

A Computational Study of Rear-Facing and Forward-Facing Child Restraints

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ABSTRACT

A recent study of U.S. crash data has shown that children 0-23 months of age in forward-facing child restraint systems (FFCRS) are 76% more likely to be seriously injured in comparison to children in rear-facing child restraint systems (RFCRS). Motivated by the epidemiological data, seven sled tests of dummies in child seats were performed at the University of Virginia using a crash pulse similar to FMVSS 213 test conditions. The tests showed an advantage for RFCRS; however, real-world crashes include a great deal of variability among factors that may affect the relative performance of FFCRS and RFCRS. Therefore, this research developed MADYMO computational models of these tests and varied several real-world parameters. These models used ellipsoid models of Q-series child dummies and facet surface models of American- and Swedish- style convertible child restraints (CRS). The dummy-seat models in FFCRS and RFCRS orientations have been validated against sled test data, and then used to simulate several real-world conditions.

These simulations show that the advantage of RFCRS was maintained under conditions of oblique collisions, pre-impact braking, and loose internal belts, but not for an out-of-position case with a gap between the child's back and child restraint. In general, this research indicates that children can benefit from being seated in rear facing restraints past the age of one, and that larger child restraints should be made available in the US to accommodate these larger children. The result also indicates that further improvements in RFCRS should address the out-of-position situation to realize further reductions in injury.

INTRODUCTION

CHILD RESTRAINT HISTORY AND STATISTICS

Over the last 30 years, the rate of deaths from motor vehicle crashes for children 1-3 years old has dropped by 50%, largely due to the introduction and increased

use of child restraint systems (CRS), as well improvements in CRS design and usage recommendations. From 1975 to 2000, NHTSA estimates that 4,816 lives have been saved as a result of CRS use, including child safety seats or adult belts (*US DOT HS 810 698*). Despite significant advances in child safety systems, motor vehicle crashes remain the largest single cause of death for children 1-4 years old in the United States (*Hoyert et al 2006*).

The choice of forward-facing (FF) or rear-facing (RF) is one of the most important considerations in CRS design and selection, as they restrain the child through fundamentally different mechanisms. In frontal crashes, the most common crash mode (*DOT HS 809 919*), FFCRS decelerate the child through contact with the belt system. This ideally loads bone structures of the child such as the pelvis, ribs, sternum and clavicle, but can result in severe neck loads, large accelerations and significant excursions for the unrestrained head. The majority (64%) of significant injuries to children in crashes are to the head or brain (*Partners for Child Passenger Safety, 2000*), either localized injuries from direct impact or diffuse axonal injuries caused by large angular accelerations of the head that can occur with or without direct impact (*de Jager et al. 2005*).

In contrast, RFCRS decelerate the child through contact with the internal surface of the car seat, spreading the loads over the child's back and reducing loads on the neck and linear and angular accelerations on the head. Large rotations of RFCRS during a crash should be prevented because neck loads can increase greatly if the neck and spine of the child rotate into alignment with the deceleration vector of the vehicle (*van Rooij 2003*). RFCRS should not be installed in the front seats of vehicles because they can be struck by rapidly deploying airbags (*Weber 93*). RFCRS can also benefit from being in the rear seats when a front seat is very close to the CRS. This proximity helps couple the CRS to the vehicle and reduces the angle of rotation (*van Rooij et al. 2003*).

Current American Academy of Pediatrics policy recommends that rear-facing seats should be used at least until the child is 1 year old and weighs 20 lb (9.1 kg), and that children should remain rear-facing as long as possible provided they are below the maximum weight for the child seat, and the top of the head is below the top of the seat back (AAP 2002). However, this recommendation is often misinterpreted to mean that children should be moved to forward-facing seats as soon as they reach the 1 year and 20 lb (9.1 kg) criteria. While some convertible RFCRS in the U.S. have weight limits up to a maximum of 30 or 35 lb (14 or 16 kg), very few children are kept rear-facing after 1 year, and it has been reported that 30% of children are turned forward facing even before 1 year of age (*Child Passenger Safety* 2000)..

In contrast, RFCRS in Sweden are manufactured to accommodate children up to the age of 4, followed by a transition directly to booster seats. A recent Volvo crash study of the Swedish accident data has shown an effectiveness of 90% for children in rear-facing child seats relative to unrestrained children (*Jakobsson et al.* 2005). No direct comparison could be made between RFCRS and FFCRS because children are transitioned directly from RFCRS to booster seats; however, the study found that injury rates of children 2-4 years old are approximately 85% higher for booster seats than RFCRS.

A recent study of U.S. crash data has shown that children 0-23 months of age restrained by FFCRS are 76% more likely to be seriously injured compared to children restrained by RFCRS (*Henary et al.* 2007). When looking at all crash types (frontal, side, rear) and the 1-year old group separately, this study showed that children in FFCRS are 5 times more likely than those in RFCRS to be seriously injured. One unexpected finding was that when considering side crashes and children of all ages in the study (0-23 months), injury was 5 times more likely to occur in a FFCRS than a RFCRS. The authors explained that even in side crashes, there is a frontal component that can, in a FFCRS, cause the child's head to move forward and out of the protection of the side wings, but in a RFCRS cause the child's head to remain within the side wings.

Motivated by the real-world injury trends of this epidemiological study, child seat sled tests were performed at UVA using Q1.5 and Q3 dummies (*Sherwood and Crandall* 2007). These sled tests were performed under standardized US test conditions and provided a more detailed study of kinematics, forces and accelerations in a controlled comparison between RFCRS and FFCRS. While the test results showed that RFCRS had a decided advantage for head and neck injury, real-world crashes include a great deal of variability in key factors that may affect the relative performance of FFCRS and RFCRS.

In an effort to examine some of these factors and bridge the gap between the accident data and sled tests, this

paper includes the development and validation of MADYMO computational models based on the experimental tests, and examines the relative performance of FFCRS and RFCRS with the application of some real-world conditions. Conditions studied included oblique impacts, pre-impact braking, internal harness slack, and improperly positioned children. By using models to supplement the sled tests, a large number of scenarios were systematically evaluated.

