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Collision Safety Improvements for Light Rail Vehicles Operating in Shared Right of Way Street Environments

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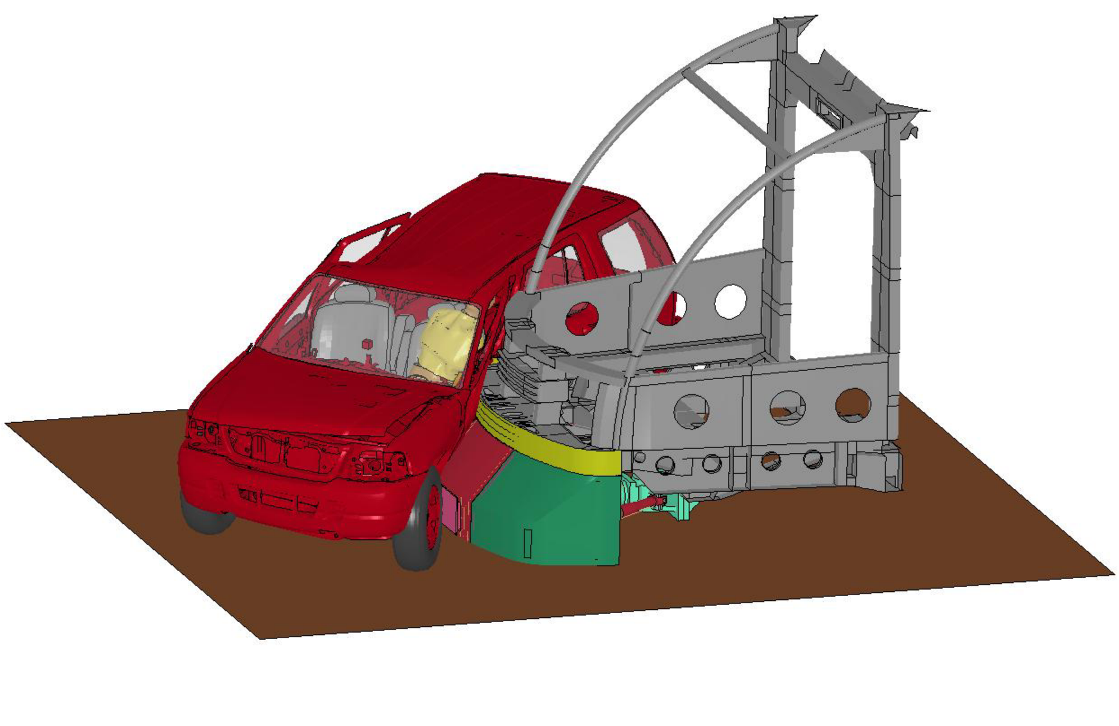

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The majority of fatalities that occur from light rail vehicle (LRV) operations are occupants of automobiles that are struck by the LRVs. Recent developments of crashworthiness standards for LRVs by the American Society of Mechanical Engineers (ASME) Rail Transit Vehicle Standards Committee included consideration of a wide variety of crash scenarios including collisions between LRVs and street running automobiles. The requirements included in the standard are primarily to create an enclosed front end geometry where the struck vehicle will not be entrapped or overridden. A smooth enclosed front end profile is a primary requirement for improving the compatibility of LRVs colliding with automobiles.
The focus of this study was to investigate the potential for reducing injuries to automobile occupants struck by LRVs with the addition of appropriate front-end structures. In particular, a prototype bumper system design with an improved profile and segmented energy-absorbing corner bumpers was developed. The technical approach for this project was focused on assessing detailed injuries from an unbelted Side Impact Dummy (SID) using detailed nonlinear dynamic finite element simulations. Impact conditions focused on normal (90 degrees) and oblique (45 degrees) impacts. The resulting bumper suitable for retrofit on LRVs showed marked improvements to automobile passenger safety for a variety of automobile types.

15. SUBJECT TERMS
Light Rail Vehicle, Transportation Safety, Front End Structures, Automobile Impact, Crashworthiness, Crash Energy Management, CEM, Occupant Protection, Injury Mechanics, Side Impact Dummy, SID

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Acronyms

AIS	Abbreviated Injury Scale
ASME	American Society of Mechanical Engineers
BH	Bumper Height
CEM	Crash Energy Management
CG	Center of Gravity
FE	Finite Element
HAG	Height Above Ground
HIC	Head Injury Criteria
LRV	Light Rail Vehicle
LSTC	Livermore Software Technology Corporation
NASS	National Automotive Sampling System
NCAC	National Crash Analysis Center
SID	Side Impact Dummy
TAG	Total Height Above the Ground
TCRP	Transit Cooperative Research Program
TTI	Thoracic Trauma Index

Executive Summary

Over the past decade there has been an increasing focus on improving the crash safety of light rail vehicles (LRVs). During this period, the American Society of Mechanical Engineers (ASME) has had an ongoing committee with the objective of preparing safety standards for structural design requirements of heavy rail, light rail, and streetcar car bodies. The standard for LRVs (referred to as RT-1) was issued in September of 2009 [1]. This ASME RT-1 committee recognized the need to include LRV leading end design criteria in the RT-1 standard to protect the motor vehicle occupants.

The largest percentage of LRV accidents occur with motor vehicles and cyclists/pedestrians [2]. The most common collision is the motor vehicle turning left in front of the LRV resulting in an oblique collision with the right front corner of the LRV. This configuration has been shown to have a high probability of injury to the automobile occupants for various LRV designs for collision speeds of 20 mph or greater [3].

The objective of this project was to develop a novel segmented bumper design with different energy-absorbing characteristics for frontal and corner impacts. This bumper design would include an improved geometric profile making the front-end less aggressive to automobiles and pedestrians. By improving the collision compatibility, the bumper would also reduce the LRV derailment potential in these impacts. Finally, developing a bumper design that could be retrofit onto existing LRVs was a goal of the project.

In this project, we developed a new bumper system that utilizes both an improved geometric profile making the front-end less aggressive to automobiles and pedestrians and a segmented design that will actuate at much lower forces in corner collisions with automobiles. The project was conducted in three stages. First, a bumper profile geometric design study was conducted using high-fidelity finite element (FE) crash analyses. This first stage determined the geometric characteristics of a bumper system that minimize injury potential for a range of collisions with highway vehicles. The second stage was to conduct a design study for adding actuating corner bumper segments with energy absorption capabilities. The objective was to demonstrate the advantages of this design and size the components. Finally, based on the requirements established in the second stage, hardware components were designed to meet these requirements.

The FE crash simulations in this project were performed using LS-DYNA. These simulations utilize previously developed FE models of a Siemens S70 LRV and existing highway vehicle models developed and validated under US DOT sponsorship and Applied Research Associates, Inc. (ARA).

Two design concepts were considered in this study for integrating a segmented bumper with energy absorption capability on an LRV. The first design concept utilizes a bumper with a folding coupler. In this design the corner bumpers remain fixed, but the center bumper is raised

and lowered when needed during operation to deploy the coupler. This would provide a relatively easy and cost-effective approach to retrofitting an LRV for a folding coupler.

The second option for the bumper offers an even simpler design that does not involve raising and lowering the bumper to couple with another LRV. For LRVs that can use a shorter coupler, the coupler head could be directly integrated into the bumper so that the entire bumper swings with the coupler. In order to allow the entire bumper to swing, the corner energy absorbers can be attached to the coupler pivot or close to the coupler anchor. This latter option was chosen for the prototype bumper design.

The resulting bumper from this project showed marked improvements to automobile passenger safety for a variety of automobile types. The results clearly show that careful selection of the front end bumper profile can significantly reduce the probability of injuries to automobile occupants. A profile that is low enough to engage the door frame structures of small and light vehicles, with an adequate vertical height to engage the same structures on taller SUVs and with an angled profile provided the best overall performance. Addition of a segmented corner bumper with the correct force-deflection characteristics for energy absorbers further reduces the potential for injuries. A prototype bumper design that implements these characteristics has been developed and retrofit to an S70 LRV. The efficacy of this design has been demonstrated with LS-DYNA crash simulations.

Section 1 Introduction

Over the past decade there has been an increasing focus on improving the crash safety of light rain vehicles (LRVs). During this period, the American Society of Mechanical Engineers (ASME) has had an ongoing committee with the objective of preparing safety standards for structural design requirements of heavy rail, light rail, and streetcar car bodies. The standard for LRVs (referred to as RT-1) was issued in September of 2009 [1]. This ASME RT-1 committee recognized the need to include LRV leading end design criteria in the RT-1 standard to protect the motor vehicle occupants.

A similar trend was occurring in the LRV industry where new LRV systems were increasingly including requirements for enclosed front end deigns or bumper systems. These enclosed front end geometries are preferable for aesthetic reasons and because they are much more compatible for collisions with highway vehicles. In addition, when properly designed, the enclosed front end can reduce damage in these collisions and reduce collision repair time and costs.

The largest percentage of LRV accidents occur with motor vehicles and cyclists/pedestrians (62% and 38% respectively) [2]. The most common collision is the motor vehicle turning left in front of the LRV resulting in an oblique collision with the right front corner of the LRV. This configuration (approximately a 45 degree impact), also has a high probability of injury to the automobile occupants for various LRV designs both with and without bumper systems for collision speeds of 20 mph or greater [3].

The objective of this project was to develop a novel segmented bumper design with different energy-absorbing characteristics for frontal and corner impacts. This bumper design would include an improved geometric profile making the front-end less aggressive to automobiles and pedestrians. By improving the collision compatibility, the bumper would also reduce the LRV derailment potential in these impacts. Finally, the ability to retrofit the bumper onto existing LRV designs was a goal of the project.

Crash simulations performed as part of the TCRP Project C-17 [3] demonstrated that the addition of a rigid bumper enclosure, resulting in a smooth LRV front-end profile and lower contact zone between the LRV and the automobile, has a significant potential for reducing injuries and fatalities in side collisions. However, the specific geometric parameters that provide the greatest level of injury reduction are not known. Similarly, energy-absorbing capabilities for most LRVs are designed to protect against a 5 mph collision with another LRV. This level of energy absorption does not appear to offer much advantage in collisions with automobiles over the performance of a rigid bumper since the side crush strengths of automobiles are too low to activate the energy absorbers. As a result, it is difficult to develop a bumper system that will both dissipate a significant amount of energy in collisions with automobiles but still be suitable for preventing damage in the 5 mph collision between two identical LRVs.

In this project, we developed a new bumper system that utilizes both an improved geometric profile making the front-end less aggressive to automobiles and pedestrians and a segmented design that will actuate at much lower forces in corner collisions with automobiles. A detailed description of the prototype design is given in Section 6.

The project was conducted in three stages. First, a bumper profile geometric design study was conducted using the same high-fidelity modeling tools utilized in the TCRP Project C-17 [3]. This first stage determined the geometric characteristics of a bumper system that minimize injury potential for a range of collisions with highway vehicles. The second stage was a design study for adding actuating corner bumper segments with energy absorption capabilities. The objective was to demonstrate the advantages of this design and size the components. Finally, based on the requirements established in the second stage, hardware components were designed to meet these requirements.

The finite element (FE) crash simulations in this project were performed using LS-DYNA. These simulations utilize previously developed FE models of a Siemens S70 LRV and existing highway vehicle models developed and validated under US DOT sponsorship and Applied Research Associates, Inc. (ARA). An example of side impact between the S70 and a Dodge Neon using these models is shown in Figure 1.

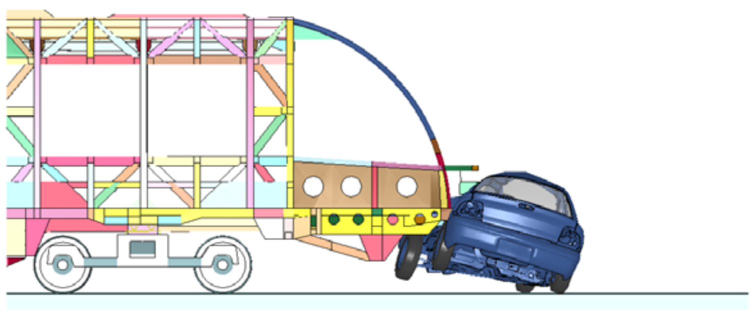
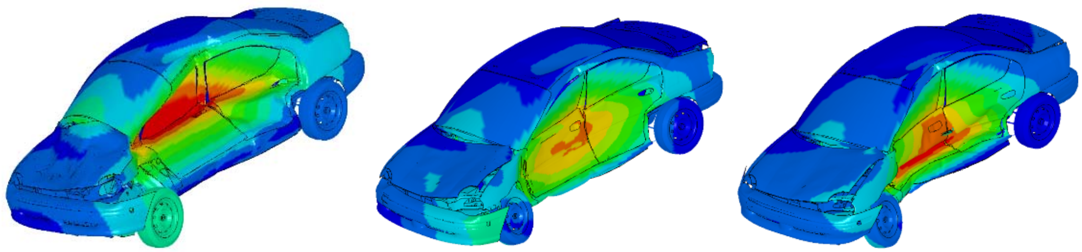


Figure 1. Simulation of a 20 mph Collision of a Siemens S70 LRV and Dodge Neon [3].

Injury potential in the TCRP Project C-17 was evaluated from the injury probability as a function of maximum lateral crush as determined from research on side impact safety of automobiles provided by the National Automotive Sampling System (NASS). Data from NASS correlates injury probability to physical intrusion into the vehicle [4]. However, this method has a limited ability to assess injuries from LRVs. It was developed from automobile accident data, not LRV accidents, and does not account for differences in the collision behaviors such as the large variations in the location of maximum intrusion, as shown in Figure 2 for a side impact on a Dodge with and without two LRV bumper designs.

A model of the U.S. Side Impact Dummy (SID) was included in the impacted vehicles to perform an improved assessment of injury risk with the bumper designs. Direct measures of injury were extracted from the SID model. These injury measures, combined with other measures of the collision dynamics, were used to assess the improvements in bumper performance.



(a) Without bumper (94%) **(b) With bumper (69%)** **(c) With pilot beam (75%)**

Figure 2. Calculated crush for 90 degree, 20 mph collision between an S70 LRV and a Dodge Neon. Probability of Injury (MAIS 3+) shown in parenthesis [3].

1.1 Proposed Bumper Design

Providing increased protection of pedestrians and automobile passengers from LRV collisions can be achieved from either improving the geometry of the collision interface and/or adding energy dissipation to the LRV front end structures that are compatible with the forces of these collisions. The Transit Cooperative Research Program Project C-17 found that the addition of a smooth bumper enclosure on the front end of the LRV can significantly reduce the injury potential in many collision scenarios. However, the relative performance of different bumper profiles was not assessed and other studies have shown that this profile can have a significant effect on the injury potential [5]. Similarly adding energy absorption is difficult due to the wide variation of collision forces possible from frontal collisions and less severe oblique corner collision. This proposed bumper design addresses both of these safety issues.

The proposed bumper retrofit design investigated in this project is shown in Figure 3. The design consists of a stiff segmented bumper attached by joints where the side segments are free to rotate independently. These side segments are attached to their own hydraulic energy absorbers that are designed to be activated in an oblique corner collision. A flexible bumper cover can be included that encompasses these internal structures.

The central energy absorbers can be designed to protect against the normal (90^{o}) impact as shown in Figure 4(a). Alternatively, the central energy absorbers can be selected to protect against the 5 mph LRV collision which is a common CEM requirement for energy absorbing front end structures. A potential design is to use coupler system energy absorbers in place of the central energy absorbers. The corner energy absorbers are designed to be compatible with the relatively low side crush force levels in an oblique side impact with an automobile.

This is a significant innovation in bumper design with the segmented bumper and hydraulic energy absorbers that can be tailored to a lower force for corner collisions with automobiles. The corner impact is the most common type of accident and results in many of the serious injuries and fatalities of LRV operations. By allowing the corner segment to move independently, it also allows the bumper to engage a greater area on the vehicle, as shown in Figure 4. The larger contact patch distributes the impact loads on the struck vehicle further reducing crush intrusions and injury risk. Finally, the rotation of the side bumper segment modifies the corner profile of the LRV and more effectively deflects the struck automobile out of the path of the LRV.

The geometry of the bumper will protrude in front of the existing end sill of the LRV in order to allow sufficient stroke of the energy absorbers, while maintaining operational requirements (e.g. cab-end length restrictions, vertical track curvature, operator visibility, and ease of component maintenance and replacement). The geometry is expected to have two key features:

(1) The bottom of bumper will be low (likely the minimum distance to the top of rail operationally) in order to best engage the automobile door sill structures. The low enclosure height will also limit penetration of components or debris under the LRV and reduce derailment risk of the LRV.

(2) The bumper will protrude the most near the bottom edge. This is in contrast to some existing bumper profiles, as shown in Figure 5. This feature serves the dual purpose of engaging the lower structure of the automobile first and providing a more smooth front-end for pedestrian impact. A lower impact point on the automobile delivers load into higher-strength regions of the vehicle and produces less chance of override. An example of such a design is currently in use on the Dusseldorf tram, as shown in Figure 6.

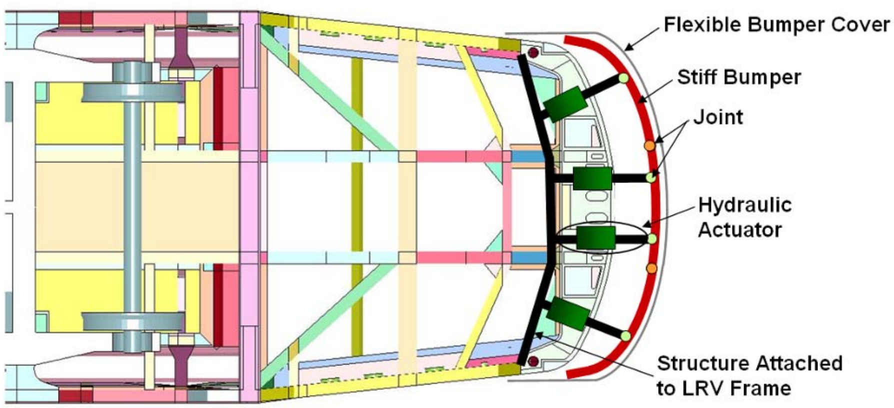
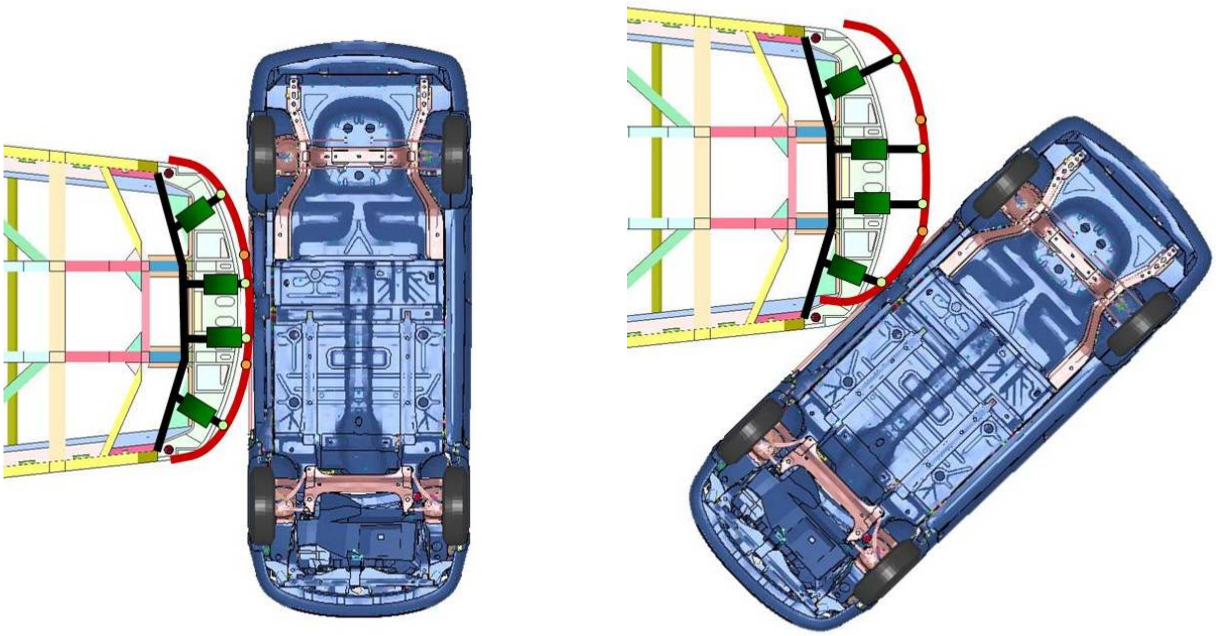
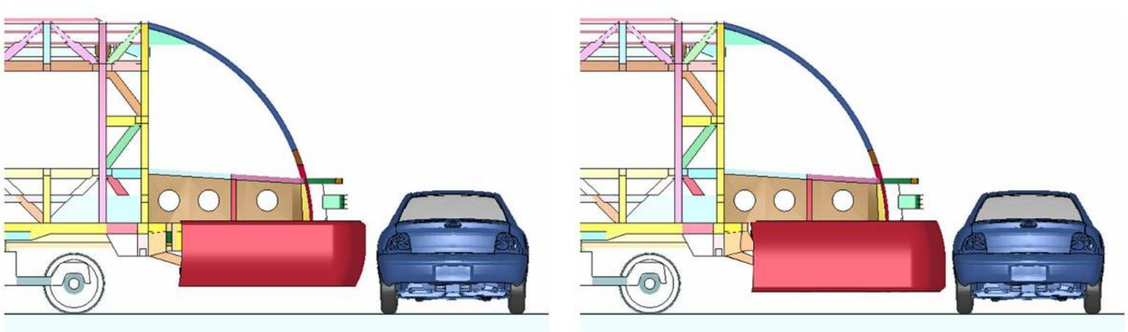


Figure 3. Proposed segmented bumper retrofit on the front-end of a Siemens S70 LRV.



