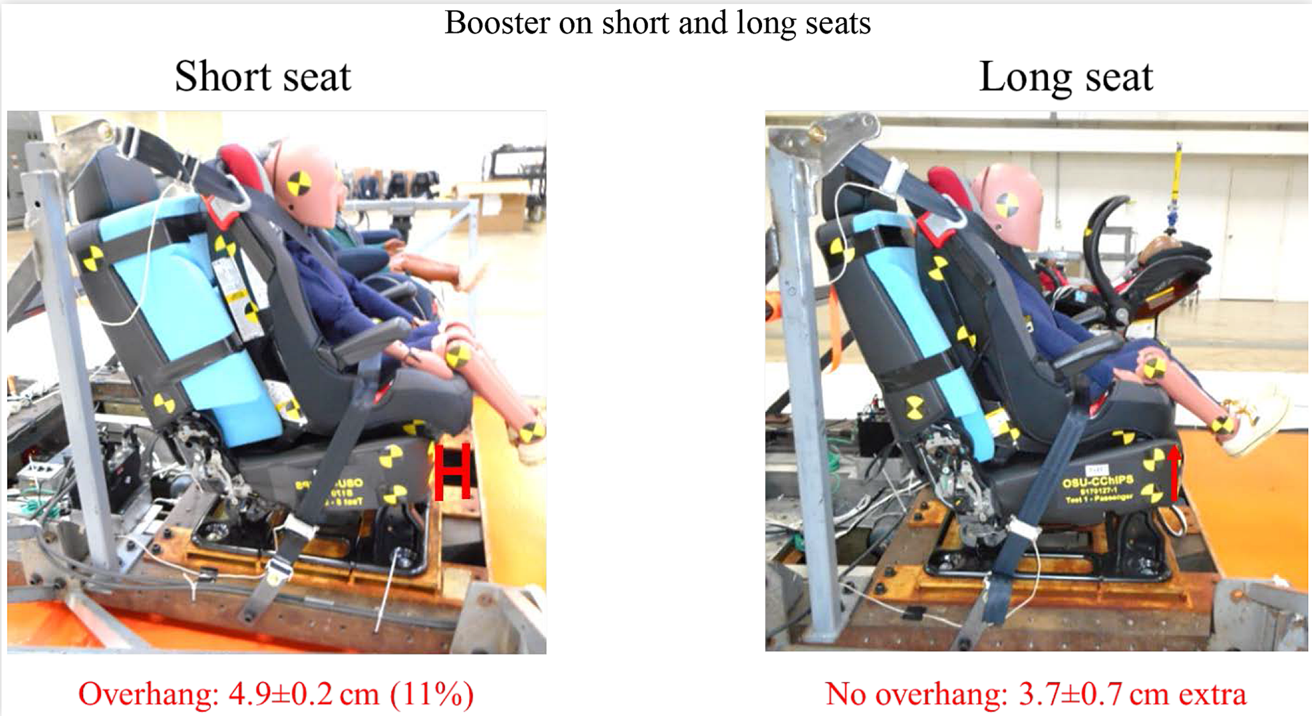
NHTSA - National Highway Traffic Safety Administration