HYPOTHESIS

RFCRS are more effective than FFCRS in protecting the head and neck of children up to the age of 3 in pure frontal crashes similar to FMVSS 213 as well as in oblique crashes, in crashes with pre-impact braking, when slack is present in the internal harness, or when the child is improperly positioned.

PROJECT OVERVIEW

There were two major phases to this research: model development and validation, followed by a parametric sensitivity study. During the first phase, models were built from the known geometries and initial conditions of sled tests. The model responses were compared to those of the sled tests and, when necessary, model characteristics were tuned until they matched sufficiently well to compare the desired injury measures. In the subsequent sensitivity study, these validated baseline models were used to examine a wider variety of scenarios than were feasible with physical testing. Conditions examined included four oblique collision conditions, four levels of pre-impact braking, two levels of internal harness slack, four combinations of slack and pre-impact braking, and an out-of-position dummy. The effects of these parameters on injury measures were the primary goal of this computational research, with a focus on examining the effects of these parameters on the relative likelihood of injury to the head and neck in FFCRS and RFCRS.

METHODS

SLED TEST INFORMATION

Test Matrix, Overall Information

Validation data for this study's MADYMO computational models comes from seven sled tests performed as part of a larger experimental study at the University of Virginia Center for Applied Biomechanics (*Sherwood and Crandall* 2007). These seven tests included two child seats in FF and RF orientations, each tested with two child dummies, a Q1.5 and Q3. The two CRS tested were a U.S. convertible seat (Evenflo Triumph, model number 3591208 P1), and a European convertible seat (Fair Bimbofix G 0/1 Isofix, ECE approval number 04443513). The Q3 was not tested in a RF Evenflo because the dummy was too large to be positioned properly. During this test series, the Evenflo was tested twice in one frontal condition to judge

repeatability: the Q1.5 in a RF Bimbofix and the Q3 in the FF Evenflo.

Evenflo Triumph

The Evenflo Triumph is a U.S.-style convertible CRS, designed for children 5-30 lb (2.3-13.6 kg) in the RF orientation and children 20-40 lb (9.1-18.1 kg) in the FF orientation. This CRS was attached to the vehicle buck using the LATCH system typical of CRS in the US. The Evenflo was placed on the vehicle seat and secured with two belts (Figure 1). A flexible lower belt (LATCH belt) attaches the Evenflo to the rigid LATCH (Lower Anchors and Tethers for Children) attachments of the vehicle seat, and a flexible upper tether was attached to the top of the CRS. For the FF Evenflo, this upper tether was routed over the top of the vehicle seat to the appropriate anchorage at the rear of the seat base. The upper tether for the RF Evenflo was attached to the floor of the vehicle to aid initial positioning and to prevent large rebounds, although this method of attachment was not specified in the Evenflo user's manual (Sherwood and Crandall 2007). This upper tether in the RF has been shown to have little effect on kinematics and injury measures in frontal collisions, as it loses tension when the buck starts to decelerate (Sherwood *et al.* 2005).

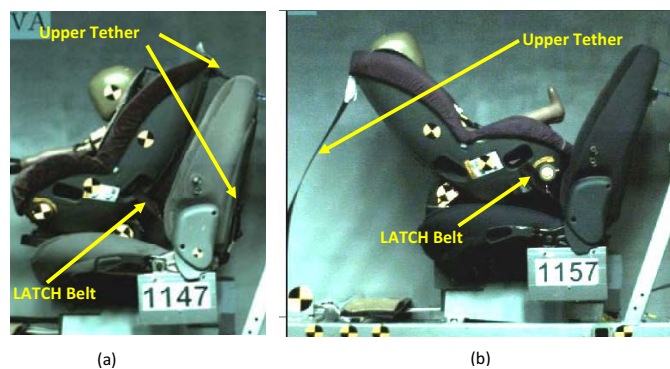


Figure 1: Belts Connecting Evenflo CRS to Vehicle Seat (a) Forward Facing (b) Rear Facing. Both are pictured during the deceleration pulse to show how the belts were loaded.

Fair Bimbofix

The Fair Bimbofix is a European-style convertible CRS, designed for children 0-4 years of age (up to 40 lb (18.1 kg)) in the RF orientation and children 9 months to 4 years of age (20 to 40 lb, 9.07 to 18.1 kg) in the FF orientation. In contrast to the Evenflo, the Bimbofix attached to the vehicle seat's LATCH attachments with a rigid leg extending to the floor (Figure 2). Once fastened to the LATCH attachments, the seat was free to rotate around them so that the leg rested firmly on the floor. The geometry of the vehicle seat, floor, and leg was such that the leg did not interact with the vehicle seat cushion. A significant amount of the CRS motion during these sled tests was due to deformations within the Bimbofix itself. The inner shell of the Bimbofix was

made of a reinforced foam material, which deformed structurally under head contact in the RF orientation.

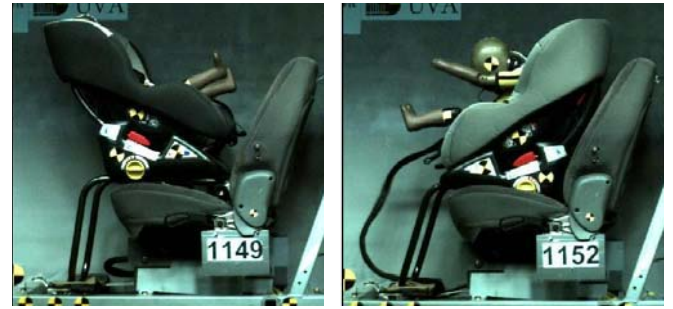


Figure 2: Bimbofix CRS in RF and FF Orientations

Vehicle Seat and Buck

All CRS were tested on the same type of vehicle seat, a second row captain's chair from a popular minivan with anchorages for the LATCH system of the Evenflo and ISOFIX system of the Bimbofix. The frame of this seat was supported to create a durable, consistent test system (Sherwood and Crandall 2007). To support the leg of the Bimbofix, a plate of $\frac{1}{4}$ in (6.35 mm) thick steel with a layer of rubber and carpet was used to simulate an actual vehicle floor. In each sled test, the buck had an initial velocity of 48 km/h and was decelerated with a pulse similar to that specified by FMVSS 213.

