REAR-FACING CHILD SAFETY SEAT PERFORMANCE IN FRONTAL NCAP LEVEL CRASHES

Gary R. Whitman, Arlie V. Hart, III, Larry Sicher, Brian Benda, Louis A. D'Aulerio
ARCCA, Inc
United States
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ABSTRACT

Objective

To study the performance of Rear-Facing Child Safety Seats (RFCSS) when installed in the center-rear occupant position of vehicles involved in New Car Assessment Program (NCAP) severity level frontal crashes, the authors conducted a series of simulated frontal crash tests using a horizontal accelerator.

Method

The authors conducted two series of simulated frontal crash tests using a horizontal accelerator (sled facility) to assess RFCSSs of different designs. The first used a free-standing bench seat, the second used a sled buck constructed from a small domestic SUV. The tests included infant-only (with and without a base) and convertible CSSs, untethered and tethered.

Results and Data Sources

Without a tether, the RFCSSs experienced severe forward translation and forward and downward rotation. This kinematic resulted in the RFCSSs impacting the front-center console, and the infant dummy experiencing very high head accelerations and Head Injury Criteria (HIC) values, indicating a high risk of serious head injury. The use of a tether, with one end attached to the top portion of the CSS's seat back and the other attached to structure behind the CSS's occupant position, resulted in a significant reduction of the forward and downward rotation of the RFCSS. This prevented impact with the front seats and center console, and resulted in a significant reduction in peak head acceleration and HIC values.

Discussion and Limitations

RFCSSs are very effective in providing crash protection to young children in frontal crashes. Particularly in Europe and Australia, where RFCSS are often prevented from rotating by various devices, including: tethers, floor supports, rigid attachment, and/or by positioning the RFCSS against the vehicle's interior. Without these devices, RFCSS can rotate forward and downward significantly during a frontal crash. The amount of rotation depends upon the quality of the RFCSS installation and the geometry of the vehicle interior. The rotation and translation of the RFCSS may result in it impacting the vehicle interior, and/or allow the infant to slide up the RFCSS seat back, increasing the potential for head impact. The Federal Motor Vehicle Safety Standard 213 requires that RFCSSs limit their seat back rotation to 70 degrees from vertical when tested in a 48 kph (30 mph) delta-V simulated frontal crash. Real-world crashes are often more severe. This is why adult restraint systems are assessed in the NCAP frontal crash testing at a delta-V of 56 kph (35 mph). The National Highway Traffic and Safety Administration currently includes CSSs in the rear outboard occupant positions of vehicles tested in the NCAP. However, the public is often advised to install CSSs in the center-rear occupant position where head impact risks are different than at the outboard positions.

This study was limited to frontal crashes. Additional testing in other crash directions is needed to identify the potential benefits of anti-rotation devices in those crash scenarios.

Conclusions/Relevance

The use of anti-rotation devices with RFCSSs significantly increases the crash protection provided infants during frontal crashes.

BACKGROUND

Field experience and testing has demonstrated that the best crash protection for infants and young children is provided by rear-facing child safety seats (RFCSS).[1,2,3,4,5,6] This is particularly true in frontal collisions. Frontal collisions are the most frequent type of crash and typically result in the highest delta-Vs and peak accelerations. A primary advantage of the RFCSS in frontal crashes is that the seatback is the main restraint structure for the child. The RFCSS seat back widely distributes the retraining load to the head and torso of the child, and prevents significant movement of the head relative to the torso, thereby minimizing neck loads. CSS manufacturers in the U.S., NHTSA, and other organizations dedicated to child passenger safety, recommend RFCSSs be installed at angles ranging from 30° to 45° from the vertical. RFCSSs frequently incorporate indicators to show the installer what the manufacturer's recommended installation angle is. Due to the RFCSS seat back's inclined plane, as the child loads the CSS' seat back during a frontal crash, a forward and downward force is applied to the seat back. When the CSS is only secured to the vehicle by the lap belt portion of the seat belt or the lower LATCH (Lower Anchors and Tether for Children) strap, as is the case with the majority of RFCSS in the U.S., the force applied will cause the CSS to rotate forward and downward about the lap belt, compressing into the vehicle seat bottom cushion. This movement increases the potential for the CSS and child's head to impact objects forward of their occupant position, and for the infant to slide up the RFCSS seat back, thus exposing the infant's head to potential impact and the neck to increased loading. Typically, the objects impacted are the front seats and the front center console. These kinematics were observed during Transport Canada frontal crash testing reported by Tylko.[7] To counter this hazard, European and Australian RFCSS incorporate several different means to limit their forward and downward rotation. [8] One approach is the Australian-type tether design. This tether design attaches to the RFCSS at the head end and wraps around the RFCSS toward the rear of the vehicle, over the vehicle seat back, and attaches to the vehicle behind the RFCSS occupant position (Figure 1). During a frontal crash, the tether minimizes forward and downward rotation. Frontal crash sled testing conducted by the University of Michigan Transportation Research Institute indicated that the Australian-type tether reduced RFCSS forward displacement, head and chest acceleration, and neck loading during frontal crash testing. [9] Another method used in Europe to limit RFCSS forward and downward rotation is the leg support. The leg support attaches to the head end of the RFCSS and extends down to the floor of the vehicle (see Figure 2). During a frontal crash, the leg support prevents forward and downward rotation of the RFCSS. Other European RFCSS are positioned more forward on the vehicle's seat so that they are supported by the back of the front seat. In a frontal crash, the back of the front seat prevents forward and downward rotation. In the U.S., a RFCSS must limit the rotation of its seat back to no more than 70 degrees from vertical during the 48 kph (30 mph) delta-V simulated frontal crash sled test required by FMVSS 213. It must do so while only secured by the vehicle's lap belt or lower LATCH strap. While FMVSS 213 does not permit the use of tethers or leg supports to comply with its requirements, it does not prevent manufacturers from providing these devices as supplements to the lap belt or lower LATCH strap attachment.