RF - Rear facing

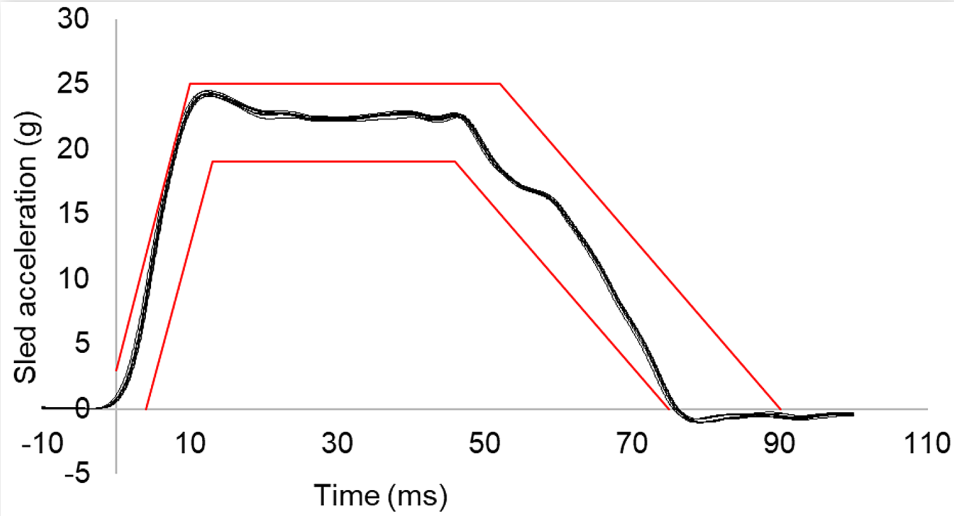
SUV - Sport utility vehicle

Appendix A: Setup Photos

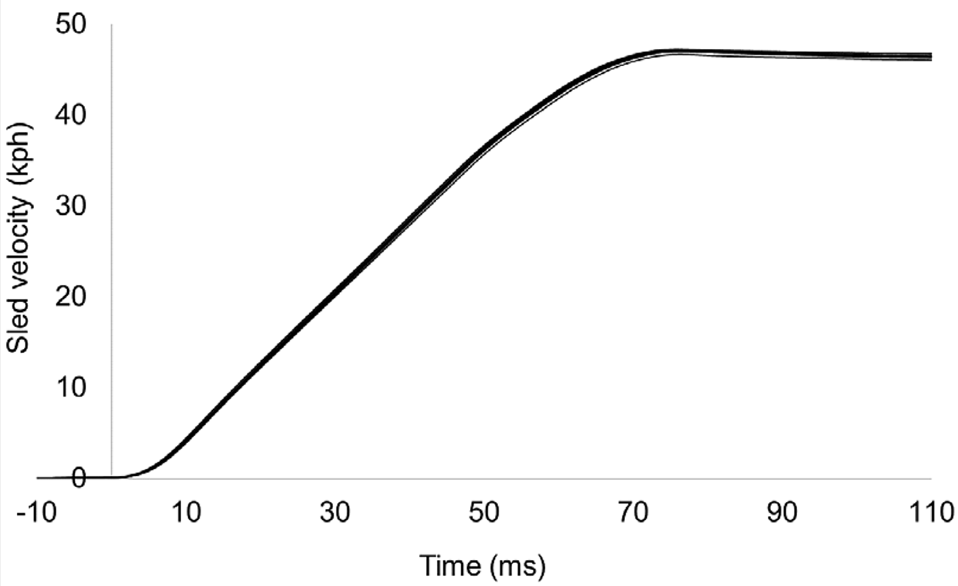



Booster on short and long seats
Short seat
Long seat
Overhang: 4.9±0.2 cm (11%)
No overhang: 3.7±0.7 cm extra