Q1.5 and Q3 Dummies

The most recent hardware revisions (2004) of the Q1.5 and Q3 dummies were used in this series of sled tests. The Q1.5 dummy was instrumented with triaxial accelerometer arrays at the head CG (center of gravity), chest CG and pelvis CG; load cells at the upper neck, and lumbar spine; and chest displacement sensors. The Q3 was similarly instrumented with the same accelerometers, an additional load cell at the lower neck, but without a chest deflection sensor.

MODEL DEVELOPMENT

Evenflo

The surface of the Evenflo and the belt attachment locations were digitized using a three-dimensional coordinate measuring device (FARO arm, model G1002, FARO Technologies Incorporated, Lake Mary, FL). From these coordinates, a mesh was formed in Altair Hypermesh® (Figure 3) and exported into MADYMO format. Assuming symmetry in the model, only one half of each CRS was digitized and then reflected in Hypermesh to obtain the full mesh. The resulting facet surface was non-deformable. The height of the Evenflo base was increased to avoid problems when the CRS penetrates into the vehicle seat more than the height of the base (Figure 3 (c)).

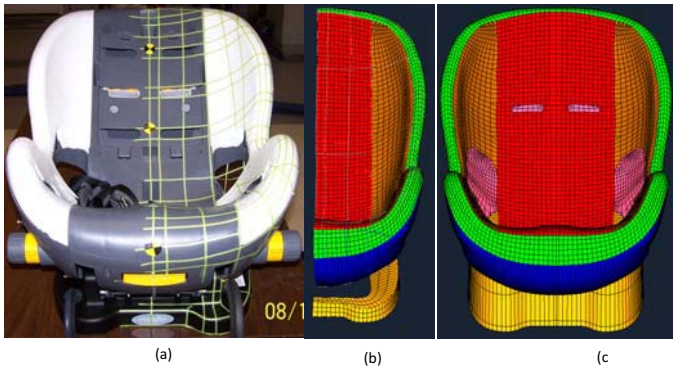


Figure 3: (a) Evenflo CRS with tape mesh applied for digitization (b) & (c) half and full meshes of the CRS in Hyperview. Comparing (b) and (c) shows the extra depth added to the CRS base.

The LATCH belt was modeled as a single 5-segment multibody belt (Figure 4). The ends of the belt were located at small tensioning masses that removed slack from the belt during the pre-simulation time. From this mass, the LATCH belt was run through a LATCH attachment, through the locations of the appropriate openings on the CRS, and to the opposite LATCH attachment and tensioning mass.

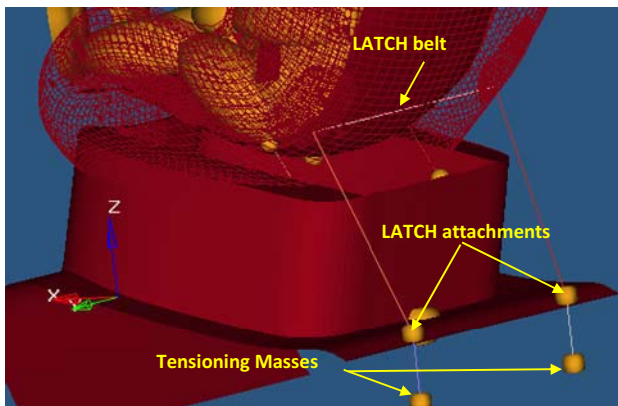


Figure 4: Example of Modeled LATCH attachment for the Evenflo CRS (FF, Q1.5)

The upper tether of the FF Evenflo was implemented as a belt between the anchoring location at the top of the CRS and an approximate location the top of the vehicle seat (Figure 5). A baseline stiffness characteristic for the LATCH belt and upper tether was obtained from a belt manufacturer and manually tuned by comparison with model kinematics. Tuning was needed to account for compliance in the belt-CRS interface and in the extra belt material routed through the CRS. This same characteristic was used for all Evenflo models.

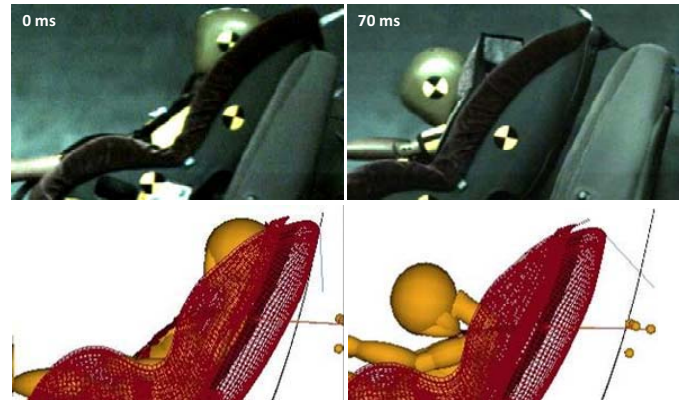


Figure 5: Model implementation of top tether (Evenflo; FF; Q1.5)

For the RF Evenflo, the upper tether was included in the model as a multibody belt running from the top of the Evenflo to the anchor point on the floor of the buck obtained through 3-D digitization; however, as in the test, this upper tether had little effect on the crash event until the Evenflo rebounds, well after the significant forces and accelerations.

The Evenflo model itself was attached to the inertial reference frame by an unconstrained free joint, allowing motion in all degrees of freedom under the constraints of the latch belt, upper tether, and contact with the vehicle seat. This attachment to the vehicle seat was a key difference between the Evenflo and Bimbofix.

Contact characteristics between the dummy head and Evenflo padding were obtained from a basic stress-strain load test and tuned to match the sled tests. While the hardware Q-dummies were not available for testing during model development, the Evenflo padding conditions were comparable to those measured in a 2005 study using a Universal Testing Machine with a CRABI 12 month dummy headform (Abdelilah *et al.* 2005). The resulting force-penetration characteristic was similar in shape to that used in the Evenflo model (Figure 6). The model characteristic needed to best match the tests is more compliant; possible reasons are that Abdelilah's tests used a different dummy head, did not include the thin outer layer of padding in this Evenflo CRS, and had a non-deformable steel surface underneath the foam, whereas the inner plastic shell of the Evenflo was slightly compliant.