Figure 1. **RFCSS w/Australian Tether.**

Figure 2. **RFCSS w/Foot Support.**

A real-world crash investigated by the authors involved an infant restrained in an infant only CSS, secured rear facing in the rear center occupant position of a small sport utility vehicle (SUV). The front of the SUV impacted the side of a mid-size pickup truck. The crash resulted in a delta-V of 53-64 kph (33-40 mph). During the crash, the infant sustained a severe head injury. The testing reported in this paper was conducted with a sled buck based on the SUV. The testing confirmed that the infant's injury resulted from impact of the RFCSS and the infant's head directly with the center console between the front seats, and that the injurious impact would have been prevented had the infant been restrained in a tethered RFCSS. Similar testing was also conducted using the freestanding seat specified in FMVSSS 213 to compare the performance of the infant seat when installed in an actual vehicle to its performance when installed in the FMVSS 213 seat fixture.

APPROACH

Two series of simulated frontal crash testing were conducted on a horizontal accelerator (sled tests). The first series was conducted using the freestanding FMVSS 213 bench seat fixture (Figure 3), while the second series used a vehicle buck constructed from a small domestic SUV. (Figure 4). The sled pulse used in both test series was based on the NCAP test accelerations measured at the left and right rear cross-member in two tests of the SUV. [10, 11] The resulting pulse produced a delta-V of approximately 66-68 kph (41-42 mph), with a peak acceleration of 45-47 g, and pulse duration of 100 ms (Figure 5).

Figure 3. **FMVSS 213 Seat Fixture.**

Figure 4. **Small SUV Sled Buck.**

Three different RFCSSs were selected for testing in both test series—two rear-facing-only (RFO) CSSs, and one rear-facing convertible CSS. The RFO CSSs could be installed with and without an installation base. Table 1 provides a description of each CSS tested. All CSSs tested incorporated energy-attenuating expanded polystyrene foam lining the interior surfaces of the side wings and seat back.

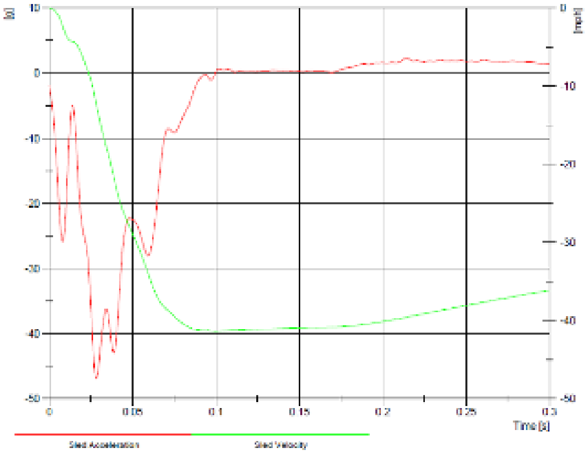

Figure 5. **Sled Test Pulse from Series 1, Test 1.**

Table 1.
Rear-Facing CSS Tested

CSS A	Infant only CSS, no tether available
CSS B	Infant only CSS, tether compatible
CSS C	Convertible CSS, tether compatible

All tests were conducted with a CRABI 12-month Anthropometric Test Device (ATD) instrumented with tri-axial head and chest accelerometers and upper neck load cells. The ATD was secured in each CSS in accordance with manufacturer's instructions. Each CSS was secured to the vehicle seat in accordance with the CSS instructions. High-speed video cameras were mounted overhead and on each side of the test fixture to record the kinematics of the CSS and ATD. Sled acceleration was measured and recorded.

Test Series 1

In the Test Series 1, the RFCSSs were secured to the FMVSS 213 seat fixture using the LATCH lower anchors, except for Test 1-1, which was secured using a lap belt as that RFCSS configuration was not compatible with LATCH. Table 2 provides the matrix for Test Series 1.