(a) 90 degree impact (b) 45 degree impact

Figure 4. Proposed bumper retrofit functionality during normal and 45 degree impacts with a Dodge Neon.



(a) Existing bumper profile (b) Less aggressive lowered profile

Figure 5. Proposed bumper retrofit geometries.

Figure 6. Low bumper profile on the Dusseldorf tram.

1.2 Technical Approach

The detailed collision analyses performed in this study used the LS-DYNA finite element code (LS-DYNA Version 971). LS-DYNA is a commercially available nonlinear explicit finite element code for the dynamic analysis of structures [6]. The initial foundation of LS-DYNA was the public domain DYNA3D finite element code developed at the Lawrence Livermore National Laboratory [7]. Since 1987, the code has been extensively developed and supported by the Livermore Software Technology Corporation (LSTC) and is used for a wide variety of crash, blast, and impact applications.

The impact analyses described in this report used a variety of capabilities and algorithms in LS-DYNA. A brief description of these capabilities is described in the following section. A significantly detailed description of the analysis methods is provided in the LS-DYNA Theoretical Manual [8].

Section 2 Finite Element Model Development

2.1 Target Vehicle Selection and Models

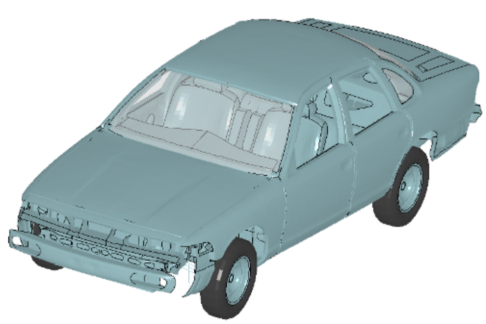
Several vehicle FEA models were used for this study, most of which were developed by the National Crash Analysis Center (NCAC) [9]. A Ford Crown Victoria model developed by ARA personnel was used to represent a large sedan [10]. To represent a range of sizes, weights, and height above ground of passenger vehicles, the following vehicles were chosen:

- Compact Sedan – Dodge Neon
- Large Sedan – Ford Crown Victoria
- Small SUV – Toyota Rav4
- Large SUV – Ford Explorer

The FEA models of each vehicle are shown in Figure 7. The Neon is a light car that is low to the ground while the Rav4 is also light but higher off the ground. The Ford Explorer is a heavy truck that is high off the ground while the Crown Victoria is also heavy but lower to the ground. Table 1 gives the curb weight, average rocker panel height, and center of gravity (CG) height for the vehicles used in this study.

Ford Explorer (NCAC)

Dodge Neon (NCAC)



Ford Crown Victoria (ARA)

Toyota RAV4 (NCAC)

Figure 7. Vehicle FEA models used for assessing bumper designs.

Table 1. Weights, average rocker panel and CG height for the highway vehicles in impact analyses.

Vehicle	Curb Weight		Average Rocker Panel Height		CG Height Above Ground	
	(kg)	(lb)	(mm)	(in)	(mm)	(in)
1996 Dodge Neon	1121	2469	167	6.6	533	21.0
2003 Ford Explorer	1853	4081	355	14.0	638	25.1
2000 Toyota Rav4	1221	2690	290	11.4	611	24.1
1997 Ford Crown Victoria	1713	3774	164	6.4	606	23.9

2.2 Vehicle Interior and Side Impact Dummy (SID)

The vehicle finite element models used for this study were developed to capture their crash behavior and include only the relevant structural components. The seats, door panels, and other interior components were not included in the models. In order to accurately model occupant-vehicle interaction in the side impact scenarios considered in this study, padded seats and a driver door panel were added to the existing vehicle models.

Front driver and passenger bucket style seat models from an existing Ford Crown Victoria model were used as a basis for the seat models in the Neon, Explorer, and Rav4. All the vehicles have bucket seats, though sizing is somewhat different for each vehicles of interest. For the Neon and Rav4, the seats were sized down in all directions by 10 percent and the base rails and lower seat pad were altered for a lower profile more typical of small occupant vehicles. For the Explorer, the full size Crown Victoria seats were used. For the Crown Victoria, no alterations to seats were made from the existing seat model.

The seat models were placed in the respective vehicles for typical occupant positioning, such that the head rest was generally aligned with or slightly behind the B-pillar. The seats were secured to the vehicle structures with individual rigid constraints positioned at the appropriate frame bolt locations. The seat model consists of a steel underframe and cushion support, along with foam cushions for the seat, backrest, and head rest. The basic seat model used in the analyses is shown in Figure 8.

Figure 8. Driver and passenger seat models.

The side impact dummy (SID) was used since it is most appropriate for assessing injury potential in the side-impacted vehicles. A SID model [11,12] was positioned in the driver seat for both vehicles. The legs were extended forward at an angle representative of a driving position in the respective vehicles. The SID was placed on the seat without seatbelt restraints. The positioned SID from vehicles used in the study is shown in Figure 9. A driver side door panel was incorporated into both vehicle models to improve the contact between the SID and the vehicle and to model the expected cushioning from the door panel armrest. The main panel was modeled as an elastic material with properties of plywood. The simple panel geometry was generated for each vehicle to mimic the interior contour of the underlying structure. The panel was secured to the door structure with six discrete spring elements, three along the top edge, and three along the bottom edge. The loose connection with the structure was adequate to hold the panel in place while allowing for realistic deflection of the panel under contact loads.

Where appropriate, a foam armrest was incorporated into the door panel. The armrest used the same compressible low-density foam model from the SID shoulder pad, and was encased in a rubber shell element outer jacket. The armrest was positioned at the hip of the driver in the vehicles and made similar in size and shape to the armrest in the actual vehicle. Note that the RAV4 model does not have an armrest. In the actual vehicle, a small accessory pod protrudes from the door panel near the steering wheel but it would not interact with the passenger in a side or oblique impact. Therefore, it was not included in the Rav4 model used in this study.

The interior door panels positioned with the SID and seats can be seen in the cutaway views for each vehicle in Figure 10. The armrest and dummy foam crush characteristics can be seen in Figure 11.

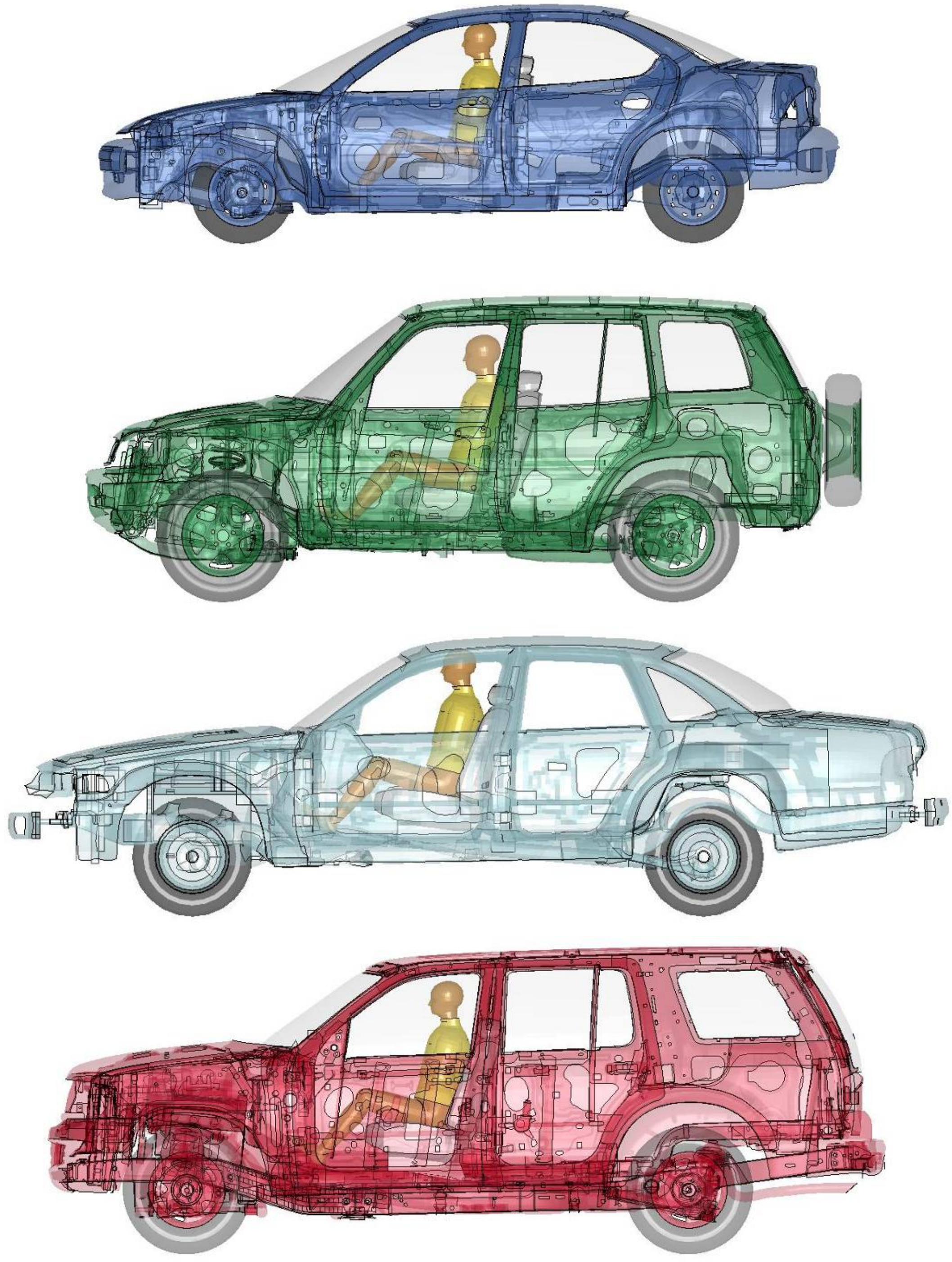
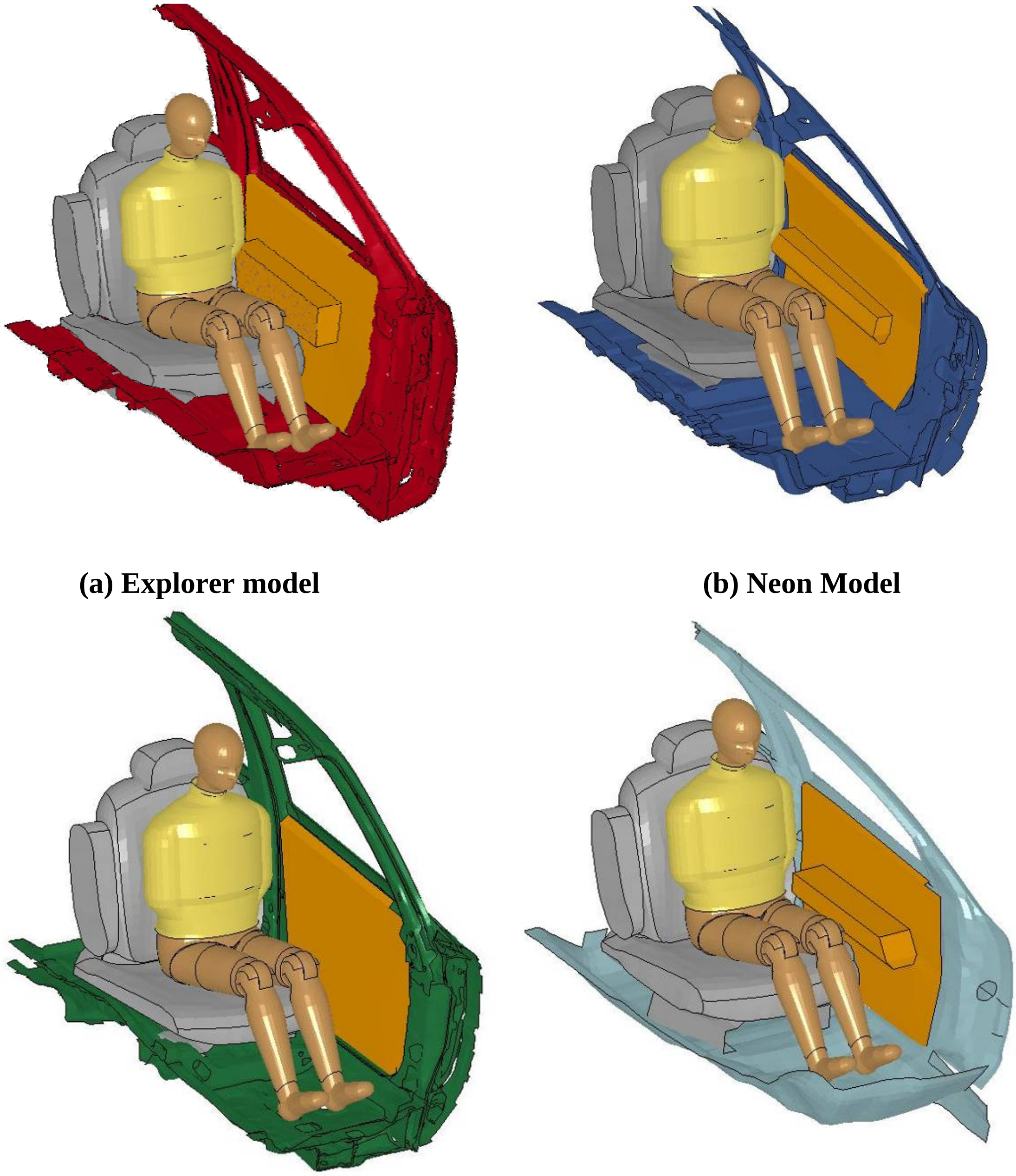


Figure 9. SID model positioned in the highway vehicles used in the impact analyses.



(a) Explorer model (b) Neon Model

(c) Rav4 Model (d) Crown Victoria model

Figure 10. Cutaway views illustrating relative positioning of SID, seat, and interior door panel models.

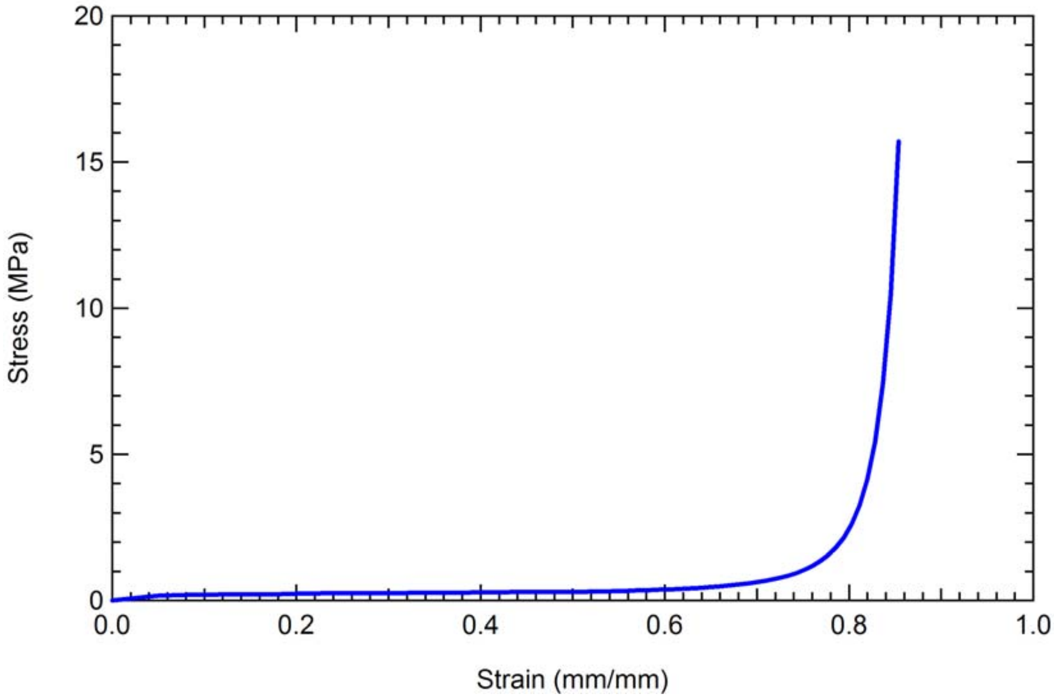


Figure 11. Interior armrest foam crush characteristics.

Section 3 Methodology for Evaluating Bumper Performance

Injury criteria derived from an unbelted Side Impact Dummy (SID) were used to assess bumper performance. Explicit modeling of the SID allows for an improved assessment of the driver pelvis, thorax, and head injury potential from the various collision scenarios. These parameters were correlated the Abbreviated Injury Scale (AIS) as specified by the Association for the Advancement of Automotive Medicine (AAAM) to determine probability of injury in the occupant. In general, the AIS severity levels indicate the following types of injury:

- AIS 1 – Minor
- AIS 2 – Moderate
- AIS 3 – Serious
- AIS 4 – Severe
- AIS 5 – Critical
- AIS 6 - Unsurvivable

The injury criteria parameters and their injury ranges are discussed in detail below.

3.1 Occupant Injury

Three SID injury criteria were evaluated in this study: the Head Injury Criteria (HIC), the Thoracic Trauma Index (TTI), and the resultant pelvis acceleration. These criteria are explained in detail in the sections below. Data for the criteria was obtained using accelerometers defined as *ELEMENT_SEATBELT_ACCELEROMETER. Figure 12 shows the locations of these accelerometers. The upper spine accelerometer was not used in this study.

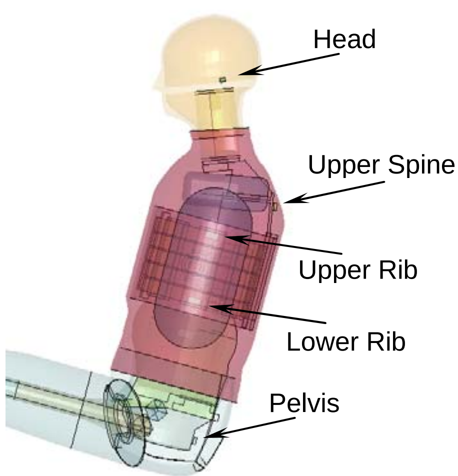


Figure 12. Location of accelerometers in SID model (all SID parts are shown as transparent).

3.1.1 Head Injury Criteria

The head injury criterion (HIC) is defined as:

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1)$$

Where the time interval t_2-t_1 is either 36 ms or 15 ms and the *a(t)* is the resultant acceleration in g's [14]. In this study, a HIC value with a range of 36 ms is used to determine the probability of injury using the AIS. A HIC of 1000 is considered acceptable [14]. The AIS severity levels for HIC are defined as:

- AIS 1 – Headache or dizziness
- AIS 2 – Unconscious less than 1 hour – linear fracture
- AIS 3 – Unconscious 1 - 6 hours – depressed fracture
- AIS 4 – Unconscious 6 - 24 hours – open fracture
- AIS 5 – Unconscious greater than 25 hours – large hematoma
- AIS 6 – Non-survivable [15]

The HIC probability of injury curves are shown in Figure 13. At a HIC of 1000, the probability of an AIS severity level of 3+ is about 50%.

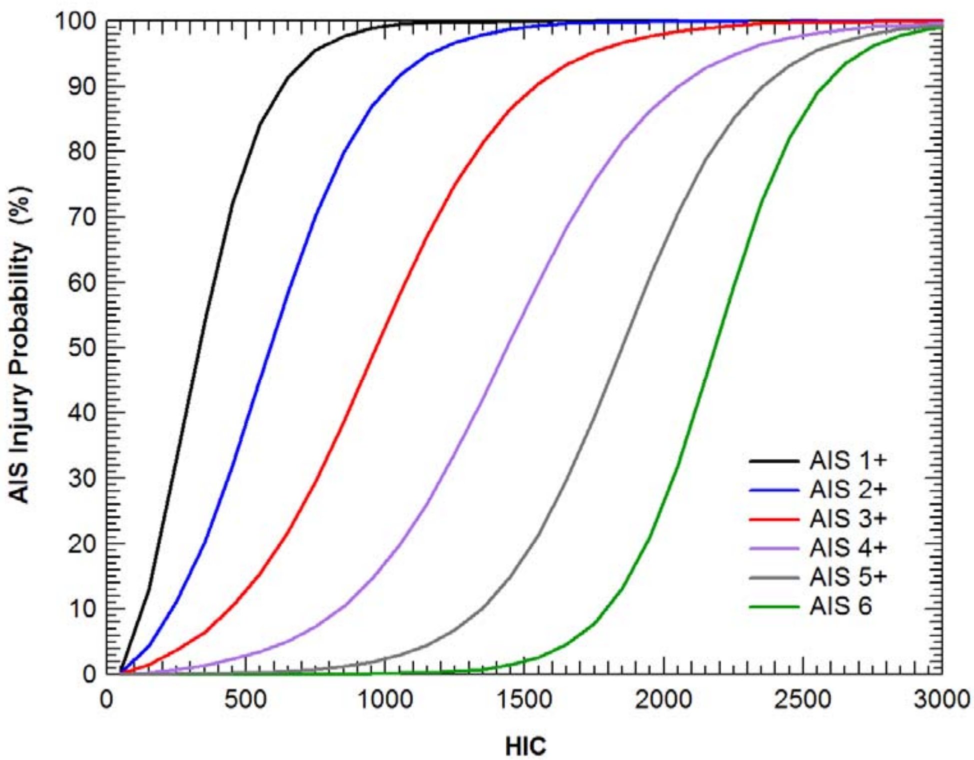


Figure 13. Injury probability as a function of HIC [16].