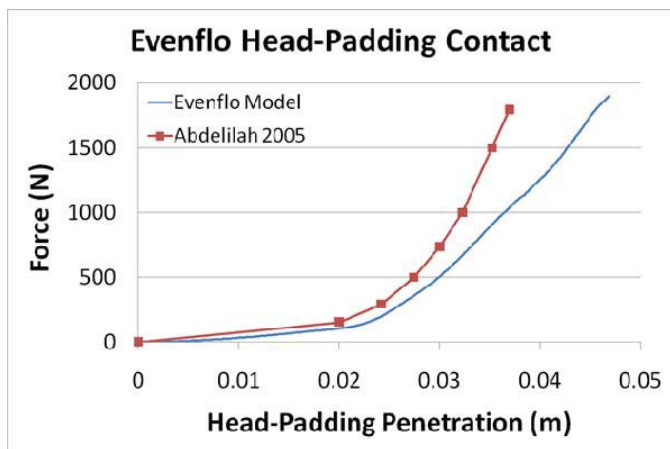


Figure 6: Head-Contact used for Evenflo model.

Bimbifix

Bimbifix geometry, except for the inner foam shell, was obtained from manufacturer CAD drawings (Figure 7). Geometry of the inner foam shell was obtained with the FARO arm, as described previously for the Evenflo. From these meshes, a non-deformable surface was created for use in MADYMO.

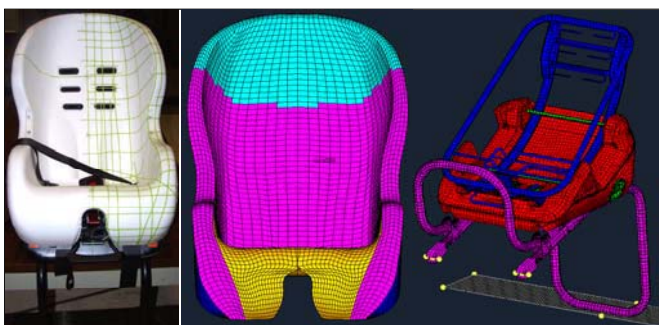


Figure 7: Bimbifix CRS with tape mesh for digitization, along with full mesh of shell and the full geometry of the underlying CRS structures

A revolute joint was used to connect the CRS to the inertial space of the vehicle seat, allowing the CRS to rotate freely about the line of the LATCH attachments (Figure 8). This motion was constrained by contact between the leg and the floor of the buck, resulting in a more rigid connection to the vehicle than the previously described Evenflo system. While overall CRS motion was small, the internal structures of the Bimbifix allowed significant motions and deformations within the CRS itself. To capture this internal CRS motion, an additional revolute joint was placed at one of the connection points between the leg and the CRS. This second rotational joint was restrained with a stiffness characteristic to give the appropriate amount of internal CRS motion.

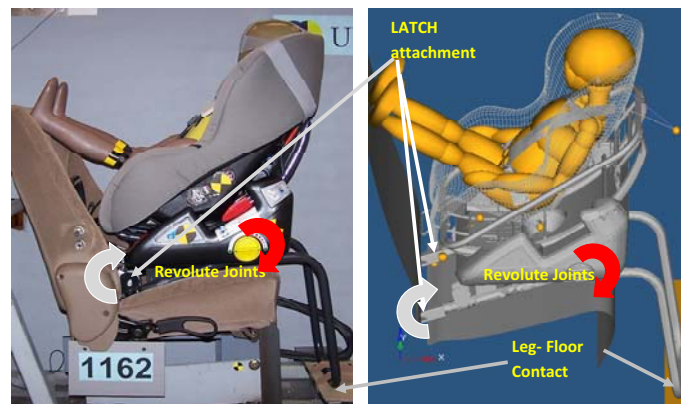


Figure 8: Example of Bimbifix-Vehicle Seat Connection (RF, Q3)

The head-contact characteristics for the RF Bimbifix were also obtained through iteration based on head accelerations. The Bimbifix used different padding than the Evenflo, and was not similar to any of Abdelilah's static tests. The inner shell of the Bimbifix was made of a reinforced foam material and a significant portion of the head-CRS compliance was due to structural deformation rather than compression of the relatively thin padding material covering the shell. Different head-CRS contact definitions were used for the Q1.5 and Q3 dummies because their heads contacted different locations on the shell (Figure 9); the Q1.5 contacted lower, and left a small indentation in the foam shell, while the Q1.5 contacted higher and actually cracked the shell. Accordingly, head contact for the Q1.5 was slightly stiffer than for the Q3, and the Q3 characteristic included a region of lower stiffness representing the cracking of the shell. Both Bimbifix characteristics were steeper than the Evenflo (Figure 10) because the padding covering the shell was much thinner on the Bimbifix. The same characteristics were used for the FF orientations as the RF orientation, but the head lost contact with the CRS as soon as the crash pulse was applied.

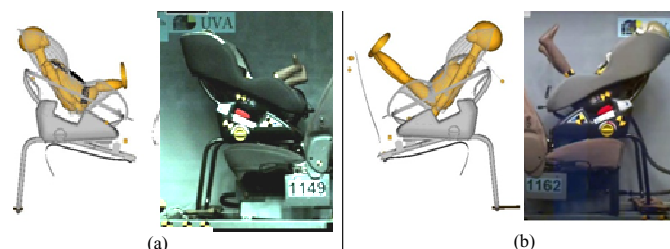


Figure 9: Q1.5 (a) and Q3 (b) in RF Bimbifix. The head of the Q1.5 was lower and does not bend the shell. The heavier Q3 head contacted near the top of CRS and bends the shell.

