A Numerical Investigation into HIC and N_{ij} of Children for Forward and Rearward Facing Configurations in a Child Restraint System

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Abstract

This study explores the various differences in potential for injury in 3-year-old children in the case of a frontal collision. A crash analysis between forward and rearward facing children, both restrained in a five-point child restraint, was performed using numerical simulation methods. This comparison was carried out by conducting numerical simulations of these situations using the criteria outlined in FMVSS 213. The injuries that were assessed included neck and head injury, as those types of injuries can be the most devastating and sometimes fatal. In this study, it was determined that when the 3-year-old Hybrid III dummy model is in a rearward facing position, the child sustains less neck loads and head accelerations than the forward facing dummy model. In other words, a 3-year-old child would sustain lower levels of Neck Injury Criteria (N_{ij}) and Head Injury Criteria (HIC). In fact, the difference in the N_{ij} values is quite significant. In North America, the standard for restraining young children states that for a child under the age of 12 months, the child should be restrained in a child seat facing the rear of the vehicle. After 12 months of age, the child can then face forward. This study has opened the forum to debate if this standard should be reconsidered as to save the lives of thousands of children being injured and dying unnecessarily at the hands of vehicle collisions.

Keywords: Child Safety, Vehicle Crash Testing, Head and Neck Injury Potential

Notation:

CRS	Child Restraint System
FE	Finite Element
FEMB	Finite Element Model Builder
FMVSS	Federal Motor Vehicle Safety Standard
FTSS	First Technology Safety Systems
NHTSA	National Highway Traffic Safety Association
QSS	Quality Safety Systems
UMTRI	University of Michigan Transportation Research Institute
$F_{resultant}$	Resultant Force/Load
F_x	Force in the x-direction
F_y	Force in the y-direction
F_z	Force in the z-direction
F_Z	Axial Tensile/Compressive Neck Force
F_{ZC}	Critical Axial Tensile/Compressive Neck Force
HIC	Head Injury Criteria
HIC_{15}	Head Injury Criteria in a 15ms window
HIC_{36}	Head Injury Criteria in a 36 ms window
$M_{resultant}$	Resultant Moment
M_x	Moment in the x-direction
M_y	Moment in the y-direction

M_Y	Bending Flexion/Extension Moment
M_{YC}	Critical Bending Flexion/Extension Moment
M_z	Moment in the z-direction
N_{ij}	Normalized Neck Injury Criteria

Introduction

The study of vehicle child safety has been an important issue in the minds of government, vehicle manufactures, and parents. In a study released by Statistics Canada [1], it was determined that unintentional accidents are the leading cause of death of children in Canada. Furthermore, it was stated that automobile accidents account for the majority of unintentional deaths among children. In the year 2000, there were 32 deaths and 3,148 injuries due to automobile accidents for children between the ages of 0 – 4 in Canada [1]. According to Sachs and Tombrello [2], the National Highway Traffic Safety Administration (NHTSA) estimated that approximately 30,500 children under the age of 5 were injured in motor vehicle crashes in 1997 in the United States, and 604 children under the age of 5 were killed. In a study released by the University of Michigan Transportation Research Institute (UMTRI) [3], Weber determined that young children are at risk for devastating head and neck injuries because of their fragile physiology. In general, neck injury is thought to occur mostly due to rear-end collisions. However, Mousny et al. [4] found that almost one third of all neck injuries occur in frontal impacts in the United States. This finding suggests that there is more to be learned about children and their injuries in frontal impact collisions.

In North America, the recommended standard for the seating of children in child safety seats is for children to remain rearward facing until the age of 12 months. After this age, governing bodies recommend that children may be positioned in a forward facing child safety seat. The injury potential for children over the age of 12 months in a frontal collision has never been tested in a rearward versus forward facing configuration. North American manufactured child safety seats do not allow for proper legroom for older children whereas in other parts of the world, namely Sweden, children sit in rearward facing child seats until the ages of 3 and 4. Skold [5] suggested that the development of the rearward facing child safety seat for toddlers in Sweden has reduced the risk of serious injuries. According to BMW World [6], fewer than 2 children a year die in rear facing child safety seats. Other countries with low child fatality rates include the Netherlands, England, Norway, and Germany. It was previously mentioned that the death rates for children under the age of 5 in the United States and Canada are 604 and 32, respectively. The populations of the United States, Canada, and Sweden are 290 million, 32 million, and 8.9 million, respectively [7-9]. The percentage of child deaths compared to the total population of their respective countries was calculated and then normalized with respect to Sweden's death percentage. In doing this, it was determined that for every child that dies in a vehicle collision in Sweden, 4.45 and 9.27 children die in Canada and the United States, respectively.

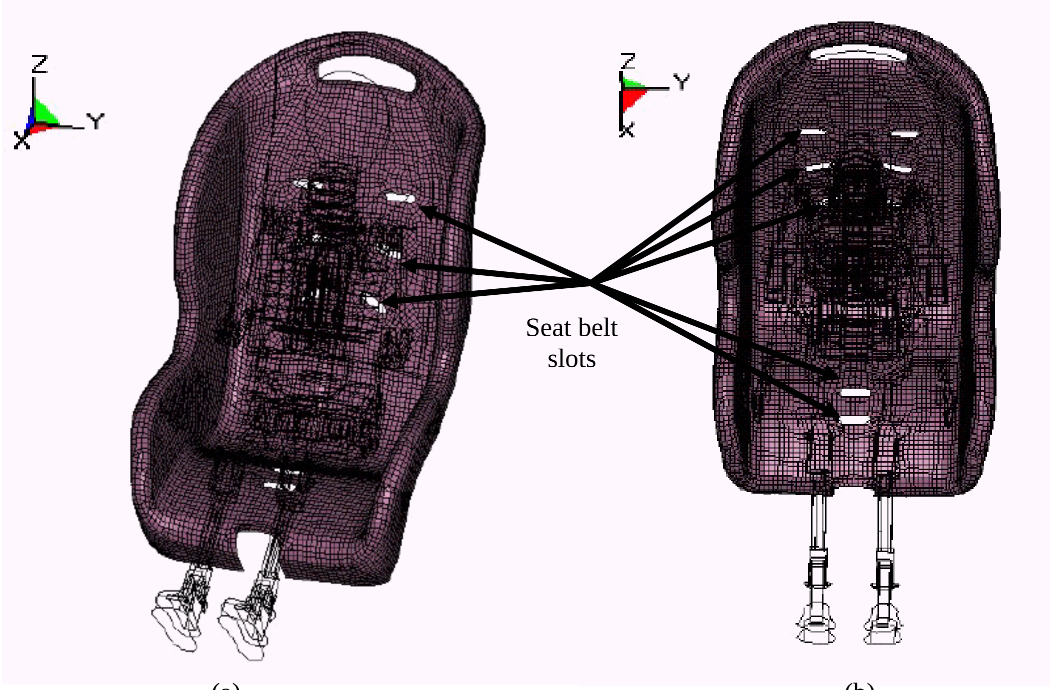
In North America, there have been no accommodations made for children over the age of 12 months to sit comfortably in rearward facing child safety seats. To test the effects of a rearward facing seat on a 3-year-old child is physically impossible due to the size of child allowed to fit rearward facing. Based on this information, it appears that an investigation into the effects of forward facing and rearward facing child seats in a frontal impact situation may be potentially worthwhile.

