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Crashworthiness Evaluation of Light Rail Vehicle Interiors

DECEMBER 2011

FTA Report No. 0005
Federal Transit Administration

PREPARED BY

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National Institute for Aviation Research (NIAR)
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U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Edwin Adilson Rodriguez, Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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13. ABSTRACT

Statistically, light rail transit (LRT) systems have higher injury rates on a per-passenger-mile basis than heavy rail and commuter rail systems, because in most cities, light rail vehicles (LRVs) operate on city streets. Passenger safety is dependent on the configuration and severity of the accident, as well as the degree of crashworthiness engineered in the overall vehicle design. Passengers can be injured or killed as the result of two main mechanisms that arise because of sudden acceleration or deceleration of a vehicle, or because of mechanical damage to the vehicle structure. These mechanisms are the following: (1) primary collision of the vehicle with another vehicle or obstacle, which results in two main outcomes: occupant-compartment crush and consequent reduction of survival space, or penetration of the compartment by parts of the impacting vehicle; and (2) secondary impacts between the occupant and the interior of the vehicle (compartment interior surfaces, other occupants, or loose objects) that occur after initiation of the primary collision. The objective of this research is to identify the injury mechanisms to passengers in LRVs and to propose future areas of research that will lay the foundation necessary to generate transit rail vehicle interior design guidelines that enhance the safety of passengers during collisions. Results of this study show that the most common and severe injuries to LRV passengers involve the head, neck (neck extension, flexion, shear, and compression), and femur (compression) regions. These injuries are primarily the result of body-to-body contact between unrestrained passengers and/or body-to-seat structure contacts.

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FOREWORD

Light rail systems are one of the most important modes of transportation available in the United States. Most light rail systems operate on city streets. This close proximity to street traffic and pedestrians results in a higher per-passenger-mile injury rate than that of heavy and commuter rail systems. Due to the relatively low speed of LRVs operating in urban cores, the majority of passenger injuries from collisions stems from secondary impacts with some part of the vehicle's interior surfaces (seats, grab handles, poles, etc.) or other passengers, rather than from ejection or collapse of the vehicle structure. Data from the National Transit Database (2002–2005) indicate a yearly average of 4,433 injuries and fatalities in U.S. heavy rail transit systems, 1,625 injuries and fatalities in commuter rail systems, and 605 injuries and fatalities in light rail transit systems [1]. However, these data do not discern between injuries and fatalities of pedestrians, occupants of rail vehicles, or occupants of motor vehicles. Therefore, the severity of injuries and fatalities caused by secondary impacts in rail transit vehicles is unknown. The objective of this research is to identify injury mechanisms to LRV passengers and to propose future areas of research that will lay the foundation for future interior design guidelines of light rail vehicles.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Major metropolitan areas throughout the United States provide light rail transit (LRT) services. Typically, light rail vehicles (LRVs) operate on city streets and in semi-exclusive and exclusive right-of-way environments. Statistically, light rail systems have higher injury rates on a per-passenger-mile basis than heavy rail and commuter rail systems, because LRVs in most cities operate on city streets with at-grade crossings [1]. Occupant safety is dependent on the configuration and severity of the accident, as well as the degree of crashworthiness engineered in the overall vehicle design. Occupants can be injured or killed as a result of two main mechanisms that arise from the sudden acceleration or deceleration of a vehicle, or because of mechanical damage to the vehicle structure. These involve the primary collision impact of the vehicle against another vehicle or obstacle, with two main possible results: occupant compartment crush and consequent reduction of survival space, or penetration of the compartment by parts of the impacting vehicle; and secondary impacts between the occupant and the interior of the vehicle (compartment interior surfaces, other occupants, or loose objects) at some time following initiation of the primary collision [2].

Due to the relatively low speed of LRVs operating in urban cores (below 35 mph [55 kph]), the majority of passenger injuries from collisions stems from secondary impacts with some part of the vehicle's interior surfaces (seats, grab handles, poles, etc.) or other passengers, rather than from ejection or collapse of the vehicle structure. Data from the National Transit Database (2002–2005) indicate a yearly average of 4,433 injuries and fatalities in U.S. heavy rail transit systems, 1,625 injuries and fatalities in commuter rail systems, and 605 injuries and fatalities in light rail transit systems [1]. However, these data do not discern between injuries and fatalities of pedestrians, occupants of rail vehicles, or occupants of motor vehicles. Therefore, the severity of injuries and fatalities caused by secondary impacts in rail transit vehicles is unknown.

The objective of this research is to identify injury mechanisms to LRV passengers and to propose future areas of research that will lay the foundation for generating guidelines for designing the interior of transit rail vehicles that will enhance the safety of passengers during collisions.

This research project is divided into four working packages (WPs):

- WP I: Literature review of rail transit passenger protection and crashworthiness standards.
- WP II: Data collection of general design parameters of the LRV interior, and CAD model generation of the generic LRV interior.
- WP III: Development of LRV and interior multibody (MB) and finite element (FE) models.

- WP IV: Identification of LRV interior crashworthiness design issues for typical low-, mid-, and high-severity crash scenarios.

Results of this study show that the most common and severe injuries to LRV passengers involve the head (head injury criteria [HIC]), neck (neck extension, flexion, shear, and compression), and femur (compression) regions. These injuries are primarily the result of body-to-body contact between unrestrained passengers and/or body-to-seat structure contact.

SECTION

1

Introduction

Light rail vehicles operate on city streets, which are typically semi-exclusive and exclusive right of-way environments. According to the Transit Cooperative Research Program (TCRP) Report 69, published in 2001 [1], 77 percent of the total mainline track length of the eleven light rail transit (LRT) systems studied fell under the category of semi-exclusive right-of-way, with light rail vehicle (LRV) speeds greater than 35 mph (55 km/h); nevertheless, only 13 percent of the average annual total accidents occurred at crossings along these higher-speed segments. Therefore, 87 percent of the LRV accidents occurred on city streets where these vehicles share the street with other road users. According to data reported in TCRP Report 69, 62 percent of LRV collisions involved motor vehicles, and 38 percent of the cases involved cyclists or pedestrians.

Statistically, LRT systems have higher injury rates on a per-passenger-mile basis than heavy rail and commuter rail systems because in most cities they are operated on city streets with at-grade crossings [2].

Occupant safety is dependent on the configuration and severity of the accident, as well as the degree of crashworthiness engineered in the overall vehicle design. Occupants can be injured or killed as a result of two main mechanisms that arise from the sudden acceleration or deceleration of a vehicle, or because of structural damage to the vehicle:

- Primary collision of the vehicle against another vehicle or obstacle, with two main possible results: occupant compartment crush and consequent reduction of survival space, or penetration of the compartment by parts of the impacting vehicle.
- Secondary impacts between the occupant and the interior of the vehicle (compartment interior surfaces, other occupants, or loose objects) at some time following initiation of the primary collision.

Due to the relatively low speed of LRVs operating in urban areas (below 35 mph [55 kph]), the majority of passenger injuries occurs from collisions stemming from secondary impacts with some part of the interior surfaces (seats, grab-handles, poles, etc.) or other passengers, rather than ejection or collapse of the vehicle structure.

Data from the National Transit Database (2002–2005) indicate a yearly average of 4,433 injuries and fatalities in U.S. heavy rail transit systems, 1,625 injuries and fatalities in commuter rail systems, and 605 injuries and fatalities in light rail transit systems [2]. However, the data do not discern between injuries and fatalities of pedestrians, occupants of rail vehicles, or occupants of motor vehicles. Therefore, the severity of injuries and fatalities caused by secondary impacts in rail transit vehicles is unknown.

The objective of this research is to identify the injury mechanisms to LRV passengers and to propose future areas of research that will lay the foundation necessary for generating guidelines for transit rail vehicle interior design that will enhance the safety of passengers during collisions. State-of-the-art computational and experimental techniques are used to accomplish these goals. This research will benefit from ongoing work at the National Institute for Aviation Research (NIAR) at Wichita State University (WSU) on safety in mass transit buses. As shown in Figure 1-1, the interior layout and hardware of mass transit buses are similar to that used by the LRV industry. This will allow NIAR/WSU to use existing test fixtures and collaborative research agreements with interior hardware suppliers and thereby conduct a more in-depth analysis than a conventional literature review or accident survey. Past experience has shown a lack of public domain accident data and injury mechanisms, hence making the proposed approach a cost-effective scientific method to study LRV crashworthiness design issues.

Research Technical Approach - Working Packages Description

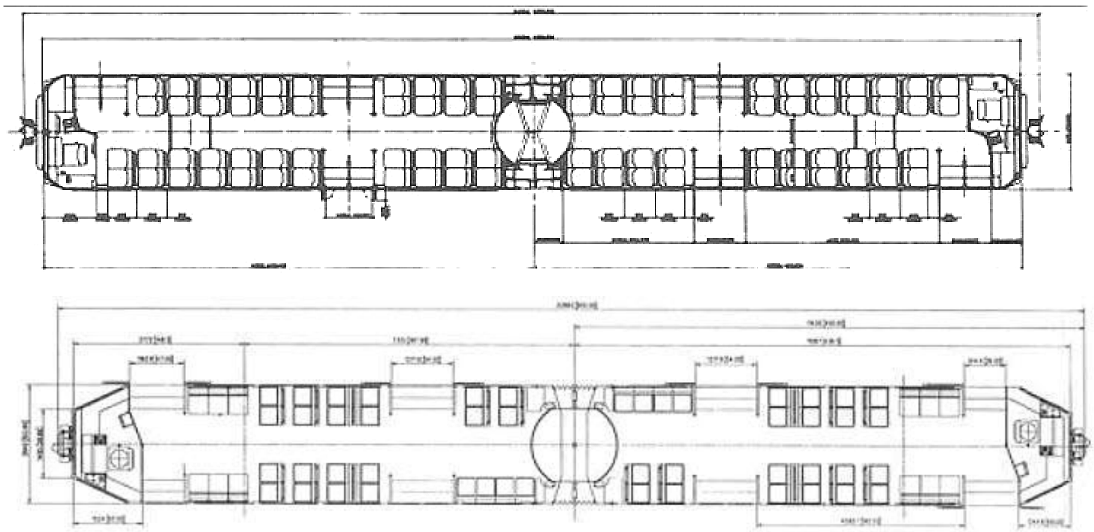
This research project is organized into four working packages (WPs):

- **WP I: Literature Review of Rail Transit Passenger Protection and Crashworthiness Standards**. Literature review of rail transit passenger protection research studies. Survey of existing standards and regulations related to rail transit passenger protection. Identification of areas where further standardization may be needed.
- **WP II: Data Collection of General Design Parameters of LRV Interiors and CAD Model Generation of Generic LRV Interior**. Survey of interior configurations of existing light rail transit vehicles. Definition of typical LRV interior designs, seating equipment, seating arrangement, and other interior components. Generation of CAD models of typical interiors for further numerical analysis.
- **WP III: Development of LRV and Interior Numerical Model**. Generation of a finite element (FE) structural model and multibody (MB) interior model for a generic LRV configuration. Use of this generic LRV FE model throughout the project to evaluate the crashworthiness performance of LRV interiors during typical crash scenarios defined in WP I. Identification, using the basic requirements of these generic models, of the typical injury mechanism to passengers, and development of a definition of future follow-up research to improve passenger safety.
- **WP IV: Identification of LRV Interiors Crashworthiness Design Issues for Typical Crash Conditions**. Development of a good understanding of the structural and occupant response of a typical LRV for various crash conditions, to identify current LRV interior design issues and propose future areas of research. Use of detailed computational

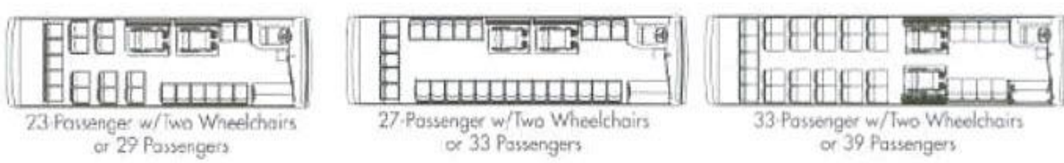
models in conjunction with component tests to analyze the structural performance of LRVs and collision partner vehicles for various impact conditions defined in the analysis of WP I, to provide insight on the structural crash performance of these vehicles, and to gain an understanding of occupant injury mechanisms.

Figure 1-1

Comparison of Interior Layouts and Hardware of Typical Light Rail Vehicle and Typical Mass Transit Bus



(a) Typical LRV Interior Layout



(b) Typical Mass Transit Bus Interior Layout

(c) Typical LRV Interior (left) Typical Mass Transit Bus Interior (right)

SECTION

2

United States Light Rail Vehicle Fleet Survey

This section provides a general overview of the United States LRV fleet and some of its characteristics. According to the data collected, 25 transit agencies operate LRVs in the United States (Table 2-1).

In this study, LRVs will be classified using three main categories based on the proportion of low-floor area present:

- **Category 1** refers to a 100 percent high-floor LRV. This means that approximately 9–15 percent of it is low floor, with up to 48 percent low floor. Prior to 1990, this was a typical LRV configuration. This category of LRV is still in service, and some transit agencies continue to manufacture these vehicles [3].
- **Category 2** refers to a 70 percent low-floor LRV and typically means that 50–75 percent of the LRV is low floor. The majority of new orders in the U.S. are Category 2, and some are equipped with crash energy management (CEM) components [3].
- **Category 3** LRVs are not found in the U.S. but are popular in Europe. They are referred to as 100 percent low floor. The entire vehicle has low floors with low-level entrances throughout the vehicle. In the analysis of the U.S. LRV fleet, Category 2 is referred to as low floor because there are no Category 3 LRVs in the U.S. [3].

Table 2-1

U.S. Transit Agencies with LRVs in Service

Location	Agency
Baltimore, MD	MTA
Boston, MA	MBTA
Buffalo, NY	NFTA
Camden, NJ	NJ Transit
Charlotte, NC	LYNX
Cleveland, OH	GCRTA
Dallas, TX	DART
Denver, CO	RTD
Houston, TX	MetroRail
Hudson-Bergen, NJ	NJ Transit
Los Angeles, CA	LACMTA
Minneapolis/St. Paul, MN	Metro Transit
Newark, NJ	NJ Transit
Oceanside, CA	Sprinter
Philadelphia, PA	SEPTA
Phoenix, AZ	Valley Metro
Pittsburgh, PA	The T
Portland, OR	TriMet MAX

Location	Agency
Sacramento, CA	RT
Saint Louis, MO	Metro Transit
Salt Lake City, UT	TRAX
San Diego, CA	SDMTS
San Francisco, CA	Muni Metro
San Jose, CA	VTA
Seattle/Tacoma, WA	Sound Transit

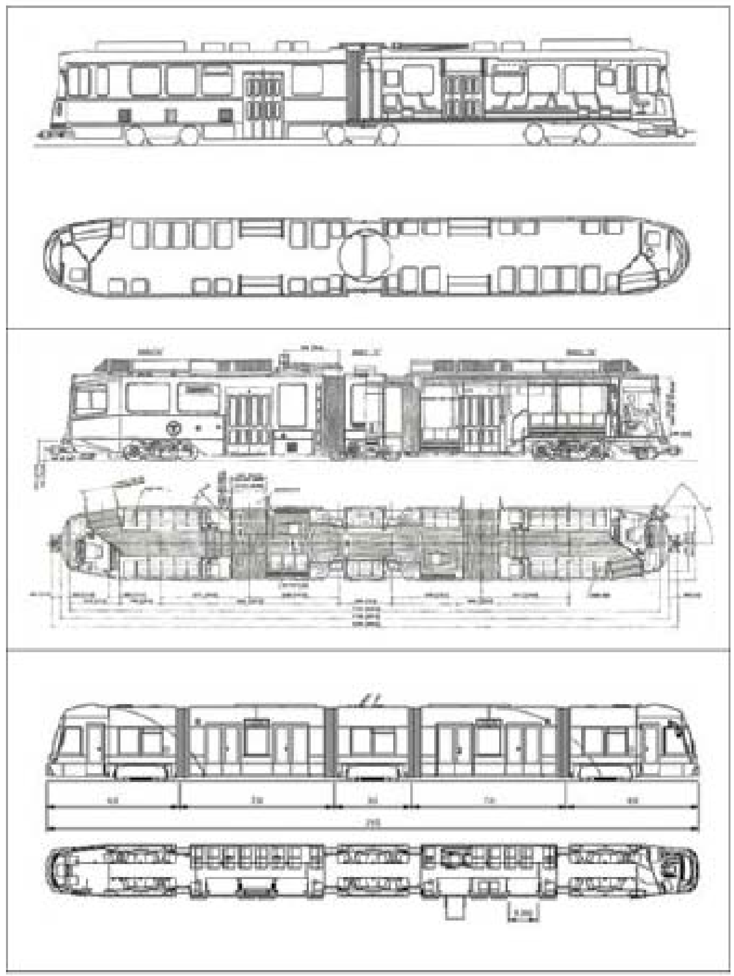
Figure 2-1

Light Rail Vehicle Categories [3]

Cateogry 1
100% High Floor

Cateogry 2
70% Low Floor

Cateogry 3
100% Low Floor



LRV Transit Agencies and Manufacturers Overview

According to the data collected, 25 transit agencies operate 2,005 LRVs in the United States (see Table 2-1 and Table 2-2). The LRV fleet is composed of Category 1 and Category 2 LRVs, 66 and 34 percent, respectively. These can be very similar in design, except for the low-floor percentage. Usually, both categories have one articulation. Category 2 is divided into two subcategories:

LRVs with and without CEM components (62% with and 38% without). Currently, no U.S. transit agencies are operating Category 3 LRVs (100% low floor).

Table 2-2 is a compilation of data for the entire U.S fleet; highlighted portions are models for which no data were available. This table is broken down by agency (make) first and then by model. As mentioned previously, each transit agency can custom order certain features; therefore, even though two agencies might have the same make and model, their LRVs are considered unique for this study. As can be seen, approximately 2,005 LRVs are operating in the U.S.; this number is subject to change as agencies develop new light rail lines and refurbish and replace existing LRVs. Refurbishing old cars usually extends the operational life of the LRVs and can make them more accessible to occupants with reduced mobility. This is done by replacing the 100 percent high-floor layouts to configurations with low-floor sections. Currently, the U.S. fleet is operating with approximately 68 percent high floor, Category 1 LRVs. The remaining 32 percent is Category 2, with 70 percent low floor, of which 38 percent of those units are without CEM components. This is better illustrated in Figure 2-2 (percentages are based on a total of 2,005 LRV units).

Table 2-2

U.S. LRV Fleet Information by Manufacturer

U.S. LRV Models Studied					
Make	**Category**	**Car Total**	**Model**	**Car Total**	**Agency**
ABB Traction/ Bombardier	2	53	ABB+Bombardier	53	Baltimore, MA
Kinkisharyo	1	229	Type 7	114	Boston, MA
				115	Dallas, TX
Kinkisharyo	2	307	NJ Transit	52	Hudson, NJ
				21	Newark, NJ
				100	Phoenix, AZ
				35	Seattle/Tacoma, WA
			VTA	99	San Jose, CA
AnsaldoBreda	1	220		48	Cleveland, OH
			P2550	21	LACMTA*
			LRV2/LRV3	151	San Francisco, CA
AnsaldoBreda	2	95		95	Boston, MA

U.S. LRV Models Studied

Make	Category	Car Total	Model	Car Total	Agency
Tokyo Car Company	1	26	Tokyo Car	26	Buffalo, NY
Siemens	1	510	SD100	49	Denver, CO
			SD160	68	
			P2020	52	LAMTA in CA
			SD-400	55	Pittsburgh, PA
			U2A	36	Sacramento, CA
			SD-400	31	St. Louis, MO
			SD-460	56	
			SD100	23	Salt Lake City, UT
			SD160	17	
			SD100	71	San Diego, CA
			U2	52	
Siemens	2	158	S70	16	Charlotte, NC
			S70	18	Houston, TX
			SD660 Types 2 & 3	79	Portland, OR
			S70 Type 4	22	Portland, OR
			SD70	11	San Diego, CA
			DMU	12	Oceanside, CA**
Stadler GTW Diesel	2	20	Sadler Diesel	20	Camden, NJ
Other	1	159	St. Louis Car PCII	18	Philadelphia, PA*
			Kawasaki K-Car	141	Philadelphia, PA
Nippon Sharyo	1	68	P850	68	LACMTA
Bombardier	2	27	Flexity Swift	27	Minneapolis, MN
Bombardier	1	55	Type 1	26	Portland, OR
			UTDC	29	Salt Lake City, UT*
CAF	1	68		28	Pittsburgh, PA
				40	Sacramento, CA
Škoda	2	10		3	Seattle/Tacoma, WA
				7	Portland, OR
TOTAL		**2,005**		**2,005**	

* Reference not found.
** Outlier data not used for futher configuration analysis.

Figure 2-2

Composition of U.S. LRV Fleet by Category

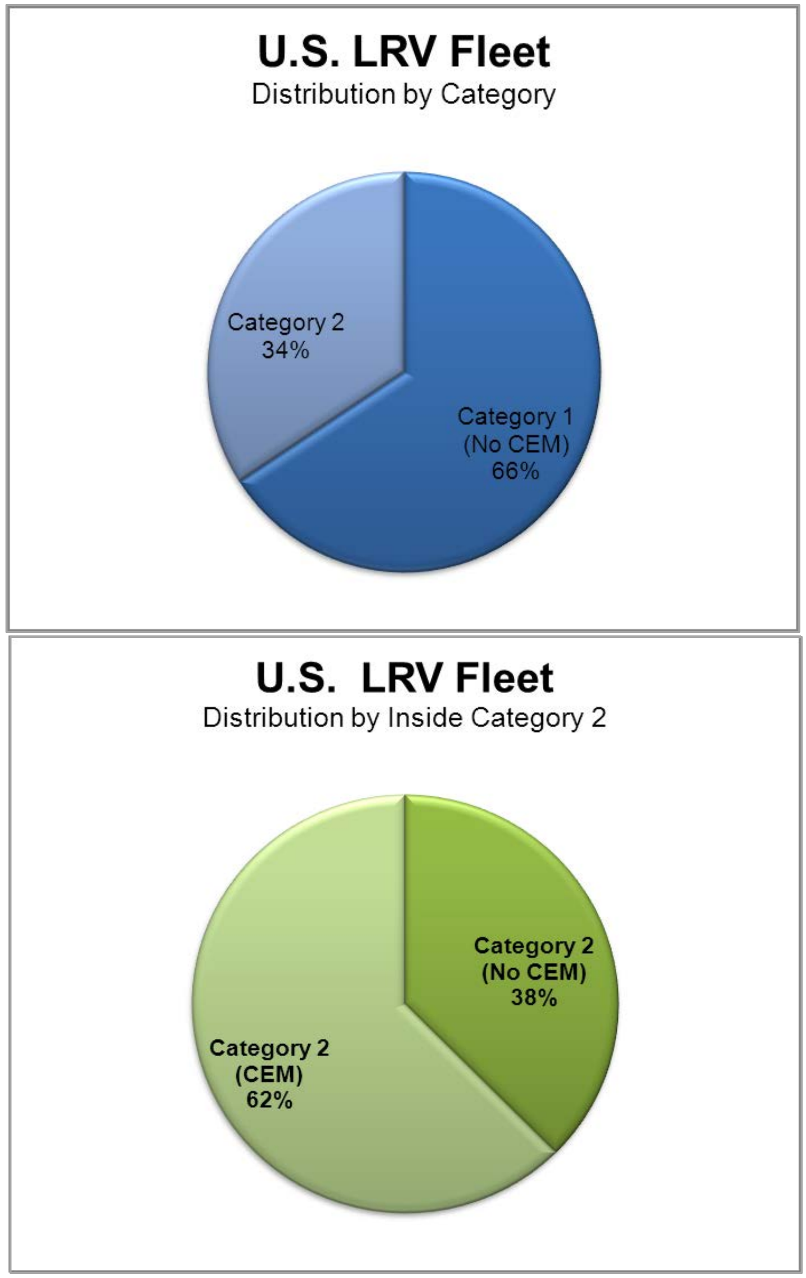
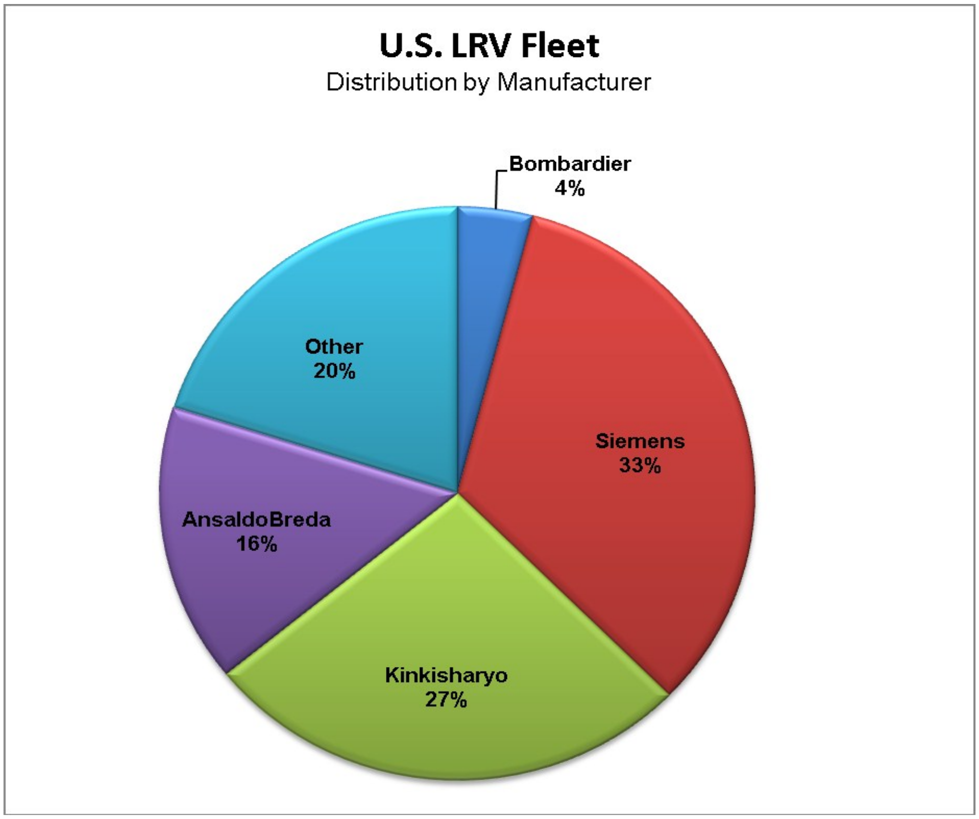


Figure 2-3 shows the composition of the LRV fleet by manufacturer. As can be seen, the three largest LRV suppliers are Siemens, Kinkisharyo, and AnsaldoBreda. These companies produce roughly 76 percent of the LRVs operated by U.S. transit agencies.

Figure 2-3

Composition of U.S. LRV Fleet by Manufacturer



LRV Fleet Interior Survey

This section documents important interior characteristics of the LRVs under consideration in this project. Items such as length, weight, number of seats, types of seats, and other important characteristics of the existing LRVs are shown. An explanation of how the data were gathered and how these data are presented also is shown in this section. To properly analyze LRV passenger safety, it is important to study and categorize the interior of LRVs. The differences found in the current LRV layouts are due to the varying necessities of the operating agencies.

All data presented in this section were analyzed to define the most representative type of seats that are found in the current fleet of LRVs. Later in this paper, the information is used to analyze typical injuries observed when using these types of seats. Results obtained from these models are shown in the section titled, "Crashworthiness Evaluation," and section titled, "Finite Element Model - Accident Reconstruction." Figure 2-4, Figure 2-5, and Figure 2-6 show some examples for each one of the LRV's categories.show some examples for each one of the LRV's categories.

Figure 2-4

Sample LRV Interior Layout – Category 1

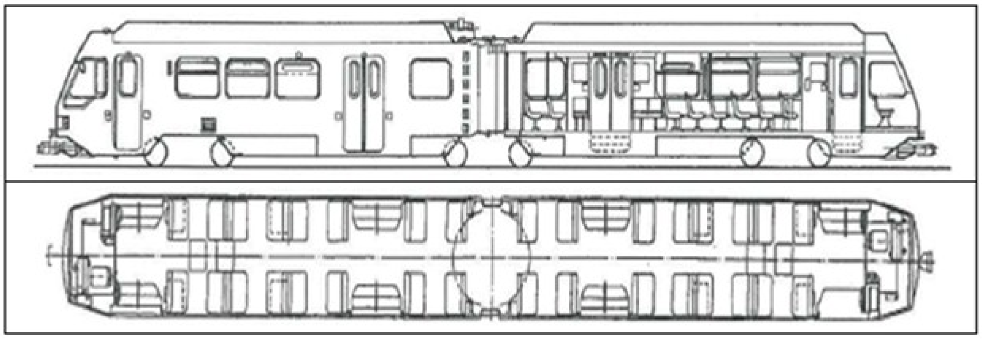


Figure 2-5

Sample LRVs in Service without CEM Components

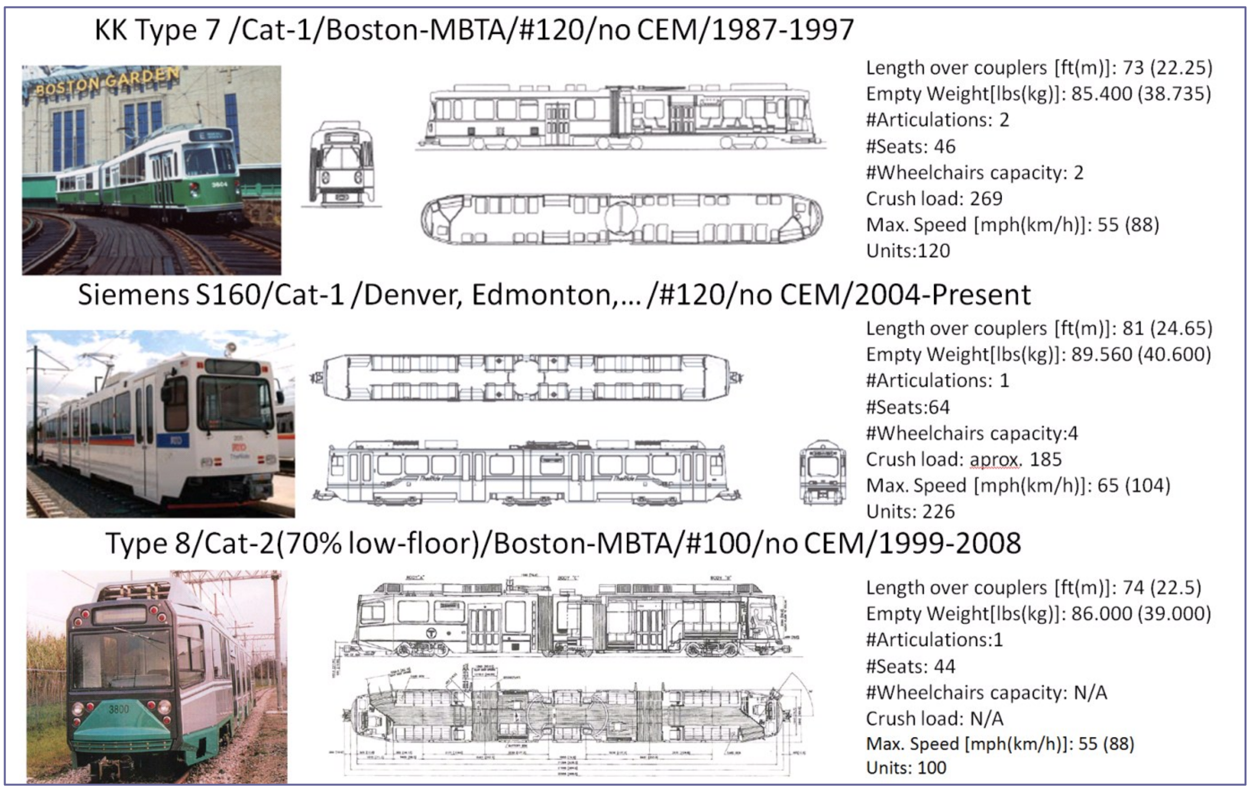
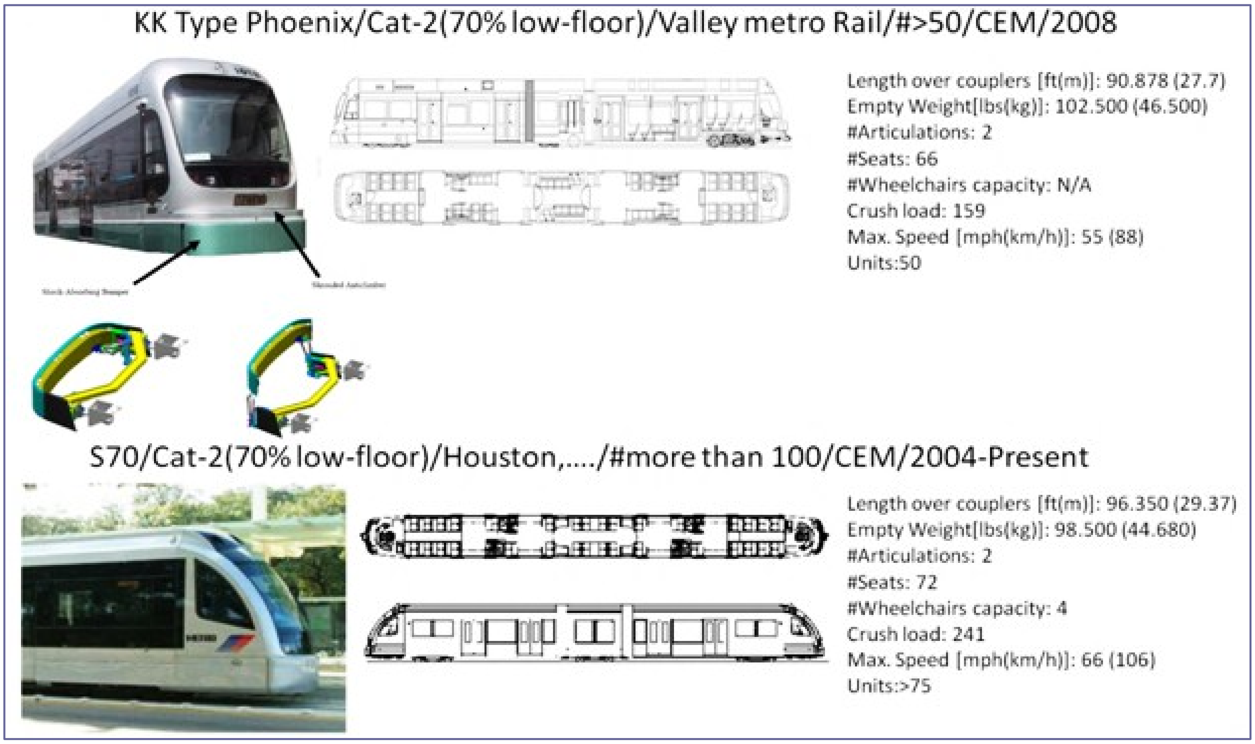


Figure 2-6

Sample LRVs in Service with CEM Components



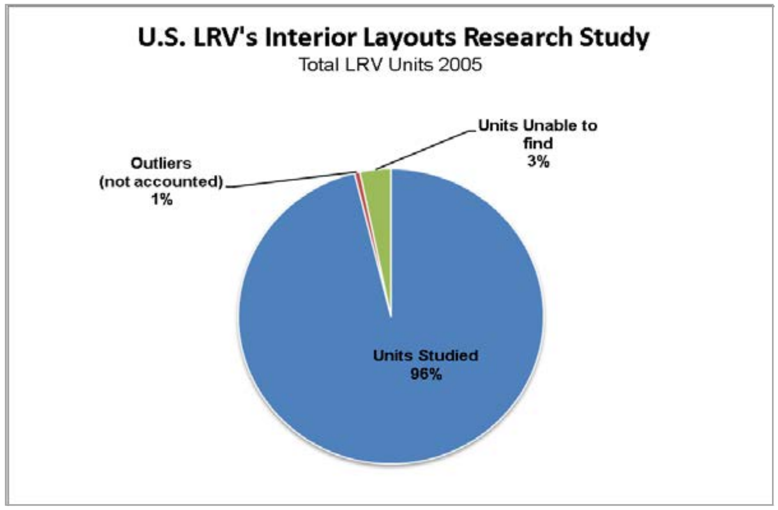
Study of United States LRV Fleet

Interior and exterior data were not found for all U.S. agencies, but data that were found are analyzed in this section. Approximately 2,005 LRV units are distributed throughout different U.S. transit agencies. The interiors of 1,925 of these units were studied in this section. No interior information was found for 68 units, and the remaining 12 units were considered outliers due to their very different sizes and weights. Consequently, 80 units were not studied.   Figure 2-7 illustrates the units studied and their composition.

Table 2-3 shows specifically where the 1,937 studied units operate as well as their makes and models. Highlighted data was considered an outlier and therefore not used in the comparisons. The Siemens Diesel DMU is not very similar to other LRVs when compared by dimension and weight.

Figure 2-7

Results of Study of LRV Interior Layouts of U.S. Fleet



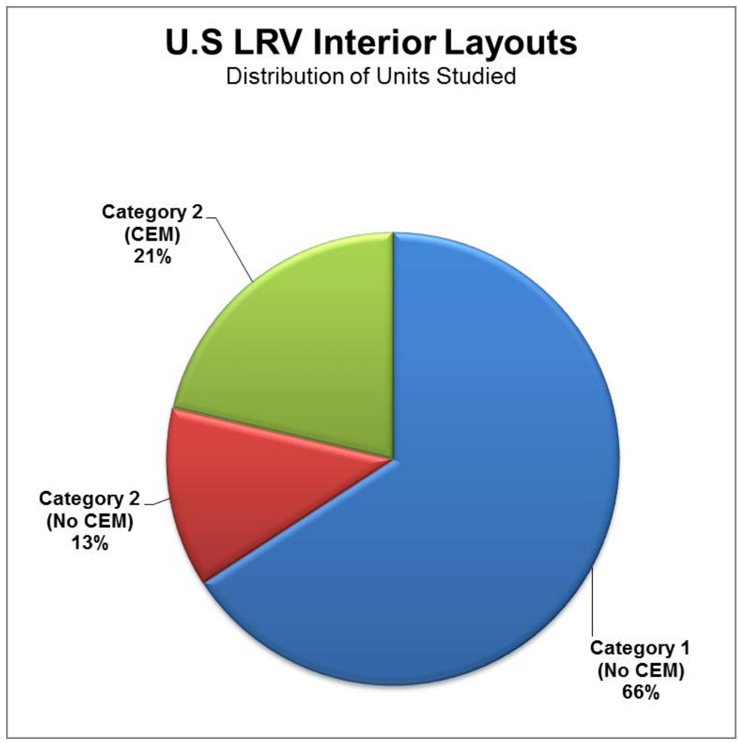


Table 2-3

U.S. LRV Models Studied

No.	Model Type	No. Units	City	Cate-gory (1, 2)	Crash-worthiness Components	Empty Weight (lbs)
1	Breda Type 8 (MBTA)-Boston	95	Boston	2	No CEM	79,000
2	Siemens SD160-Denver	68	Denver	1	No CEM	89,560
3	Siemens SD70-Houston	18	Houston	2	CEM	98,500
4	Kinkisharyo (Valley Metro)-Phoenix	100	Phoenix	2	CEM	102,500
5	Kinkisharyo (DART)-Dallas	115	Dallas	1	No CEM	140,000
6	Kinkisharyo Type 7 (MBTA)-Boston	114	Boston	1	No CEM	85,400
7	Siemens SD160-S.Lake City	17	Salt Lake City	1	No CEM	89,560
8	Siemens SD70-San Diego	11	San Diego	2	CEM	95,700
9	Siemens SD70-Charlotte	16	Charlotte	2	CEM	96,800
10	Siemens SD70-Portland	22	Portland	2	CEM	99,500
11	Breda (Muni Metro)-San Francisco	151	San Francisco	1	No CEM	79,000
12	Kinkisharyo (NJ Transit)-Hudson-Newark	73	Hudson-Newark	2	CEM	99,208
13	Breda (GCRTA)-Cleveland	48	Cleveland	1	No CEM	83,776
14*	Siemens DMU Sprinter (Diesel)-Oceanside	12	Oceanside	2	CEM	134,000
15	Škoda (Sound Transit)-Washington	3	Washington	2	CEM	63,500
16	Kinkisharyo (Sound Transit)-Seattle	35	Seattle	2	CEM	102,500
17	Siemens U2 (MTS)-San Diego	52	San Diego	1	No CEM	77,161
18	Siemens SD 100 (MTS)-San Diego	71	San Diego	1	No CEM	89,000
19	Kinkisharyo (VTA)-San Jose	99	San Jose	2	No CEM	97,444
20	Siemens SD 400-Pittsburg	55	Pittsburg	1	No CEM	88,000
21	Siemens U2A-Sacramento	36	Sacramento	1	No CEM	77,175
22	Stadler GTW Diesel-Camden	20	Camden	2	CEM	109,600
23	Nippon Sharyo P850-Los Angeles	68	Los Angeles	1	No CEM	98,000
24	Bombardier Flexity Swift-Minneapolis	27	Minneapolis	2	CEM	88,105
25	CAF-Pittsburgh	28	Pittsburgh	1	No CEM	100,000
26	CAF-Sacramento	40	Sacramento	1	No CEM	93,735
27	ABB Traction-Baltimore	53	Baltimore	2	No CEM	108,000
28	Tokyu Car-Buffalo	26	Buffalo	1	No CEM	71,000
29	Siemens SD100-Denver	49	Denver	1	No CEM	88,000
30	Siemens P2020-Los Angeles	52	Los Angeles	1	No CEM	98,000
31	Siemens SD-400-St. Louis	31	St. Louis	1	No CEM	90,390
32	Siemens SD-460-St.Louis	56	St. Louis	1	No CEM	93,000
33	Siemens SD100-Salt Lake City	23	Salt Lake City	1	No CEM	88,000
34	Siemens SD660 Types II & III-Portland	79	Portland	2	CEM	109,000
35	Bombardier Type I-Portland	26	Portland	1	No CEM	92,150
36	Skoda-Portland	7	Portland	2	CEM	56,000
37	Kawasaki K-Car-Philadelphia	141	Philadelphia	1	No CEM	59,500
Totals		1,937				

*Outlier

Data Interpretation

The data are separated in two distinct ways, biased and non-biased. Biased, or average biased, is presented based on the number of units per agency compared to the total number studied, i.e., a model with more units would carry more weight. The non-biased results, or average, are presented so that each of the 18 models receives equal weight. This analysis is done for each model of LRV. The data gathered and analyzed are the following:

- Main Characteristics: Empty weight, length, width, passenger capacity, and total number of seats.
- Interior Layouts (number of): Forward-facing seats, rear-facing seats, side-facing seats, recliner seats, and wheelchair spaces.

Figure 2-8 shows an example of the LRV results: the left bar chart shows the main characteristics, while the right bar chart examines the interior layouts. The charts were prepared for Category 1 without CEM, Category 2 without CEM, and Category 2 with CEM. For each case, two averages were charted—an unbiased average and a biased average.

Results

Each category is presented in a separate section, and then the averages of each are compared and discussed.

Category 1 without CEM Components

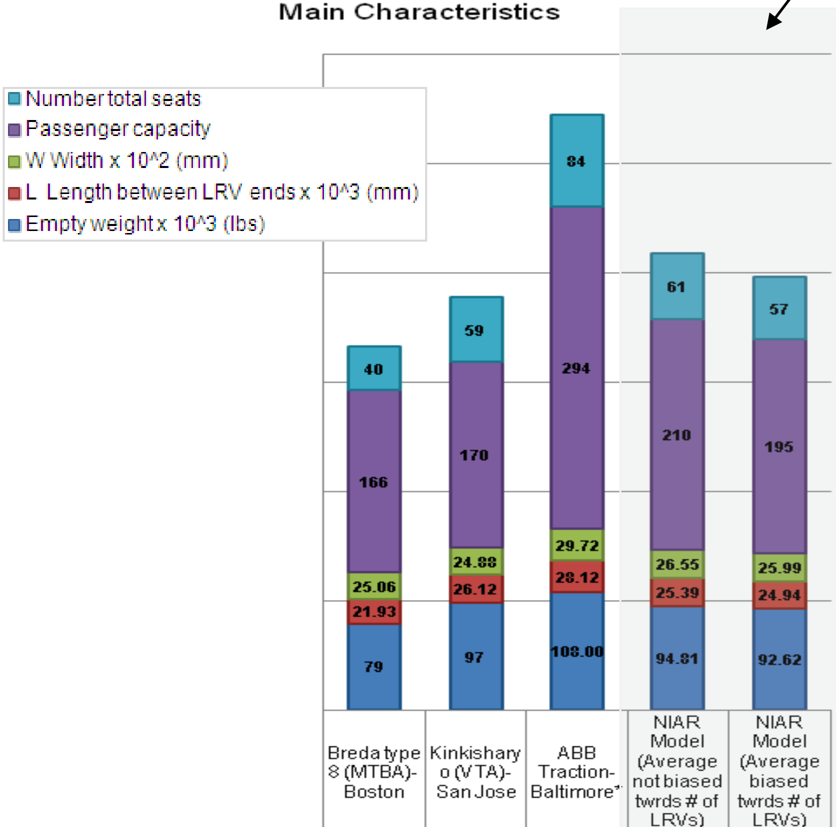
Category 1 **(**high-floor LRVs**)** normally has 9–15 percent low floor, with some having up to 48 percent low floor. Figure 2-9 shows a typical Category 1 LRV without CEM components with one articulation; most were purchased before 1990, and many are still in service. Category 1 makes up 66 percent of the U.S. LRV fleet, which is approximately 1,361 units, as shown previously in Figure 2-2. A total of 1,199 of these 1,361 units are analyzed in this section. Figure 2-10Figure 2-`10 shows the percentages of Category 1 LRV models without CEM components by agency that operates the LRVS and the locations where these LRVs are in use.

Figure 2-8

Example of U.S. LRV Model Results

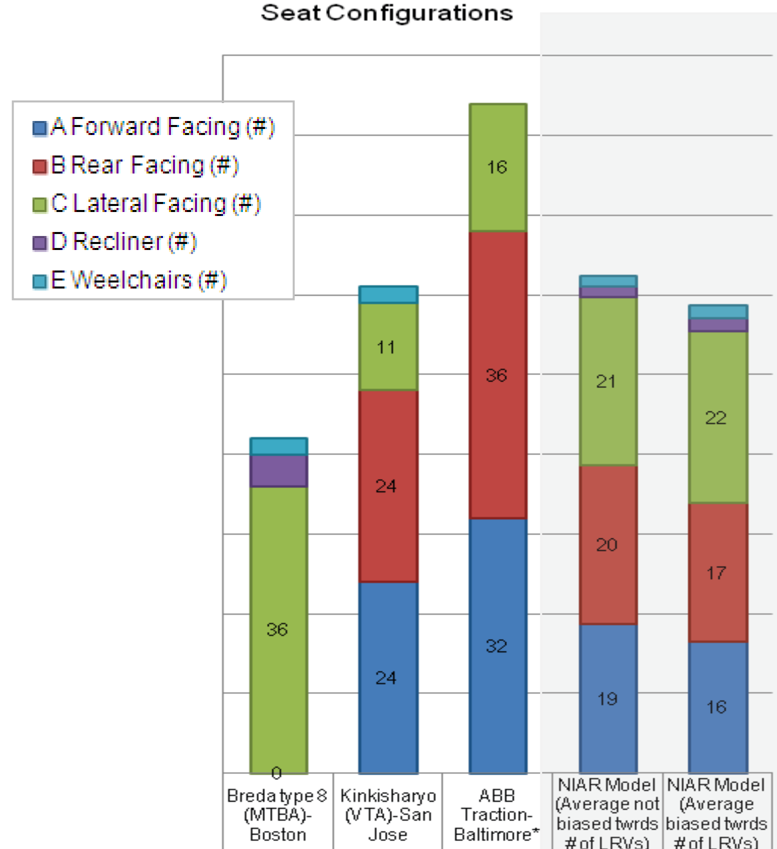
Average Values

Category 2 (without CEM)
U.S. LRV Models
Main Characteristics



	Breda type 8 (MTBA)-Boston	Kinkisharyo (VTA)-San Jose	ABB Traction-Baltimore*	NIAR Model (Average not biased twrds # of LRVs)	NIAR Model (Average biased twrds # of LRVs)
Number total seats	40	59	84	61	57
Passenger capacity	166	170	294	210	195
W Width x 10^2 (mm)	25.06	24.88	29.72	26.55	25.99
L Length between LRV ends x 10^3 (mm)	21.93	26.12	28.12	25.39	24.94
Empty weight x 10^3 (lbs)	79	97	108.00	94.81	92.62

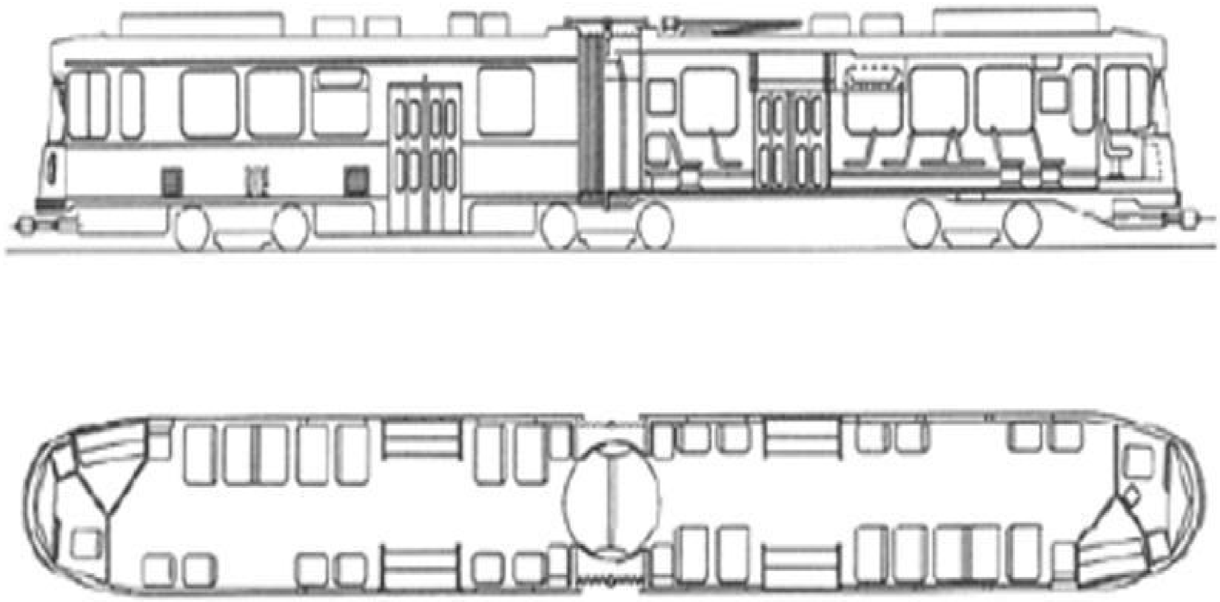
Category 2 (without CEM)
U.S. Interior Layouts
Seat Configurations



	Breda type 8 (MTBA)-Boston	Kinkisharyo (VTA)-San Jose	ABB Traction-Baltimore*	NIAR Model (Average not biased twrds # of LRVs)	NIAR Model (Average biased twrds # of LRVs)
E Weelchairs (#)	2	2	0	1	2
D Recliner (#)	4	0	0	1	2
C Lateral Facing (#)	36	11	16	21	22
B Rear Facing (#)	0	24	36	20	17
A Forward Facing (#)	0	24	32	19	16

Figure 2-9

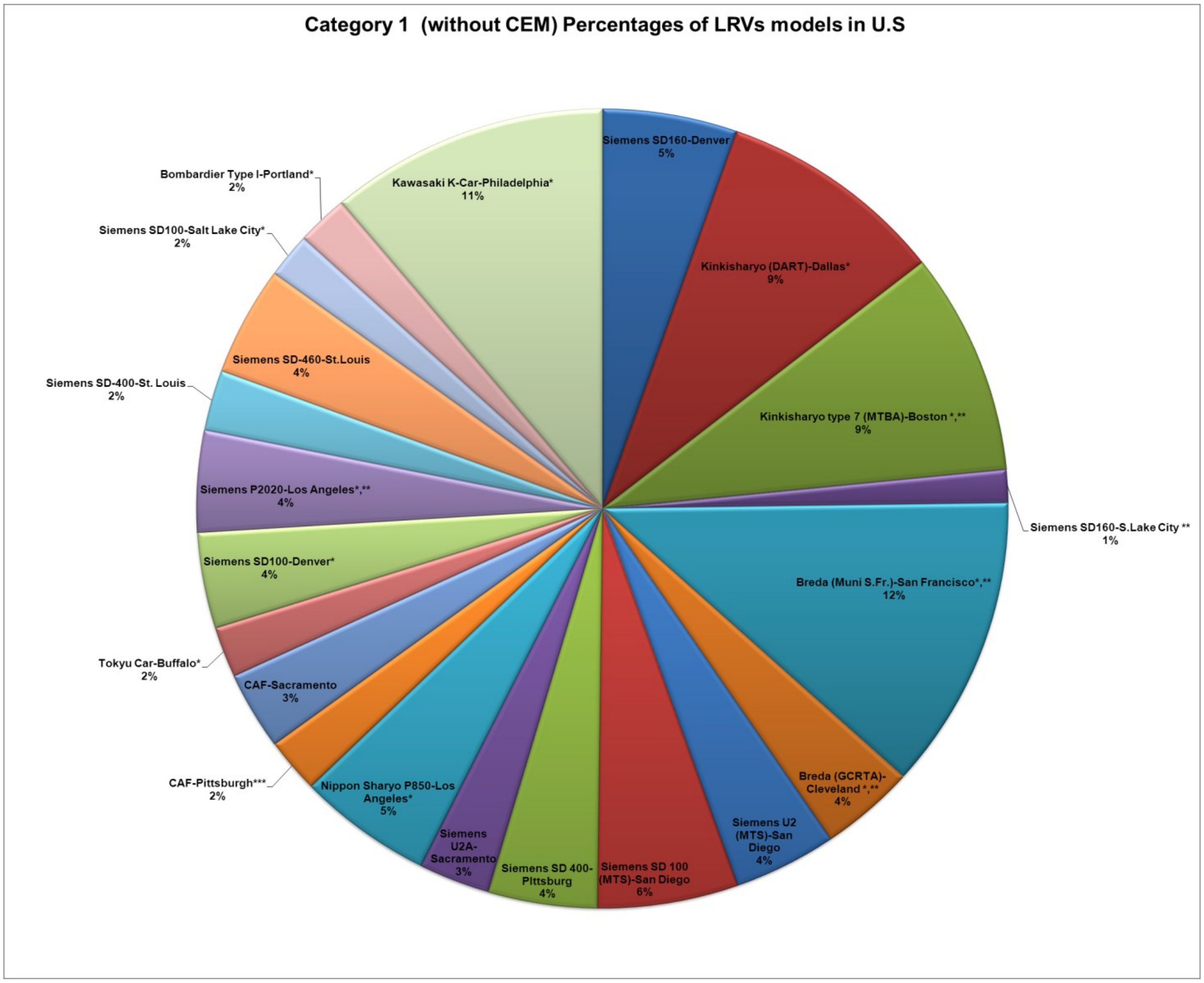
Typical U.S. Category 1 LRV Model without CEM Components [3]



In the first bar chart Figure 2 11, the main characteristics—number of seats, passenger capacity, width, length, and empty weight—are presented for all Category 1 units with one articulation without CEM components. Figure 2 12 shows the number of seats and how they are configured for these same Category 1 units. It is interesting to note that there are no designated places for wheelchairs in older Category 1 LRVs. However, newer units in Denver and Dallas are accessible for passengers with limited mobility. In both charts, the two bars on the far right are the averages that will be examined later to see how the two categories compare.

Figure 2-10

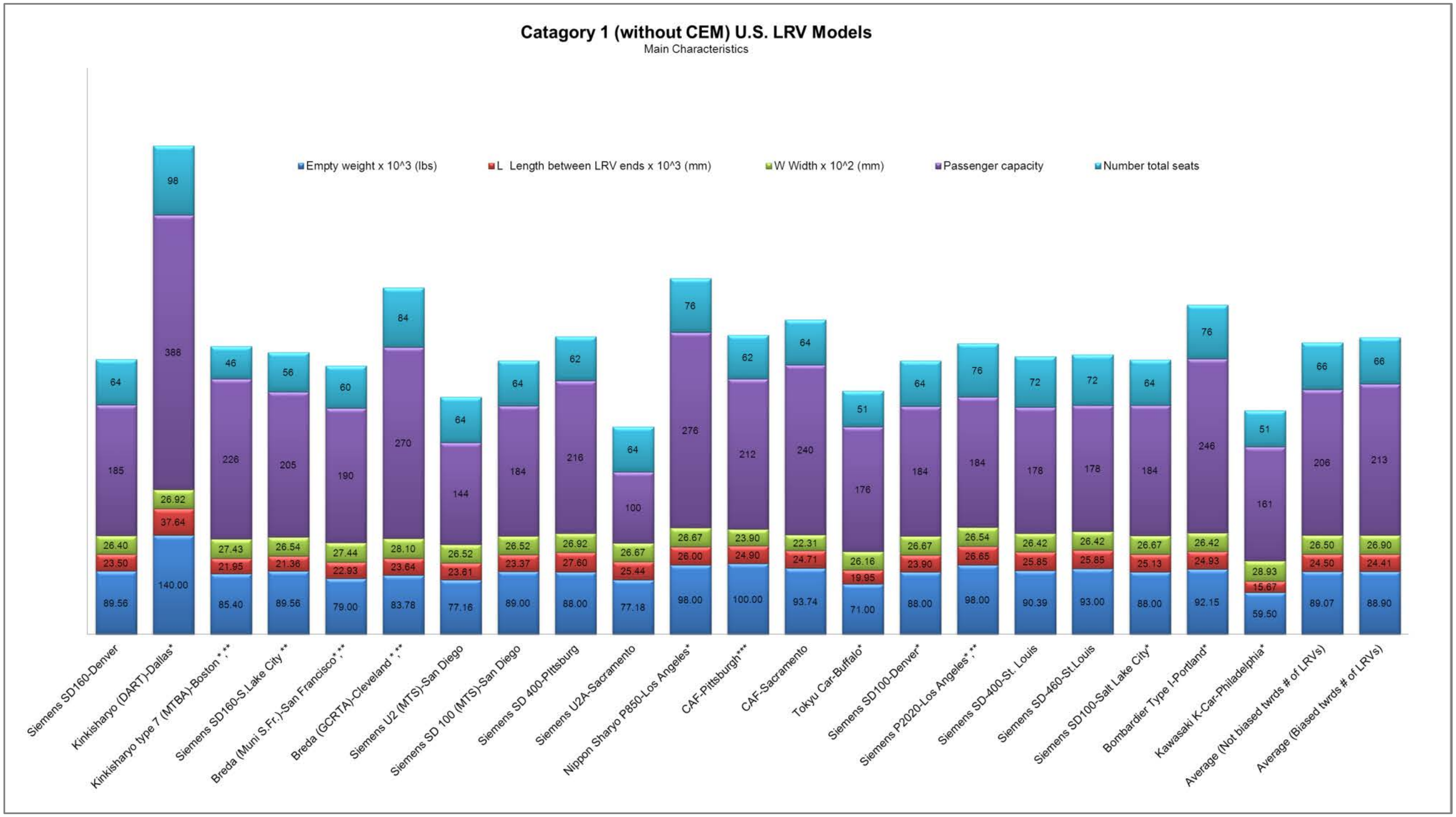
Percentages of U.S. Category 1 LRV Models without CEM Components



* Assuming fivepassengers/m2.
** Wheelchair accessibility not shown on available layout sketches used for this study.
*** Interior layout not found.

Figure 2-11

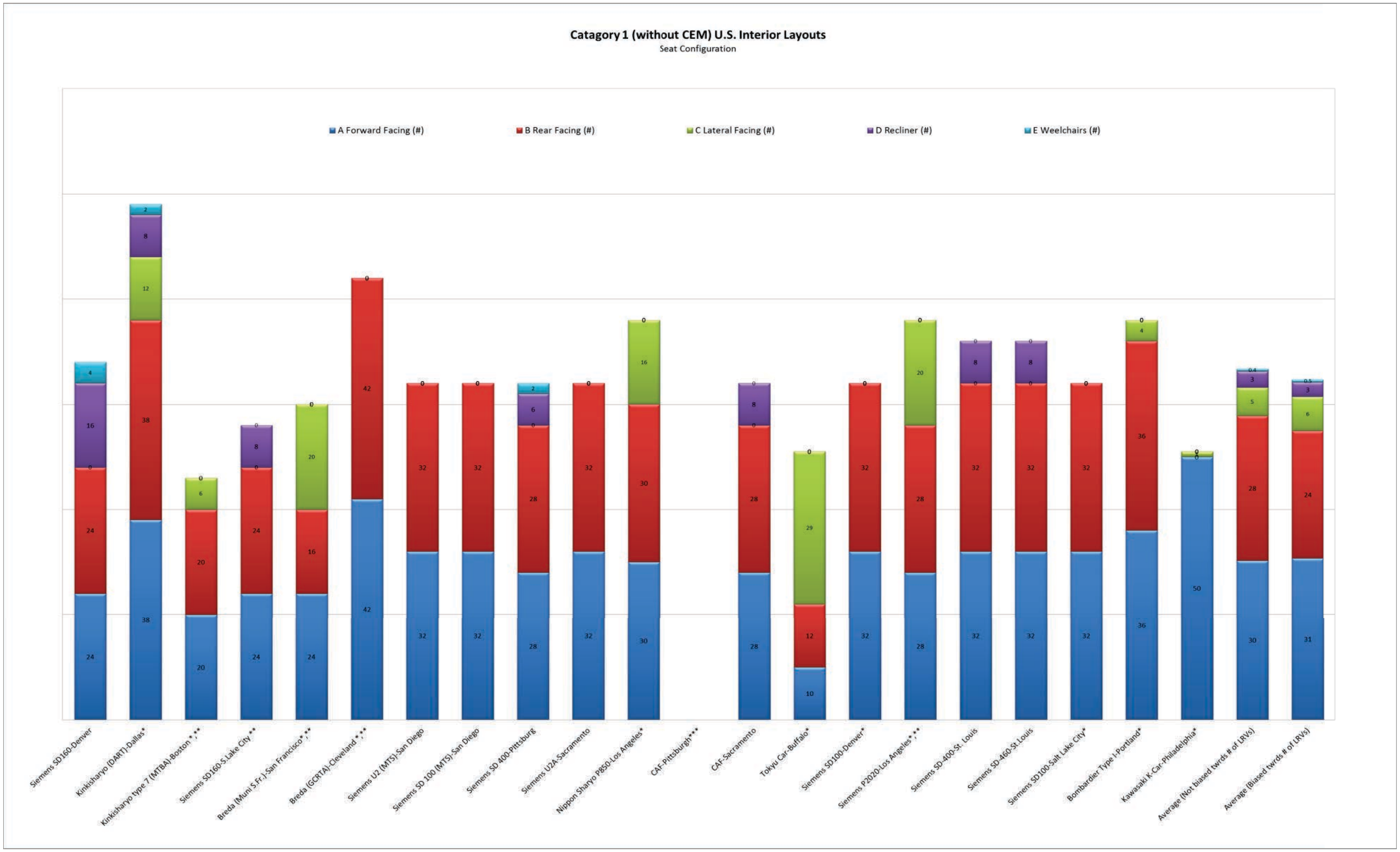
Main Characteristics of U.S. Category 1 LRV Models without CEM Components



* Assuming 5 passengers/m2.
** Wheelchair not shown on available layout sketches used for this study.
*** Interior layout not found.

Figure 2-12

Seat Configurations of U.S. Category I LRV Interior Layouts without CEM Components



* Assuming 5 passengers/m2.
** Wheelchair not shown on available layout sketches used for this study.

Category 2 without CEM Components

Category 2 (low-floor LRVs) normally has between 50 and 75 percent low floor. Figure 2-13 shows a typical Category 2 LRV without CEM components and two articulations. All variations of Category 2 LRVs make up 34 percent of the U.S. LRV fleet, which is approximately 658 units, as shown previously in Figure 2-2. Category 2 LRVs without CEM components has 247 units. Figure 2-14 shows the percentage distribution of these units by agency. Figure 2-15 shows the main characteristics for all Category 2 units without CEM components. Figure 2-16 shows the seat configuration of Category 2 LRV layouts without CEM components.