3.1.2 Thoracic Trauma Index

The thoracic trauma index (TTI) is defined as:

$$TTI(d) = \frac{1}{2}(G_R + G_{LS})$$

Where G_R is the greater of the upper rib peak acceleration or the lower rib peak acceleration and G_{LS} is the lower spine peak acceleration. For passenger cars with 4 side doors such as the ones used in this study, a TTI of less than 85 g's is acceptable [17]. The AIS severity levels for TTI are defined as:

- AIS 1 – Soft tissue injury consisting of laceration and contusion, one rib fracture
- AIS 2 – Major skin laceration and partial tear of the bronchus, 2-3 rib fractures
- AIS 3 – Minor heart and lung contusion, >3 rib fractures on one side, <3 on other
- AIS 4 – Severe heart and lung contusion, torn aorta, flail chest
- AIS 5 – Major aortic laceration, heart perforation, bilateral flail chest
- AIS 6 – Non-survivable [15]

The TTI probability of injury curves are shown in Figure 14. Note that at 85 g's, the probability of AIS severity level of 3+ is 0%.

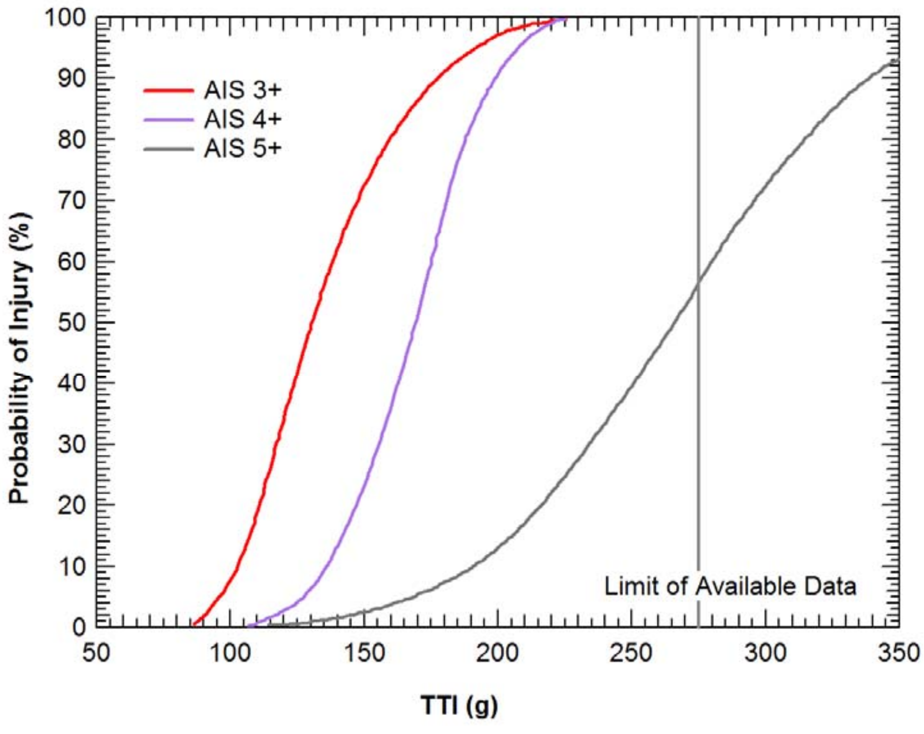


Figure 14. Injury probability as a function of TTI [18].

3.1.3 Pelvis Resultant Acceleration

The pelvis injury criterion used in this study is the peak pelvic resultant acceleration measured in g's. An accelerometer placed in the middle of the pelvis in the SID model was used to obtain the pelvic acceleration. A peak pelvic acceleration of 130 g's or less is considered acceptable [17].

Section 4 Bumper Geometry Design Study

The objective of the bumper geometry design study was to determine the geometric characteristics of a bumper system that minimize injury potential for a range of collisions with highway vehicles. The geometric design parameters were developed based on operational constraints and evaluated at impact speeds that lead to significant injuries to the automobile occupants.

4.1 Vehicle Operational Requirements

The plan geometry of an LRV bumper is limited by its operational envelope in minimum radius curves. The minimum height above rail is dependent on the vehicle suspension and the worst case sagging track curve. Separate analyses were performed for two representative LRVs, the Siemens S70 and SD160, in order to determine limits on the plan width of the bumper and its minimum height above rail. In these analyses, generally accepted values in the light rail industry for the minimum horizontal and vertical curves are used, although they are not state or federally regulated.

For typical LRV systems, the minimum horizontal curve radius is, 82 feet (25m). There are exceptions to this minimum radius, although they are rare. Reverse horizontal curves generally are separated with a 40 foot (12 m) tangent section. A two-dimensional geometric simulation was used to determine the vehicle position and envelope as it travels down the track. The simulation did not include inertial effects since operation in minimum radius curves are usually accompanied by severe speed restrictions. No vehicle failures were included in the calculation. No track spirals were assumed for curve entries in the calculations. The space available for projecting the bumper was extrapolated from the existing vehicle envelopes.

Results from this simulation are shown in Figure 15. The static plan view envelope is shown in the figure. Bumper geometry was extrapolated to conform with this envelope. Bumper widths were constrained based on this extrapolation.

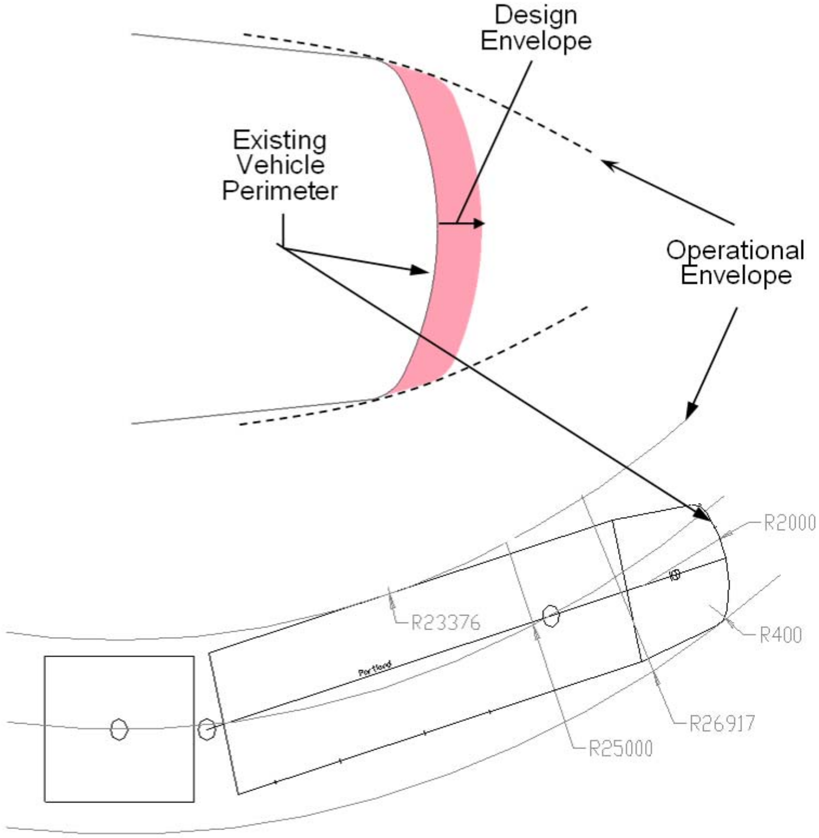


Figure 15. Bumper plan view operational envelope.

The minimum height above rail for the bumper was determined by considering contact with the ground in a worst case condition. The worst case considered is failed suspension in a sagging track curve, since this would point the vehicle front end into the track. The minimum sag radii generally required for light rail vehicles is 1150 foot (350 meter) sag. The height of connection point between the carbody and the truck was reduced by 74 mm to account for failures such as secondary and primary suspension collapse together with significant wheel wear. The calculation was preformed on an A-car end since the adjacent articulation has only one degree of freedom, the yaw rotation, which would also push the front end towards the track. Coupled ends were not considered since the failed suspension vehicle coupler is lifted by being connected to a vehicle with nominal suspension. Again, inertial effects were not considered since such extreme track geometry usually requires significant speed restrictions. For these analyses, the bumper was extended 200 mm beyond the end of the existing vehicle to represent the addition of a bumper, as shown in Figure 16.

Analyses were conducted for the S70 and SD160 LRVs. Results of this analysis for the S70 are shown in Figure 17. The minimum bumper height required for the S70 is 235 mm with 14 mm clearance and for the SD160 it is 200 mm with 4 mm clearance. The S270 requires the highest bumper and was therefore used as the minimum in the geometry study.

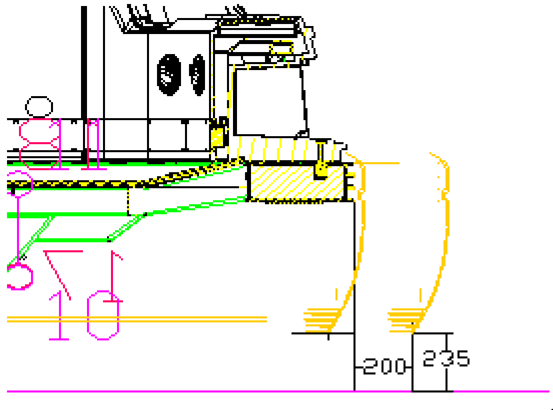


Figure 16. Initial conditions on level tangent track with operational suspension.

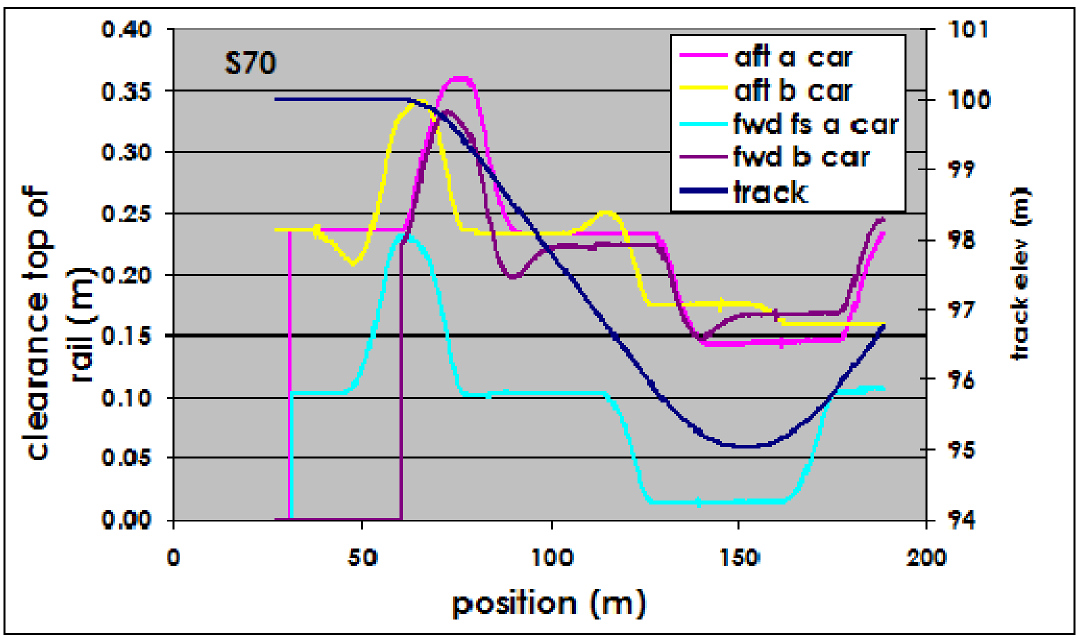


Figure 17. Clearance above the top of rail for the S70 LRV with a failed suspension in a sagging track curve.

4.2 Simplified LRV and Bumper Model – Geometry Study

To reduce the model size and run times for the bumper geometry study, a model was developed with a bumper and a rigid mass to account for the trailing mass of the rest of the LRV. The original LRV and bumper model and the simplified model are shown in Figure 18. The density of the rigid body was scaled to match that of the LRV and its motion was constrained to move linearly in the impact direction. A comparison of the vehicle crush in a simulation with the LRV and bumper and a simulation with the bumper only is shown in Figure 19. The maximum crush between the two runs varies by ~1%.

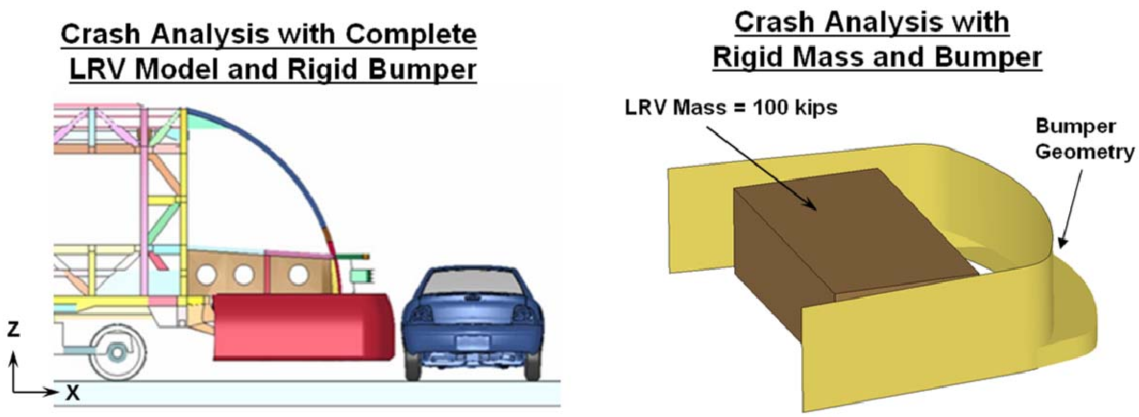


Figure 18. LRV and bumper models used for crash analyses.

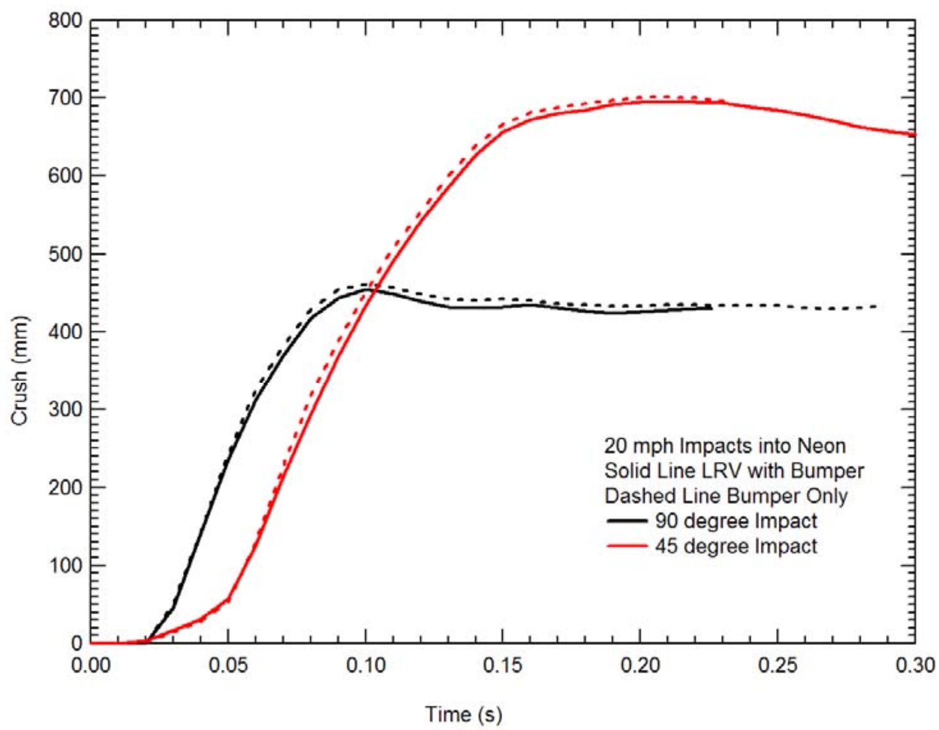


Figure 19. Comparison of LRV and bumper simulation against bumper only simulation.

4.3 Bumper Geometry Design Parameters

Four geometric design parameters were considered for the front end bumper profile, as shown in Figure 20. These are:

1. Height above the ground (HAG) – varied from minimum for operation (23.5 cm) to just above the bottom of the Neon door.

2. Bumper height (BH) – maximum height the same as the head girder on the Siemens S70 LRV.

3. Profile transition slope angle (ANGLE) – varies degree of loading horizontally and vertically.

4. Bumper forward extension distance (DEPTH) – maximum chosen such that for most bumper heights, the vehicle is only impacted by this portion of the bumper if no angle is present. The minimum engages both vertical portions of the bumper, but with significant load still in the lower portion.

The bumper total height above the ground (TAG) was kept constant at the height of the head girder on the Siemens S70 LRV. The minimum, maximum and baseline values studied for each variable are also shown in Figure 20.

	Min -1	Base 0	Max +1
HAG	23.5 cm	35.5 cm	47.5 cm
BH	14.6 cm	27.9 cm	73.4 cm
DEPTH	15 cm	22.5 cm	30 cm
ANGLE	30°	0°	60°

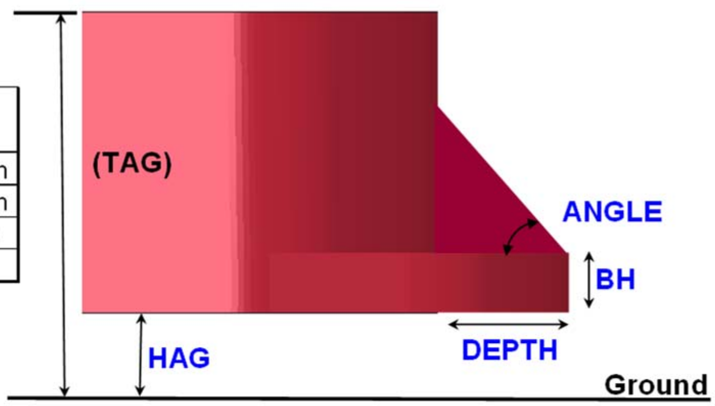


Figure 20: Bumper front end profile design parameters.

A set of potential geometric designs for the bumper were developed that used appropriate bounds established from vehicle operational requirements. Various potential bumper designs were evaluated at 24.1, 32.2 and 40.2 km/hr (15, 20 and 25 mph) impact speeds for 90 degree impacts with the Dodge Neon and Ford Explorer to establish a design impact speed. An impact speed of 32.2 km/hr (20 mph) was selected to refine the bumper design. It is at this speed that there are significant probabilities that ‘Serious’ to ‘Severe’ injuries can occur to the vehicle occupants.

From these preliminary results, five bumper geometries were developed for further study, as shown in Figure 21. It was clear even from the low speed impacts that the lowest HAG offered the best performance, so only the lowest value was considered. Likewise, the maximum depth always improves performance. Performance of these five profiles was evaluated as compared to an existing bumper design used on LRVs in operation, bumper 6, also shown in the figure.

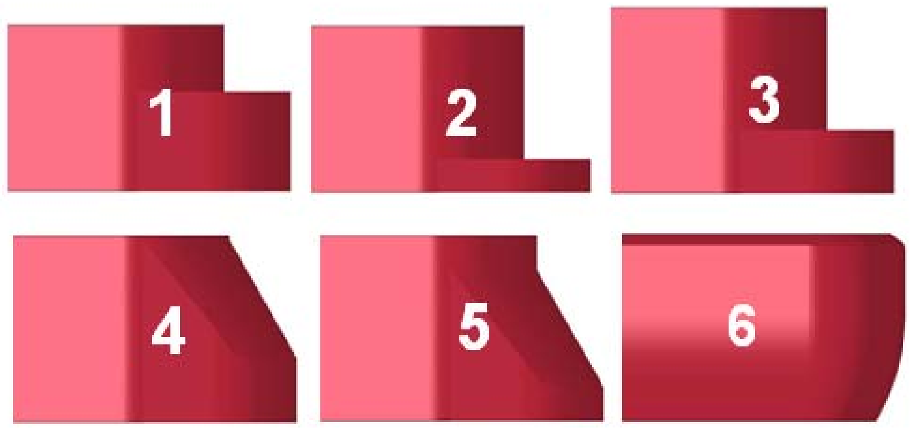


Figure 21. Bumper profiles considered in the geometry study.

4.4 Bumper Geometry Performance Results

The six bumper profiles shown in Figure 21 were evaluated at 32.2 km/hr (20 mph) for 90 degree impacts. These were compared to impacts from an S70 LRV with no bumper and with exiting bumper geometry, bumper 6. Three measures of injury were evaluated from the response of the SID; thoracic, pelvis and head injury. Detailed results from the SID response were correlated with probability of injuries to the head and thorax. Pelvic injury is not typically evaluated in this way, but rather uses a pelvic fracture criterion of 130 g without any associated distribution of probabilistic uncertainty.

The calculated injury probabilities for 32.2 km/hr (20 mph) 90 degree impacts are shown in Figure 22 to Figure 24. The evaluations of the various bumper profiles found that for the 90 degree impact simulations that bumper profile 4 and 5 provided the best performance for the Neon and Explorer, showing marked reductions in injury probability in all three body regions. This improvement was most significant in the thorax. Additional impact analyses were then performed for the Crown Victoria and RAV4 in order to evaluate which bumper profile was best for a broader variety of vehicles. Bumper profile 5 still yielded good results, but profile 4 was best overall. Reductions in the probability of thoracic injury exceeded 80% for several vehicles. This is a very significant improvement in injury potential. Probability of serious head injury was also improved for all vehicles while pelvic accelerations are well below the level for pelvic fracture.