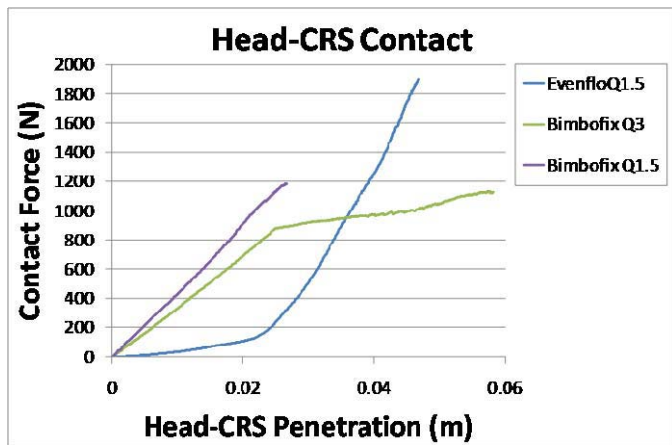


Figure 10: Head-CRS contact characteristics for Bimbofix and Evenflo models. Penetration was defined between the head and the location of the non-deformable facet surface of the CRS. Contact force is the reaction force resulting from a given penetration.

Child Harness Systems

Both Evenflo and Bimbofix used a 5-point restraint system for the child harness. The two seats differed in that the Evenflo included a chest clip, and that the Evenflo had a longer crotch strap that positioned the hip belts higher than on the Bimbofix. The belts were modeled using finite element mesh belts anchored to the CRS at the appropriate locations with multibody belts.

The buckle was modeled with three ellipsoids, and one end of each of the 5 FE belts was attached to this buckle. The crotch strap was attached directly with a multi-body belt, while the shoulder belt and lap belt on each side were connected via a slip ring located at the buckle. This type of connection was needed for belts in the model to match those in the physical tests by allowing material to slide between the shoulder and lap sections. Belts were implemented similarly for the Bimbofix, except the crotch strap was modeled as a multi-body belt because it was too short for a FE belt to be practical or necessary.

Vehicle Seat and Buck

Vehicle seat and floor geometry were recorded with FARO digitization. A facet surface mesh of the vehicle seat and a multibody plane were shaped from these FARO points. The coordinate system used for the models was selected to match the tests. X was positive in the direction of initial vehicle motion, Y was positive toward the left side of the vehicle when facing in the direction of travel, and Z was positive up (Figure 11).

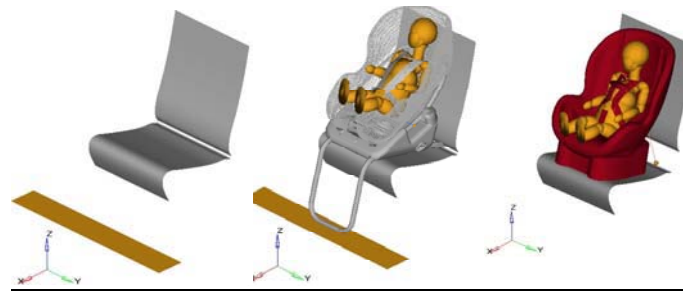


Figure 11: Vehicle Seat and Floor Model: Coordinate system and views with no CRS, Bimbofix, and Evenflo.

Both the vehicle seat and the floor were non-deformable meshes with contact defined by force-penetration stiffness curves. The vehicle seat back was given a stiff contact characteristic and used to properly position the Evenflo CRS. The stiffness characteristic between the Evenflo and vehicle seat was determined by performing a static loading test of the Evenflo on the vehicle seat. Starting from this data, the loading and unloading curves were manually tuned to best match kinematics and dummy signals from all three Evenflo sled tests; the same loading and unloading curves were used for all of the Evenflo models (Figure 12). The loading curve needed to match the tests was stiffer than measured experimentally. This is likely because during static testing some load was supported by the seat back, and because initial compression of the vehicle seat in the sled tests was larger than in the models. No contact was defined between the Bimbofix seat and vehicle seat because the leg geometry prevented contact during the sled tests.

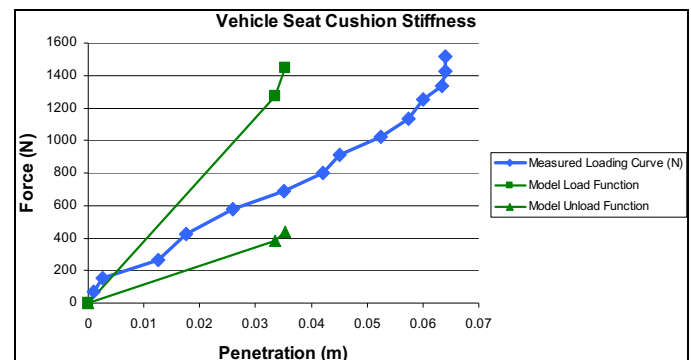


Figure 12: Vehicle Seat Loading Curve as measured experimentally, and loading and unloading curves used for Evenflo model

The floor contact definition was determined through iteration, assuming a linear elastic profile. Models of tests on the driver side of the buck (Q1.5) used lower floor stiffness than simulations of tests on the passenger side (Q3) due to differences in the buck floor. The floor of the buck interfacing with the Bimbofix leg consists of a ¼ in (6.35 mm) thick piece of steel covered with a layer of carpet and rubber padding to represent an actual vehicle floor. This steel plate was fastened to the buck at three points, and the span of the driver's side floor was longer than the passenger side floor because of buck asymmetry. Because this plate bent elastically

during the test, the driver side was more compliant than the passenger side.

Each sled test had an initial velocity in the positive X-direction, and the buck was brought to a stop by an acceleration pulse in the negative X-direction. Instead of prescribing the acceleration pulse to a moving buck in the negative X-direction, the models apply the pulse as an acceleration field to the dummy and CRS in the opposite (positive) X-direction. This was done to disregard the initial velocity of the buck, dummy, and child restraints; the vehicle seat model is fixed in the inertial reference space. To validate each baseline model, the acceleration from each respective sled test was used and the model kinematics and dummy signals were compared between test and model.