Figure 2-13

Typical U.S. Category 2 LRV Model without CEM Components [3]

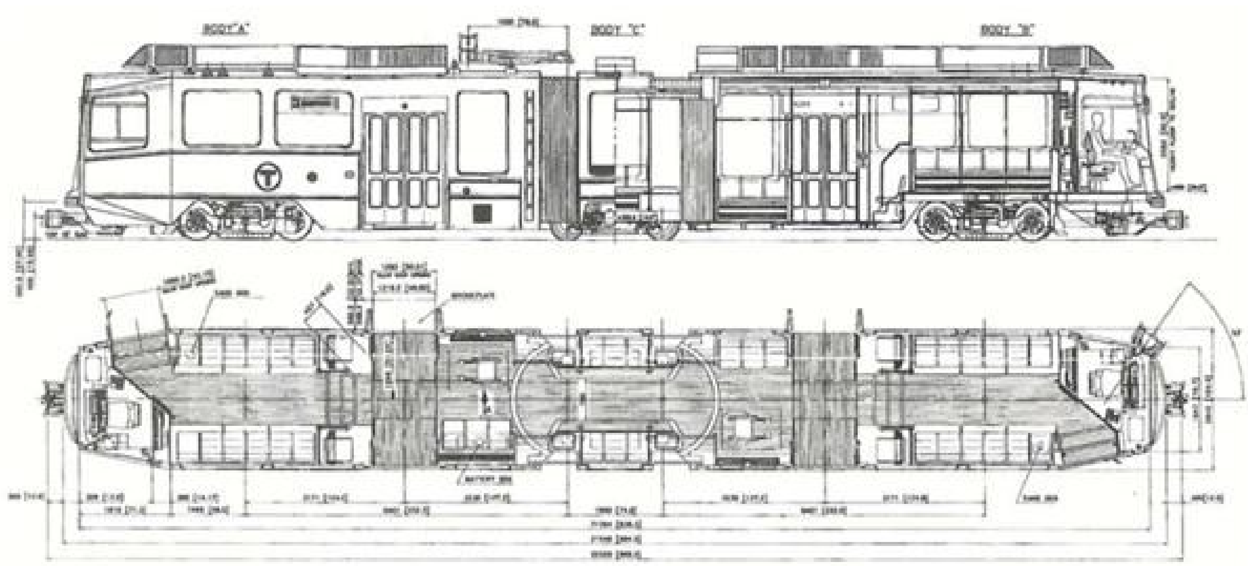
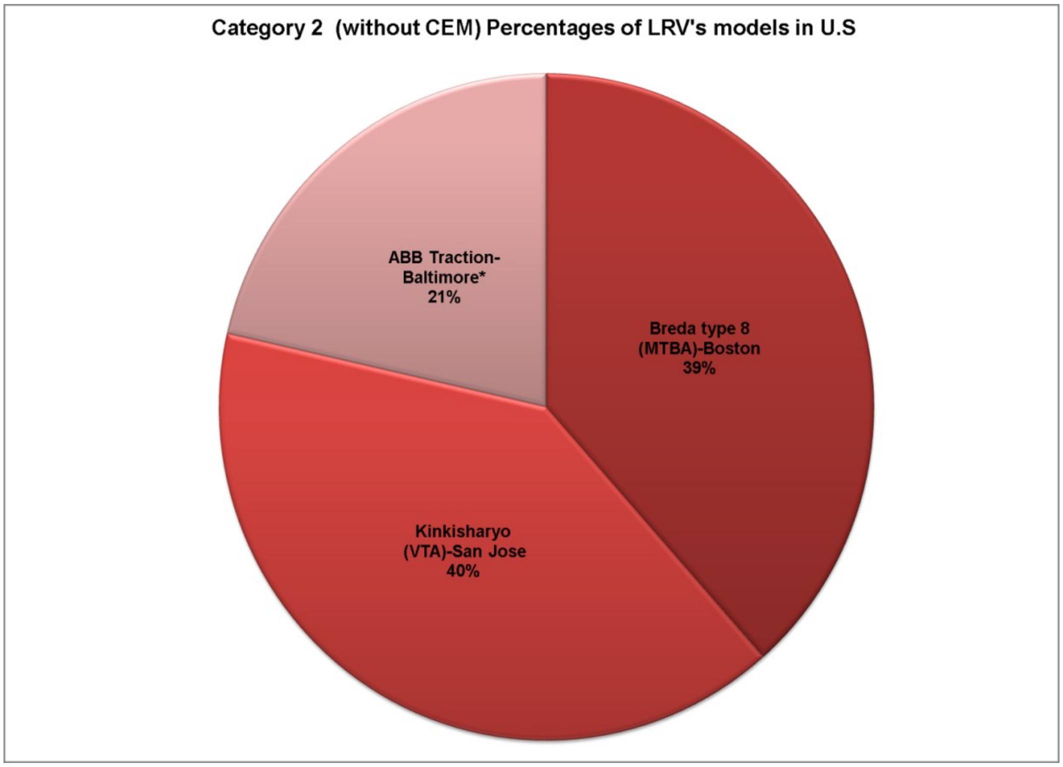


Figure 2-14

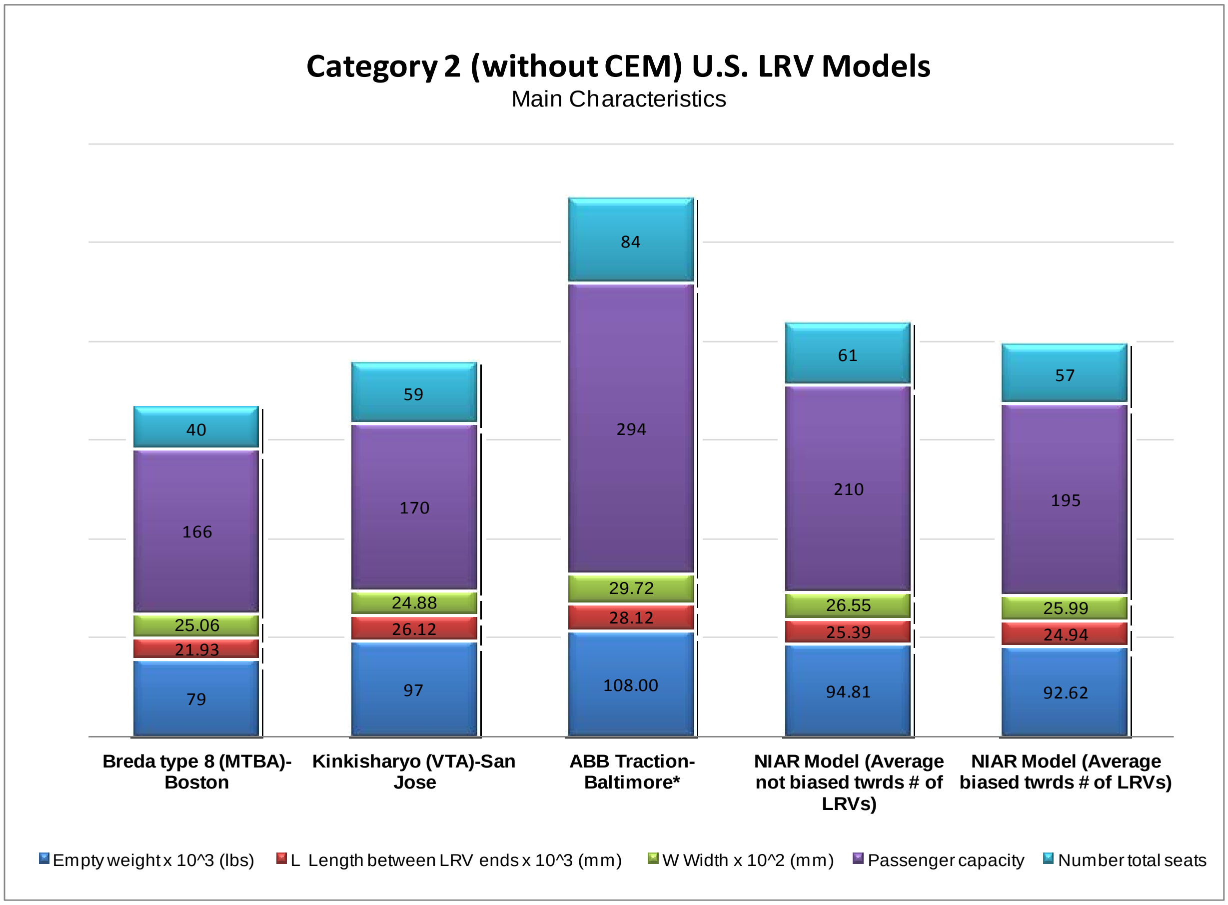
Percentages of U.S. Category 2 LRV Models without CEM Components



*Assuming five passengers/m2

Figure 2-15

Main Characteristics of U.S. Category 2 LRV Models without CEM Components



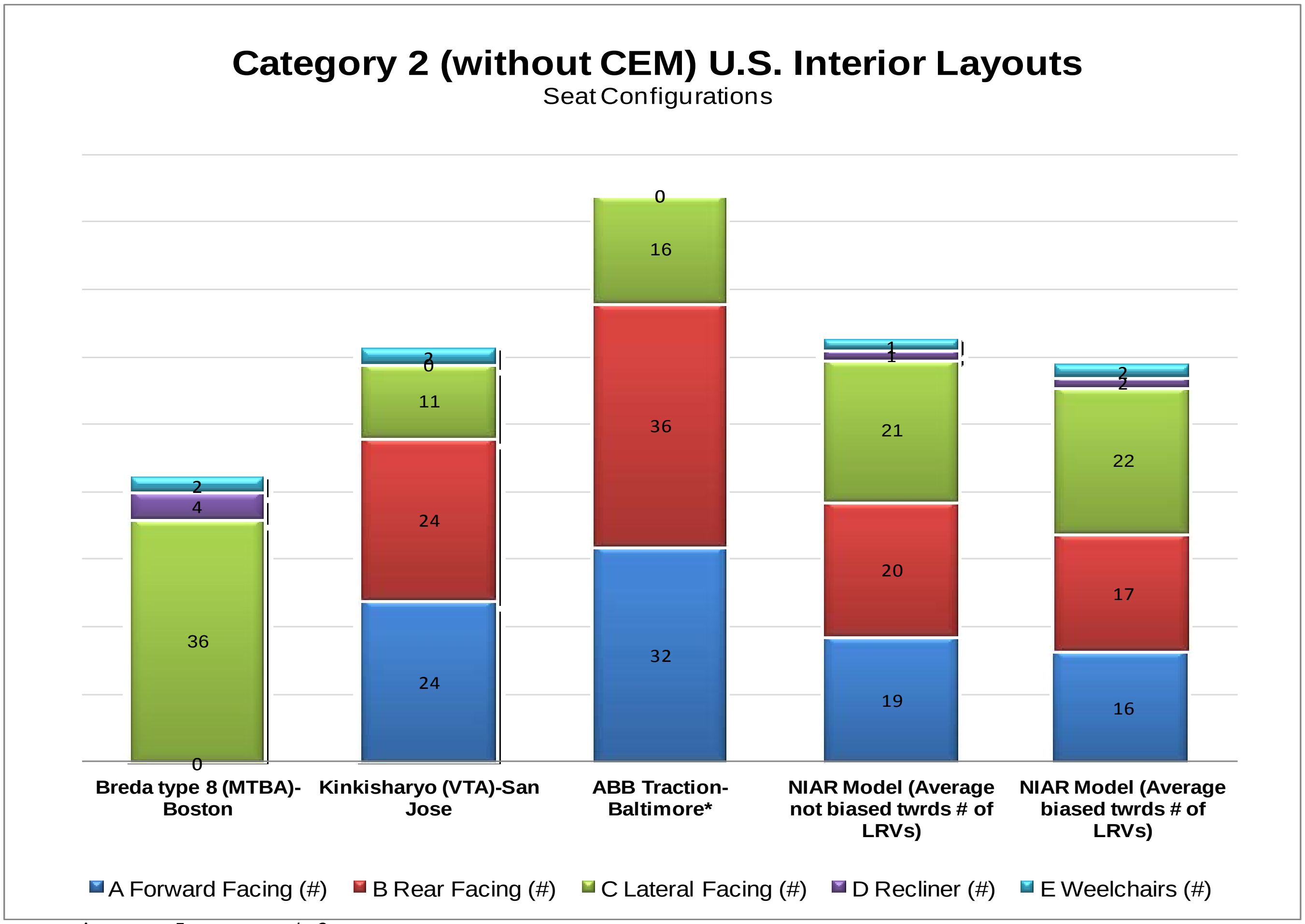
Assuming 5 passengers/m².

Category 2 with CEM Components

Category 2 (low-floor LRVs) normally has between 50 and 75 percent low floor. Figure 2-17 shows a typical Category 2 LRV with CEM components and two articulations. All variations of Category 2 make up 34 percent of the U.S. LRV fleet, which is approximately 658 units, as shown previously in Figure 2-2. Category 2 with CEM has 411 units. Figure 2-18 shows the percentage distribution of these units by agency. Figure 2-19 shows the main characteristics for all Category 2 units with CEM components. Figure 2-20 shows the number of seats in Category 2 LRV layouts with CEM components and how they are configured.

Figure 2-16

Seat Configurations of U.S. Category 2 LRV Interior Layouts without CEM Components



Assuming 5 passengers/m2.

Figure 2-17

Typical U.S. Category 2 LRV Model with CEM Components [3]

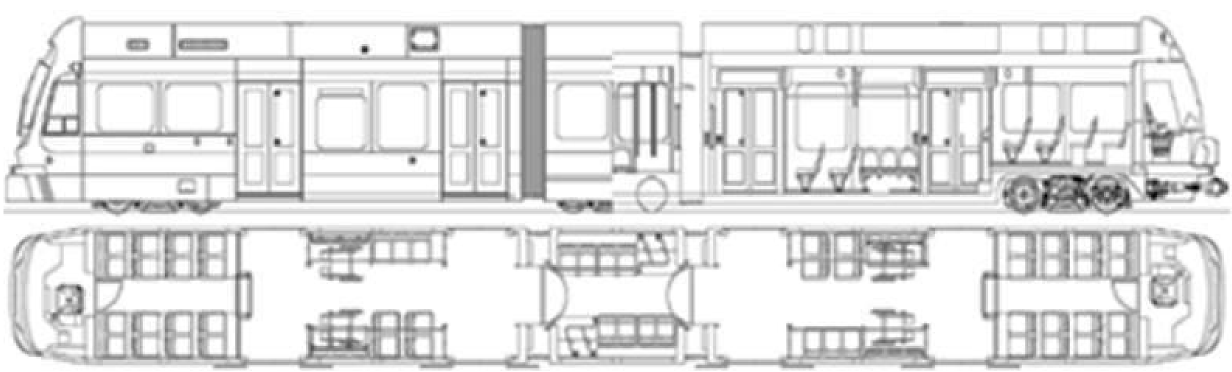
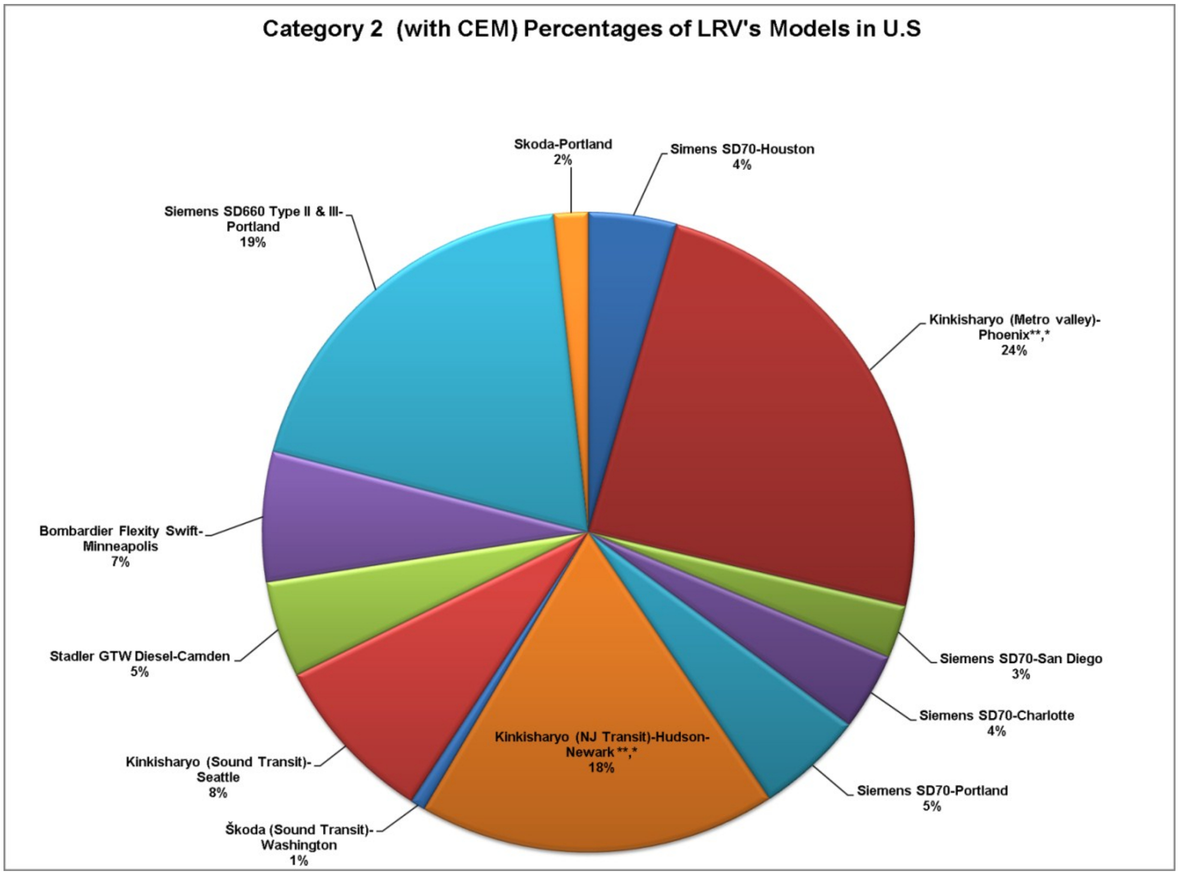


Figure 2-18

Percentages of U.S. Category 2 LRV Models with CEM Components

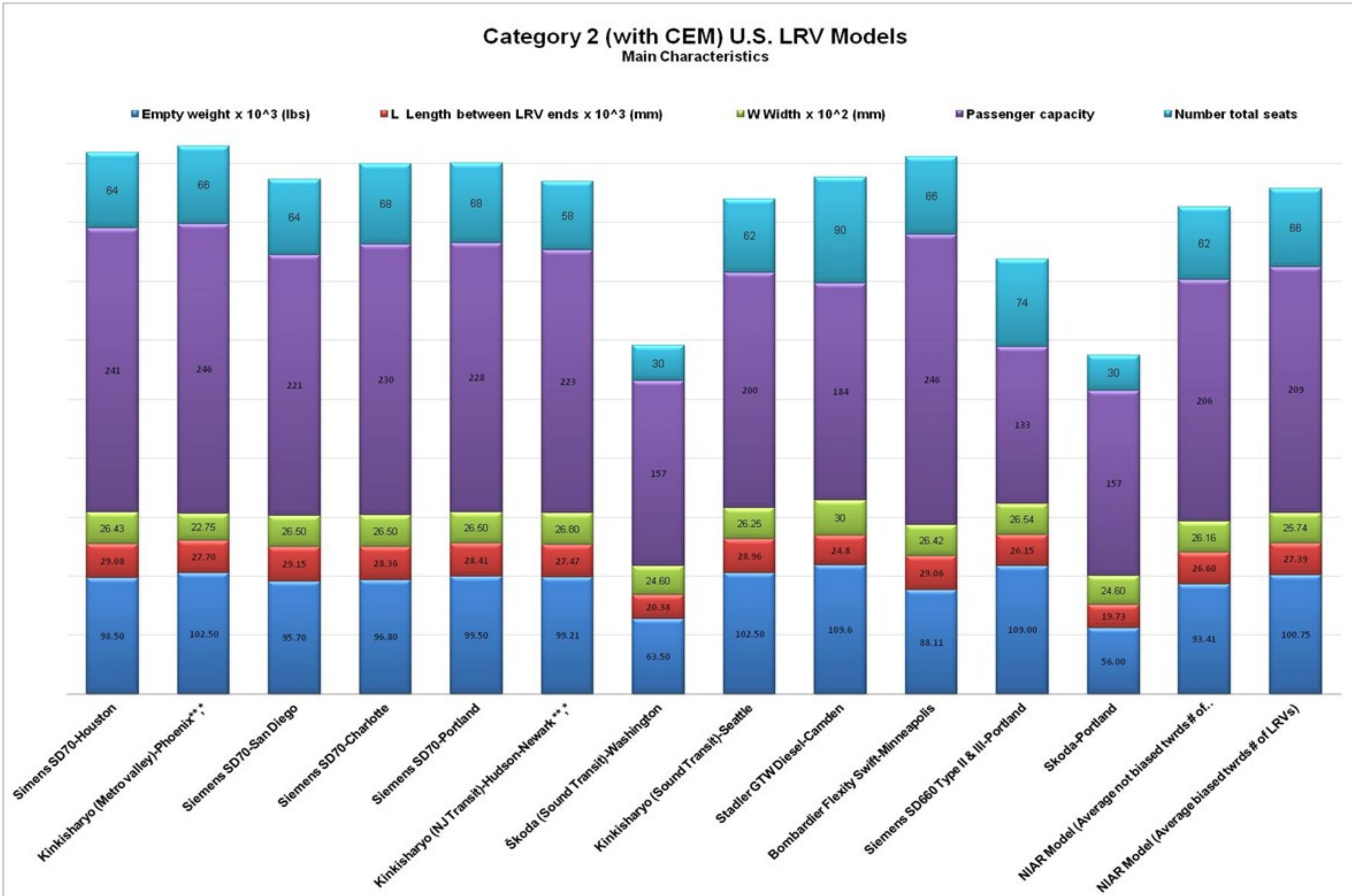


* Assuming fivepassengers/m^2.

** Wheelchair accessibility not shown on available layout sketches used for this study.

Figure 2-19

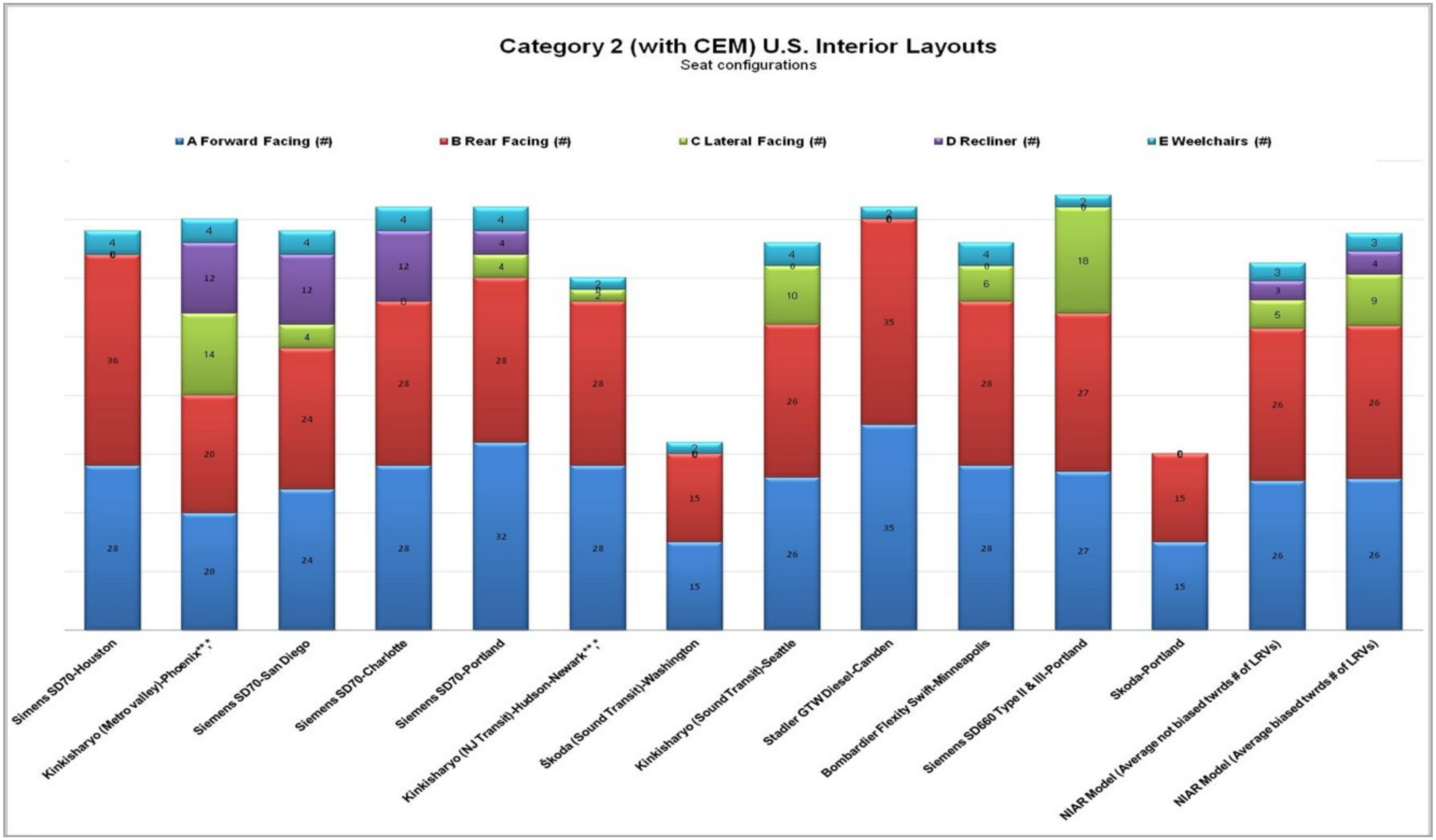
Main Characteristics of U.S. Category 2 LRV Models with CEM Components



** Wheelchair accessibility not shown on available layout sketches used for this study.

Figure 2-20

Seat Configurations of U.S. Category 2 LRV Interior Layouts with CEM Components



* Assuming 5 passengers/m2.

** Wheelchair accessibility not shown on available layout sketches used for this study.

Average Results for Main Characteristics and Interior Layouts of Available LRVs

A summary of all data gathered for the available LRVs is presented in this section. As explained earlier, these data are interpreted in two distinct ways, biased and unbiased. Biased, or average biased, data are based on the number of units per agency compared to the total number studied, i.e., a model with more units carries more weight. The unbiased, or average, results are presented for each LRV model receiving equal weight. Figure 2-21shows the average of the main characteristics analyzed in this section.

According to the biased data, on average, a current LRV has a total of 63 seats with the capacity for about 206 passengers. The average dimensions are approximately 2,621 meters in width and 25.58 meters in length. The average empty weight is approximately 94,090 lbs (42,678 kg). Compared to the unbiased data, the main differences in LRVs are found in overall passenger capacity and empty weight. This means that there are more LRVs in use with less passenger capacity and larger weight.

Figure 2-22 shows the average of the different seat configurations analyzed in this section. The differences between biased and unbiased data are, again, very small, with the main difference being lateral-facing seats. This type of configuration is more common when considering all available LRVs.

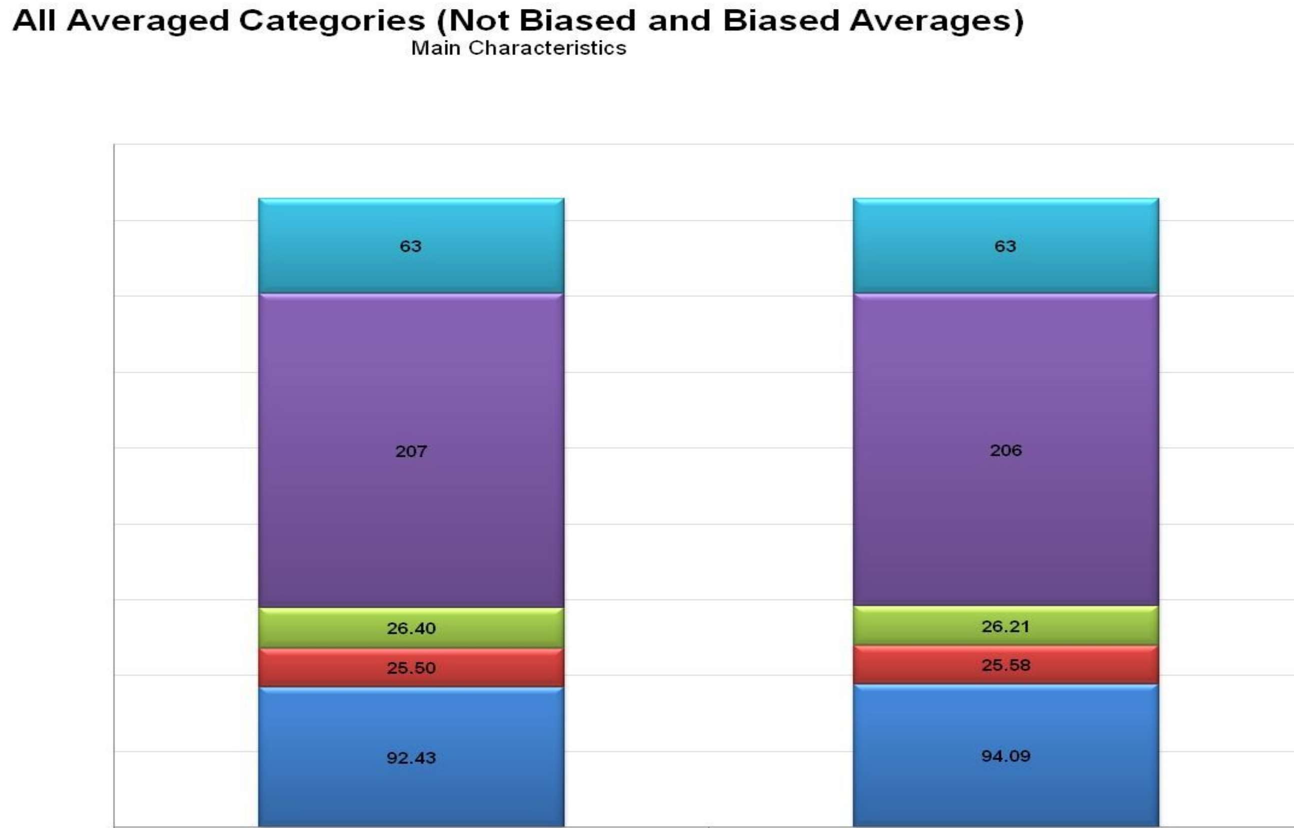
Overall, it is possible to conclude that forward-facing seats and rear-facing seats are the most commonly-used seating arrangements in current LRVs. In fact, most existing LRVs are produced with two main cabins attached by a small middle cabin that contains the articulations. This positioning results in most current LRVs being symmetric (Figure 2-13 and Figure 2-17), and as a result, the average number of forward- and rear-facing seats are very similar.

The third most-used type of seating arrangement is lateral-facing seats, which account for approximately 20 percent of total LRV seating. Finally, on average, two spaces are available for wheelchairs. Usually, most of these spaces share room with recliner seats, which are able to be folded and stored to make room for the wheelchair.

A more detailed survey of existing LRV interiors is discussed in the following section.

Figure 2-21

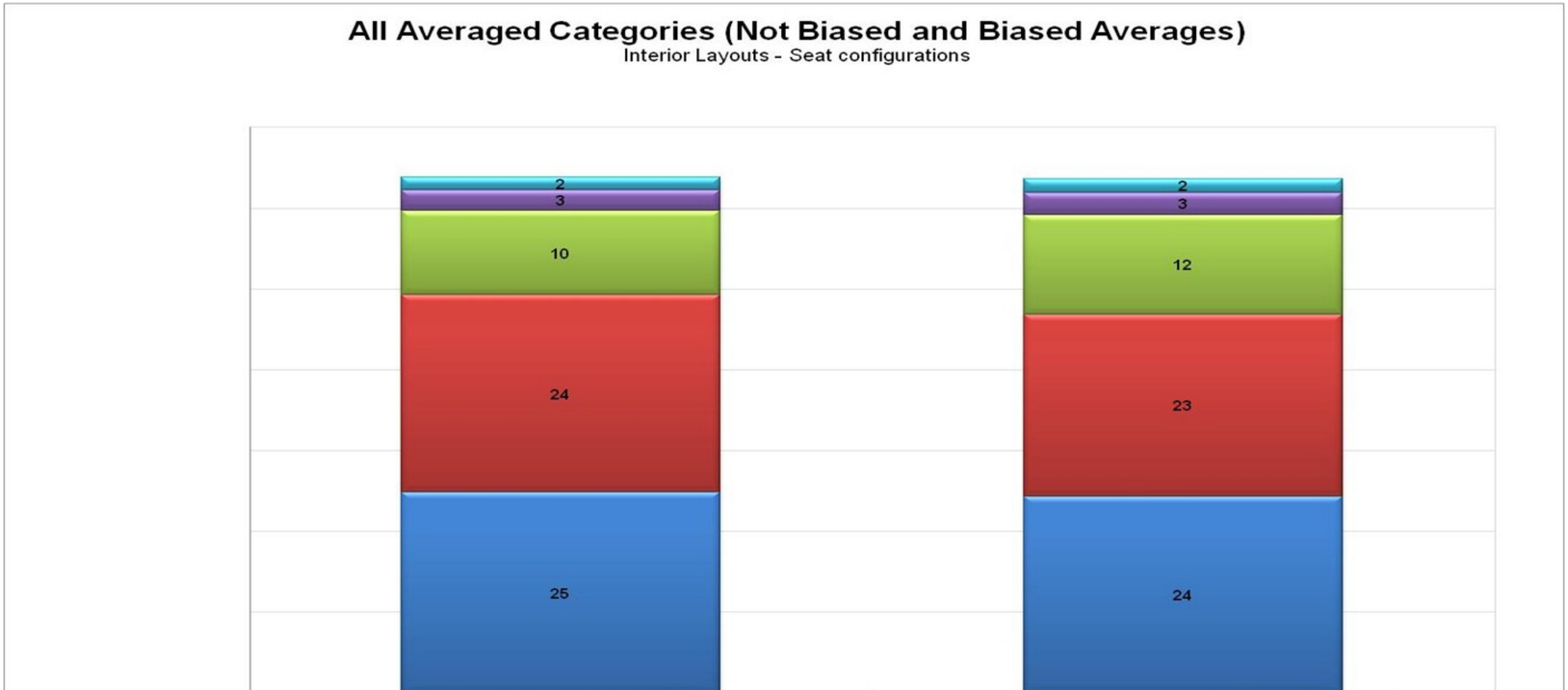
Averages of LRV Main Characteristics



	Averaged U.S. LRV Model (Not Biased twrds # of LRVs)	Averaged U.S. LRV Model (Biased twrds # of LRVs)
Number total seats	63	63
Passenger capacity	207	206
W Width x 10^2 (mm)	26.40	26.21
L Length between LRV ends x 10^3 (mm)	25.50	25.58
Empty weight x 10^3 (lbs)	92.43	94.09

Figure 2-22

Averages of LRV Seat Configurations



	Averaged U.S. LRV Model (Not Biased twrds # of LRVs)	Averaged U.S. LRV Model (Biased twrds # of LRVs)
E Weelchairs (#)	2	2
D Recliner (#)	3	3
C Lateral Facing (#)	10	12
B Rear Facing (#)	24	23
A Forward Facing (#)	25	24

Survey of LRV Specific Interiors

This section contains results from a detailed survey of the possible configurations of seats found in current LRVs. Figure 2-23 compares old and new interior designs for different LRVs.

Figure 2-23

Old and New Interior Designs for LRV

According to all layouts studied, a total of 13 types of configurations were defined. Table 2-4 shows the different types of seats analyzed the number of seats in each configuration and the percentage of this configuration of the total. The results are also shown in a bar chart format as Figure 2-24.

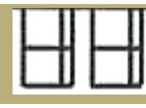
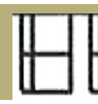
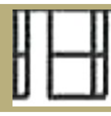
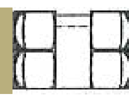
A total of 113,822 seats were studied. This number takes into account the number of LRVs that exist with that specific interior layout. For example, if the Siemens LRV from Los Angeles has 24 forward-facing seats and there are 59 LRVs with that layout, a total of 1,416 forward-facing seats were counted for this model.

From Table 2-4 and Figure 2-24, it is possible to see that the unidirectional forward-facing seats (type 1), unidirectional rear-facing seats (type 2), seats facing each other (type 5), and lateral seats facing each other (type 6) represent approximately 73.9 percent of the total.

The results from this section are used throughout the rest of the paper to evaluate the principal types of injuries found in existing LRVs.

Table 2-4

Interior Seat Configuration Survey—Percentage of Seats per Configuration

Type of Configuration		Total Seats	Percentage
Unidirectional Forward-Facing Seats (1)		25,196	22.1
Unidirectional Rear-Facing Seats (2)		19,998	17.6
Forward-Facing Seats Monument (3)		8,888	7.8
Rear-Facing Seats Monument (4)		8,044	7.1
Seats Facing Each Other (5)		21,904	19.2
Lateral Seats Facing Each Other (6)		17,057	15.0
Single Seat Forward and Rear (7)		4,734	4.2
Lateral Seat Facing Forward/Rear Double Seat (8)		1,713	1.5
Lateral Seat Facing Wheel Chair (9)		1,096	1.0
Lateral-Facing Rear/Forward Single Seat (10)		862	0.8
Forward and Rear Seat Facing Wheelchair (11)		2,268	2.0

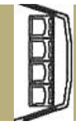
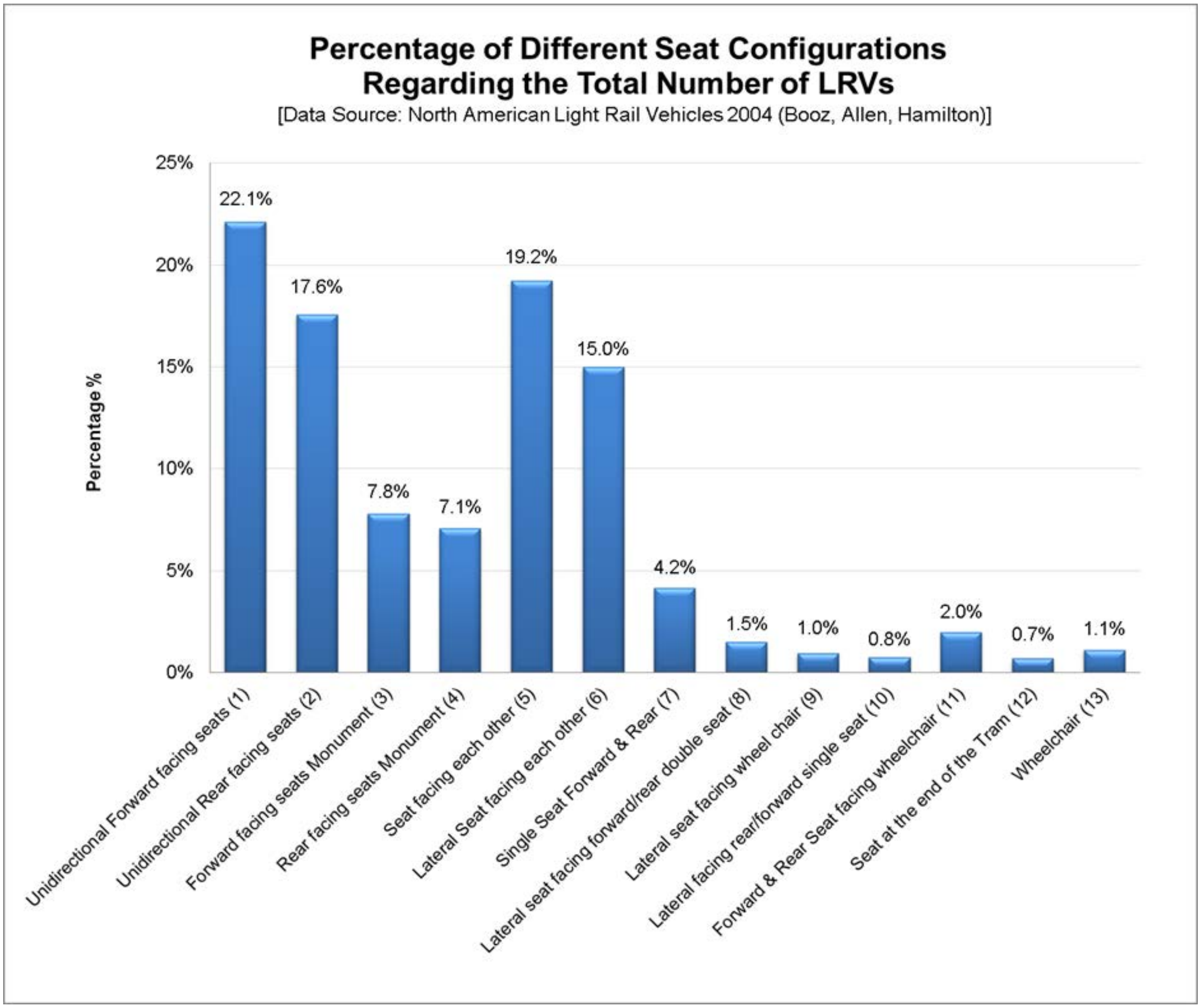
Type of Configuration		Total Seats	Percentage
Seat at End of Tram (12)		796	0.7
Wheelchair (13)		1,266	1.1

Figure 2-24

Percentage of Seat Configurations for Total Number of LRVs



SECTION

3

Literature Review of Accident Data on LRVs

This section includes a summary of all relevant LRV statistical data from applicable sources. As can be seen, the data is not as complete as might be expected.

The principal reports and surveys used to obtain the statistical data are as follows:

TCRP Report 69: "Light Rail Service: Pedestrian and Vehicular Safety" [1]

This report provides documentation and the results of a study to improve the safety of light rail transit in semi-exclusive right-of-ways where light rail vehicles operate at speeds greater than 35 mph through street crossings and pedestrian pathways.

Data related to this project is presented in Chapter 2 of that report. This chapter presents an overview of each of the 11 LRT systems studied in the United States and Canada and summarizes the accident information. These data were collected from different time frames depending on the LRT system. Also important to note is the fact that the data do not show any information about type of accident, only if the accident was between the LRV and a vehicle, pedestrian, or cyclist.

Transit Safety and Security Statistics and Analysis 2003 Annual Report [2]

This report includes information about the number of accidents, with a comparison between modes, and data about the type of accidents, differentiating between collision and derailments. It also contains plots and tables illustrating fatalities, injuries, fires, robberies, number of vehicles, and passengers.

Most data discussed in this report are from 1996 to 2003; however, some of the data have been updated through 2007 with information available at the Transit Safety and Security web page [2].

TCRP Report 17: "Integration of Light Rail Transit into City Streets" [4]

This report addresses the safety and operating experience of light rail transit systems operating in shared (on-street or mall) right-of-ways at speeds that do not exceed 35 mph. It is based on agency interviews, field observations, and accident analyses of 10 LRT systems in the United States and Canada. These systems—in Baltimore, Boston, Buffalo, Calgary, Los Angeles, Portland, Sacramento, San Diego, San Francisco, and San Jose—provide a broad range of current LRT operating practices and problems.

The accident data of the 10 selected LRT systems were analyzed based on statistics from the Federal Transit Administration (FTA) Section 15 Report for 1992 and the multiyear accident information obtained from each system, including the highest-accident locations.

2008 Public Transportation Fact Book (Part 1 and Part 2) [5]

The *Public Transportation Fact Book* presents statistics describing the entire United States transit industry from 1995 through 2006, with additional detail and overview presentations for 2006. Also included are definitions of reported data items. The *Public Transportation Fact Book Part 2: History* presents primary data items for the entire time period they have been reported in fact books and other statistical reports prepared by APTA and its predecessor organizations. Many data items are reported for every year beginning in the 1920s, and ridership is reported from 1907.

This report focuses more on the number of LRV passengers and the capacity of the transport system than on the type and number of LRV accidents. Also, the *Public Transportation Fact Book Part 2* has data with more years to compare.

Passive Safety of Tramways for Europe [6]

Based on a LRV statistics study, reference collision scenarios were identified, including an evaluation of their consequences in terms of material damage and injuries and fatalities as applied to city tram operations in Europe. An assessment of acceptable risk also has been considered, with the aim of appraising how safety levels in LRV operations compare with other existing modes of public transportation. In this survey, 21 operators participated, which corresponded to a total aggregate network length of 1,777 km. This represents about 30 percent of the total network length of EU operators (5,121 km). In this study, a total of 59,000 accidents with 7,600 casualties were reported from 21 European operators in the last ten years. Using the data from these 21 operators, typical conditions for city tram crashes were obtained.

Conclusions: Accident Data Literature Review

The total number of LRV vehicles and corresponding passengers has increased approximately 50 percent over the last 10 years, as shown in Figure 3-1. Still, as shown in Figure 3-2 and Figure 3-3, light rail passengers represent 4.1 percent of the total unlinked passenger trips, if all modes are taken into account, and only 3.6 percent of total passenger miles by mode. It is interesting to note that while the total number of passengers and vehicles increased, as shown in Figure 3-4 and Figure 3-5, the number of incidents remained relatively stable, as shown in Figure 3-6. In contrast, the number of incidents has been constant, and the number of collisions and derailments did not experience any decrease, as shown in Figure 3-7 and Figure 3-8. Based on this information, it can be assumed that the number of incidents reported is less, but the magnitude of them is larger, due to the increase in number of fatalities. It is important to notice that while the number of fatalities has increased during the last several years, the number of injuries actually has been reduced. Studying the trends plotted illustrates that the decrease of injuries is directly associated with the revision of the National Transit Database (NTD) to coincide with other U.S. Department of Transportation (DOT) modes. Therefore, the decrease in the number of people injured in LRV crashes could not be directly comparable with previous years.

Figure 3-1

Number of LRV Passengers from 1990 to 2007

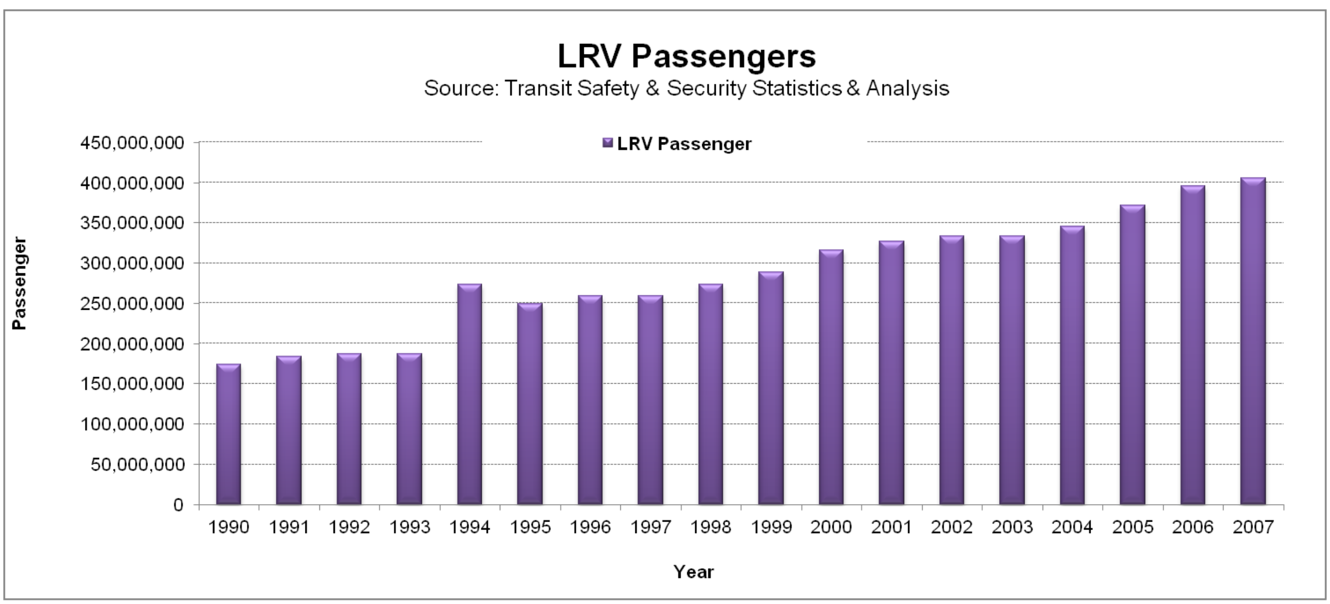


Figure 3-2

Percentage of Unlinked Passenger Trips by Mode of Transportation

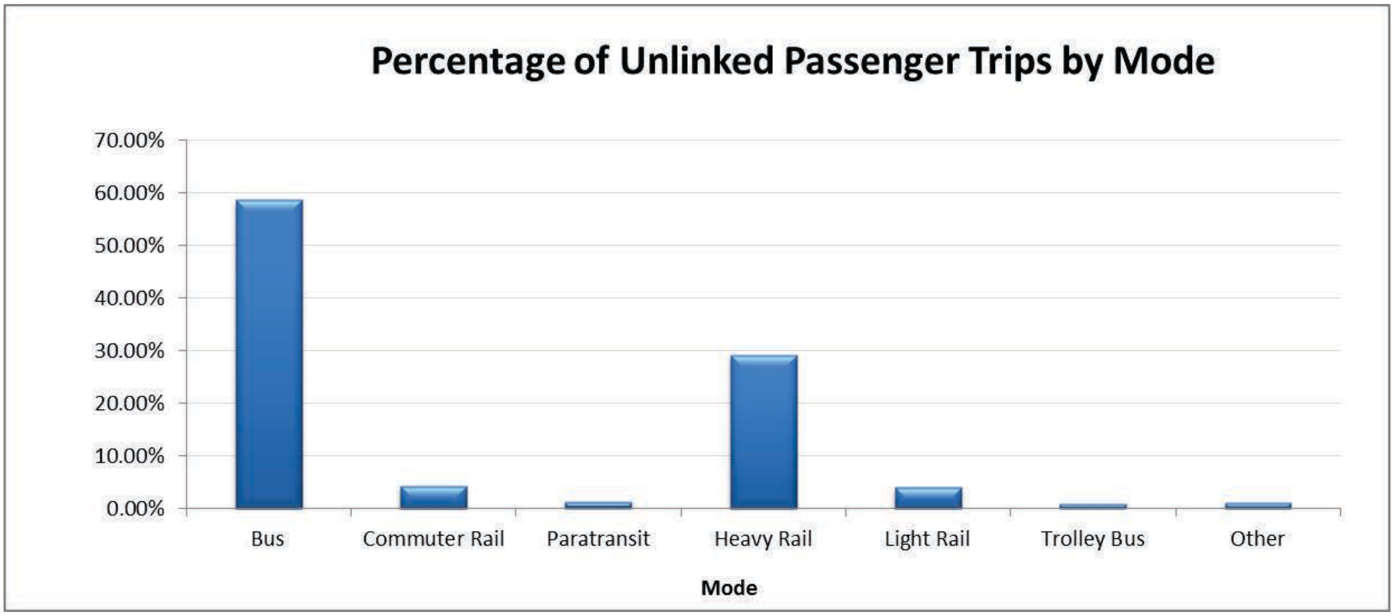


Figure 3-3

Percentage of Passenger Miles by Mode of Transportation

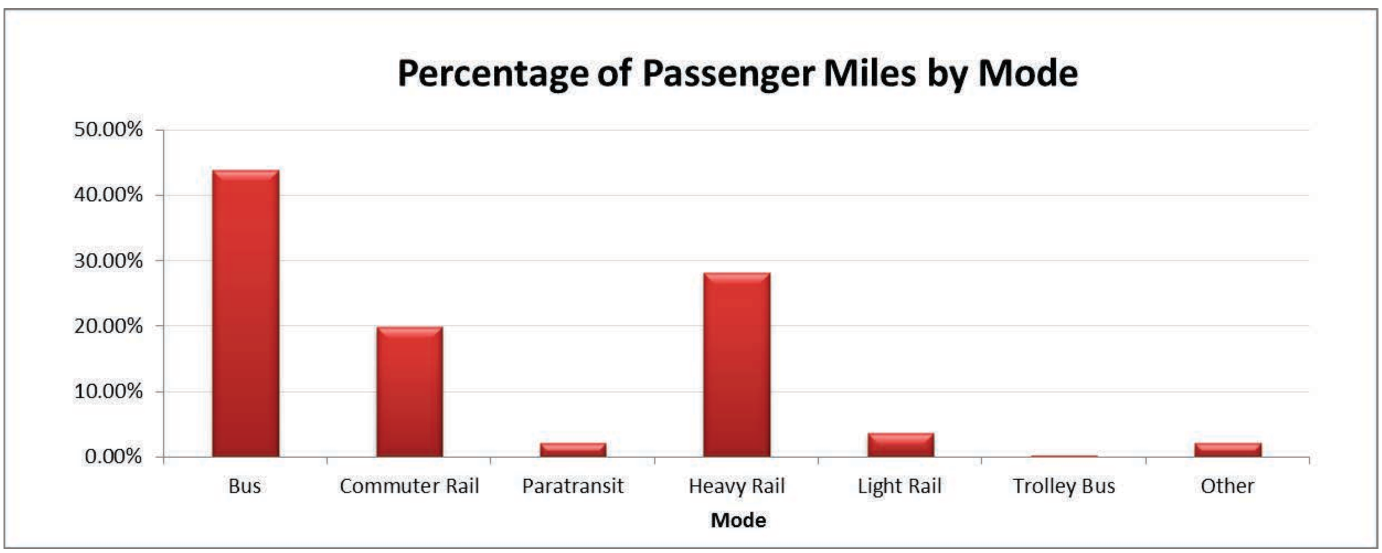


Figure 3-4

Number of LRV Vehicles Miles from 1990 to 2007

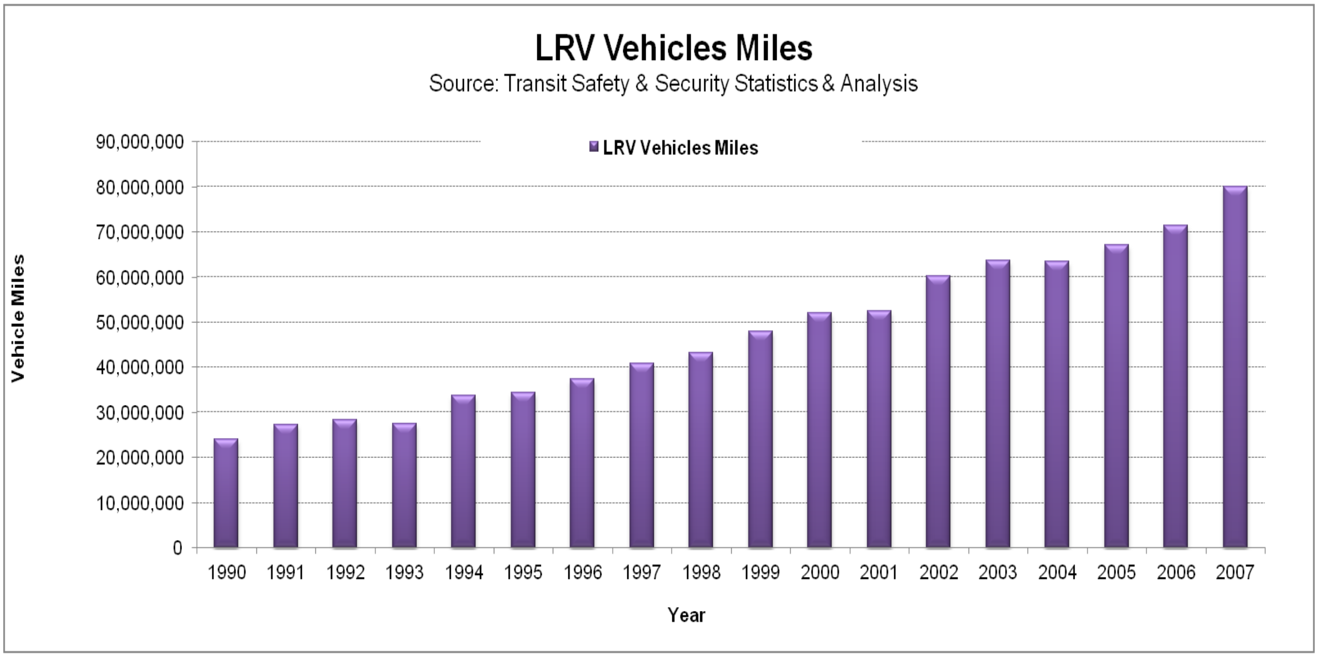


Figure 3-5

Number of LRV Passenger Miles from 1990 to 2007

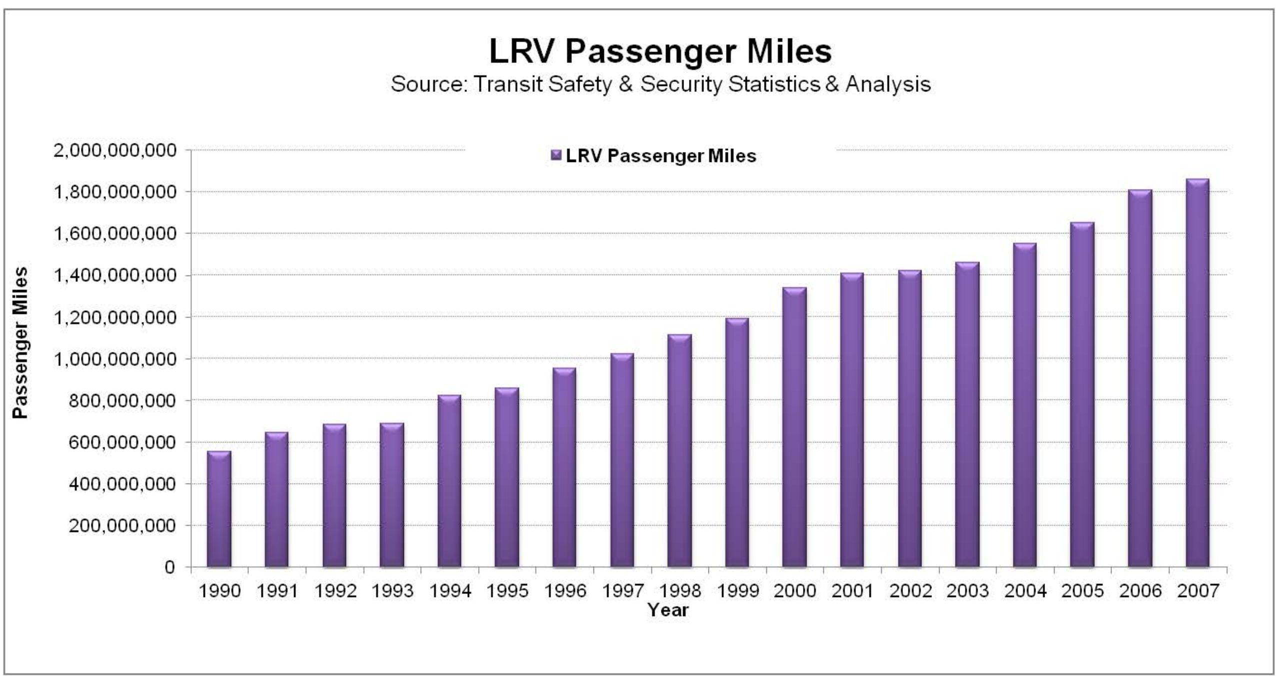


Figure 3-6

Number of LRV Reported Incidents from 1990 to 2007

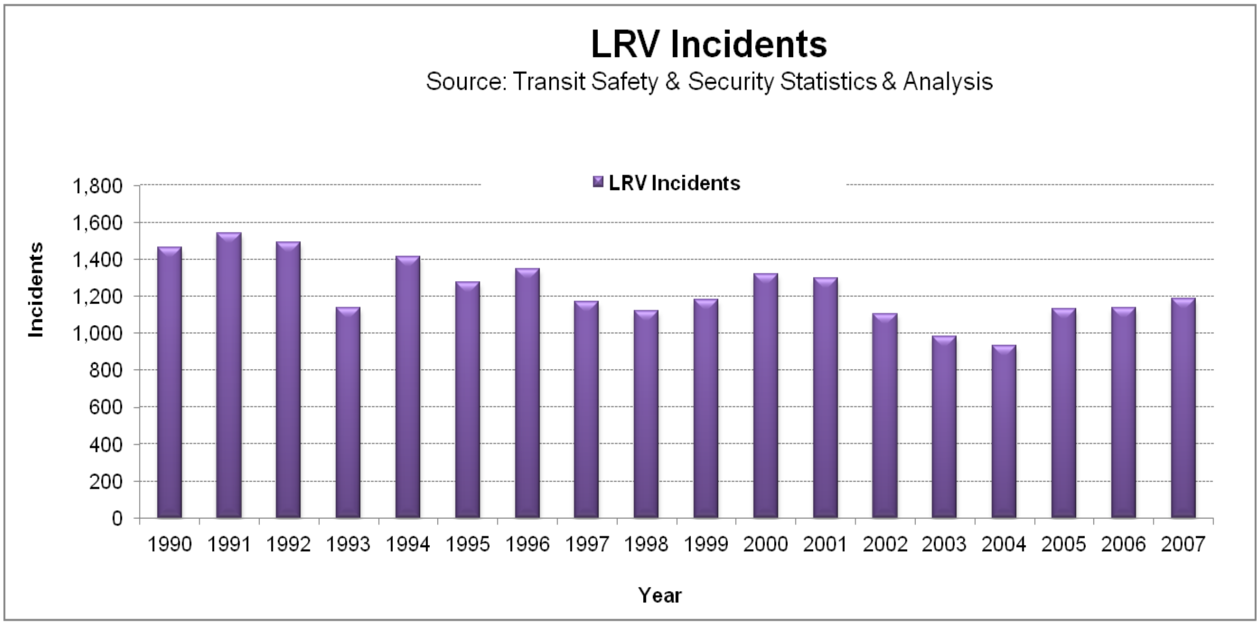


Figure 3-7

Number of LRV Reported Collisions from 1990 to 2007

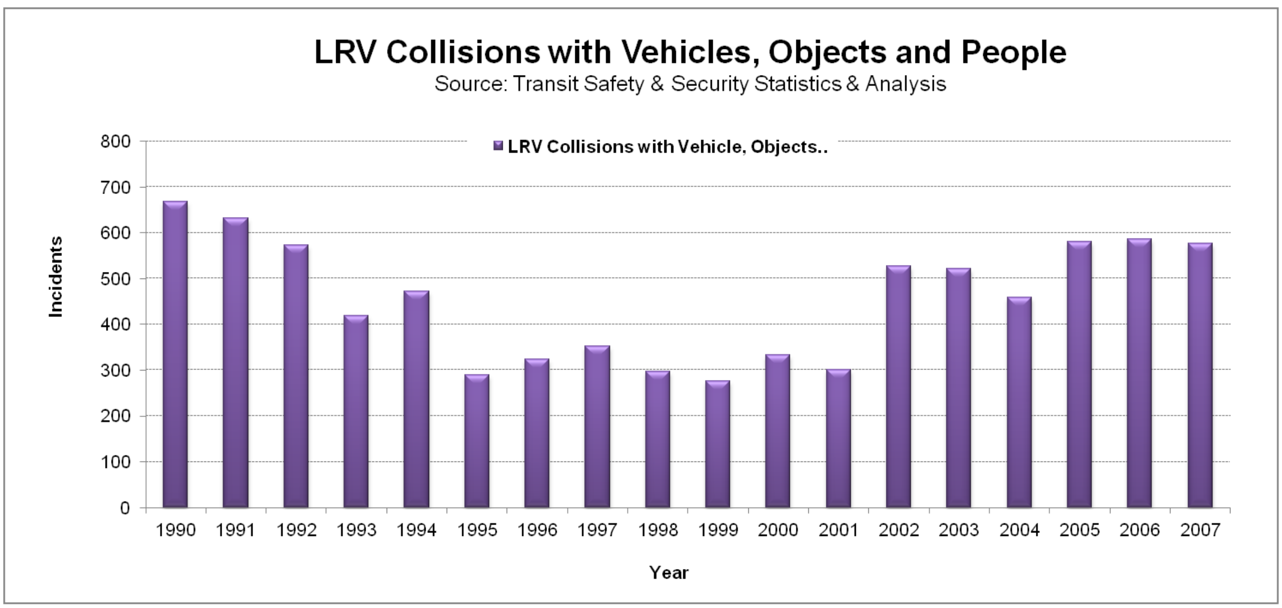


Figure 3-8

Number of LRV Reported Derailments from 1990 to 2007

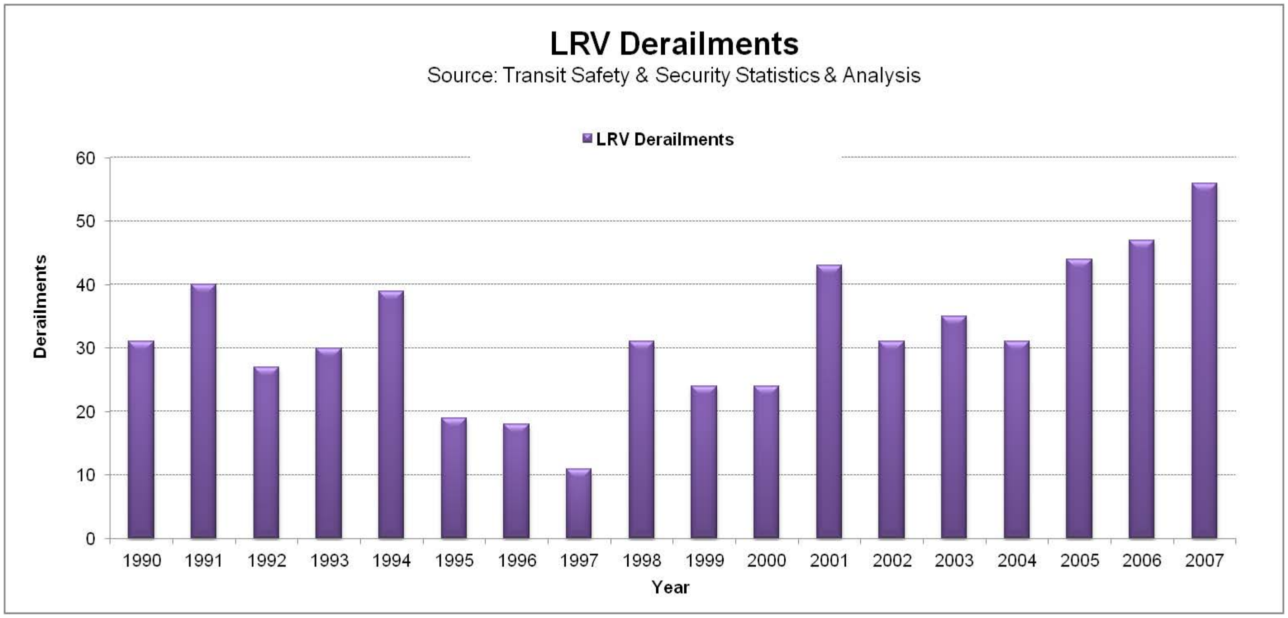


Table 3-1

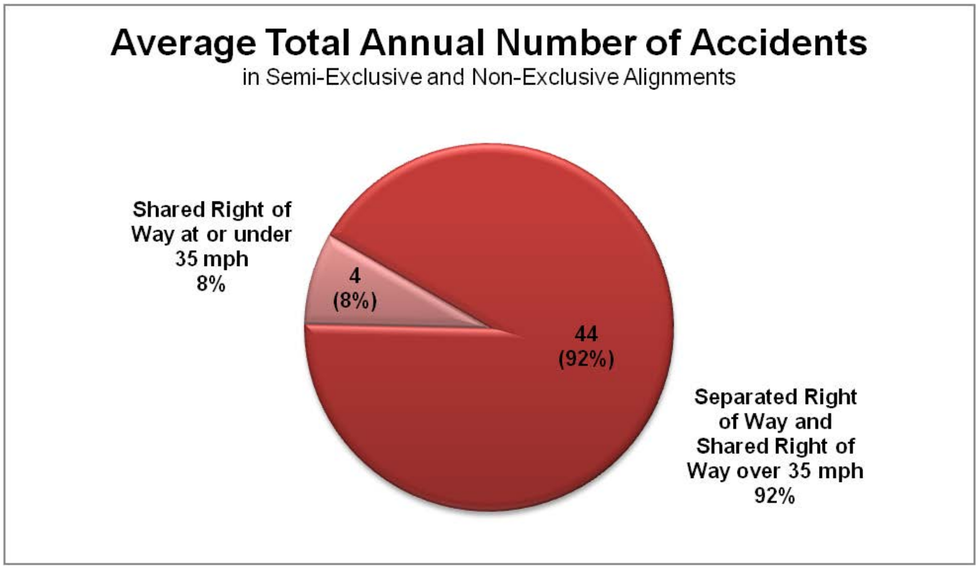
Accidents Summary for LRT Systems Surveyed [4]

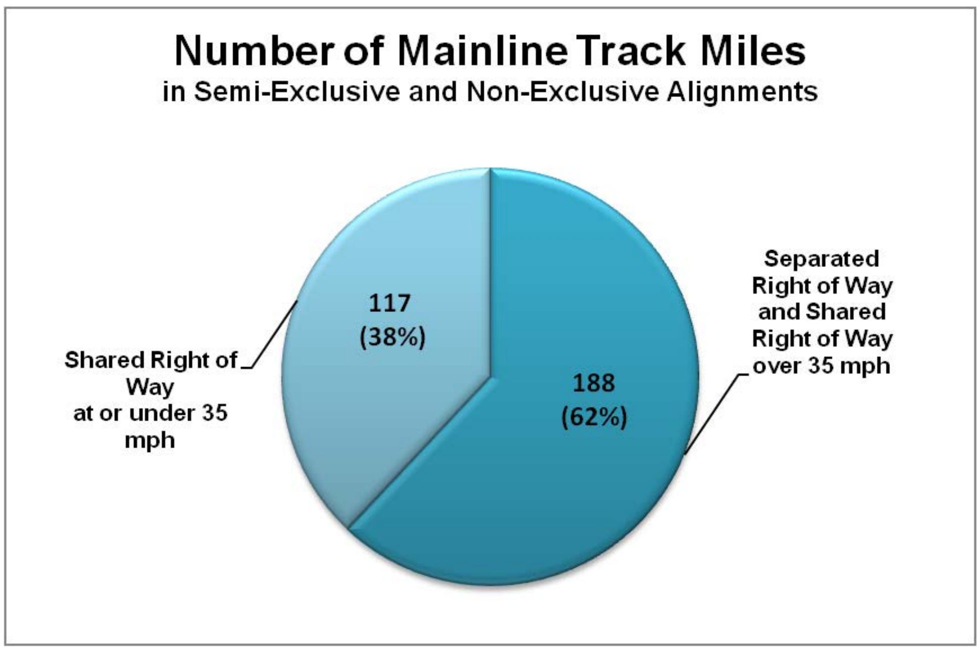
LRV SYSTEM	BALTIMORE		BOSTON		BUFFALO		CALGARY		LOS ANGELES		PORTLAND		SACRAMENTO		SAN DIEGO		SAN FRANCISCO		SAN JOSE		ALL SYSTEMS	
Period	4/92-7/94		7/89-8/93		2/85-11/93		5/81-12/93		7/90-6/94		7/86-6/94		11/86-12/93		7/81-6/94		1/86-12/93		7/87-12/93			
No. of Years	2.3		4.2		8.8		12.7		4		8		6.3		13		8		6.5			
Collision Type	No.	Pct.	No.	Pct.(a)	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct. (b)	No.	Pct.	No.	Pct. (c)	No.	Pct.	No.	Pct.
Auto turns in front of LRV	55	0.86		0.38	0	0	206	0.73	129	0.56	76	0.41	-	0.59	298	0.85	-	0.27	106	0.64	1350	0.47
Auto other	2	3%		58%	10	100%	(incl.)	(incl.)	73	31%	81	44%	-	38%	(incl.)	(incl.)	-	71%	50	30%	1265	44%
Pedestrian	7	11%		4%	0	0%	77	0.27	31	13%	27	15%	-	3%	54	0.15	-	2%	10	6%	241	9%
Total	64	100%	97(d)	100%	10	100%	283	100%	233	100%	184	100%	143	100%	352	100%	1322	100%	166	100%	2856	100%
Mainline Track Miles (approx.) (e)	24		49		12		35		43		27		35		66		53		35		379	
Average Accidents Per Year Per Mainline track Mile	1.16		1.98		0.09		0.64		1.35		0.85		0.77		0.41		3.12		0.73		1.11	
Mainline Trackmile in Semi-Exclusive or Non-Exclusive Alignments (approx.)	6		16		2		20		27		13		8		9		39		15		155	
Accident Index (f)	4.6		6.1		0.6		1.1		2.2		1.8		3.4		3		4.2		1.7		2.9	

(a) Percentage for six highest-accident locations.
(b) Percentage for two highest-accident locations.
(c) Percentage for three highest-accident locations
(d) FTA Section 15 Report for 1992.
(e) Includes only tracks where LRVs operate in revenue service.
(f) Accident index = total accidents/year/semi-exclusive or non-exclusive mainline track miles.

Figure 3-9

Number of Mainline Track Miles and Number of Accidents by Alignment Type [4]





After reviewing the available information, it was concluded that there is a significant lack of current data for LRV accidents, since most data are confined to the mid-1980s to late-1990s. The data that are available are considered incomplete because of a lack of exact injury and fatality data. Also, different criteria were used to classify the types of accidents that occurred. Nevertheless, two useful papers were found that aid in understanding the principal characteristics and conditions of LRV accidents, [4] and [1].