A model of a bumper with profile 4 is shown on the front of the S70 LRV in Figure 10, demonstrating an aesthetic design and its geometric compatibility with the Neon. The figure shows that the bumper engages low on the vehicle with the initial crush occurring at a level approximately aligned with the rocker panel. Vehicle and SID responses are compared to impacts with the S70 LRV without a bumper, respectively, are shown in Figure 26. Note that the vehicle structure is engaged below the occupant with Bumper 4, where impact occurs roughly shoulder height without. The bumper 4 geometry results in a smooth intrusion into the vehicle across the pelvis and thorax. At late time for the low Neon, the occupant ends up under the vehicle when no bumper is used.

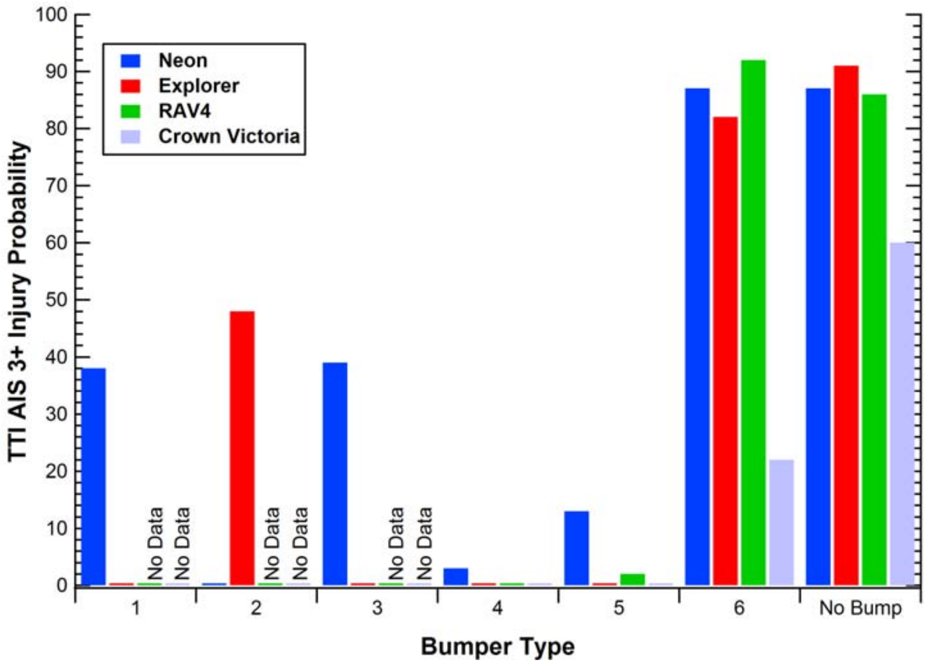


Figure 22. Probability of 'Serious' (AIS 3+) thoracic injury from 32.2 km/hr (20 mph), 90 degree impacts.

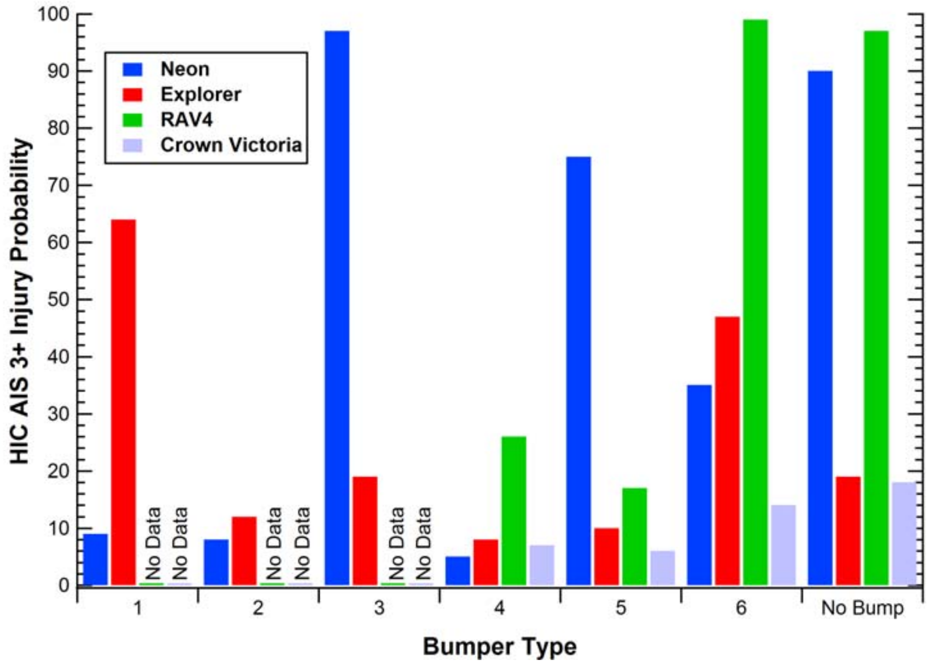


Figure 23. Probability of 'Serious' (AIS 3+) head injury from 32.2 km/hr (20 mph), 90 degree impacts.

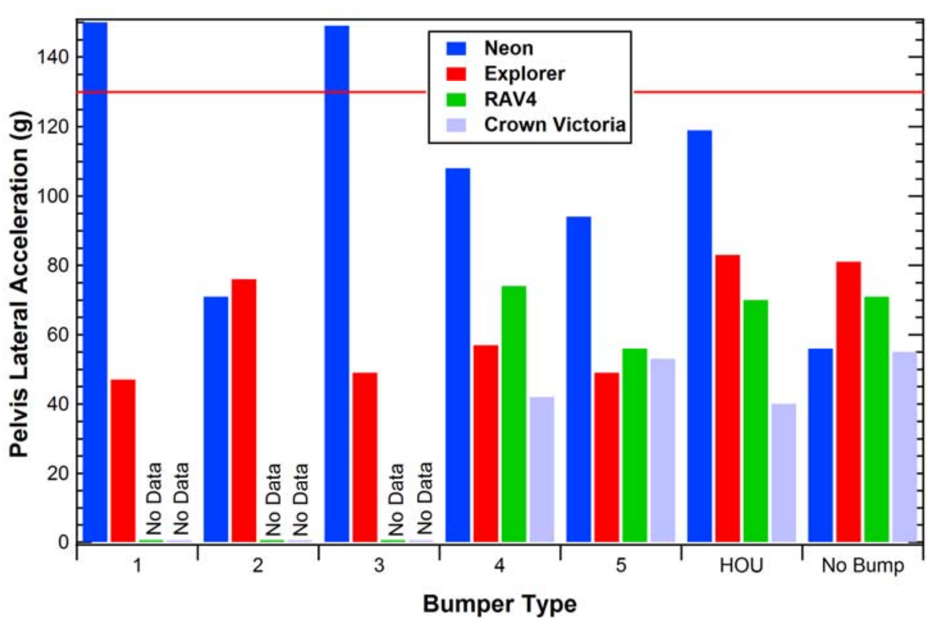


Figure 24. Pelvis acceleration from 32.2 km/hr (20 mph), 90 degree impacts.

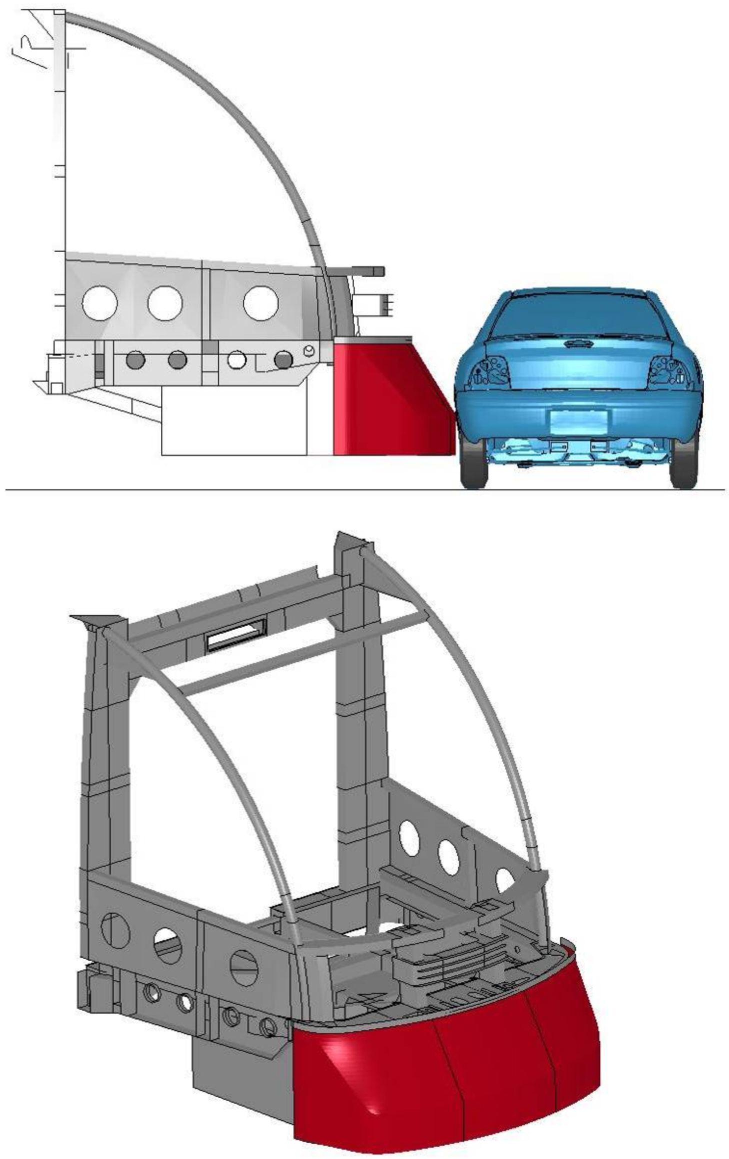
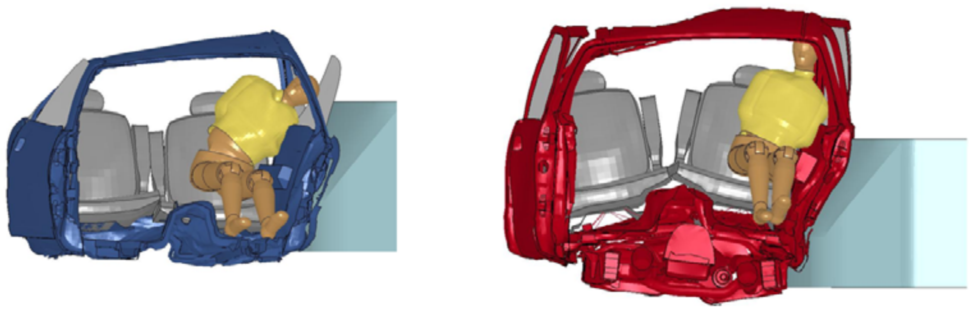
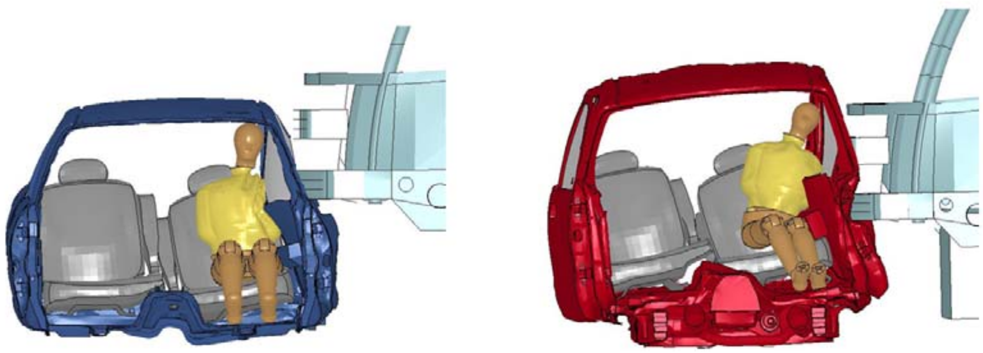


Figure 25. Bumper 4 shown on the front of S70 LRV.

Vehicle response at late time is shown in Figure 27. Note that there is no override of either automobile when impacted by bumper 4. There is also no significant lifting or roll of the impacted automobile. These improved collision kinematics resulting from the Bumper 4 profile are also important when considered along with the initial injury measures. They show that the potential for additional injuries at later times should be reduced as well. Bumper profile 4 was selected for the segmented bumper design.

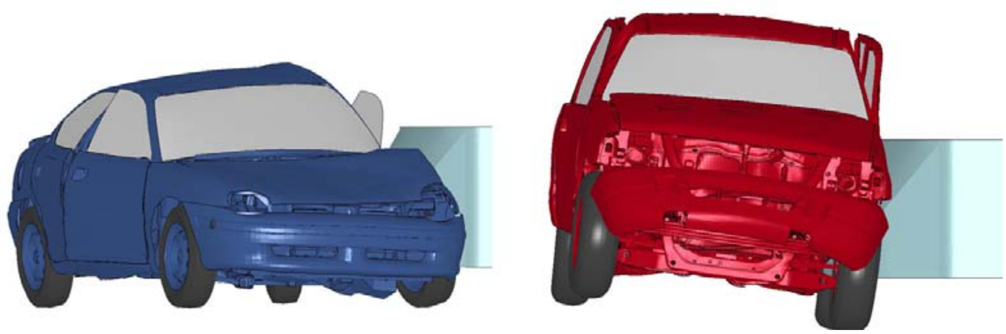


(a) Bumper 4

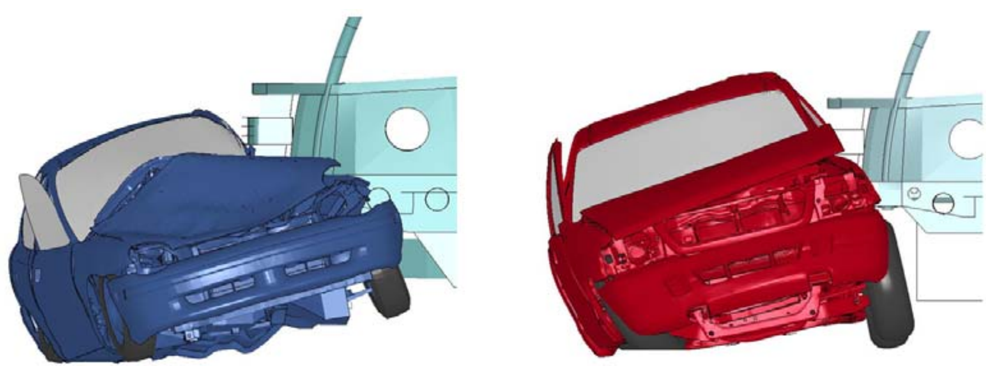


(b) No Bumper

Figure 26. Vehicle and SID response at the time of peak injury.



(a) Bumper 4



(b) No Bumper

Figure 27. Neon and Explorer response at late time.

Section 5 Segmented Bumper CEM Design Study

The objective of this study was to demonstrate the potential improvements to crash response by segmenting the bumper and adding crash energy management (CEM) features to the design. The focus was on sizing of CEM components and functionality requirements of bumper hardware. For this purpose, the simplified model of a segmented bumper, discussed in the next section, was used with the bumper profile that provided the best results from the bumper geometry study (bumper profile 4). The initial simulations performed with a 45 degree impact angle showed that injuries were greatly reduced from that without a bumper. As the objective is to further reduce 'Serious' (MAIS 3+) or 'Severe' injuries (MAIS 4+), the impact speed was increased to 42.2 km/hr (30 mph) for the 45 degree impact. In this way, reductions in these types of injuries could be investigated.

5.1 Simplified LRV and Bumper Model – Segmented Bumper Study

The approach used for the segmented bumper design study was the same as that used for the geometry study where a simplified bumper model was developed, as shown in Figure 28 . The model included the rigid LRV mass attached to the bumper. Hinges were placed in the bumper so that the corners could actuate. Hinges were modeled using *CONSTRAINED_JOINT_ REVOLUTE in LS-DYNA. Energy absorbers were attached to the center and corner bumpers by attaching nonlinear spring elements between the bumper and the trailing mass using nonlinear discrete elements. The trailing mass was constrained to only translate in the direction of travel.

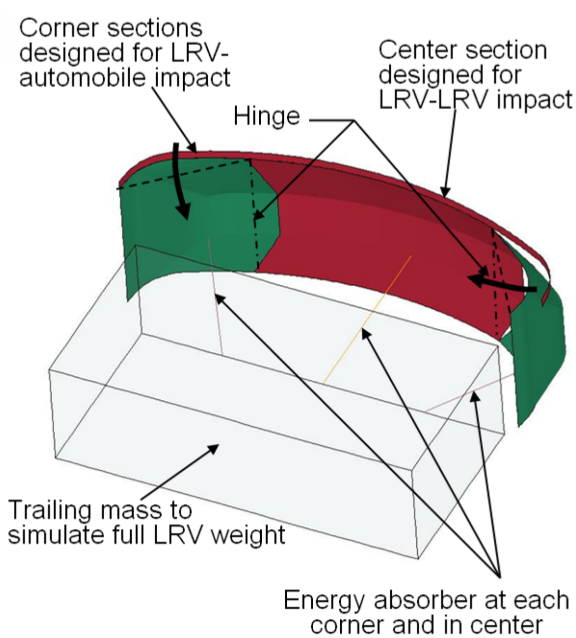


Figure 28. Simplified model of segmented bumper with trailing LRV mass.

5.2 Segmented CEM Bumper Design Parameters

Three parameters were considered in the design of the segmented bumper. These are the center bumper width, the size of the corner energy absorbers, and their stroke length. The two variations considered for the center bumper width are shown in Figure 29. The larger center bumper width was selected to potentially accommodate the use of a design where only the center portion of the bumper is moved when two LRVs are coupled together. The design requires this bumper width in order to provide clearance for the swing envelope of the coupler in operational conditions. In this design, the corner bumpers would not need to be raised and lowered, simplifying the front end structures needed.

Variations in the size (i.e. force limit) for the corner energy absorbers were selected based on the force-crush behavior of the four vehicles considered when impacted at 45 degrees at 40.2 km/hr (25 mph) with the bumper 4 geometry. These force-crush behaviors are shown in Figure 30. Force limits of 30, 60, 90 and 120 kN (6.7, 13.5, 20.2, and 27.0 kips) were selected based on the approximate peak crush forces seen in the various automobiles considered during the time the SID is initially impacted. The load-displacement curves applied to the idealized energy absorbers used in the simulations is also shown in the figure with dotted lines.

The maximum stroke length of the energy absorber may be limited in some LRV designs by interference with existing structures. Limiting the stroke could have a positive or negative impact on the injury response, depending on the vehicle. For these reasons, limits on the stroke were considered for a 10.16, 20.32, 30.48 cm (4, 8 and 12 inch) stroke.

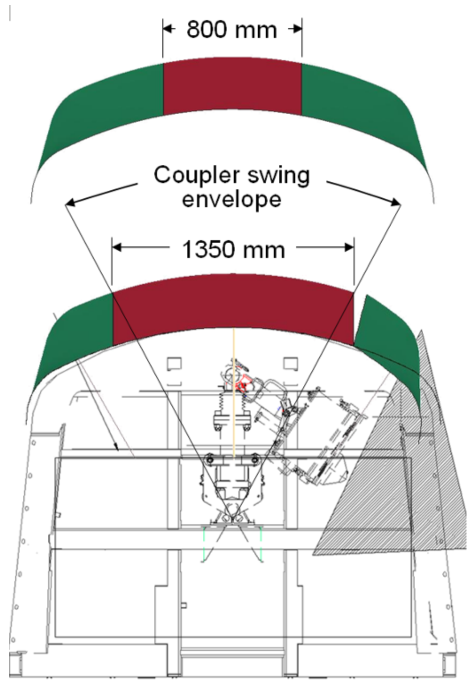


Figure 29. Plan view of segmented bumper notionally attached to the front end of an S70 LRV with swinging coupler.

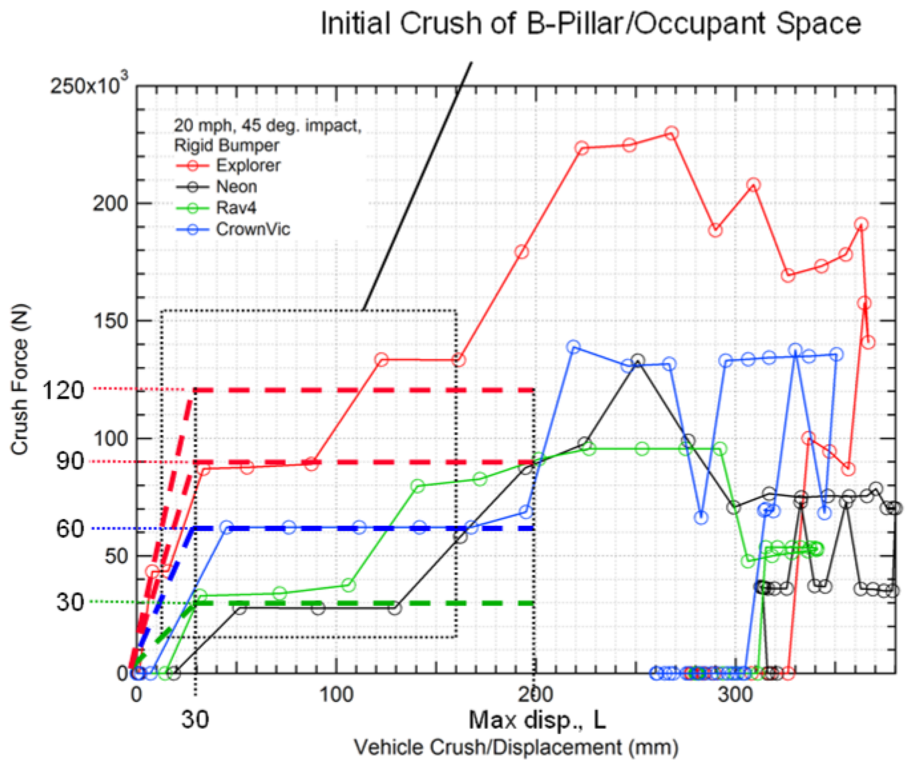


Figure 30. Force-crush behavior of the Neon, Rav4, Crown Victoria and Explorer when impacted at 40.2 km/hr (25 mph), 45 degrees with bumper 4.