Preprocessing

In this study, a Hybrid III three-year-old dummy model was employed. Donated by First Technology Safety Systems (FTSS), the dummy model is comprised of 12,172 elements and 11,698 nodes. There are zero-length beam elements and nodes located in specific areas of the body used to provide numerical observations similar to the experimental load cells and accelerometers. The Hybrid III three-year-old dummy model is completely deformable and is complex combination of various material characteristics, joint stiffnesses, masses, and element formulations.

Modeling of all Entities

FEMB was used in the meshing all of the parts of the system. The child safety seat was modeled using a rigid material model. Only the pertinent surfaces were considered when meshing the seat since it was modeled using a rigid material model. The values used for the material properties were of typical polypropylene properties. Figure 1 illustrates the meshed child safety seat.



(a) (b)

Figure 1. Meshed model of child safety seat illustrating (a) isometric and (b) top views.

The seat belt was designed to fit properly around the Hybrid III 3-year-old dummy and to fit through the top slots of the child seat. The belt and the clasps are illustrated in Figure 2. The last two rows of nodes at the end of the belts were constrained to follow the motion of the seat in the x-direction. The material model used was *MAT_FABRIC, Material 34 in LS-DYNA.

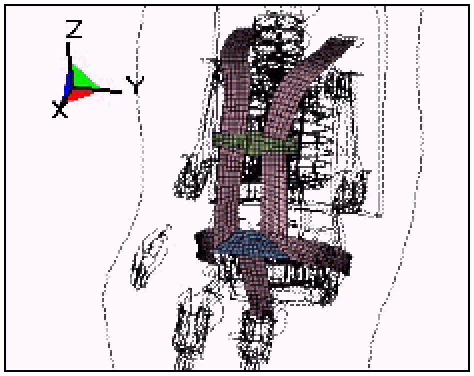


Figure 2. Meshed seat belt and clasps model.

The clasps were modeled as rigid entities and using the same polypropylene mechanical characteristics as used for the child seat model.

The foam insert, illustrated in Figure 3, serves to further protect the child as well as to provide some comfort against the plastic seat. This material was modeled as low-density foam, Material Type 57. Foam with similar material characteristics as the foam insert was subjected to compressive testing to obtain the load-deflection model to input in the LS-DYNA input file. Figure 4 illustrates the entire system with all parts.

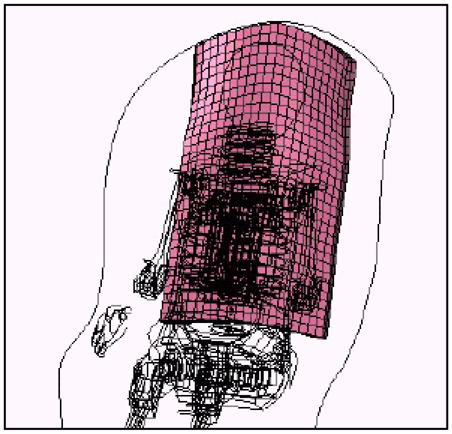


Figure 3. Meshed model of foam insert.

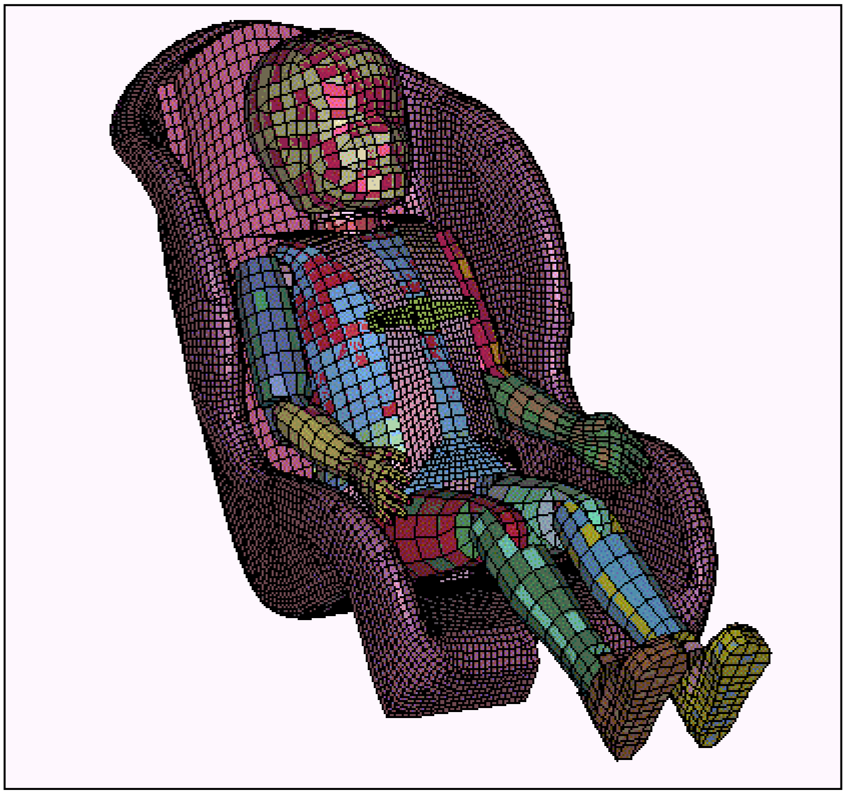


Figure 4. Hybrid III 3-year-old dummy model restrained in a five-point restraint in a forward facing position.

The rearward facing simulation was accomplished by reversing the direction of the acceleration pulse and rotating the child seat back to an angle of 45 degrees to the vertical. Figure 5 illustrates the configurations of both the forward and rearward facing configurations. The forward facing configuration was rotated at an angle of 20 degrees to the vertical. The seat and

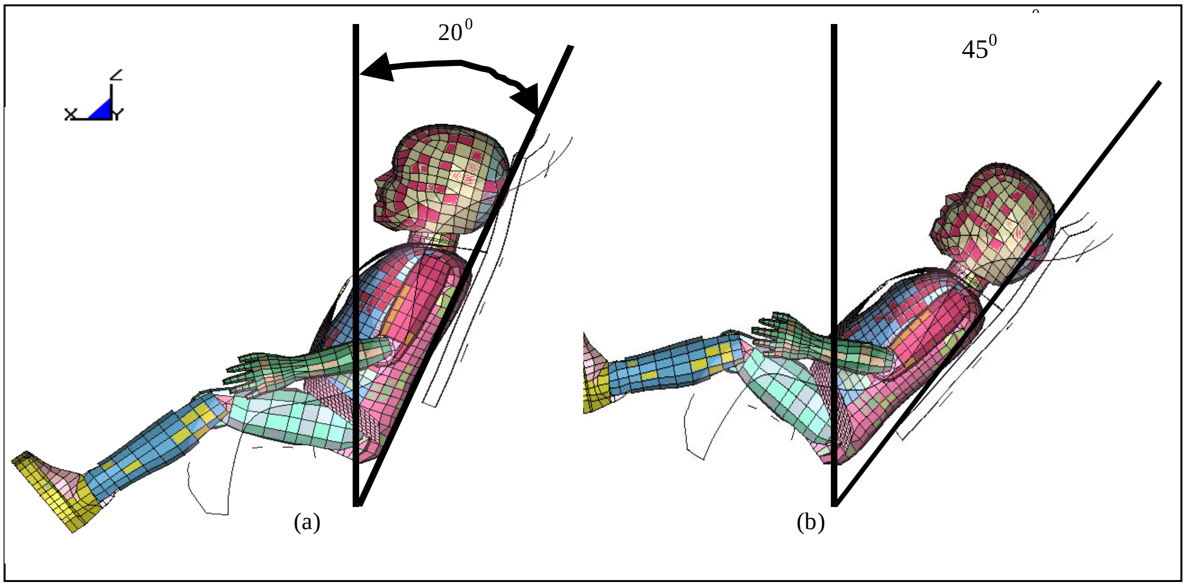


Figure 5. Hybrid III 3-year-old dummy model in (a) forward and (b) rearward configurations.