Appendix B: Sled Pulse

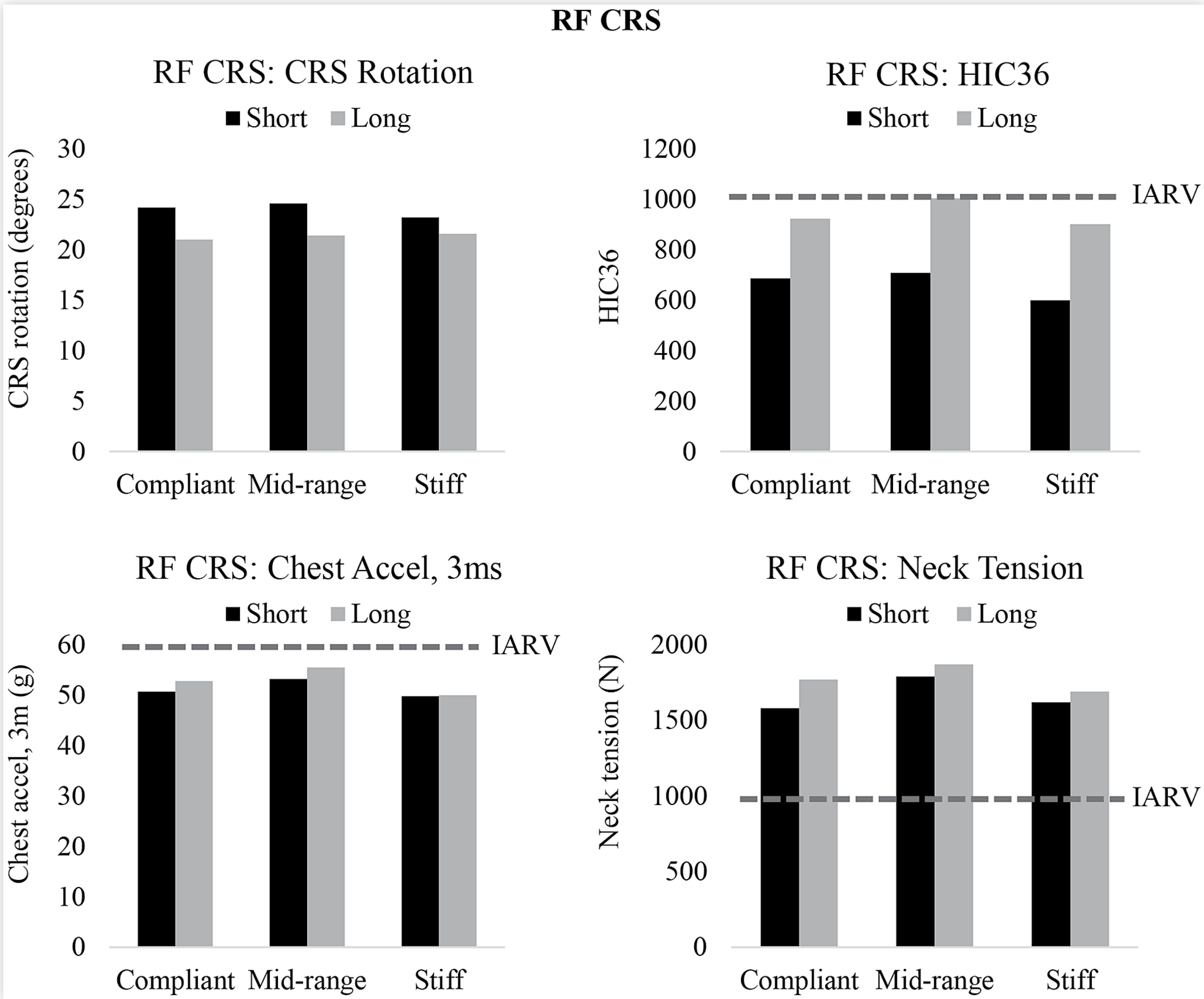