Table 2.
Test Series 1 Matrix

Test No.	Test Unit	Base Used	Tethered	Initial Seat Back Angle (degrees from vertical)
1-1	CSS A	No	No	42
1-2	CSS A	Yes	No	42
1-3	CSS B	Yes	Yes	46
1-4	CSS B	Yes	Yes	45
1-5	CSS C	N/A	Yes	35
1-6	CSS B	Yes	Yes	35

Test Series 2

In Test Series 2, the RFCSS were secured in the center rear occupant position of the SUV sled buck using the vehicle lap-belt-only available at that occupant position. Table 3 provides the matrix for Test Series 2.

Table 3.
Test Series 2 Matrix

Test No.	Test Unit	Base Used	Tethered	Initial Seat Back Angle (degrees from vertical)
2-1	CSS A	Yes	No	42
2-2	CSS B	Yes	Yes	40
2-3	CSS C	N/A	Yes	35

TEST RESULTS

Appendix A provides a summary of all instrumentation data from Test Series 1 and 2.

Test Series 1

Test 1-1. During Test 1-1, CSS A, an RFO CSS installed without its base and untethered slid forward on the test fixture seat and rotated downward until the CSS was almost entirely beyond the front edge of the seat. The CSS also rotated downward to the point that the CSS seat back was nearly horizontal (Figure 6a). The foot-end of the CSS deformed inward severely due to loading by the lap belt (Figure 6b). The HIC15 was 333.

Figure 6a. **Test 1-1 Side View.**

Figure 6b. **Test 1-1 Overhead View.**

Figure 6. **Test 1-1 Maximum Excursion.**

Test 1-2. During Test 1-2, CSS A, an RFO CSS installed with its base, slid forward significantly, but less than in Test 1-1 (Figure 7a). However, the downward rotation of the CSS was greater than that observed in Test 1-1, such that the seat back rotated beyond horizontal (Figure 7b). The HIC15 was 528.

Figure 7a. **Test 1-2 Side View.**

Figure 7b. **Test 1-2 Side View.**

Figure 7. **Test 1-2 Maximum Excursion.**

Test 1-3. During Test 1-3, CSS B, an RFO installed with its base and tethered performed well in spite of deformation to the structure to which the tether was secured, and compression of the top of the test seat's seat back cushion by the tether. The CSS remained entirely on the test fixture's seat bottom, and the seat back rotation was significantly reduced compared to Tests 1-1 and 1-2 (Figure 8). The infant dummy's head, however, still displaced to the top edge of the CSS's seat back. Had the tether anchorage structure not deformed and the vehicle's seat back been configured to be more representative of real-world seats, it is expected that the CSS rotation would have been further reduced, with corresponding reduction in head displacement as well. The HIC15 was 931.

Figure 8a. **Test 1-3 Side View.**

Figure 8b. **Top View.**

Figure 8. **Test 1-3 Maximum Excursion.**

Test 1-4. During Test 1-4, CSS B, an RFO CSS installed with its base and tethered, performed very well in regards to kinematics. The structure to which the tether was secured did not deform. The CSS did not displace significantly forward or rotate downward (Figure 9). Post test, it was determined that several of the ATD's neck data channels failed and consequently the data set is missing some values. The HIC15 was 589.

Figure 9a. **Test 1-4 Side View.**

Figure 9a. Test 1-4 Top View.

Figure 9. **Test 1-4 Maximum Excursion.**

Test 1-5. During Test 1-5, CSS C, a rear-facing convertible CSS, performed very well in regards to kinematics. The CSS remained entirely on the test fixture's seat bottom and the CSS did not rotate significantly forward or downward (Figure 10). The HIC15 was 872.

Figure 10a. **Test 1-5 Side View.**

Figure 10b. **Top View.**

Figure 10. **Test 1-5 Maximum Excursion.**

Test 1-6. During Test 1-6, the same model CSS B tested in Test 1-4 was used. During this test, the tether strap failed after being used in two previous tests. As a result, the CSS slid forward and experienced greater downward and forward rotation than during Test 1-4, demonstrating the improved performance provided by an intact tether (Figure 11).

Figure 11a. **Side View.**

Figure 11b. Top View.

Figure 11. **Test 1-6 Maximum Excursion.**

The change in the infant seat's seat back angle during the test is provided in Table 4. The instrumentation data is provided in Appendix A.

Table 4.
Test Series 1 Test Data

Test No.	Test Unit	Maximum Change in CSS Seat Back Angle (degrees)
1-1	CSS A	27
1-2	CSS A	42
1-3	CSS B (1)	17
1-4	CSS B	1
1-5	CSS C	0
1-6	CSS B (3)	33

(1) Tether anchor deformed forward (2) Neck load cell data acquisition system malfunctioned (3) Tether strap failed

Test Series 2

Test 2-1 During Test 2-1, CSS A, an RFO CSS with its base and untethered was tested. It displaced forward, partially off the front edge of the vehicle seat bottom and rotated downward and forward (Figure 12). The resulting HIC15 was 1653.4. The Neck Tension/Extension Nij was 2.42.