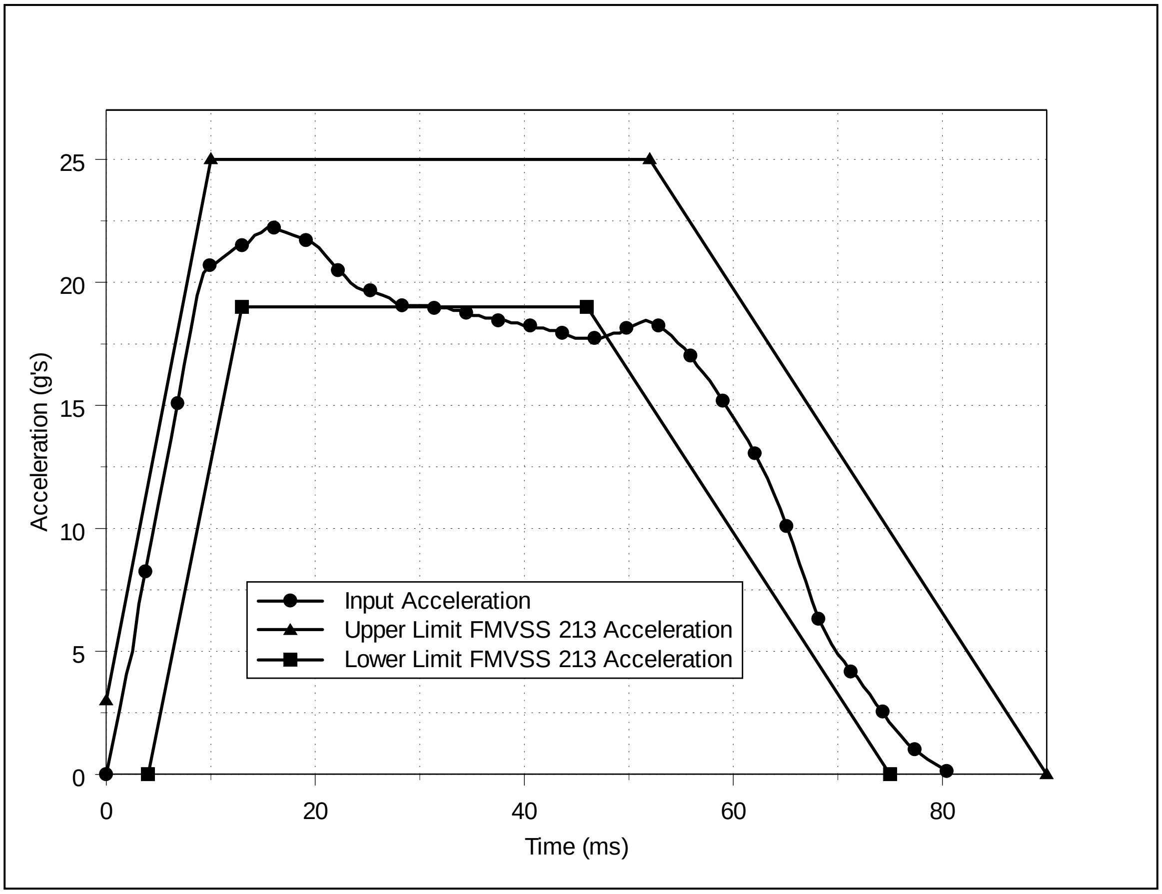


Figure 6. FMVSS 213 standard input acceleration versus time curve.

the last two rows of the ends of the seat belt were constrained to follow the FMVSS 213 input acceleration illustrated in Figure 6. The simulations were run using double precision version of LS-DYNA and required approximately 14 hours to complete.

The positioning of the dummy model into the child seat was accomplished using EASiCrash LS-DYNA. The simulations were run using the double precision version of LS-DYNA (release 3711) on a personal computer with dual 2.0 GHz AMD Athalon processors with 500 MB of DRAM.

Extraction of Injury Data from Hybrid III 3-year old Dummy Model

Head and Chest Accelerations

The determination of head and chest accelerations was accomplished through nodes that acted as accelerometers in the dummy models. They obtained acceleration data in three local directions, X, Y, and Z.

Upper and Lower Neck Forces and Moments

This research examined the forces and moments in the upper and lower neck region. These values were collected through the use of zero length beam elements that acted as load cells.

Analysis of Forces and Moments of the Upper and Lower Neck

The forces and moments endured in the upper and lower neck regions of the child dummy model were then analyzed by determining resultant forces and resultant moments through Equations 1 and 2.

The resultant forces and moments (in the upper and lower neck) in both rearward and forward facing configurations were analyzed and compared.

Head Injury Criteria

Equation 3 was used in determining the head injury criteria for the three-year-old Hybrid III dummy model.

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \cdot dt \right]^{2.5} \cdot (t_2 - t_1) \qquad \text{Equation 3}$$

The HIC was analyzed using a 36 ms sampling window as well as a 15 ms sampling window. The proposed maximum allowable HIC value for a 3-year-old Hybrid III dummy is 570, which was scaled down from the 50th percentile Hybrid III dummy.

Neck Injury Criteria

Equation 4 was used in determining the neck injury criteria for the Hybrid III 3-year-old dummy model. It is shown again here for clarity of the explanation that follows below.

$$N_{ij} = \left({F_Z}/{F_{ZC}} \right) + \left({M_Y}/{M_{YC}} \right) \qquad \text{Equation 4}$$

The Neck Injury Criteria, N_{ij}, is a linear combination of the normalized neck axial load (tension or compression) and normalized neck moment about the occipital condyle. F_Z is the force in the z- direction in the neck. This would be defined as an axial force pulling the head away from the shoulders, or oppositely, compressing the neck. The F_{ZC} is defined as the critical force for that area. M_Y is the moment about the y-axis. This can be defined as the tendency for the head and neck to bend towards the chest (flexion) and/or toward the back (extension) (Figure 11). The neck injury criterion was determined based on a value of 2120 N for F_{ZC} in both tension and compression. The value of M_{YC} a value of 68 N·m in flexion and 27 N·m in extension is used for analysis. The maximum N_{ij} value allowed is 1.0, regardless of dummy size.

Discussion of Results

Comparison of the Forces and Moments Observed in the Upper and Lower Neck

Forward and Rearward Facing Resultant Upper Neck Forces

Figure 7 illustrates the resultant upper neck forces versus time for the forward and rearward facing Hybrid III 3-year-old dummy model.