Q1.5 and Q3 Dummy Models

This project uses the research version of the Q1.5 and Q3 dummy models included with MADYMO version 6.3.2. These multi-body models were developed and validated by TNO automotive through component testing (*van Rooij et al. 2005*).

BASELINE MODEL VALIDATION

Kinematics Comparison

Matching the kinematics of the model to the test was an important tool in the development and validation process. Model and test kinematics were examined side by side and used to determine needed changes to the models. The main quantifiable kinematic assessment for these sled tests was X-excursion (Figure 13). For FFCRS, X-excursion was defined as the distance along the X-axis from the LATCH attachments to the forward-most point of the head. For RFCRS, X-excursion was defined as the forward-most point of the CRS. It was important to measure this point rather than some other because the leading edge of the CRS is the point most likely to impact another vehicle structure. Tracking a target on the CRS was not necessary because the entire excursion time history was not needed, only the maximum. Excursions were measured in the sled tests using the Phantom Camera Control Software, Version 8.1.607. Altair Hyperview was used to manually measure excursions in the baseline models. The point on the dummy or CRS measured for maximum excursion was not necessarily the same point between the sled test and model; however, the kinematics were similar enough between test and model that the point measured was near the top of the head for FFCRS and the uppermost edge of the RFCRS.



Figure 13: X-Excursions as defined for the model validation. FFCRS excursion was measured from the LATCH bars to the forward-most point of the head. RFCRS excursion was measured from the LATCH bars to the forward-most point of the CRS

Comparison of Dummy Signal Time Histories

Acceleration and load time histories were compared between the models and the tests. The Q3 and Q1.5 dummy models measure accelerations at the head CG, chest CG, and pelvis CG, with the positive x-axis pointing toward the anterior of the dummy and the positive z-axis pointing toward the lower extremities (Figure 14). Time history comparisons are included in the appendix.



Figure 14: Locations and orientations of accelerometers on forward facing Q1.5 Dummy Model. The Q3 has accelerometers in similar locations.

Relative Magnitudes of Injury Measures

Peak resultant head acceleration (head LAC), HIC15 (HIC), peak upper neck tension (neck tension), peak head angular acceleration (head AAC), X-excursion, and Y-excursion were used to draw conclusions from the larger set of simulations. To ensure that the models will properly predict these injury measures, it was important to compare the relative magnitudes of injury measures between RF and FF orientations of the same dummy-CRS combination. Angular accelerations were not available from the sled tests, so no comparison was made with the simulations.

PARAMETER SENSITIVITY STUDY

The validated models were used to determine whether the apparent advantage of RFCRS evident under standard test conditions is increased, maintained, or

While the model validation stage defined excursion as distance to the forward-most point of the head or CRS, this was not practical to measure in each of the simulations of the sensitivity study since point to be measured could not be defined a priori. Instead, for the parameter sensitivity study, excursions were defined as the maximum distance between the head CG and the center of the LATCH attachments (Figure 15). Excursions in both FFCRS and RFCRS were measured to the head CG. Z-excursions were not considered because motion in the Z-direction is not likely to result in head impact.

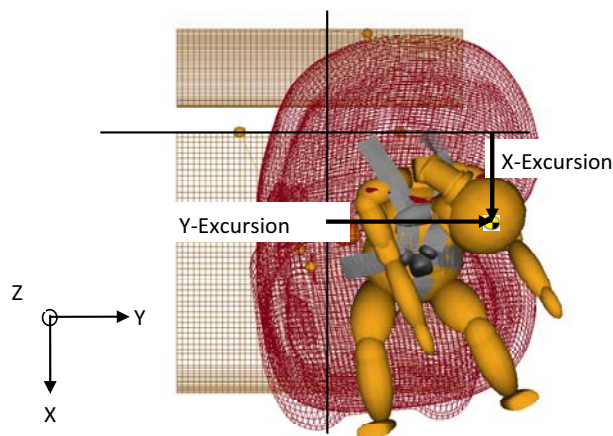


Figure 15: Excursion as defined in the parameter sensitivity study: distance from the center of the LATCH attachments to the head center of gravity. This is a top view of the Q1.5 in a forward facing Evenflo undergoing an oblique crash at 45 degrees. Location of the head CG is shown approximately in this figure.

it was decided that it was more important to study more levels of each condition rather than more combinations.

Table 1: Combinations of Parameters Modeled and Injury Measures Considered: 16 simulations were run for each of the 7 Dummy-CRS combinations, yielding 112 simulations.

	Forward Facing				Rear Facing		
	Evenflo		Bimbofix		Evenflo	Bimbofix	
	Q.15	Q3	Q1.5	Q3	Q1.5	Q1.5	Q3
Baseline	Baseline Simulations validated against sled tests						
Oblique	Impact Pulse applied at 15, 30, 45, and 60 degrees						
Braking	Hard Braking (0.7g) applied for 125, 250, 375, and 500 ms prior to deceleration pulse						
Slack	Two levels of slack in the internal harness: 2.5 and 5 cm						
Slack & Braking	5 cm of slack along with 4 braking durations: 125, 250, 375, 500 ms						
Out-of-position	One out-of-position scenario: 2.5 cm spacer between dummy and CRS						
Injury Measures	Peak Head Linear Acc	HIC 15	Peak Head Angular Acc		X head excursion	Y head excursion	Peak Upper Neck Tension

Oblique Collisions

Oblique collisions are those that occur at an angle of up to 60 degrees from purely frontal, and current NHTSA frontal crashworthiness tests specify crash tests at 30 degrees (*DOT 810 698*). This angle can affect injury measures by changing the child-to-CRS, and the CRS-to-vehicle interaction.

These MADYMO simulations implemented oblique collisions by applying the acceleration pulse measured from sled test 1147 at an angle from the X-axis (Figure 16). Angles of 0, 15, 30, 45, and 60 degrees from the X-axis were examined in this study. While oblique conditions will generate different vehicle crash pulses, the pulse from 1147 was retained to facilitate comparisons across different impact angles.