In regard to the results observed in this analysis, most accidents occur when the LRV is traveling in a shared right-of-way scenario. In 1994, 88.7 percent of the accidents occurred in a shared right-of-way where the LRV was traveling under

35 mph; however, this type of track represents only 30.3 percent of the total track length for that year. During the time frame studied, 50 percent of accidents involved an automobile, 36 percent involved a truck or bus, and 11 percent involved pedestrians. Examining all available data for the metro systems reported in references, [1], [4], and [7], and, most of the accidents involved an automobile. Also, almost half of these accidents (47%) involved a vehicle turning in front of the LRV as shown in Table 3-1. A large percentage of the total accidents in all the surveyed systems occurred in shared right-of-way scenarios, which usually account for the smallest percentage of the systems' total right-of-way route miles. Indeed, as shown in Figure 3-9, 92 percent of total accidents for all surveyed systems occurred in a shared right-of-way where LRVs operate less than 35 mph, even though this type of right-of-way comprises only 38 percent of the total mainline track miles.

TRCP 69 [1] paper is a continuation of the TRCP 17 [4] survey and shows the types of accidents and quantity of track lines where the LRV goes above 35 mph. The accident rate at higher speed LRV crossings is 69 percent less than at lower speed LRV crossings. Even considering that there are fewer higher-speed LRV crossings per kilometer of track compared with where LRVs operate in a street or pedestrian/transit mall at lower speeds, higher-speed LRT crossings have a better overall safety. Table 3-3 indicates that while 77 percent of the total track length of the 11 LRT systems are at higher speeds, semi exclusive right-of-ways (types b.1 and b.2, excluding type a), only about 13 percent of the total accidents occurred at crossings along these sections of track (Figure 3-10). In fact, for all 11 LRT systems surveyed, the percentage of track in semi-exclusive type b.1 and b.2 right-of-ways is always greater than the percentage of accidents that occur along these two types of right-of-ways, excluding Edmonton and St. Louis where all the crossings (and thus all accidents) are in semi-exclusive type b.1 and b.2 right-of-ways. Despite the fact that these higher-speed LRV crossings (where LRVs operate at speeds greater than 55 km/h [35 mph]) along semi-exclusive type b.1 and b.2 right-of-ways have a better overall accident record (as indicated in Table 3-2 and Table 3-3), collisions at these crossings tend to be more severe than those at lower speed LRV crossings.

As indicated with data provided by three LRT systems, 19 percent of the total LRV motor vehicle collisions at LRT crossings along right-of-ways where LRVs operate at speeds greater than 55 km/h (35 mph) resulted in fatalities, compared with only 1 percent at lower speed crossings. In Figure 3-12 , LRV-pedestrian collisions did not show as dramatic a difference, with 29 percent of the higher speed collisions resulting in fatalities, compared with 18 percent with the lower speed collisions.

Table 3-2

Summary of Accident Experience at LRT Crossings (through 1996)

LRT System	Average Total Accidents (a)	Semi-Exclusive Right of Way, types b.1 & b.2 (above 55 km/h)			Semi-Exclusive and Non-Exclusive Right of Way, types b.3, b.4, b.5, c.1, c.2 & c.3 (below 55 km/h)		
		Average Annual Accidents (a)	Average Annual LRT Crossing-Years (b)	Average Annual Accidents per LRT Crossing Year	Average Annual Accidents	Average Annual LRT Crossing-Years (b) (c)	Average Annual Accidents per LRT Crossing-Year
Baltimore	29.8	0.8	18	0.0	29.0	21	1.38
Calgary	12.2	5.1	20	0.3	7.1	13	0.55
Dallas	6.0	2.0	22	0.1	4.0	14	0.29
Denver	34.0	0.5	2	0.3	33.5	29	1.16
Edmonton	1.7	1.7	8	0.2	d	d	d
Los Angeles	50.7	10.7	28	0.4	40.0	56	0.71
Portland (e)	20.8	0.1	4	0.0	20.7	74	0.28
Sacrameonto	20.5	2.2	14	0.2	18.3	62	0.30
Saint Louis	0.5	0.5	11	0.1	d	d	d
San Diego	28.5	5.9	43	0.1	22.6	42	0.54
San Jose (e)	25.2	0.2	3	0.1	25.0	59	0.42
Average	20.9	2.7	16	0.2	18.2	34	0.54

a) Includes all semi-exclusive and non-exclusive right-of-way types (types b and c).

b) LRT crossing-years indicate the number of crossings that have LRVs operating through them for one year. One crossing-year is equal to one crossing in operation for one year. The average annual LRT crossing-years indicate the average number of crossings operating for an entire year, per year of operation. For most LRT systems (those which have not had any significant extensions), this figure is simply equal to the number of LRT crossings. For those systems that have been implemented incrementally, this value differs from the actual total number of crossings. For example, the San Diego LRT system along semi-exclusive right-of-ways, type b.1 and b.2, 29 crossings have been in operation for 17 years (South Line), 25 crossings have been in operation for 9 years (East Line), and 13 crossings have been in operation for about 0.5 years (North Line to Old Town and East Line extension to Santee). Thus, the total number of crossing-years is calculated as follows: (29 crossings x 17 years) + (25 crossings x 9 years) + (13 crossings x 0.5 years) = 724.5 crossings-years. In 1996, the San Diego LRT system had been in operation a total of 17 years. Therefore, the total number of crossings-years per year (or average annual LRT crossings-years) was 724.5 crossings-years/17 years = 43 average annual LRT crossing-years.

c) Includes all streets with traffic movements across LRT tracks.

d) The Edmonton and Saint Louis LRT systems do not have semi-exclusive or non-exclusive right-of-ways where LRVs travel at speeds lees than 55 km/h.

e) Accident rates for the Portland and San Jose LRT systems along semi-exclusive and non-exclusive right-of-ways where LRVs travel at speeds less than 55 km/h account for accidents through 1994

Table 3-3

Summary of Accident Experience at LRT Crossings in Percentage (through 1996) [1]

LRT System	Average Total Accidents per year (a)	Semi-Exclusive Right of Way, types b.1 & b.2 (above 55 km/h)		Semi-Exclusive & Non-Exclusive Right of Way, types b.3, b.4, b.5, c.1, c.2 & c.3 (below 55 km/h)	
		Percent of Average Total Accidents per Year	Percent of Total Semi-Exclusive and Non-Exclusive Track length (b)	Percent of Average Total accidents per Year	Percent of Total Semi-Exclusive and Non-Exclusive Track length (b)
Baltimore	29.8	3%	82%	97%	18%
Calgary	12.2	42%	89%	58%	11%
Dallas	6.0	33%	90%	67%	10%
Denver	34.0	1%	62%	99%	38%
Edmonton	1.7	100%	100%	0%	0%
Los Angeles	50.7	21%	76%	79%	24%
Portland (e)	20.8	1%	26%	100%	74%
Sacrameonto	20.5	11%	73%	89%	27%
Saint Louis	0.5	100%	100%	0%	0%
San Diego	28.5	21%	89%	79%	11%
San Jose (e)	25.2	1%	7%	99%	93%
Average	20.9	13%	77%	87%	23%

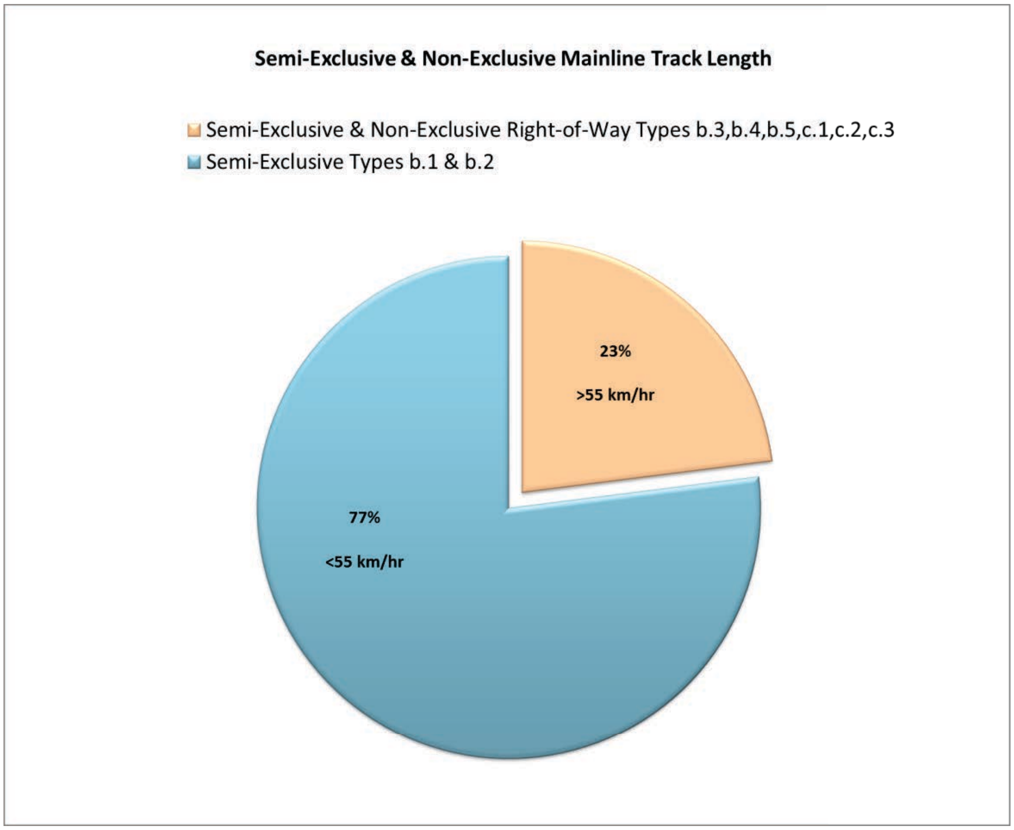
a) Includes all semi-exclusive and non-exclusive right-of-way types (types b and c).

b) From Table 2-1.

c) Accident rates for the Portland and San Jose LRT systems along semi-exclusive and non-exclusive right-of-ways where LRVs travel at speeds less than 55 km/h account for accidents through 1994.

Figure 3-10

Mainline Track Length and LRT Crossing Accidents Comparison [1]



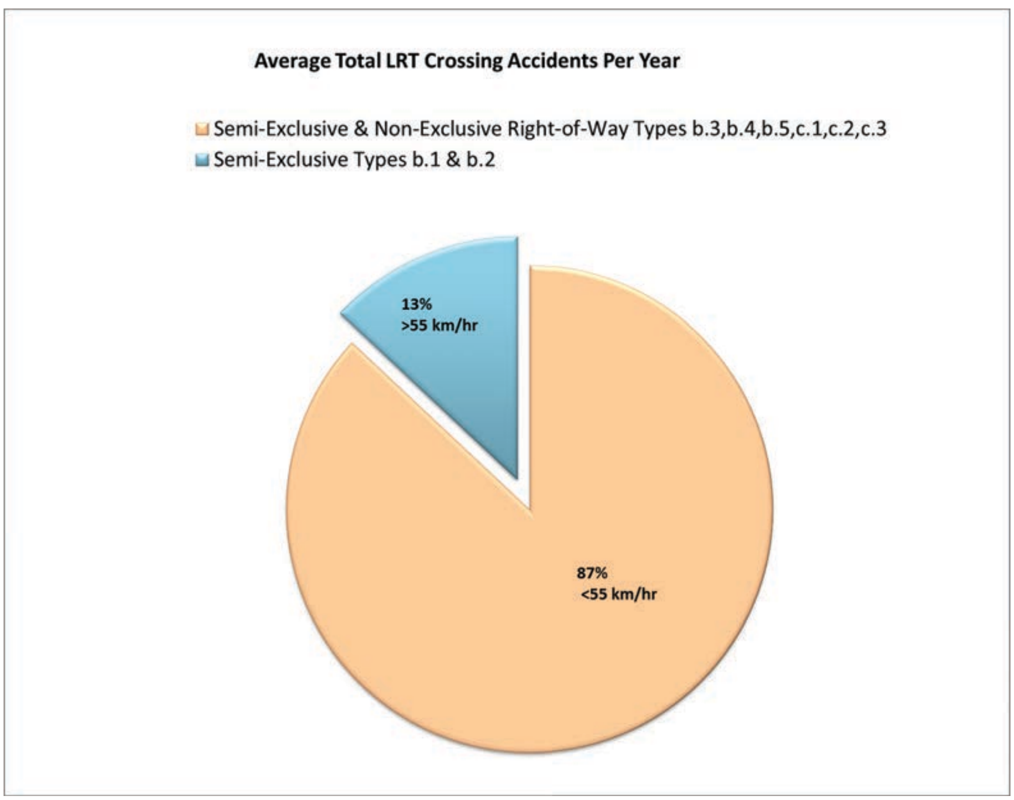
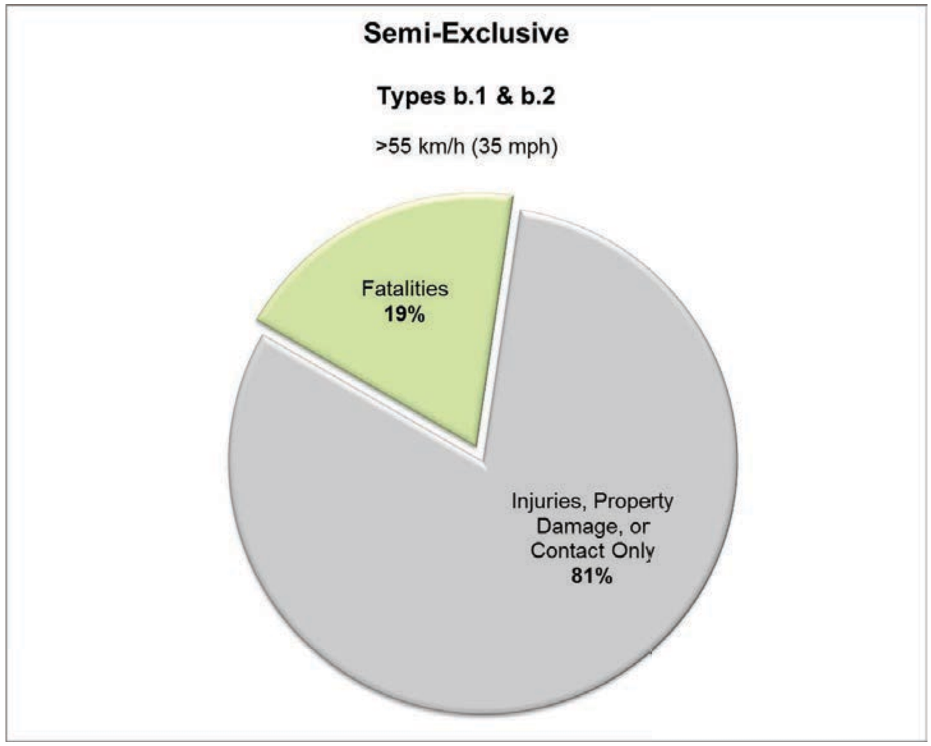


Figure 3-11

LRV-Motor Vehicle Collision Severity Comparison [1]



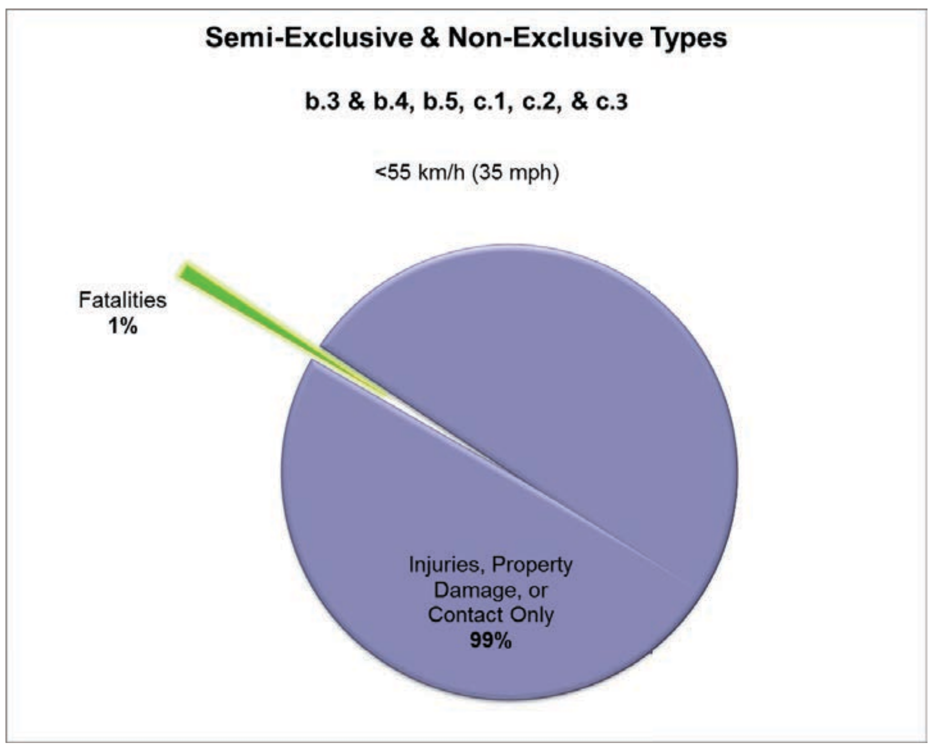
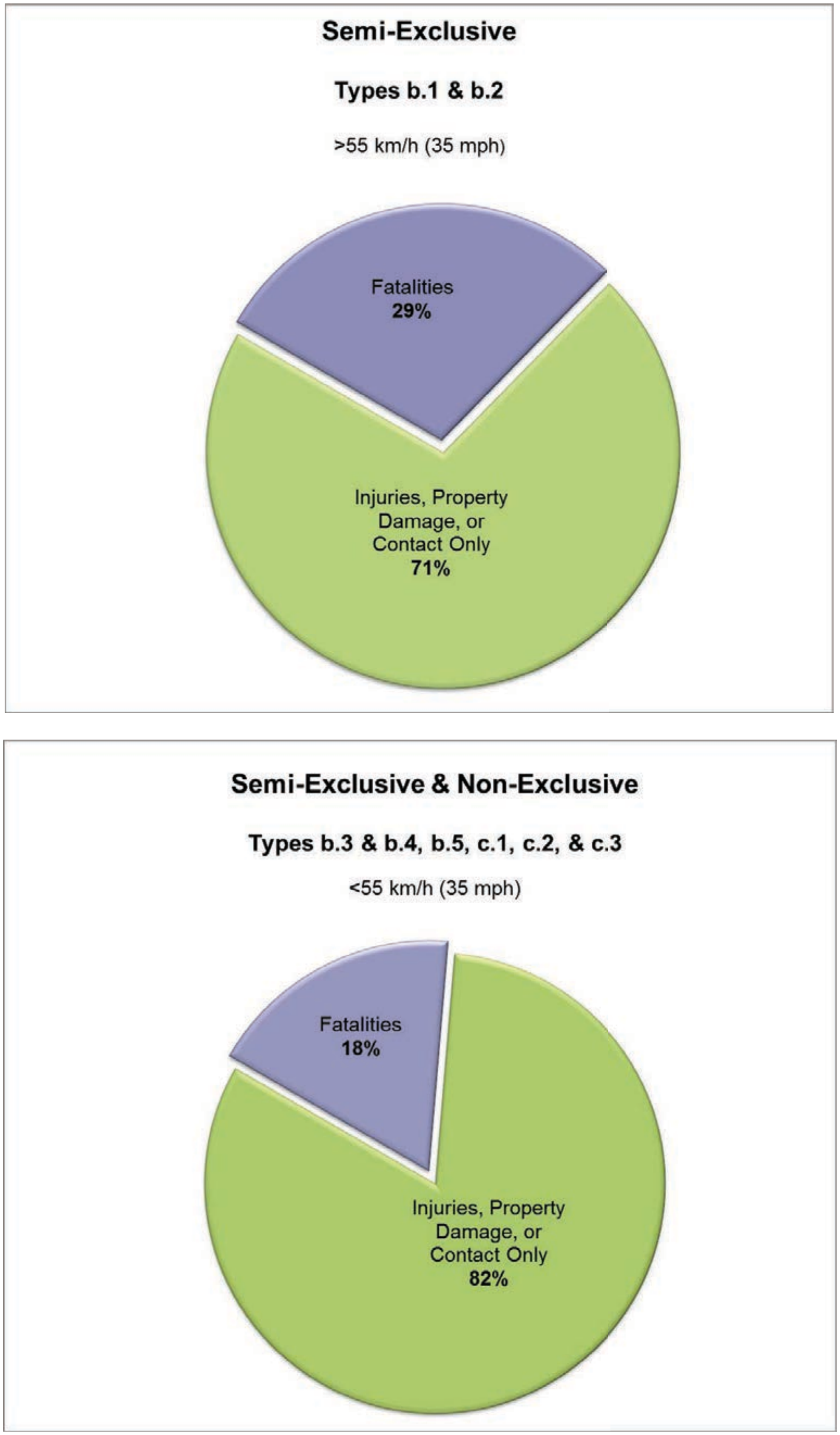


Figure 3-12
LRV-Pedestrian Collision Severity Comparison [1]



It should be noted that the above analysis on collision severity is based on data provided by three LRT systems: Denver, Edmonton, and Los Angeles. The data provided to the research team by the other LRT systems did not classify accidents by severity in enough detail to include them in the analysis [1].

In conclusion:

- Most LRV accidents occur at tracks with shared right-of-ways and when the LRV is traveling under 35 mph. Eighty-seven percent of total accidents in which a light rail vehicle is implicated occurred in a non-exclusive track where the LRV shares the road with other vehicles or pedestrians [1].
- In 1994, most accidents involved a vehicle (approximately 86%), 50 percent of these accidents involved an automobile, and only 11 percent of the accidents involved pedestrians [4]
- The most common type of collision in most cities involves vehicles turning in front of an LRV or during a left-hand turn [4] [7].
- Of the total accidents for all surveyed systems, 92 percent occurred in shared right-of-ways where LRVs operate under 35 mph, even though this type of right-of-way comprises only 38 percent of the total mainline track miles [4].
- Although only 13 percent of the total accidents occurred at tracks where the LRV goes above 35 mph, this type of track represents 77 percent of the total track length.
- Under conditions when the LRV operated above 35 mph, 19 percent of the accidents at tracks ended in a fatality; however, only 1 percent of the accidents at tracks where the LRV operated below 35 mph ended in a fatality.
- Occasionally, LRVs suffered rear-end collisions with other stopped LRVs [7].

SECTION

4

Definitions of LRV Crash Conditions

The main objective of this project was to identify injury mechanisms of LRV passengers. This section details the most common types of injuries based on seating configuration. Results of the most significant injury-seat configurations obtained through the interior survey are presented here. For this study, a multibody technique was used to model the LRV interior and passengers, due to the low computational cost and accuracy of the results. This modeling technique allows researchers to study multiple load cases and seating arrangements in a short period of time. Due to the similarities between current LRVs and bus seats, a series of tests conducted by the NIAR was used to validate the multibody seat models. Appendix A shows how the validation of the model was completed. Figure 4-1, Figure 4-2, and Figure 4-3 show the generic LRV FE model used to evaluate different crash conditions. Figure 4-4 shows the FE model library used for this evaluation.

Figure 4-1

NIAR Generic LRV CAD Model

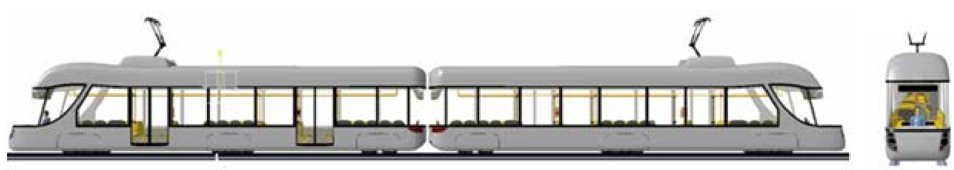


Figure 4-2

NIAR Generic LRV Finite Element Model

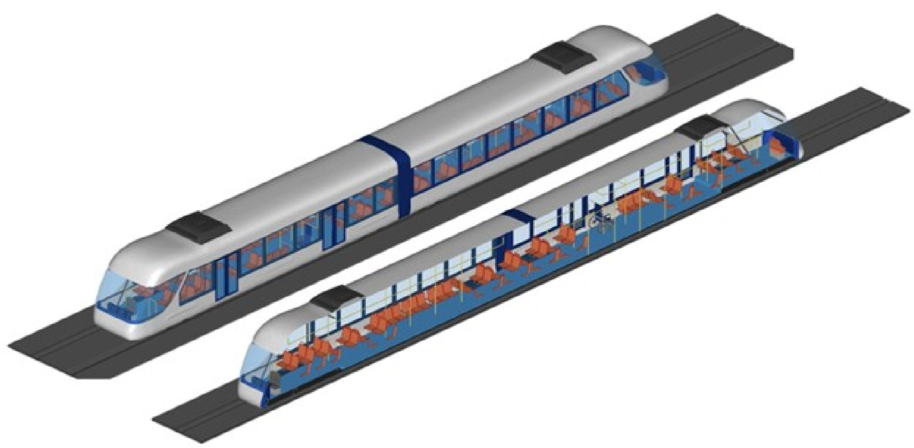


Figure 4-3

NIAR Generic LRV Finite Element Model Interior

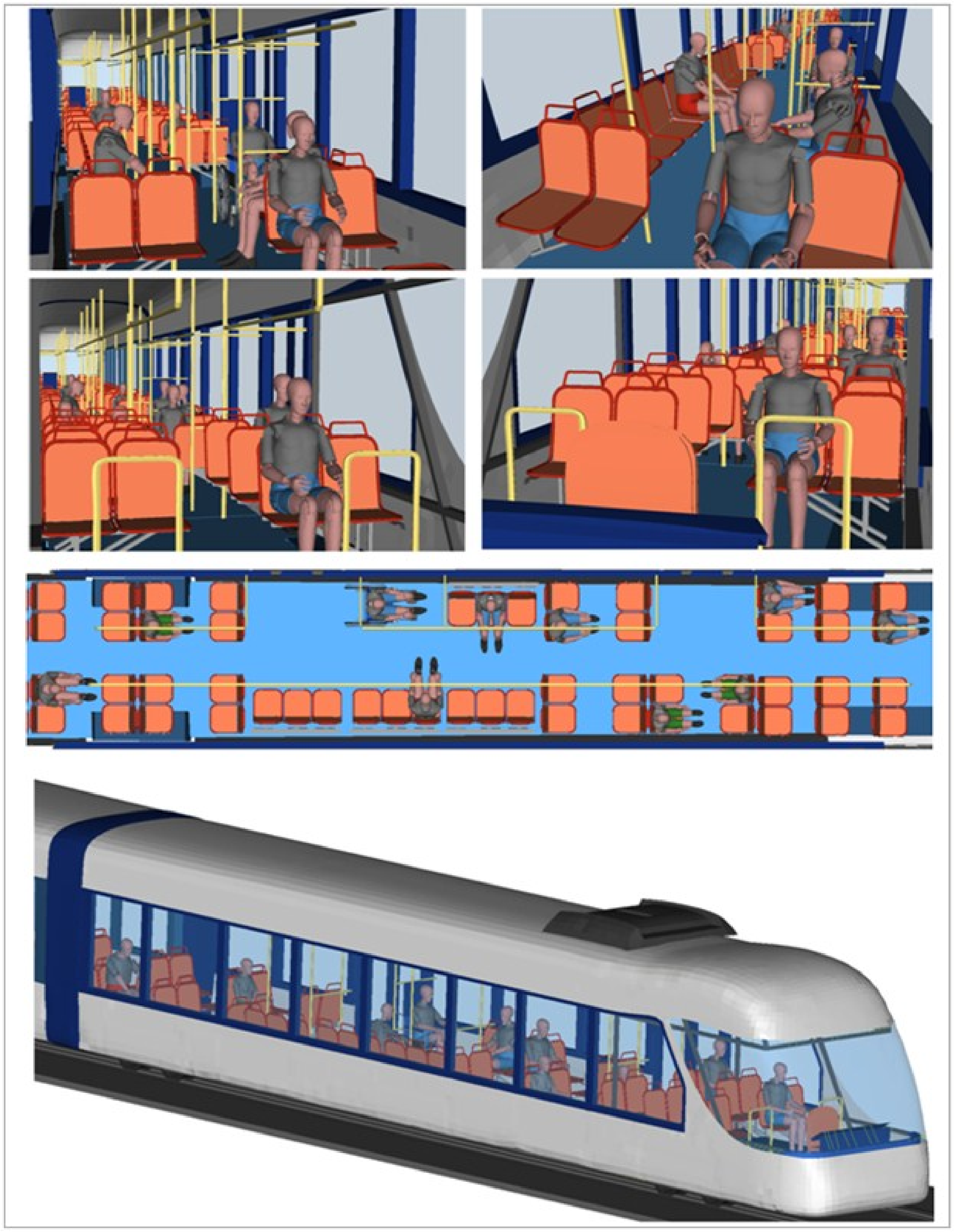
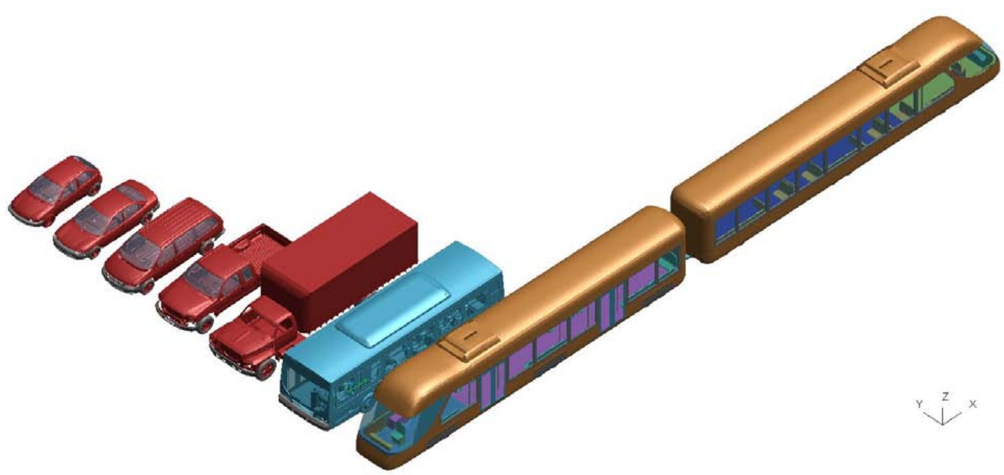


Figure 4-4

Finite Element Model Library



Preliminary Crashworthiness Evaluation for Low-, Mid-, and High-Energy Impact Conditions

Once seat models were validated using the dynamic sled test (see Appendix A, Test 06221-8), the injuries from four different energy level conditions were evaluated for a typical forward-facing seat LRV layout:

- LRV 20 mph and LRV 0 mph (LRV type N—High Energy)
- LRV 20 mph and Bus 0 mph (LRV type N—Medium Energy)
- LRV 20 mph and Mini-Van 0 mph (LRV type N—Low Energy)
- LRV 20 mph and LRV 0 mph (LRV type 0—High Energy)

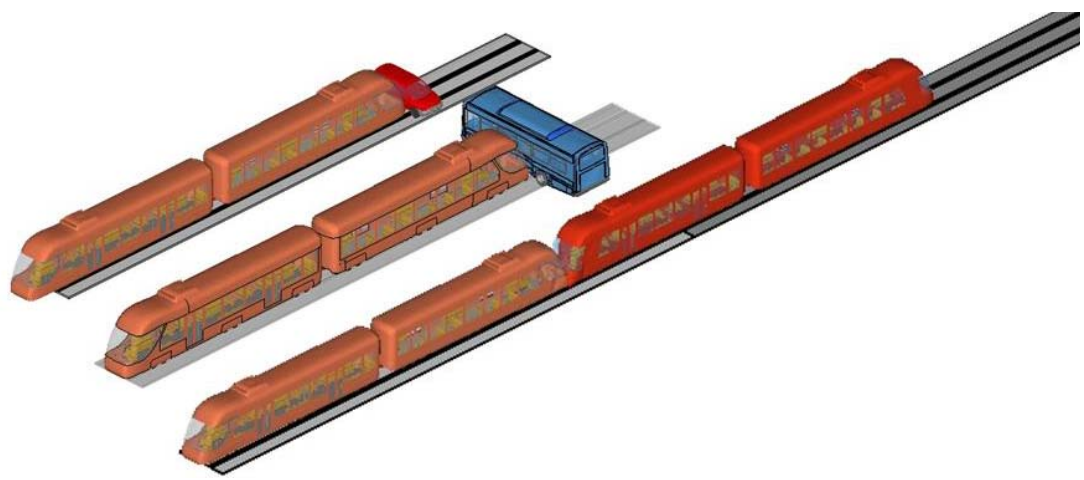
LRV type N represents a generic LRV created by NIAR with an empty weight of approximately 42 tons. LRV type 0 represents an LRV used in "Development of Crash Energy Management Performance Requirements for Light-Rail Vehicles" [8].

Figure 4-5 shows the three FE models used for this preliminary crashworthiness evaluation.

The 95th, 50th, and 5th percentile occupants were used in the evaluation in this section. These ATDs represent the most of the range of sizes of the U.S. current population.

Figure 4-5

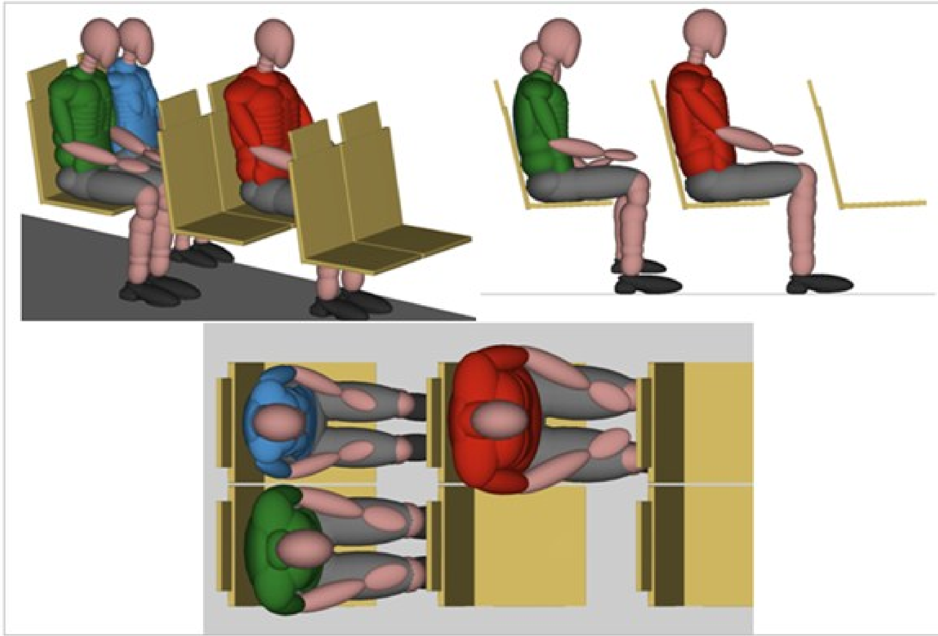
Finite Element Models Evaluated for Preliminary Crashworthiness



The following model was used for all impact conditions (Figure 4-6).

Figure 4-6

Multibody Model for Low-, Mid-, and High-Energy Impact Conditions



As explained above, three ATDs were used in this model. To help distinguish between ATDs, three different colors were used. These colors remain constant throughout the report. Red is used for the 95th percentile, green for the 50th percentile, and blue for the 5th percentile.

Low-Energy Crash Condition: LRV at 20 mph and Mini-Van at 0 mph (LRV Type N)

This crash represents a low-energy scenario and, therefore, less hazardous for passengers in the LRV. In this scenario, due to the differences in mass between the vehicles (LRV approx. 42 tons, mini-van approx. 2 tons), the energy absorbed by the LRV is very small compared to the energy absorbed by the mini-van. As a result, no major injuries to LRV passengers should be expected from this crash scenario.

The following plots show the acceleration and velocity of the operator compartment for this scenario (Figure 4-7). The first spike illustrates the point at which the LRV strikes the mini-van. Observe that the acceleration remains low (less than 2 g's in the x-direction)

Figure 4-7

Acceleration Pulse of Low-Energy Crash Scenario (LRV Type N at 20 mph and Mini-Van at 0 mph)

The acceleration pulse obtained through the FE model above (Figure 4-8) was used in the multi-body model shown below inFigure 4-6 to evaluate possible injuries. All injuries are normalized with FMVSS 208 limits so they can be shown in the same bar chart. Figure 4-8 shows the kinematic of the simulation at 0 ms and 250 ms. Because of the low pulse, no contact between occupants and seats was observed.

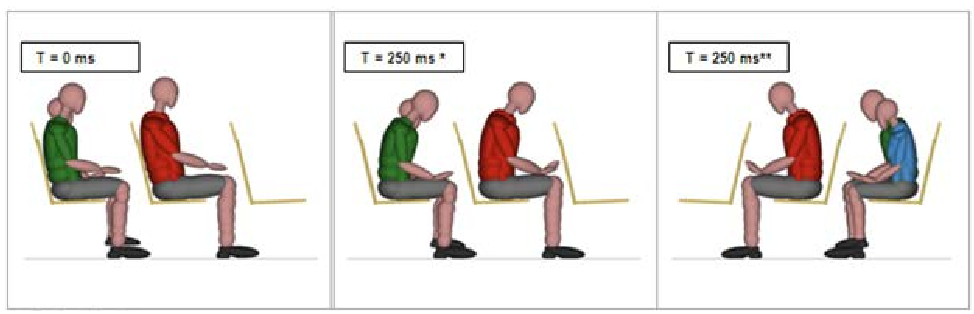
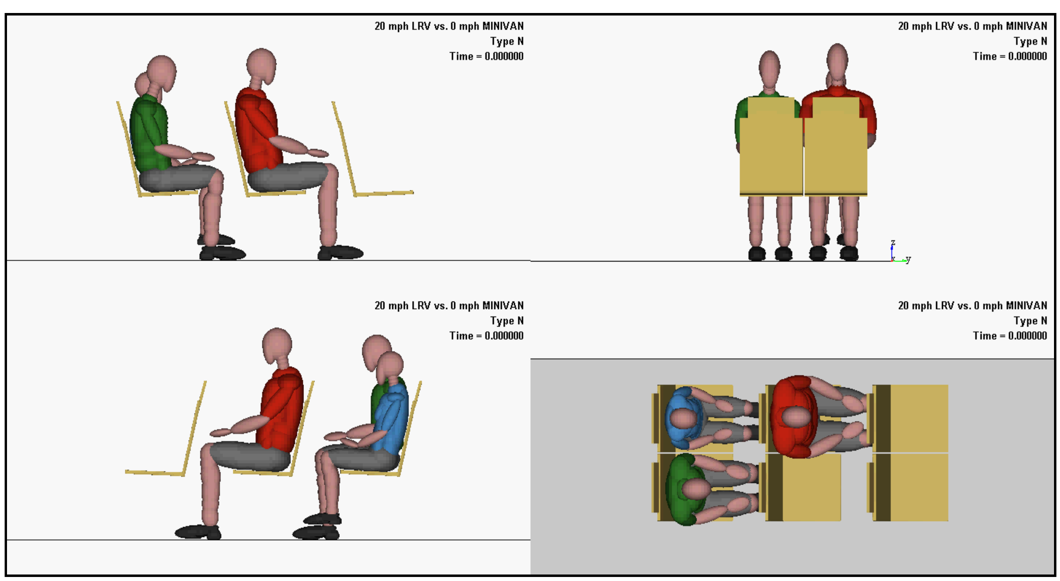


Figure 4-8

Kinematics of Low-Energy Crash Scenario (LRV Type N at 20 mph and Mini-Van at 0 mph)

* Right-side view.
** Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile.



Video 4-1

LRV Type N at 20 mph vs. Mini-Van 0 mph Low Energy Crash Scenario

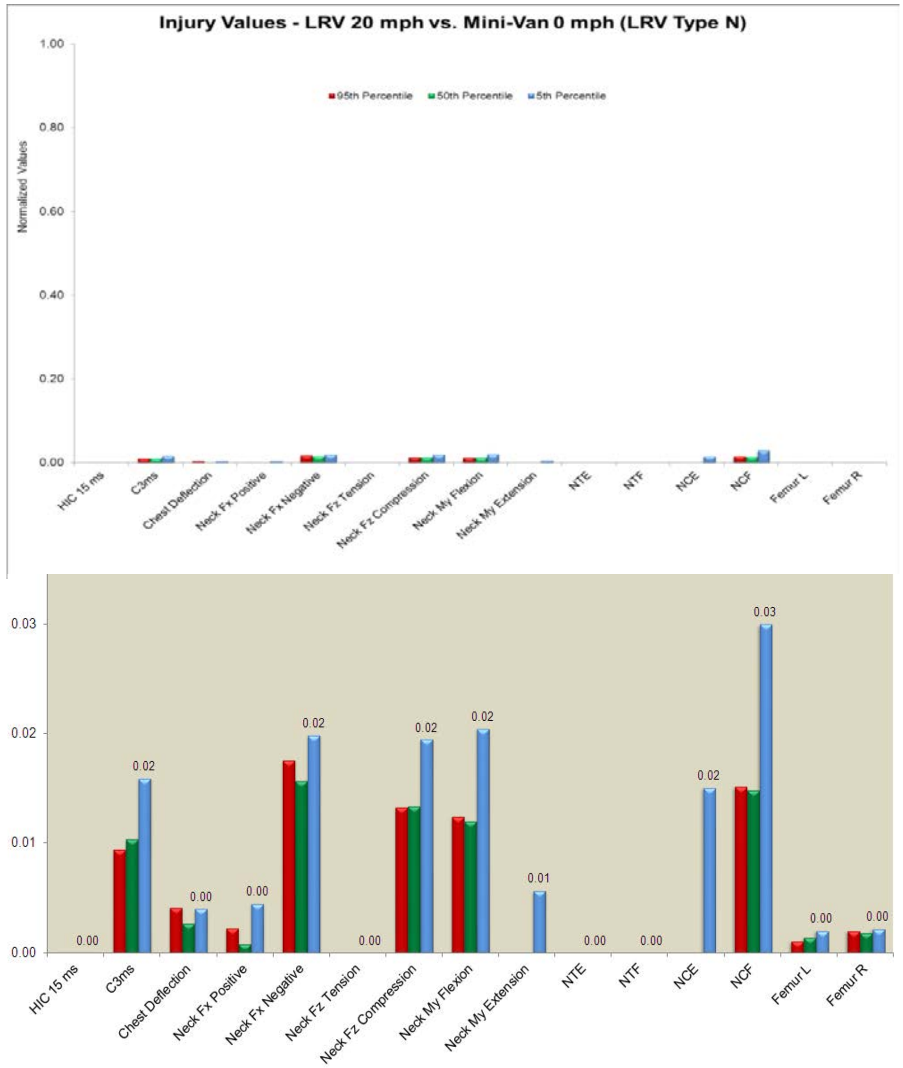


Figure 4-9

Normalized Injury Values of Low-Energy Crash Scenario (LRV Type N at 20 mph and Mini-Van at 0 mph)

Due to the low level of energy absorption by the LRV, the injuries observed are much lower than current FMVSS 208 limits (Figure 4-9). Because no injuries were observed this crash scenario was not studied for rear impact conditions, or with aft facing seats.

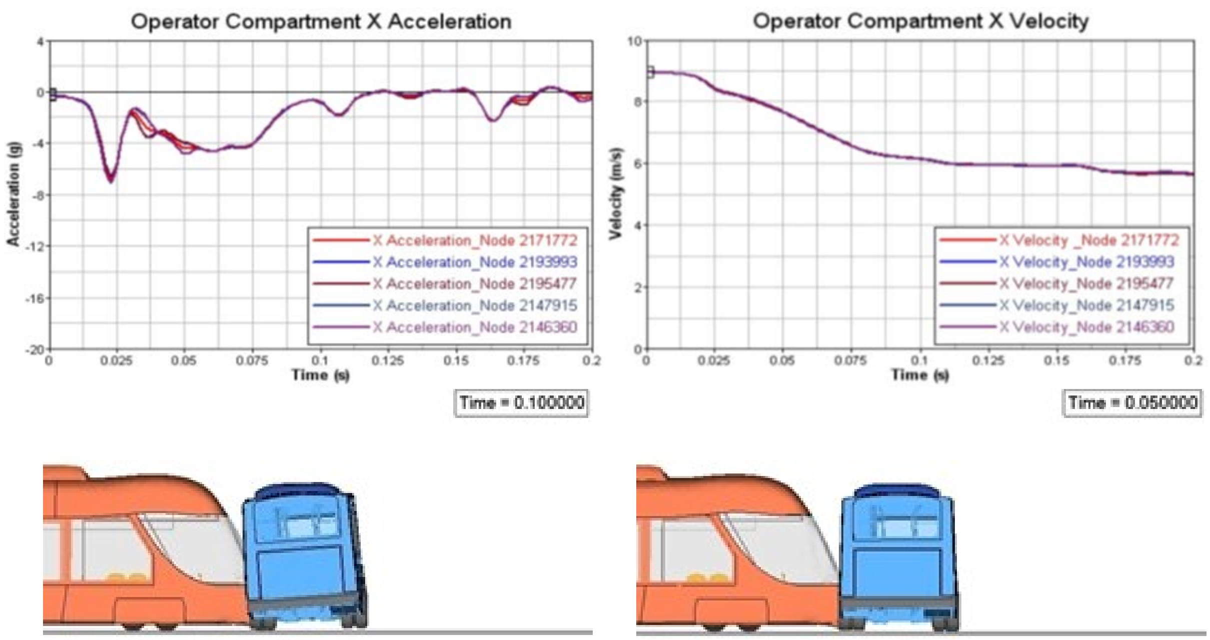
Medium-Energy Crash Condition: LRV at 20 mph and Mass Transit Bus at 0 mph (LRV Type N)

This crash scenario represents a medium-energy collision between a LRV type N traveling at 20 mph and a stationary bus (0 mph). For this scenario, the difference in mass between both vehicles is smaller and, therefore, some injuries can be expected for LRV passengers (Bus weight: 9.65 tons).

Again, the same approach as before was used. First, the FE model is run to obtain an acceleration pulse. The acceleration pulse is then used in the multibody model to analyze passenger injuries. The acceleration pulse on the compartment is shown in Figure 4-10.

Figure 4-10

Acceleration Pulse of Mid-Energy Crash Scenario (LRV Type N at 20 mph and Mass Transit Bus at 0 mph)



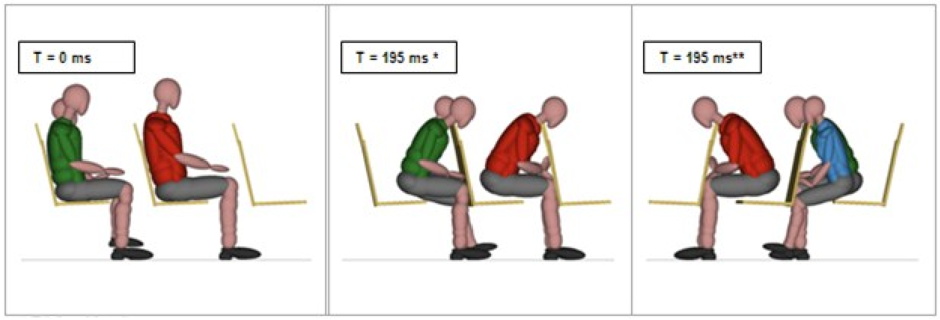
For this scenario, the acceleration pulse shape is similar to the low energy scenario. However, the average acceleration in the x-direction is approximately double that obtained for the low energy impact condition.

Observe that with an increase in target vehicle mass the energy absorbed by the LRV increases and, therefore, results in more occupant injuries (Figure 4-12). Seats designed for average sized occupants result in the 50th percentile ATD incurring smaller injuries and the 5th percentile ATD incurring larger injuries.

Figure 4-11 shows the kinematics for this medium energy crash scenario. The initial time and moment of impact are represented. The figure shows that the 50th and 95th percentile ATDs impacts the headrest with the neck. Due to its shorter height, the 5th percentile ATD, impacts directly into the back of the headrest, increasing the severity of injuries to the neck region. A detailed picture of the contact is shown below (Figure 4-12).

Figure 4-11

Kinematics of Mid-Energy Crash Scenario (LRV Type N at 20 mph and Mass Transit Bus at 0 mph)



* Right-side view
** Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile

Video 4-2

LRV Type N at 20 mph vs. Bus 0 mph Mid-Energy Crash Scenario

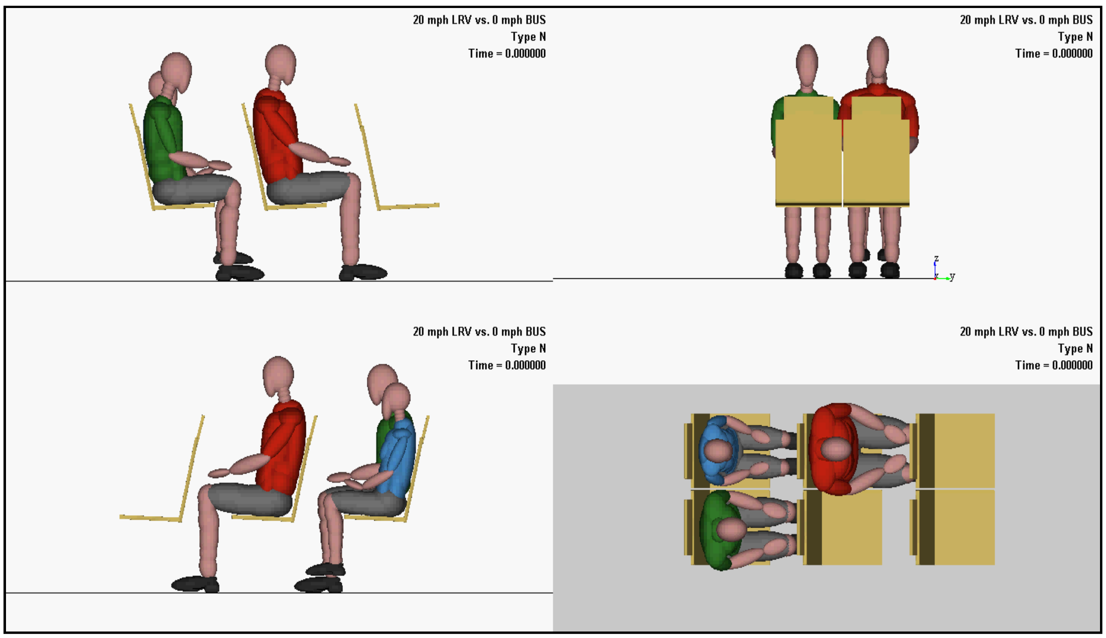


Figure 4-12

Normalized Injury Values of Mid-Energy Crash Scenario (LRV Type N at 20 mph and Mass Transit Bus at 0 mph)

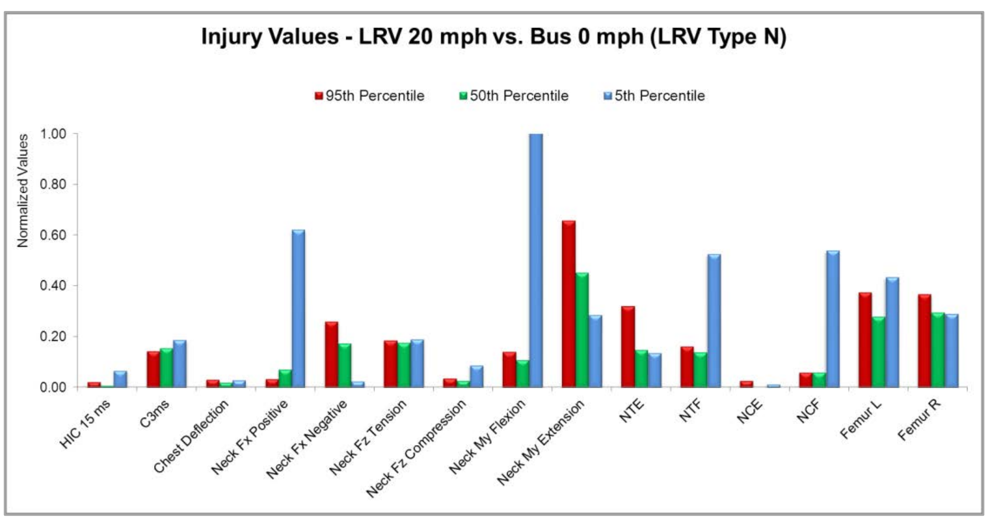
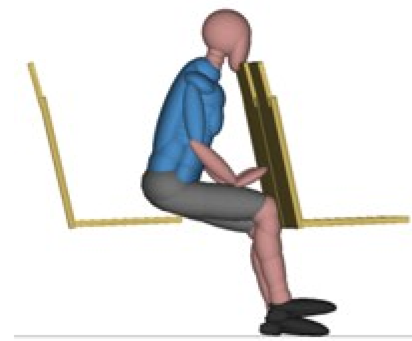


Figure 4-13 shows the jaw of the 5th percentile ATD impacting the headrest. This contact produces higher moments and forces on the neck region. Because the injuries in this crash scenario were still not very severe, they were not included in the study of rear-impact conditions or aft-facing seats.

Figure 4-13

Impact 5th Percentile ATD with Headrest in Mid-Energy Crash Scenario (LRV Type N at 20 mph and Mass Transit Bus at 0 mph)



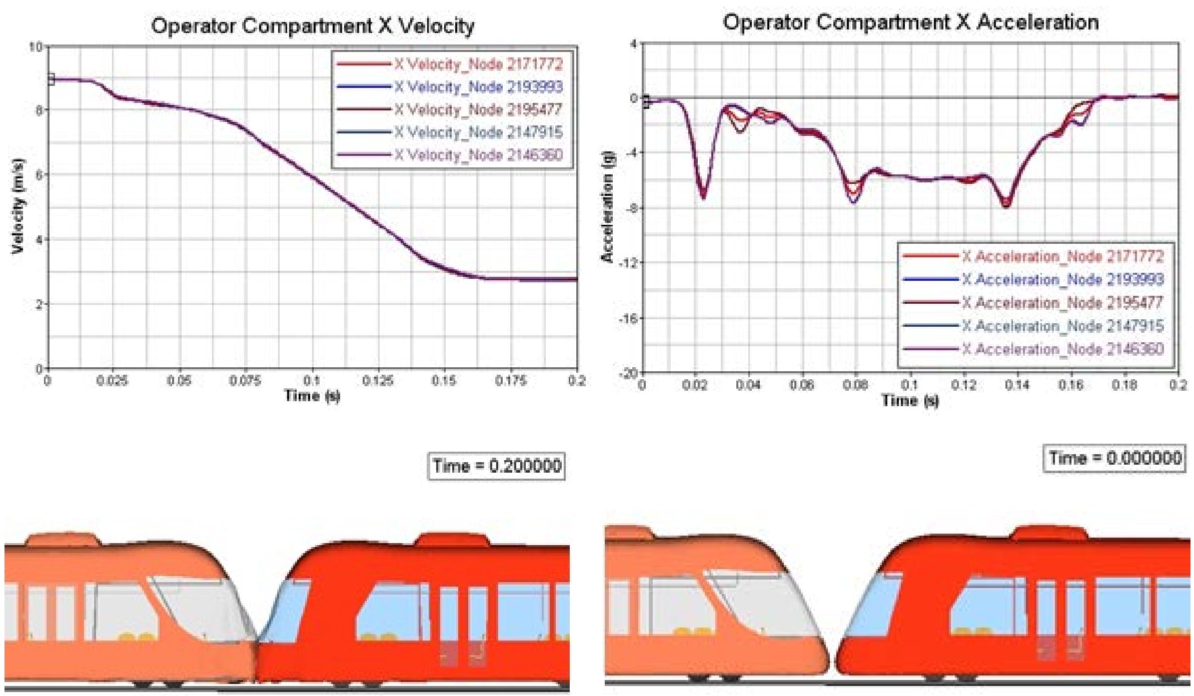
High-Energy Crash Condition A: LRV at 20 mph and LRV at 0 mph (LRV Type N)

This crash scenario represents a high-energy collision between a LRV type N traveling at 20 mph and another LRV type N which is stationary (0 mph). This scenario represents a high-energy collision due to the equal mass of both vehicles. This type of crash will be considered as the worst case scenario.

Again, the acceleration pulse for this crash scenario is obtained using the method described earlier. The following plots show the acceleration and velocity of the operator compartment in the x-direction (Figure 4-14).

Figure 4-14

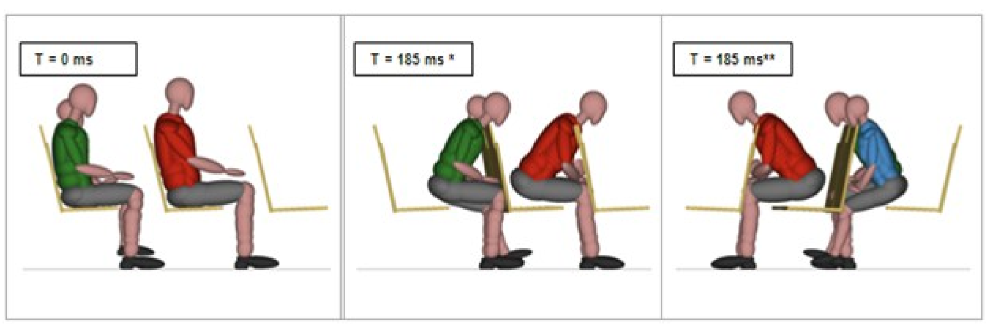
Acceleration Pulse of High-Energy Crash Scenario (LRV Type N at 20 mph and LRV Type N at 0 mph)



Most injuries occur to the neck region due to direct or indirect impact with the headrest. Due to the 95th percentile ATD's height, there was an impact of the chest with the headrest causing a large neck (Figure 4-15).

Figure 4-15

Kinematics of High-Energy Crash Scenario (LRV Type N at 20 mph and LRV Type N at 0 mph)



* Right-side view

**Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile

Video 4-3

LRV Type N at 20 mph vs. LRV 0 mph High Energy Crash Scenario

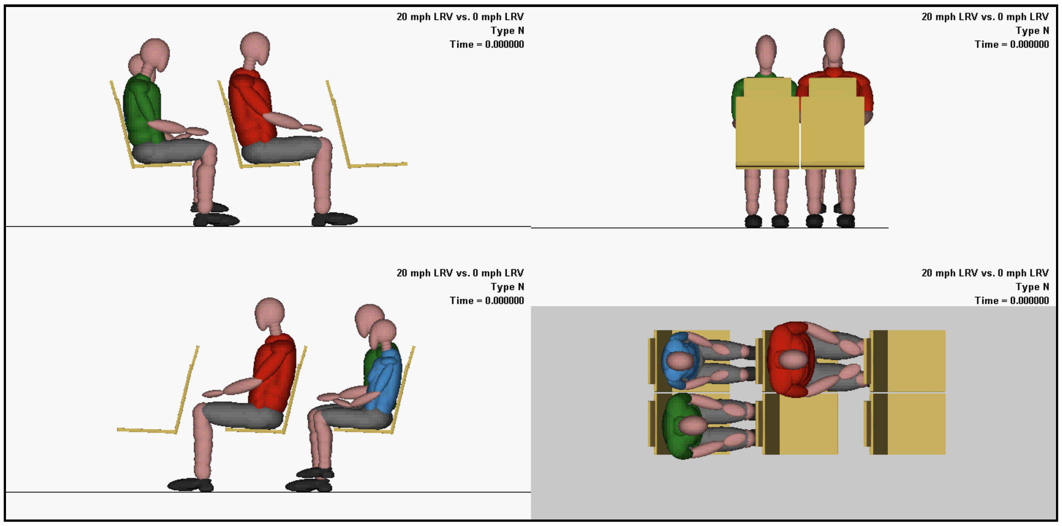


Figure 4-16

Normalized Injury Values of High-Energy Crash Scenario—Frontal Impact (LRV Type N at 20 mph and LRV Type N at 0 mph)

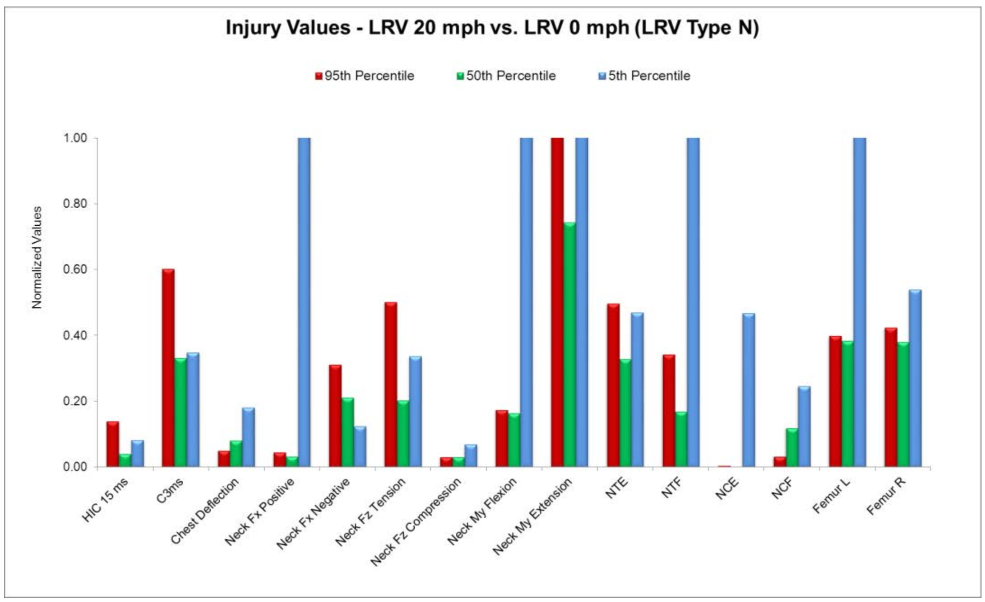


Figure 4-16 shows the injury values normalized according to the FMVSS 208 limits. Once more, the 5th percentile incurred the largest injuries. The 95th percentile also has some injury values above current limits. The 50th percentile values were below the acceptable limits; however, values for the neck region were relatively large.

Due to the severity of the acceleration pulse and the resulting injuries, this crash scenario also was studied for a rear impact condition with forward-facing seats, or a frontal impact with aft facing seats. This condition is run using the same pulse as before but applied in the opposite direction. The layout and initial setup for this impact condition is identical as the one shown in Figure 4-6.

The injury values obtained are shown on the following bar chart. Figure 4-17 shows that no major injuries should be expected for this type of crash scenario.

Due to the rear impact, only the neck extension moments appeared slightly large. However, this value is well below current FMVSS 208 limits.

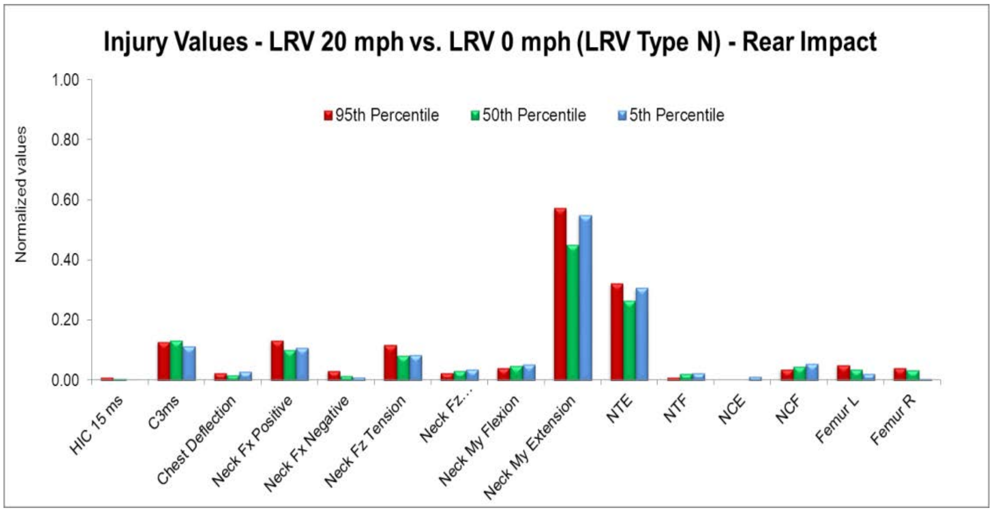


Figure 4-17

Normalized Injury Values of High-Energy Crash Scenario-Rear Impact (LRV Type N at 20 mph and LRV Type N at 0 mph)

Figure 4-18 shows the kinematics of the impact. Observe that maximum extension occurs around 200 ms for the three occupants. This extension could be minimized with improvements to the seatback stiffness and headrest design.

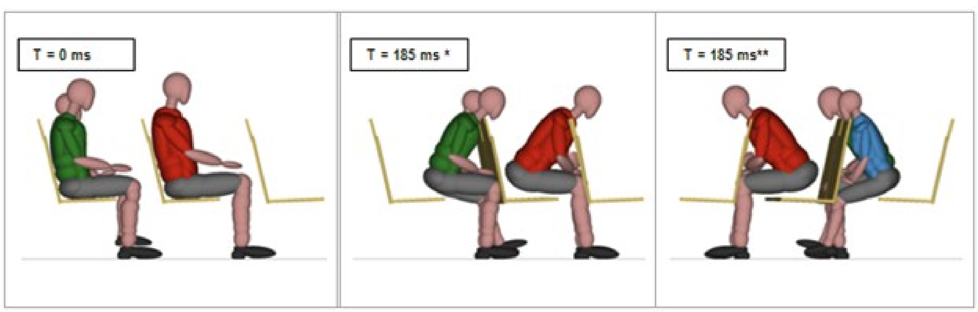
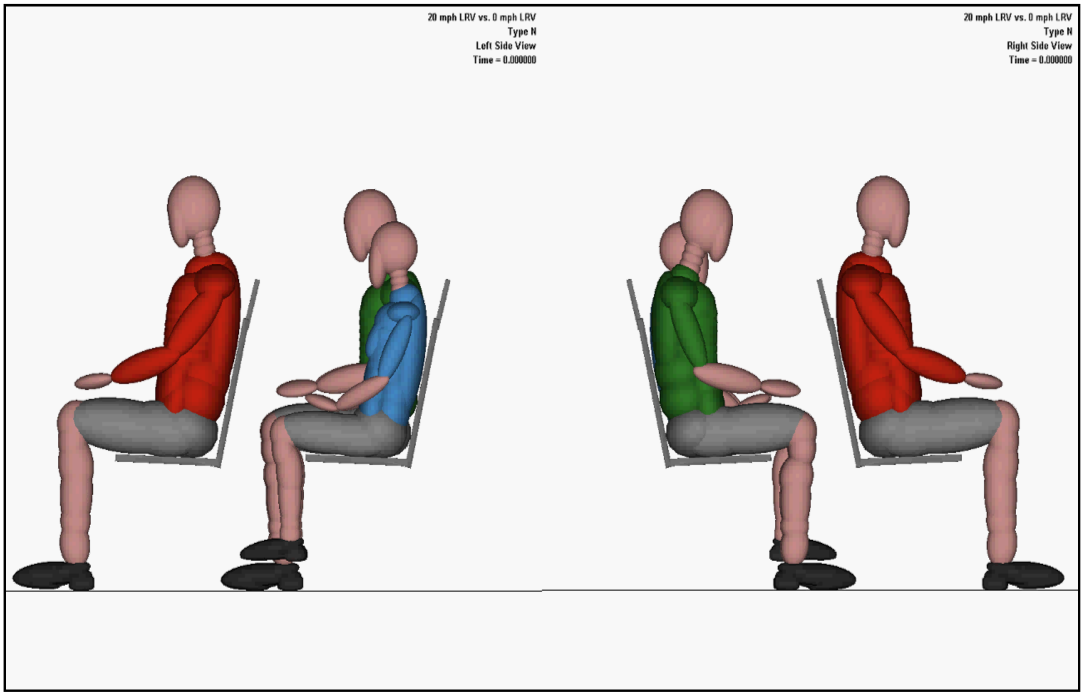


Figure 4-18

Kinematics of High-Energy Crash Scenario Rear Impact (LRV Type N at 20 mph and LRV Type N at 0 mph)

* Right-side view

** Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile



Video 4-4

LRV Type N at 20 mph vs. LRV 0 mph Rear Impact Crash Scenario

High-Energy Crash Condition B: LRV at 20 mph and LRV at 0 mph (LRV Type O)

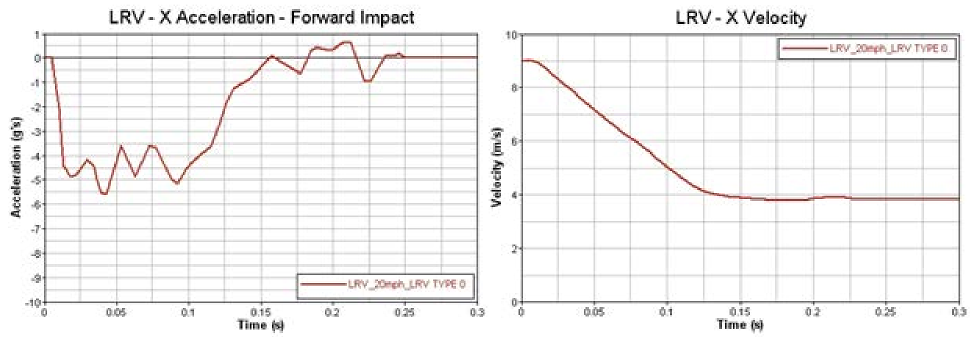
The fourth, and last, crash scenario represents the collision between a LRV type 0 traveling at 20 mph and another LRV type 0 which is stationary (0 mph). This scenario represents another high-energy collision due to the equal mass of both vehicles. Similar to above, this type of crash also can be considered a worst case scenario.