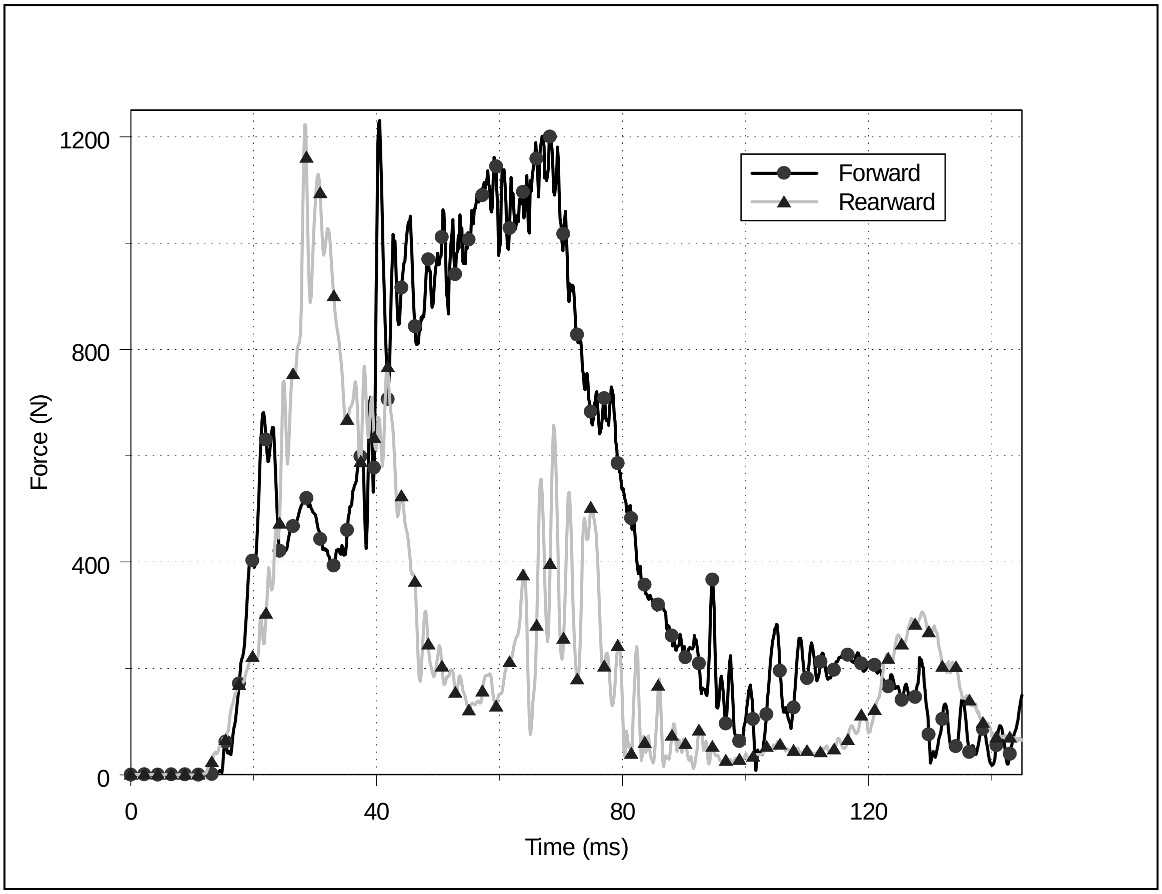


Figure 7. Resultant upper neck forces for forward and rearward facing simulations.

The force subjected to the Hybrid III 3-year old dummy's upper neck was at a peak at a value of 1200 N in both the forward and rearward facing curves. However, the forward facing child was subjected to a relatively high value of force in the upper neck region for at least twice the duration of the rearward configuration. This is noteworthy considering that there is a greater potential for damaging injuries the longer one is subjected to a force. In a study released by NHTSA and written by Desantis-Klinich et al. [11], it was concluded that the duration of the acceleration sustained is an important factor in determining the potential injury incurred by a child or child dummy.

Forward and Rearward Facing Resultant Lower Neck Forces

Figure 8 illustrates the resultant lower neck forces versus time for the forward and rearward facing Hybrid III 3-year-old dummy model.

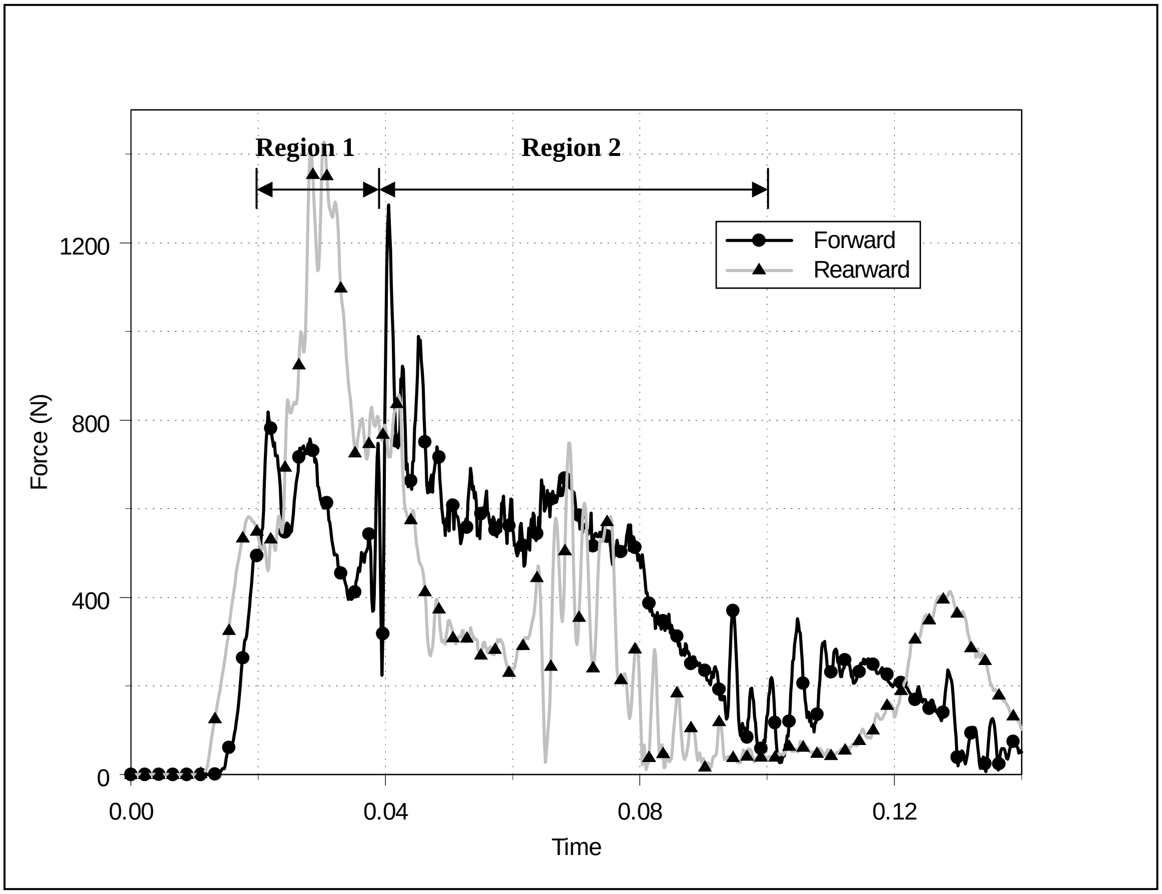


Figure 8. Resultant lower neck forces for forward and rearward facing simulations.