5.3 Bumper Performance Results

5.3.1 Center Bumper Width

Detailed injury measures for the SID were assessed for a 45 degree impact at 48.2 km/hr (30 mph) for both center bumper widths. Probabilities of injury to the head and thorax as well as pelvic acceleration were determined, as shown in Figure 31 to Figure 33. There was not a significant effect on pelvic accelerations, where all remained well below the injury threshold. The 0.8 m width reduced the probability of injury for the Neon, but increased it drastically for the Explorer with negligible effect on the other vehicles. The probability of head injuries were reduced by using a less wide center bumper for the RAV4 and Explorer, but it increased the probability for the Neon. These are mixed results. There does not appear to be a clear reason in terms of injury probability to select either center bumper width and may be best left to operational considerations.

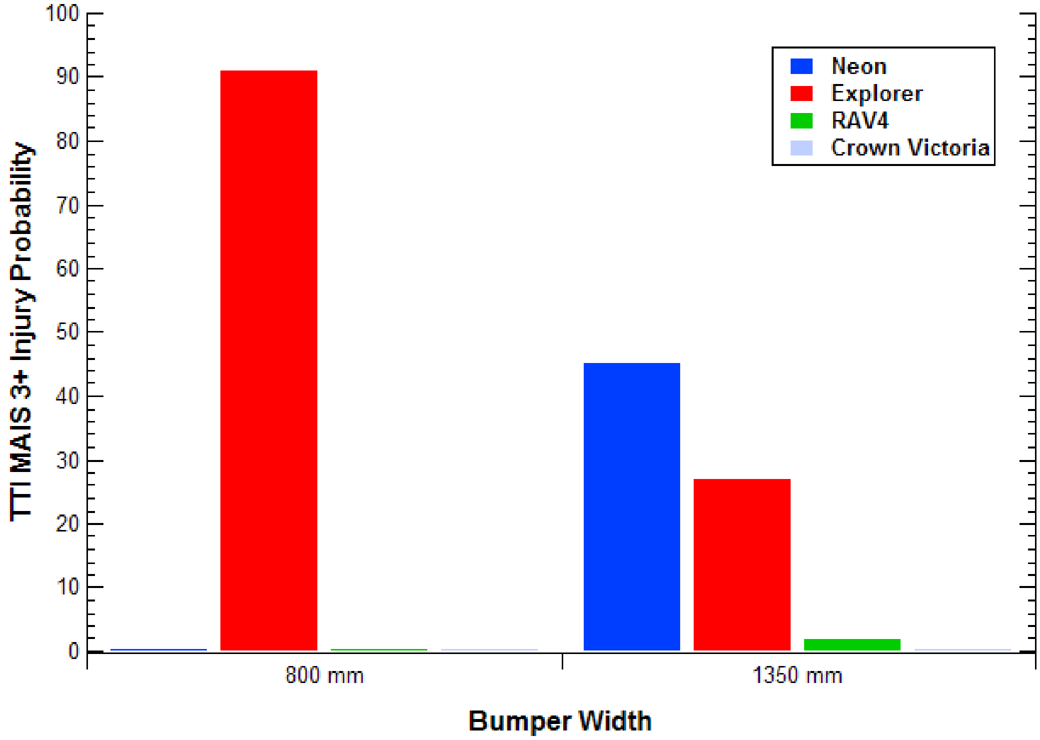


Figure 31. Probability of 'Serious' (AIS 3+) thoracic injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of bumper width.

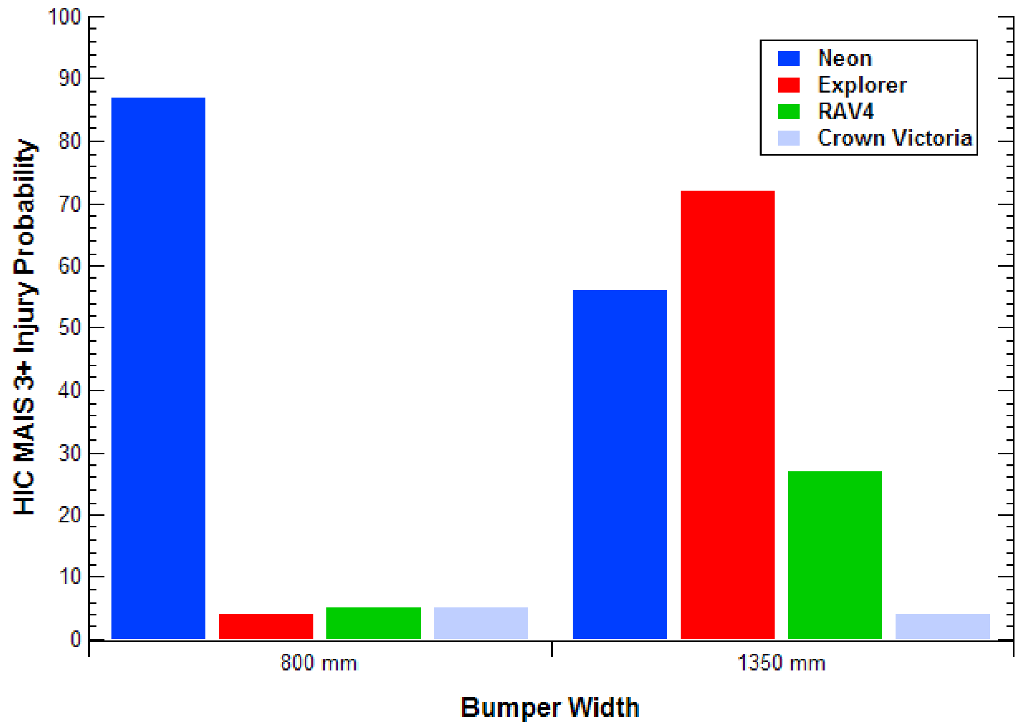


Figure 32. Probability of 'Serious' (AIS 3+) head injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of bumper width.

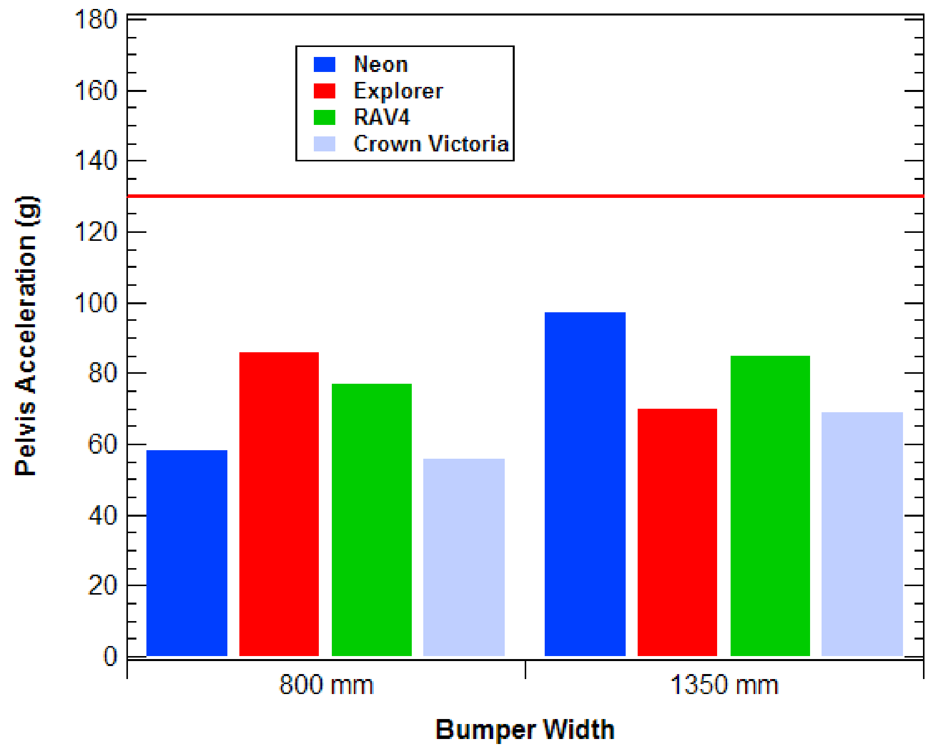


Figure 33. Pelvis acceleration from 48.2 km/hr (30 mph), 45 degree impacts as a function of bumper width.

5.3.2 Sizing of Corner Energy Absorbers

In order to determine the best size (force limit) for the corner energy absorbers, detailed SID injury measures were assessed for a 45 degree impact at 48.2 km/hr (30 mph). Once again, probability of injuries to the head and thorax as well as pelvic acceleration was determined, as shown in Figure 34 to Figure 36 for various force limits. Actual force-stroke behavior from an existing coupler was used for the center energy absorber. The rigid bumper (un-segmented and no corner actuation) collision response and injury measures were calculated and provided in the figures for comparison.

The segmented design clearly increases the performance of the bumper as compared to a rigid bumper when the correct energy absorbers are used. The optimal force limit, however, appears to depend on the vehicle and injury type. For example, approximately 90 kN appears best for the thorax and 120 kN for head. Results for the Crown Victoria do not follow a clear trend as in the other vehicles. There is an increase in thoracic and head injury probability at a force limit of 120 kN above that of a rigid bumper. It decreases again to below the rigid case at 90 kN. A 90 to 100 kN force limit appears to be the best choice. A 90 kN force limit was selected for the prototype design.

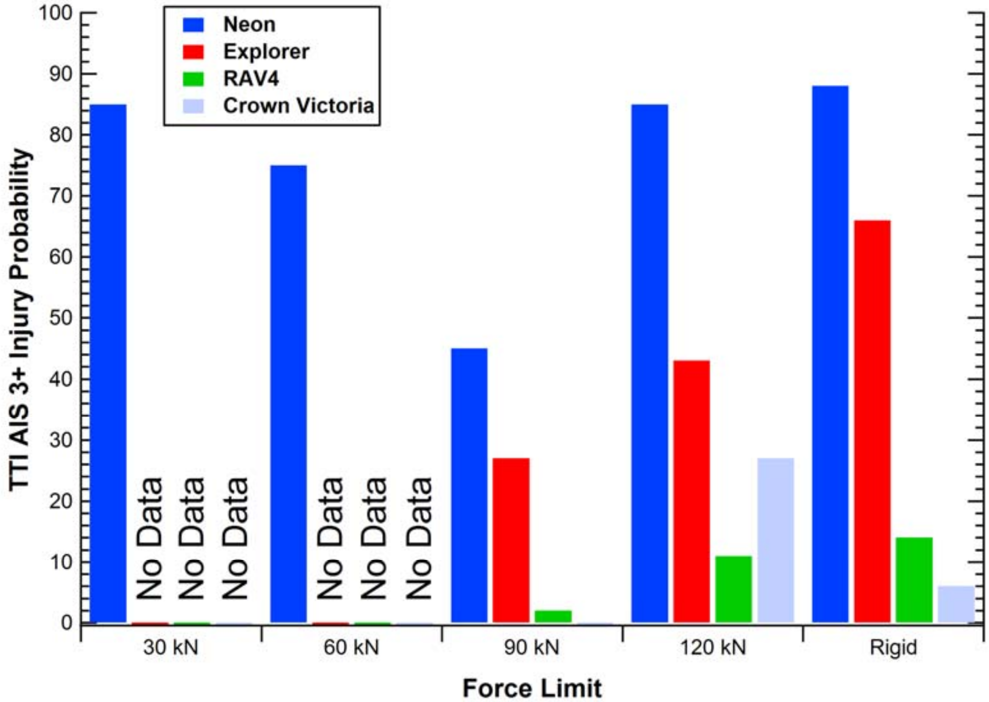


Figure 34. Probability of 'Serious' (AIS 3+) thoracic injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber force limit.

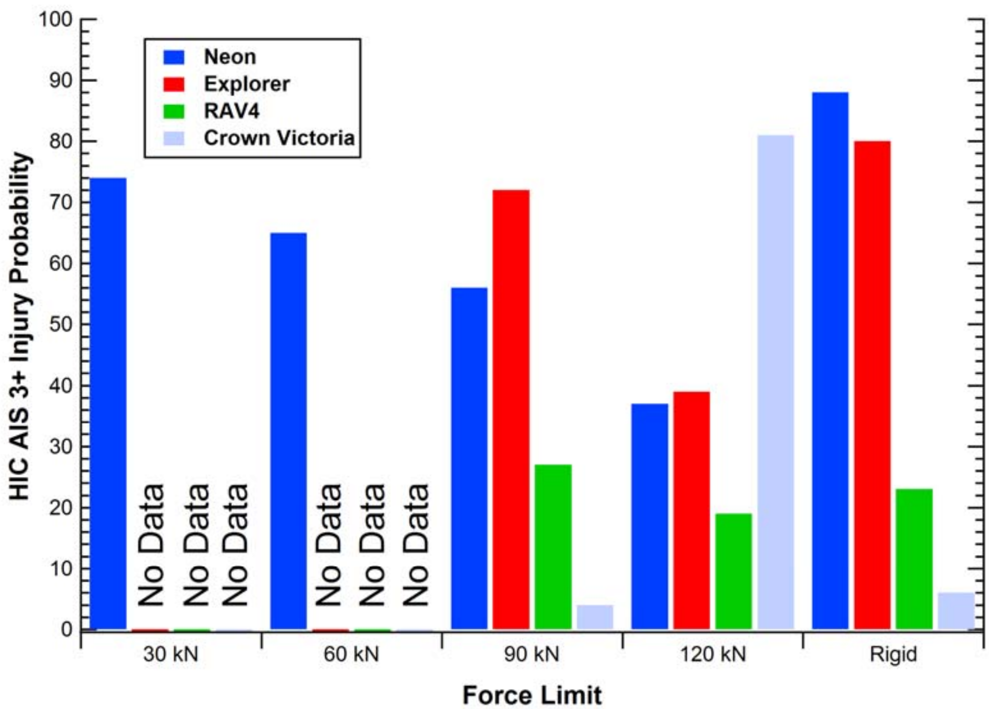


Figure 35. Probability of 'Serious' (AIS 3+) head injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber force limit.

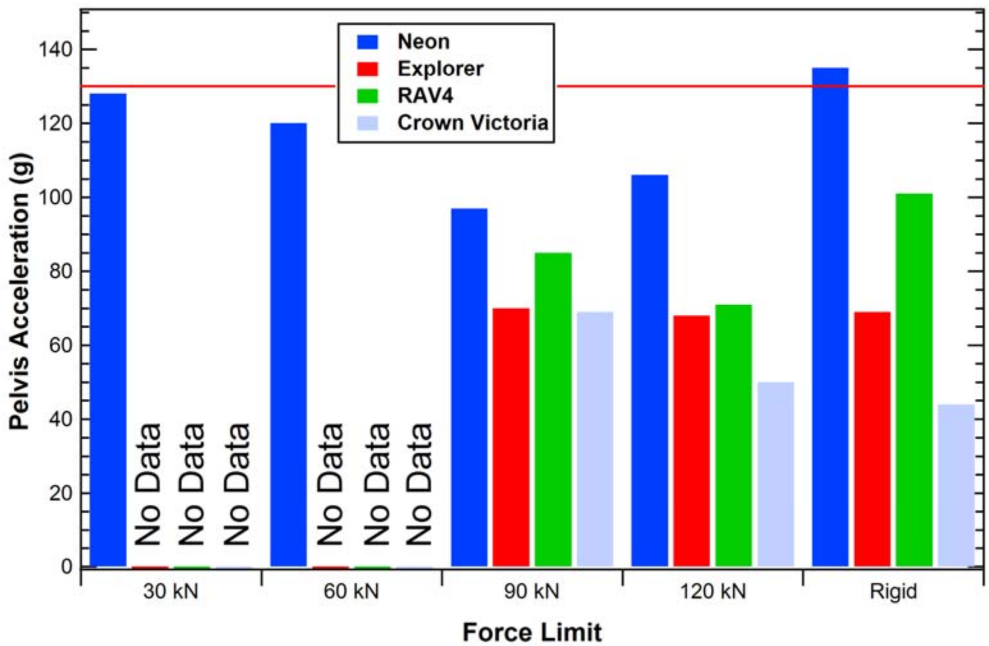


Figure 36. Pelvis acceleration from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber force limit.

5.3.3 Corner Energy Absorber Stroke

In determining the best force limit for the energy absorbers, the maximum stroke never exceeded 10.16 cm (4 inches) for the 90 kN energy absorber on any of the vehicles except the Ford Explorer (Neon: 8.6 cm, RAV4: 6.6 cm, Crown Victoria: 6.4 cm). In some cases the loads were not high enough and in others the head girder engaged the vehicle, limiting the stroke. The stroke limits therefore would have no effect on any but the Ford Explorer. The effect of absorber stroke was only considered for this vehicle type.

Injury results for occupants in the Ford Explorer with 90 kN and 120 kN energy absorbers with stroke lengths limited to 10.16, 20.32, 30.48 cm (4, 8 and 12 inch) are shown in Figure 37 through Figure 39. Since the 90 kN energy absorber appears to provide the best performance, the discussion will be focused on these results. There is little to no effect on pelvic accelerations. The probability of thoracic injuries is greatly reduced by allowing the absorber to stroke beyond 10.16 cm (4 inches), but limited to 20.32 cm (8 inches). Allowing a full 30.48 cm (12 inch) stroke increases the probability of injury again. For head injuries, we see the opposite trend where the 30.48 cm stroke limit offers the best performance. Without further study on other vehicles where the stroke exceeds 10.16 cm (4 inches), or for other impact points, there does not seem to be a clear argument for limiting the stroke length.

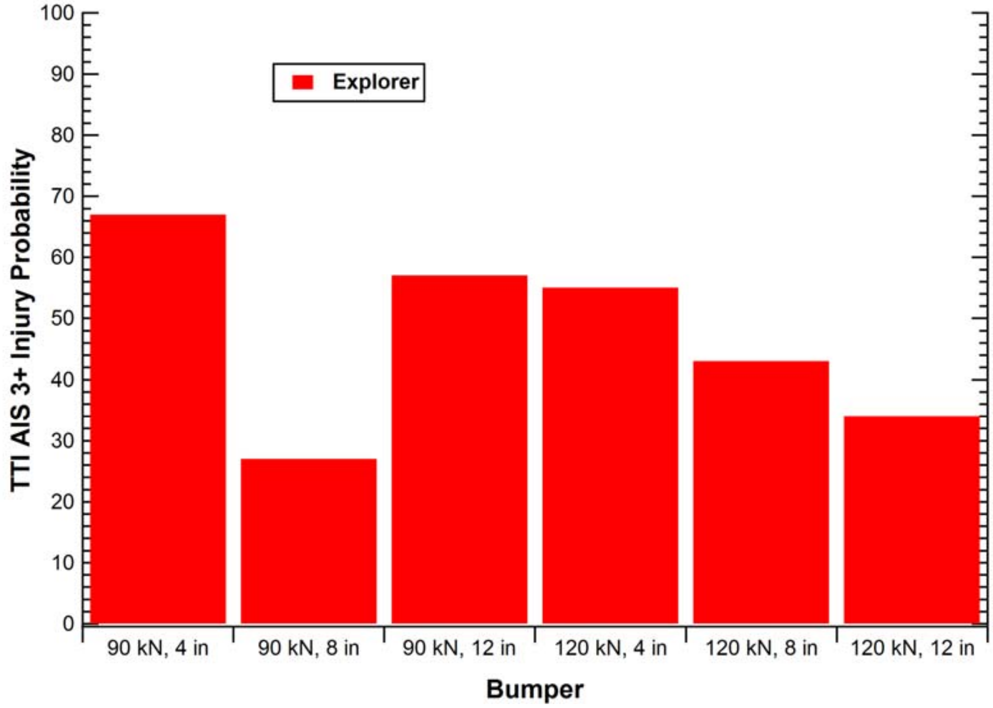


Figure 37. Probability of 'Serious' (AIS 3+) thoracic injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber stroke limit.

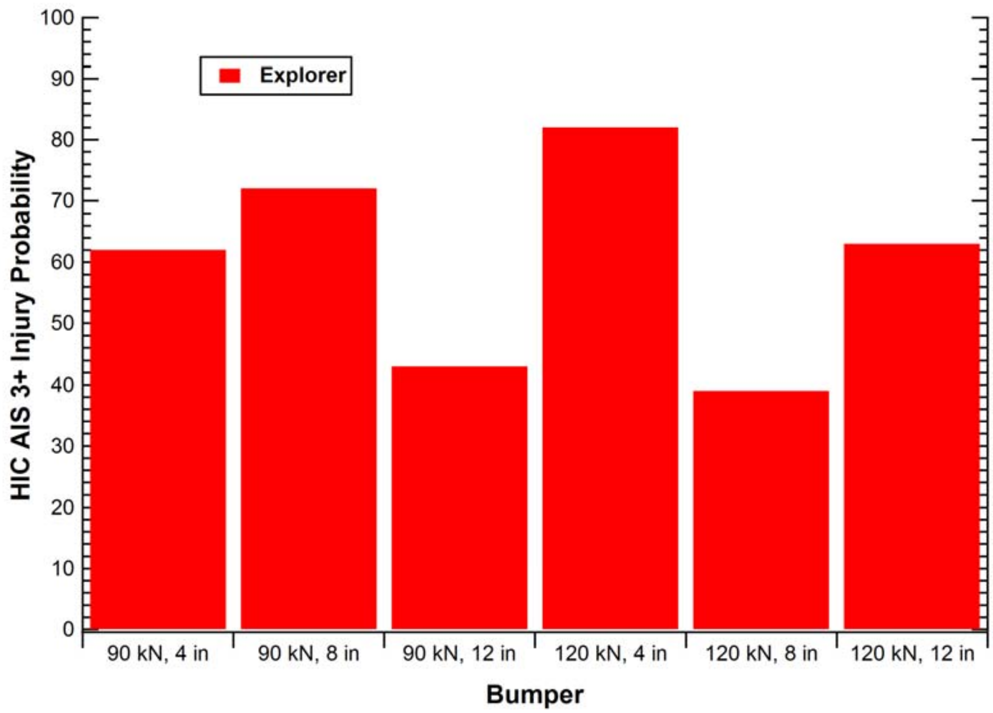


Figure 38. Probability of 'Serious' (AIS 3+) head injury from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber stroke limit.