Due to differences in structural design between LRV type 0 and type N, the acceleration pulse is slightly different. The LRV type 0 is designed using the Crash Energy Management approach and, therefore, the acceleration pulse obtained is smaller than the one obtained for LRV type N.

The acceleration and velocity in the x-direction for the operator compartment is shown in Figure 4-19. This acceleration pulse is obtained directly from the report, “Develop of Crash Energy Management Performance Requirements for Light-Rail Vehicles” [8].

Figure 4-19

Acceleration Pulse of High-Energy Crash Scenario (LRV Type 0 at 20 mph and LRV Type 0 at 0 mph)



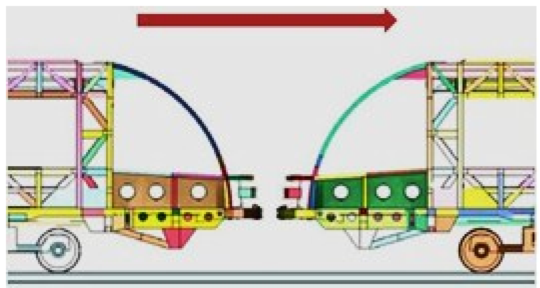
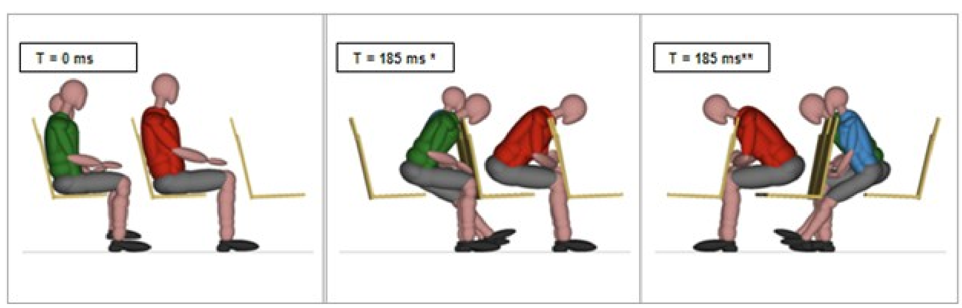


Figure 4-20 shows the kinematics of this simulation. At 185 ms after the impact, the maximum values are obtained for the neck moments. Similar conclusions as those obtained for the LRV type N were obtained. Most of the injuries occurred to the neck region due to its direct or indirect impact with the headrest.

Figure 4-20

Kinematics of High-Energy Crash Scenario -Frontal Impact (LRV Type 0 at 20 mph and LRV Type 0 at 0 mph)



* Right-side view
** Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile

Video 4-5

LRV Type 0 at 20 mph vs. LRV 0 mph High Energy Frontal Impact Crash Scenario

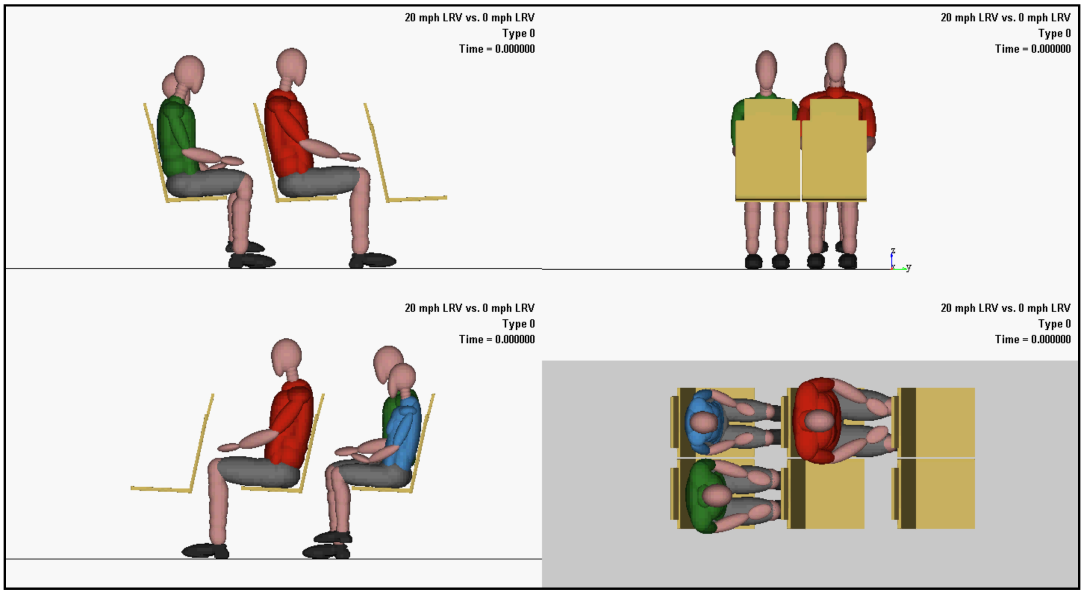
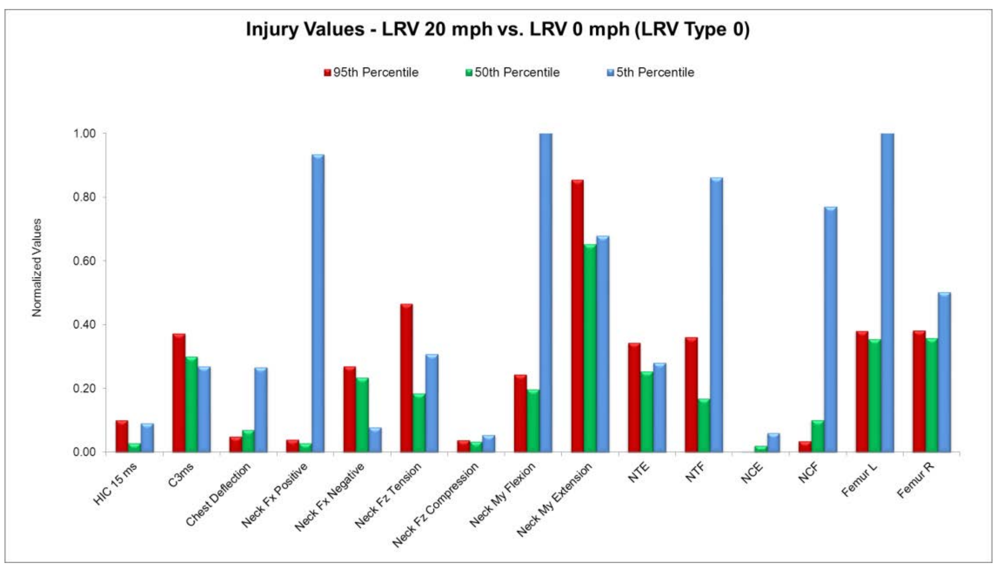


Figure 4-21 shows injury values normalized to FMVSS 208 limits. Once more, the 5th percentile ATD sustains the greatest injuries. For this case, the 95th percentile ATD had all injury values below the FMVSS 208 limits. The 50th percentile ATD sustained injuries similar to those in crash scenario number three.

Figure 4-21

Normalized Injury Values of High-Energy Crash Scenario - Frontal Impact (LRV Type 0 at 20 mph and LRV Type 0 at 0 mph)



This scenario also was studied for a rear-impact condition with forward-facing seats and a frontal impact with aft-facing seats. These conditions are run using the same pulse as applied above but in the opposite direction. The layout and initial setup for this impact condition is identical to the one shown in Figure 4-6.

The injury values obtained are shown in the following bar chart.

Figure 4 22 reveals similar results to those obtained for the LRV type N. As such, no major injuries should be expected for this type of crash scenario. Because of the rear type of impact, the neck extension moment is larger. However, this value is even smaller than the one obtained for LRV type N.

Figure 4-22

Normalized Injury Values of High Energy Crash Scenario - Rear Impact (LRV Type 0 at 20 mph and LRV Type 0 at 0 mph)

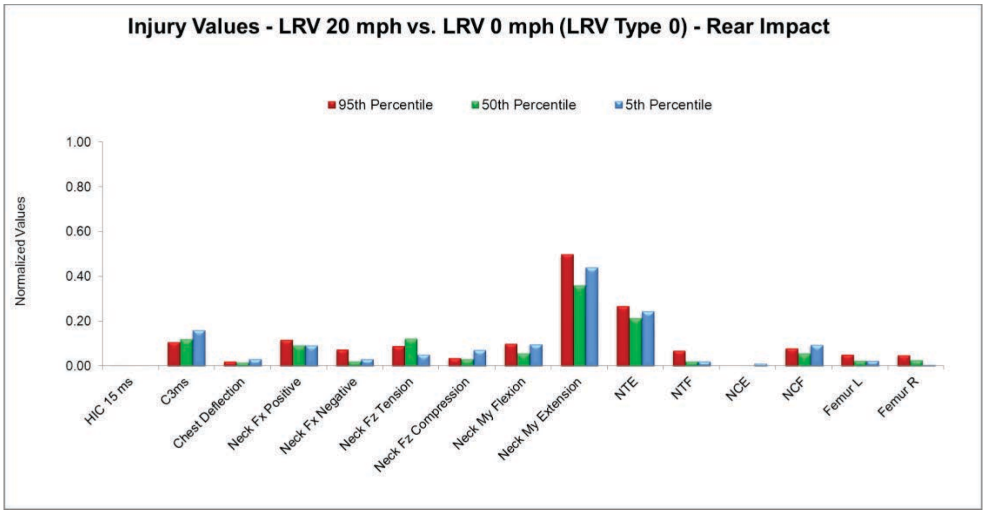
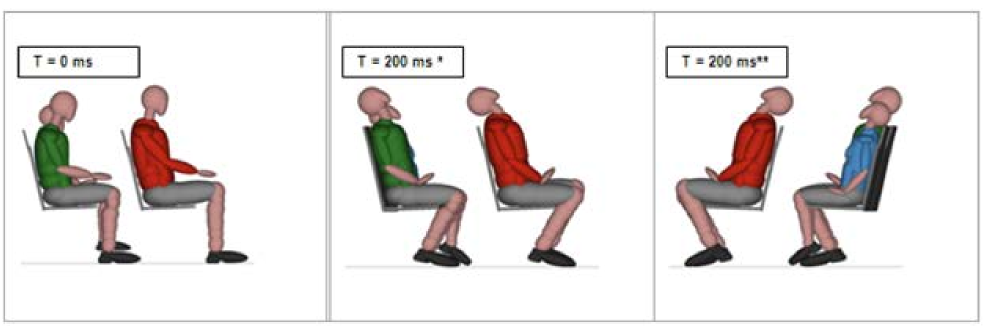


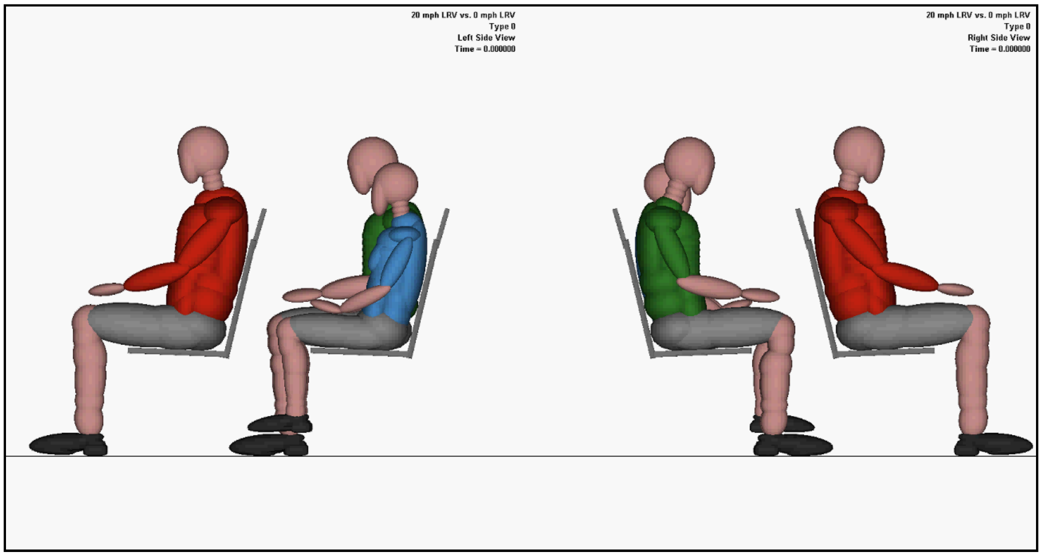
Figure 4-23 shows the kinematics of the simulation. The moment of maximum extension for the necks of the three occupants occurs around 200ms. Almost no differences are found between types N and 0. The larger values observed for the neck extension is again due to the seatback design.

Figure 4-23

Kinematics of High-Energy Crash Scenario—Rear Impact (LRV Type 0 at 20 and LRV Type 0 at 0 mph)



* Right-side view
**Left-side view: red 95th percentile, green 50th percentile, and blue 5th percentile



Video 4-6

LRV Type 0 at 20 mph vs. LRV Type 0 at 0 mph High Energy Rear Impact Crash Scenario

Summary of Low-, Mid-, and High-Energy Impact Conditions

From all the crash scenarios studied, only those with high energy (LRV vs. LRV) seem to be hazardous for occupants. Additionally, only when occupants are traveling towards the direction of impact are injury values high. Thus, both rear-impact scenarios analyzed in this section had low levels of injuries.

In accordance with the results shown in sections 0 and0, neck moments and shear forces are the most common type of injury. Also, femur forces could exceed the injury criteria limits for the 5th percentile ATD.

The injuries sustained in the neck region are directly associated with the height and stiffness of the seat headrest. To improve the safety of occupants, a new seat headrest should be designed. Suggestions include using different heights and some type of padding material.

On the other hand, the high femur forces obtained for the 5th percentile ATD are related to the stiffness of the seat back. Some new padding materials could be used on the knee impact region to improve safety.

Emergency Braking Condition

The LRV, as a mode of transportation, does not appear to have a large number of accidents per year. Also, the probability of these accidents occurring in a high-energy impact scenario is low. There is, however, a pre-impact condition that could occur much more often and that is the use of emergency braking

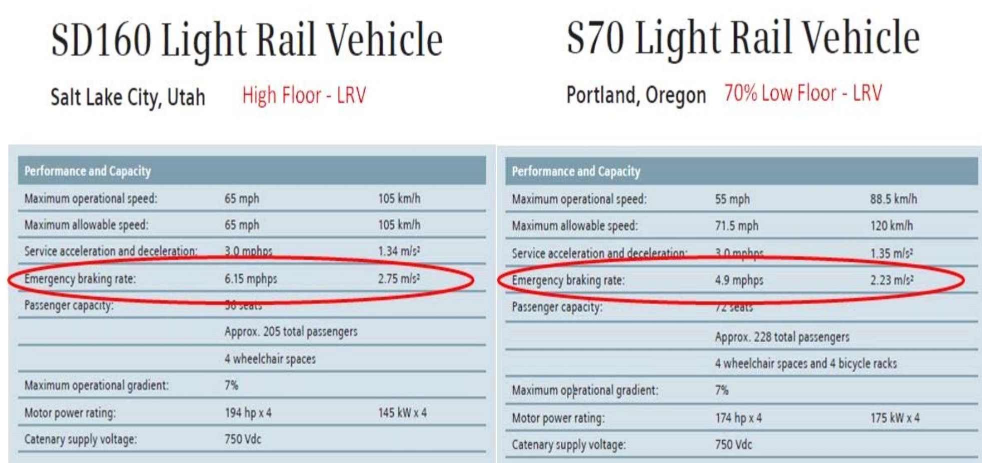
This section analyzes two emergency braking scenarios. The first represents an emergency braking event for occupants in forward-facing seats, and the second corresponds to the same event for occupants sitting in an aft-facing seat.

According to the literature, the maximum level of deceleration observed during a emergency braking stop comes from LRV models like the SIEMENS SD160 (Category One, "High Floor without CEM"). On these LRVs, the level of deceleration can approach 2.75 m/s2. See Figure 4-24

In contrast, newer LRVs, like the SIEMENS SD70 (Category Two, "Low Floor with CEM"), decelerate closer to2.2 m/s2. See Figure 4-24.

Figure 4-24

Performance Characteristics of Siemens SD160 and Siemens S70



SD160 Light Rail Vehicle

Salt Lake City, Utah High Floor - LRV

Performance and Capacity		
Maximum operational speed:	65 mph	105 km/h
Maximum allowable speed:	65 mph	105 km/h
Service acceleration and deceleration:	3.0 mphps	1.34 m/s²
Emergency braking rate:	6.15 mphps	2.75 m/s²
Passenger capacity:	30 seats	
	Approx. 205 total passengers	
	4 wheelchair spaces	
Maximum operational gradient:	7%	
Motor power rating:	194 hp x 4	145 kW x 4
Catenary supply voltage:	750 Vdc	

S70 Light Rail Vehicle

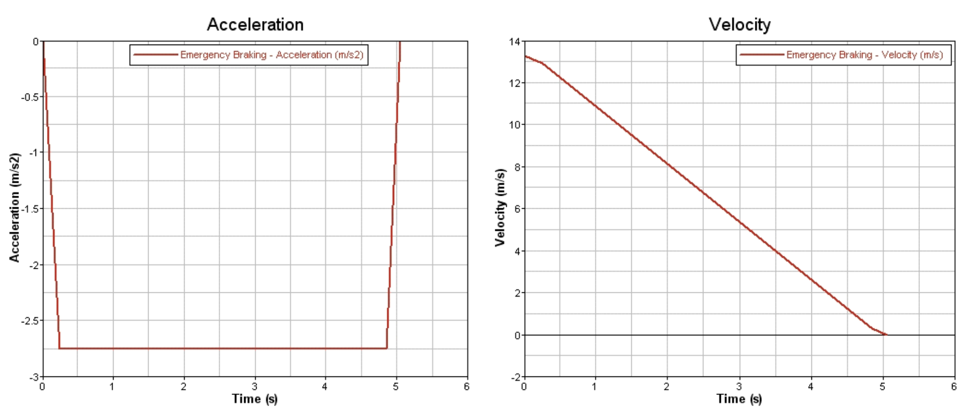
Portland, Oregon 70% Low Floor - LRV

Performance and Capacity		
Maximum operational speed:	55 mph	88.5 km/h
Maximum allowable speed:	71.5 mph	120 km/h
Service acceleration and deceleration:	3.0 mphps	1.35 m/s²
Emergency braking rate:	4.9 mphps	2.23 m/s²
Passenger capacity:	72 seats	
	Approx. 228 total passengers	
	4 wheelchair spaces and 4 bicycle racks	
Maximum operational gradient:	7%	
Motor power rating:	174 hp x 4	175 kW x 4
Catenary supply voltage:	750 Vdc	

Using the maximum level of deceleration (2.75 m/s2), an acceleration pulse was created. The pulse shown in Figure 4-25 represents an emergency braking stop for one LRV traveling at 30 mph.

Figure 4-25

Emergency Braking Pulse of LRV 30 mph to 0 mph



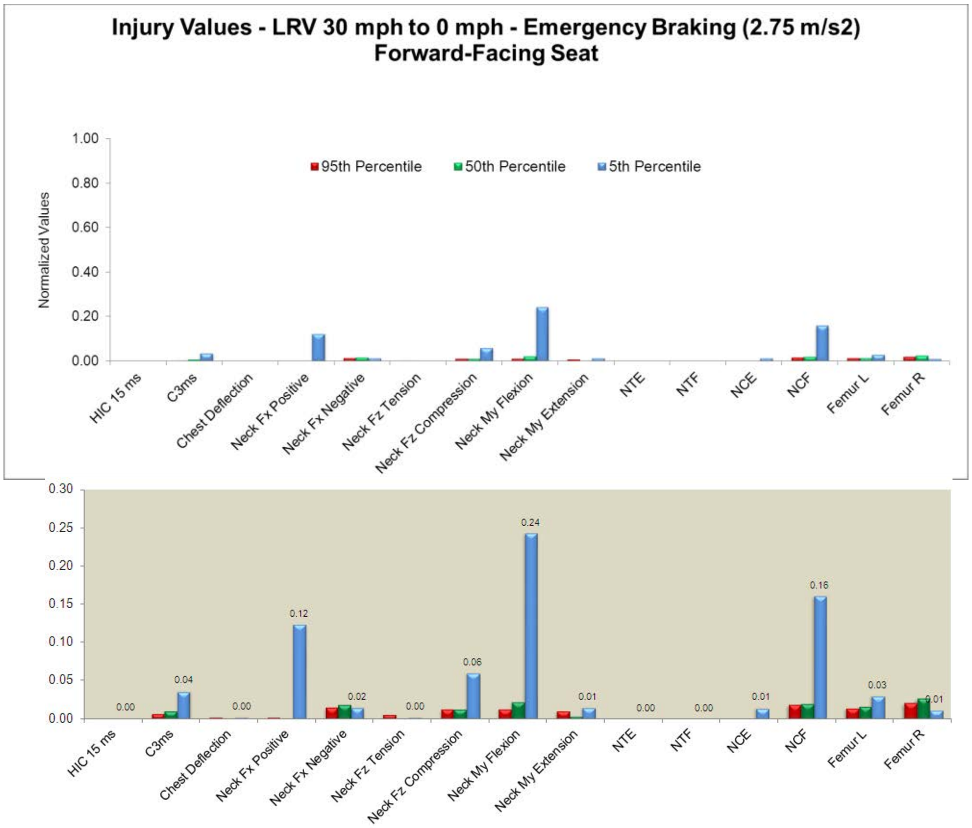
The same layout used for analysis in Section 4 is used. See previous Figure 4-6.

The results for both configurations are shown in the following bar charts (Figure 4-26 and Figure 4-27). Due to the large duration of the pulse (5s) and its low magnitude, no major injuries are observed.

Actually, it takes one and half seconds for the occupants to impact the headrest. Thus, further studies with more complex human-like ATDs should be conducted to identify the real behavior of the occupants during this type of scenario.

Figure 4-26

Normalized Injury Values for Emergency Braking Condition – Forward-Facing Seats



Video 4-7

LRV Emergency Braking from 30 mph to 0 mph – Forward Facing Seats Scenario

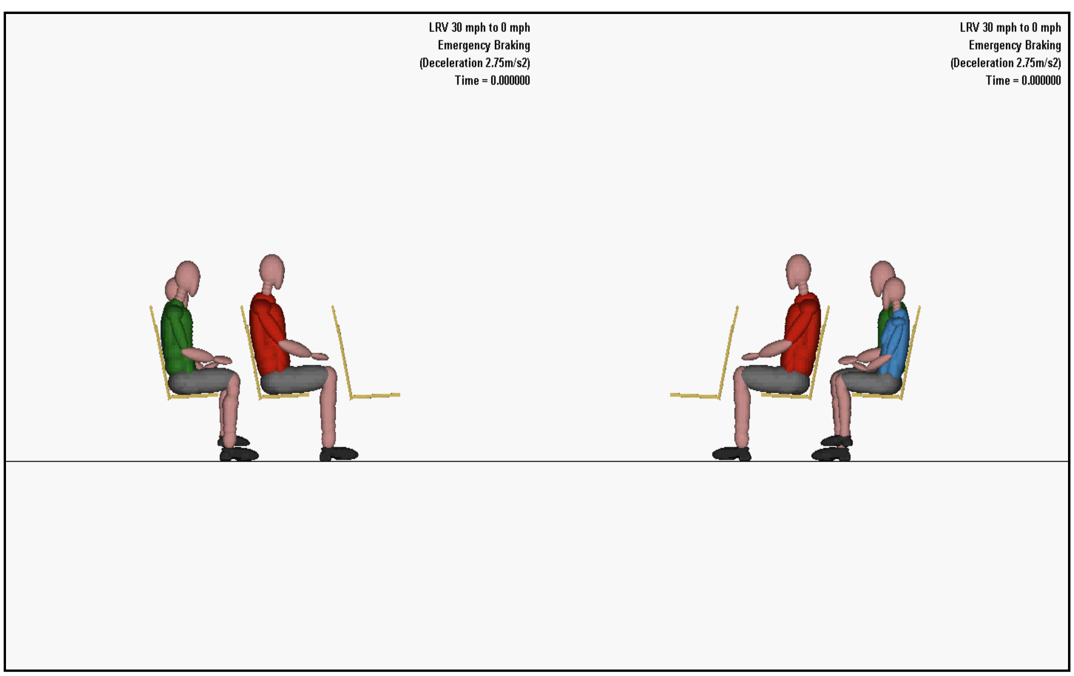
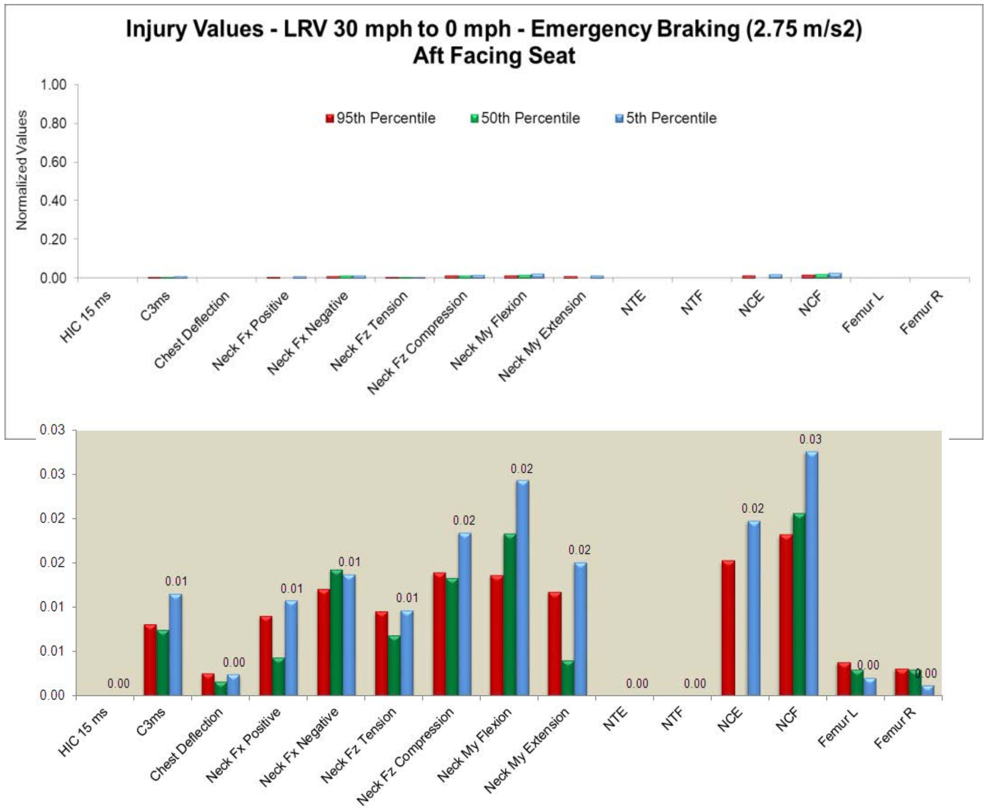


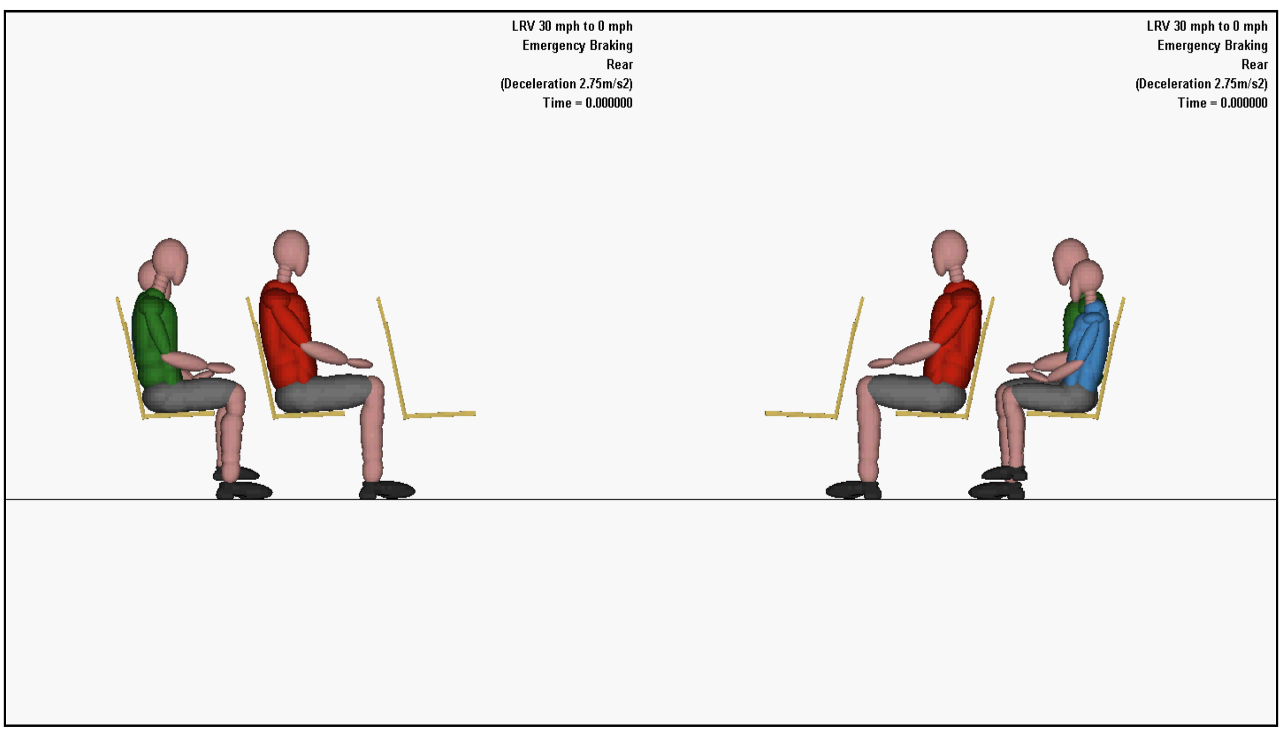
Figure 4-27

Normalized Injury Values for Emergency Braking Condition— Aft-Facing Seats



Video 4-8

LRV Emergency Braking from 30 mph to 0 mph – Aft Facing Seats Scenario



SECTION

5

Crashworthiness Evaluation of LRV Interior

This section analyzes the different types and levels of injuries that a passenger can suffer depending on seating position. To quantify the severity of injuries, the FMVSS 208 injury criterion was used (Table 5-1). Figure 5-1 shows the most common neck injury mechanisms. A summary of the types of seats analyzed in this project is shown inTable 5-2. The seat arrangements analyzed in this section represent the most common type of seats currently found in LRVs (see Section 2).

As mentioned in Section 4, the worst-case scenario is the high-energy pulse, since no greater injuries were observed for the low- and medium-impact severity. Thus, the pulse representing the LRV at 20 mph and LRV at 0 mph with the LRV Type 0 was used for all analyses.

Table 5-1

Injury Criteria—FMVSS 208 Limits

Injury Criterion Performance Limits (ICPLs)	50th Percentile ATD	5th Percentile ATD		6-Year-Old Child	3-Year-Old Child	12-Month-Old Child
		In-Position	Out-of-Position			
HIC (15 max)	700	700		700	570	390
Chest Res. Acc (3 ms) in G's	60	60		60	55	50
Chest Deflection (mm)	63	52		40	34	N/A
Femur Load (N)	10,000	6805		N/A	N/A	N/A
Neck Peak Tension (N)	4,170	2620	2070	1490	1130	780
Neck Peak Compression (N)	4,000	2520		1820	1380	960
Neck Criteria N_{ij}	1	1		1	1	1
Neck Flexion (Nm)**	190	95		60	42	27
Neck Extension (Nm)**	57	28	38	24	17	11
Neck Shear (N)**	3,100	1950		1400	1200	1080

* Injury criteria for 95th percentile ATD is same as for 50th percentile ATD.
** Due care.

Figure 5-1

Neck Injury Mechanisms

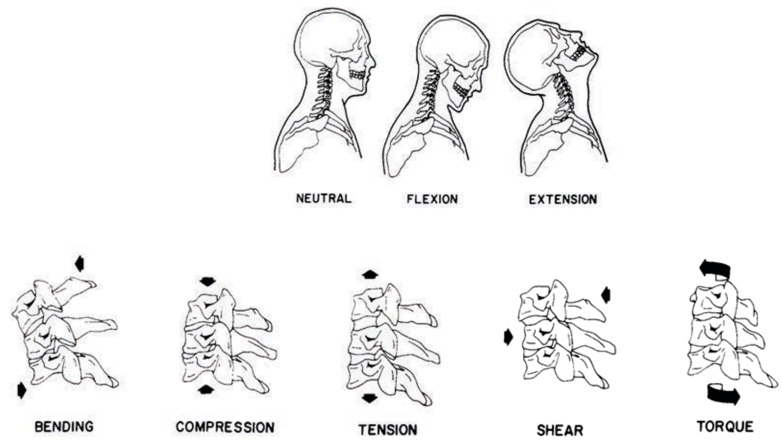
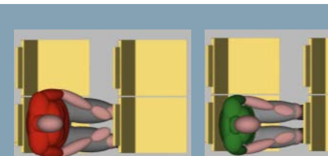
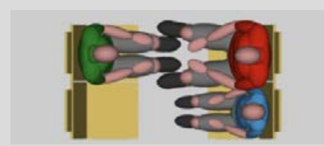
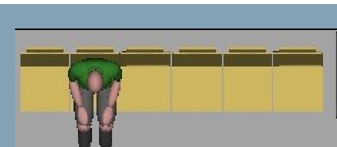
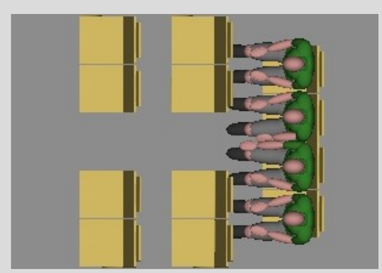
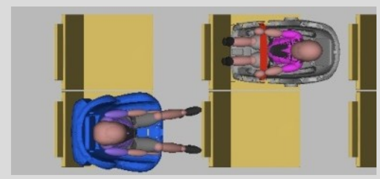
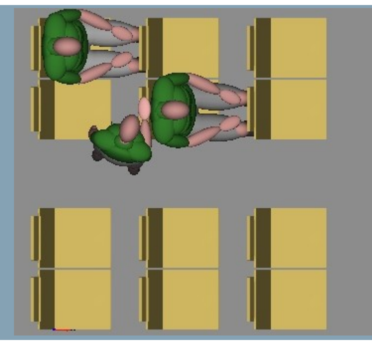


Table 5-2

Summary of Analyzed Seating Arrangements

Seating Arrangement – Summary Analysis	
Seating Arrangement 1 Forward-Facing Seats	
Seating Arrangement 2 Facing Seats	
Seating Arrangement 3 Lateral-Facing Seats	
Seating Arrangement 4 Row of Forward-Facing Back Seats	

Seating Arrangement – Summary Analysis	
Seating Arrangement 5 Wheelchair	
Seating Arrangement 6 Child Seats	
Seating Arrangement 7 Standing Passengers	

Seating Arrangement 1: Forward-Facing Seats Analysis in Outboard and Inboard Positions

Because the current LRV seats are usually attached to structure using a cantilever beam, different levels of injuries can be expected for both seat positions (outboard and inboard). Thus, both positions were analyzed for the 5th, 50th, and 95th percentile ATDs.

Figure 5-2 shows the normalized injury values for the outboard configuration. As expected, all injury values are below FMVSS 208 limits for the 95th and 50th percentile ATDs. However, the results obtained for the 5th percentile ATD had high values for both neck flexion moment and neck shear force as a consequence of the impact with the headrest. As a result, the NIJ, NTF, and NCF values also are high. Figure 5-3 shows the kinematics of the simulation. It is important to observe the amount of rotation of the impacted seat due to its cantilever beam configuration. Larger rotations are observed for the 95th percentile ATD because of its larger weight when compared to the 50th and 5th percentile ATDs.

Figure 5-4 shows the normalized injury values for the inboard configuration. For this configuration, the 5th percentile behaved similar to the outboard condition with the addition of having femur forces above acceptable limits. Although the injury values for the 95th and 50th percentile ATDs are below the FMVSS 208 limits, a small increase in injury values can be observed as a result of the smaller rotation of the impacted seat (see Figure 5-5).

Figure 5-2

Normalized Injury Values of High-Energy Impact with Forward-Facing Seats in Onboard Position

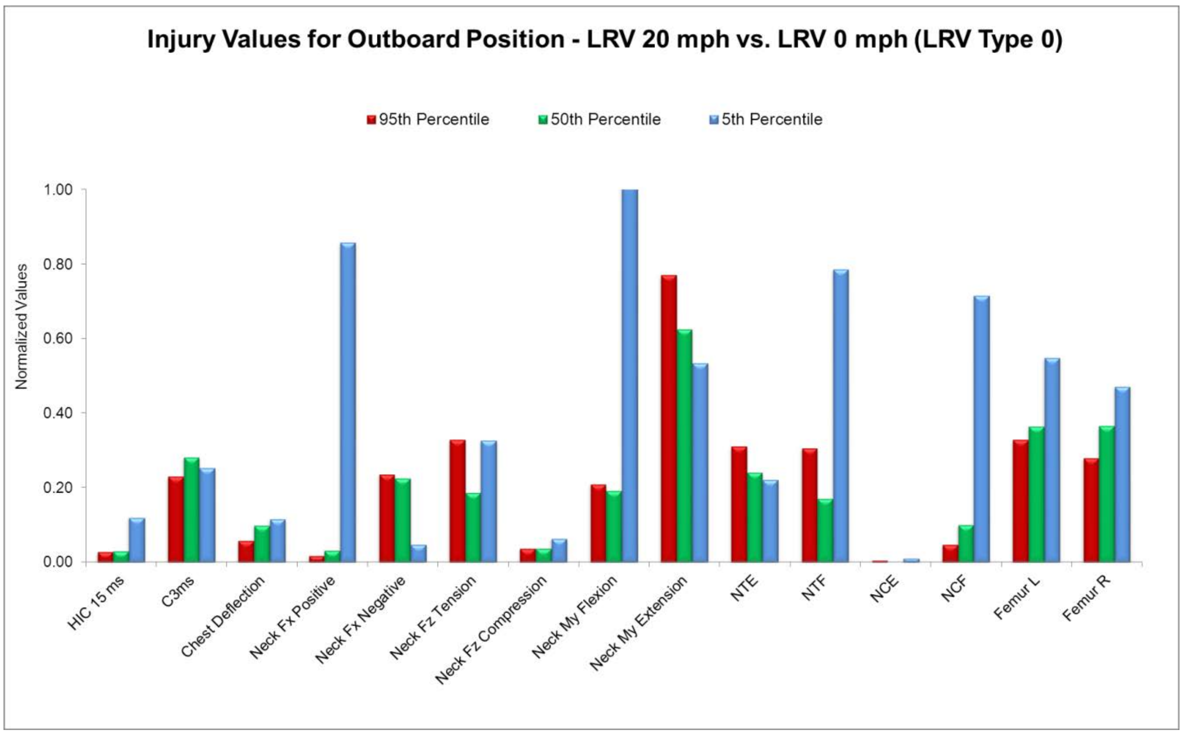
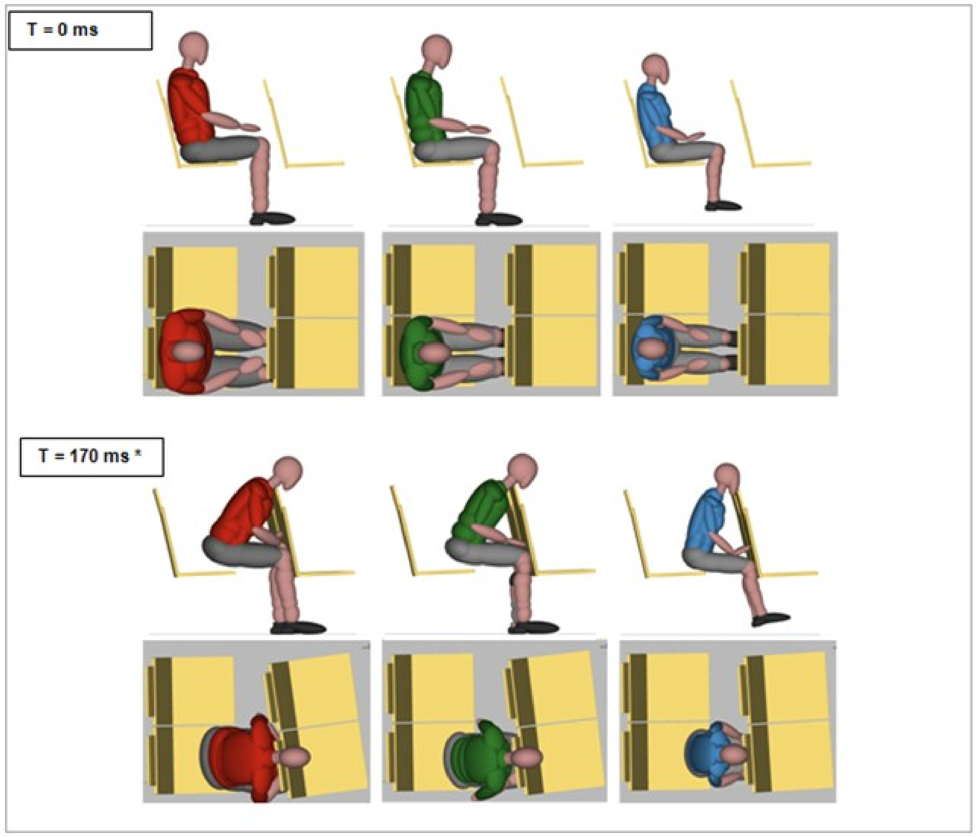


Figure 5-6 summarizes the results from the outboard and inboard configurations. As a consequence of using forward-facing seats for this configuration, similar results as the ones obtained in Section 4 were observed. The 5th percentile has very high injury values due to the headrest design. The 95th percentile has also some high results for the inboard configuration on the neck region. Finally, the 50th percentile has all the injury values analyzed between the limits.

Figure 5-3

Kinematics of High-Energy Impact in Forward-Facing Seats in Outboard Position



Red 95^{th} Percentile, Green 50^{th} Percentile, and Blue 5^{th} Percentile

Video 5-1

LRV High Energy Crash – Forward Facing Seats in Outboard Scenario

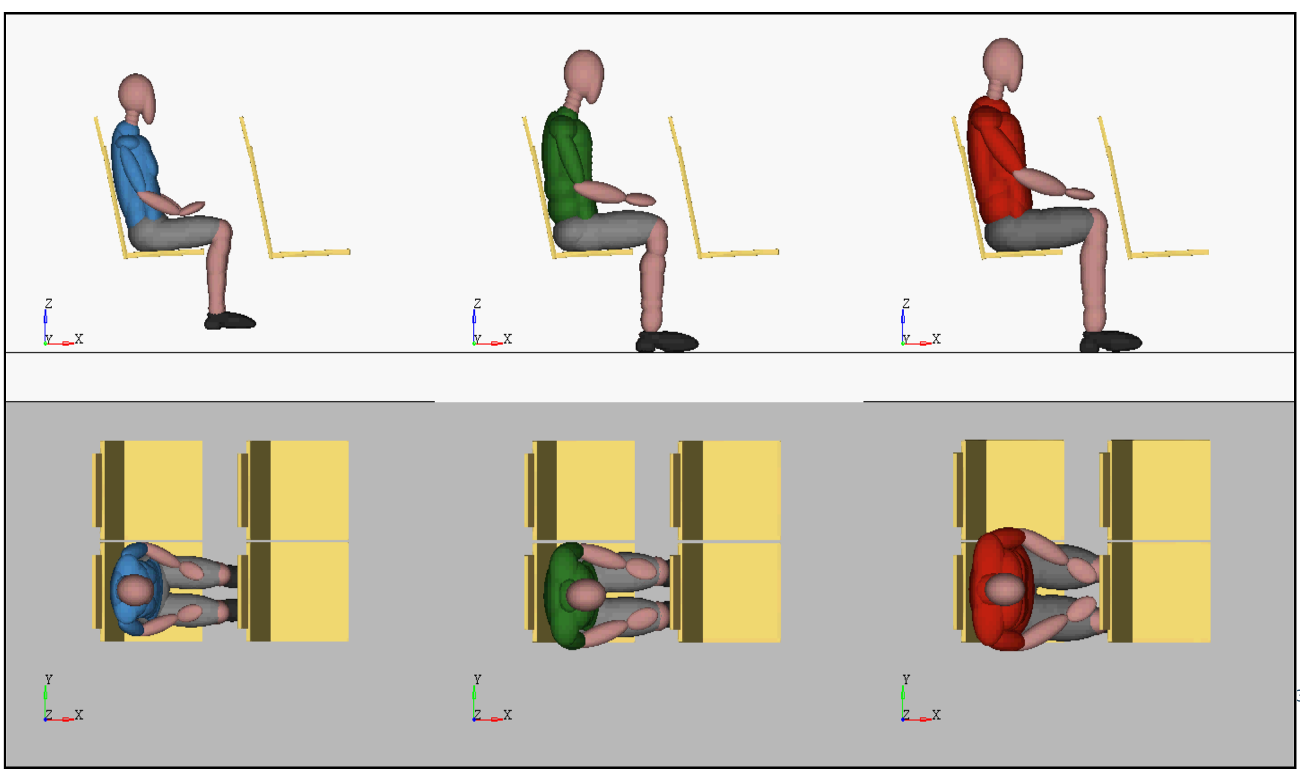


Figure 5-4

Normalized Injury Values of High-Energy Impact with Forward-Facing Seats in Inboard Position

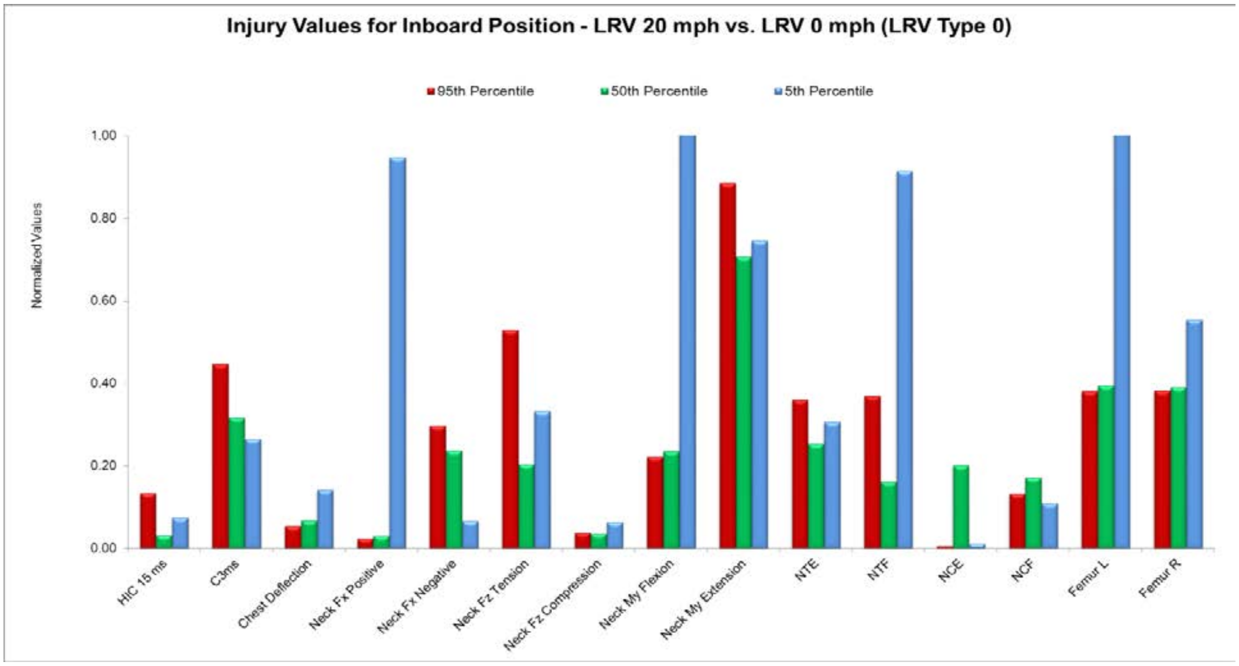
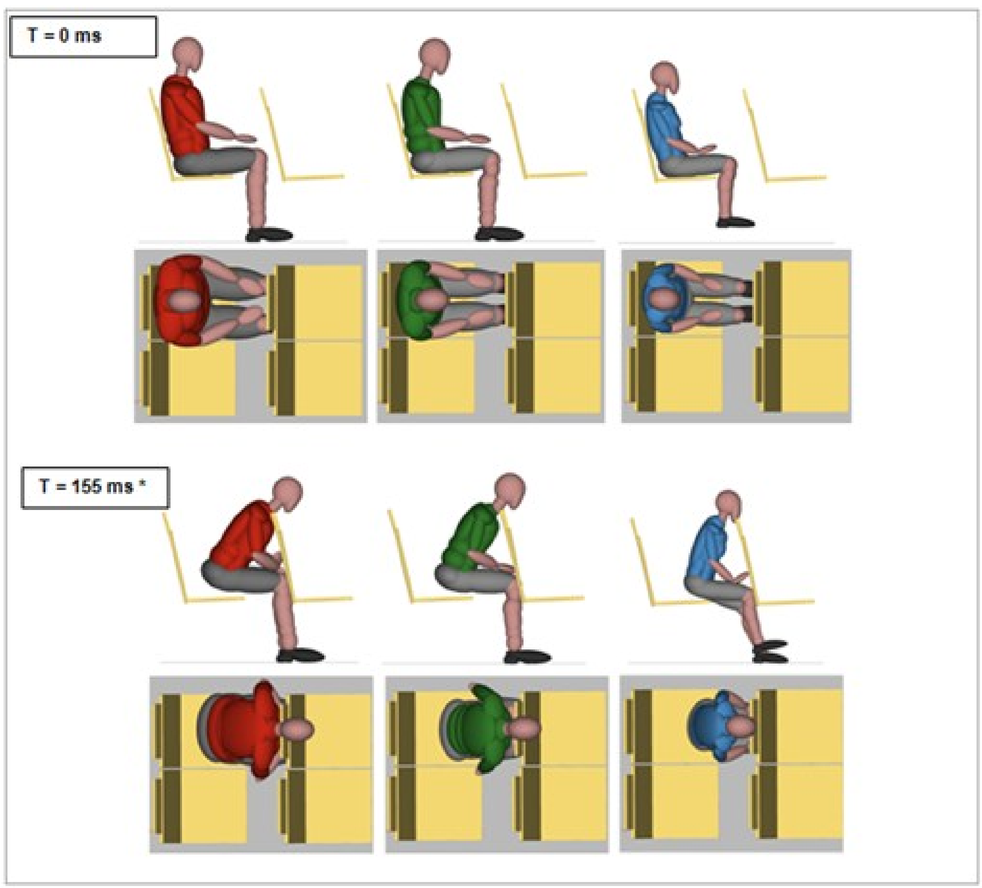


Figure 5-5

Kinematics of High-Energy Impact in Forward-Facing Seats in Inboard Position



Video 5-2

LRV High Energy Crash – Forward Facing Seats in Inboard Scenario

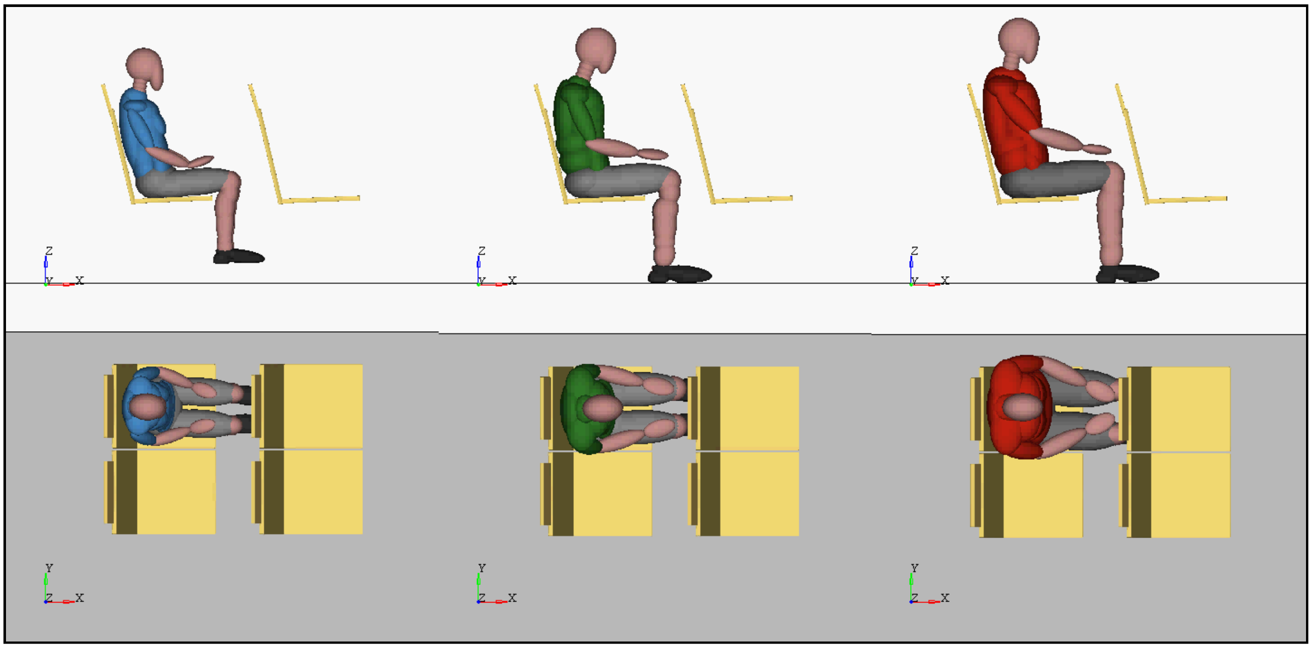
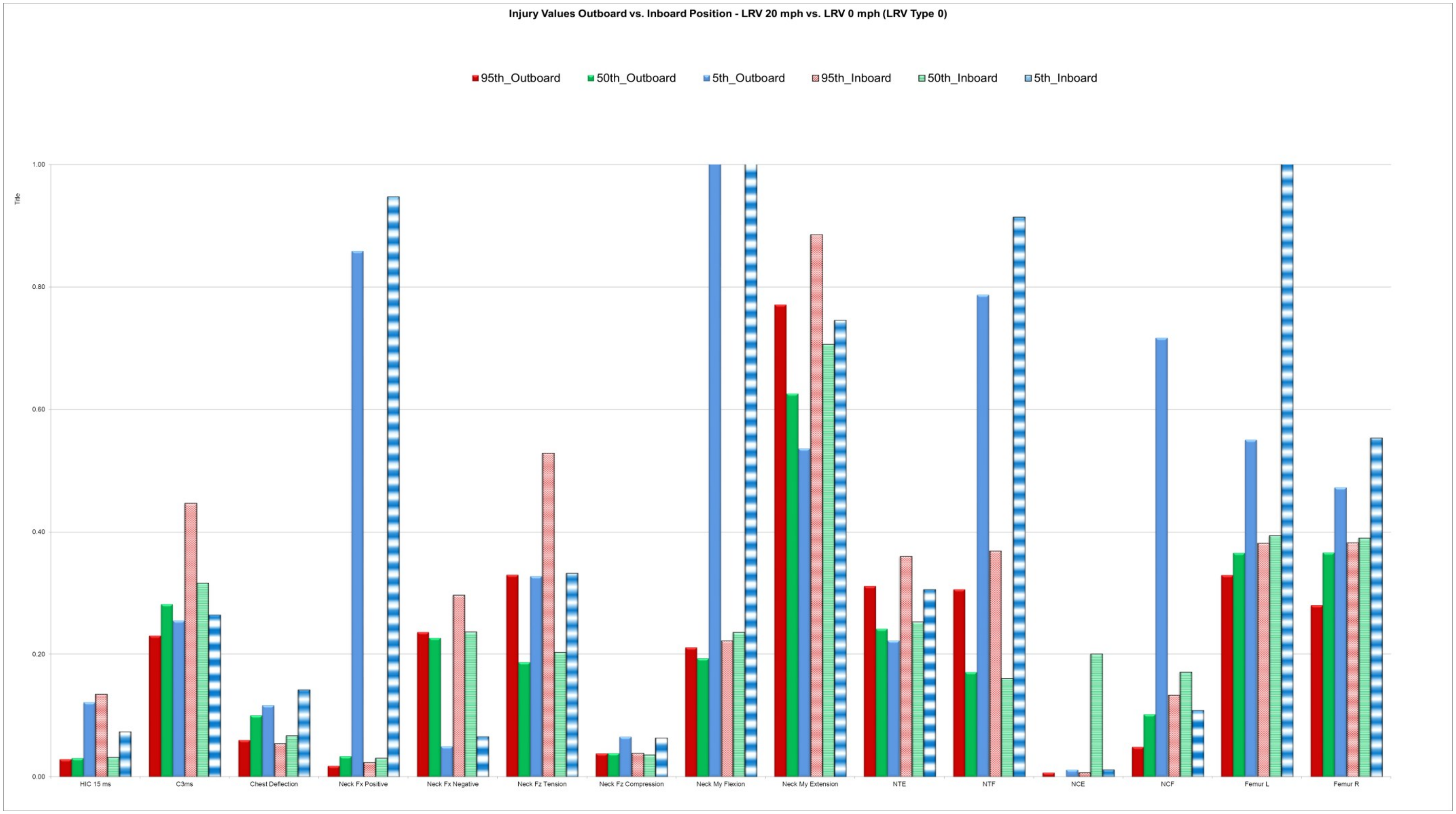


Figure 5-6

Normalized Injury Values of High-Energy Impact with Forward-Facing Seats in Outboard and Inboard Positions



Seating Arrangement 2: Facing-Seats Analysis

Facing seats are analyzed in this section. According to the layout survey from Section 2 and shown in Figure 2-24, this type of seating arrangement represents approximately 19 percent of the total number of seats available on the current U.S. LRV fleet. Actually, this seating arrangement represents the second type of seat most used in current layouts.

Figure 5-7

Example of Facing Seats

The high-energy pulse obtained from the collision of two type 0 LRVs was used for this analysis.

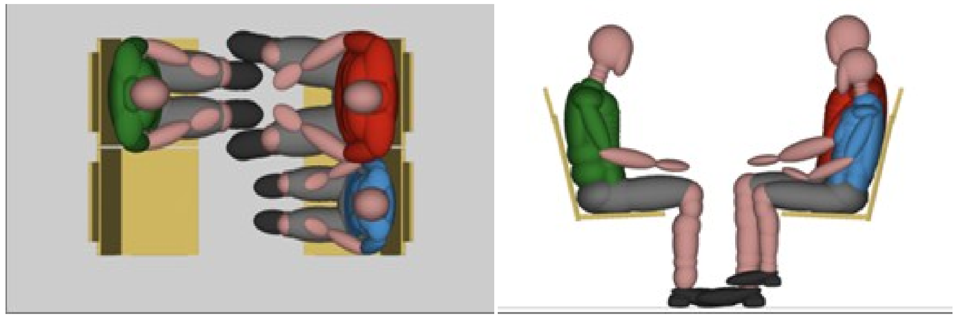
Regardless of the type of impact, a front-facing seating configuration will lead to contact between occupants. Therefore, all possible combinations of occupant arrangements were analyzed. The injury values of the following combinations are shown in this section: 5th percentile ATD impacting a 50th percentile ATD, 50th percentile ATD impacting a 5th percentile ATD, 50th percentile ATD impacting a 95th percentile ATD, 95th percentile ATD impacting a 50th percentile ATD, 95th percentile ATD impacting a 5th percentile ATD, and 5th percentile ATD impacting a 95th percentile ATD.

Configuration 1

For this configuration, the 50th percentile ATD is facing the 95th percentile ATD, and the 5th percentile ATD is sitting adjacent to the 95th percentile ATD. Thus, the 5th and 95th percentile ATDs will experience a rear impact, while the 50th percentile will experience a frontal impact (see Figure 5-8).

Figure 5-8

Facing-Seats Configuration 1



The moment of impact at t = 0.240 s is represented in Figure 5-9. The head of the 50th percentile impacts the chest of the 95th percentile causing high compression forces on the neck of the 50th percentile. Figure 2-10 shows all injury values for this configuration. Both impacting ATDs, 50th and 95th percentiles, are associated with large values for some injuries attributable to the contact. All injury values for the 5th percentile ATD are below the FMVSS 208 limits.

Figure 5-9

Configuration 1 Impact—Contact Moment t = 0.240 s

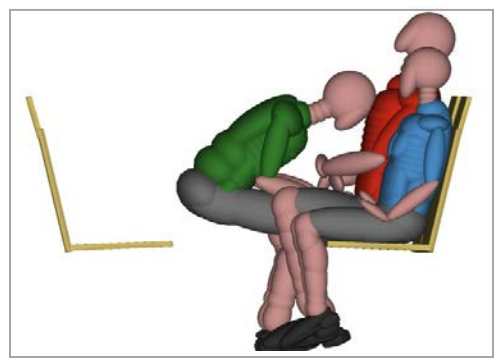
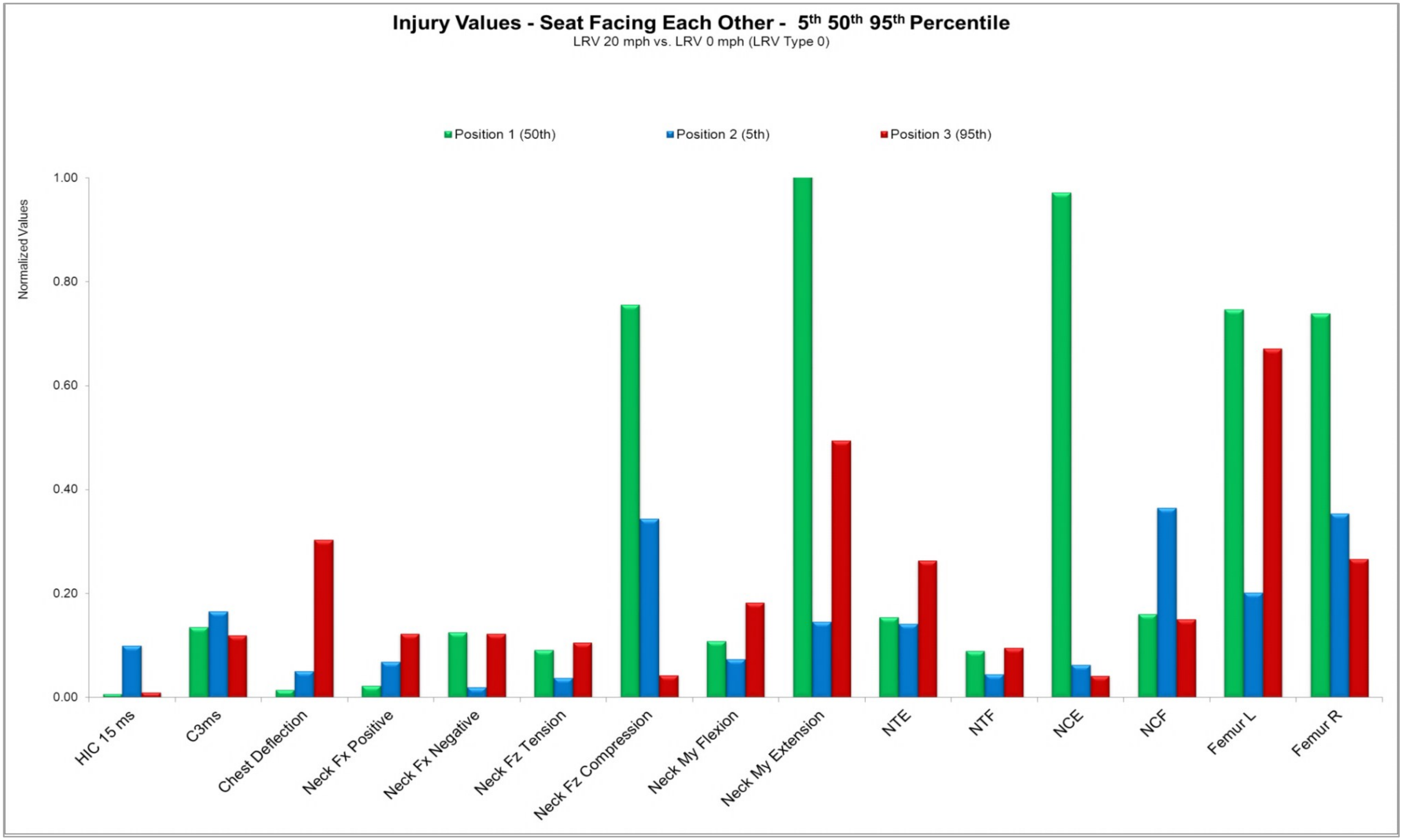


Figure 5-10

Normalized Injury Values of Facing-Seats Configuration I Impact



Configuration 2

For this configuration, the 50th percentile ATD is facing the 5th percentile ATD, and the 95th percentile ATD is sitting adjacent to the 5th percentile ATD. Thus, the 5th and 95th percentile ATDs will experience a rear impact, while the 50th percentile AD will experience a frontal impact (see Figure 5-11).

The moment of impact is represented in Figure 5-12.

The head of the 50th percentile ATD impacts the chest of the 5th percentile ATD causing high compression forces on the neck of the 50th percentile ATD. Most of the energy is transferred by contact between the legs. Actually, because of this direct contact between the legs, the injury values for both 5th and 50th percentile ATDs on the femur region are very large.

Figure 5-13 shows all injury values for this configuration. Both impacting ATDs, 50th and 5th percentiles, are associated with large values for some injuries attributable to the contact. The 95th percentile ATD has very low injury values, because there was no contact with other occupants; therefore, injury values were below FMVSS 208 limits.

Figure 5-11

Facing-Seats Configuration 2

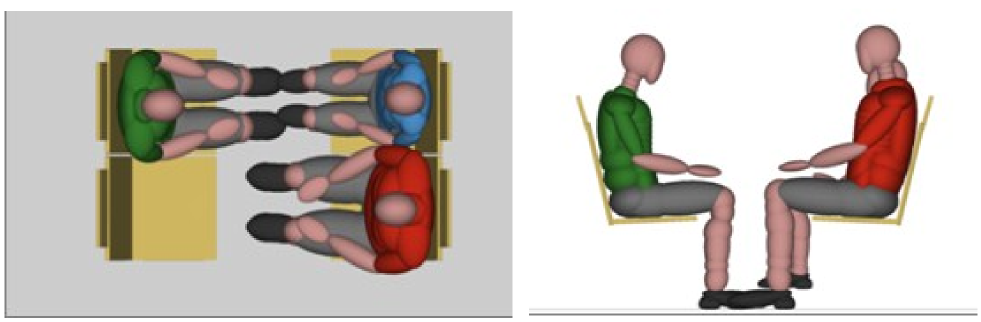


Figure 5-12

Configuration 2 Impact - Contact Moment t = 0.265 s

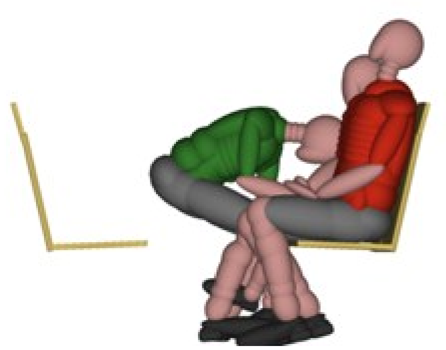
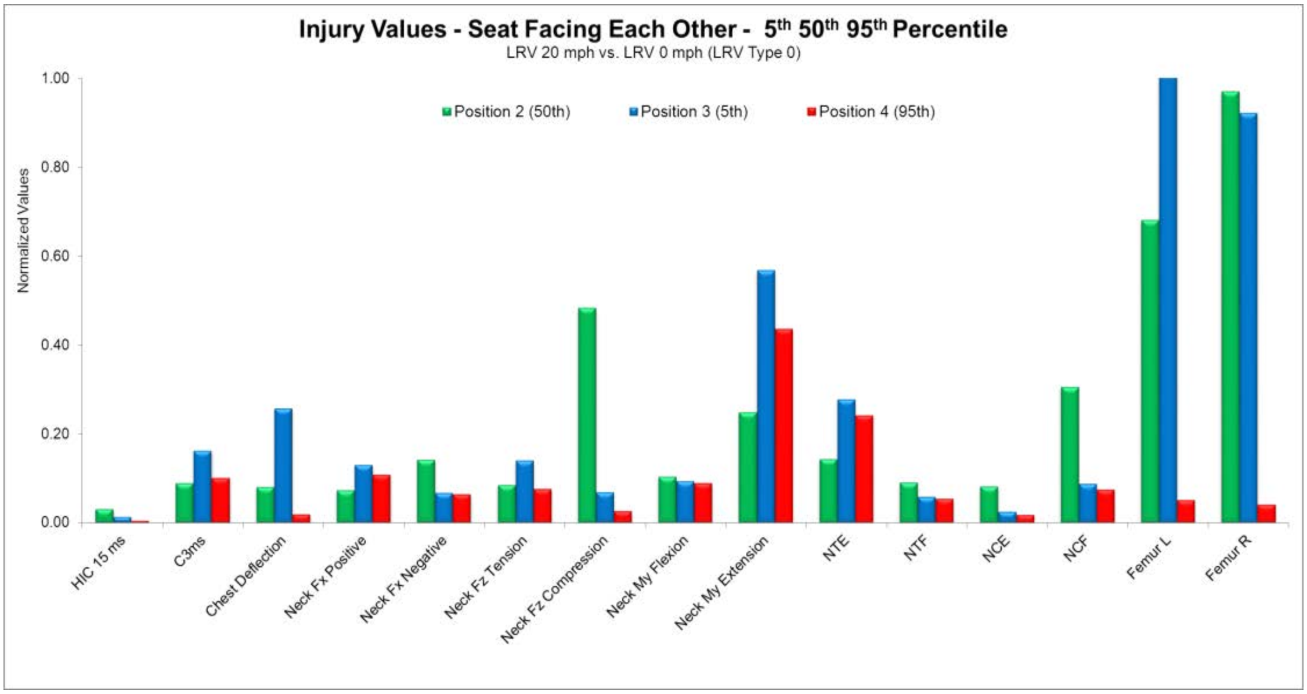


Figure 5-13

Normalized Injury Values of Configuration 2 Impact



Configuration 3

For this configuration, the 5th percentile ATD is facing the 50th percentile ATD, and the 95th percentile ATD is sitting adjacent to the 5th percentile ATD. Thus, the 50th percentile ATD will experience a rear impact, while the 5th and the 95th percentiles will experience a frontal impact (see Figure 5-14)).