[Note: Top View Camera Malfunctioned.]

Figure 12. **Test 2-1 Maximum Excursion.**

Test 2-2 During Test 2-2, CSS B, an RFO CSS with base and tethered, performed significantly better in regards to kinematics than CSS A in Test 2-1. CSS B did not displace forward or rotate significantly (Figure 13). There was no impact between the carrier and the front center console. The infant dummy's head did, however, slide above the top of the CSS's seat back. The HIC15 was 970.5. The Neck Tension/Extension Nij was 3.06.

Figure 13a. **Test 2-2 Side View.**

Figure 13b. **Top View.**

Figure 13. **Test 2-2 Maximum Excursion.**

Test 2-3 During Test 2-3, CSS C, a rear-facing convertible CSS with tether, performed very well compared to test 2-1 and 2-2. The bottom of CSS C displaced forward but remained on the vehicle seat bottom, and the CSS did not rotate forward or downward (Figure 14). Due to the forward displacement of the CSS's bottom while the top was tethered, the seat back angle actually became 7 degrees more upright. The HIC15 during the test was 786 and the Neck Tension/Extension Nij was 1.15.

Figure 14a. **Test 2-3 Side View.**

Figure 14b. **Test 2-3 Top View.**

Figure 14. **Test 2-3 Maximum Excursion.**

Test data from Test Series 2 is provided in Table V. Instrumentation data is provided in Appendix A.

Table 5.
Test Series 1 Test Data

Test No.	Test Unit	Maximum Change in CSS Seat Back Angle (degrees)
2-1	CSS A	13
2-2	CSS B	4
2-3	CSS C	-7

DISCUSSION

Kinematics

CSS A

Dummy head displacement was greatest with CSS A. When used without its base, the loading applied by the securing lap belt at the foot-end of the CSS caused the side walls of the CSS to deform inward. This deformation shortened the distance between the two lap belt hooks on the CSS. The shortened distance reduced the length of the lap belt path, creating excess lap belt length. The excess lap belt allowed the CSS to displace forward, sliding nearly off the front edge of the seat. When secured with its base, the belt path was not as severely altered, therefore the forward displacement was less. Due to its lack of tether, however, this CSS rotated severely forward and downward when tested, both with and without its base. In Test Series 2, similar extreme rotation resulted in this CSS impacting the center front console with its head end, and resulted in a very high HIC (1653) and Nij (2.42) values. Similar results were observed during frontal crash testing conducted by Transport Canada, in which untethered rear-facing CSSs were secured in the second row center occupant position.[12] Tylko reported that "Contact with the center console was observed in small and large vehicles and at crash speeds as low as 40 km/h. In all cases, forward excursion of the infant seat was great enough to cause a significant portion of the infant restraint to slide off the front edge of the vehicle seat."

CSS B

CSS B was very effective in controlling the kinematics of the seat and dummy. Even when the tether was compromised, rotation of this CSS was significantly reduced. When the tether remained intact, there was virtually no rotation of this CSS (1 and 4 degrees). The top of the dummy's head moved up to the top of the CSS seat back, but even when tested in a vehicle, this motion did not result in the dummy's head striking anything.

CSS C

The kinematics with CSS C, the tethered rear-facing convertible CSS, were the best overall. There was essentially no forward or downward rotation of the head portion of the CSS in either of the test series. In Test Series 2, the CSS seat back angle actually became more upright due to some forward displacement of the bottom while the top was restrained by the tether. The forward displacement of the CSS bottom was due to approximately 30.5 mm (1.25") of slippage of the securing vehicle lap belt through its locking latchplate. This slippage was likely due to a compatibility problem between the CSS and the vehicle, as the geometry of the two resulted in an angle between the LATCH strap and its adjuster that compromised the performance of the locking latchplate. The dummy's head remained well below the top of the CSS seat back and was well-supported. Similar frontal crash sled testing of rear-facing CSS conducted by Sherwood, et al., did not reveal a significant kinematic difference between Australian tethered and untethered RFCSS. [13] That testing was conducted at approximately the FMVSS 213 frontal crash pulse, with a delta-V of 49 kph (30 mph), peak acceleration of 23 G, and a duration of 85 msec, and did not include any infant-only CSSs. The lower severity of the Sherwood tests and the lack of infant-only CSSs likely accounts for the smaller difference between tethered and untethered configurations.