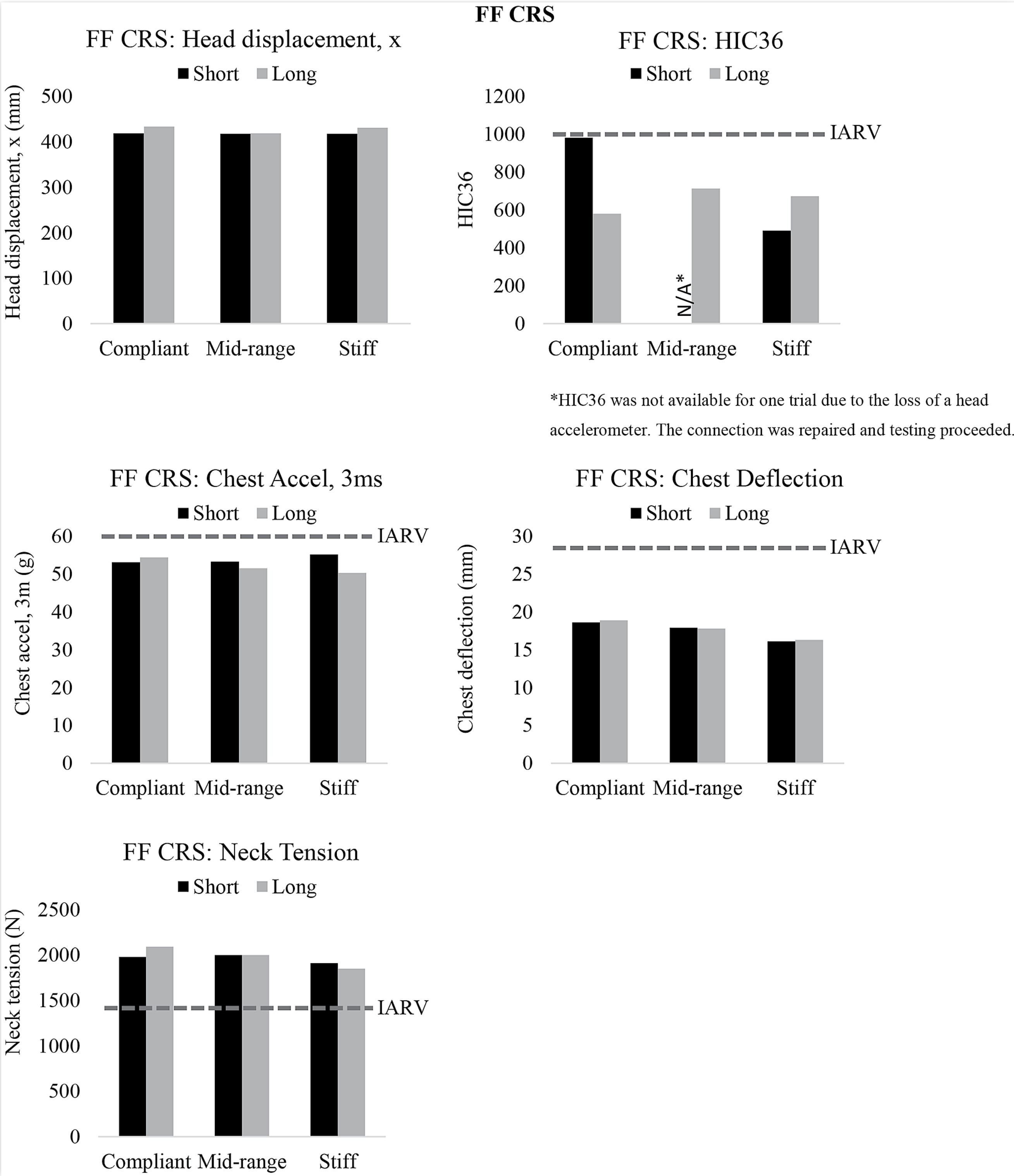
Sled pulse (acceleration) with FMVSS 213 corridor in red