The moment of impact is represented inFigure 5-14. In this instance, the head of the 5th percentile ATD impacts the chest of the 50th percentile ATD causing high compression forces on the neck of the 5th percentile ATD. At the same time, the femur forces are very large. Because of the direct contact between legs, the injury values for both 5th and 50th percentile ATDs are very large. In this configuration, the 95th percentile ATD also has very large injury values in the neck and femur regions caused by direct contact with the seat in front of it.

Figure 5-16 shows all injury values for this configuration. All occupants, regardless of size and position, have at least one injury value above acceptable limits.

Figure 5-14

Facing-Seats Configuration 3

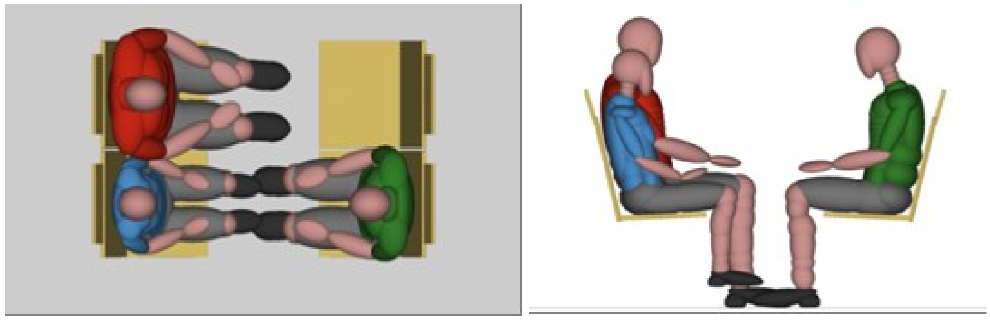


Figure 5-15

Facing-Seats Configuration 3 Impact - Contact Moment t = 0.275 s

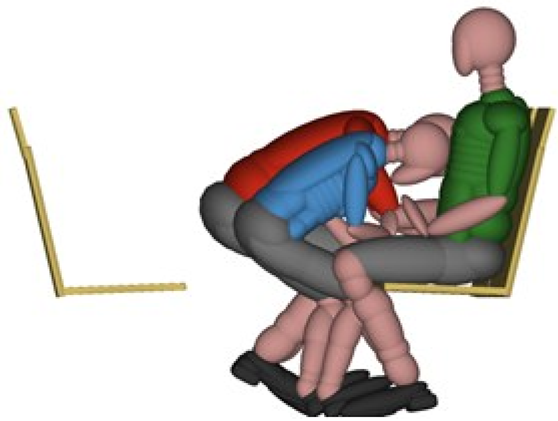
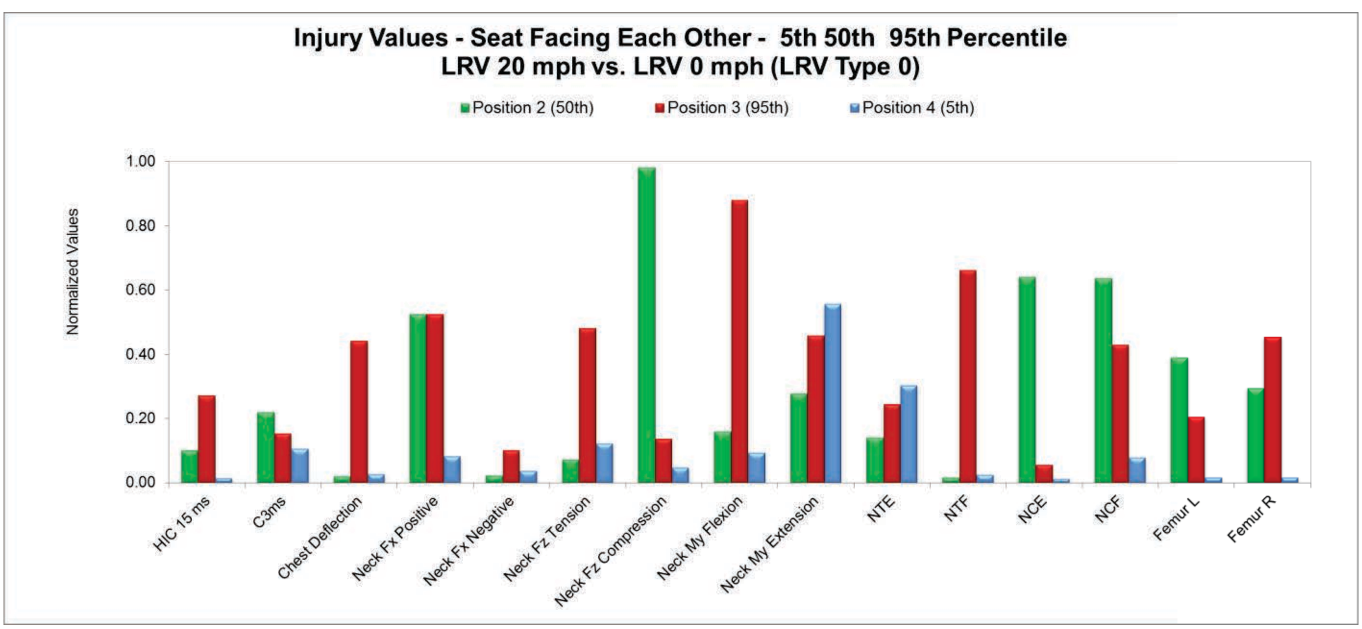


Figure 5-16

Normalized Injury Values of Facing-Seats Configuration 3 Impact



Configuration 4

For this configuration, the 5th percentile ATD is facing the 95th percentile ATD, and the 50th percentile ATD is sitting adjacent to the 5th percentile ATD. Thus, the 95th percentile ATD will experience a rear impact, while the 5th and 50th percentile ATDs will experience a frontal impact (see Figure 5-17).

The moment of impact is represented in Figure 5-18. In this instance, the head of the 5th percentile ATD impacts the chest of the 95th percentile ATD. No high injury values were found for the 5th percentile ATD. However, some relatively high values were observed on the femurs of the 95th percentile ATD due to the impact. For this configuration, the 50th percentile ATD incurs the worst injury as a result of the impact with the seat in front of it. High neck compression forces and neck flexion moments were observed. At the same time, femur forces were also high due to contact with the seat pan.Figure 5-19 shows all normalized injury values for this configuration. Only the 50th percentile ATD shows injury values above or near acceptable limits.

Figure 5-17

Facing-Seats Configuration 4

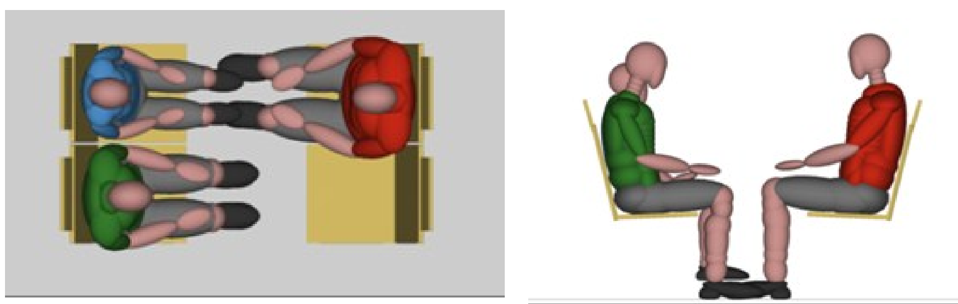


Figure 5-18

Facing-Seats Configuration 4 Impact - Contact Moment t = 0.300 s

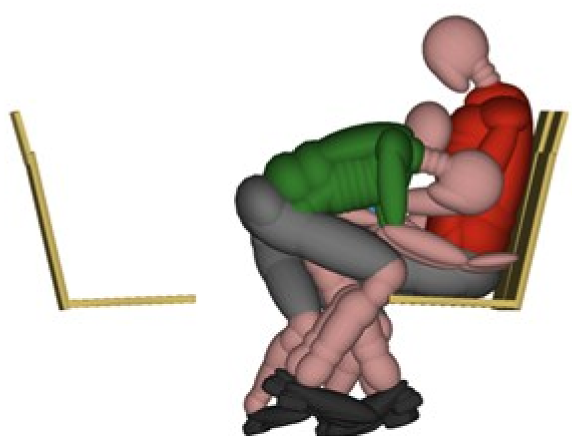
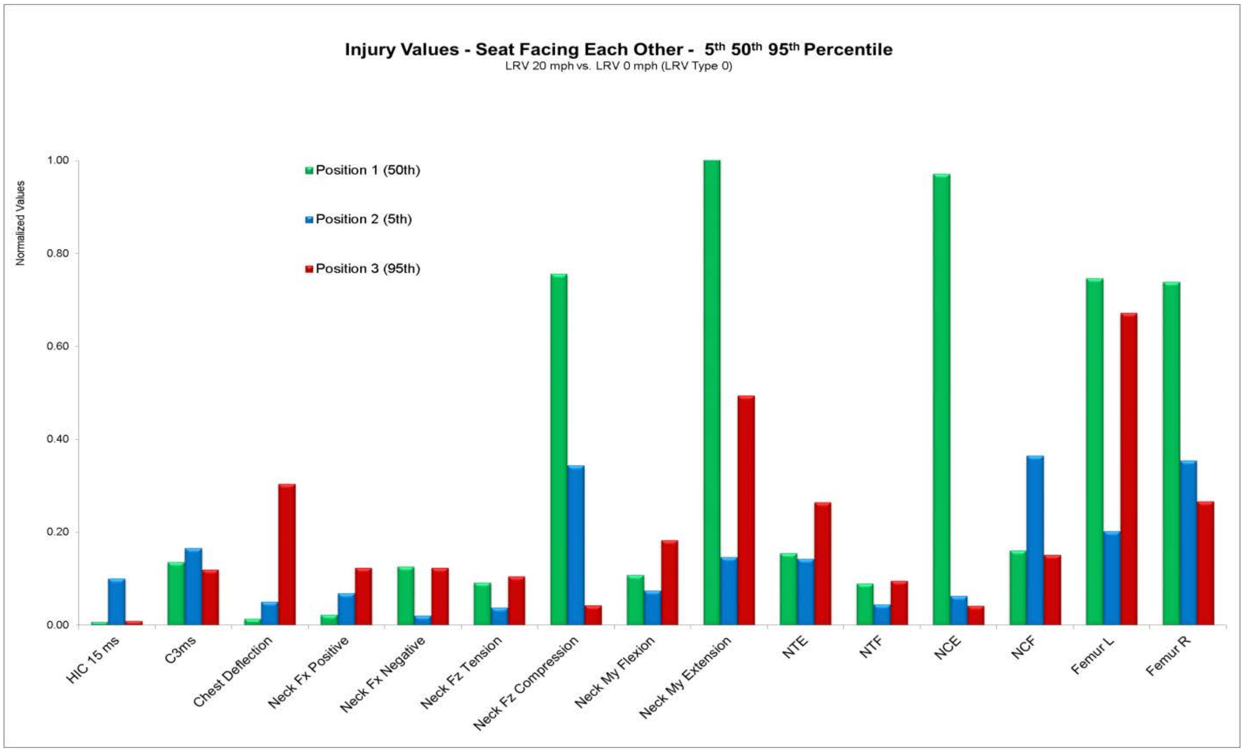


Figure 5-19

Normalized Injury Values of Facing-Seats Configuration 4 Impact



Configuration 5

For this configuration, the 95th percentile ATD is facing the 5th percentile ATD, and the 50th percentile ATD is sitting adjacent to the 5th percentile ATD. Thus, the 5th and 50th percentile ATDs will experience a rear impact, while the 95th percentile ATD will experience a frontal impact (see Figure 5-20).

The moment of impact is represented in Figure 5-21. In this instance, the head of the 95th percentile ATD impacts the chest and head of the 5th percentile ATD causing high injury values for both. Most injuries occur in the neck region. The femur forces also are high due to the contact. In this configuration, the 50th percentile ATD has very low injury values. No interaction between it and the other ATD occupants increased its level of safety.

Figure 5 22 shows all injury values for this configuration. Neck injuries can be expected for both the 5th and 95th percentile ATDs. Also, some injuries on the legs can occur.

Figure 5-20

Facing-Seats Configuration 5

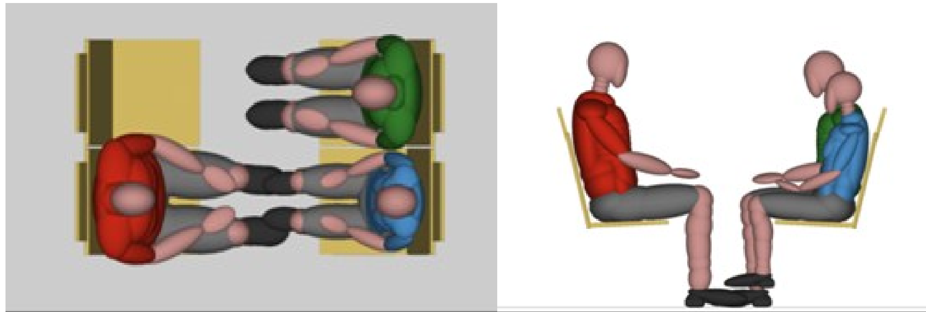


Figure 5-21

Facing-Seats Configuration 5 Impact - Contact Moment t = 0.280 s

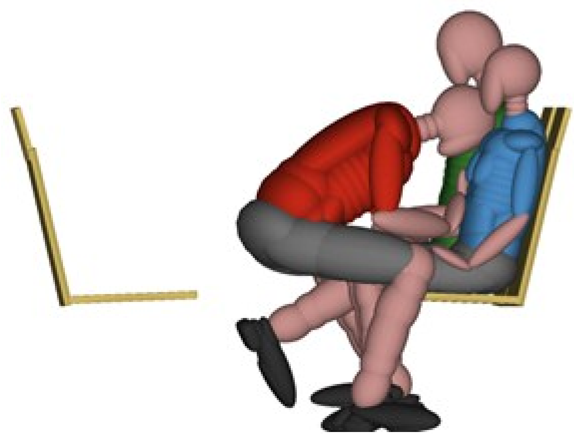
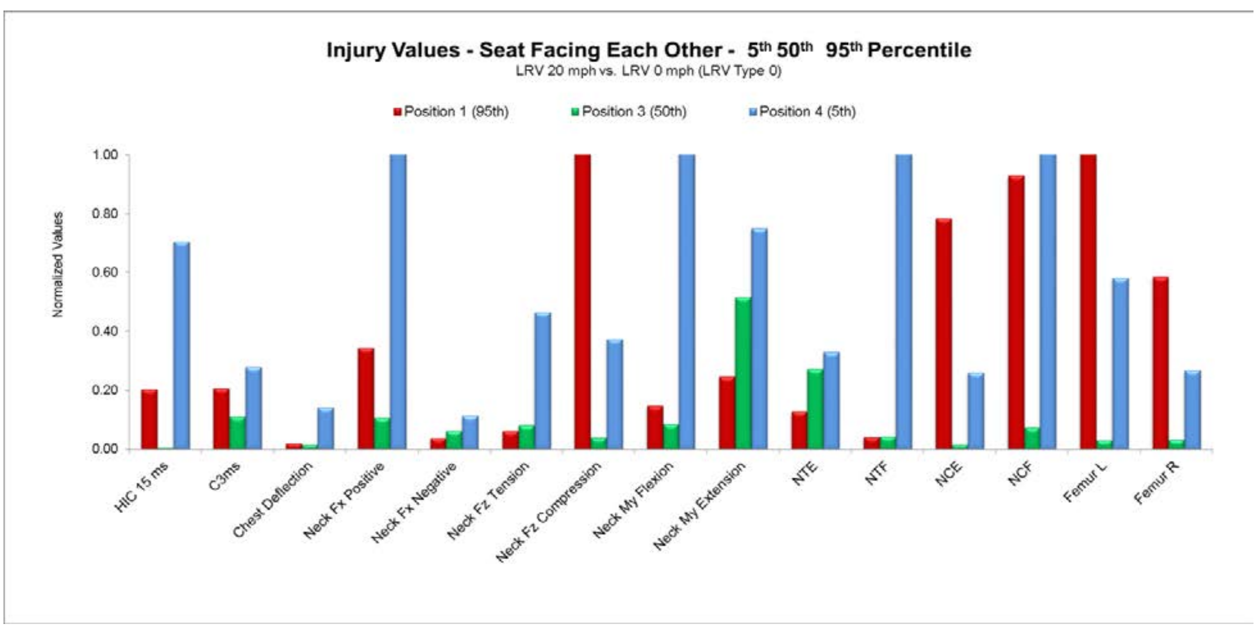


Figure 5-22

Normalized Injury Values of Facing-Seats Configuration 5 Impact



Configuration 6

For this last configuration, the 95th percentile ATD is facing the 50th percentile ATD, and the 5th percentile ATD is sitting adjacent to the 95th percentile ATD. Thus, the 50th percentile ATD will experience a rear impact, while the 5th and the 95th percentile ATDs will experience a frontal impact (see Figure 5-23).

The moment of impact is represented in Figure 5-24. In this instance, the head of the 95th percentile ATD impacts the chest and head of the 50th percentile ATD causing high injury values for both in the neck region (high compression values for the 95th percentile ATD and high tension values for the 50th percentile ATD). No high values for the femur forces were observed due to the initial position of the 95th percentile ATD. The 5th percentile ATD has very large injury values in the neck region due to contact with the seat in front of it.

Figure 5-25 shows all injury values for this configuration. All occupants, regardless the size and position have at least one injury value above acceptable limits.

Figure 5-23

Facing-Seats Configuration 6

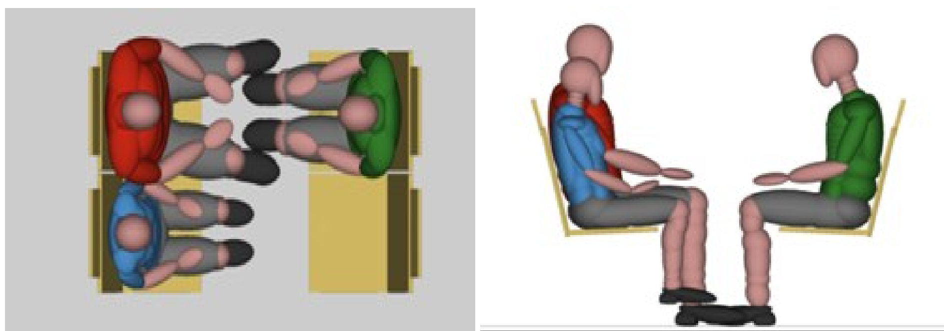


Figure 5-24

Facing-Seats Configuration 6 Impact - Contact Moment t = 0.250 s

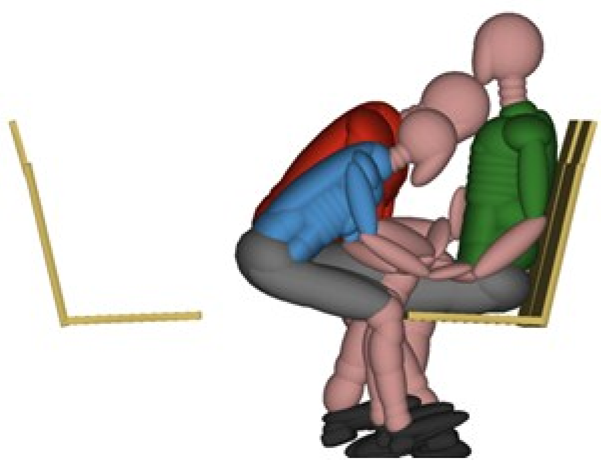
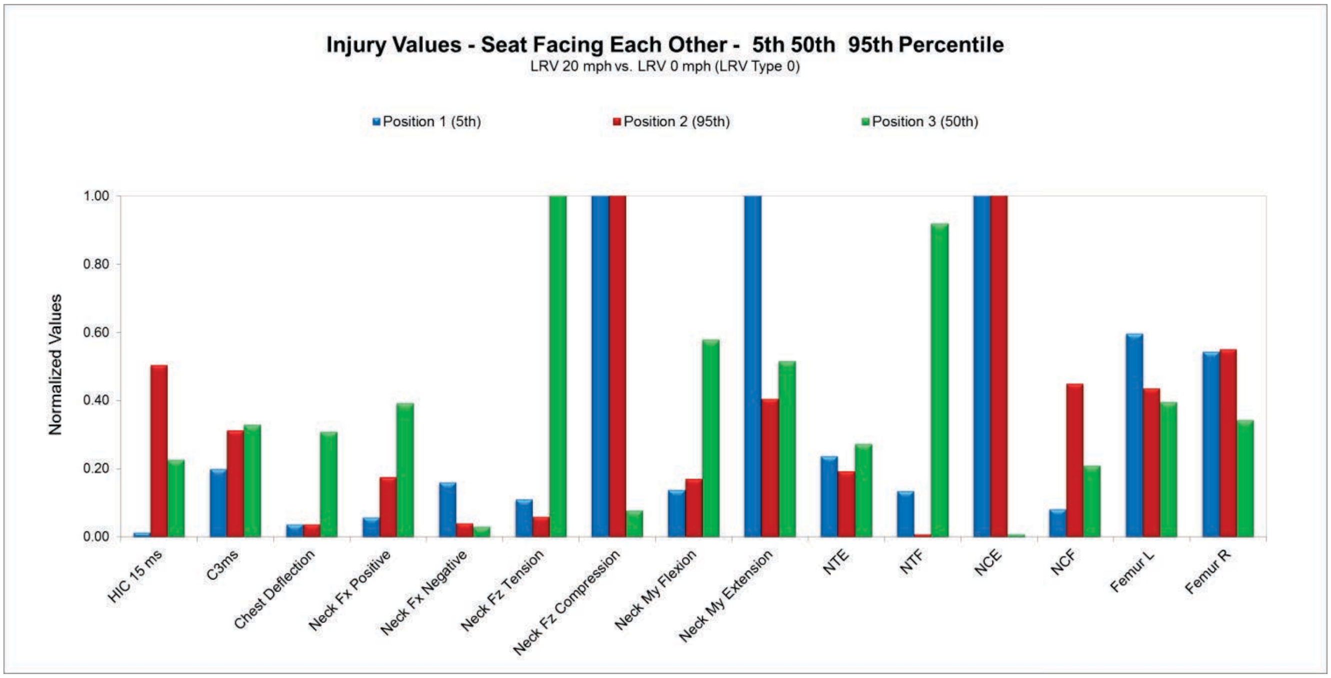


Figure 5-25

Normalized Injury Values of Facing-Seats Configuration 6 Impact



Conclusions for Facing-Seat Configurations

Six different configurations were analyzed in this section, each with a different arrangement of the three most representative types of ATDs (5^{th}, 50^{th}, and 95^{th} percentiles). With these six arrangements, all possible combinations were studied.

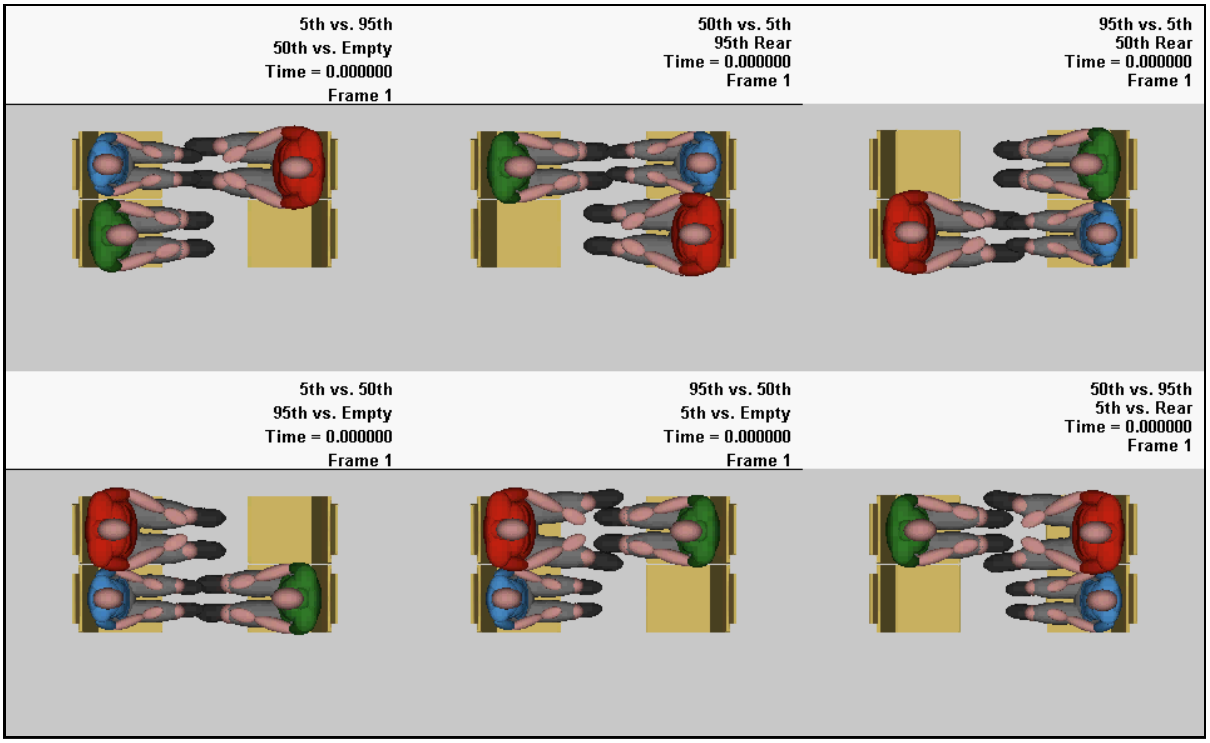
According to the results, all configurations studied contain at least one occupant with at least one injury value larger than current FMVSS 208 limits. Most injuries are due to contact between occupants. Thus, injuries can be expected in the head, neck, and lower extremities.

When the passenger is facing an empty seat, the results obtained also are above current limits for the neck and femur regions. Only when the ATD is sitting in a position opposite of the impact and without any other passenger in front will the results remain below the limits.

After analyzing this type of configuration, it is concluded that these types of seats pose a danger for all occupants. Because it is impossible to control who sits where in an LRV, this type of configuration should be avoided when considering new layouts. Also, the size of the occupant is not an important factor where injuries are concerned, as similar results were obtained regardless of target occupant size.

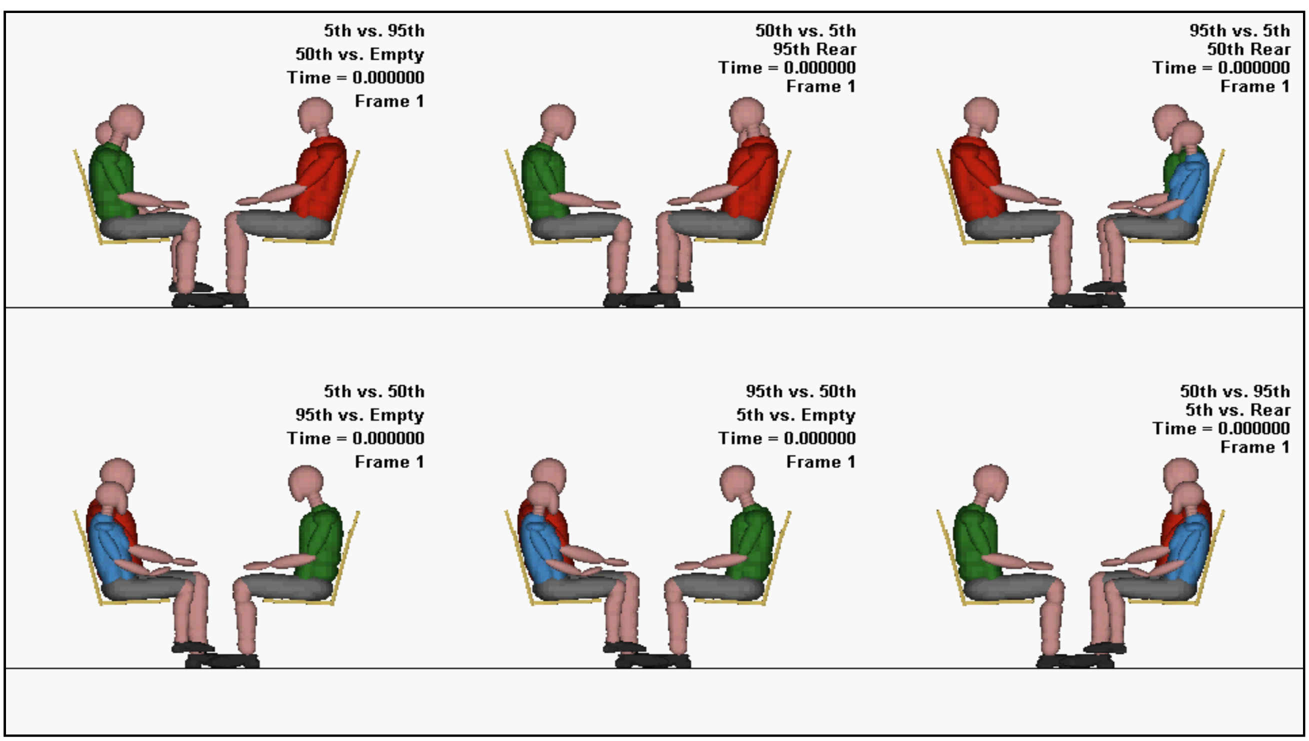
Video 5-3

Forward Facing Seats Configuration Impact Scenario – Top View



Video 5-4

Forward Facing Seats Configuration Impact Scenario – Side View



Seating Arrangement 3: Lateral-Facing-Seats Analysis

The fourth type of configuration most often used in the current fleet of LRVs in the U.S. is the lateral-facing or side-facing seat. This type of seating is very common for the middle section of the cabin near entrances. This configuration is directly associated with an increase in available room for standing passengers, thus increasing the LRV passenger capacity. This is useful for LRVs operating in high-use regions such as metropolitan areas.

To evaluate the safety for this type of seating, the high-energy pulse obtained from the LRV type 0 was used. Due to the longitudinal position of this type of seating, both frontal and rear impacts can be studied using the same model (Figure 5-26).

Figure 5-26

Example of Lateral-Facing Seats

The analysis for this type of seating was divided into two different parts:

- Exit Velocity Analysis: Due to the different number of seats in lateral seating arrangements, a study was conducted to analyze the relative velocity of the passenger in relation to the seated position (see Figure 5-29 later in this section).
- Current LRV Layout Analysis: Using the worst-case scenario from the aforementioned study, a complete analysis was done to evaluate the following:
  - Representative lateral-facing seat layouts (Figure 5-27 and Figure 5-28).
  - Occupant-to-occupant interactions for typical lateral-facing seat layouts studied in the previous section.

Figure 5-27

Forward-Facing, Lateral-Facing, and Aft-Facing Seat

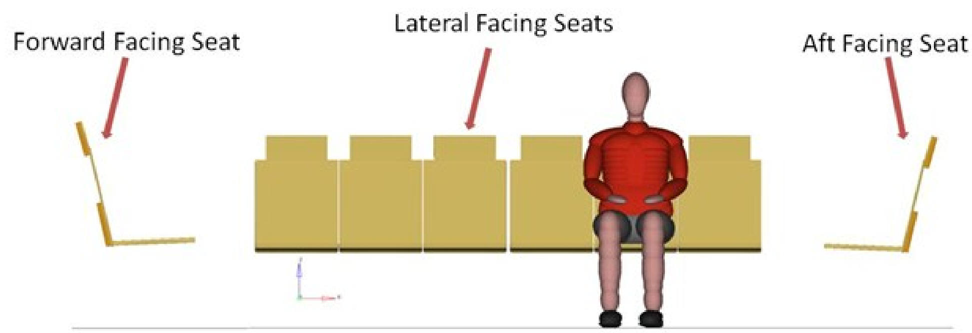
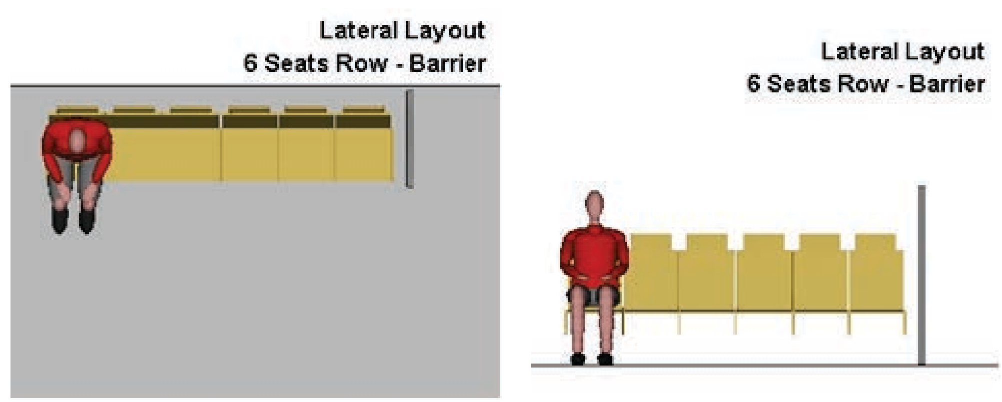


Figure 5-28

Lateral-Facing Seats with Barrier



Exit-Velocity Analysis

According to all layouts available for analysis (Section 0 “Survey of LRV Specific Interiors”), the number of lateral-facing seats in a row usually ranges from one to six. From a total of 11 LRVs where lateral facing seats were found, the following apply:

- Six of them (54.5%) have a row with three seats.
- Five of them (45.5%) have a varying number of lateral-facing seats per row ranging from one to six.

The maximum exit velocity for the occupant was evaluated according to occupant seating position. Exit velocity is defined as the impact velocity of the ATD with the barrier (Figure 5-29). The exit velocity for the six positions is compared for the purpose of analyzing which position shows the largest impact velocity. The 5th, 50th, and 95th percentile ATDs were used for this analysis.

Figure 5-29

Analysis of Exit Velocity in Lateral-Facing Seats

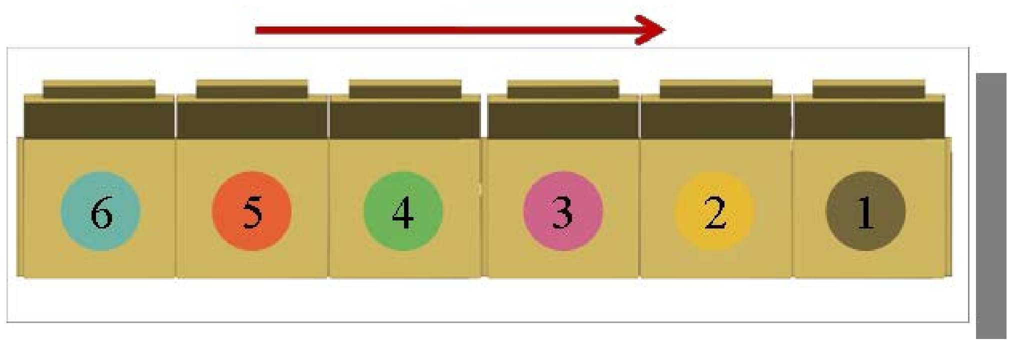
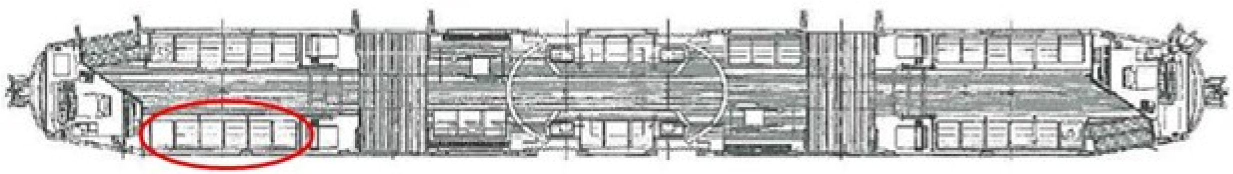


Figure 5-30 through Figure 5-33 show some examples of LRV interior where different numbers of lateral facing seats in a row can be found:

- Six lateral-facing seats:

Figure 5-30

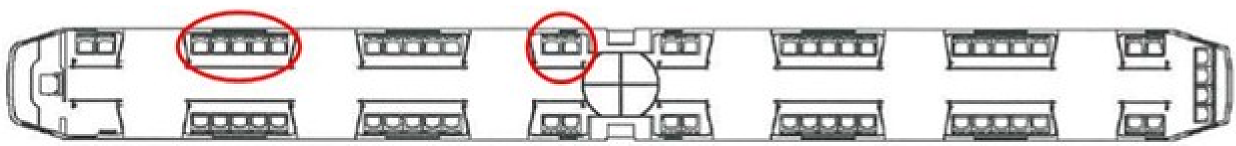
Six Lateral-Facing Seats Configuration [3]



- Five and two lateral facing seats:

Figure 5-31

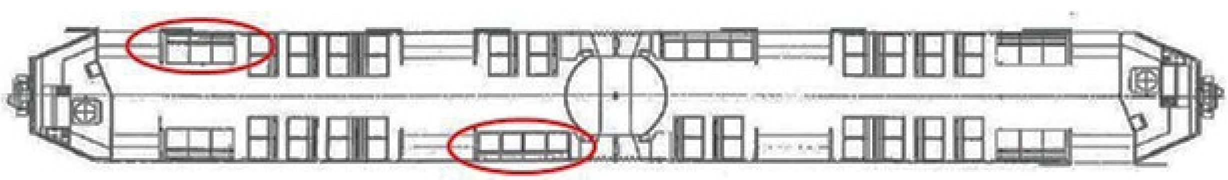
Five and Two Lateral-Facing Seats Configuration [3]



- Three lateral-facing seats (most typical scenario) and four lateral-facing seats:

Figure 5-32

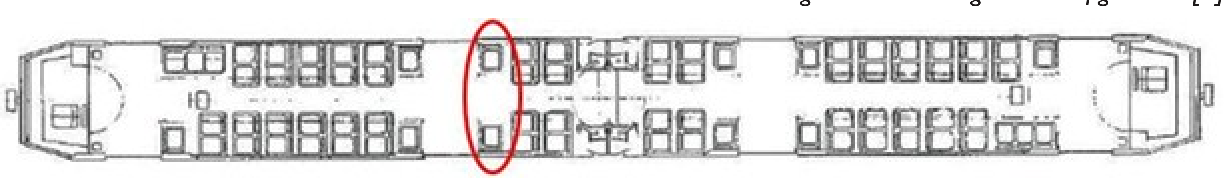
Three and Four Lateral-Facing Seats Configuration [3]



- Single lateral-facing seat:

Figure 5-33

Single Lateral-Facing Seat Configuration [3]



The setup model used in this section was shown previously in Figure 5-28. The exit velocities of the passengers were recorded during the entire event for each of the six positions, and the results are shown in Figure 5-34.

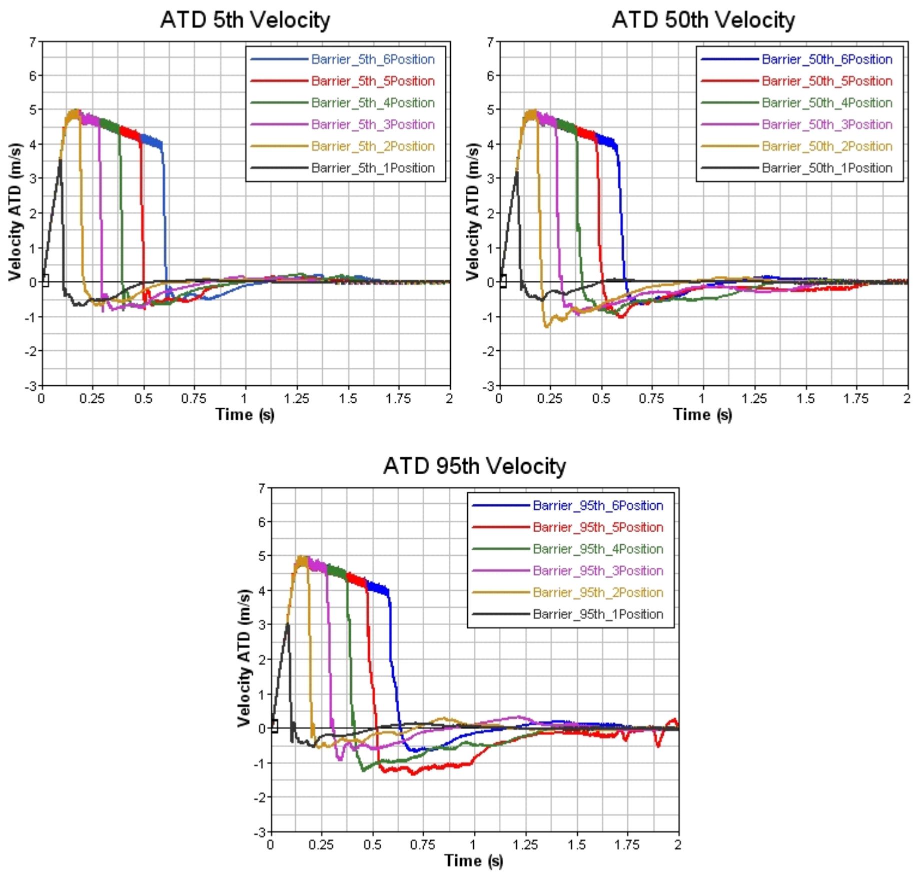


Figure 5-34

Exit Velocities of 5^{th}, 50^{th}, and 95^{th} Percentile ATDs in Lateral-Facing Seats

As expected, all occupants showed similar behavior. The passenger seated in the first seat position had the smallest impact velocity. This is because the proximity of the barrier to the passenger is small, and the passenger does not have enough time to build relative velocity before impact. In contrast, the passenger seated in the second seat had the highest impact velocity. In this position, the occupant has enough time to build the maximum relative velocity an instant before impact with the barrier. Positions three to six reach their maximum velocity, but due to friction and contact with the seat pans, the impact velocity is reduced just before contact (for this analysis, the coefficient of friction between the ATDs and the seats is 0.2).

Figure 5-35 summarizes these results, with equations that follow. This bar chart shows the impact velocity as a function of the distance between the center line of the seat pan and the barrier in meters.

Figure 5-35

Analysis Results of Impact Velocity of ATDs in Lateral-Facing Seats

95th $y = 0.7918x^5 - 6.7958x^4 + 22.549x^3 - 35.986x^2 + 27x - 2.9252$ (5-1)

50th $y = 0.8595x^5 - 7.1839x^4 + 23.19x^3 - 35.967x^2 + 26.213x - 2.511$ (5-2)

5th $y = 0.8803x^5 - 7.152x^4 + 22.478x^3 - 33.967x^2 + 24.04x - 1.6007$ (5-3)

The variable x (m), or distance (1) in Figure 5-36, represents the distance between the center of the seat pan and the barrier, and y (m/s) is the exit velocity. If the velocity of impact is desired, then x needs to be corrected by the following, or distance (2) in Figure 5-36

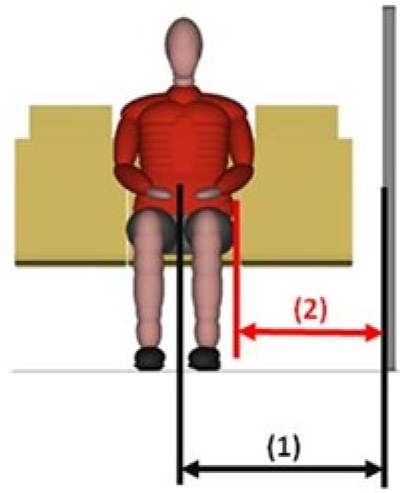
95th x = Distance between Seat Pan Center and Barrier – 0.203 (m) (5.4)

50th x = Distance between Seat Pan Center and Barrier – 0.183 (m) (5.5)

5th x = Distance between Seat Pan Center and Barrier – 0.156 (m) (5.6)

Figure 5-36

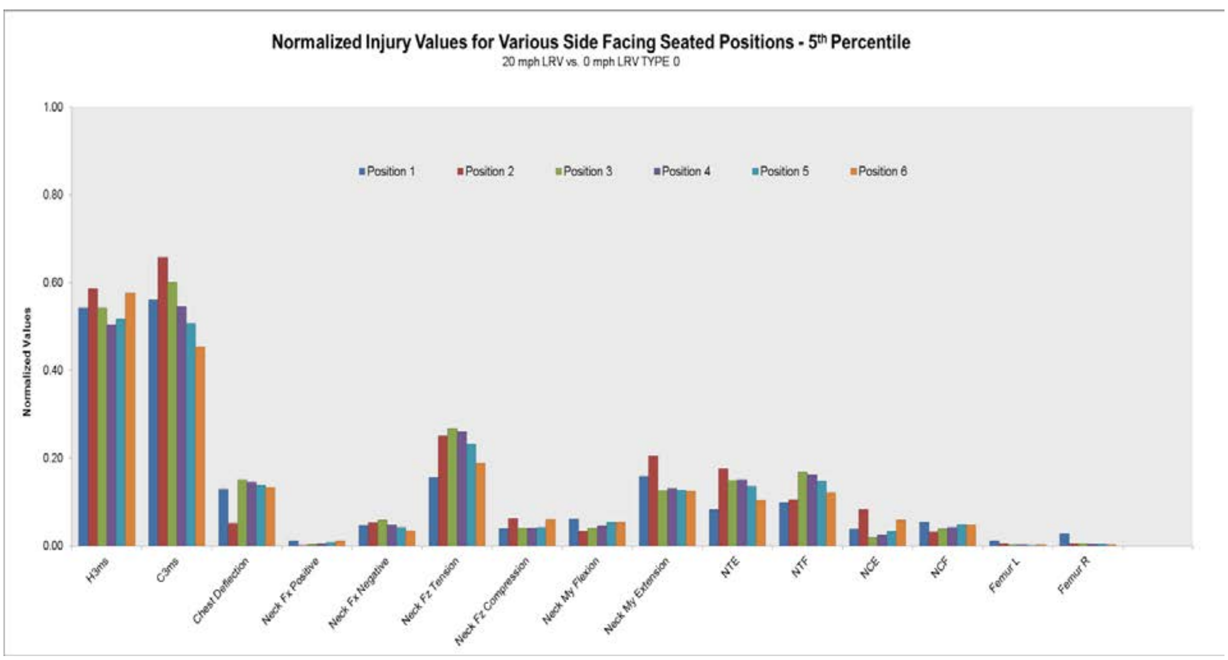
Distance between Occupant and Barrier in Lateral-Facing Seats



The injury values for the entire series of simulations done in this analysis are shown in Figure 5-37 to Figure 5-39. The worst injury values obtained for the 5th and 50th percentile ATDs are when the occupants were seated in the second position (Figure 5-37 and Figure 5-38, respectively). In contrast, the worst injury values were observed when the 95th percentile ATD was seated in position three (Figure 5-39).

Figure 5-37

Normalized Injury Values of 5th Percentile ATD—Exit Velocity Analysis



Video 5-5

LRV Side Facing Seats Configuration Impact Scenario – 5th Percentile

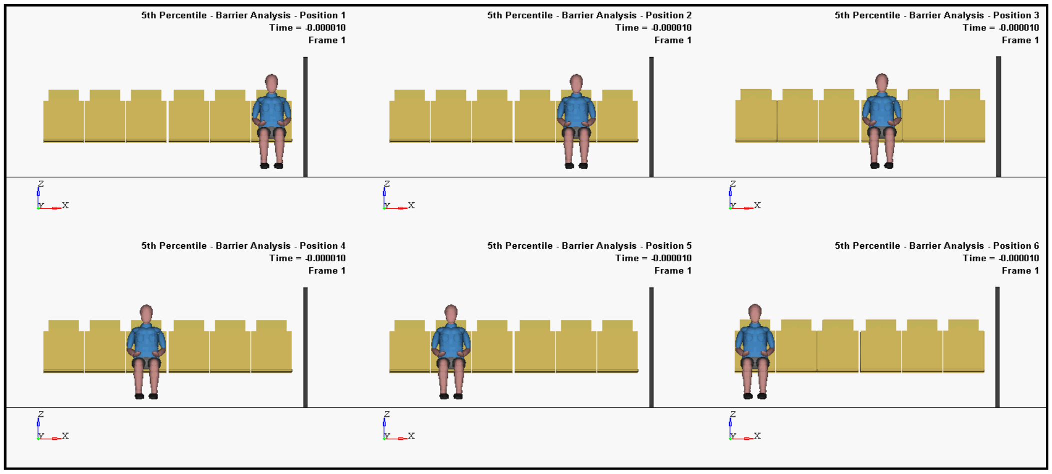
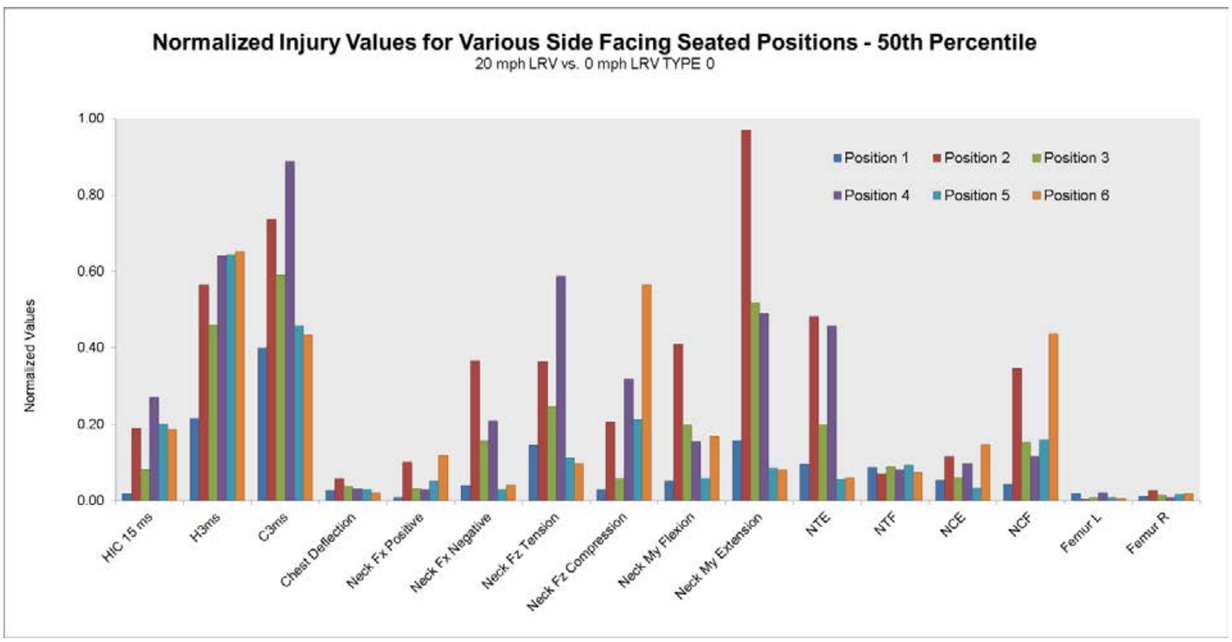


Figure 5-38

Normalized Injury Values of 50th Percentile ATD—Exit Velocity Analysis



Video 5-6

LRV Side Facing Seats Configuration Impact Scenario – 50th Percentile

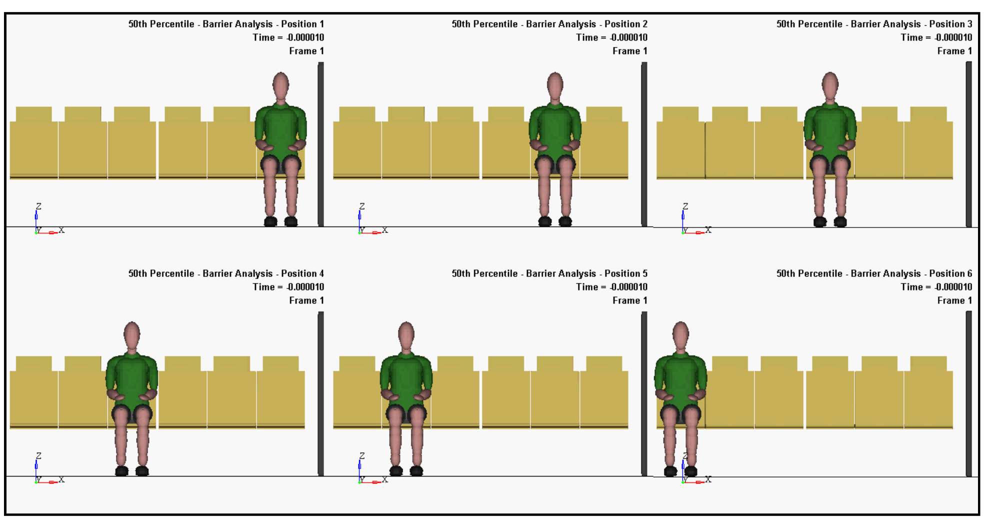
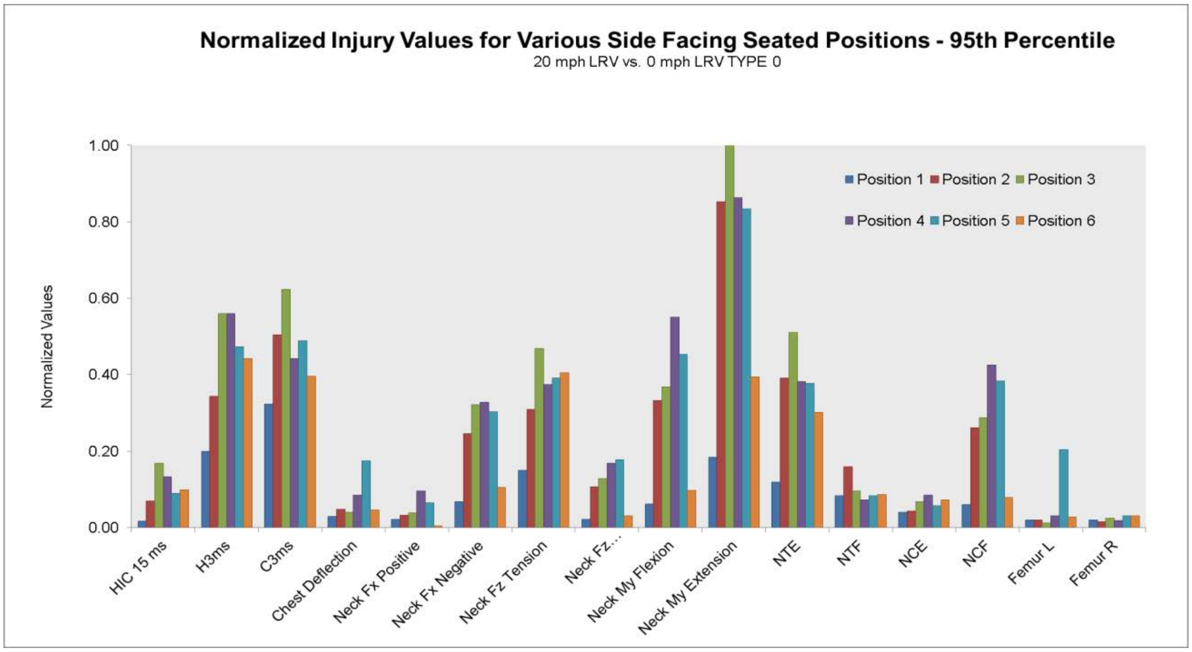


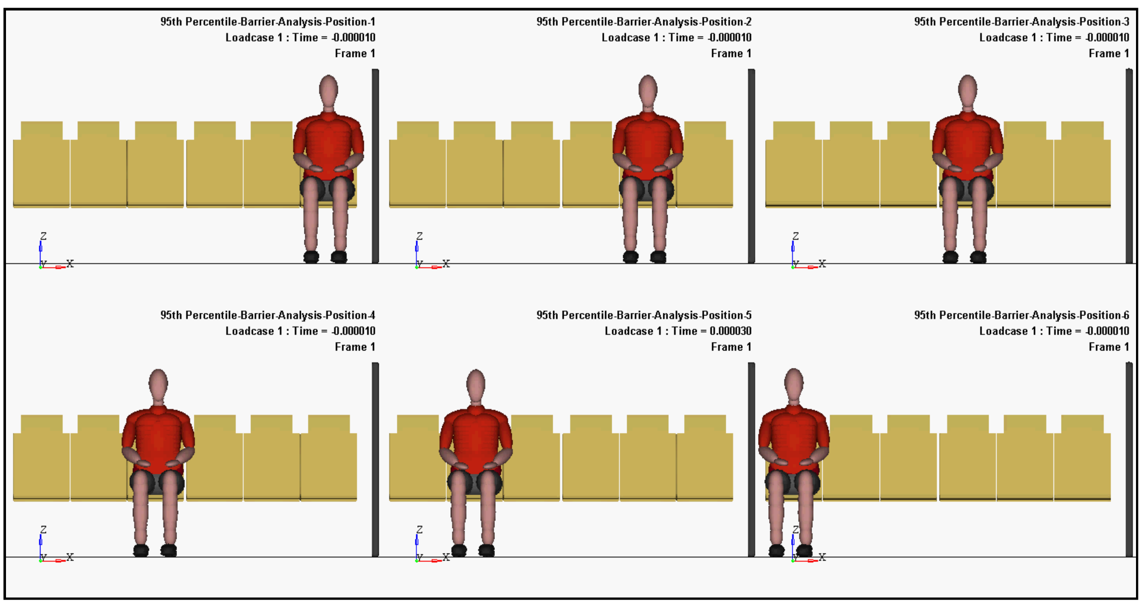
Figure 5-39

Normalized Injury Values of 95th Percentile ATD—Exit Velocity Analysis



Video 5-7

LRV Side Facing Seats Configuration Impact Scenario – 95th Percentile



To summarize, in general, the maximum impact velocity for the ATDs appears when they are placed on the second seat. In this position, the passenger has enough time to build up the maximum velocity and, at the same time, the impact surface is very close. Thus, the worst injuries can be expected in this position. Although the maximum velocity reached by the passengers was the same when sitting in positions three to six, the impact velocity was smaller due to the friction with the seat surfaces.

The second seating position is selected for a more complete analysis in the following section "Current LRV Layout Analysis."

Current LRV Layout Analysis

The most representative configurations available for lateral-facing seats are studied in this section. These layouts can be found in some of the current LRVs. Figure 5-40 shows the layout of an LRV with both lateral-facing seats next to aft-facing seats, as well as lateral-facing seats next to forward-facing seats.

Figure 5-41 shows an LRV layout with a lateral-facing seat next to a barrier or monument (any rigid structure in the passenger's path).

Figure 5-40

Lateral-Facing Seats with Combinations of Forward and Aft-Facing Seats [3]

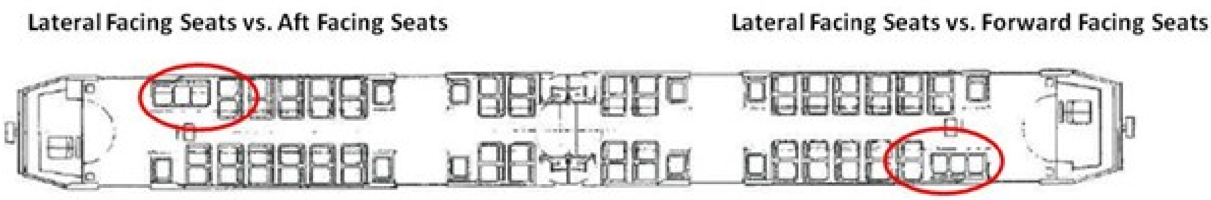
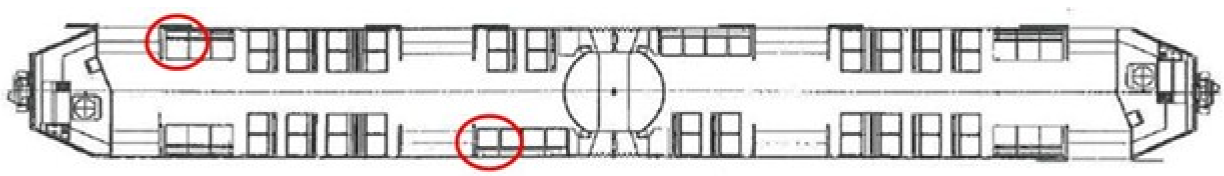


Figure 5-41

Lateral-Facing Seats with Barrier or Monument [3]



In addition, all possible combinations of the 5th, 50th, and 95th percentile ATDs in lateral-facing seats were studied. Table 5-3 shows the test matrix having a total of 27 runs.

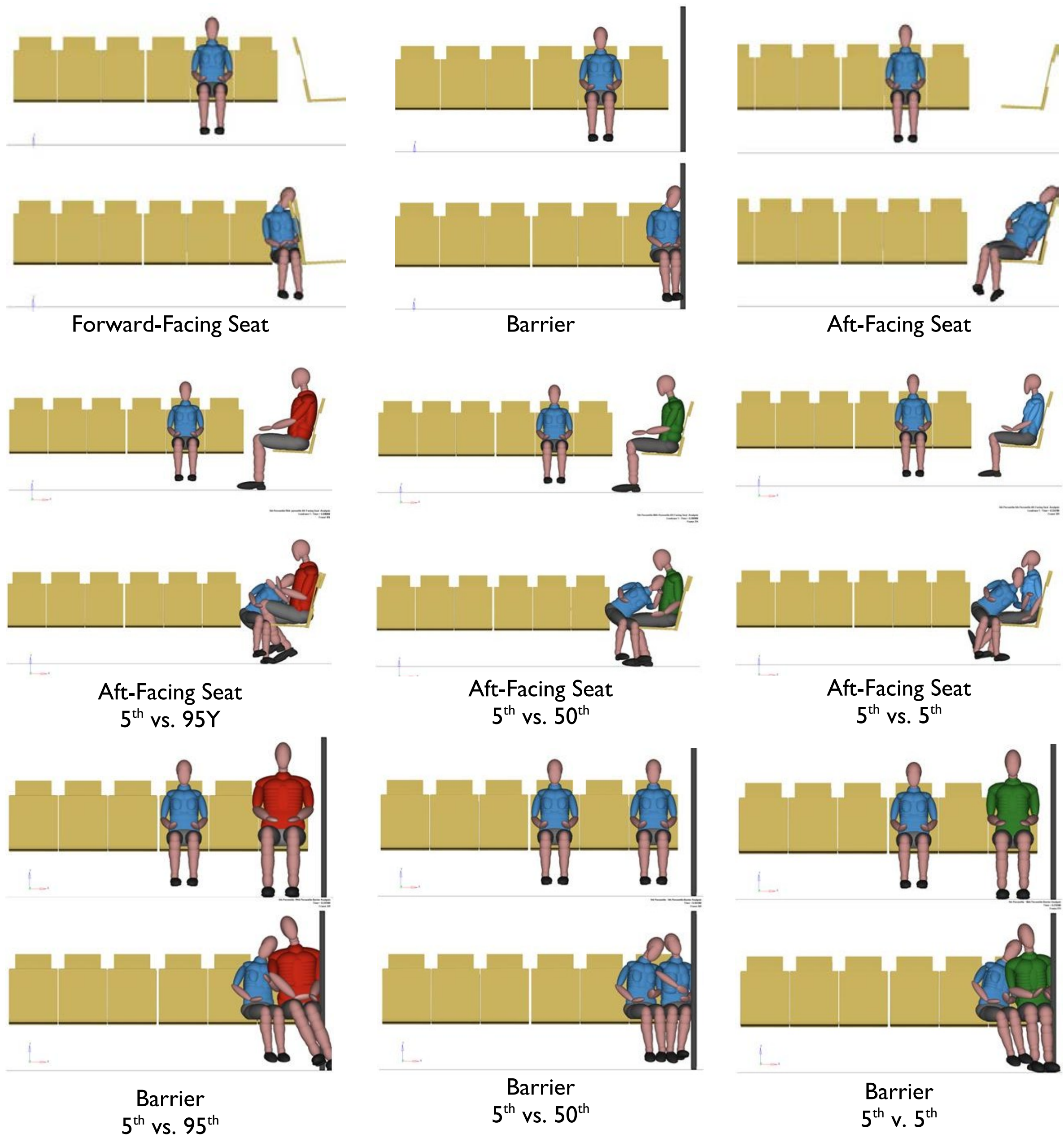
Table 5-3

Test Matrix of Lateral-Facing Seat Analysis (27 runs)

Layout	95th	50th	5th
Barrier	X	X	X
Barrier with 95th Percentile ATD	X	X	X
Barrier with 50th Percentile ATD	X	X	X
Barrier with 5th Percentile ATD	X	X	X
Forward-Facing Seat Empty	X	X	X
Forward Facing Seat with 95th Percentile ATD	X	X	X
Forward-Facing Seat with 50th Percentile ATD	X	X	X
Forward-Facing Seat with 5th Percentile ATD	X	X	X
Rear-Facing Seat	X	X	X

Figure 5-42

Kinematics of 5th Percentile ATD in Lateral-Facing Seats - All Possible Combinations



Red = 95th percentile, green = 50th percentile, and blue = 5th percentile.