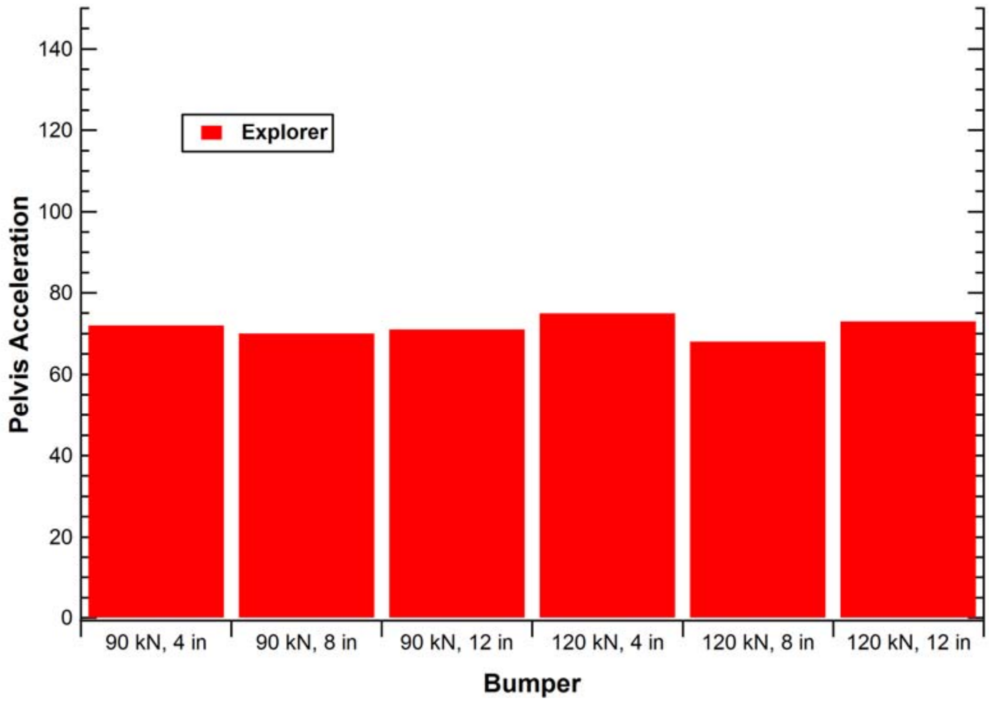


Figure 39. Pelvis acceleration from 48.2 km/hr (30 mph), 45 degree impacts as a function of energy absorber stroke limit.

Section 6 Design of the Prototype Segmented Bumper

6.1 Conceptual Design for Integrating a CEM Segmented Bumper

Two design concepts were considered for integrating a segmented bumper with energy absorption capability into the front end of LRVs. The first design concept utilizes a bumper with a folding coupler. In this design the corner bumpers remain fixed, but the center bumper is raised and lowered when needed during operation to deploy the coupler. This design would provide a relatively easy and cost-effective approach to retrofitting an LRV for a folding coupler.

A second option for bumper functionality was also developed that offers an even simpler bumper design that does not involve raising and lowering the bumper to couple with another LRV. For LRVs that can use a shorter coupler, the coupler head could be directly integrated into the bumper so that the entire bumper swings with the coupler. In order to allow the entire bumper to swing, the corner energy absorbers can be attached to the coupler pivot or close to the coupler anchor, as shown in Figure 40. In order to support the potentially high vertical loads on the bumper during impact with an automobile, a radial coupler bar could be added as shown in the figure. The functionality of this bumper design for automobile and LRV impacts is shown in Figure 41. During operation, when coupled to another LRV, the bumper would swing as shown in Figure 42. This latter design was chosen for the prototype bumper design analysis.

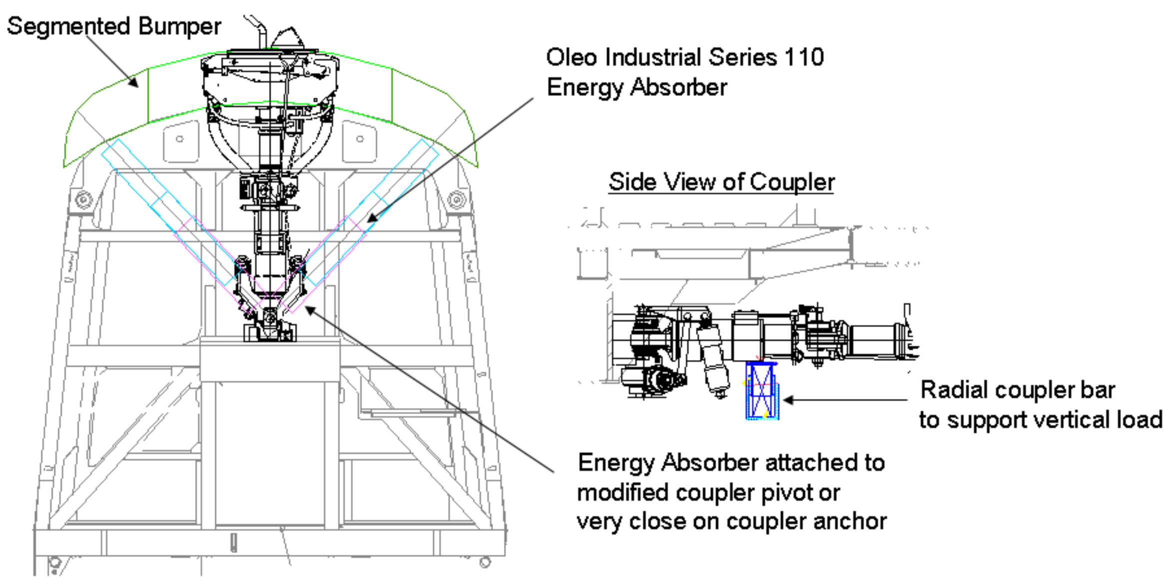
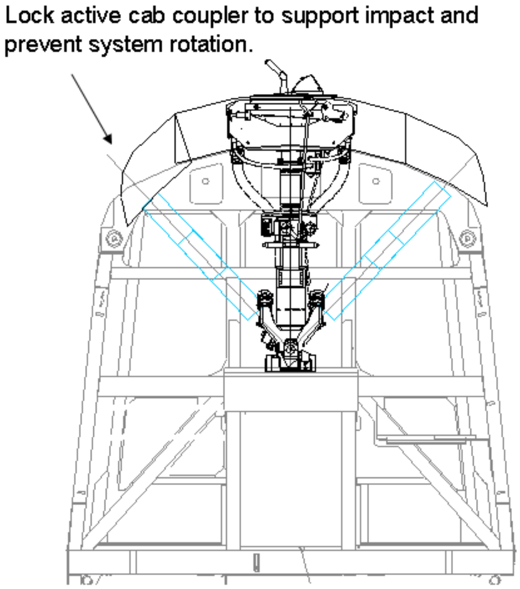
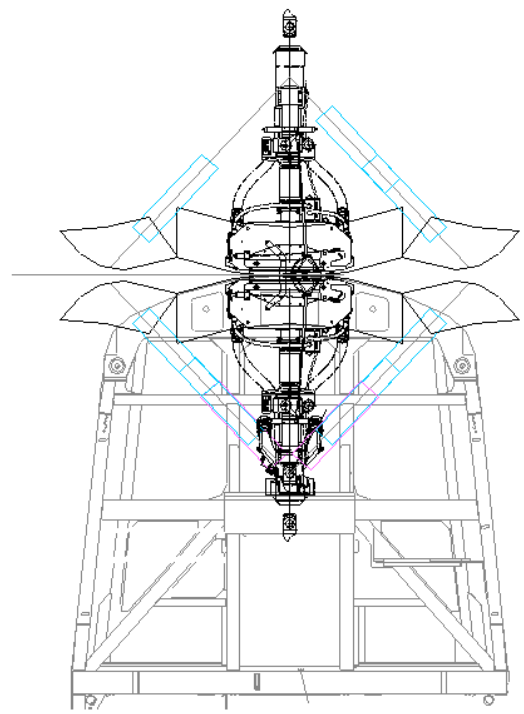


Figure 40. Segmented bumper retrofit conceptual design.



(a) Auto impact



(b) LRV-LRV impact

Figure 41. Segmented bumper retrofit conceptual design functionality in auto and LRV impacts.

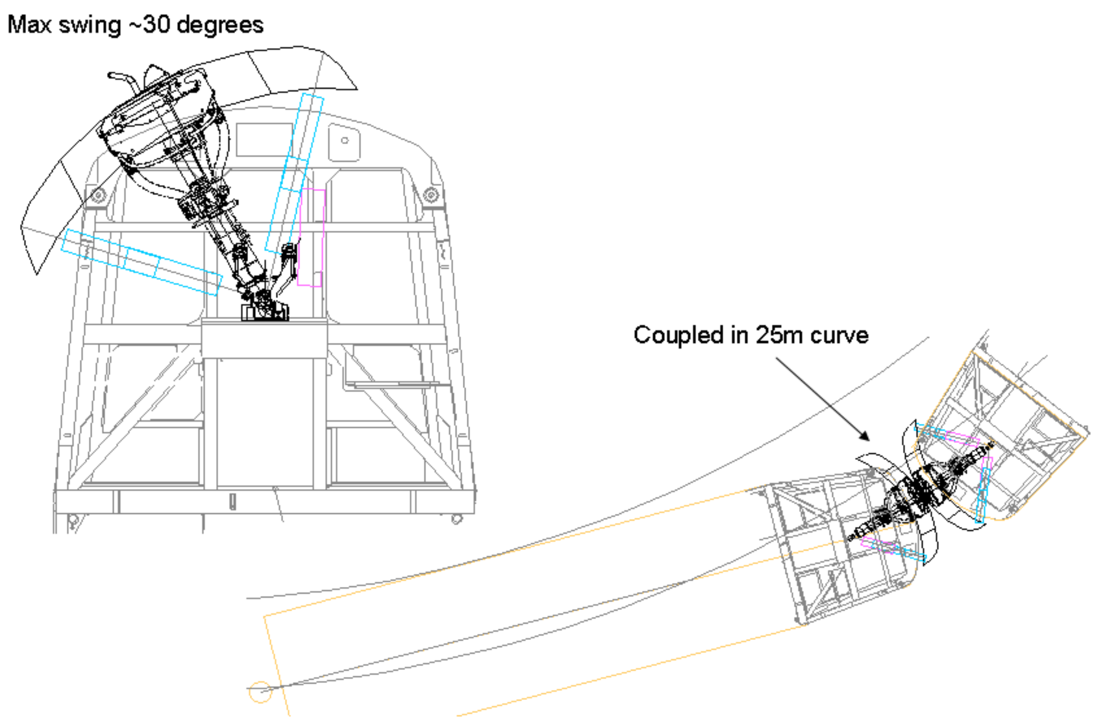


Figure 42. Segmented bumper retrofit conceptual design functionality during coupled operation.

6.2 Selection of Corner Energy Absorbers

Based on the segmented bumper CEM design study results, the best characteristics for the corner energy absorbers are to provide a 90 to 100 kN peak load with a stroke of 20.3 cm (8 inches) or more. Several hydraulic energy absorbers produced by Oleo International were considered. A hydraulic energy absorber was selected because it is fully recoverable after impact, minimizing the amount of repair time to an LRV after an accident. The products made by Oleo International were considered because they can be tuned for a specific response.

The Industrial Heavy Duty Series, Industrial Light Duty Series and Industrial Series 110 energy absorbers were considered. The Series 110 and Heavy Duty Series provide the right combination of peak load capacity (>350 kN) and maximum stroke (20 cm). Use of an absorber with a peak load capacity more than three times the design load prolongs the life of the absorber. Either product appears to be suitable for the prototype bumper. Final selection would be made based on the specific LRV to be retrofit.

6.3 Prototype Bumper Design

The prototype bumper design retrofit to an S70 LRV is shown in Figure 43. The design includes a fiberglass bumper shell supported by a high-strength steel bumper frame. The corner energy absorbers are attached to the frame and the hinge for the bumper/coupler assembly. The bumper is supported by the coupler through the forward attachment ring around the coupler shaft and connection to the coupler head. The aft attachment ring provides lateral restraint to the coupler. It has pinned restraint links that can be quickly removed to allow the coupler to swing when coupled to another LRV. A hole has been cut into the center fiberglass bumper to allow access to the coupler face, as shown in Figure 44.

The total weight of the prototype design is 280 kg (0.62 kips), which adds approximately 0.6% to the overall LRV weight of 45 Mg (100 kips). This does not include the weight savings that would be obtained if the LRV design already includes a front end enclosure structure that would be replaced by this bumper. In addition, this weight could probably be reduced further with an effort to optimize the design.

The LS-DYNA model shown in Figure 43 includes a simplified model of a typical coupler design and articulating joint, as shown in Figure 45. The model shown includes an articulating joint at the base of the coupler assembly. Similarly, simplified models for the Oleo 110 series energy absorbers were developed, as shown in Figure 46. Both of these models include discrete elements to produce the force-displacement behavior of the energy absorber. Detailed engineering sketches of the entire bumper assembly are shown in Figure 47 to Figure 49.

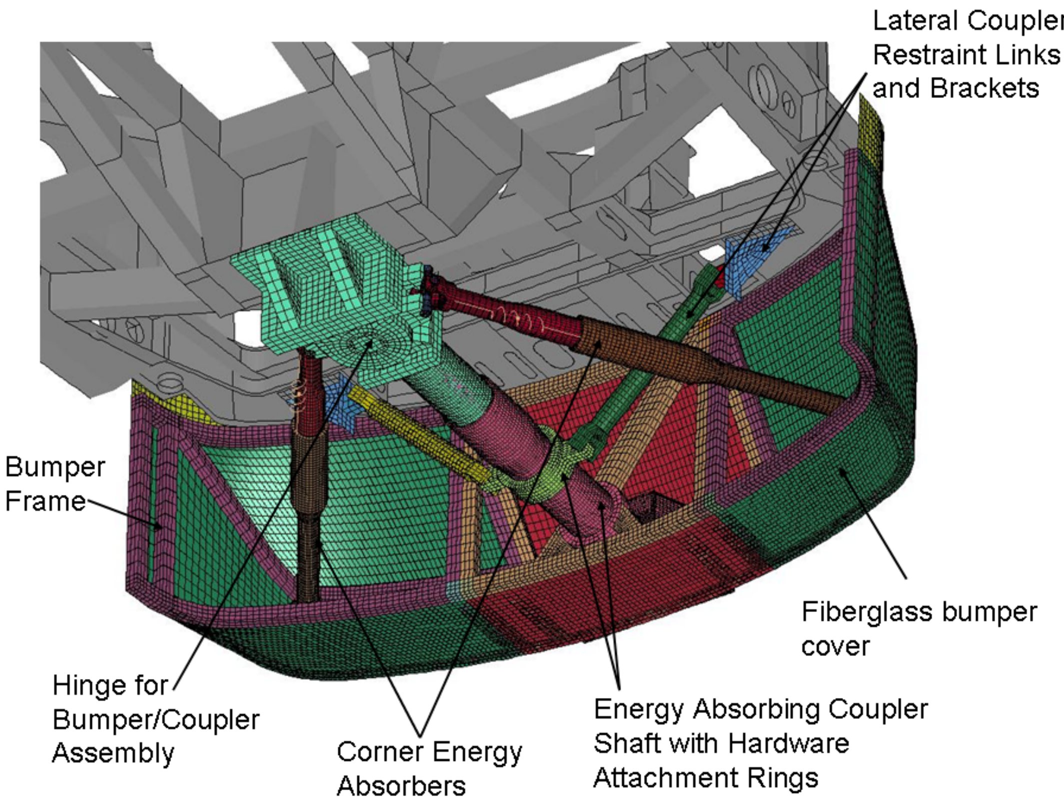


Figure 43. LS-DYNA model of the detailed bumper design retrofit to an S70 LRV.

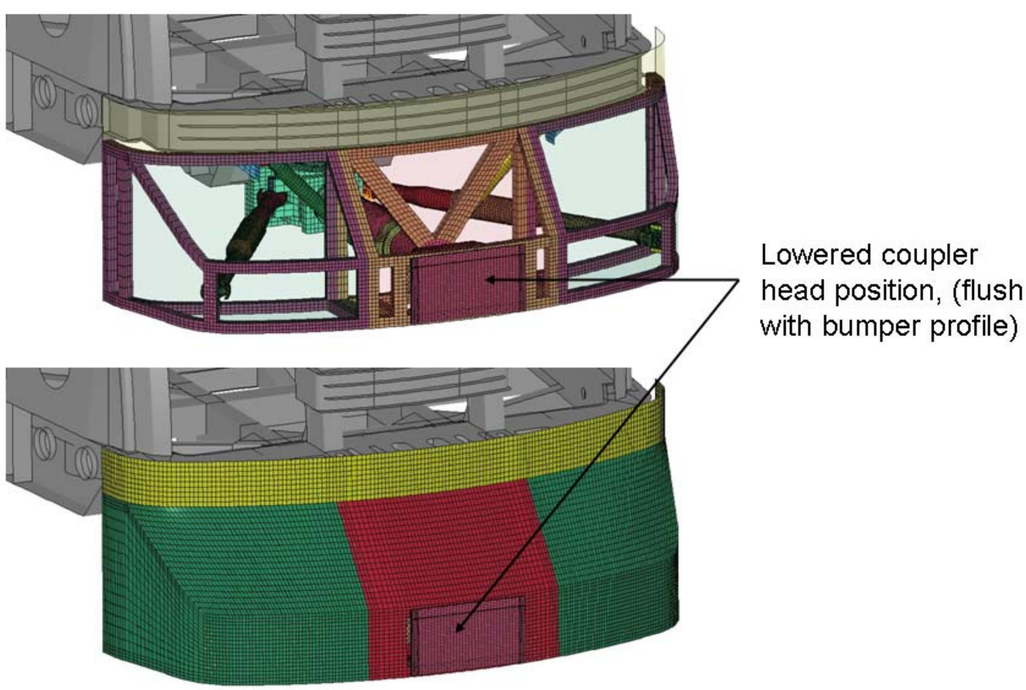
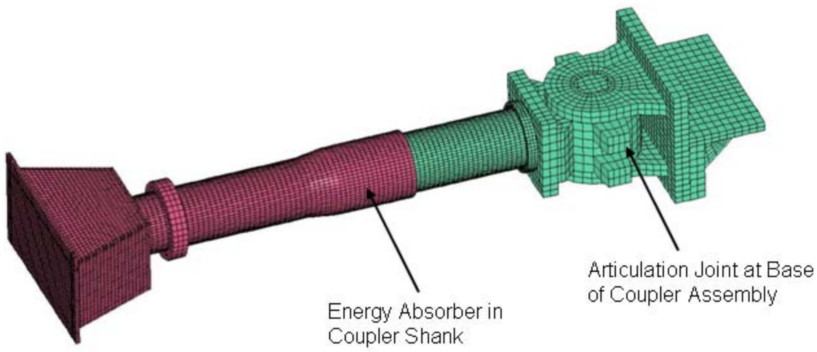


Figure 44. Front view of bumper showing coupler head position with and without the fiberglass cover.

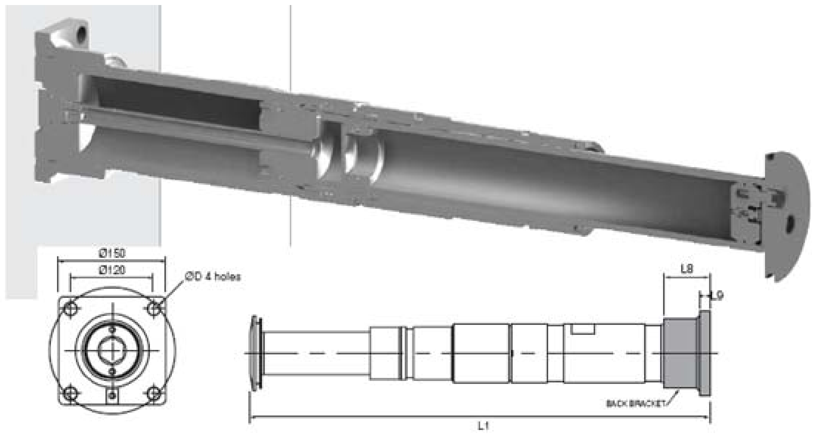
(a) Dellner Automatic Coupler [19]. **(b) Dellner Articulated Coupler Joint [20].**



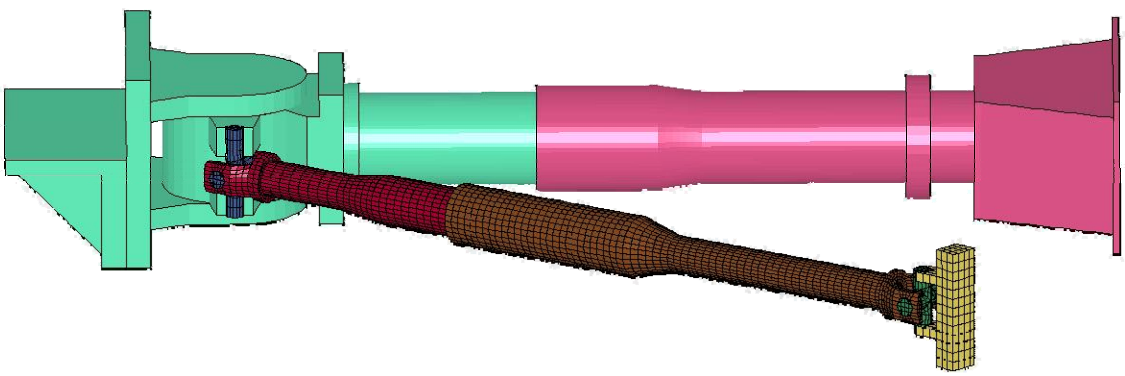
(c) Simplified model of coupler with integrated energy absorber and articulation joint.