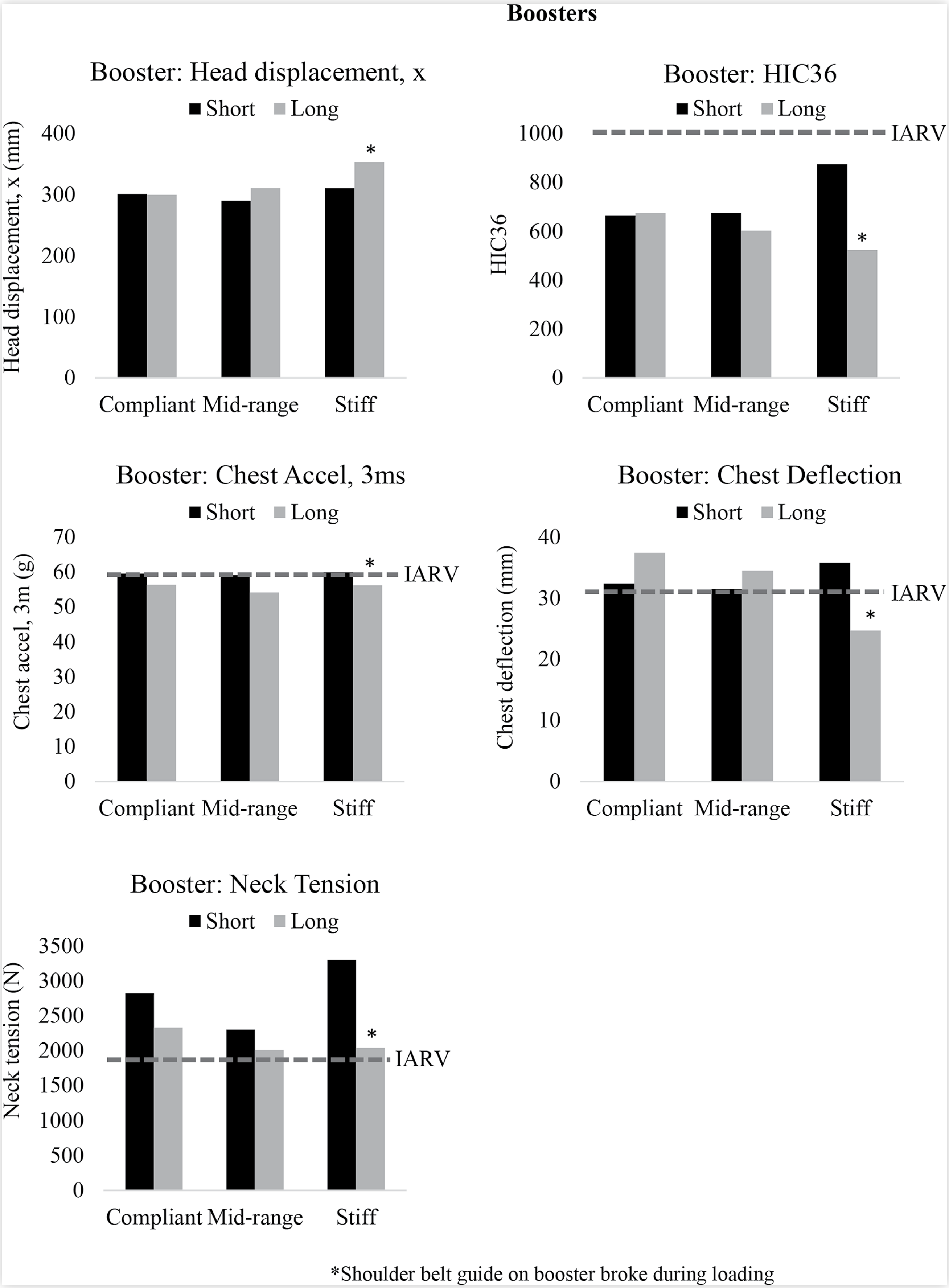


Sled pulse (velocity) in kph

Appendix C: Bar Graphs of Injury Metrics




FF CRS
FF CRS: Head displacement, x
Short
Long
Head displacement, x (mm)
500
400
300
200
100
0
Compliant
Mid-range
Stiff
FF CRS: HIC36
Short
Long
HIC36
1200
1000
800
600
400
200
0
IARV
N/A*
Compliant
Mid-range
Stiff
*HIC36 was not available for one trial due to the loss of a head accelerometer. The connection was repaired and testing proceeded.
FF CRS: Chest Accel, 3ms
Short
Long
Chest accel, 3m (g)
60
50
40
30
20
10
0
IARV
Compliant
Mid-range
Stiff
FF CRS: Chest Deflection
Short
Long
Chest deflection (mm)
30
25
20
15
10
5
0
IARV
Compliant
Mid-range
Stiff
FF CRS: Neck Tension
Short
Long
Neck tension (N)
2500
2000
1500
1000
500
0
IARV
Compliant
Mid-range
Stiff