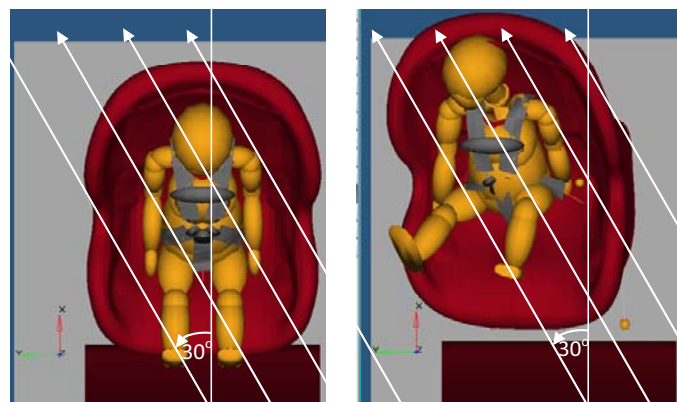


Figure 16: Acceleration pulse applied at 30 degrees from the X-axis (Evenflo RF, Q1.5)

Pre-Impact Braking

Pre-impact braking occurs in a large percentage of crashes, and was found to be present in over two-thirds

of accidents involving child occupants (Czernakowski and Otte 1993). Pre-impact braking can affect injury measures by bringing the CRS and the child into contact with the restraint system early and by changing the child's initial position at the onset of the crash. A 1993 sled test series found that pre-impact braking can reduce HIC, maximum head acceleration and maximum neck loads for dummies in FFCRS (Czernakowski and Otte 1993). Conditions of those sled tests were somewhat different than the tests modeled for this research. This research used a more biofidelic dummy (Q3 instead of P3), higher pre-impact speed (48 km/h instead of 37 km/h), and a higher rate of braking (6.86 m/s² instead of 4 m/s²). Under these new conditions, it was important to examine whether pre-impact braking could reduce injury measures of dummies in FFCRS enough to give them an advantage over RFCRS.

These simulations implemented pre-impact braking by applying an acceleration of 0.7 g in the positive X-direction for a period of time before the impact pulse begins (500 ms is shown in Figure 17). Pre-impact braking durations of 0, 125, 250, 375, and 500 ms were examined.

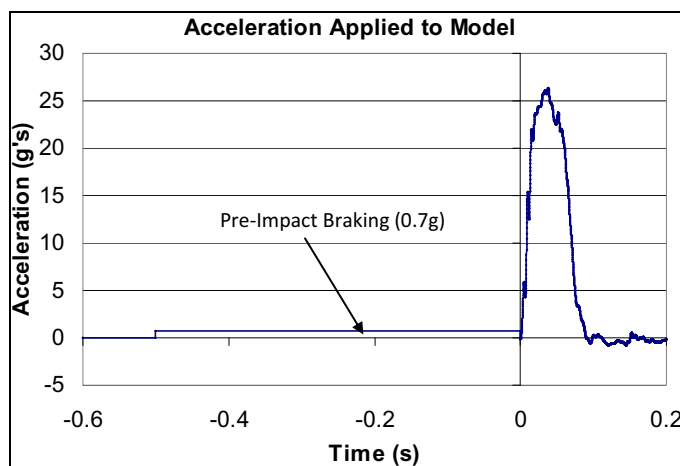


Figure 17: Diagram of braking and impact pulse applied to the dummy and CRS. Pre-impact braking was applied for times of 0, 125, 250, 375, or 500ms as shown here.

Internal Harness Slack

Proper restraint usage is a major factor in CRS performance. Critical misuses include improper CRS selection for child size, placement of the CRS in close proximity to airbags, improper installation, and loose child harness straps. A 2004 NHTSA study found that loose vehicle seat-CRS attachment and loose child harnesses are the most common forms of child seat misuse, with 51.9% of rear-facing convertible seats, and 50.9% of forward-facing convertible seats exhibiting loose child harness straps (DOT 809671). A loose internal harness theoretically causes higher forces and accelerations on the child's head, neck and chest as a result of the child being poorly coupled to the vehicle.

This research examined the effect of loose child harnesses on injury measures and the relative magnitude of this effect between RFCRS and FFCRS. Slack levels of 0, 2.5 and 5 cm on the 5-point child harness were implemented. To evenly distribute this slack, half of the desired level was added to each of the shoulder and hip internal harness anchor points. In addition, simulations were run with combinations of 5 cm of internal harness slack and all four pre-impact braking durations.

Out-of-Position Child

The baseline sled tests and simulations placed the dummy in a standard position with the head and back in contact with the CRS. A 2005 photographic study found that children adopt a wide variety of poses, including resting their head on the side CRS wing, holding their feet in their hands, slouching to rest their legs on the front seat, completely escaping the shoulder belts, and leaning forward in their restraints (van Rooij et al. 2005). Since neither the exact position nor the relative frequency of these positions has been quantified, this research considers a nominally out-of-position child that has leaned forward as if to get a better view (Figure 18). An ellipsoid was used to create a gap of 2.5 cm between the dummy spine and the CRS, which added a small amount of slack to the harness system, roughly 1 cm. Contact between spacer ellipsoid and dummy was removed at the onset of the crash pulse.

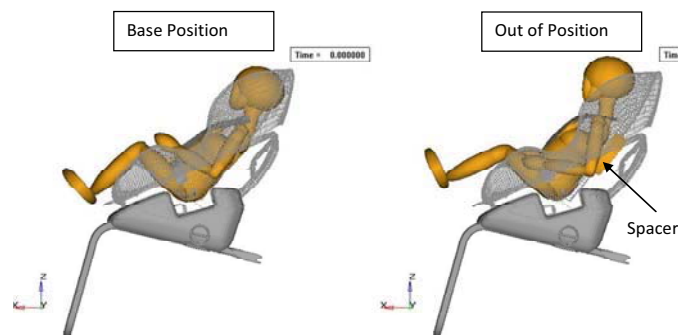


Figure 18: Q3 Dummy Model in the FF Bimbofix Seat. Out-of-position dummy is pictured on the right, with an ellipsoid providing 2.5 cm of space between the dummy's back and the CRS.