Figure 45. Example coupler and simplified LS-DYNA model.

It should be noted that the bumper profile used in the prototype design has been slightly modified in order to retrofit the S70 LRV. The angle of the bumper profile needed to be reduced from 60 degrees to 49.9 degrees in order to accommodate the head girder of the LRV, as shown in Figure 47. This modification does have potentially negative ramifications on the crash performance, as discussed in the next section. In performing this particular retrofit, one may want to make modifications to the existing LRV front end structures for new vehicles in order improve this performance.



(a) Back mounted Oleo 110 Series Industrial Energy Absorber [21]



(b) Simplified model of corner energy absorber with U-Joints at ends

Figure 46. Example corner energy absorber and simplified LS-DYNA model.

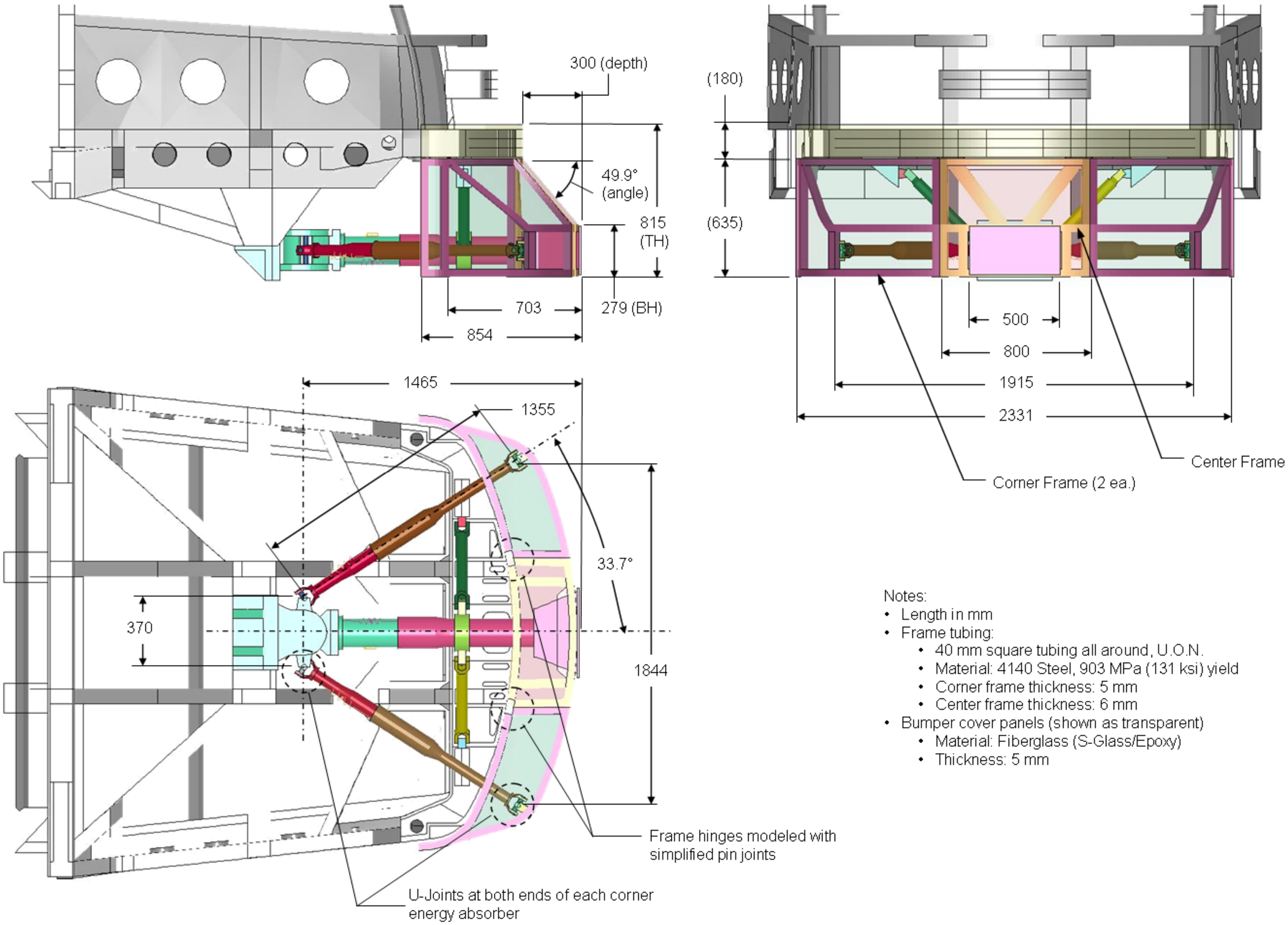


Figure 47. Detailed engineering sketches of the prototype bumper design.

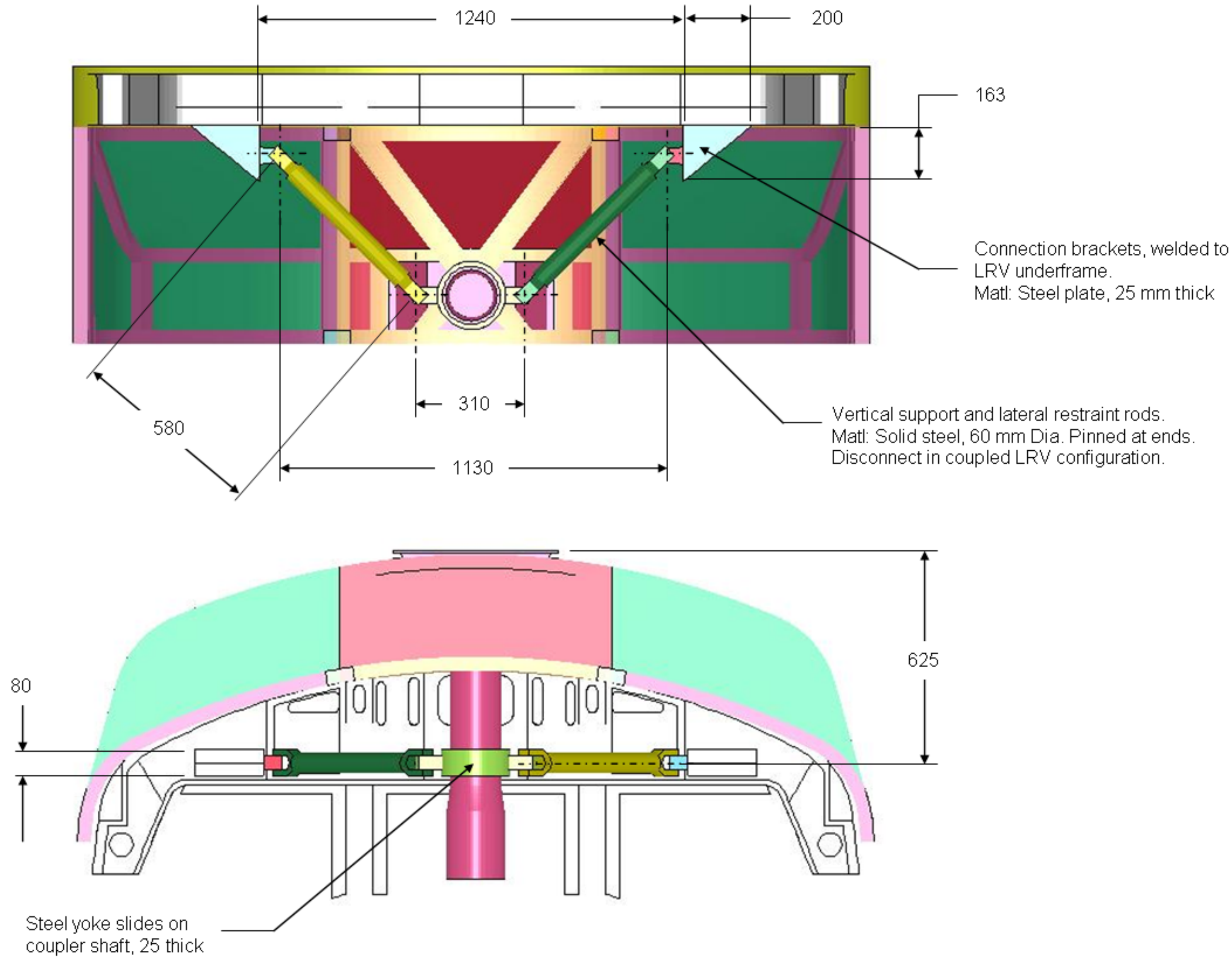


Figure 48. Detail: Lateral/vertical restraint system for uncoupled operating condition.

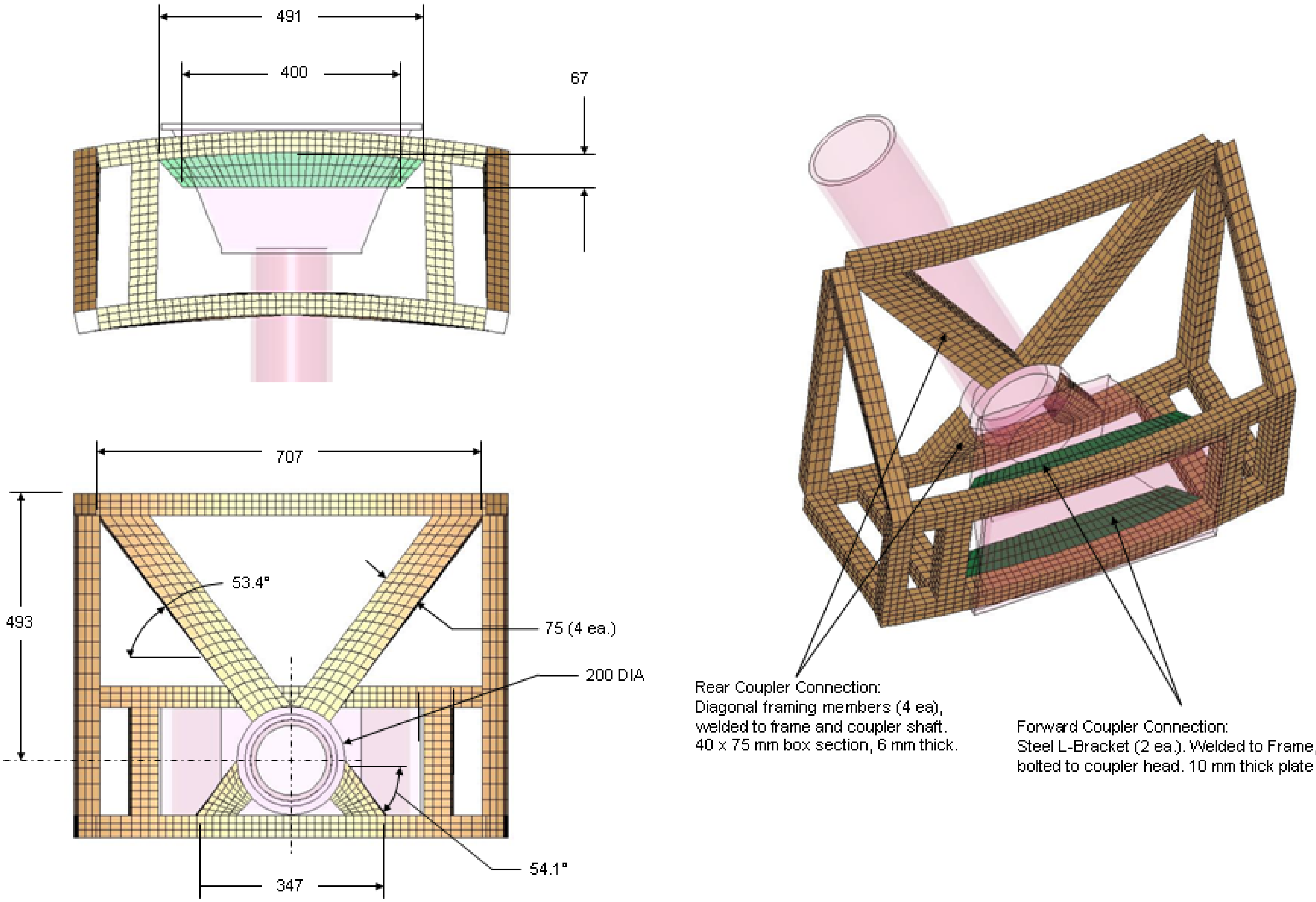


Figure 49. Detail: Connection of center frame to coupler.

6.4 Crash Performance of the Prototype Bumper

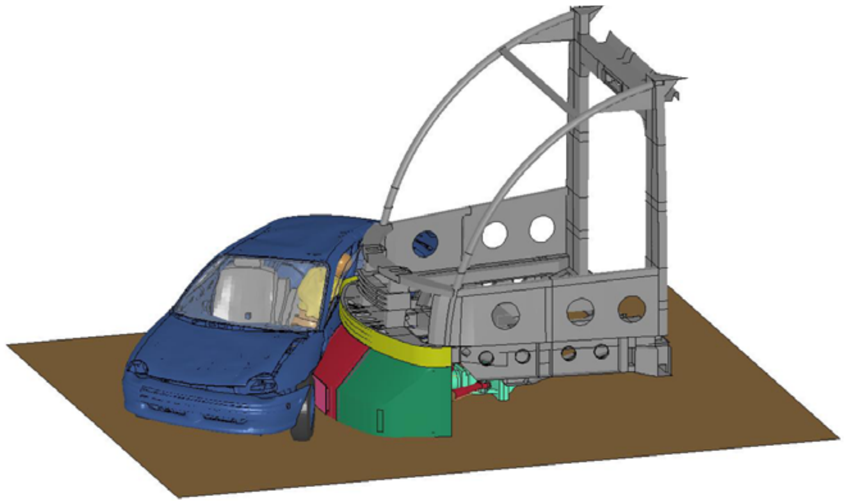
Crash simulations of the prototype bumper design were performed with the Dodge Neon and Ford Explorer at 32.2 km/hr (20 mph) at an impact angle of 90 degrees and at 48.2 km/hr (30 mph) at an impact angle of 45 degrees, as was done in the preliminary design studies. These analyses had two objectives. The first objective was to ensure that the structure of the bumper can survive the crash event. The second objective was to confirm that its performance is similar to that from the simplified bumper analysis. Therefore, detailed injury measures for the SID were assessed. As this particular retrofit required a different angle on the bumper, there are some differences in the crash response. However, the overall collision behaviors analyzed here agree well with the simplified analyses.

Impacts of the S70 LRV retrofit with the prototype bumper on both the Neon and Explorer target vehicles are shown in Figure 50 and Figure 51, respectively. In both simulations, all components of the bumper remain in the material elastic range, minimizing damage to the bumper for the designed impact speeds. For example, the Von Mises stresses in the bumper frame during the impact with the Ford Explorer are shown in Figure 52. Note that the top of the contour range is the yield stress for the high strength steel used. This illustrates that the prototype design will survive collisions with minimal repair costs.

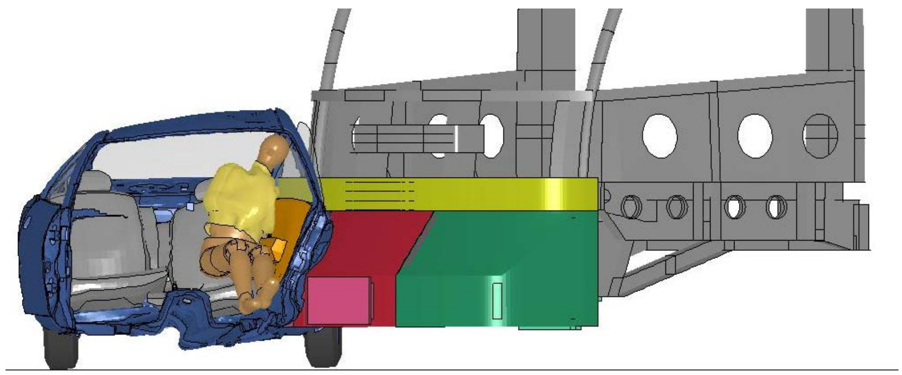
The calculated injury probabilities for 32.2 km/hr (20 mph) 90 degree impacts are shown in Figure 53 to Figure 55. Probability of thoracic injury is greatly reduced when the bumper is retrofit to the S70 LRV for this type of impact and results agree well for the Explorer when compared to the simplified analysis. Note that the prototype bumper retrofit does not perform as well as in the simplified analysis for the Dodge Neon. The reduction in bumper angle results in more intrusion for the Neon in the region of the thorax, leading to the higher injury probability. Further modification of the LRV front end structures to accommodate the 60 degree angle should improve this performance.

The probability of serious head injury is also greatly reduced for the Explorer by adding the prototype bumper and in close agreement with the simplified analysis. Impact with the Neon, however, lead to a much higher probability of head injury. Close examination of this impact shows the occupant head clearly hits the head girder of the S70 LRV, where this did not occur in the simplified analysis with larger 60 degree bumper angle. However, had the occupant been belted or restrained in some other way, this late time head injury event would probably not have occurred.

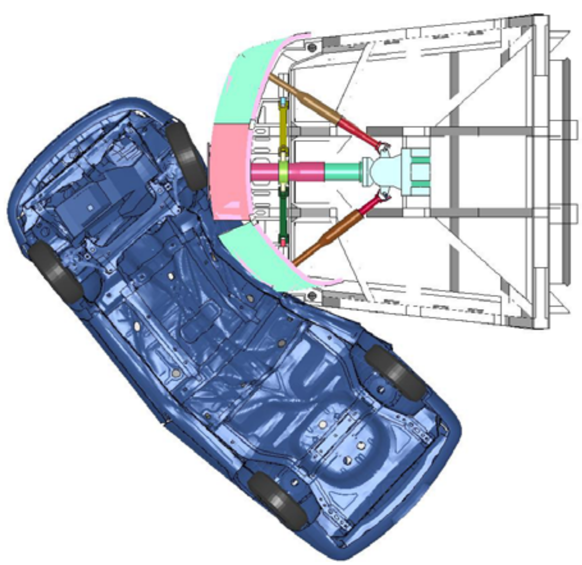
The lower bumper angle also resulted in more intrusion into the Neon, resulting in the larger pelvic acceleration shown in Figure 55. Performance of the bumper for this particular retrofit could be improved through modification to the existing structures to better accommodate a larger bumper angle.



(a) Isometric View

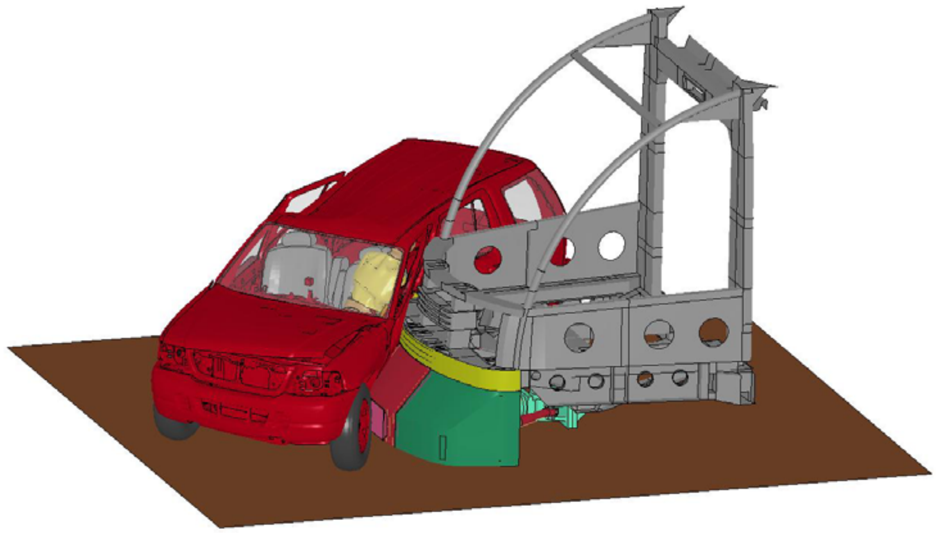


(b) View from front of Neon with front of vehicle cut away for view of SID

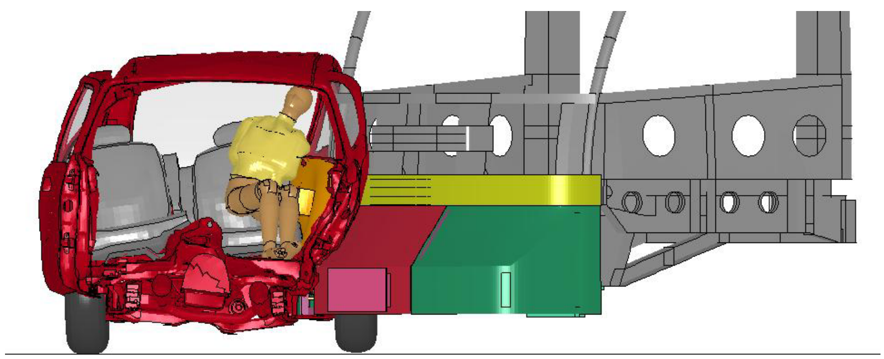


(c) View from below

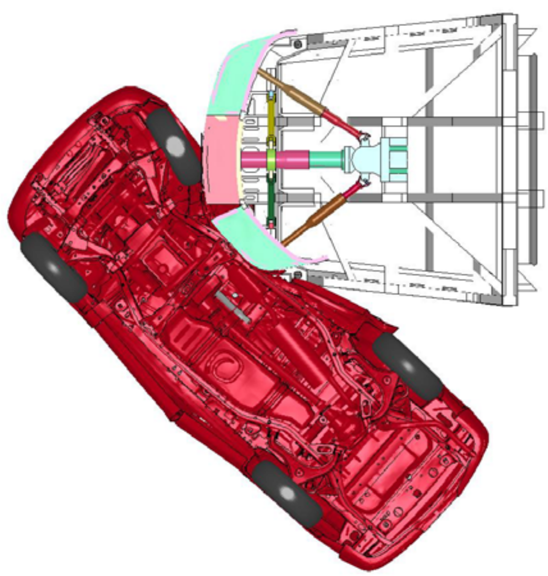
Figure 50. Oblique impact of detailed bumper design into Dodge Neon at 30 mph (snapshot at 80 ms).