Head Acceleration and HIC15

All but two tests exceeded the HIC15 limit of 390 used in FMVSS 208 for the 12 month CRABI. One CSS that did not exceed the 390 value was CSS A in Test 1-1, which reported a HIC15 of 333, but that CSS nearly slid off the front edge of the vehicle seat. The excessive forward displacement and forward and downward rotation of the CSS extended the time and distance over which the infant dummy's head was accelerated. This reduced the loading of the head into the CSS's seat back, likely resulting in the lower HIC15, and there was no structure forward of the CSS for the exposed head to strike. However, this CSS showed very dangerous kinematics. The other CSS that did not exceed the 390 HIC15 value was CSS B, when its tether failed in Test 1-6. The tether failure allowed more forward and downward rotation, which likely also reduced the extent to which the dummy head loaded the CSS seat back. An unlimited HIC level of 1000 was exceeded in four tests, those being Test 1-3 with CSS B during Test Series 1, and all of the tests in Series 2. Only CSS A exceeded an unlimited HIC of 2000. This occurred during Test 2-

1, where the HIC15 was 1653. These extremely high HIC values were caused by the forward displacement and forward and downward rotation of the CSS, causing the head-end of the CSS to impact the center console. All other tests resulted in HIC15 values between 390 and 1000.

Similarly high head accelerations were observed in frontal crash testing by Transport Canada.[14] Tylko reported that "Elevated dummy head accelerations were observed in 10 of the 24 tests conducted with the infant seat installed in the center seating position of the second row (location 15). The elevated head accelerations were the result of interaction between the back of the infant seat and the center console…"

Frontal crash sled testing conducted by Abdelilah et al.,[15] at 48 kph (30 mph) delta-V and with RFCSS rigidly supported to prevent any forward displacement or forward and downward rotation, and with the dummy's head positioned against the CSS seat back, revealed that, under those conditions, the RFCSS sufficiently limited HIC without the need for energy attenuating foam.[16] In those tests, however, there was no opportunity for the CSS to impact the vehicle's interior. The testing reported by Tylko and in this paper clearly demonstrate that, in more severe frontal crashes where there is contact with the vehicle's interior, dangerously high HIC values occur. It must be noted that in actual use, children and infants may also not always position the head against the seat back. As such, any gap between the CSS seat back and the child's head would result in the child's head developing a relative velocity to the CSS seat back during a frontal crash. As a result, when the head impacts the seat, the head accelerations experienced will be amplified, causing higher head acceleration and HIC values. Limiting RFCSS movement through the use of an Australian tether or leg support during a frontal crash will eliminate impacts with the vehicle interior, but these tests also show the need for energy attenuation in higher crash severities due to the potential of a gap between the child's head and CSS seat back.

Neck Loads

In spite of very little visually discernable neck extension, the tension/extension Nij threshold values used in FMVSS 208 for the 12 month CRABI ATD were exceeded in all of the tests conducted in both test series. Four tests exceeded an Nij of 2. These four tests were with the CSS A and B, the infant-only CSSs. These CSSs have significantly lower seat back heights and their seat backs are more flexible toward the top when compared to convertible CSSs. CSS C, the convertible CSS, had the lowest Nij values. This is likely because of its more effective seat back, due to its greater height and rigidity, combined with its effective tether. The tether prevented the CSS from tipping, which prevents the cervical spine from aligning with the crash pulse vector, and the more rigid seat back provides more effective support to the head and torso, thus minimizing the amount of neck extension. Even with CSS C, however, the neck tension/extension Nij values exceeded the FMVSS 208 threshold in both test series, with an Nij of 1.89 in Test Series 1 and Nij of 1.15 in Test Series 2. At the present time, Nij requirements have not been incorporated into FMVSS 213. According to the National Highway Traffic Safety Administration (NHTSA), one of the reasons is that the use of Nij appears to over predict the likelihood of neck injuries. Investigations of real world frontal crashes show that neck injury to children restrained in CSSs is rare when head impact is not involved.[17] Sherwood, et al., found similar test results during their testing of rear-facing CSS at 48 kph (30 mph), approximately the same as the FMVSS 213 frontal crash pulse.[18] The authors concluded that, "The high values are due to the fact that the dummy neck is likely stiffer than the child and has no range of free motion on either side of the neutral position (Crandall et al., 1999; Janssen et al., 1991). In a child, it would be expected that the minimal changes in kinematics which occur while the head and thorax are supported by the child restraint would result in negligible increase in neck joint stiffness. In the dummy, even small changes result in rapidly increasing stiffness values."[19] The NASS CDS database, created and maintained by NHTSA, was queried for real-world cases involving infants (0-1 year) in rear-facing CSS, exposed to frontal crashes of 48 kph (30 mph) delta-V or greater. Twenty-eight such cases were identified. None of the infants in these crashes sustained a cervical injury. This suggests that the high Nij values measured in the subject tests over predict the risk of neck injury and should only be used for comparative analyses. Previous epidemiology studies have found that neck injuries to infants in frontal crashes are extremely rare, and that head impact injuries are by far the most frequent mechanism of serious injuries.[20,21,22] Therefore, minimizing head excursion and the associated potential for head impact should be the top priority for rear-facing CSSs, as it is for all CSSs. Fortunately, as demonstrated by the subject testing involving CSS C, the rear-facing CSS that best minimized head excursion and the potential for head impact also resulted in the lowest risk of neck injury.