The force subjected to the Hybrid III 3-year old dummy's lower neck was at a peak value of 1300 N in the forward facing direction and 1450 N in the rearward facing situation. The peaks occurred in Region 1, as labeled in Figure 8. The peak regions lasted for a maximum of 20 ms. When observing Region 2, it was noticed that higher loads occurred for a longer period of time for the forward facing child than for the rearward facing child. Region 2 spans approximately 80 ms. If a critical value of 500 N was chosen, it was observed that the forward facing Hybrid III 3-year-old child spent more time above that critical value than the rearward facing child. Again, it is known that the longer one sustains a load, the greater the potential for injury. It is understood that a high acceleration can be sustained for a very short period of time [12]. The longer one is subjected to an acceleration, the greater potential for injury. Therefore, in the lower neck, the force endured by the rearward facing child appears to achieve less potential for injury than for a forward facing child.

Forward and Rearward Facing Resultant Upper Neck Moments

Figure 9 illustrates the resultant upper neck moments versus time for the forward and rearward facing Hybrid III 3-year-old dummy model.

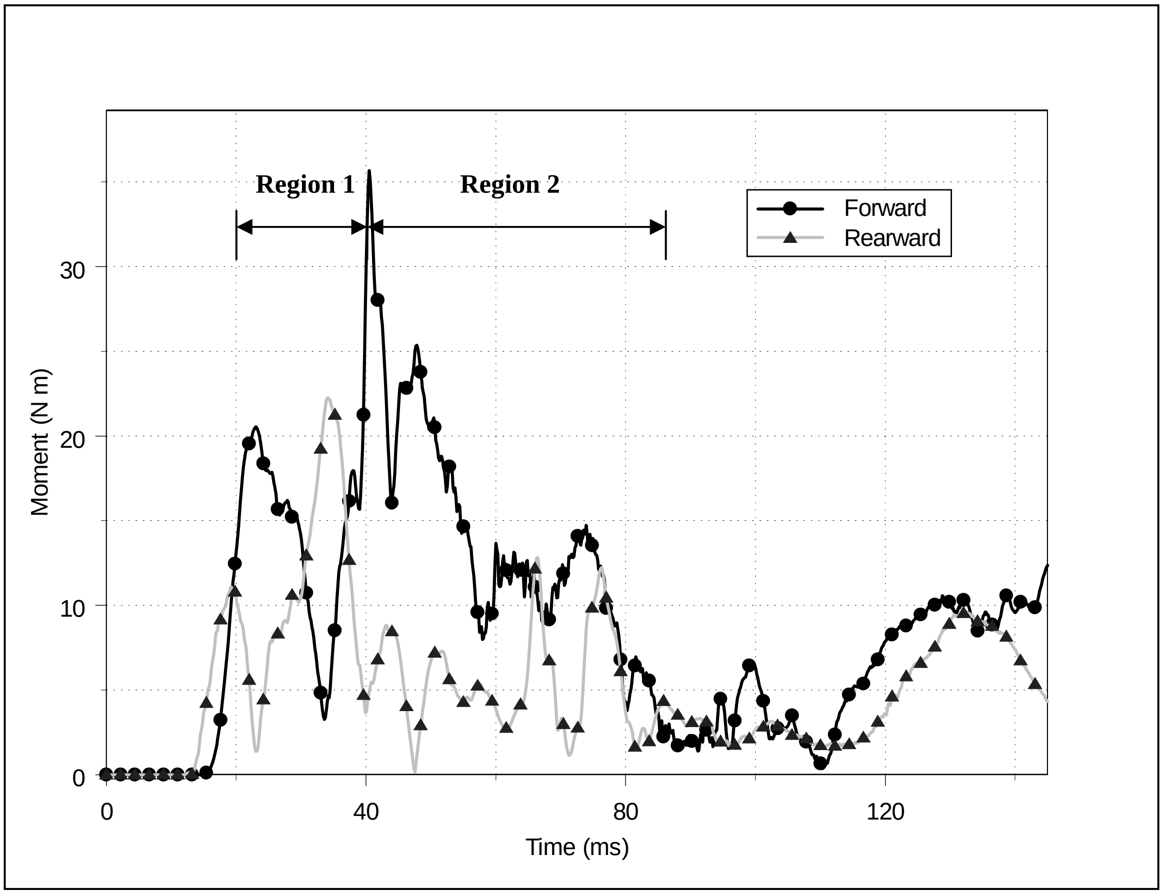


Figure 9. Resultant upper neck moments for forward and rearward facing simulations.

The forward facing Hybrid III 3-year old dummy faced a peak bending moment of slightly over 35 N·m whereas the rearward facing dummy model had a upper neck peak bending moment of 22 N·m. The peak region, Region 1, occurred for 20 ms, although the actual peak moments only lasted for a couple of milliseconds. In Region 2, the forward facing child sustained higher moments in the upper neck region then the child facing the rearward direction. Region 2 lasted just over 40 ms. Again, due to work researched by DeSantis-Klinich et al. [11], it can be concluded that since the rearward facing child was subjected to a high value of moment for a greater duration of time than the forward facing child, there was less potential for injury in the rearward facing child safety seat.

Forward and Rearward Facing Resultant Lower Neck Moments

Figure 10 illustrates the resultant lower neck moments versus time for the forward and rearward facing Hybrid III 3-year-old dummy model.