Figure 5-43

Normalized Injury Values of 5th Percentile ATD in Lateral-Facing Seats

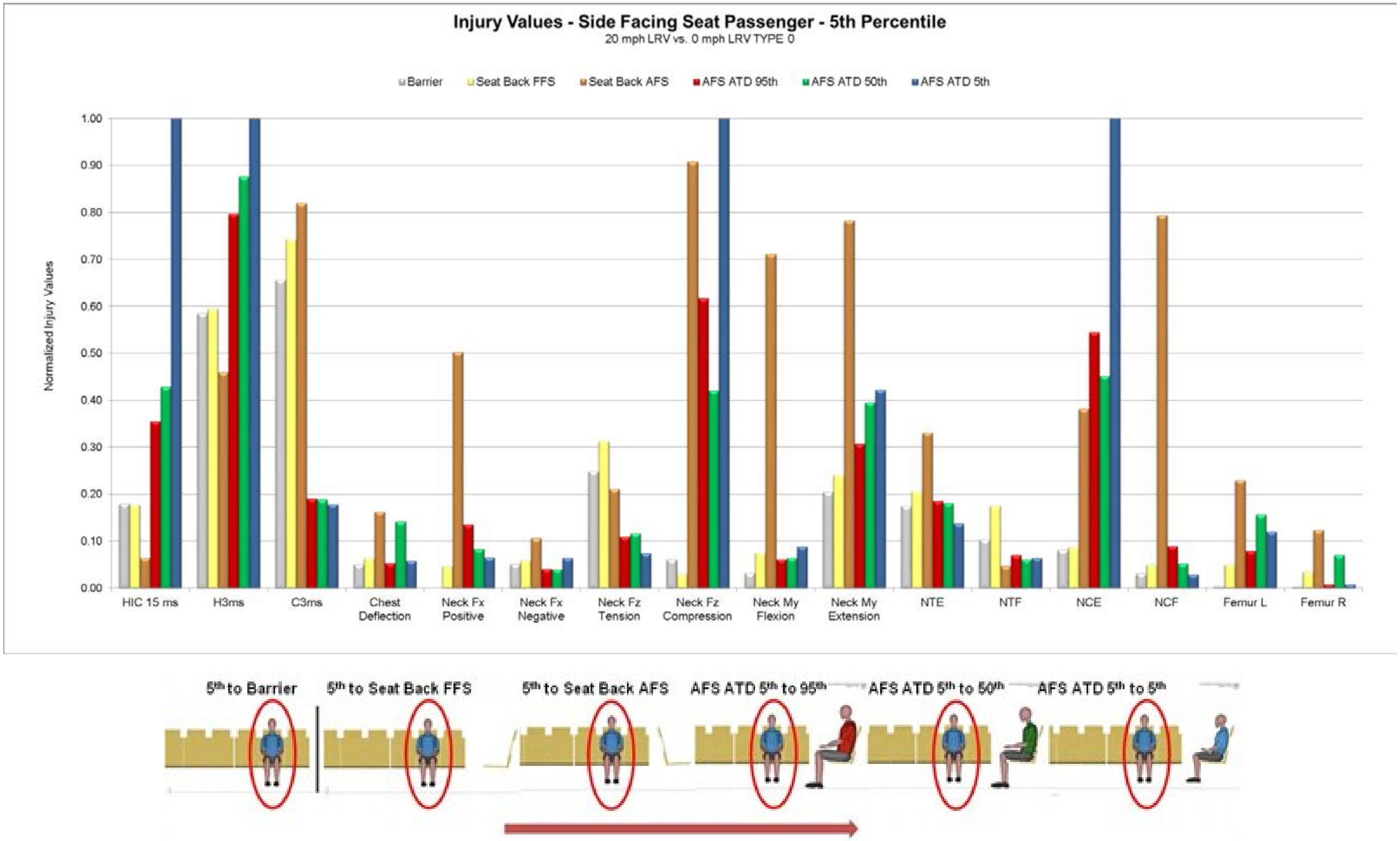
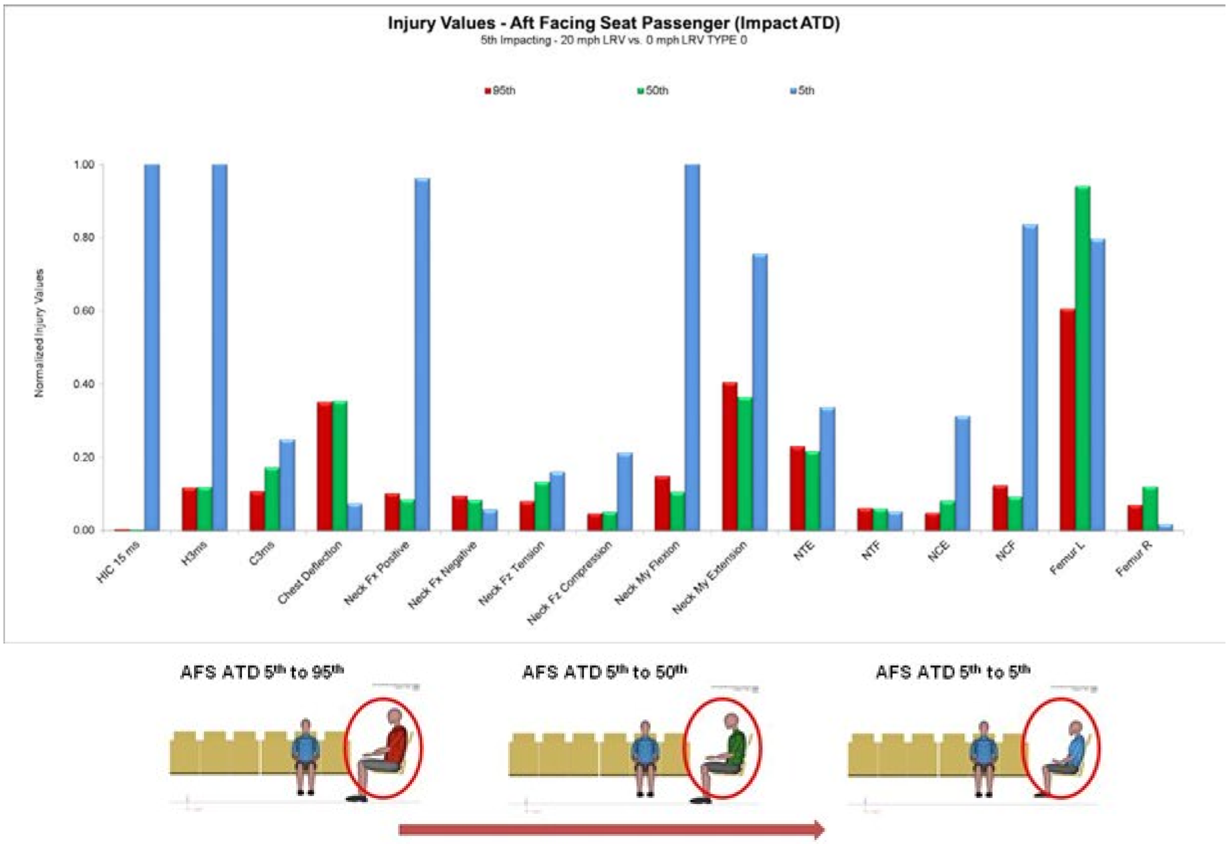


Figure 5-44

Normalized Injury Values of Impact of 5th Percentile ATD in Lateral-Facing Seat with Impact ATD



Video 5-8

LRV Lateral Facing Seats Configuration Impact Scenario – 5th Percentile

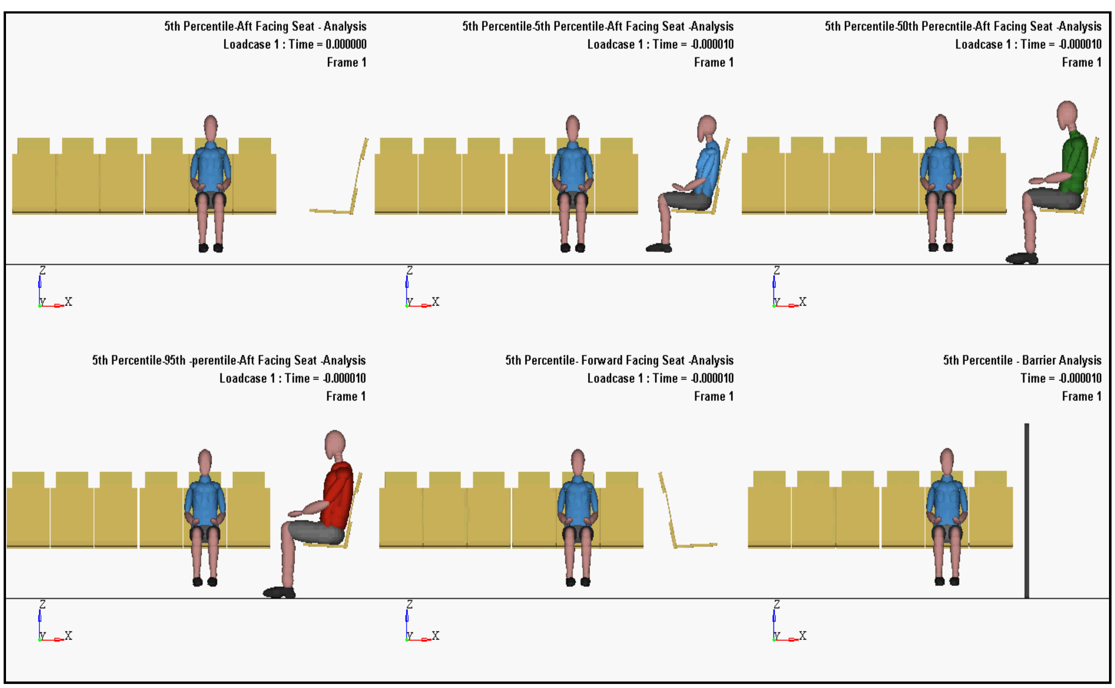
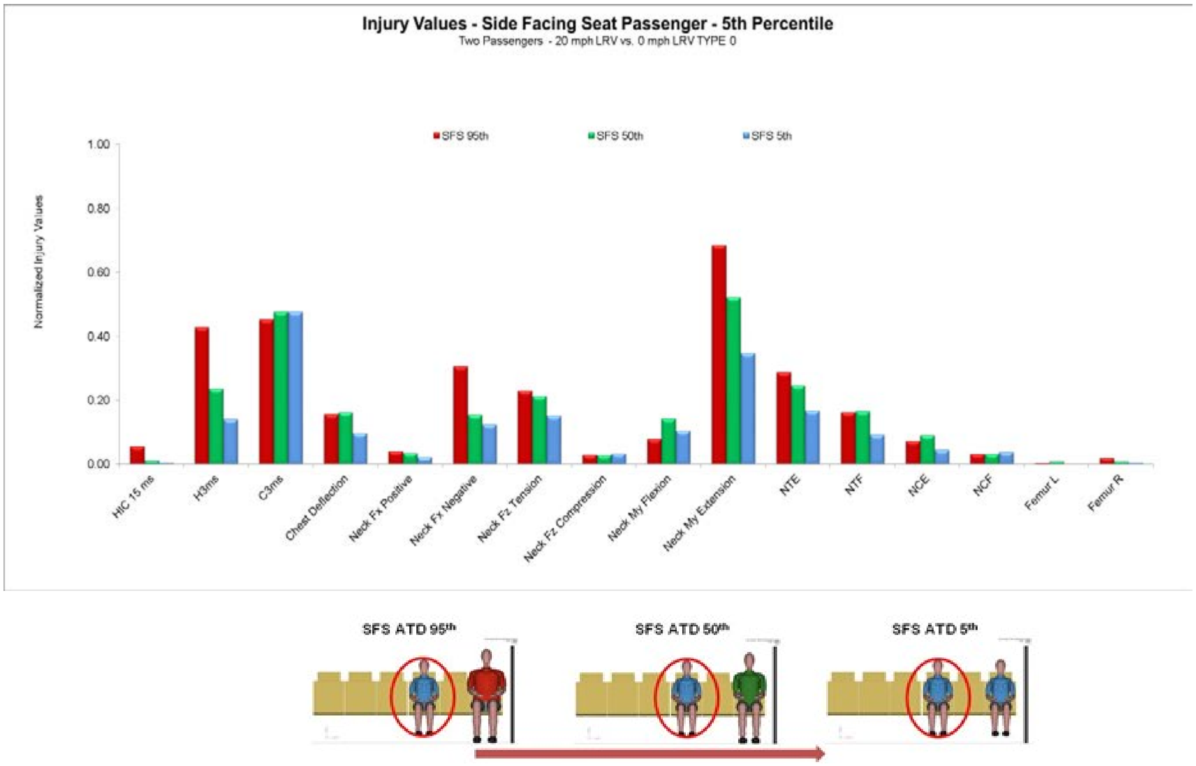


Figure 5-45

Normalized Injury Values of 5th Percentile ATD in Lateral-Facing Seats with Barrier



Video 5-9

LRV Lateral Facing Seats with Barrier Configuration Impact Scenario – 5th

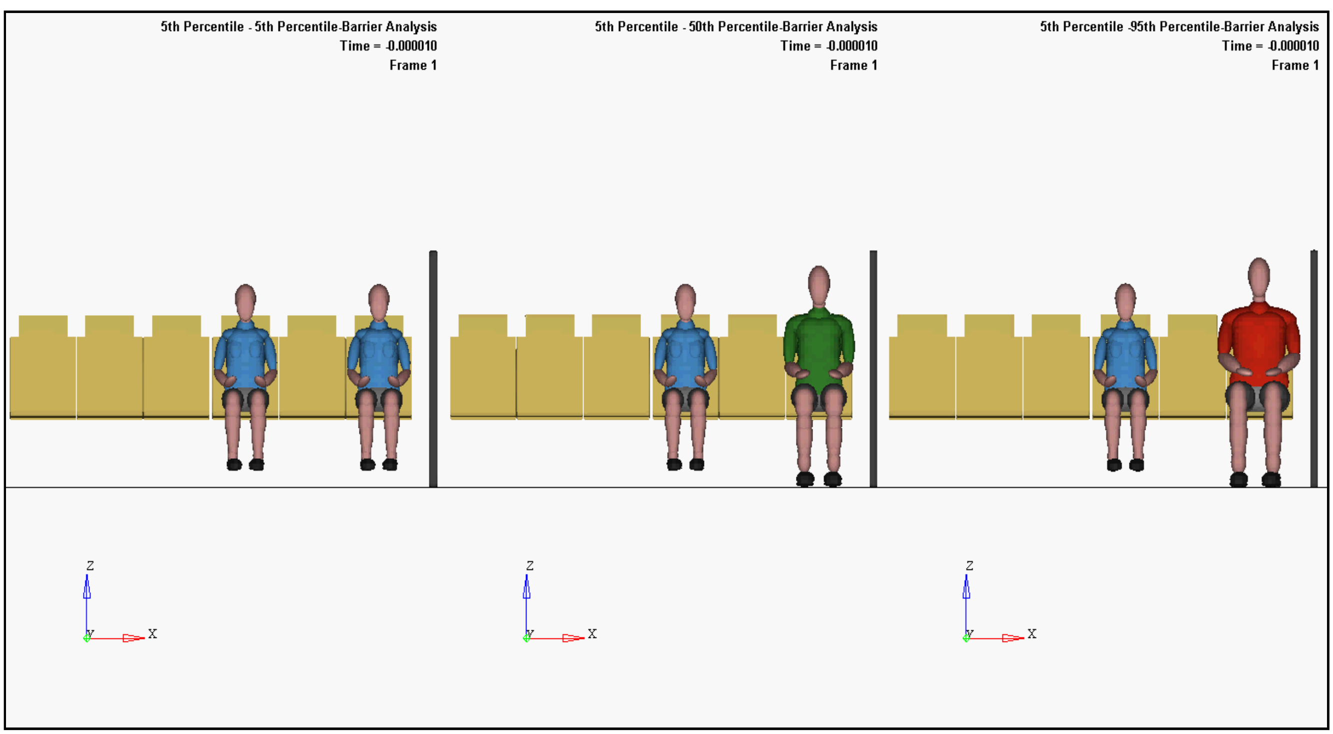
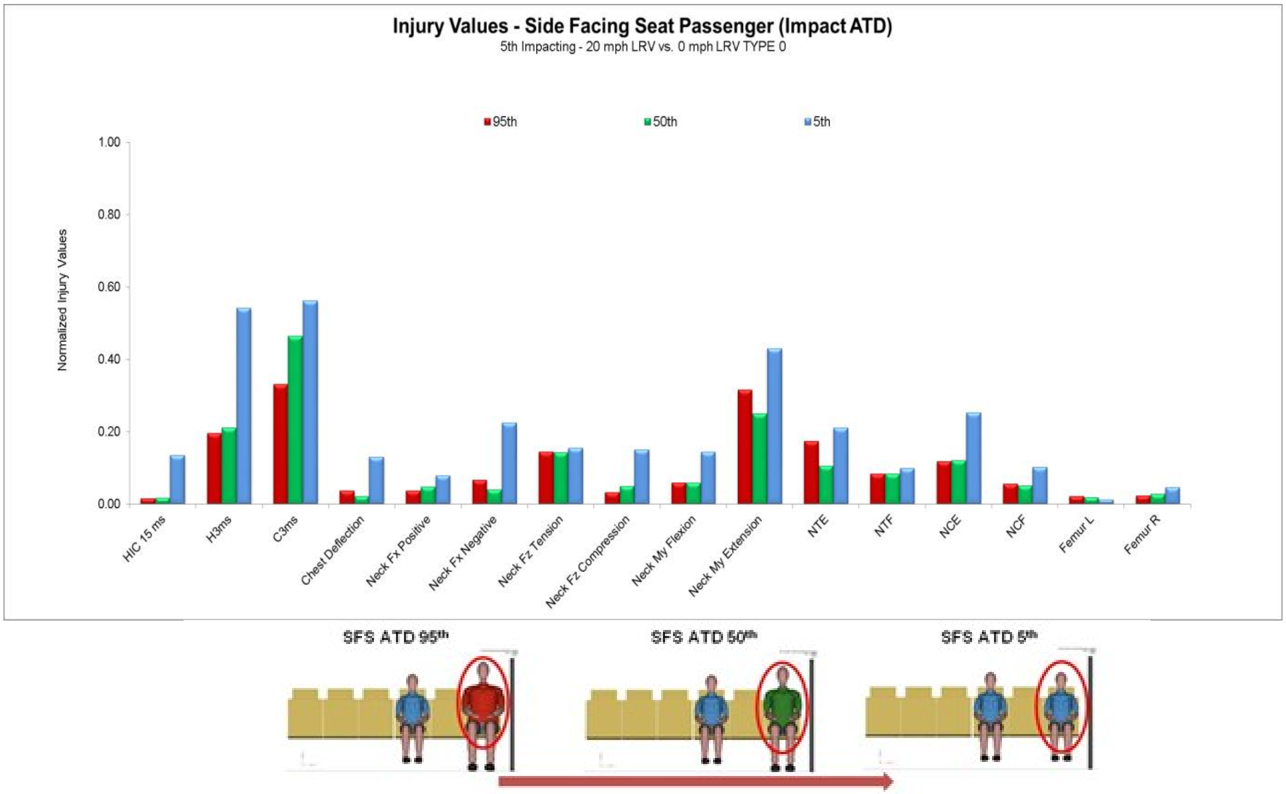


Figure 5-46

Normalized Injury Values of Impact of 5th Percentile ATD in Lateral-Facing Seat with Barrier with Impact ATDs



Red = 95th percentile, green = 50th percentile, and blue = 5th percentile.

Figure 5-47

Kinematics of 50th Percentile ATD in Lateral-Facing Seats All Possible Combinations

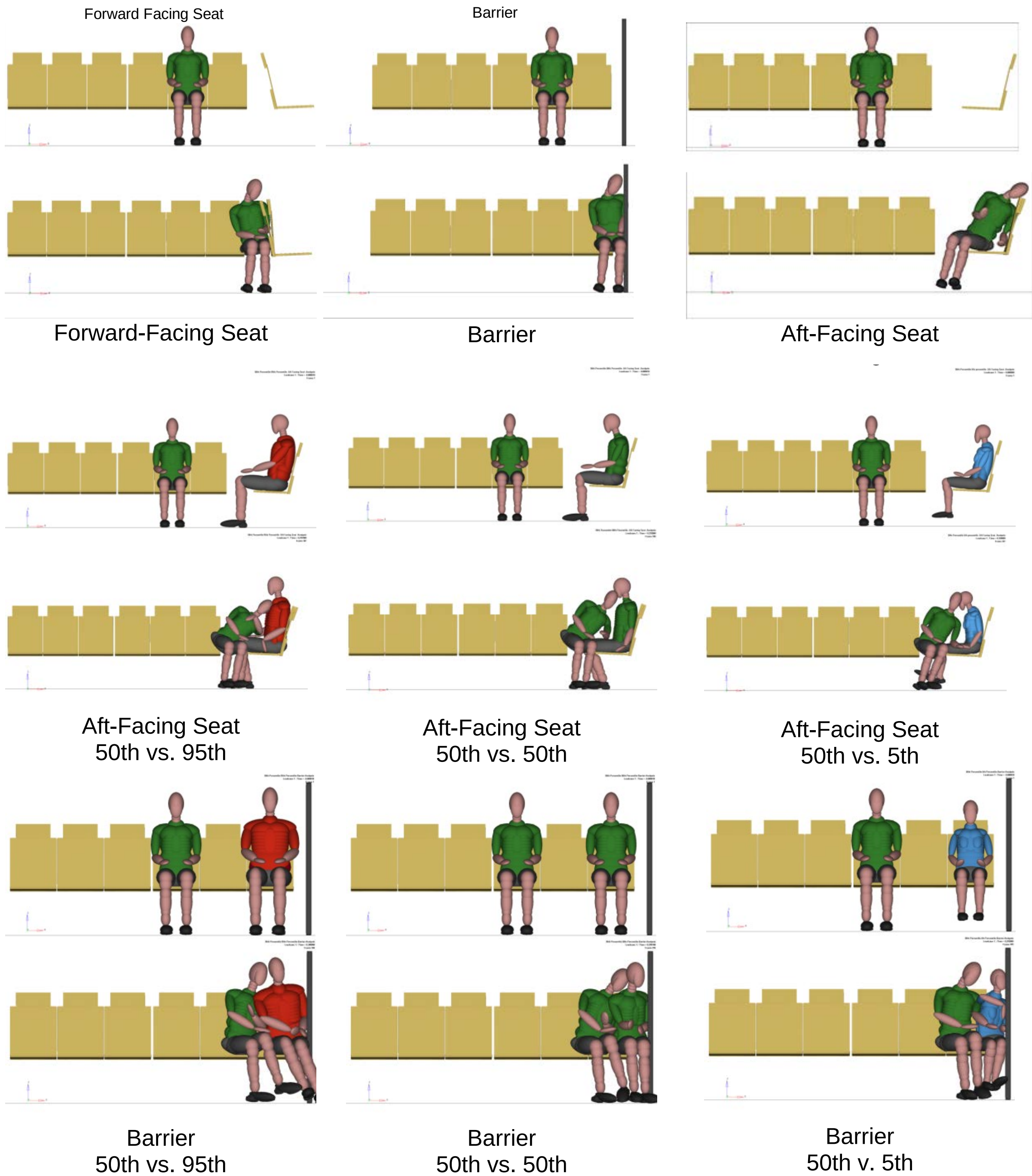


Figure 5-48

Normalized Injury Values of 50th Percentile ATD in Lateral-Facing Seats

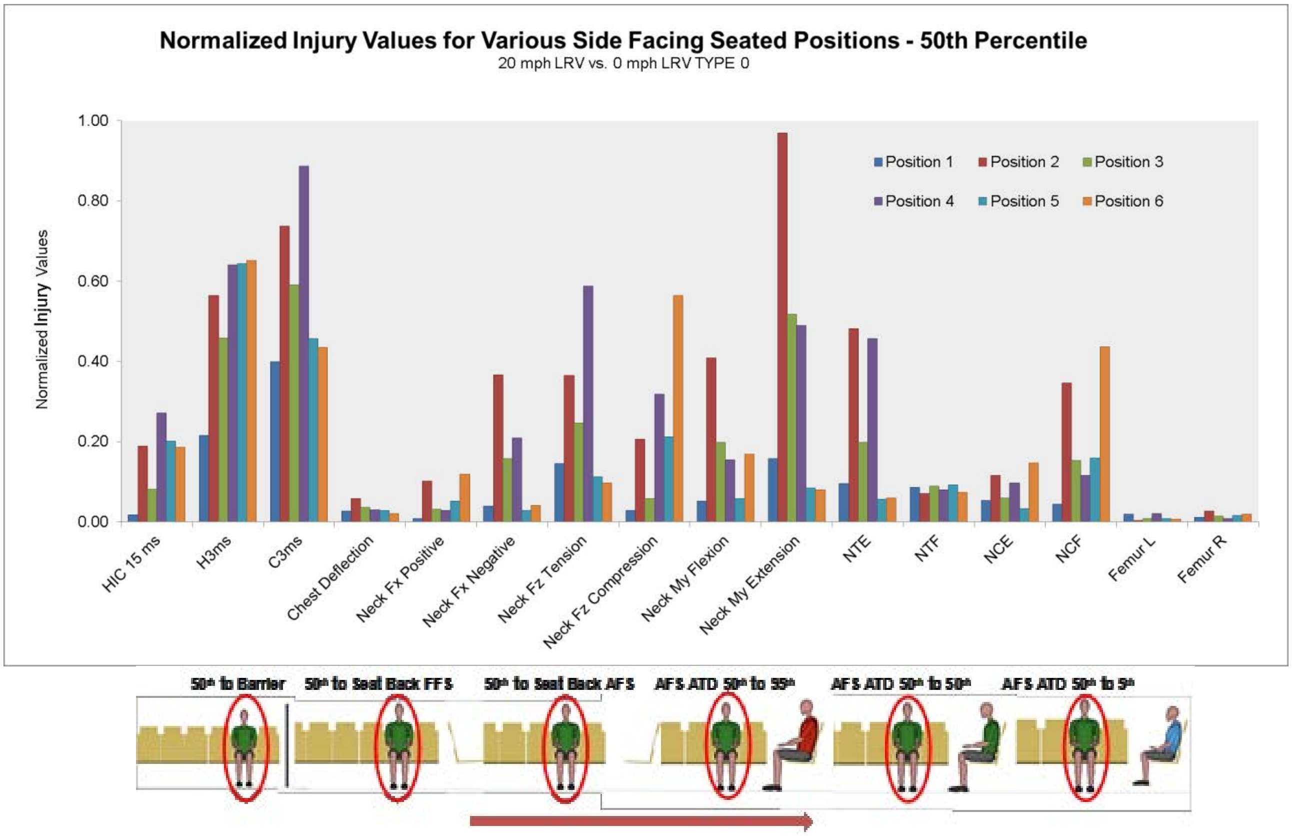
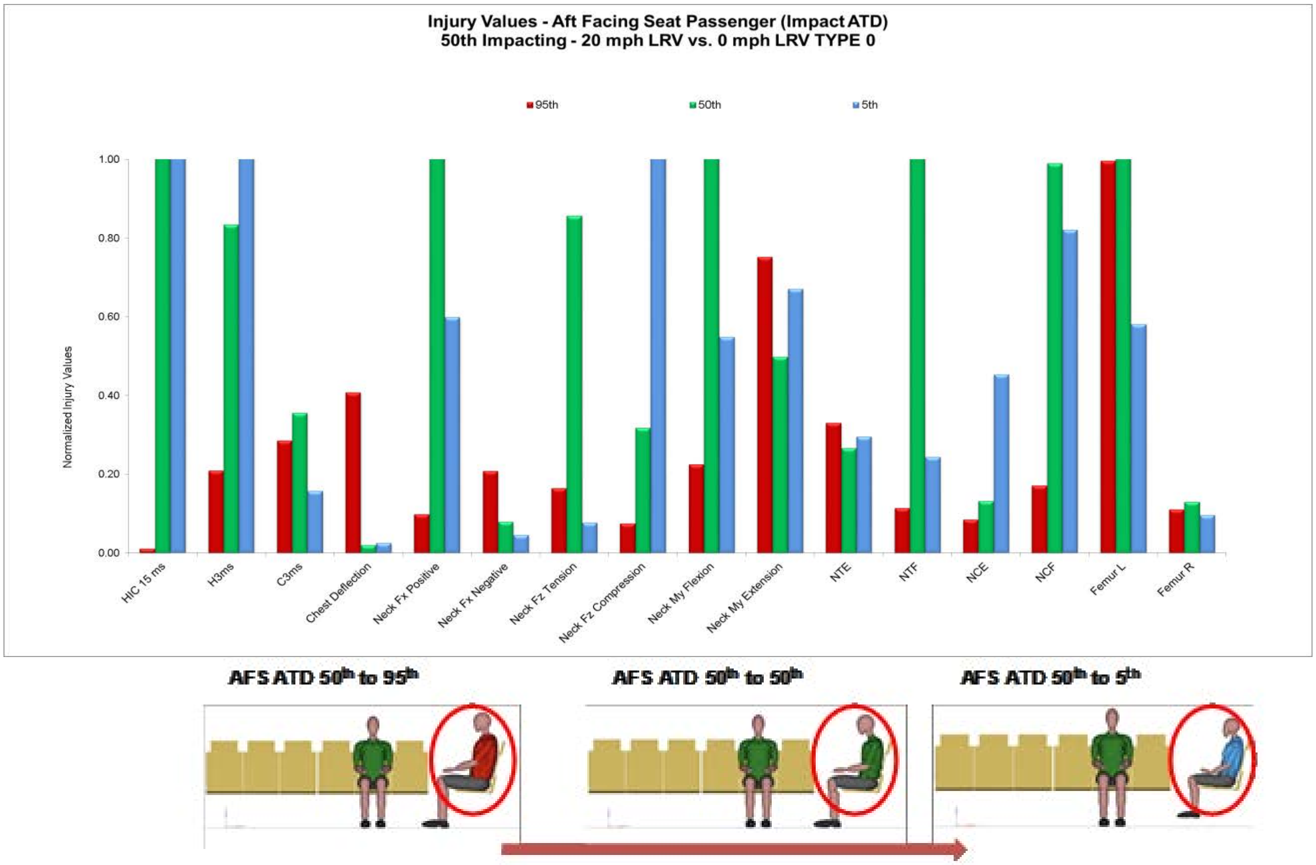


Figure 5-49

Normalized Injury Values of Impact of 50th Percentile ATD in Lateral-Facing Seat with Impact ATDs



Video 5-10

LRV Lateral Facing Seats Configuration Impact Scenario – 50th Percentile

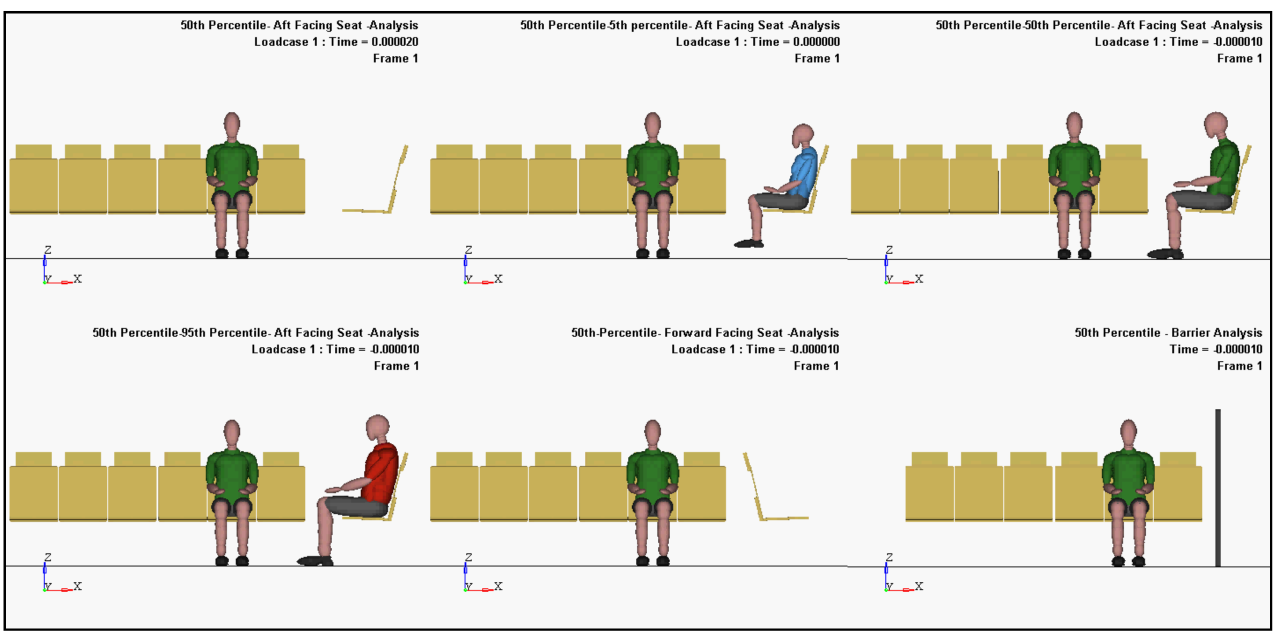
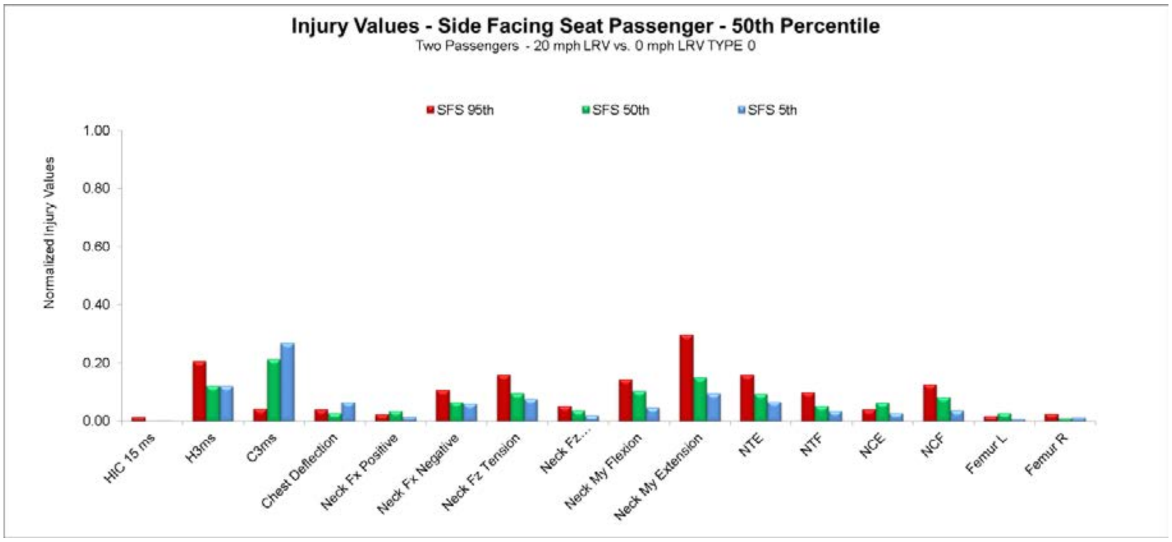


Figure 5-50

Normalized Injury Values of 50th Percentile ATD in Lateral-Facing Seats with Barrier



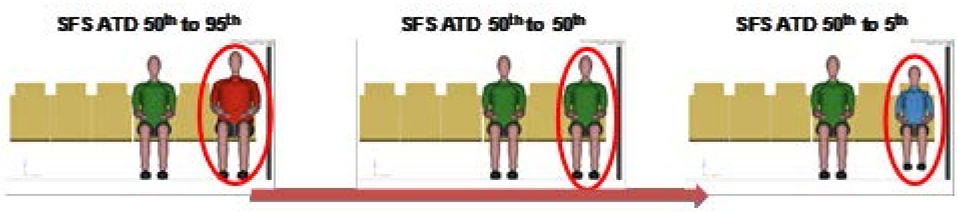
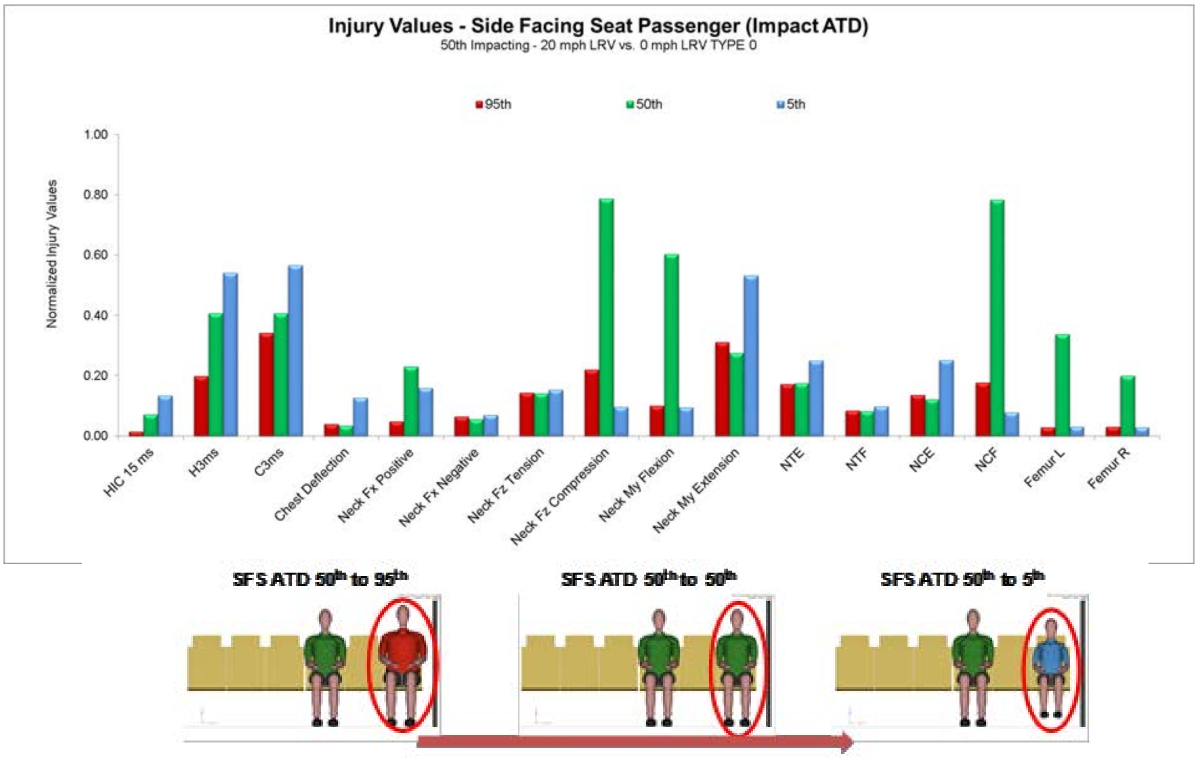


Figure 5-51

Normalized Injury Values of Impact of 50th Percentile ATD in Lateral -Facing Seats with Barrier with Impact ATDs



Video 5-11

Lateral Facing Seats with Barrier Configuration Impact Scenario – 50th Percentile

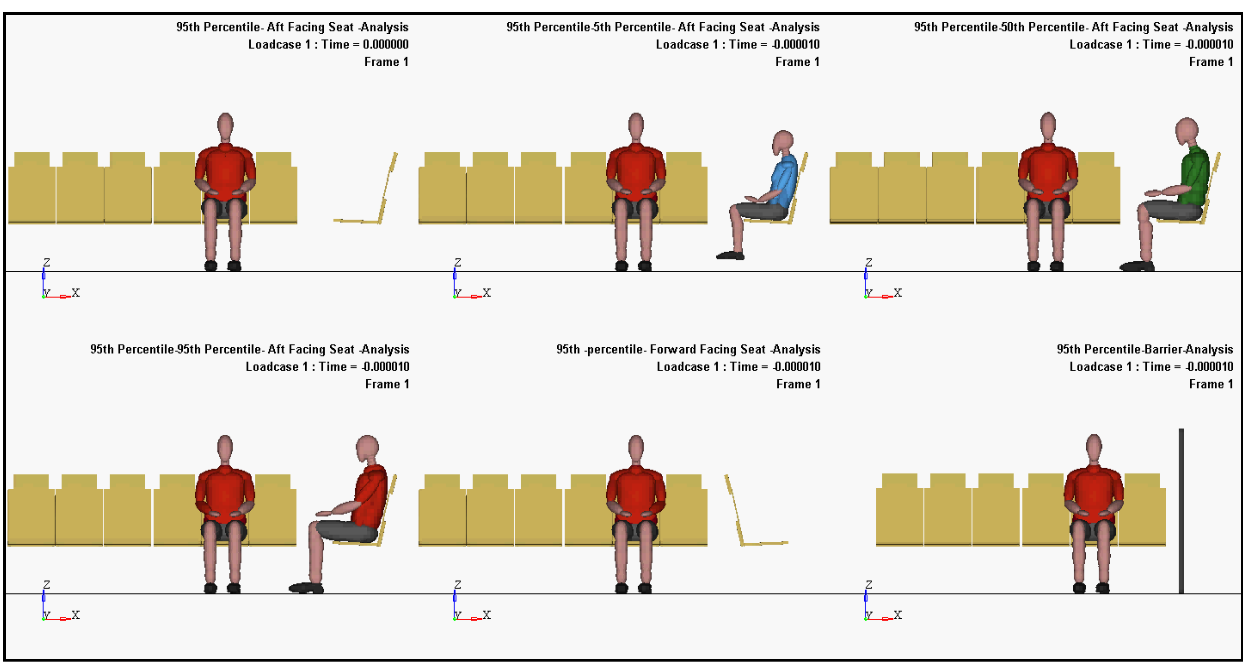
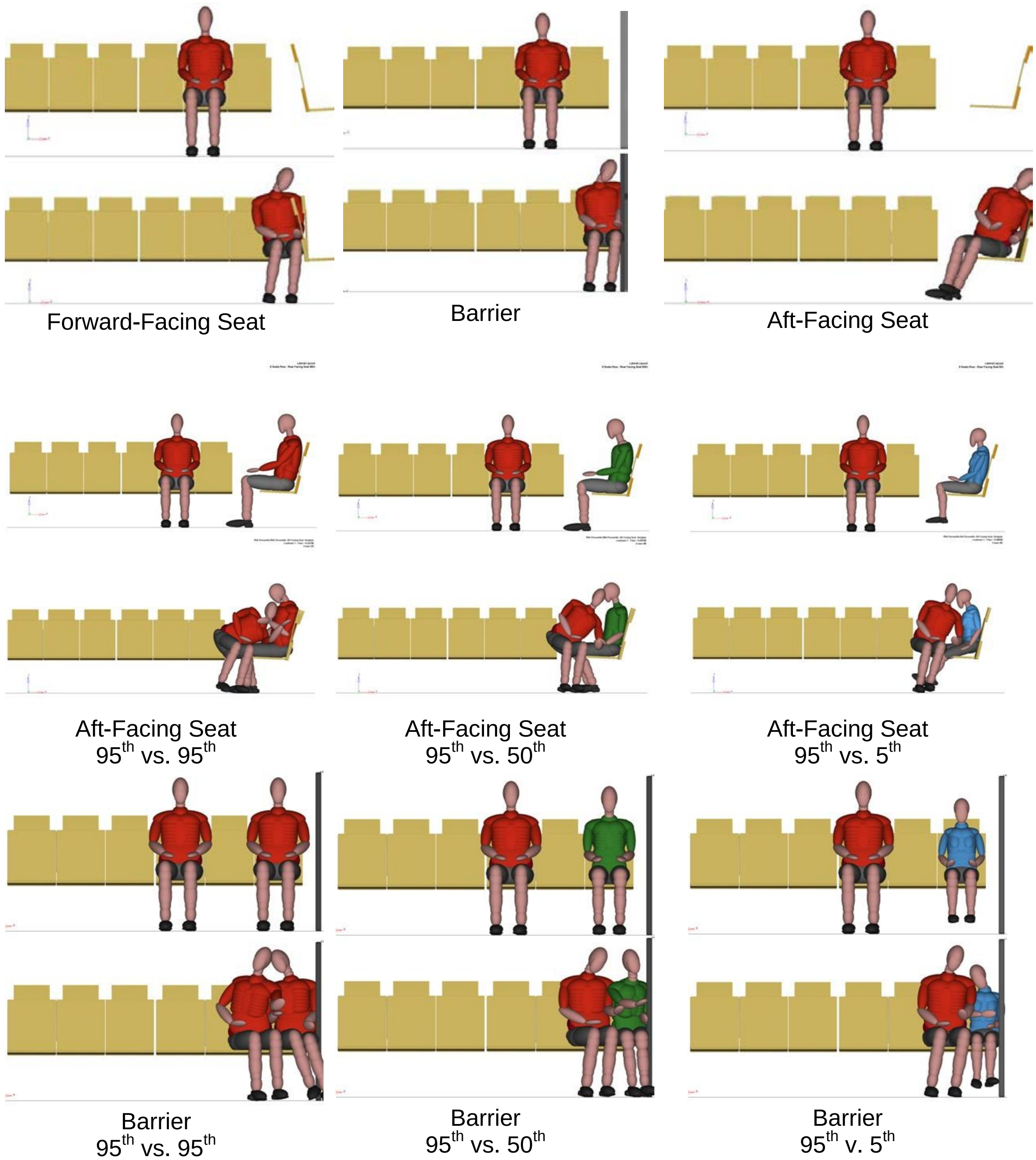


Figure 5-52

Kinematics of 95th Percentile ATD in Lateral-Facing Seats—All Possible Combinations



Red = 95th percentile, green = 50th percentile, and blue = 5th percentile.

Figure 5-53

Normalized Injury Values of 95th Percentile ATD in Lateral-Facing Seats

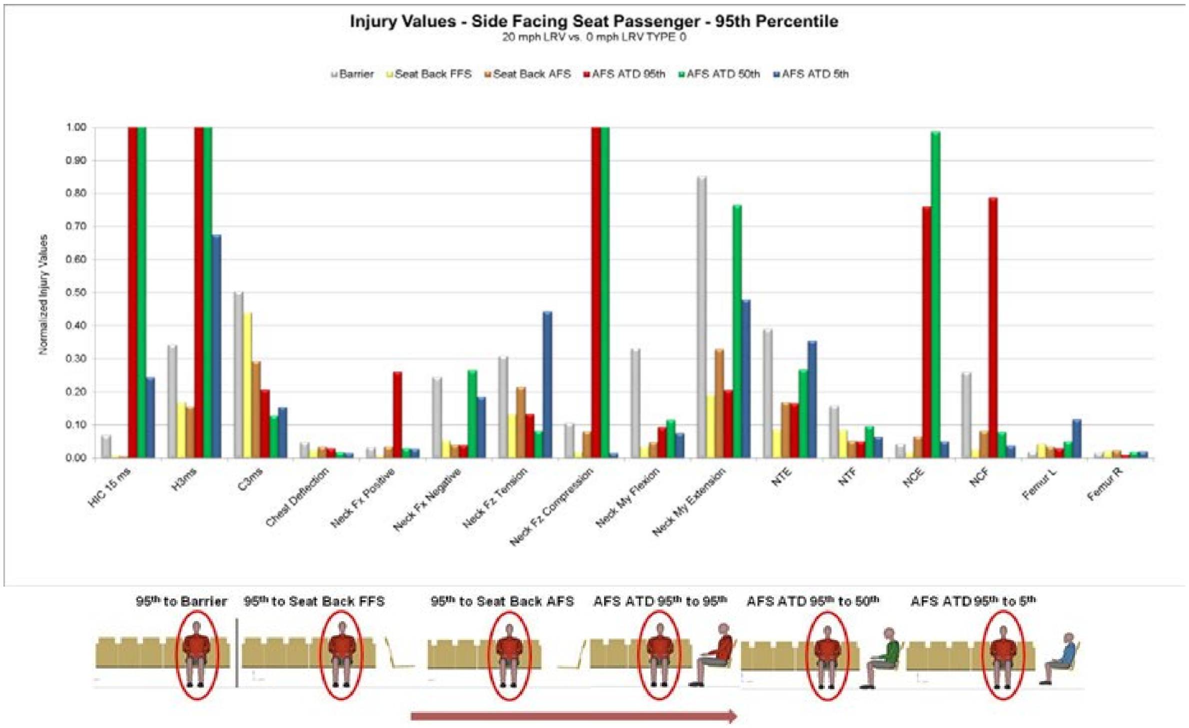
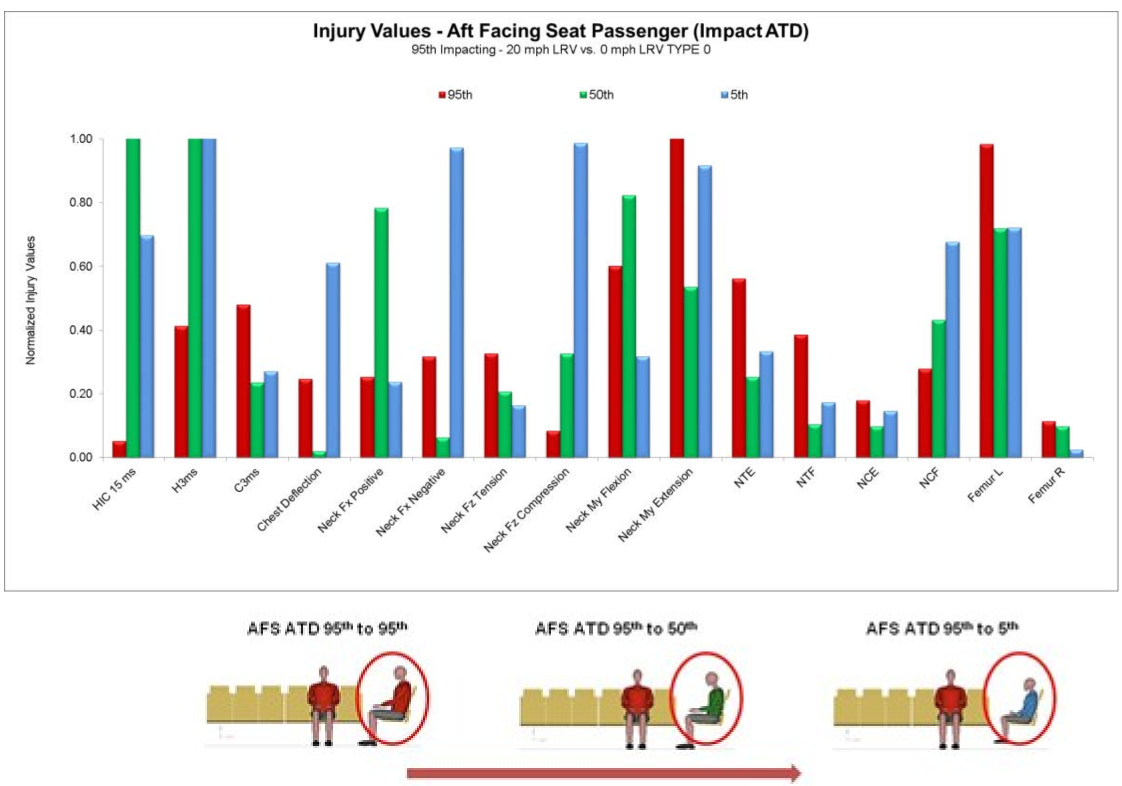


Figure 5-54

Normalized Injury Values of Impact of 95th Percentile ATD in Lateral-Facing Seat with Impact ATDs



Video 5-12

LRV Lateral Facing Seats Configuration Impact Scenario – 95th Percentile

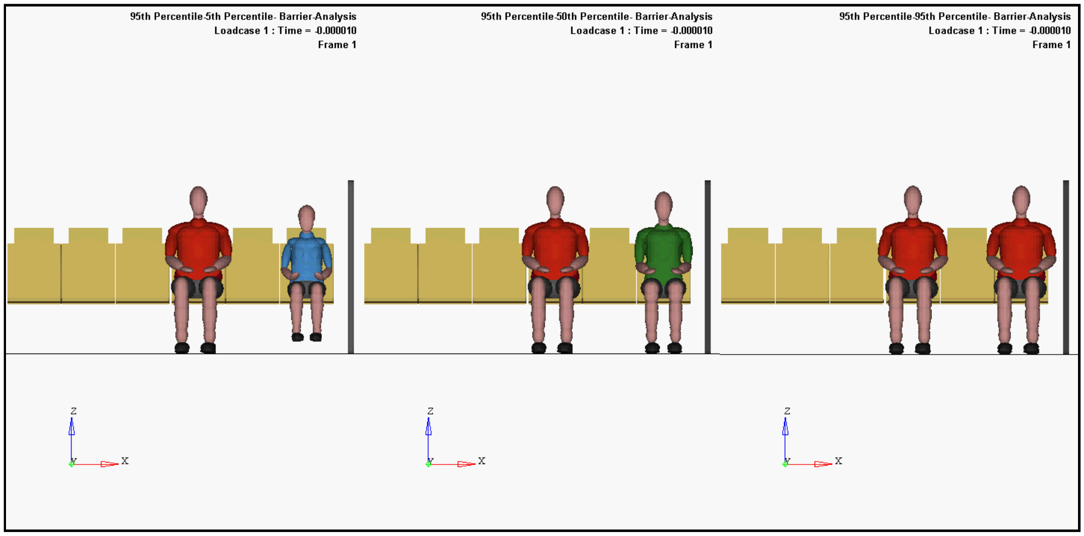


Figure 5-55

Normalized Injury Values of 95th Percentile ATD in Lateral-Facing Seats with Barrier

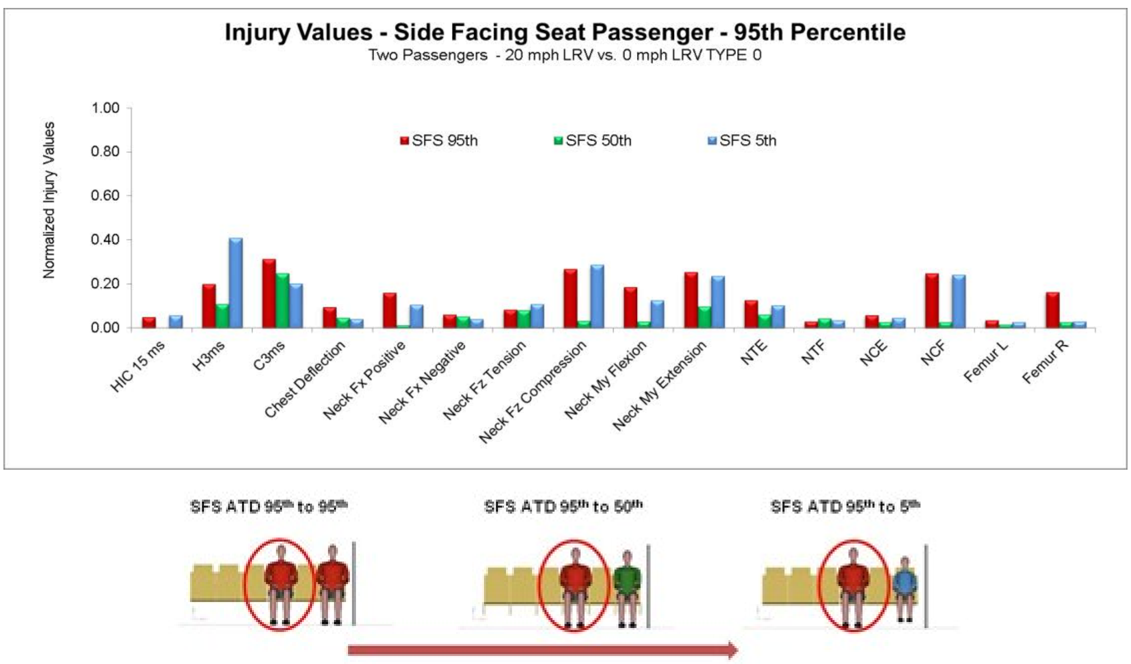
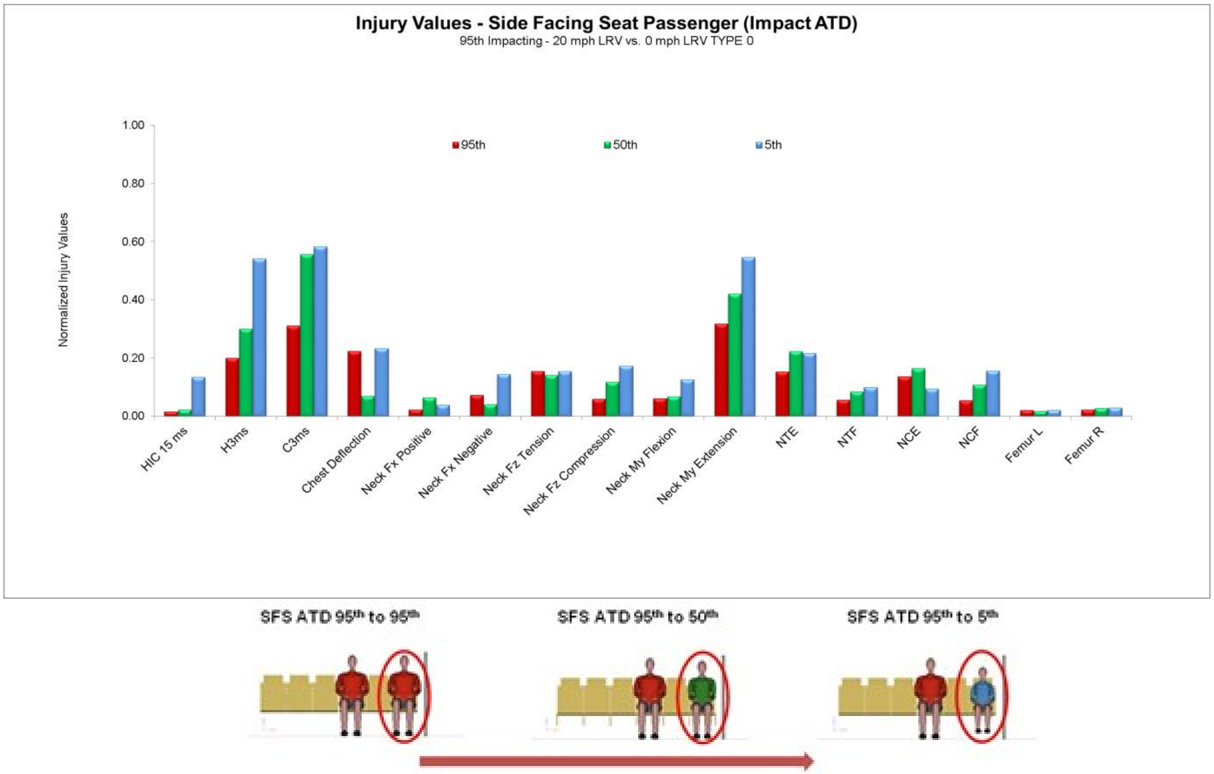


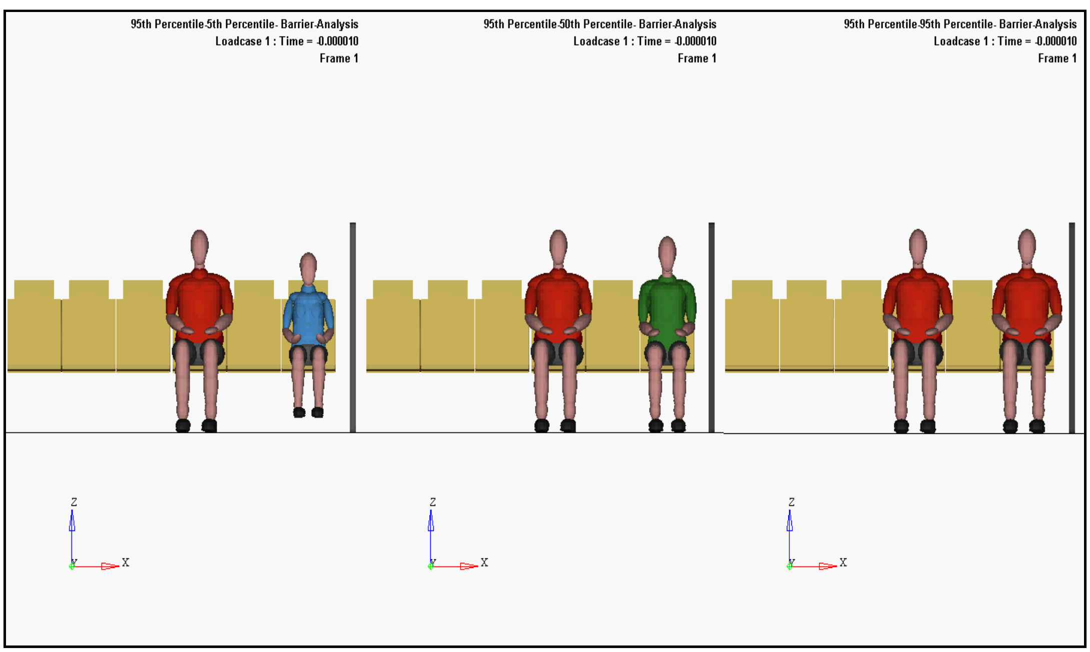
Figure 5-56

Normalized Injury Values of Impact of 95th Percentile ATD in Lateral-Facing Seat with Barrier with Impact ATDs



Video 5-13

LRV Lateral Facing Seats with Barrier Configuration Impact Scenario – 95th Percentile



After analyzing all 27 configurations, it is possible to conclude the following:

- The worst case configuration is when occupant-to-occupant contact occurs; specifically when impact occurs between passengers of the same size (contact between heads is most probable).

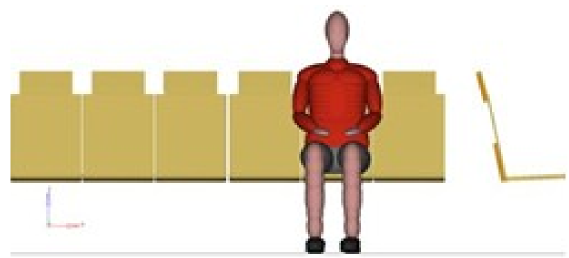
Although injuries from this type of contact are generally on the neck and head regions, some injuries can also occur to the lower extremities, in particular to the pelvis region.

Conditions where there is an empty aft-facing seat result in injuries that comply with current FMVSS 208 limits. However, it is impossible to guarantee an empty aft-facing seat. If another passenger is seated in the aft-facing seat, then the injury values are above acceptable limits.

If only one passenger is seated in the lateral-facing seat, the best configuration for minimizing injury values is a row of lateral-facing seats followed by a row of forward facing seats, as shown in Figure 5-58.

Figure 5-57

Safest Lateral-Facing Seat Configuration (Only One Seated Passenger)



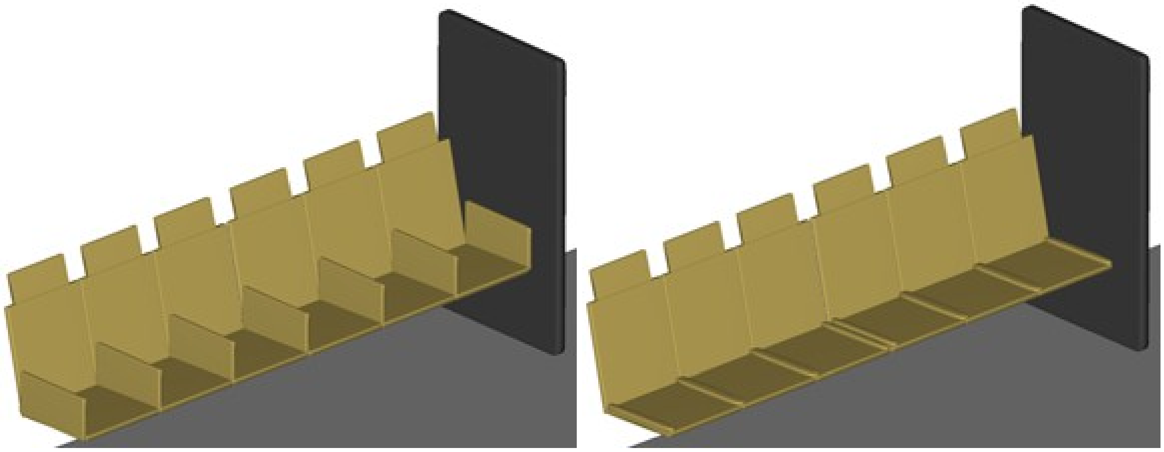
- The barrier configuration gives also good results. Nevertheless, a separate study should be conducted to improve the injuries of the neck region for the 50th and 95th percentile ATDs. New padding material on the contact region could be used.
- Further studies should be conducted to minimize injuries due to contact between passengers.
  - For lateral-facing seats, an armrest could be designed. The results of an initial analysis can be found in Section 5.
  - If it is not possible to avoid lateral-facing seats with aft-facing seats, a divider between these seats should be designed.
- For configurations with forward-facing seats, some studies could be done to minimize injuries.
  - Padding materials could be added to the seat back.
  - The seat back geometry (height, angle, rotational stiffness, etc.) could be redesigned.

Lateral-Facing-Seats Screening Analysis Involving Dividers

This section presents the results obtained for a simple screening analysis, using two simple models of dividers for the lateral-facing seats (Figure 5-58).

Figure 5-58

Lateral-Facing Seats with High and Low Dividers



The first configuration represents a lateral-facing seat with a tall divider between each seat. The height of these dividers is 200 mm. The second configuration represents a lateral-facing seat with short dividers. Actually, these dividers can be analyzed as curvatures of the seat pan. Figure 5-59 shows the seat pan of a lateral-facing seat. This seat pan has some curvature to prevent lateral movement of the occupant during acceleration and deceleration of the LRV. This curvature is simulated in the multibody model by two small ellipsoids at either lateral edge of the seat pan. The results for these models are shown on in Figure 5-60 and Figure 5-61). The results for the same models without any type of dividers are shown in Figure 5-62.

Figure 5-59

Lateral-Facing Seat Pan Curvatur

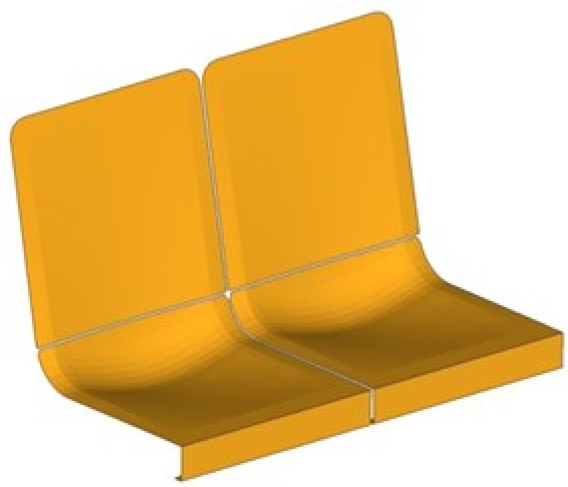


Figure 5-60

Normalized Injury Values of Lateral-Facing Seats with High Divider

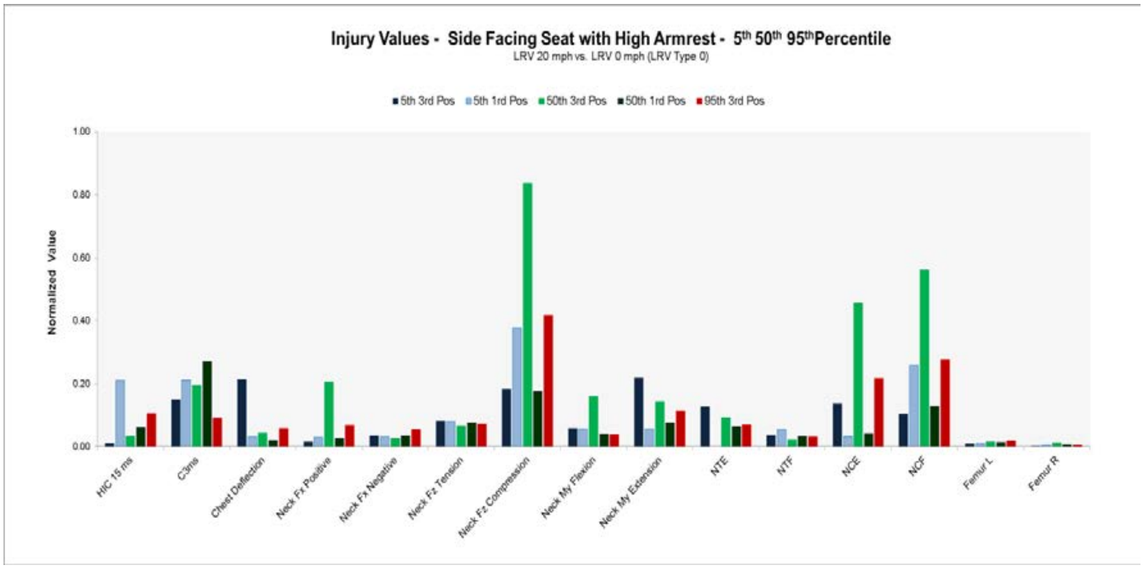


Figure 5-61

Normalized Injury Values of Lateral-Facing Seats with Low Divider (Seat Pan Curvature)

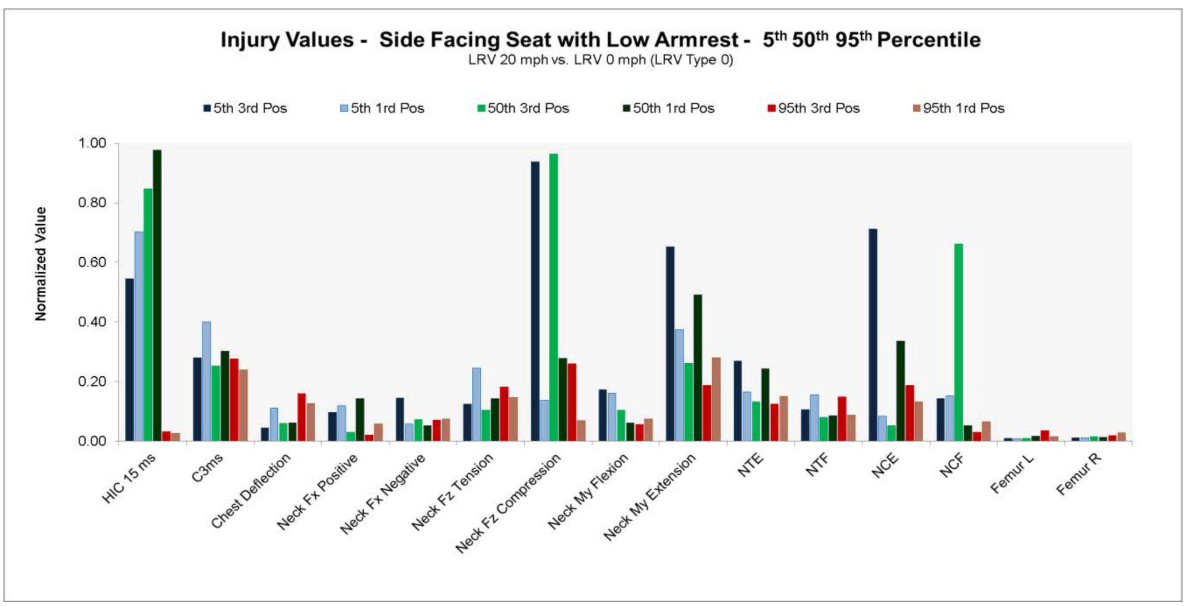
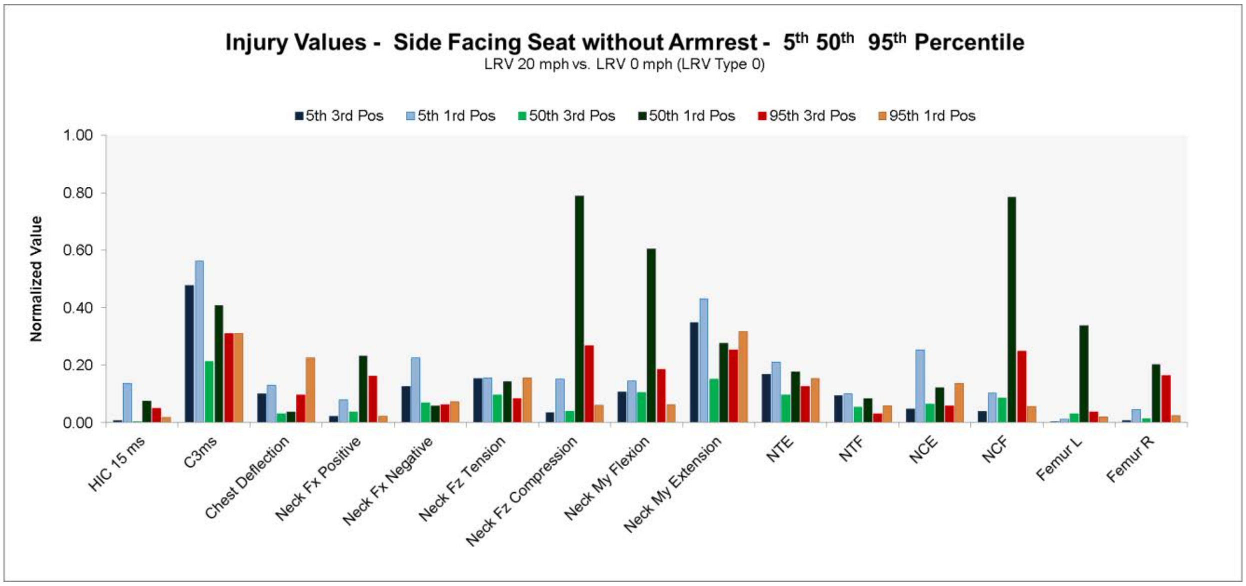


Figure 5-62

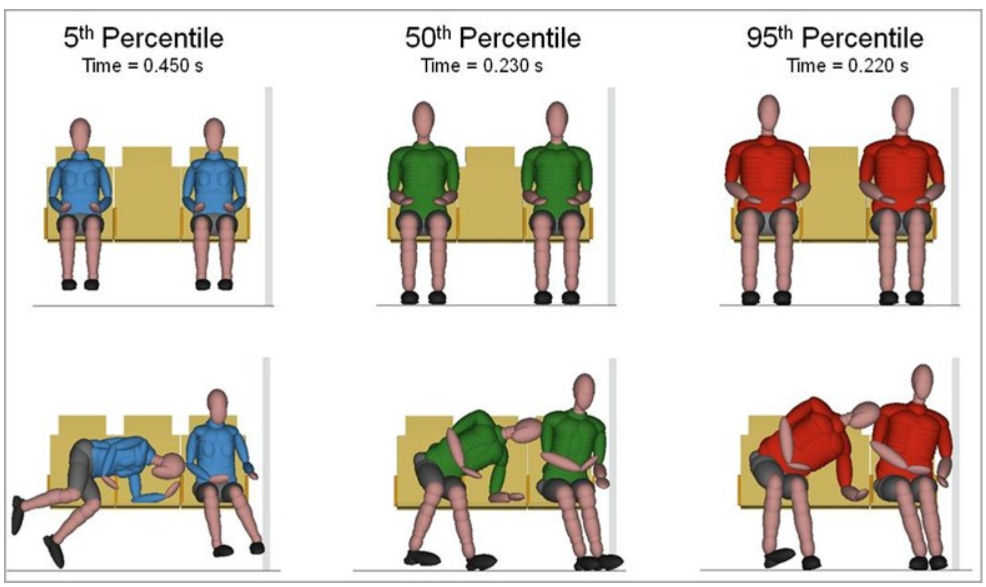
Normalized Injury Values of Lateral-Facing Seats with No Divider (Original Results)



The kinematics of ATDs in lateral-facing seats with high- and low-dividers are shown in Figure 5-63 and Figure 5-64, respectively.