The American Academy of Pediatrics now recommends children traveling in motor vehicles remain in a rear-facing CSS until at least two years of age and as long as possible.[23] This is resulting in heavier and taller children traveling in RFCSS. In a crash, the larger child will apply a greater inertial load to the CSS and the load will be applied higher due the child's higher center of gravity. This will result in greater forward translation and greater forward and downward rotation of the CSS. The taller seat height also increases the risk of head impact and neck injury. To counter these factors, Australian tethers, support legs, or other equally effective technologies, should be used to minimize RFCSS forward translation and forward and downward rotation.

Out of concern for the frequently high head accelerations observed during frontal crashes with RFCSS positioned in the second row center position and a center console forward of that position, Tylko recommended that parents and caregivers "…avoid installing rear facing infant seats in the center second row if the vehicle is equipped with a center front console." [24] The authors of this paper agree with her concern, but there are other risks that must also be considered. Such a practice would position children in outboard occupant positions where they are at greater risk of injury from vehicle intrusion during side impacts. Side impacts are known to be a leading cause of serious injury, especially to outboard occupants seated adjacent to the impact, due to the risks created by intrusion and occupant impact with the vehicle's side interior. Therefore, we recommend that parents and caregivers position their infants and young children rear-facing in the second row center occupant position whenever possible and use a RFCSS equipped with an Australian type tether or leg support. RFCSS with Australian type tethers are currently available in the U.S. from several manufacturers, and U.S. motor vehicles have been equipped with ready-to-use tether anchorages since the early 2000s. We urge other CSS manufacturers to incorporate Australian tethers or leg supports into their RFCSS as soon as possible, and also recommend that NHTSA implement a more limited RFCSS rotation requirement into FMVSS 213 to further stimulate their adoption.

Chest Acceleration

The peak chest acceleration sustained over a 3 msec duration exceeded the FMVSS 213 limit of 60 G in all the testing conducted. Chest acceleration was consistently greater with those CSSs that best limited head and torso displacement. This is likely because the chest is decelerated over a shorter distance and time duration due to the reduced CSS displacement and rotation. Real world data from Australia, where all rear-facing CSS are tethered, does not indicate a greater frequency of chest injury. Therefore, limiting CSS forward displacement and rotation does not appear to introduce a significant chest injury risk.

Real-world crash Investigation

One of the stimuli for the research testing discussed in this paper was the investigation of a real-world crash conducted by the authors. The crash involved a small domestic SUV that impacted the passenger side of a full-size pickup truck (Figure 15). A 5-month-old, 9 kg (20 lbs), 68 cm (26.8 inches) infant was restrained in the same make and model CSS as CSS A, and located in the center rear occupant position of the Ford Escape at the time of the crash. The infant carrier was secured to the vehicle using the lower LATCH strap (Figure 16). There was no intrusion into the center rear occupant position of the SUV (Figure 17).

Figure 15. **Ford Escape Post Crash.**

During the crash, the head end of the CSS impacted with the front center console and the child sustained severe brain injuries, including:

- an extensive post-traumatic subarachnoid hemorrhage,
- intra-ventricular hemorrhage,
- a severe brainstem injury including approximately ¾ of the pons,
- bilateral femur fractures

An accident reconstruction analysis determined that the Delta-V for the SUV was 53-64 kph (33-40 mph), with peak acceleration levels comparable to the NCAP level testing for that vehicle. The PDOF of the crash was slightly to the left of center, at -10 to -20 degrees.

Figure 16. **Exemplar CSS A Installed In Center Rear of an exemplar SUV.**

Figure 17. **Center rear occupant position of Ford Escape.**

The testing conducted during Test Series 1 and 2 identified the mechanism of the child's head injuries as impact of the head end of the infant seat with the front center console, and the resulting accelerations applied to the infants head. Test Series 1 and 2 also determined that had the infant been restrained by a RFCSS with an Australian type tether that the injury mechanism would have been eliminated.

NHTSA conducted NCAP testing on the same model SUV as represented in Test Series 2, with the same model CSS in the right rear occupant position as CSS A, with a 12 month CRABI ATD installed.[25] The kinematics of the CSS were substantially similar to those observed in Test 2-1, except that since there was no console forward of the right rear occupant position, and the right front seat back rotated forward, the infant safety seat did not impact any object during the test. As a result, the HIC36 measured was 907, less than half the 2031 HIC36 measured during Test 2-1. Comparison of the infant safety seats' maximum forward excursion during Test 2-1 and the SUV NCAP test are provided in Figure 18 and 19. This comparison demonstrates that without effective limitation of forward and downward rotation of rear-facing CSSs, the same frontal crash, with the same CSS, in the same row, without intrusion into the occupant space, can result in much different risks of head injury simply by using a different occupant position.