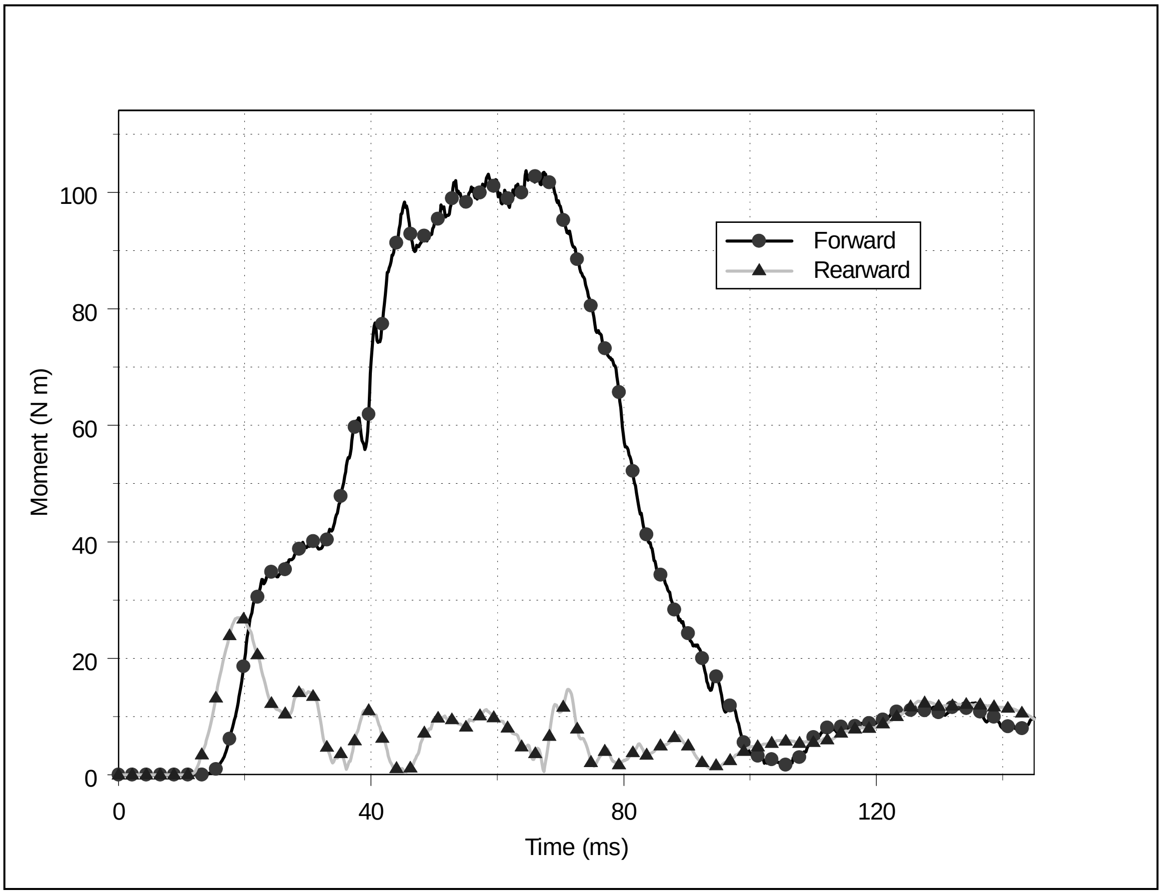


Figure 10. Resultant lower neck moments for forward and rearward facing simulations.

The forward facing Hybrid III 3-year old dummy model clearly sustained much higher bending moment in the lower neck than the rearward facing dummy model. The moment that resulted from rearward facing CRS peaked at approximately 27 N·m. The moment resulting from the forward facing configuration illustrated a maximum plateau of approximately 100 N·m. for approximately 25 ms. This graph illustrated that there was a high potential for injury in the lower neck of a child in a frontal crash. The value of the peak moment in the upper neck in the forward facing position was almost three times as large as the value for the peak moment in the lower neck in the forward facing position. The rearward facing child safety seat would provide better safety against potential for injury in the lower neck region than the forward facing CRS.

Head Injury Criteria

Figure 11 illustrates the head injury criteria using a 15 ms sampling window for both the forward and rearward facing numerical simulations. The rearward facing Hybrid III 3-year-old dummy model sustained a higher peak HIC_{15} value than the forward facing model by a magnitude value of 35. However, both values for HIC_{15} were significantly lower than the limit value of 570.

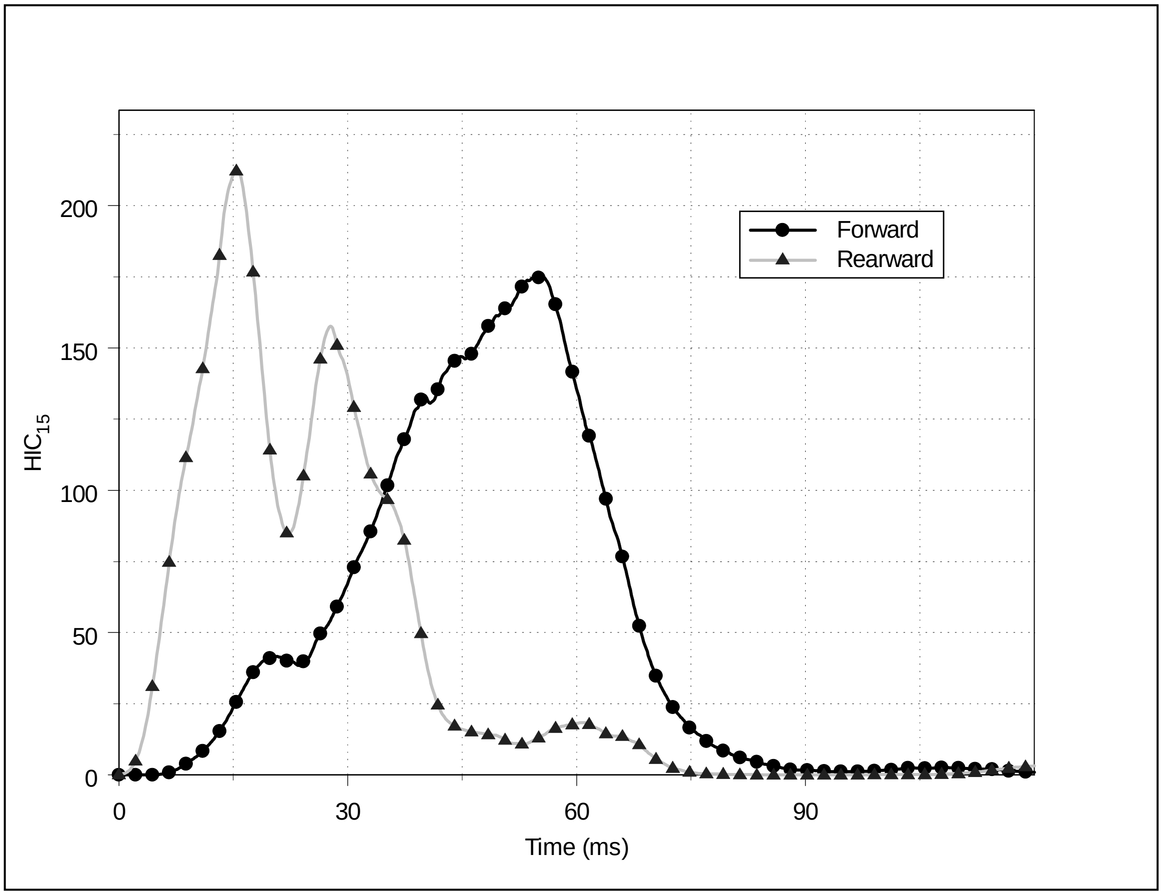


Figure 11. Head injury criteria – HIC_{15} for forward and rearward facing simulations.

The head of the forward facing child decelerated slower but experienced high values of HIC_{15} for a longer period of time.

Figure 12 illustrates the head injury criteria using a 36 ms sampling window. Both the rearward and forward facing Hybrid III 3-year-old dummy models sustained a HIC_{36} below 350 which was below the recommended standard limit of 570 for this age group.

Moreover, the child in the forward facing configuration was subjected to a higher value of HIC_{36} for a longer period of time than is the child in the rearward simulation.