Figure 5-63

Kinematics of ATDs in Lateral-Facing Seats with High Dividers



Video 5-14

LRV Lateral Facing Seats with High Dividers Configuration Impact Scenario

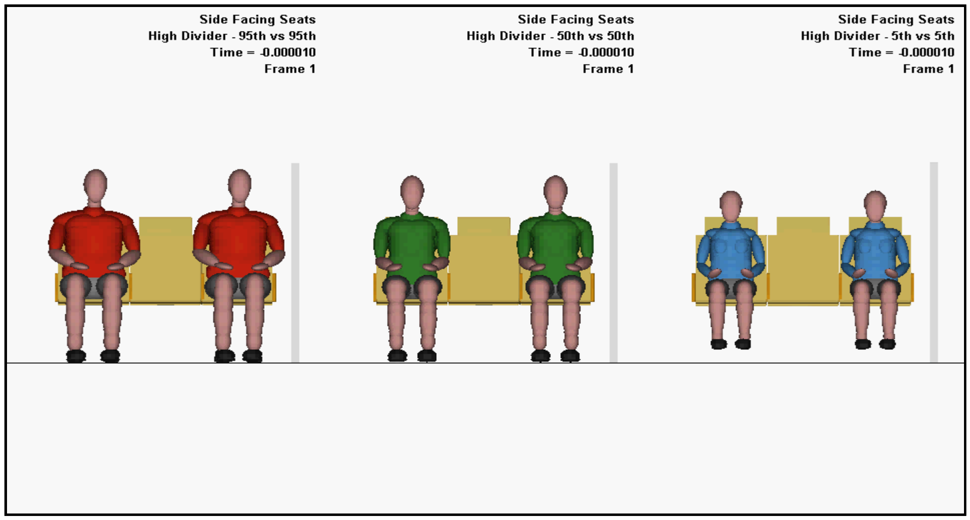
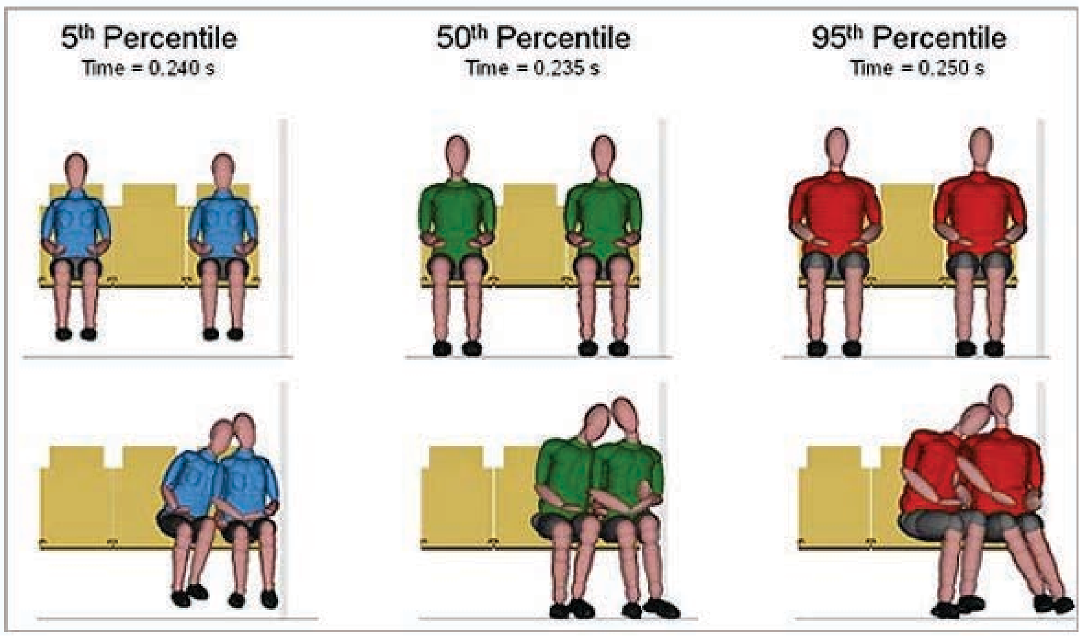


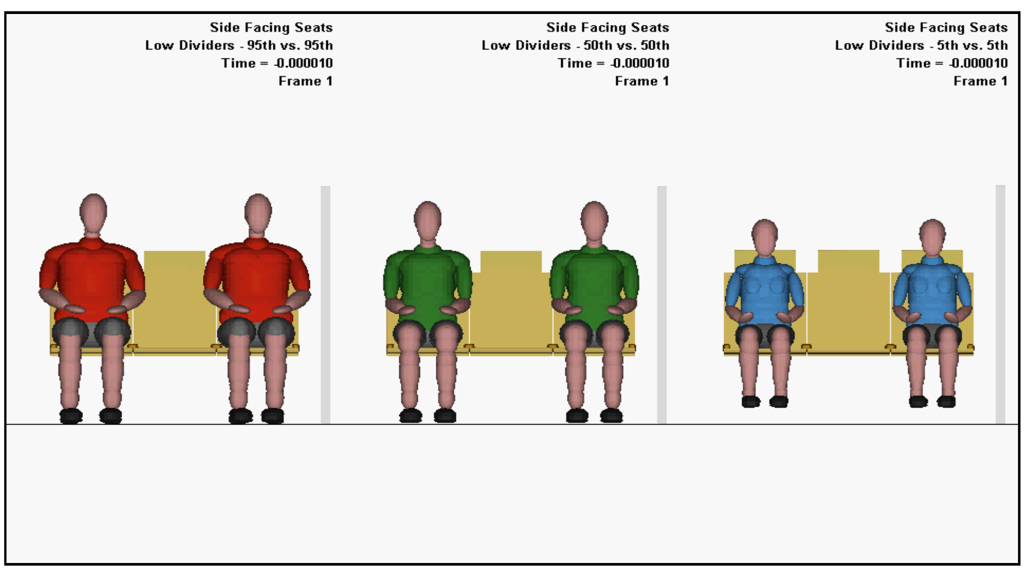
Figure 5-64

Kinematics of ATDs in Lateral-Facing Seats with Low Dividers



Video 5-15

Lateral Facing Seats with Low Divider Configuration Impact Scenario



Summarizing the results of this analysis, it is possible to conclude the following:

- Smaller dividers, or curvatures, in the seat pans seem to decrease the safety of passengers due to the change in occupant kinematics during the impact event. With this type of seat pan, a rotation is added to the passenger, and the impact on the neck and head regions is more severe.
- The use of high dividers seems to not significantly affect results. Thus, this type of divider could be used between seating. However, if this is desired, a more detailed analysis would need to be done to optimize the level of safety.
- Finally, as shown in the results of Section 0 and those obtained in this section, it is possible to state that the use of smooth surfaces without curvatures is recommended for this type of seating arrangement.

Seating Arrangement 4: Row of Forward-Facing Back Seats Analysis

Although this type of seating is not very common (see Section 2), for completeness, a small analysis was performed. The crash conditions presented in Section 4 show that the worst case scenario is a collision between two LRVs. If this type of collision occurs, high injuries are expected for occupants traveling in this type of seating arrangement (see Figure 5-65).

Figure 5-65

Example of LRV with Row of Back Seats [3]

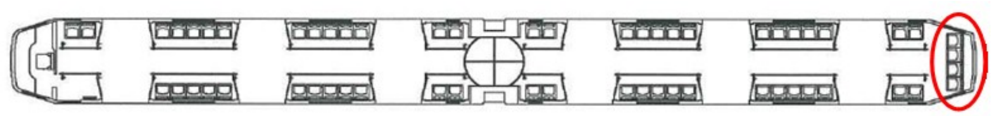


Figure 5-65 shows a row of seats at the back of the LRV facing two lateral seats. Another possible arrangement would be a row of seats in the back facing two sets of forward-facing seats. Thus, two different layouts are studied in this section.

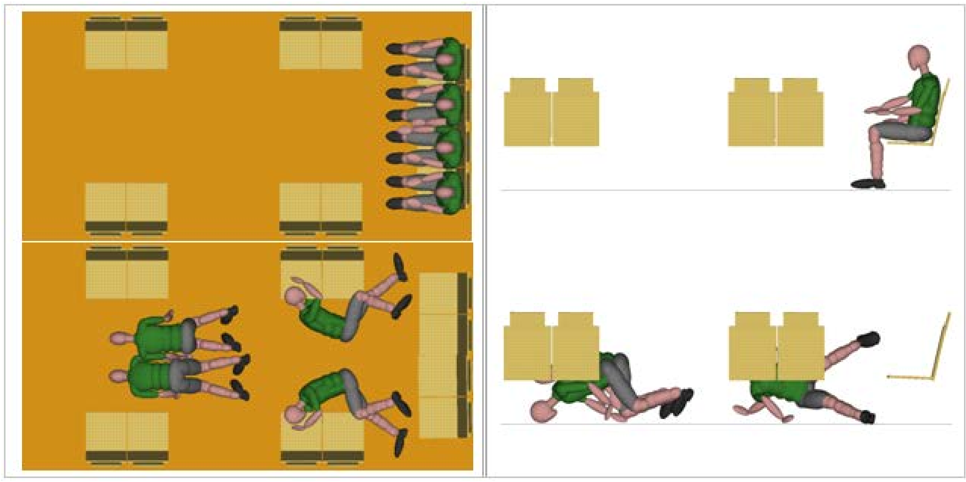
Combination of Back- and Lateral-Facing Seats

This configuration represents a row of four seats in the back of the LRV with lateral facing seats. Figure 5-66 shows the kinematics at the moment of impact (t = 775 ms) where the maximum injury values occur. Figure 5-67 shows the normalized injury values for passengers sitting in the last row of seats.

The worst positions, with very similar results, are both outboard positions. Due to impact with the floor, high injury values are expected in the head and neck regions. On the other hand, passengers sitting in the inboard positions (right and left) have smaller injury values. Nevertheless, the femur forces are relatively high as a result of direct contact with the seat pan of the lateral-facing seats.

Figure 5-66

Kinematics of 50th Percentile ATD Impact in Combination with Back- and Lateral-Facing Seats—Contact Moment t = 775 ms



Video 5-16

LRV Back and Lateral Facing Seats Configuration Impact Scenario – 50th Percentile

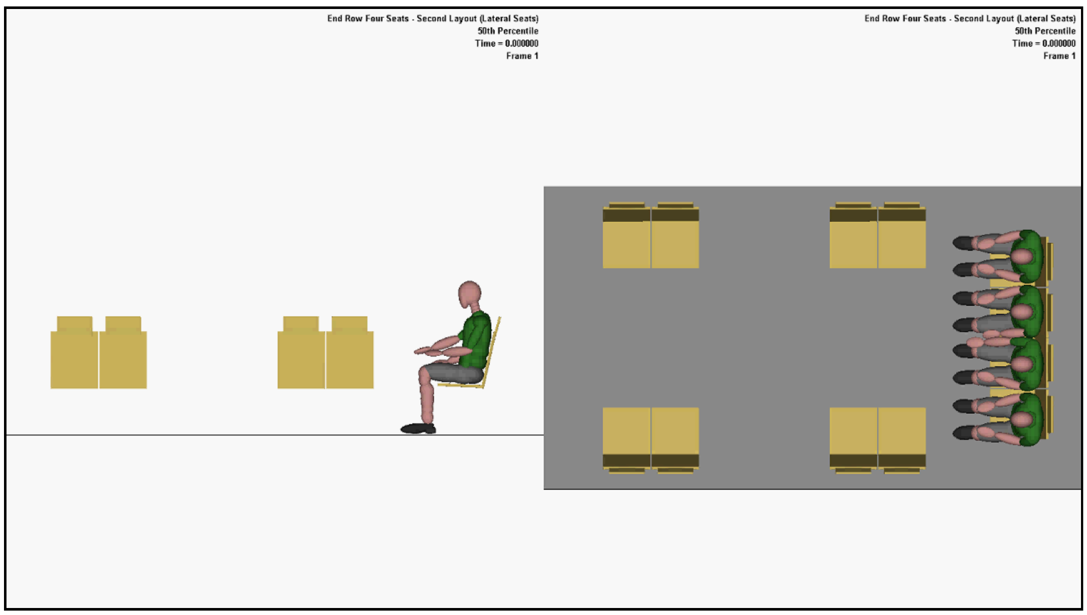
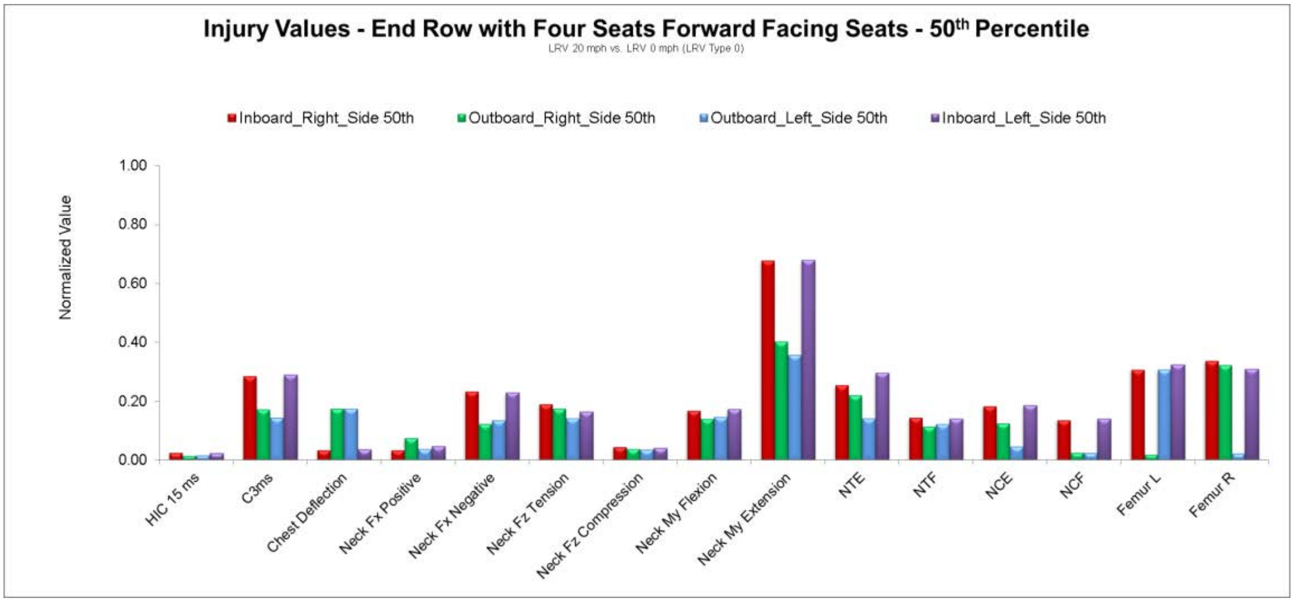


Figure 5-67

Normalized Injury Values of 50th Percentile ATD Impact in Combination with Back- and Lateral-Facing Seats



Combination of Back- and Forward-Facing Seats

The second configuration represents a row of four seats at the back of the LRV with a pair of forward-facing seats in front of them.

Figure 5-68 shows the kinematics of this model. Because of the proximity of the forward-facing seats, the moment when the higher injury values appear is approximately 280 ms. As a consequence of the seat layout, passengers traveling in the outboard positions are trapped between the forward-facing seats. Although this is not a problem from an injury standpoint, it can be a problem if an evacuation is needed.

Figure 5-69 shows the normalized injury values for this configuration. All injury values are below current FMVSS 208 criteria. Still, some high neck moments are observed for passengers traveling in the inboard positions because of the collision with the back of the forward-facing seats.

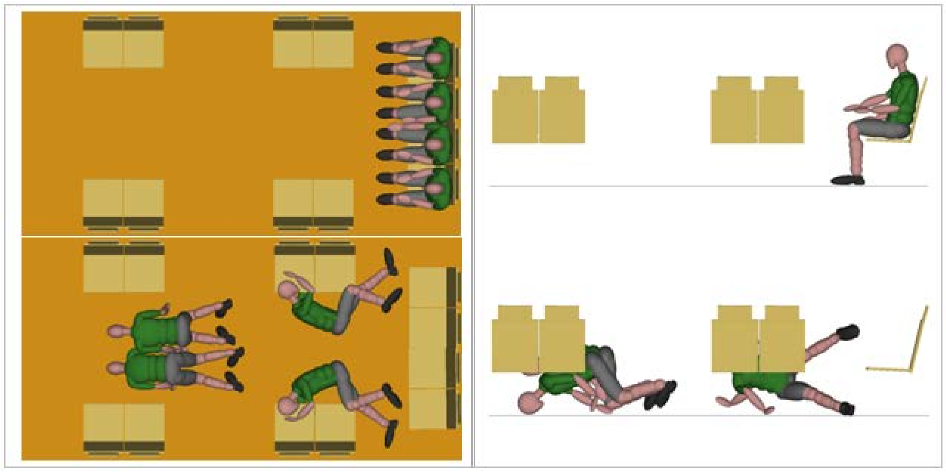
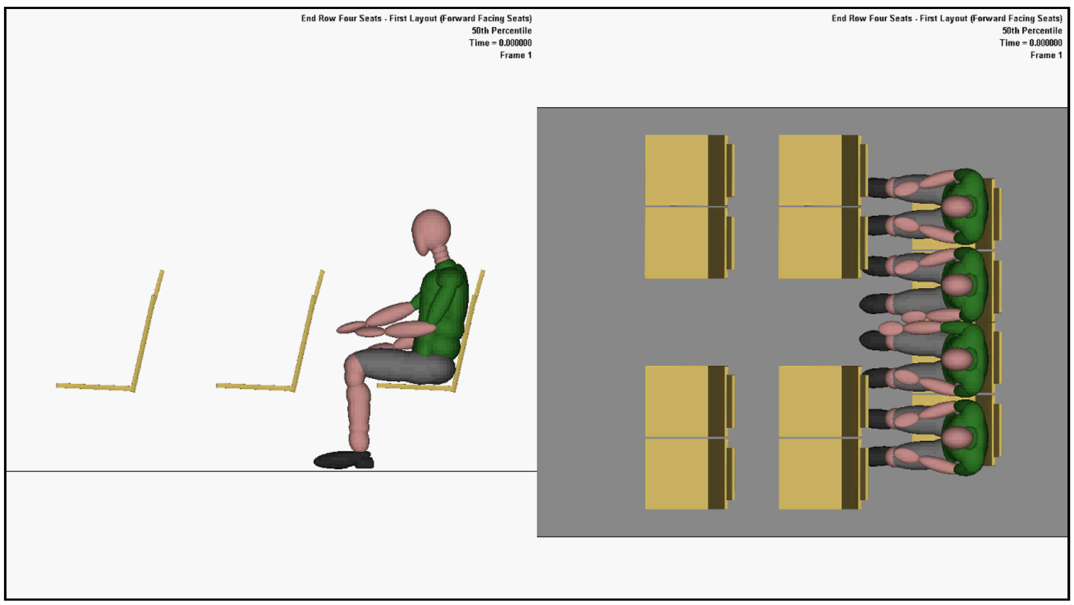


Figure 5-68

Kinematics of 50th Percentile ATD Impact in Combination with Back- and Forward-Facing Seats—Contact Moment t = 280 ms

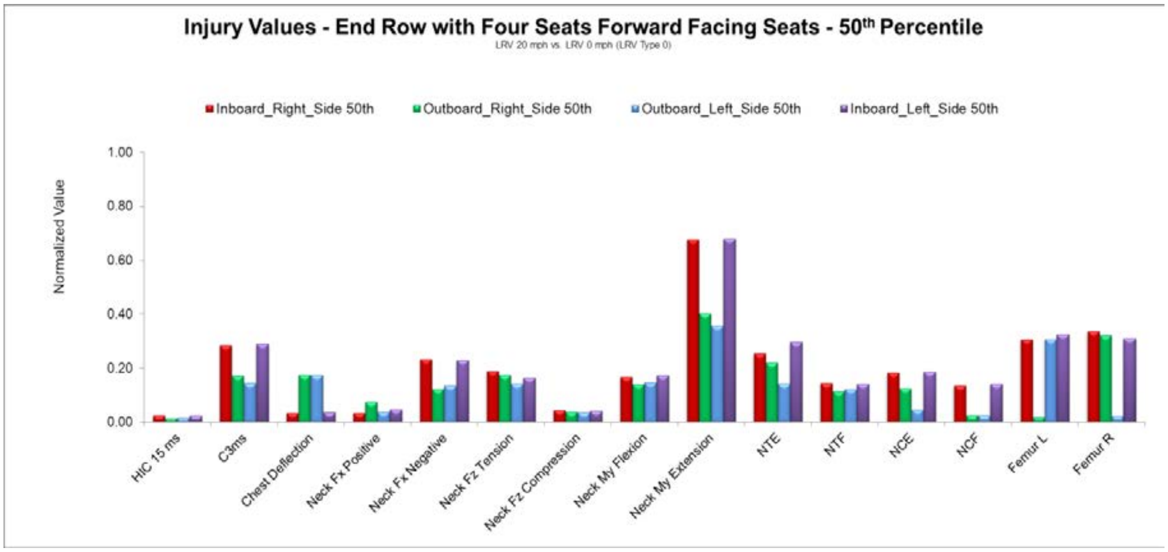


Video 5-17

LRV Back and Forward Facing Seats Configuration Impact Scenario – 50th Percentile

Figure 5-69

Normalized Injury Values of 50th Percentile ATD Impact in Combination with Back and Forward-Facing Seats



Seating Arrangement 5: Wheelchair Analysis

Wheelchair without Straps Load Analysis

As mentioned previously, and according to different sources, most current LRVs do not use any type of device to attach wheelchairs to structure. For this reason, two models were run. These models represent two of the most frequent arrangements for wheelchair spaces found in existing LRVs, as shown in Figure 5-70.

For the first scenario, the wheelchair is supported by one of the LRV monuments. This monument is a flat surface with the normal pointing towards the longitudinal edge of the LRV. In most cases, no anchors are used, and only the brakes of the wheelchair are used to maintain the correct position (Figure 5-71).

For the second scenario, the wheelchair is supported by one of the lateral LRV walls. For this model, the wheelchair is oriented in a transversal direction with respect to the LRV (Figure 5-72).

Figure 5-70

Example of Two Different Wheelchair Areas

Figure 5-71

Wheelchair without Straps with 50th Percentile ATD—Contact Moment
t = 150 ms

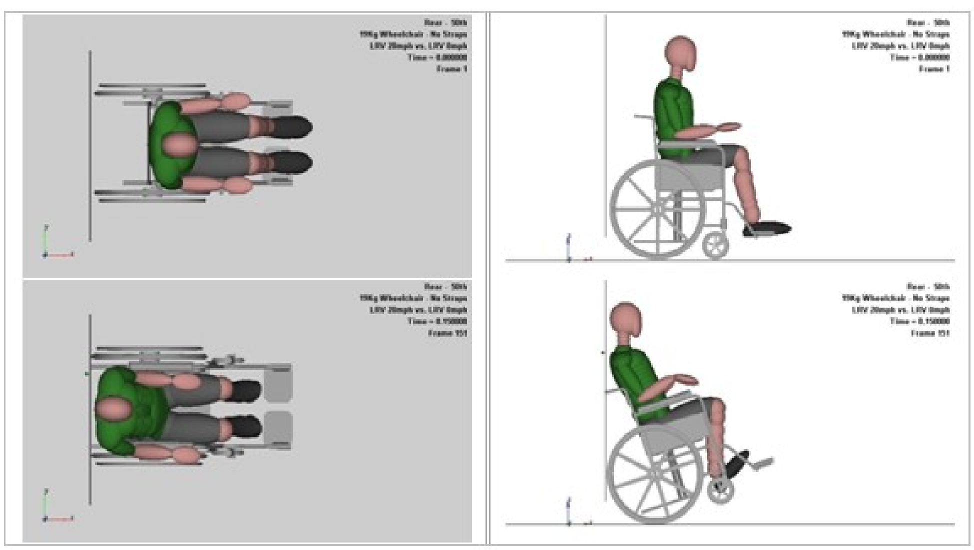
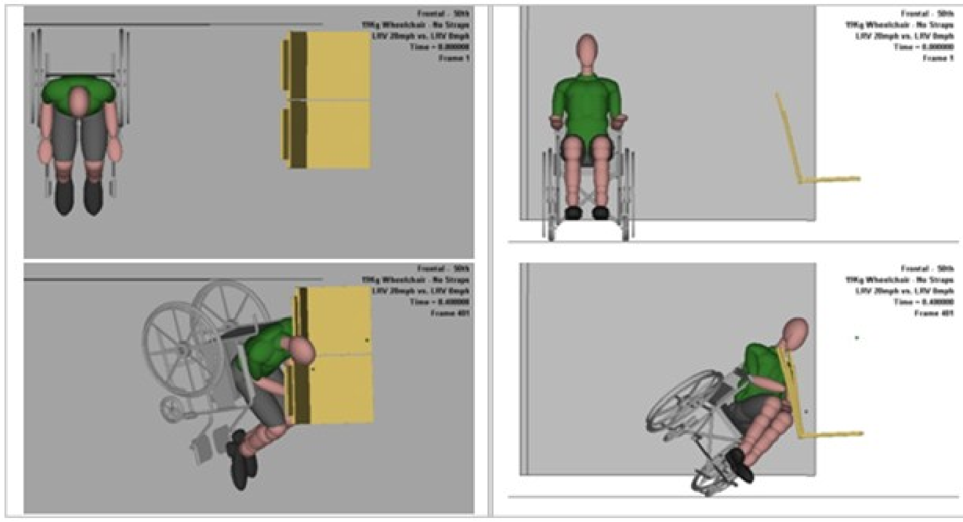


Figure 5-72

Configuration 2—Wheelchair without Straps with 50th Percentile ATD—Contact Moment t = 400 ms

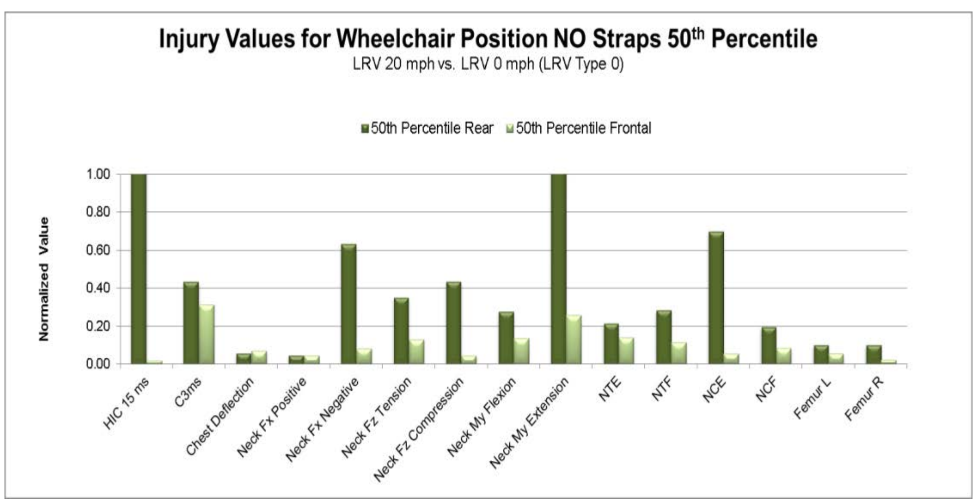


According to the injury values shown in Figure 5-78, the configuration with the wheelchair in the longitudinal direction of the LRV has very large injury values for both the head and neck regions. Due to the lack of anchor points, the wheelchair rotates, thus allowing the occupant to impact the monument. The properties used for the contact between the head and monument are the same as those used for the barrier from the lateral-facing seat study.

In contrast, the configuration with the wheelchair perpendicular to the direction of the LRV had relatively smaller injury values. Nevertheless, the kinematics of the impact show a very violent collision between the occupant and headrest. As a result, other moments and forces (Fy and Mx) not evaluated by FMVSS 208 regulations reach dangerous levels, making this configuration hazardous due to the unbelted condition.

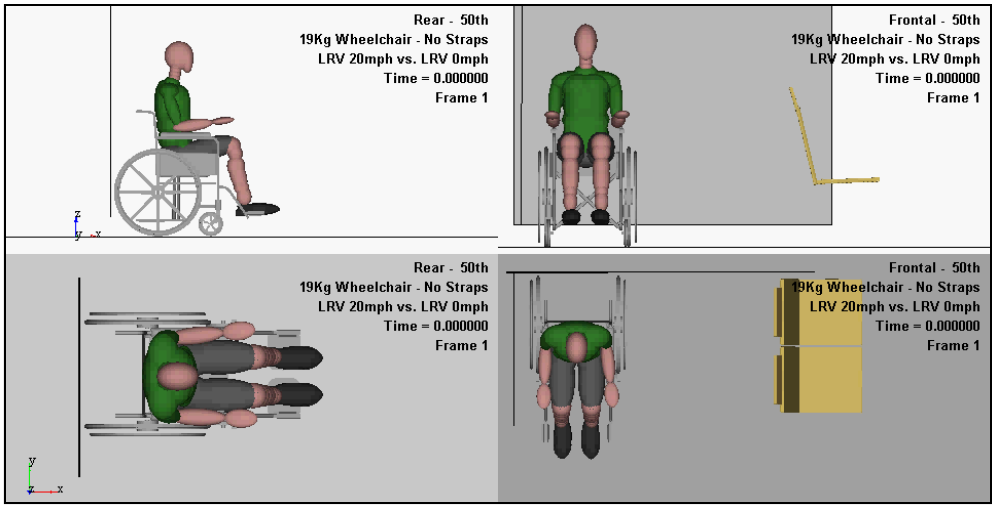
Figure 5-73

Normalized Injury Values of Wheelchair without Straps and 50th Percentile ATD



Video 5-18

Wheelchair without Straps Impact Scenario – 50th Percentile



After analyzing different conditions and understanding the principal problems associated with the positioning of wheelchairs, it is possible to conclude that some type of restraint system should be used, or designed, to improve the safety for this type of occupant.Wheelchair with Straps Load Analysis

This section illustrates the maximum forces expected for straps used in attaching wheelchairs to the structure in some LRVs. Although most current LRVs do not have any type of restraint system for wheelchairs, those that do have a different system than the one analyzed in this section. Figure 5-74 shows one of the current restraint systems used by manufacturers like Siemens in Charlotte, North Carolina.

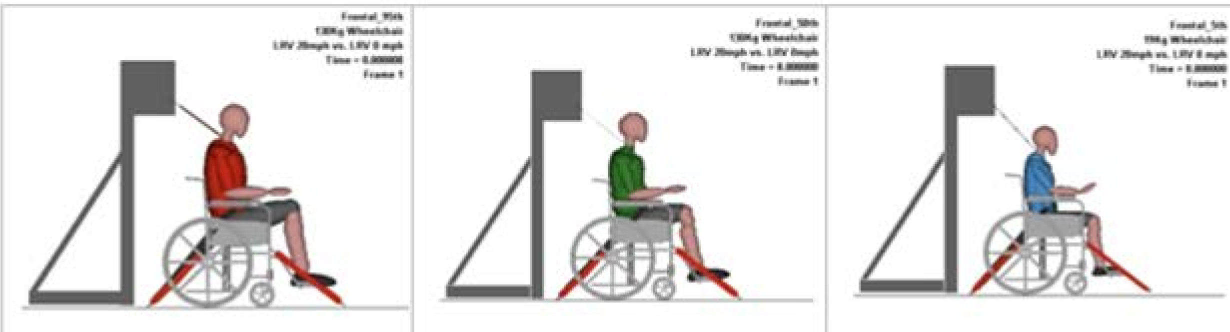
The configuration used for analysis in this project is a common design in current mass transit buses. This design uses four-point anchors for the wheelchair and a three-point belt restraint system for the occupant in the wheelchair (See Figure 5-75). The properties for the strap and wheelchair model used in this analysis are explained in Appendix B.

Figure 5-74

Wheelchair Restraint System of Siemens S70

Figure 5-75

Strap Force Analysis of Wheelchair Model



The acceleration pulse used for this analysis is the LRV type 0 traveling at 20 mph and impacting another LRV which is stationary at 0 mph. Both frontal and rear impact conditions were studied. The worst-case scenario is the rear-impact condition, due to the transfer of load between occupant and wheelchair. For the frontal-impact condition, the occupant is restrained by a three-point belt system, which reduces the amount of force transmitted to the wheelchair anchors.

Furthermore, two different wheelchair sizes were studied. The first represents a manual wheelchair with a total weight of 19 kg. The second represents an electric wheelchair with a total weight of 130 kg. This electric wheelchair was obtained by scaling the proportions and the mass of the manual until the larger dimensions and the 130 kg were reached. As a result, both models are visually similar.

Maximum Strap Forces of Impact with Wheelchair and 95th Percentile ATD

Via these series of simulations involving a wheelchair and 95th percentile ATD, it is possible to observe the differences between the strap loads for rear- and frontal-impact scenarios, as shown in Figures 5.76 to 5.79. As expected, the maximum strap force was found for the rear-impact condition and the 130 kg electric wheelchair. For this configuration, the maximum strap load is approximately 9500 N for one of the frontal anchor points (Figure 5-78). For the last scenario, a three-point belt restraint system reduces the load transferred to the straps by 45 percent. A decrease of 45 percent on the maximum strap load is observed when the 19 kg wheelchair is used instead of the 130 kg wheelchair.

Figure 5-76

Belt and Strap Forces of Frontal Impact with 130 kg Wheelchair and 95th Percentile ATD

Figure 5-77

Belt and Strap Forces of Frontal Impact with 19 kg Wheelchair and 95th Percentile ATD

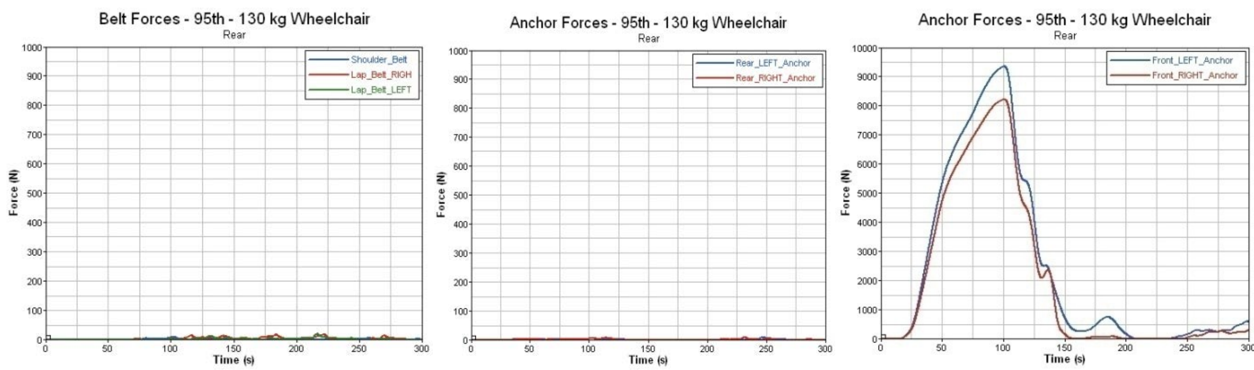


Figure 5-78

Belt and Strap Forces of Rear Impact with 130 kg Wheelchair and 95th Percentile ATD

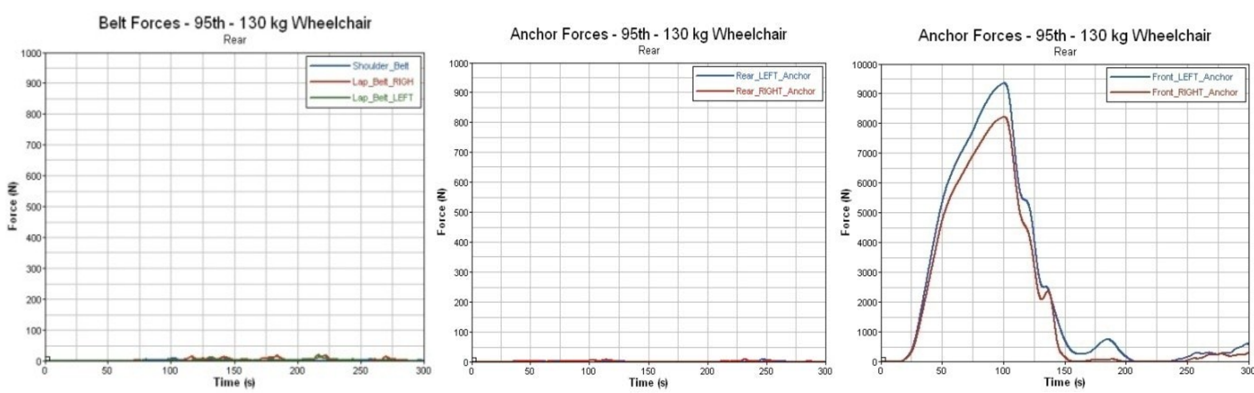
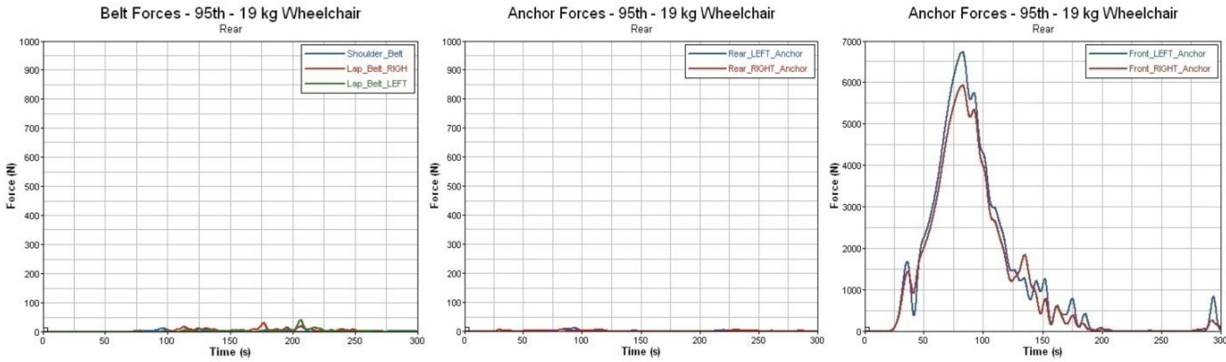


Figure 5-79

Belt and Strap Forces of Rear Impact with 19 kg Wheelchair and 95th Percentile ATD



Via these series of simulations involving a wheelchair and 50th percentile ATD, it is possible to observe the differences between the strap loads for rear- and frontal-impact scenarios, as shown in Figures 5.80 to 5.83. Once more, as expected, the maximum strap force can be found for the rear-impact condition with the 130 kg electric wheelchair. The maximum strap load is approximately 8500 N for one of the frontal anchor points, which is approximately 11 percent less than the one obtained for the 95th percentile ATD (Figure 5-82). For the frontal impact scenario, the three-point belt restraint system reduces the load transferred to the straps by 35 percent. A decrease of approximately 75 percent of the maximum strap load is observed when the 19 kg wheelchair is used instead of the 130 kg wheelchair.

Figure 5-80

Belt and Strap Forces of Frontal Impact with 130 kg Wheelchair and 50th Percentile ATD

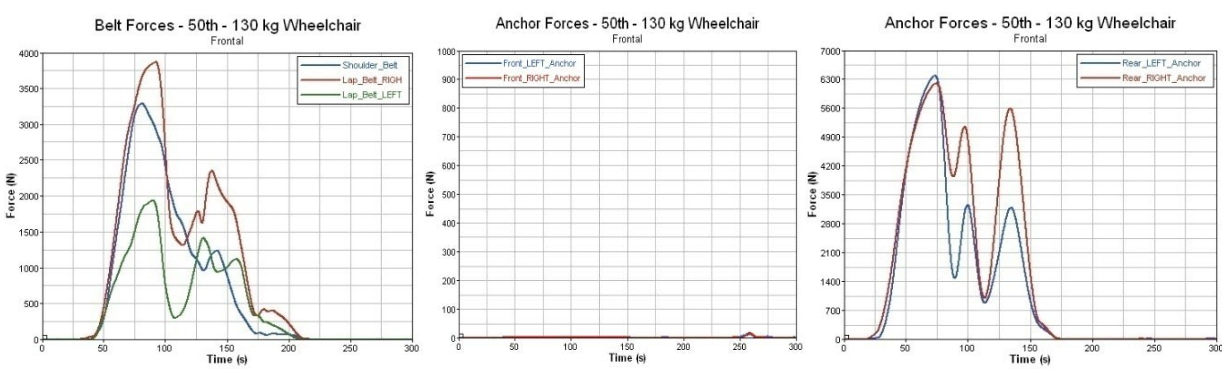


Figure 5-81

Belt and Strap Forces of Frontal Impact with 19 kg Wheelchair and 50th Percentile ATD

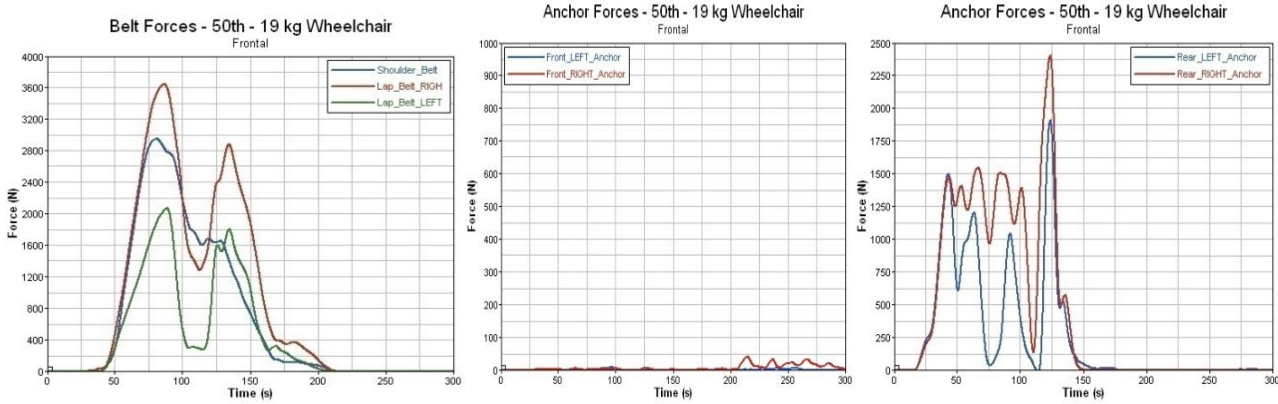


Figure 5-82

Belt and Strap Forces of– Rear Impact with 130 kg Wheelchair and 50th Percentile ATD

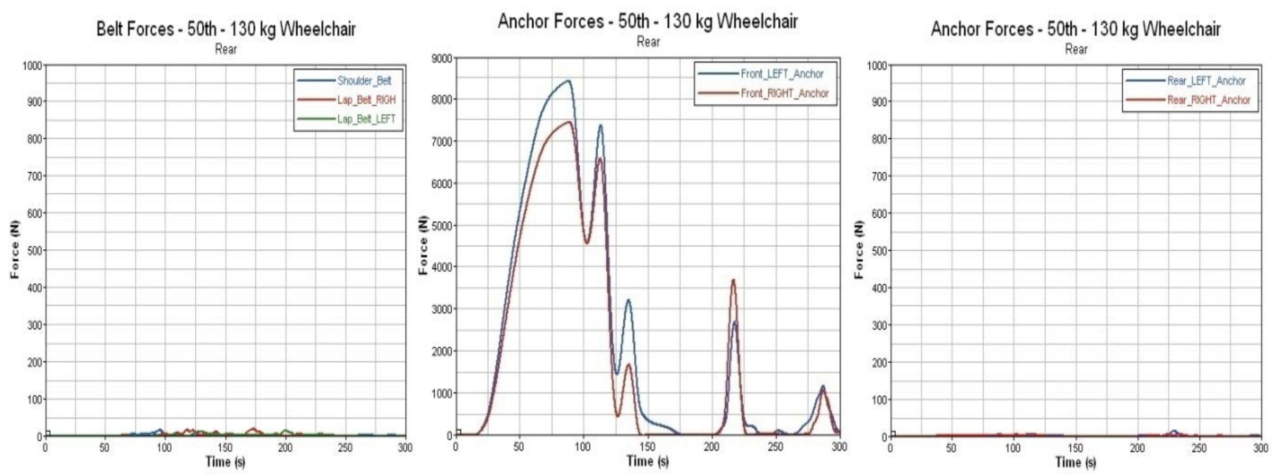
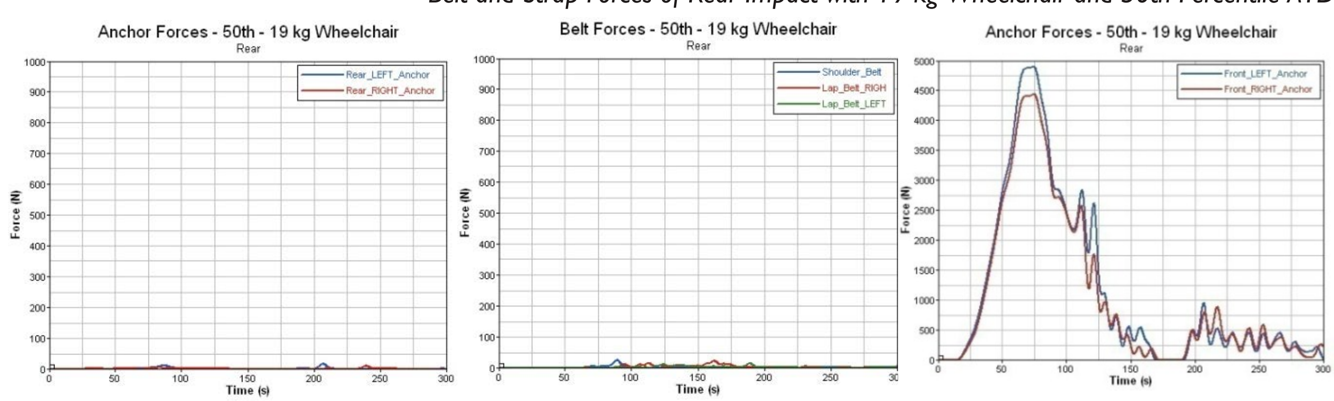


Figure 5-83

Belt and Strap Forces of Rear Impact with 19 kg Wheelchair and 50th Percentile ATD



Maximum Strap Forces of Impact with Wheelchair and 5th Percentile ATD

For the 5th percentile ATD, only the 19 kg wheelchair was evaluated, as shown in Figures 5.84 and 5.85. Again, the maximum strap load was obtained for the rear-impact configuration with a value of 4500 N. The three-point belt restraint system used for the front-impact scenario reduced the load transferred to the straps by 250 percent, with respect to the rear-impact scenario.

Figure 5-84

Belt and Strap Forces of Frontal Impact with 19 kg Wheelchair and 5th Percentile ATD

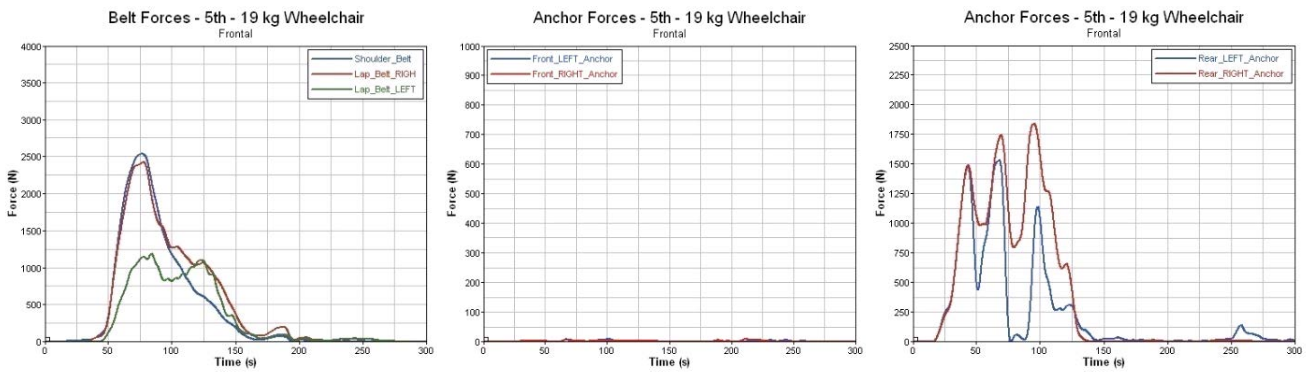
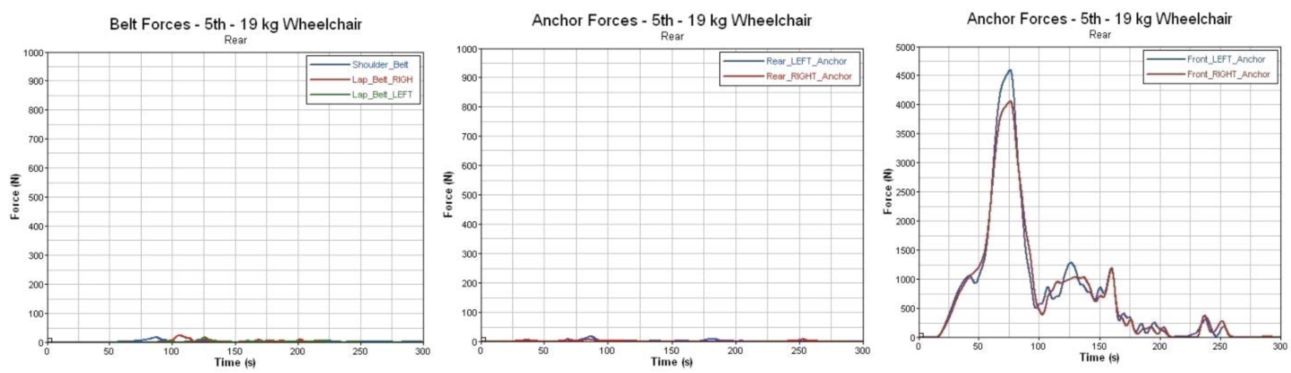


Figure 5-85

Belt and Strap Forces of Rear Impact with 19 kg Wheelchair and 5th Percentile ATD



Seating Arrangement 6: Child Seats Analysis—Strap Loads

According to various sources, current LRVs do not have any type of device or anchor points that allow for child seats to be attached to the structure or seats. Currently, two different systems are used to anchor child seats to the structure of the vehicle. These systems are used to guarantee proper anchorage of the child seat and safety of the occupant. Both systems (ISOFIX and LATCH) provide similar levels of safety for the occupant.

In a similar proposal as that for current mass transit buses [9], this section shows the maximum forces that an anchor point will need to bear to guarantee the proper support of the child seats on the current LRVs. The acceleration pulse used to calculate these forces is the pulse obtained from an LRV type 0 traveling at 20 mph and impacting another LRV that is stationary at 0 mph. Two types of child seats were studied:

- 3-Year-Old Child Seat—empty weight 11 kg
- 12-Month-Old Child Seat—empty weight 5 kg

Due to the cantilever type of attachment that current LRV seats use, a comparison between the forces reached when the seat is installed inboard or outboard was also studied. Figure 5-86 shows the results for the three-year-old child seat. As a result of the smaller rotation of the seat for the inboard position, the maximum load is reached in this location. The maximum load expected is at approximately 3000 N.

Figure 5-86

Strap Loads of Child Seat for Three-Year-Old Child in Outboard and Inboard Positions

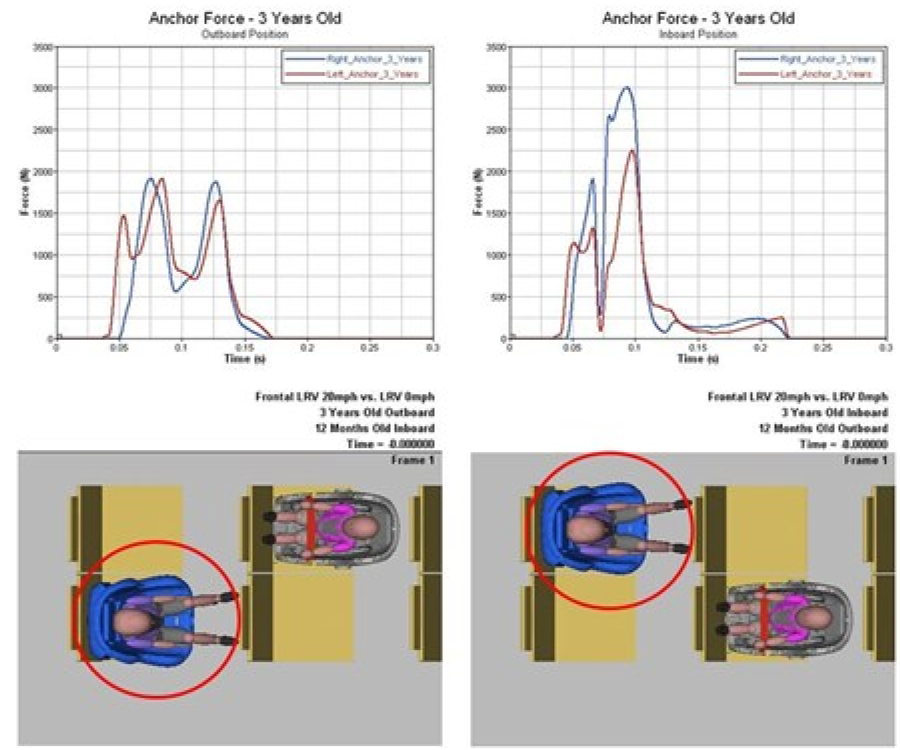
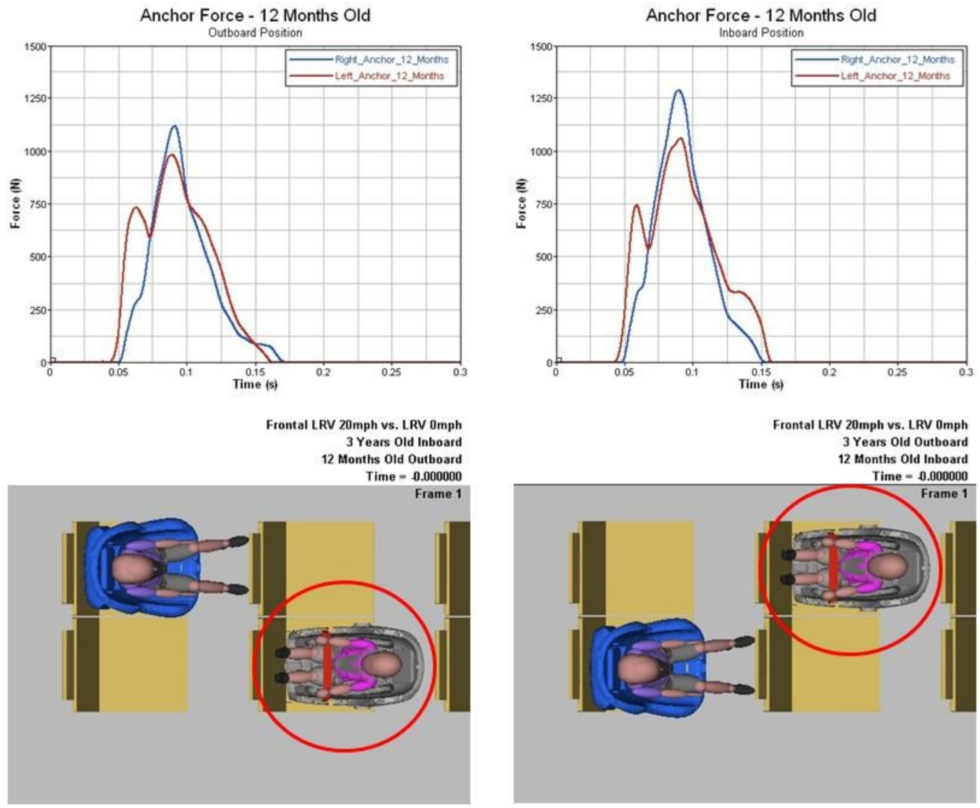


Figure 5-87 shows the results for the 12-month-old child seat. Again, as a result of the smaller rotation of the seat in the inboard position, the maximum load is reached in this location. For this child seat, due to its smaller weight, a maximum load of approximately 1250 N is reached.

Figure 5-87

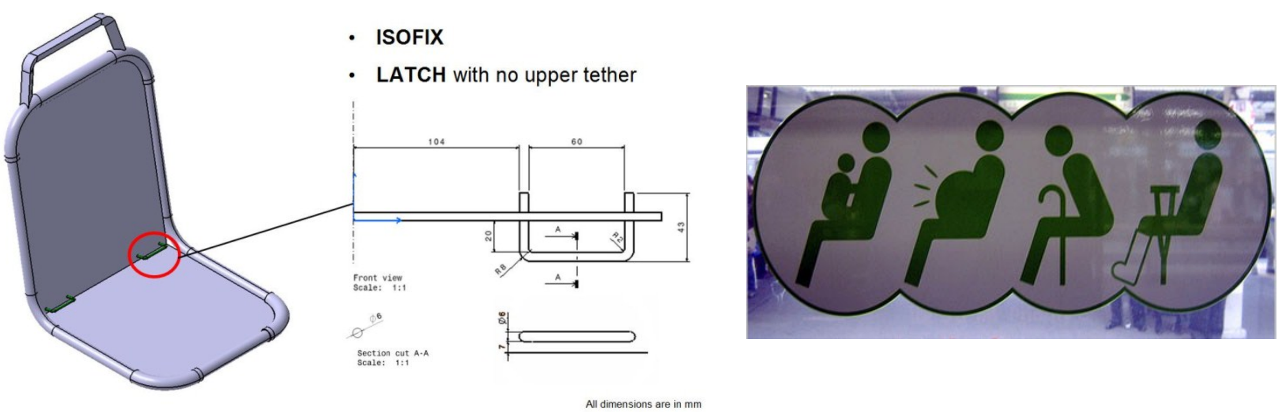
Strap Loads of Child Seat for 12-Month-Old Child in Outboard and Inboard Positions



An example of a possible design for anchor points is shown in Figure 5-88. These anchor points will need to bear at minimum a static force of 3000 N plus a factor for safety. Although the loads obtained in the outboard position are smaller, the inboard position could be used to facilitate the installation of the child seat. A sign similar to the one used for older adults or pregnant women could be used to design special seats in the LRV (Figure 5-88). The kinematics for both outboard and inboard setups are shown in Figures 5.89 and 5.90.

Figure 5-88

Examples of Possible Anchor Point Design and Sign to Designate Child-Seat Locations



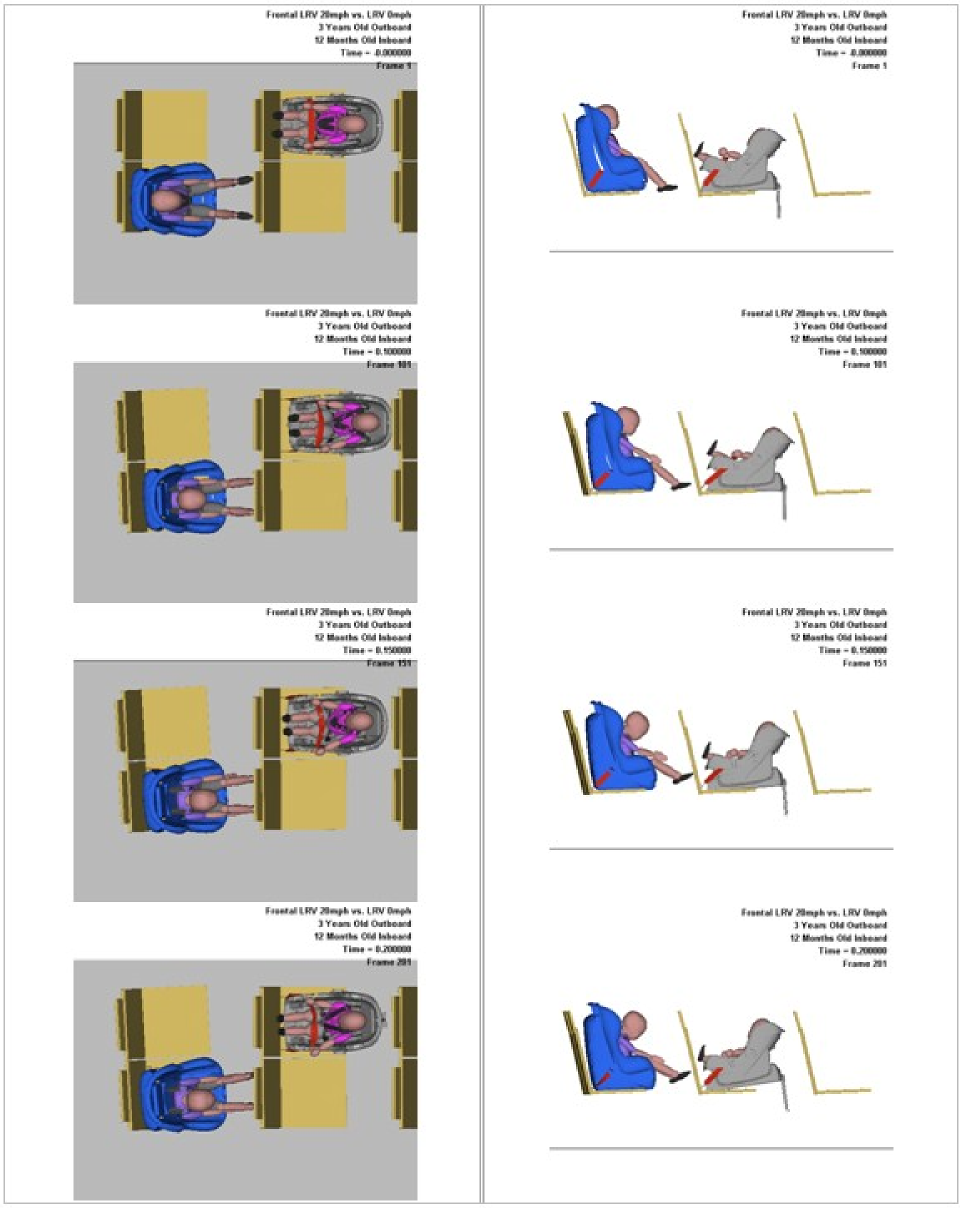


Figure 5-89

Kinematics of 3-Year-Old Child Seat (Outboard) and 12-Month-Old Child Seat (Inboard)

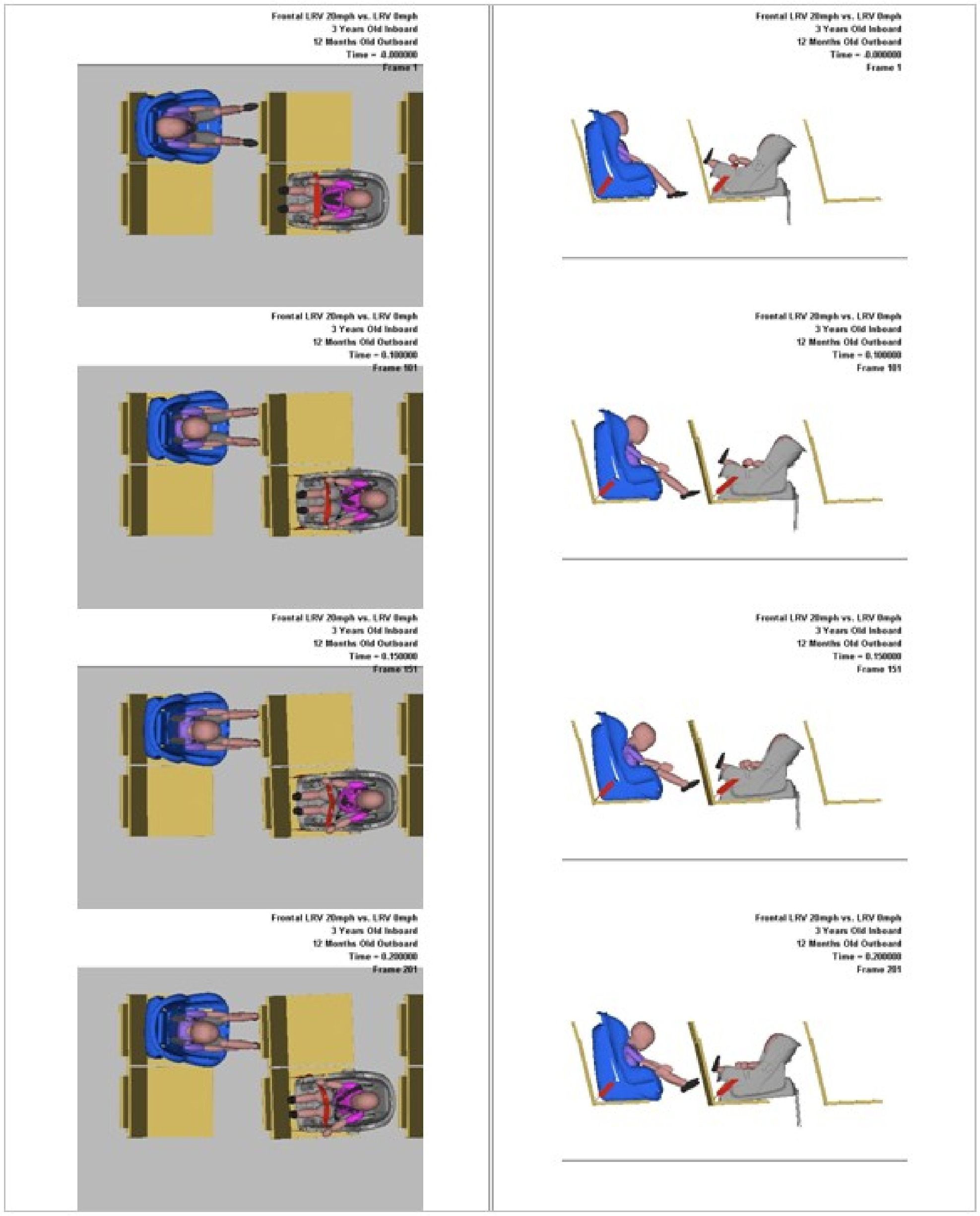
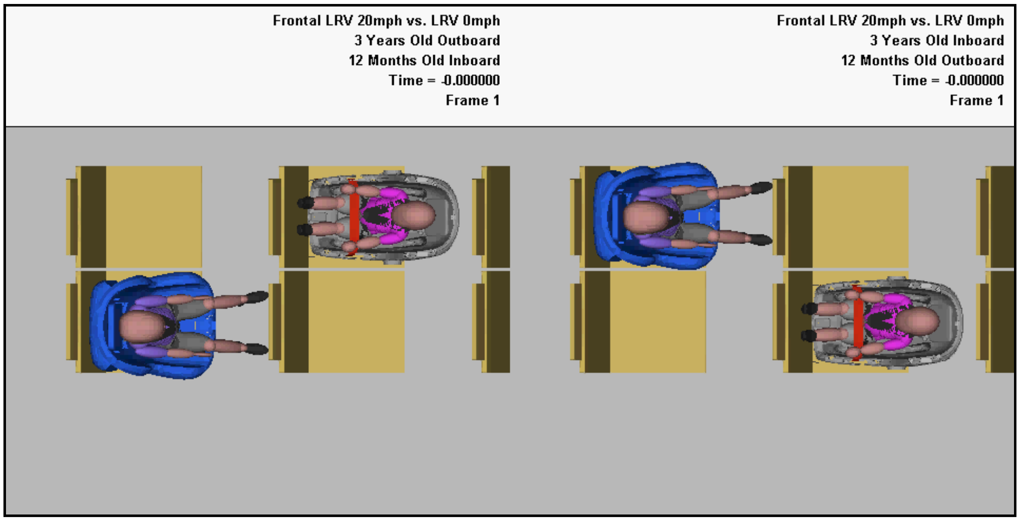


Figure 5-90

Kinematics of 3-Year-Old Child Seat (Inboard) and 12-Month-Old Child Seat (Outboard)



Video 5-19

LRV Childseats Impact Scenario

Seating Arrangement 7: Standing Passengers Analysis

LRVs usually travel short distances within city limits with a high density of passengers. As a result, numerous passengers travel in the standing position. The most common standing positions can be divided into two categories. Figure 5-91 shows an aisle between forward- and aft-facing seats. Figure 5-92 shows a large aisle between side-facing seats.