Figure 18. **Test 2-1 Maximum forward excursion.**

Figure 19. **Ford Escape maximum forward excursion.**

Leg Support for Rear-Facing Child Safety Seats

In Europe, motor vehicles are assessed for occupant crash protection in a program referred to as the Euro-NCAP. One test conducted as part of that program is an offset frontal impact into a deformable barrier at 64 kph (40 mph).[26] As part of that test, a forward-facing and a rear-facing CSS, recommended by the vehicle manufacturer, are installed in the outboard occupant positions and their dynamic performance is assessed. An 18-month infant dummy is secured in the rear-facing CSS. Review of European frontal crash NCAP testing with a RFCSS incorporating a leg support indicates that a leg support is very effective in limiting forward displacement and forward and downward rotation of the RFCSS. Fontal crash sled testing conducted by Sherwood indicates that a leg support provides increased frontal crash protection to children in RFCSS by limiting forward displacement and forward and downward rotation and maximizing crash ride down.[27]

CONCLUSIONS

The testing and crash investigation reported in this paper indicate that, in order to optimize the crash protection of children exposed to frontal crashes while restrained in a RFCSS, the RFCSS's tendency to displace forward and rotate forward and downward must be limited. This testing also indicates that an Australian type tether significantly improves the performance of RFCSS in NCAP-level frontal crashes by limiting the forward displacement and forward and downward rotation that can result in severe head impact and neck loading. Prior research and Euro-NCAP testing indicates that a foot support also effectively limits forward displacement and forward and downward rotation, and maximizes crash ride down. The use of the Australian type tether or a leg support with a RFCSS increases the effectiveness of RFCSS and reduces the potential for serious injuries and fatalities. These features also compensate for installation errors and vehicle compatibility problems, such as a loosely secured lap belt or lower LATCH strap, and vehicle buckle/latchplate incompatibility with the CSS belt path. Because head impact is the leading mechanism of serious injury, priority should be given to minimizing head impacts. This can be accomplished by the use of the Australian type tether or a leg support.

FMVSS 213 permits the seat back of an infant seat to rotate up to 70 degrees from vertical. In an actual motor vehicle, this degree of rotation will often result in the head end of the infant seat impacting a seat or center console forward of the RFCSS, as occurred in Test 2-1 and during the real-world crash discussed earlier. In the late 1990s, NHTSA realized that an 813 mm (32") head excursion limit requirement for forward-facing child safety seats was inadequate to ensure that children in such CSS would not strike their head in real-world crashes due to the limited clearance in motor vehicles. NHTSA, therefore, implemented a new a 721 mm (28") head excursion limit requirement and permitted the use of a tether in order to comply. The authors strongly recommend an analogous requirement for rear-facing CSS to further limit RFCSS rotation, and to allow the use of tethers or leg supports to comply with this additional requirement.

The findings of this study also indicate that infants are better protected when the head is well below the top of the CSS seat back. The authors recommend that, once infants properly fit a convertible CSS with its higher seat back than an infant only CSS and can maintain their head up under the more upright orientation of the convertible CSS, those infants should be transitioned to a rear-facing convertible CSS, so that they can be afforded the protective benefits of the higher seat back, more upright orientation, and likely larger side wings.

LIMITATIONS

The limited neck biofidelity of the CRABI 12 month ATD, combined with the limited knowledge pertaining to child neck injury tolerance, limits the use of the neck load data to comparisons only.

The testing conducted did not include RFCSS incorporating leg supports, and limited resources constrained the number of tests conducted in this study. Additional tests of both untethered, tethered, and leg supported rear-facing CSS is recommended to further study their performance during NCAP level frontal crash conditions.

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[1] Weber, K. (2000). "Crash Protection for Child Passengers." UMTRI Research Review **31**(3)..

[2] Kamren, B., et al., (1993) The Protective Effects of Rearward Facing CRS: An Overview of Possibilities and Problems Associated with Child Restraints for Children Aged 0- 3 Years, (SAE 933093)

[3] Carlsson, G. et al., "Rearward-Facing Child Seats – The Safest Car Restraint for Children?" Accident Analysis & Prevention Vol. 23 1991

[4] Isaksson, I. et al., "Trends and Effects of Child Restraint Systems Based on Volvo's Swedish Accident Database" SAE 973299

[5] Henary, B., et al., "Car Safety Seats for Children: Rear Facing for Best Protection" Injury Prevention 2007;13:398-402, doi:

10.1136/ip.2006.015115, 28 August 2007

[6] Jakobsson, L., et al., “Safety for the Growing Child – Experiences from Swedish Accident Data” 19th Internatioanl Technical Conference on the Enhanced Safety of Vehicles, Paper Number 05-0330, June 2005