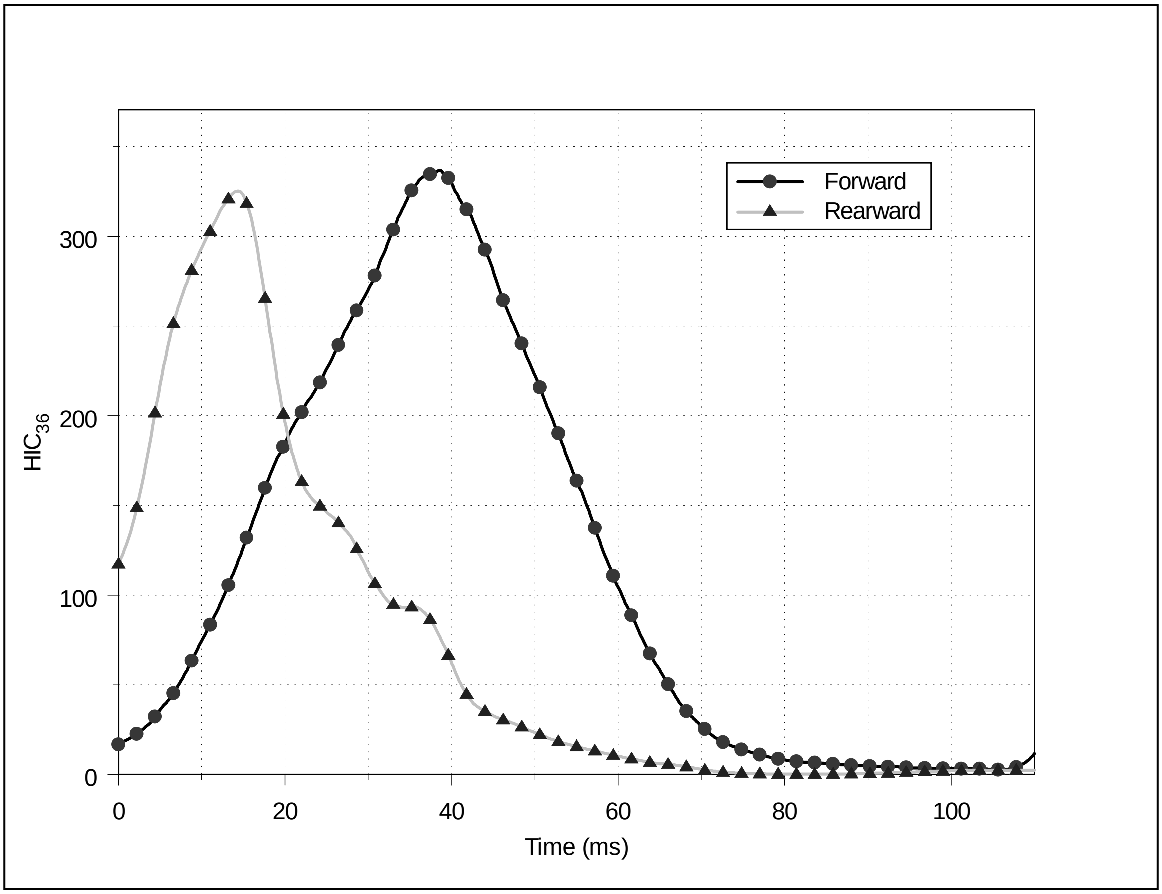


Figure 12. Head injury criteria – HIC_{36} for frontward and rearward facing simulations.

Neck Injury Criteria

Figure 13 demonstrates the neck injury criteria (N_{ij}) for the Hybrid III 3-year-old dummy model in the forward and rearward positions. The rearward facing curve was distinctly lower than the forward facing curve was. This implied that there was less potential for neck injury in the rearward facing position than in the forward facing position. The limit value for N_{ij} is 1.0. The rearward facing child surpassed this value slightly for only a short time. While the forward facing child reached values of over 1.5.

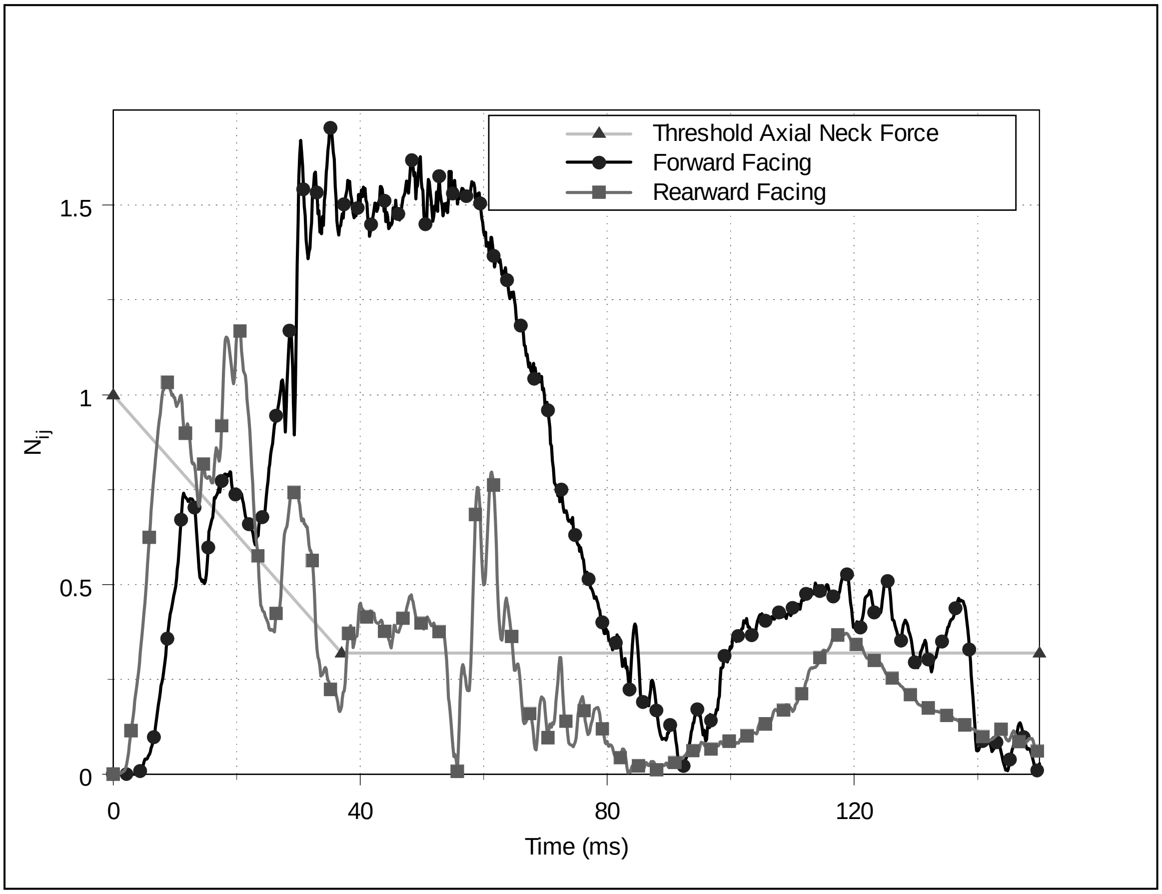


Figure 13. Normalized, forward facing, and rearward facing N_{ij} versus time.

Figure 13 also illustrates the normalized neck injury criteria tolerance curve from the publication by DeSantis-Klinich et al [11]. Clearly, the child in the forward facing CRS sustained a higher neck injury for longer periods of time than the child in the rearward facing configuration. In fact, the forward facing child's neck surpassed the tolerance limit for most of the time duration. This indicated that the length of time for which the neck was subjected to the levels of bending moments and forces was too long to prevent injury.

Injury was most likely imminent in the neck of the forward facing child for the prescribed FMVSS 213 acceleration pulse. This observation was absent for the rearward facing child. The rearward facing child fell below the tolerance limit for the majority of the time duration.