Boosters
Booster: Head displacement, x
Short
Long
Head displacement, x (mm)
400
300
200
100
0
*
Compliant
Mid-range
Stiff
Booster: HIC36
Short
Long
HIC36
1000
800
600
400
200
0
IARV
*
Compliant
Mid-range
Stiff
Booster: Chest Accel, 3ms
Short
Long
Chest accel, 3m (g)
70
60
50
40
30
20
10
0
*
IARV
Compliant
Mid-range
Stiff
Booster: Chest Deflection
Short
Long
Chest deflection (mm)
40
30
20
10
0
IARV
*
Compliant
Mid-range
Stiff
Booster: Neck Tension
Short
Long
Neck tension (N)
3500
3000
2500
2000
1500
1000
500
0
*
IARV
Compliant
Mid-range
Stiff
*Shoulder belt guide on booster broke during loading

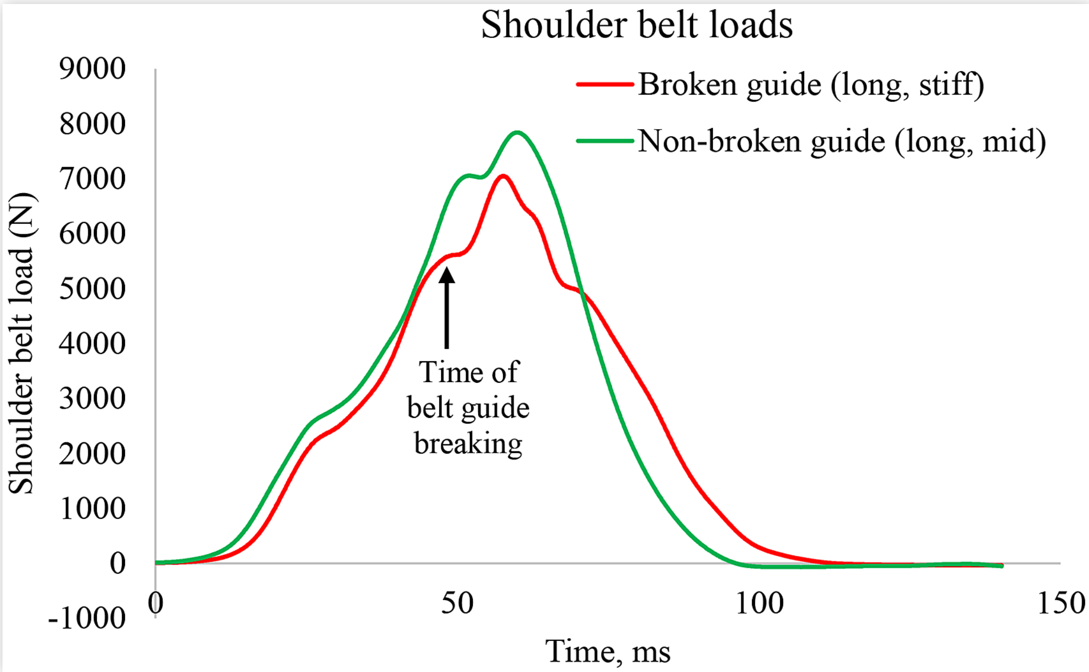
Appendix D: Photos of Damage

Evidence of bending and minor crack on RF CRS base.

Scuff marks from shoulder belt in FF CRS belt path.

Broken track of booster shoulder belt guide

Broken booster shoulder belt guide.



The shoulder belt load from the trial with the broken shoulder belt guide (red) is plotted against a similar trial with a belt guide that remained intact (green). The shoulder belt guide failed near 50 ms.

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