[7] Tylko S., Transport Canada “Interactions of Rear-Facing Child Restraints with the Vehicle Interior during Frontal Crash Tests” 22nd International Technical Conference on the Enhanced Safety of Vehicles , Washington, DC, June 13-16, 2011, Paper Number 11-0406

[8] Australian/New Zealand Standard ASNZS 1754:2004 Child Restraints Systems for use in Motor Vehicles

[9] Manary M. A., et al. “The Effects of Tethering Rear-Facing Child Restraint Systems on ATD Responses” 50th Annual Proceedings Association for the Advanement of Automotive Medicine, October 16-18, 2006

[10] New Car Assessment Program, Frontal Barrier Impact Test, Report Number NCAP-MGA-2001-016, March 16, 2001

[11] New Car Assessment Program, Frontal Barrier Impact Test, Report Number 5FEM-MGA-2001-026, April 20, 2001

[12] Tylko S., op cit. (2011)

[13] Sherwood, et al., op cit. (2004)

[14] Tylko S., op cit. (2011)

[15] Abdelilah, Y., “The Effects of Head Padding in Rear Facing Child Restraints” SAE 2005-01-1839

[16] Abdelilah, Y., op cit (2005)

[17] Department of Transportation, NHTSA, 49 CFR Part 571 [Docket No. NHTSA-03015351] Federal Motor Vehicle Safety Standards; Child Restraint Systems Final Rule, Federal Register/Vol 68, No. 121, June, 24, 2003

[18] Sherwood, et al., “The Performance of Various Rear Facing Child Restraint Systems in a Frontal Crash” 48th Annual Proceedings, Association for the Advancement of Automotive Medicine, September 13-15, 2004

[19] Sherwood, et al., op cit. (2004)

[20] Carlsson, G., et al., “Rearward-Facing Child Seats – The Safest Car Restaint for Children?” Accident Anlysis & Prevention, Vol. 23. Nos 2’3, pp 175-182. 1991

[21] Henary, B., et al., “Car Safety Seats for Children: Rear Facing for Best Protection: Injur Prevention 2007;13:398-402. doi: 10.1135/ip.2006015115

[22] Jakobsson, L., et al., “Safety for the Growing Child – Experiences from Swedish Accident Datas” Paper Number 05-0330, Proceedings 19th International Technical Conference on the Enhanced Safety of Vehicles, June 2005

[23] American Academy of Pediatrics, Policy Statement Child Passenger Safety, DOI: 10.1542/peds.2011-0213, *Pediatrics* published online Mar 21, 2011;

[24] Tylko S., op cit. (2011)

[25] NHTSA New Car Assessment Program, Frontla Barrier Crash Test, 2008 Ford Escape, Report Number: CAL-07-12, March 1, 2007

[26] Hobbs, C. A., McDonough, P.J., “Development of the European New Car Assessment Programme (Euro NCAP), Paper Number 98-S11-O-06

[27] Sherwood, et al., op cit. (2004)

APPENDIX A. TEST SERIES 1 AND 2 INSTRUMENTATION DATA

Test No.	Test Unit	Sled Delta-V (mph)\ /Accel (G)	Resultant Head Accel. (G)	HIC	HIC36	HIC15	Chest Accel 3 ms (g)	Neck Tension (N)	Upper Neck Compression (N)	Upper Neck Shear (N)	Upper Neck Flexion (N-M)	Upper Neck Extension (N-M)	NTF	NTE	NCF	NCE
1-1	CSS A	41.37/45.60	111.74	619.6	667.1	339.1	64.1	1492	1070	636/-219	10	13	.39	1.74	1.1	.59
1-2	CSS A	41.49/45.71	77.84	961.5	967.9	627.9	66.4	2376	409	686/-267	12	14	.81	2.44	.22	.29
1-3	CSS B	40.77/45.31	98.8	1359.6	1359.6	930.7	70.1	1669	291	996/-66	6	26	.26	2.73	.27	.32
1-4	CSS B	42.47/45.11	76.97	830.2	830.2	689.3	72	1976	680	680/-130	(1)	(1)	(1)	(1)	(1)	(1)
1-5	CSS C	41.84/45	87.51	975.7	975.7	671.7	72	1620	634	642/-137	6	13	.23	1.89	.16	.52
1-6	CSS B	41.95/45.34	70.02	884.6	499	362.8	62.1	1677	496	449/-280	16	12	.63	1.69	.46	.42
2-1	CSS A	41.27/45.4	169.83	2091	2091	1659.4	67.5	2107	369	776/-149	4	19	1.37	2.42	.12	.31
2-2	CSS B	42.07/45.74	94.67	1165.7	1165.7	970.5	71.8	2369	301	1120/-160	6	26	.24	3.06	.09	.49
2-3	CSS C	41.73/45.16	88.48	1029.1	1029.1	786.1	76.2	962	169	294/-249	16	9	.37	1.16	.36	.13

(1) Instrumentation failure resulted in data not being recorded