A possible explanation for the greater potential for injury in the forward facing configuration is that the back of the seat cradled the head of the child in the rearward facing simulation and did not allow for as much bending as the child in the forward facing simulation experienced. The forward facing child had nothing to inhibit the forward motion due to the crash.

Qualitative Comparison of Forward and Rearward Numerical Simulations

Figure 14 illustrates the kinematics of the forward and rearward numerical simulation observations at the same moments in time. This allowed for direct visual comparison of the two configurations.

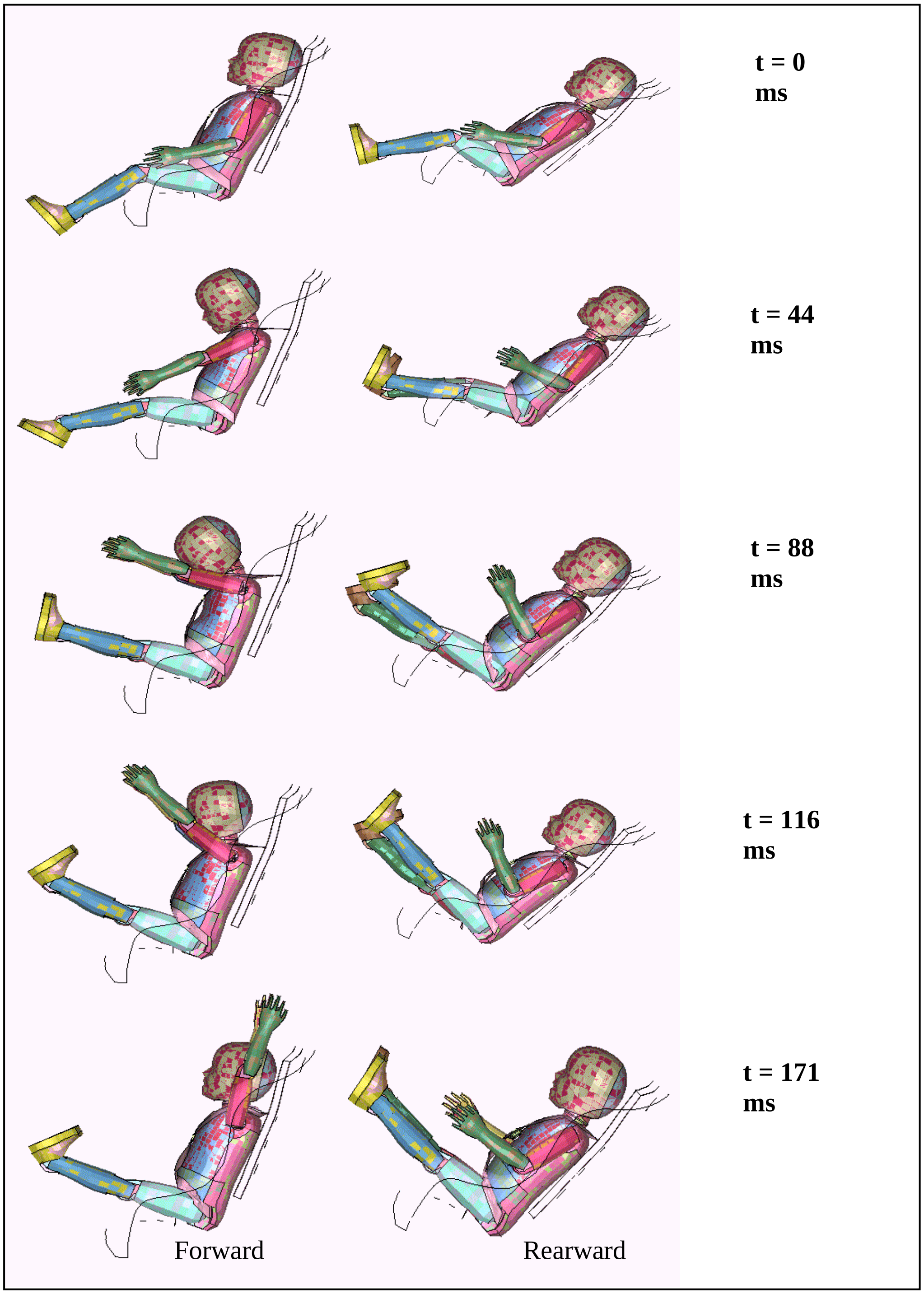


Figure 14. Forward and rearward numerical simulation images at exact time increments.

In Figure 14, the forward and rearward facing Hybrid III 3-year-old dummy models exhibited completely different kinematic positions throughout the time of the simulation. Throughout the simulation, the forward facing child experiences more severe movements than the rearward facing child. The bending of the neck and the forward translation of the head is visibly more severe for the child in the forward facing configuration for the entire simulation.

These qualitative images accompanied by the quantitative data provided in this section indicated that a more appropriate child seating configuration, with regards to occupant safety, was the rearward facing configuration.

Conclusions

Injury potential from numerically simulating a forward versus a rearward facing child was accomplished. Through these numerical simulations it was concluded that for a 3-year-old child, the rearward facing configuration is safer in terms of occupant injury to the head and neck. The following is as list of conclusions that were made based on the experiments and simulations conducted in this research.

1. The peak loads in the upper neck were similar for the forward and rearward facing configuration. However, the time durations of the force pulses were 60 ms and 20 ms for the forward facing and rearward facing configurations, respectively.

2. The child in the forward facing CRS experienced a peak lower neck force of 1300 N and the child in a rearward facing CRS experienced a peak lower neck force of 1450 N. However, the time durations of the force pulses were 80 ms and 20 ms for the forward facing and rearward facing configurations, respectively.

3. The child in the forward facing CRS experienced a peak bending moment in the upper neck of 35 N·m and the child in the rearward facing CRS experienced a peak bending moment of 22 N·m in the upper neck. However, the time durations of the bending moment pulses were 45 ms and 20 ms for the forward facing configuration and the rearward facing configuration, respectively.

4. The child in the rearward facing CRS experienced a peak bending moment in the lower neck of 105 N·m and the child in the rearward facing CRS experienced a peak bending moment of 26 N·m in the lower neck. However, the time durations of the bending moment pulses were 70 ms and 7 ms for the forward facing and the rearward facing configurations, respectively.

5. The HIC_{15} for the child in the forward facing CRS configuration was 174.93 and for the child in the rearward facing CRS configuration, the HIC_{15} was 212.3. The HIC_{36} for the child in the forward facing CRS configuration was 336.9 and for the child in the rearward facing CRS configuration, the HIC_{36} was 325.2. Both configurations yielded HIC values lower than the proposed limits. Where the 15 ms window is considered, the rearward facing child experienced slightly higher HIC values for a short period of time. Where the

36 ms window is considered, the rearward facing child sustained slightly lower HIC values than the forward facing child did.

6. The N_{ij} was substantially lower for the child in the rearward facing CRS configuration. The peak N_{ij} value for the child in the forward facing CRS configuration was 1.6 and for the child in the rearward facing CRS configuration, the peak N_{ij} value was 1.2.

7. Kinematically, the motions of the head, neck, and other limbs were quite severe for the forward facing child.

In short, the outcome of this research is based on the finding that there are safer methods of restraining children in motor vehicles. Although properly used child safety seats save lives and prevent injuries, there is more that can be done. This research is a starting point for further research and development into this area and hopefully for a safer vehicle environment for children.

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