Implementation of Non-Standard Conditions

The method of varying slack, braking, and angle of impact, is shown in the timeline below (Figure 19). Time zero was defined as the start of the crash pulse. Each simulation started at -700 ms to allow for settling and any pre-impact braking. For 200 ms, the dummy, CRS, and belts were allowed to come to equilibrium under gravity and a small force applied at the anchor points of the belts for proper belt positioning. By -500 ms, the dummy and CRS were completely settled; at this time the belts locked in place and the desired amount of slack was introduced into the internal harness system. Braking was started at a variable time between -500 and 0 ms, and maintained until time zero, the start of the

crash pulse. The pulse lasted approximately 100 ms, and the simulations run through 140 ms, although the majority of relevant events occurred prior to 100 ms.

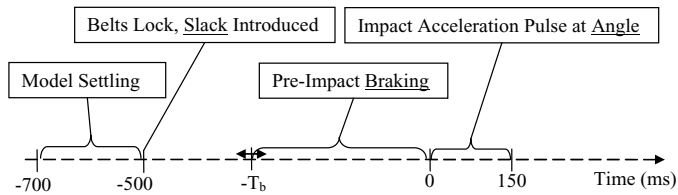


Figure 19: Simulation Timeline

RESULTS

MODEL VALIDATION RESULTS

The sled tests were found to be repeatable based on the duplicated restraint conditions for each of the dummies, with an average difference of 7.1% for HIC15, chest 3ms clip and neck tension (Sherwood *et al.* 2005). By looking at the model animations side by side with the sled test videos and comparing X-excursions, the baseline kinematics agreed well with those of the sled tests although the model heads did not rebound as quickly as the sled tests in the FFCRS.

X-excursions from the baseline models matched well with those from video analysis of the sled tests (Figure 20). Five out of the seven baseline models were within 5% of the sled tests. The maximum difference was for the Q1.5 in the RF Bimbofix, less than 10 cm (13%). Y-excursions were not compared between sled test and model because they were not significant in these frontal impacts and were not measured in the sled tests.

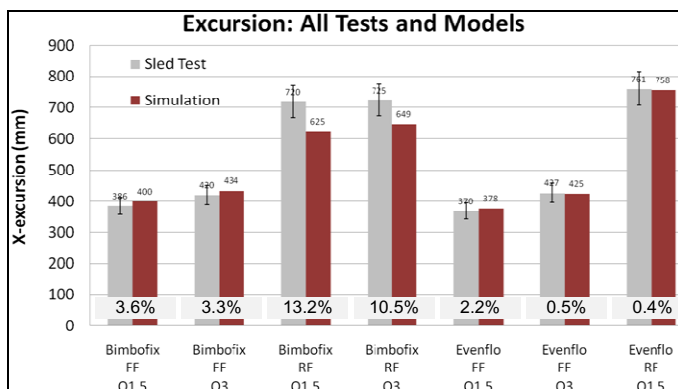


Figure 20: Comparison of Excursions for Sled Tests and Baseline Models. Absolute values of the percent difference between test and model are superimposed.

The Evenflo model results agreed well with the sled test results (Figure 21); the model neck tensions were within 10% of the tests and head LAC were all within 20%. HIC15 was between 20% and 40% lower in the models than the sled tests, but the RF model was lower than the FF, so the trend was consistent with the sled tests.

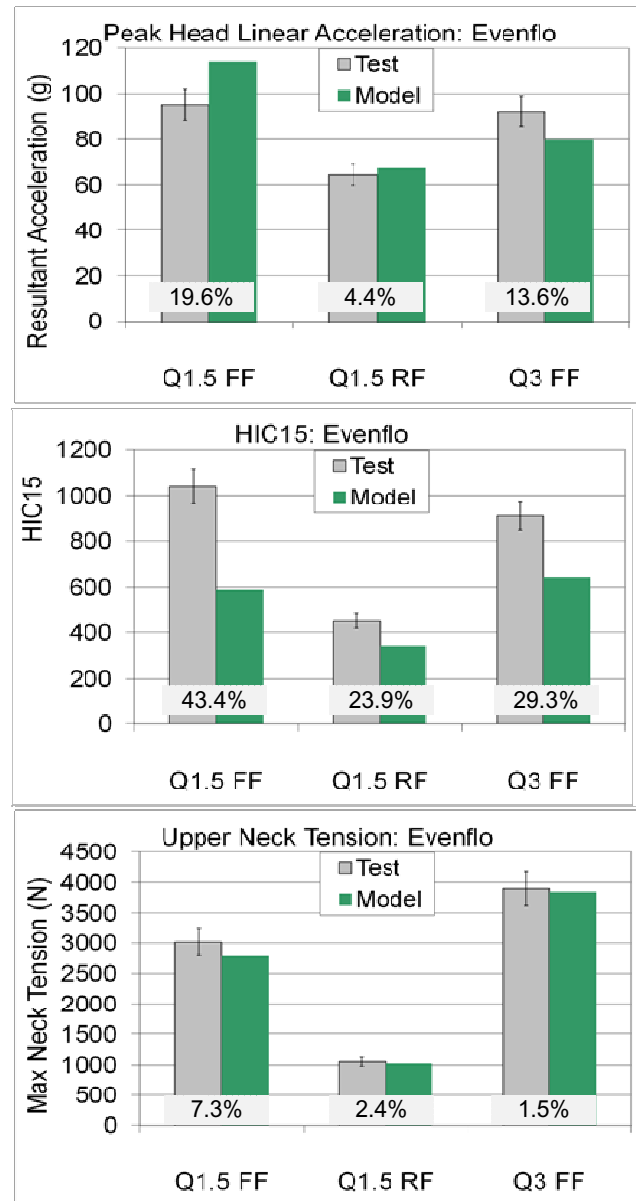


Figure 21: Comparison of Head LAC, HIC, and Neck Tension for Evenflo Sled Tests and Model. Absolute values of the percent difference between test and model are superimposed.

The Bimbofix model results also agree well with the sled test for peak head LAC and neck tension; RF neck tensions were within 10% of the sled test and FF neck tensions were within 20%. Again, the HIC values were significantly lower in the models than the tests, but consistent in relative magnitude (Figure 22).