(a) Isometric View



(b) View from front of Neon with front of vehicle cut away for view of SID



(c) View from below

Figure 51. Oblique impact of detailed bumper design into Ford Explorer at 30 mph (snapshot at 80 ms).

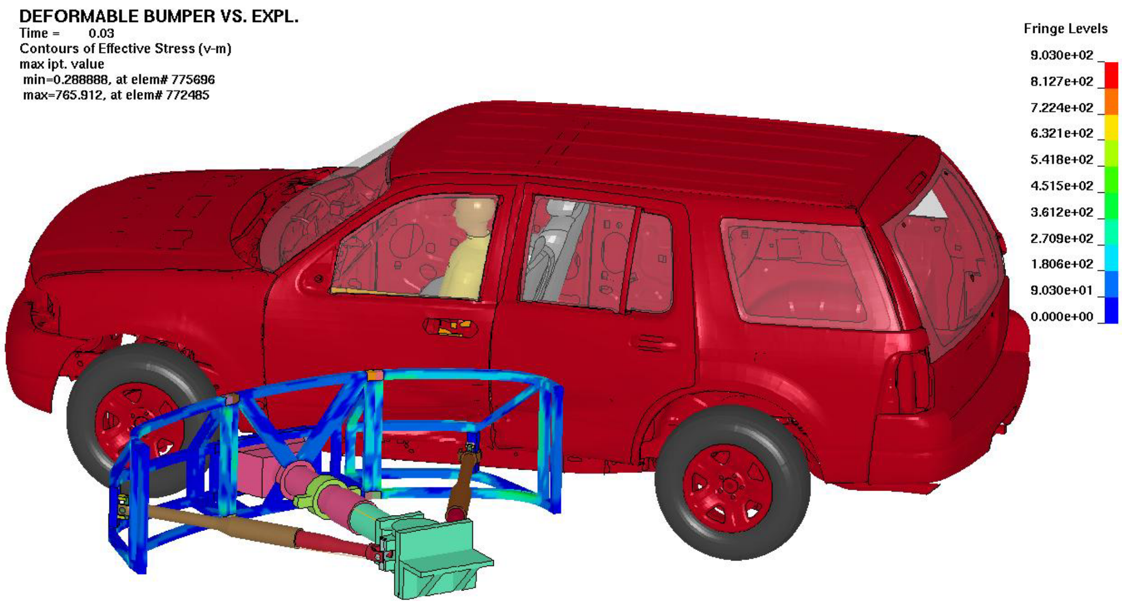


Figure 52. Oblique impact of detailed bumper design into Ford Explorer at 30 mph. Effective stress contours shown on bumper frame (max. range: 903 MPa yield stress).

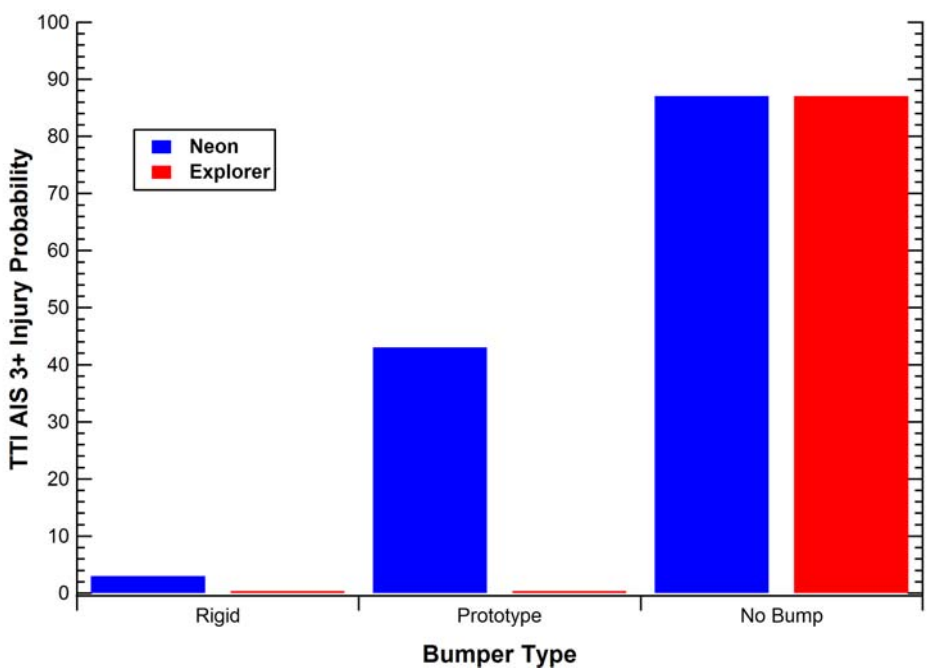


Figure 53. Probability of 'Serious' (AIS 3+) thoracic injury from 32.2 km/hr (20 mph), 90 degree impacts.

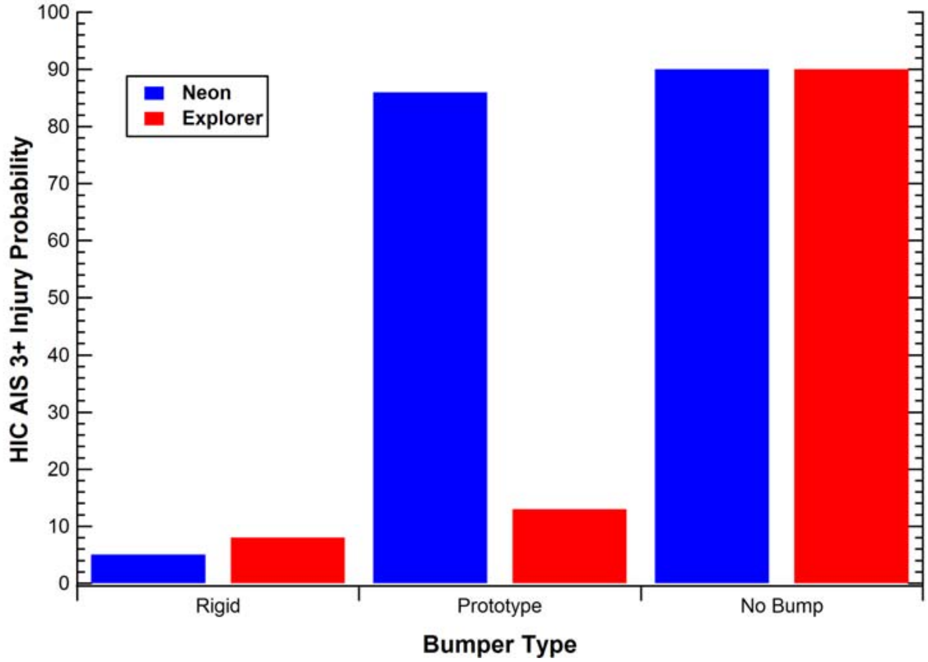


Figure 54. Probability of 'Serious' (AIS 3+) head injury from 32.2 km/hr (20 mph), 90 degree impacts.

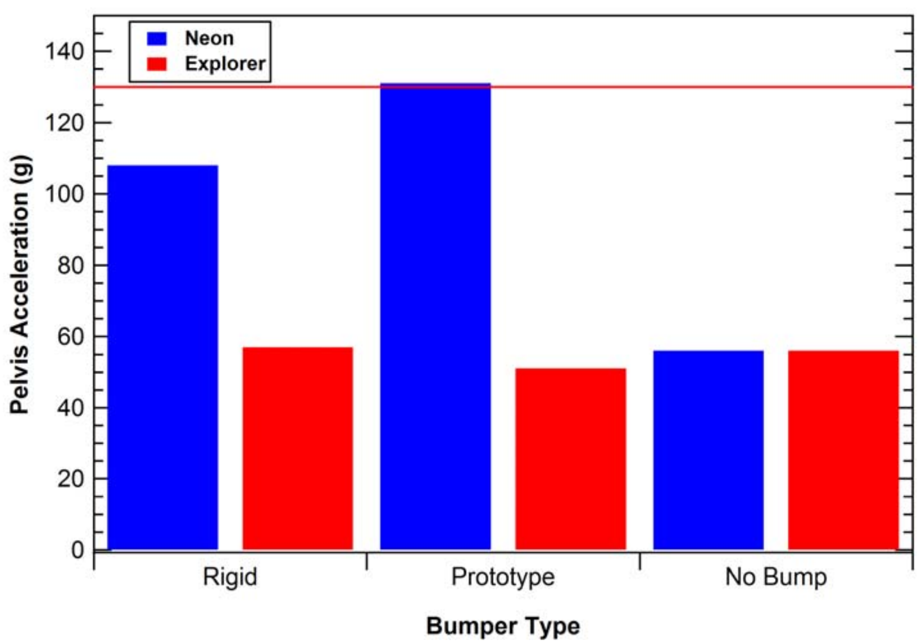


Figure 55. Pelvis acceleration from 32.2 km/hr (20 mph), 90 degree impacts.

Detailed injury measures for the SID were also assessed for a 45 degree impact at 48.2 km/hr (30 mph) as shown in Figure 56 to Figure 58. Probability of thoracic injury is greatly reduced when the bumper is retrofit to the S70 LRV. The Neon results compare well with the simplified bumper analysis, but performed better against the Explorer. Head injury results are similar to the results from the simplified analyses. Note that for the narrow (0.8 m) center bumper the probability of head injury for the Neon is still high. This is obviously not desirable, but consistent with the simplified analyses, as was shown in Figure 32. This figure showed that the probability of head injury in the Neon was high, as shown here, but much lower for the other three vehicles (less than 10%). Pelvic accelerations are reduced by the prototype bumper to be below the injury threshold in the Explorer, but slightly higher than in the simplified analysis.

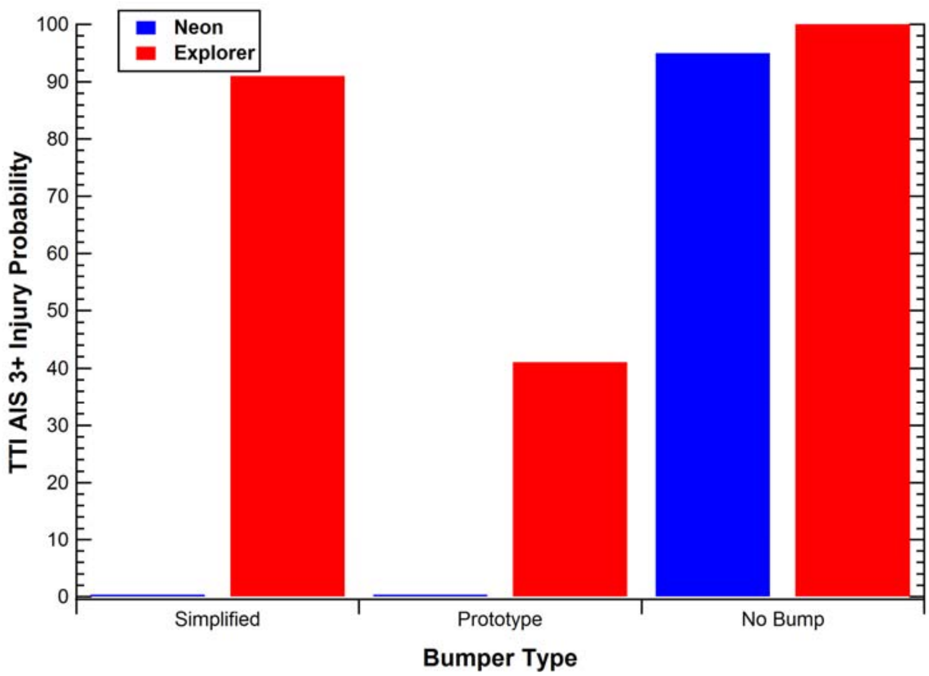


Figure 56. Probability of 'Serious' (AIS 3+) thoracic injury from 48.2 km/hr (30 mph), 45 degree impacts.

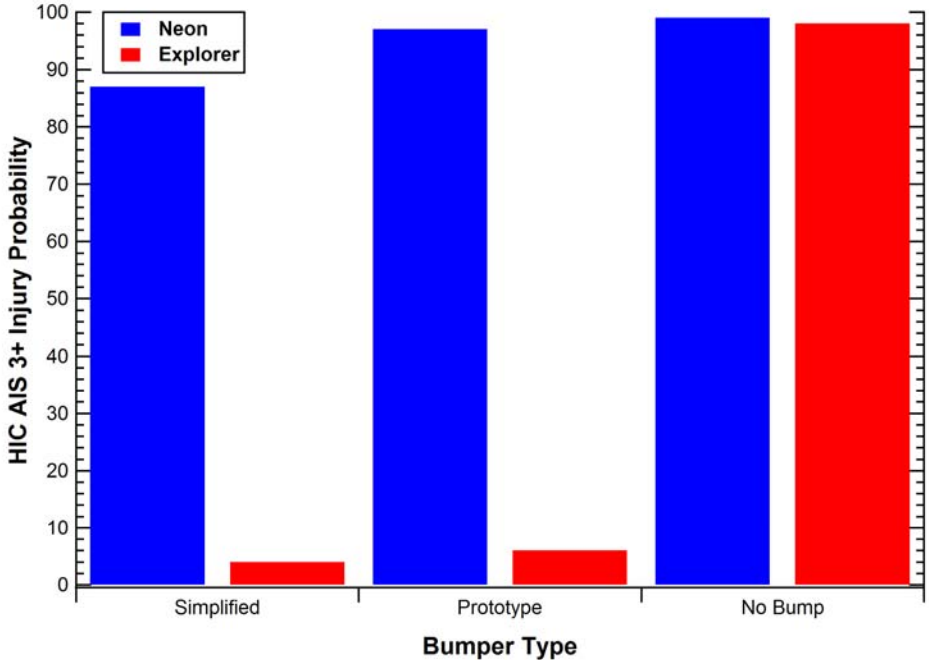


Figure 57. Probability of 'Serious' (AIS 3+) head injury from 48.2 km/hr (30 mph), 45 degree impacts.

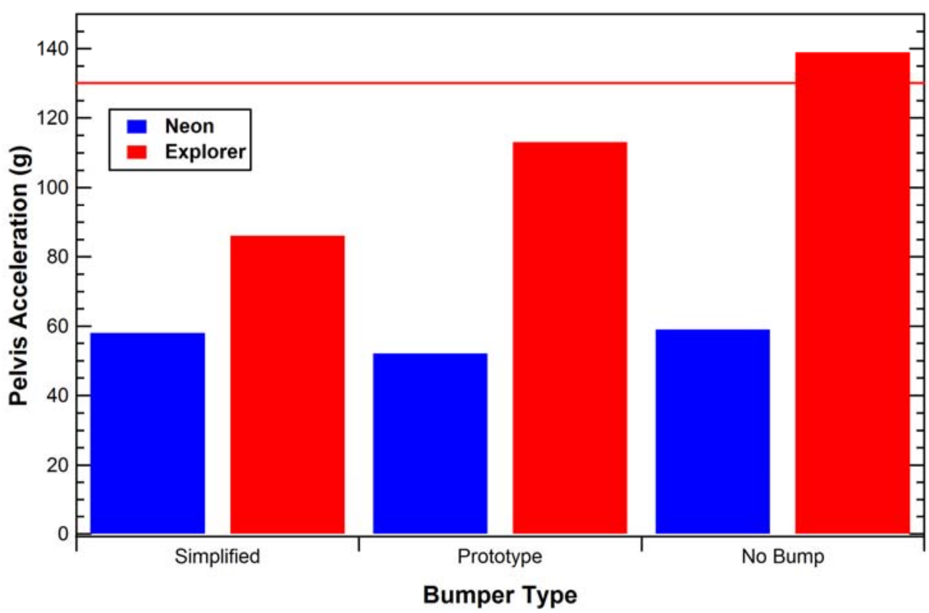


Figure 58. Pelvis acceleration from 48.2 km/hr (30 ph), 45 degree impacts.

Section 7 Conclusion and Recommendations

The focus of this study was to investigate the potential for reducing injuries to automobile occupants struck by LRVs with the addition of appropriate front-end structures. In particular, a prototype bumper system design with an improved profile and segmented energy-absorbing corner bumpers was developed. The technical approach for this project was focused on assessing detailed injuries from an unbelted Side Impact Dummy (SID) using detailed nonlinear dynamic finite element simulations. Impact conditions focused on normal (90 degrees) and oblique (45 degrees) impacts.

The resulting bumper from this project showed marked improvements to automobile passenger safety for a variety of automobile types. The results clearly show that careful selection of the front end bumper profile can significantly reduce the probability of injuries to automobile occupants. A profile that is low enough to engage the door frame structures of small and light vehicles, with an adequate vertical height to engage the same structures on taller SUVs and with an angled profile provided the best overall performance. Addition of a segmented corner bumper with the correct force-deflection characteristics for energy absorbers further reduces the potential for injuries. A prototype bumper design that implements these characteristics has been developed and retrofit to an S70 LRV. The efficacy of this design has been demonstrated with LS-DYNA crash simulations.

In the performance of this study, technical topics worthy of further safety research were identified. This study concentrated on the reduction of serious injuries and the collision conditions were selected accordingly. The bumper was therefore designed for 20 mph, 90 degree impacts and 30 mph, 45 degree collisions. The need for a study to better determine the distribution of collision conditions (speeds and angles) in actual LRV operations is needed. In addition, the robustness of the bumper design would benefit from expanded analysis for other impact conditions. Finally, a program to build and crash test a prototype bumper in order to validate the modeling and design performance would be beneficial. The following sections outline these next steps.

7.1 Expanded Analysis of a Segmented CEM Bumper for LRVs

The bumper design developed in the current study shows significant improvements to automobile passenger safety for a variety of automobile types (Dodge Neon, Ford Crown Victoria, Toyota RAV4, and Ford Explorer). These four vehicles span a wide class of vehicle sizes and heights, and were evaluated for both frontal and corner impacts using the Side Impact Dummy (SID) to evaluate injury potential of the automobile occupant.

Although the bumper design clearly demonstrates safety improvements, it should be further optimized before producing a prototype by evaluating a more complete suite of collision conditions. These conditions include impacts with additional vehicle types common in shared right-of-way environments, occupant conditions and LRV speeds and auto orientations.

Two additional vehicles common to street environments that will potentially show a significantly different crash response include small and large pickup trucks and city buses. Pickups have a significantly different weight distribution than other autos. The city bus is, of course, significantly larger. Validated vehicle finite element models for small and large pickups and city buses are available for crash analysis. It is recommended that the bumper performance be evaluated against these vehicle types and modifications made as needed.

The current study only considered the response of an unbelted SID in the driver seat. Evaluation of the bumper design should be expanded to include the response of a belted occupant. Some modifications to the bumper design may be required to accommodate the belted occupant response. The current study also only considers two impact angles for speeds leading to serious and severe injuries (AIS 3+ and AIS 4+). Impact orientations of 30 and 60 degrees and a greater range of speeds with potentially higher injury severities should be evaluated.

Finally, the current design for attaching the segmenting bumper uses a coupler for attaching the center bumper. This coupler is designed for the 5 mph LRV-to-LRV impact. It therefore activates very little when impacting an automobile. A two-stage energy absorber could be designed to replace the existing center absorber. The first stage is tailored to impact automobiles while the second for the LRV-to-LRV impact. The advantages and feasibility of such a two-stage coupler should be investigated.

7.2 Crash Testing of a Segmented CEM LRV Bumper

The final prototype bumper design developed in this study demonstrated greatly improved crash safety performance using finite element analysis. Once optimized for further impact and occupant conditions, validation testing is the next appropriate step in bumper development. It is recommended that a prototype of the bumper design and supporting structures be fabricated, energy absorbers fitted to the bumper, and the bumper retrofitted either on an LRV or a representative surrogate rail car and tested.

Testing should consist of a low-load dynamic test, representative of a 5 mph LRV-to-LRV impact, and full scale normal and oblique impact tests with automobiles. Testing should be performed with a Side Impact Dummy (SID) positioned in the driver’s position in the autos. Deflection of the energy absorber systems, accelerations of the LRV and impacted vehicle, and all instrumentation from the SID should be collected. Finally, vehicle crush should be measured. The collected data will then be compared with simulated results from the finite element simulations conducted. In this way, the finite element models can be updated based on the crash test results and final changes to the bumper design will be determined using these updated models.

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