Figure 5-91

Aisle between Forward-Facing and Aft-Facing Seats

Figure 5-92

Aisle between Lateral-Facing Seats

The standing position can be hazardous in case of an accident because the passenger does not have any type of restraint. Therefore, it will start moving, build velocity, and impact a monument or another passenger. At that moment, severe injuries can be expected in the contact region.

To simulate these two scenarios (forward- or aft-facing seats, and side-facing seats), two multibody models were created. These multibody models represent the worst-case scenario since this type of ATD does not have any tension in its extremities. As a result of the lack of tension, these ATDs will behave as a rigid body with no intention of maintaining equilibrium.

In the future, analysis could be done with ATDs that have detailed extremities, allowing the user to input some pretension on the muscles so special conditions can be simulated. Some examples of work already done can be found in the MADYMO *Human Models Manual* (June 2009).

Aisle between Forward-Facing Seats

Figure 5-93 shows a multibody model where one standing occupant is traveling in the aisle between a series of forward-facing seats. As a result of impact with the floor, the higher injuries were obtained in the chest and neck regions (Figure 5.94). Further analysis with more standing occupants should be done to determine how human-to-human contact affects the injuries. Figures 5.95 and Figure 5.96 show the positions of the passenger at various impact moments.

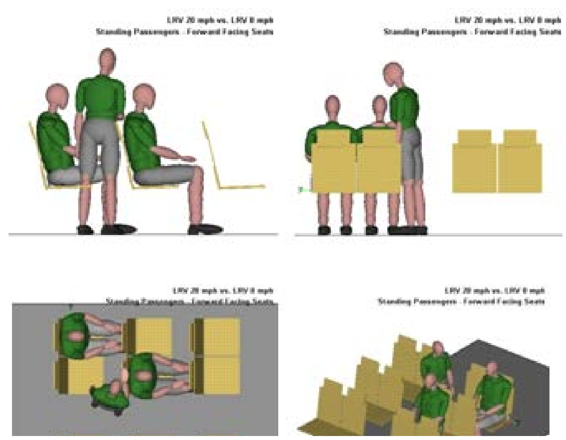


Figure 5-93

Multibody Model Showing One Passenger Standing in Aisle between Forward-Facing Seats

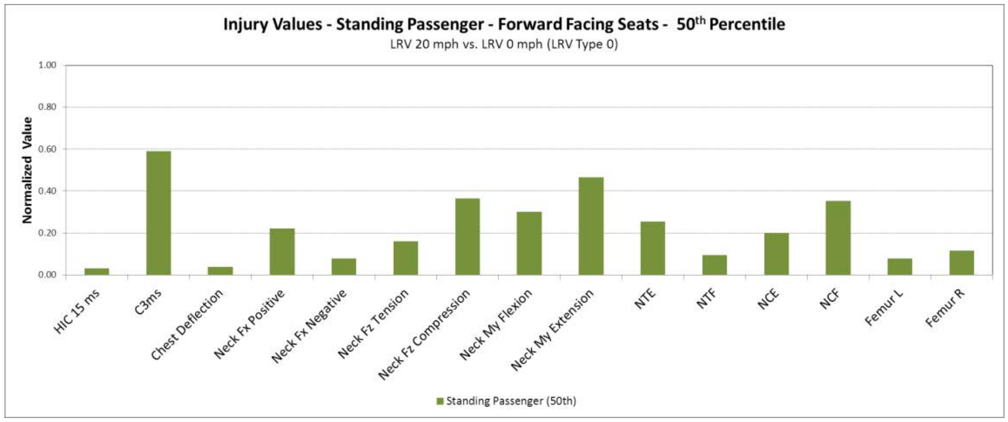


Figure 5-94

Normalized Injury Values of 50th Percentile ATD Standing in Aisle between Forward-Facing Seats

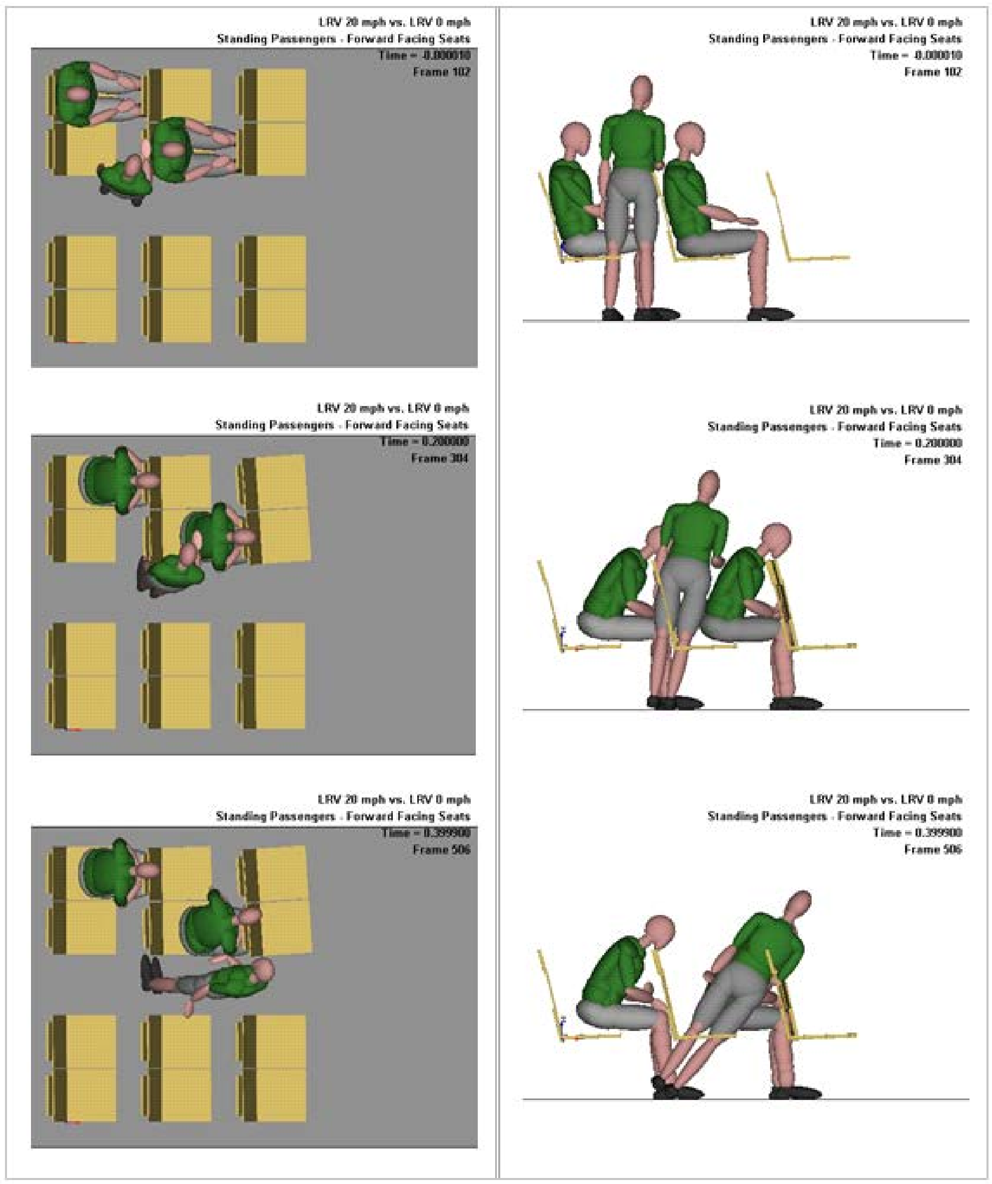
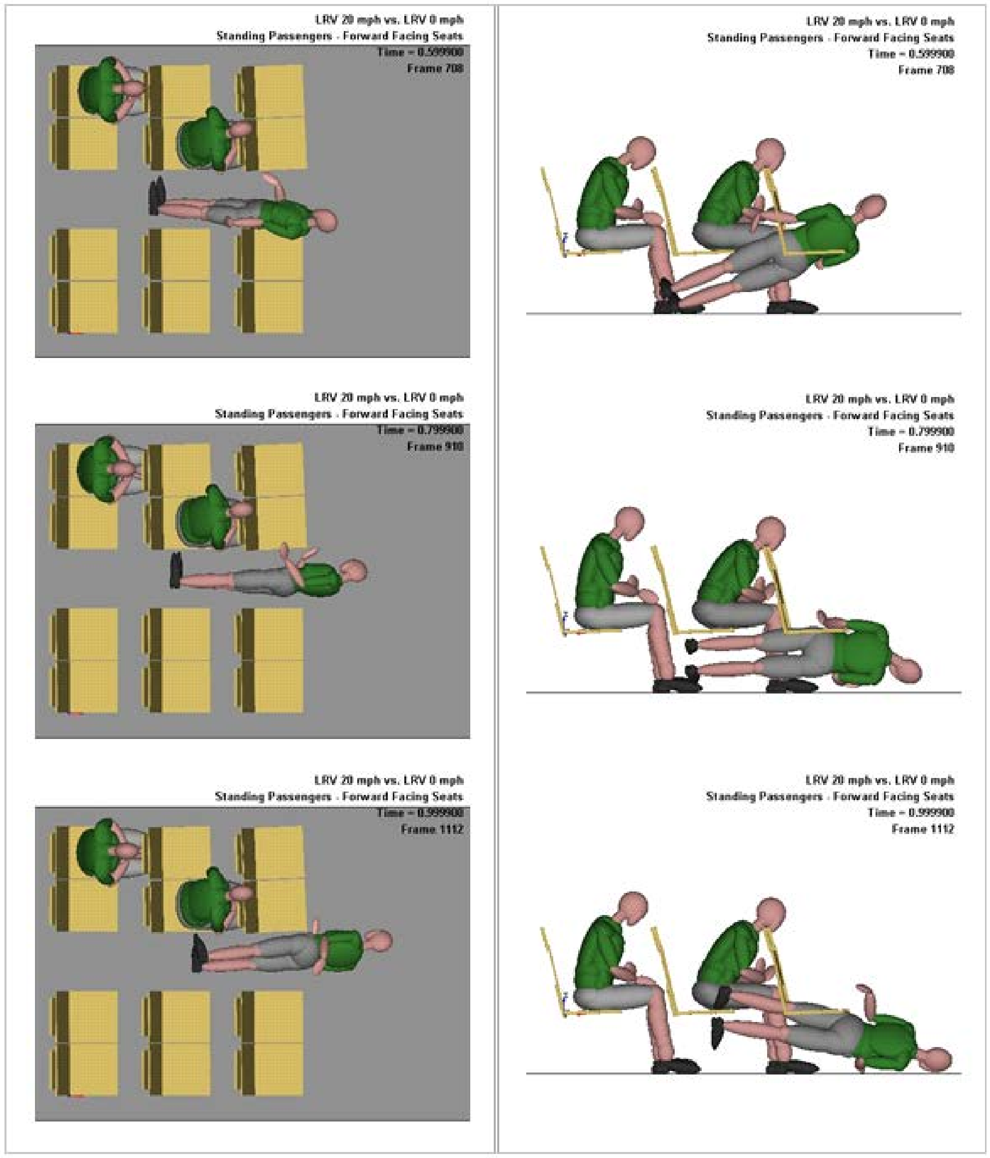


Figure 5-95

Position of Passenger Standing in Aisle between Forward-Facing Seats at 0 to 400 ms Impact Moment

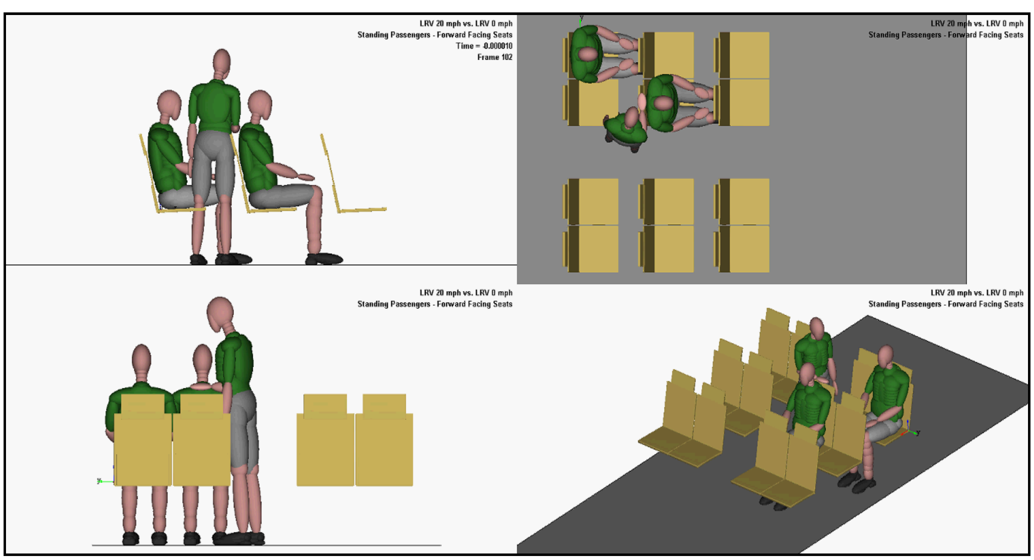
Figure 5-96

Position of Passenger Standing in Aisle between Forward-Facing Seats at 600 to 1,000 ms Impact Moment



Video 5-20

LRV Standing Passenger Impact Scenario



Aisle between Side-Facing Seats

Figure 5-97 shows a multibody model where six standing occupants are traveling in the aisle between two side-facing seats and another occupant is sitting in one of the side-facing seats. As expected, the normalized injury values (Figure 5.98) are higher because of the contact between ATDs. Head, chest, and neck regions show the largest injury values. Figures 5.99 and 5.100 show the positions of passengers at various impact moments.

Figure 5-97

Multibody Model Showing Six Standing Passengers in Aisle between Side-Facing Seats and One Seated Passenger

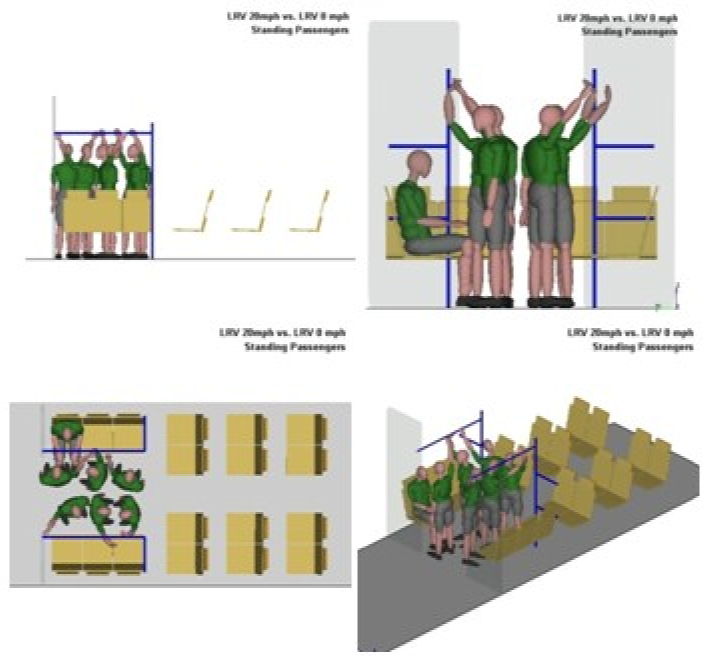


Figure 5-98

Normalized Injury Values of Six 50th Percentile ATDs Standing in Aisle between Side-Facing Seats

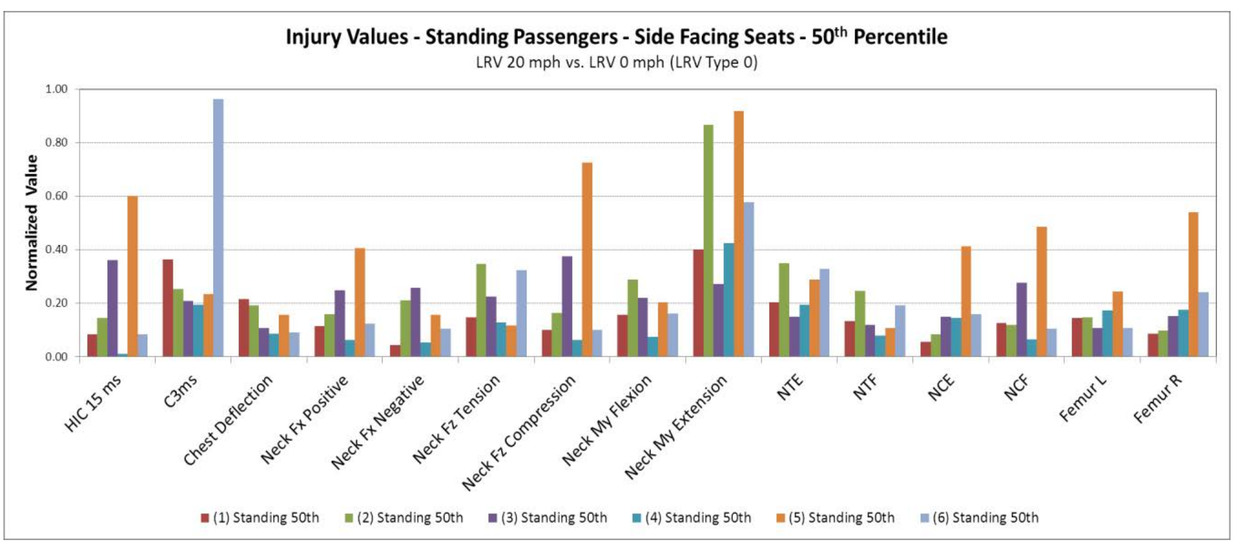
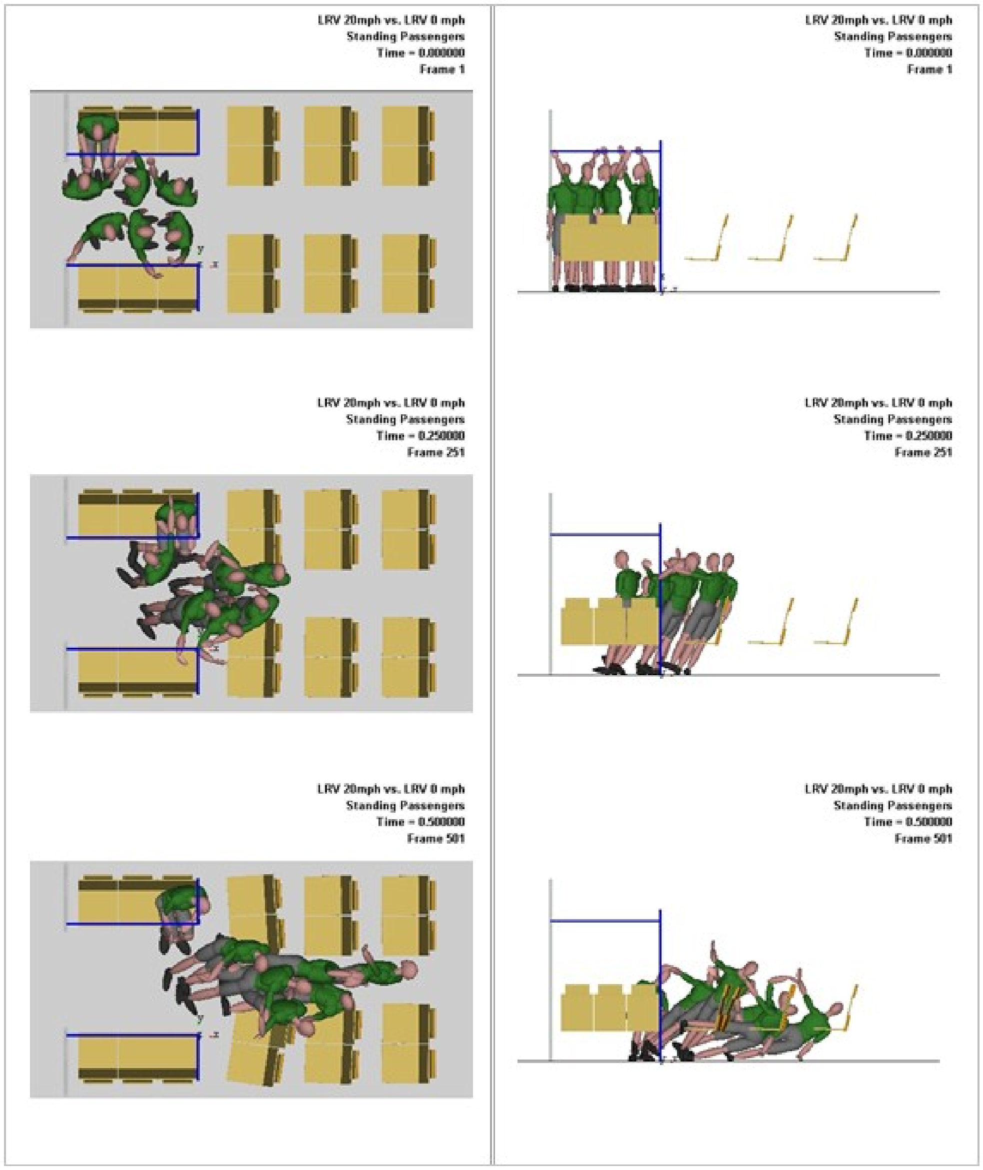


Figure 5-99

Position of Passengers Standing in Aisle between Side-Facing Seats at 0 to 500 ms Impact Moment



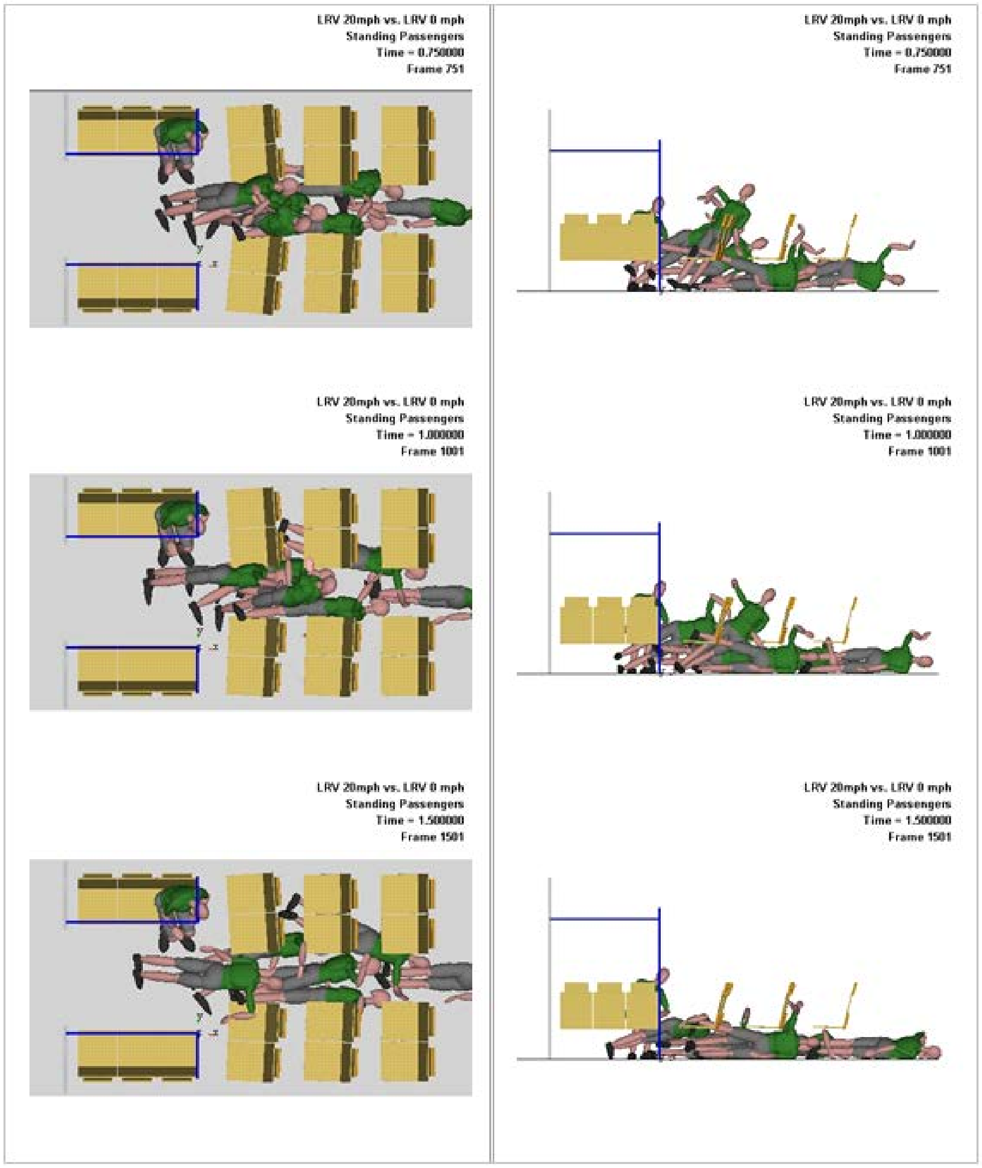
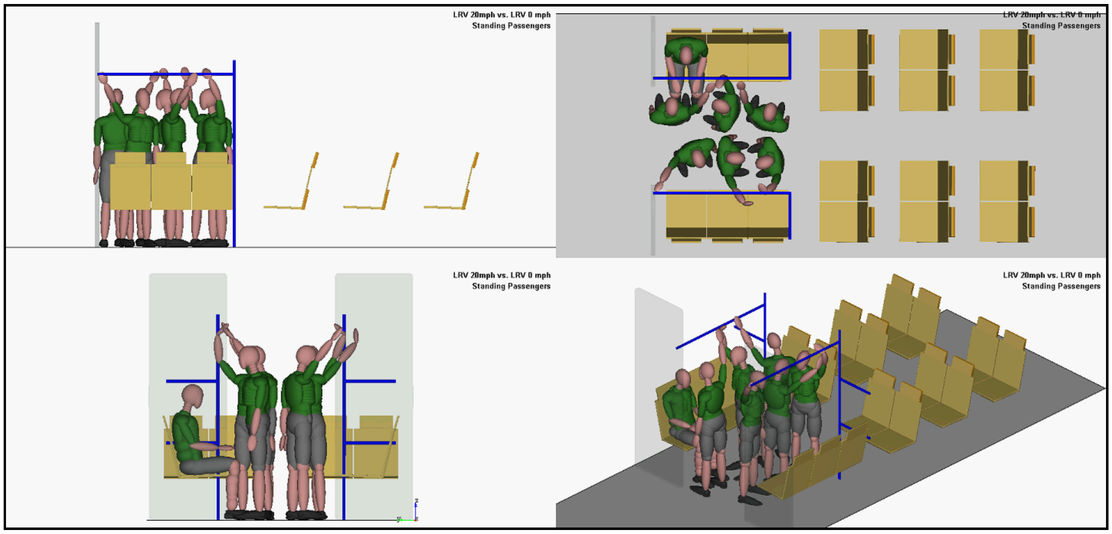


Figure 5-100

Position of Passengers Standing in Aisle between Side-Facing Seats at 750 to 1,500 ms Impact Moment

Video 5-21

LRV Standing Side Facing Passenger Impact Scenario



SECTION

6

Finite Element Model—Accident Reconstruction

The main objective of this project was to identify and study the most common types of injuries to LRV passengers. As shown in Section 4, the worst case impact conditions for LRV passengers are impact to large road vehicles (i.e., buses and large trucks). For this reason, two crash scenarios were analyzed. The first represents the collision between an LRV traveling at 20 mph and a mass transit bus crossing the LRV path at 5 mph (medium-energy impact condition). The second represents a high-energy impact where two LRVs, one traveling at 20 mph and the other stationary, collide.

Finite Element Model of LRV

The LRV exterior model was created using geometry and drawings shared by a LRV manufacturer. Drawings for forward-, aft-, and lateral-facing seats also were provided and used to defined a detailed finite element seat.

The layout used for this LRV attempts to represent the most illustrative arrangement found as a result of the survey completed in Section 3. The following seating configurations were included in the LRV interior definition:

- Forward-facing seats (or aft-facing seats depending on travel direction):
  - Facing a barrier
  - Facing anything in front of them
- Lateral-facing seats with two seats (worst-case scenario according to Section 5):
  - Facing a forward-facing seat
  - Facing an aft-facing seat
- Seats facing each other
- Operator seat

The mesh quality criteria used for this model is summarized in Table 6-1. The double seat used for forward- and aft-facing seating is shown in.Figure 6-1. The lateral-facing seats are shown in Figure 6-2. Although this type of seat can be folded in some newer LRVs, it was considered fixed for this analysis.

Figure 6-2 shows the interior cabin parts modeled in this analysis. A driver seat without any type of restraint system was added to the cabin to study operator behavior and possible injuries.

Table 6-1

Mesh Quality Criteria

Criteria	Specification
Minimum side length	5.0 mm
Warp angle less than	15 degrees
Aspect ratio less than	5:1
Minimum quadrilateral element internal angle	45 degrees
Maximum quadrilateral element internal angle	135 degrees
Minimum triangular element internal angle	30 degrees
Maximum triangular element internal angle	120 degrees
Maximum skew angle	60 degrees
Minimum Jacobian	0.7
Maximum number of triangular elements	< 5%

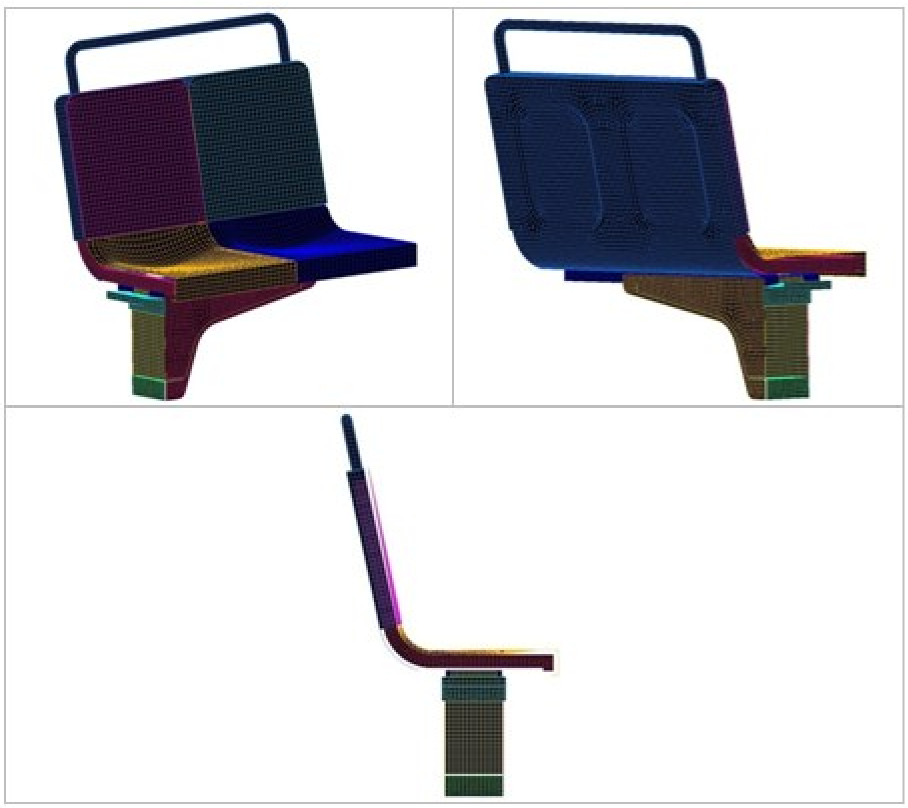


Figure 6-1

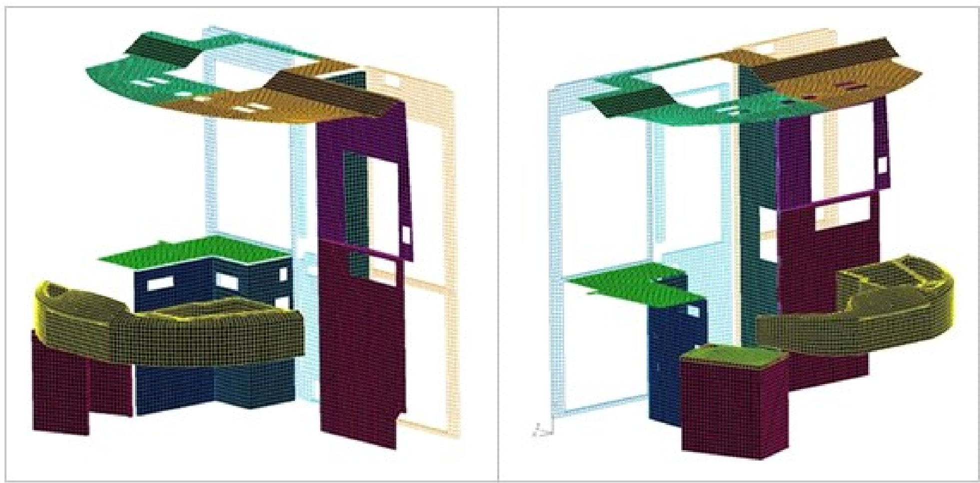
Finite Element Model of Forward-Facing and Aft-Facing Seats

Figure 6-2

f Exterior Components of LRV

Figure 6-3

Finite Element Model of Interior Cabin without Operator Seat



Once the main components for the interior were modeled, the exterior was created. Drawings and CAD files were used to create the features of the frontal cabin for the finite element model. Figure 6-4 shows two of the most important exterior components. Although not shown in this report, a very detailed structure was used for the front of the LRV. This detailed structure provides a very real behavior to the model, as the authentic stiffness and features of the frontal part of the LRV are represented. Because no lateral impacts to the LRV were analyzed in this project, no floor or lateral structures for the rest of the LRV were used. Due to the heavier weight of the LRV with respect to other vehicles on the road, no major deformations occur to the main cabin. For this reason, the interior floor of the LRV where the seats are connected was defined as being rigid.

Figure 6-4

Finite Element Model of Exterior Components of LRV

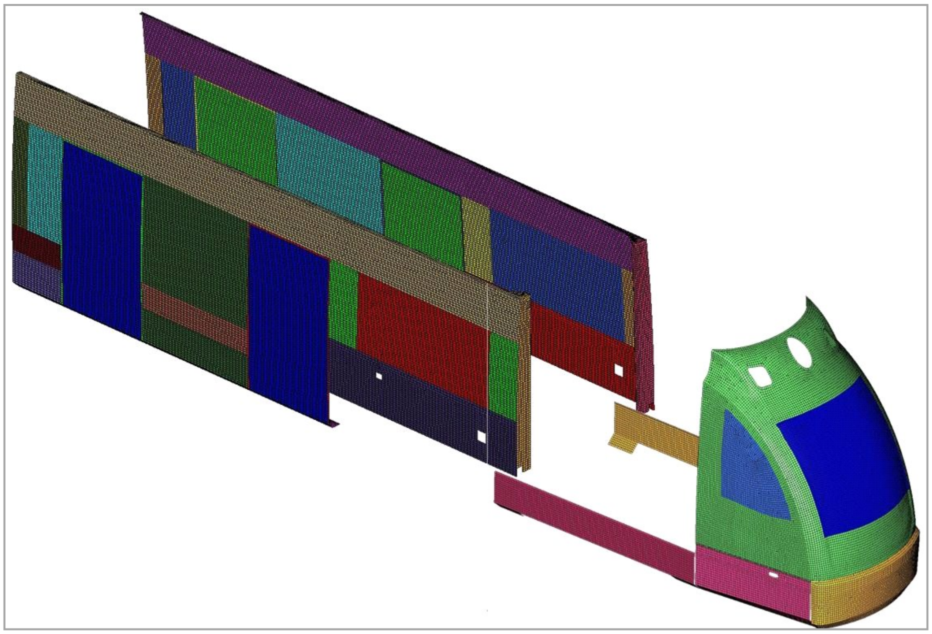
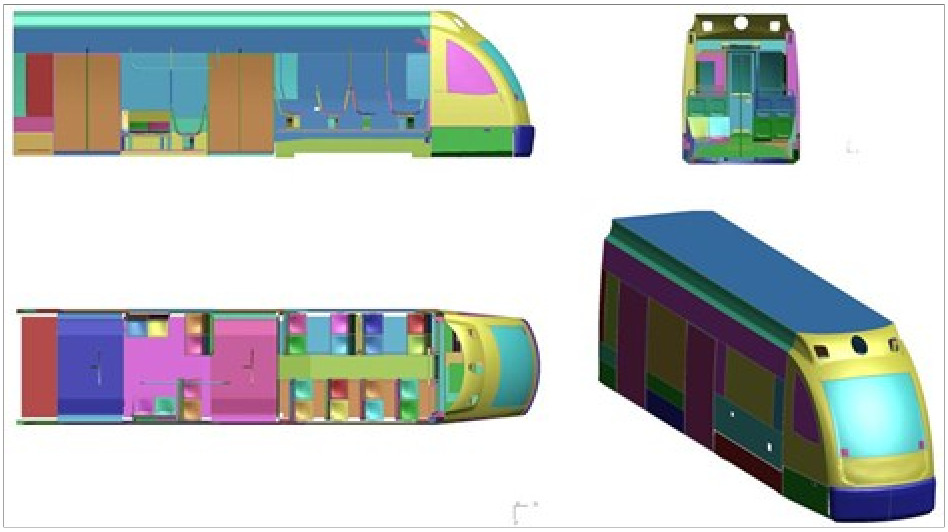


Figure 6-6 shows the finite element model for a complete car. Usually, LRVs are constructed using two main cars and a middle car where the articulation mechanisms are placed. For that reason, to complete the model, the car shown here is reflected along the X-axis and a middle cabin is created. The middle cabin is created so the length of the LRV matches the dimensions specified in the model characteristics.

Figure 6-5

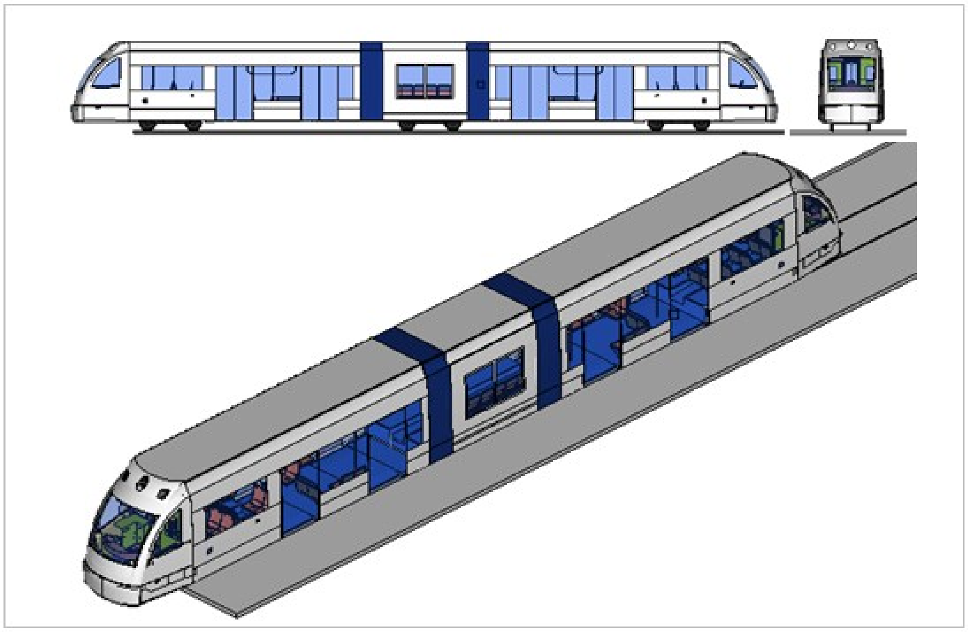
Finite Element Model of Complete Car



The total length for this model is 29,370 meters. It represents a Category 2 LRV with CEM components, and an empty weight of 44,769 tons. Being a Category 2 vehicle, this LRV has 70 percent of the floor at low level. Figure 6-7 shows the completed LRV model.

Figure 6-6

Finite Element Model of Complete LRV



Finite Element Model of LRV Interior Layout

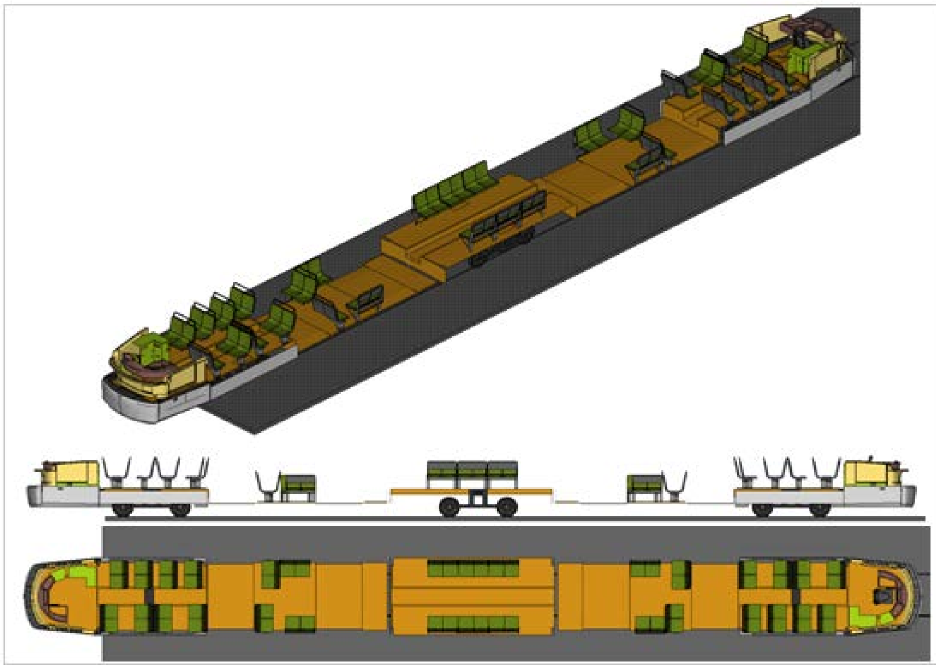
The seating arrangement used in this finite element model attempts to represent the most common type of seating found throughout the analysis completed in Section 2. Forward-, aft-, lateral-, and seat-facing seats were used in this model.

Figure 6-7 shows the final interior layout of the LRV. The total number of seats available in this model is 60. Although the percentage of each type of seat used for this model does not match with the results shown in section 0, this layout allows the analysis of most seating arrangements in one model (forward-facing seats, aft-facing seats, lateral-facing seats, and seats facing each other). The distribution of these seats is in accordance with the analysis done in Section 0:

- Unidirectional forward-facing seats: 6 (10%)
- Forward seats facing a monument: 6 (10%)
- Unidirectional aft-facing Seats: 6 (10%)
- Aft seats facing a monument: 6 (10%)
- Seats facing each other: 24 (40%)
- Lateral side seats facing each other: 12 (20%)

Figure 6-7

Finite Element Model of Complete LRV Interior Layout



Finite Element Model of Mass Transit Bus

The mass transit bus model used in this analysis was developed by the computational mechanics laboratory at NIAR (WSU) and used in the analysis of a wide range of impact conditions for the BUS project [9]. A summary of the process followed to construct the model follows:

- The mass transit bus CAD geometry was smoothed and de-featured to allow a minimum element size of 5 mm to maintain a minimum time step of one microsecond without using mass scaling.
- The element size on the main structural members (Figure 6.8) was in the range of 5 to 10 mm to capture higher curvature buckling modes.
- Mesh components were in their mid-plane.
- There were a minimum of 5 integration points if part thickness exceeds 1.5 mm.
- The mesh quality criteria were the same as those used for the LRV.
- Meshes consisted of lines parallel and orthogonal to the sides of the component.
- Additional modeling considerations were eccentricity of the non-structural components. As shown in Figure 6-9, the model accurately represents the components that move relative to the main bus structure such as the engine, transmission, fuel tank, battery compartment, roof air-conditioning unit, and seats.
- Bolts, bushings, and spot weld connections were accurately modeled.
- Tire mesh was modeled with enclosed volumes to allow internal pressure definition.

The final mass transit bus FE model consists of 302,227 elements, 298,833 nodes, 1,405 components, 43 sub-assemblies, 6 control volumes (tire model), 1,348 section properties, 29 materials, 32 kinematic joints, and 20,219 spot welds.

Figure 6-8

Finite Element Model of Mass Transit Bus with Shaded Views of Main Structural Members

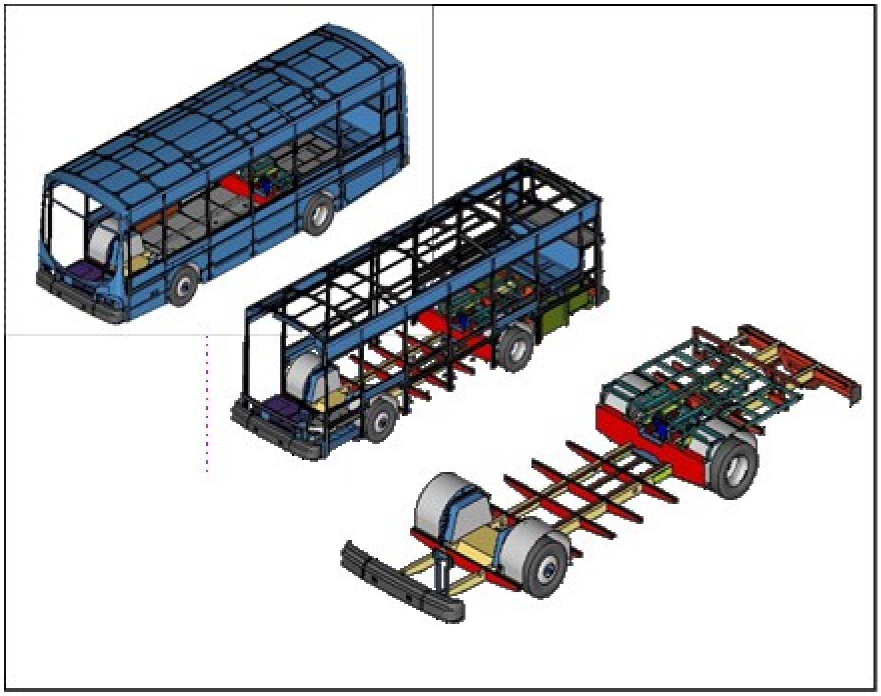
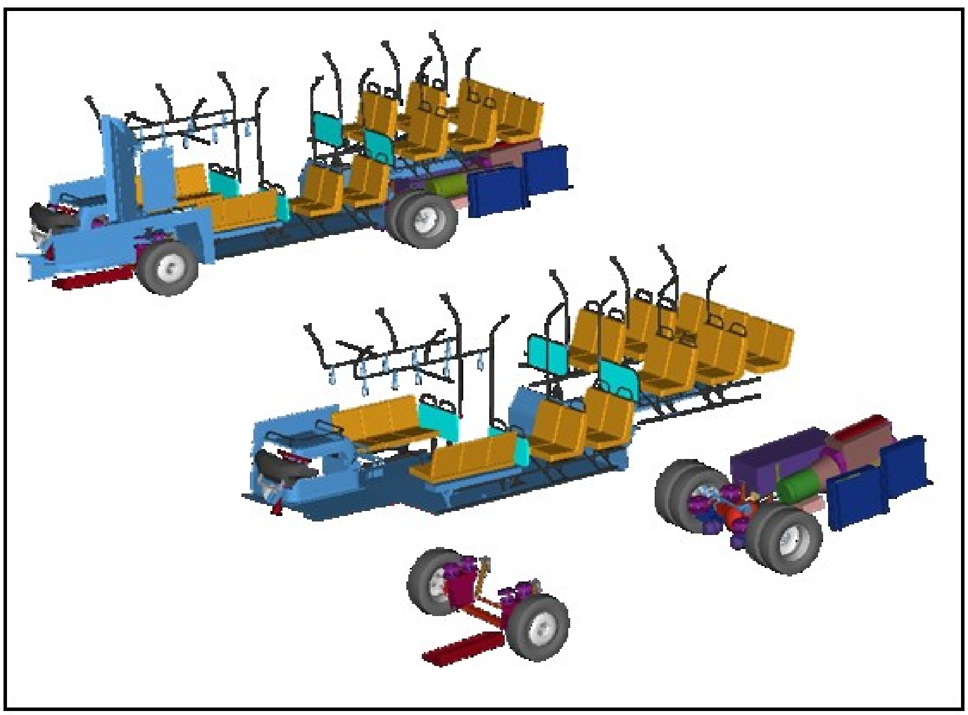


Figure 6-9

Finite Element Model of Mass Transit Bus with Shaded Views of Non-Structural Components



Impact Analysis Conditions

Two impact conditions were studied with this LRV model. The first was a low-energy impact between one LRV and one mass transit bus, and the second was a high-energy impact involving two LRVs in a head-on collision.

Low Energy Impact Analysis—LRV at 20 mph and Mass Transit Bus at 5 mph

This first impact condition represents a low-energy impact between one LRV traveling at 20 mph and one mass transit but bus traveling at 5 mph perpendicular to the LRV trajectory. This impact condition is one of the most common types of accidents where one vehicle—in this case, a mass transportation bus—travels across the LRV path and is hit on the side.

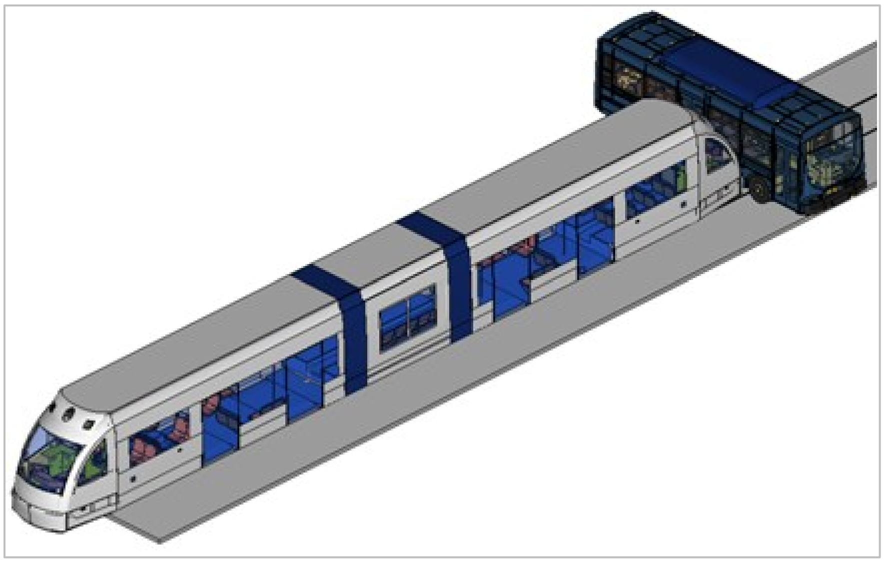


Figure 6-10

Setup of Low Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph

LRV at 20 mph and Mass Transit Bus at 5 mph (90 Degrees)

Because of the large difference in mass between both vehicles, larger structural deformations were expected on the mass transit bus. Figure 6-11 shows a close view of the front part of the LRV immediately after impact. Small deformations can be observed on the main structure. In contrast, the outer plastic shell is entirely deformed. It is important to mention that there are no intrusions into the operator cabin.

Pictures of the mass transit bus immediately after the impact are shown in Figure 6-12 and Figure 6-13. For this vehicle, due to its weaker structure as well as its small mass, larger deformations can be observed.

Large intrusions can be observed on the mass transit bus interior (Figure 6-14). Although there were no occupants in the bus, large injuries should be expected for those passengers traveling on the side-facing seats.

Figure 6-11

Front View of LRV after Low-Energy Impact

Figure 6-12

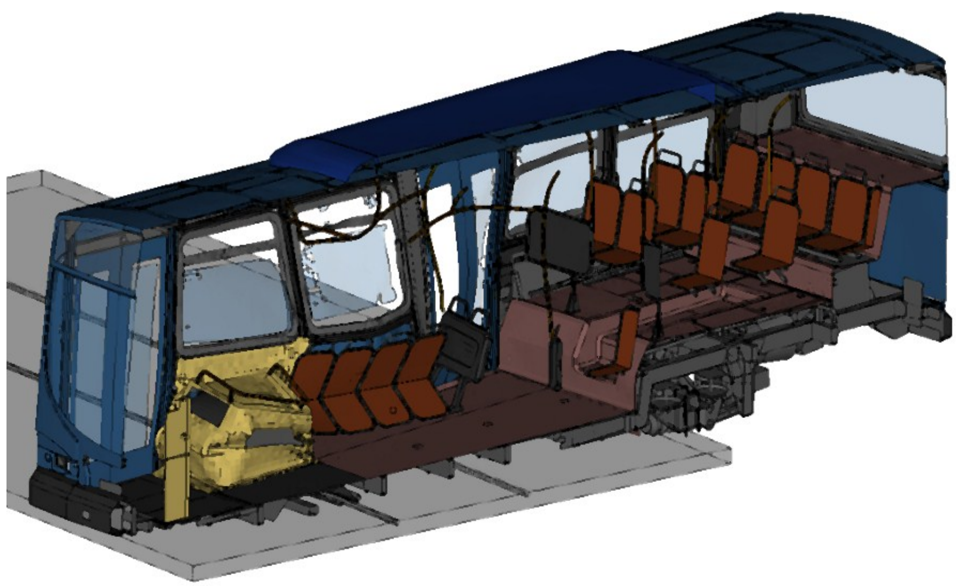
Side View of Mass Transit Bus after Low-Energy Impact

Figure 6-13

Front View of Mass Transit Bus after Low-Energy Impact

Figure 6-14

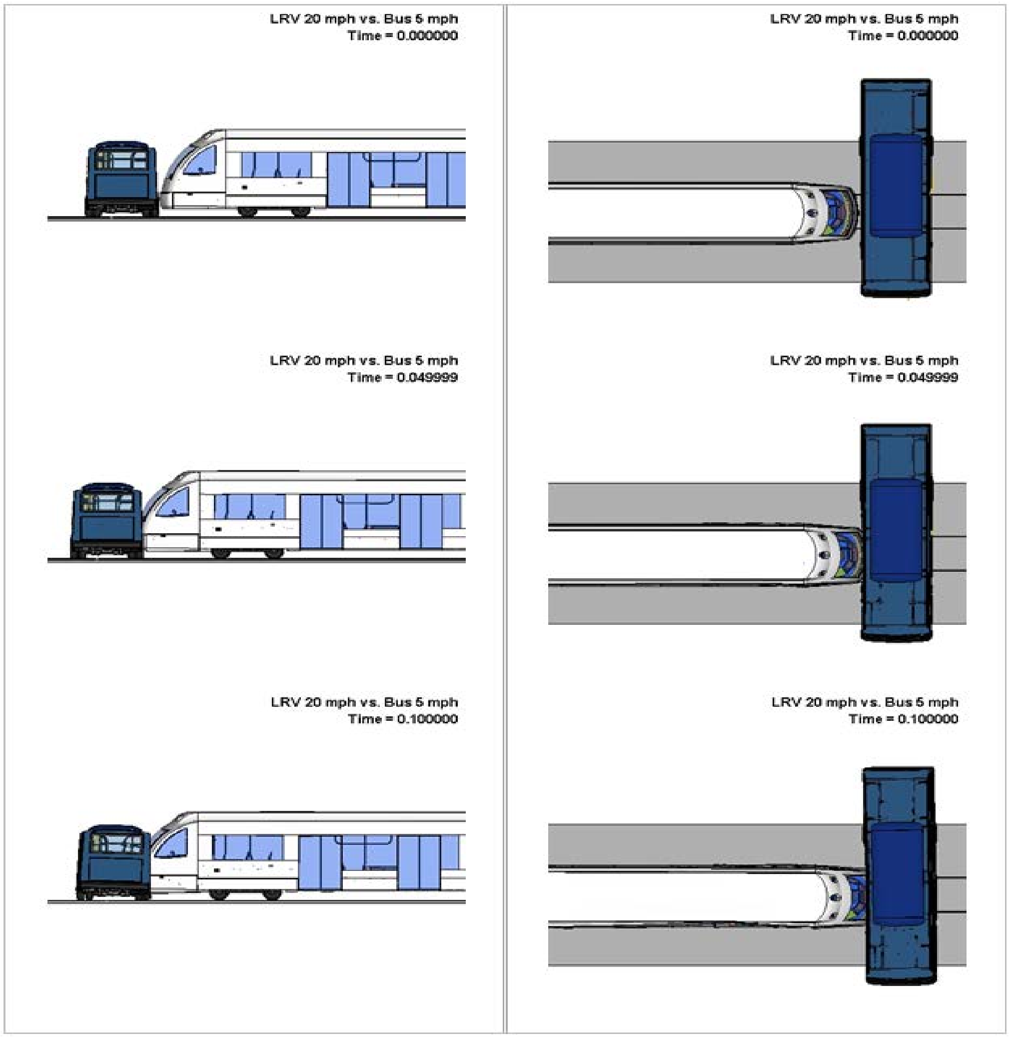
Interior Cut Section of Mass Transit Bus after Low-Energy Impact



Figures 6-15 and 6-16 show the impact kinematics. Figure 6-17 shows the acceleration pulse profile of the LRV during simulation. The largest acceleration recorded is slightly above 4 g's.

Figure 6-15

Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph—0 to 100 ms Impact Moment



Video 6-1

Low Energy 90 Degree LRV vs. Bus Collision Scenario

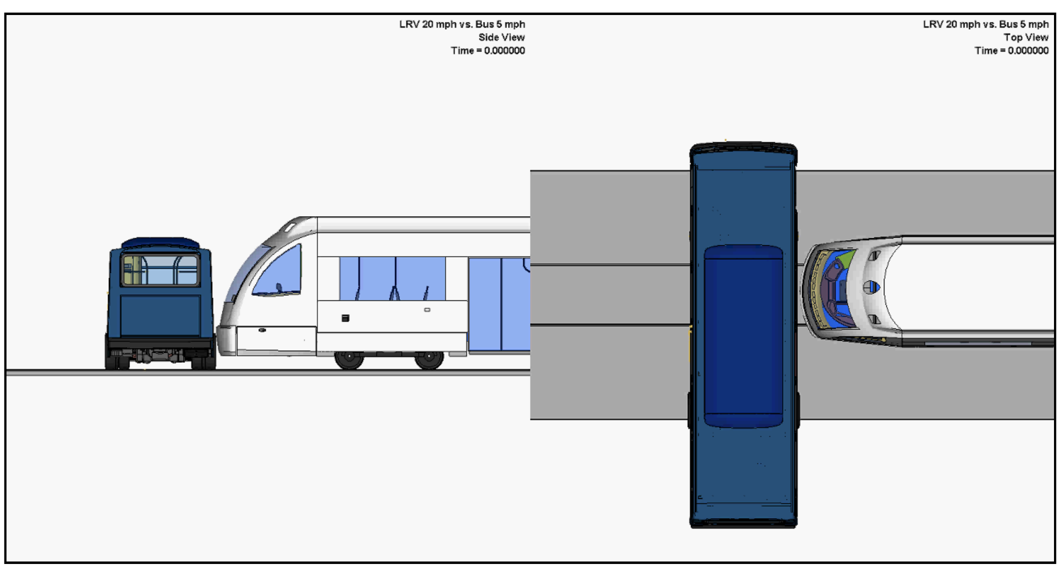
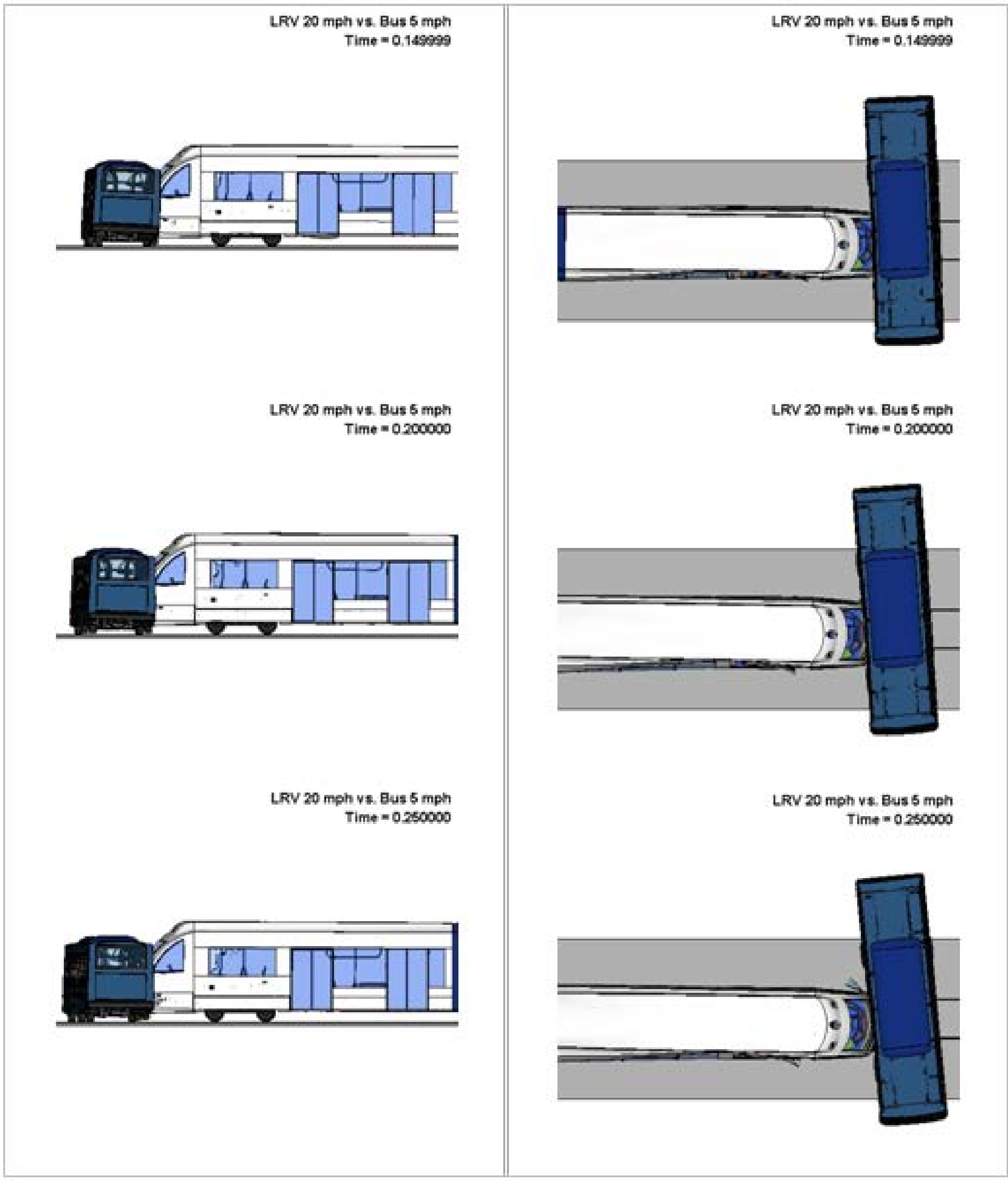


Figure 6-16

Low-Energy 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph—150 to 250 ms Impact Moment



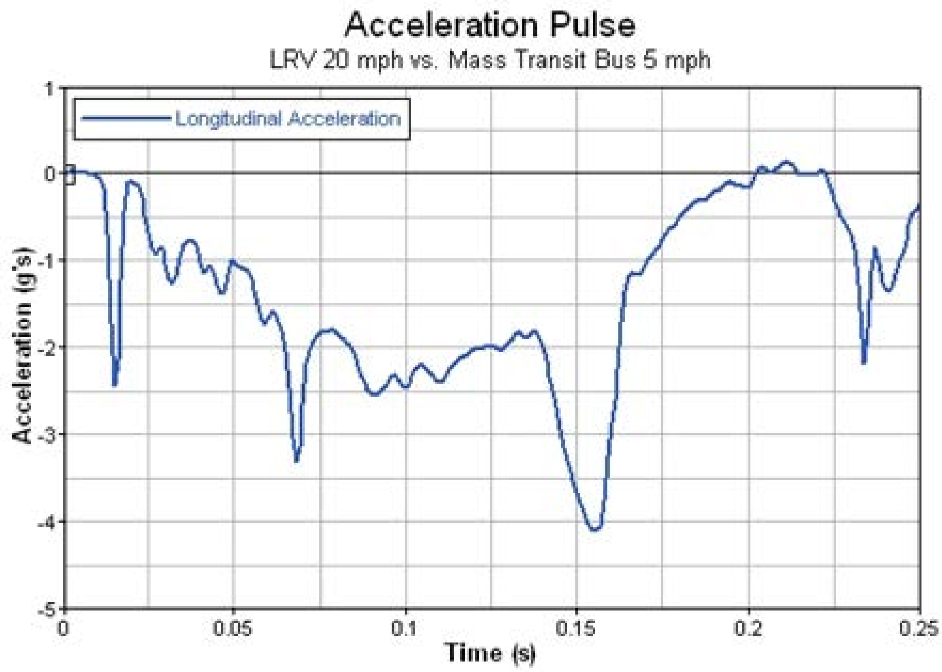


Figure 6-17

Acceleration Pulse of Low-Energy 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph

Occupant Injuries Analysis

Because the difference in mass between both vehicles is very large, this impact is considered a low-energy impact for the occupants traveling on the LRV. Eleven occupants were placed inside the LRV to be able to quantify the level of injuries. Figure 6-18 shows the layout used for the analysis and the arrangement of the occupants. The location of the occupants was chosen so that most of the scenarios studied in Section 2 could be represented.

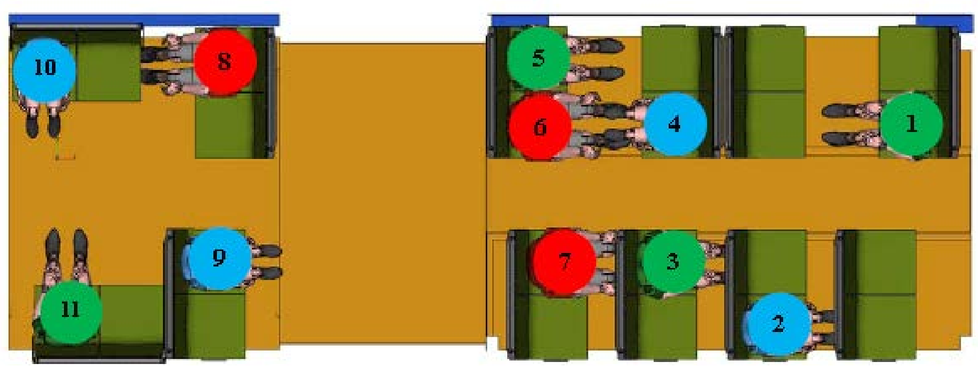


Figure 6-18

Seat Layout and Occupant Arrangement for Low-Energy Impact Condition

The colors used for this analysis are blue for the 5th percentile ATD, green for the 50th percentile ATD, and red for the 95th percentile ATD. Table 6-2 shows the number used for each ATD and a description of its location.

Table 6-2

Positions of ATDs during Low-Energy Impact

ATD Number	Percentile ATD	Position
1	50th	In aft-facing seat across from empty facing seat
2	5th	In forward-facing seat
3	50th	In forward-facing seat
4	5th	In aft-facing seat across from facing seat with ATD
5	50th	In forward-facing seat across from facing seat
6	95th	In forward-facing seat across from facing seat with ATD
7	95th	In forward-facing seat
8	95th	In aft-facing seat across from side-facing seat
9	5th	In forward-facing seat across from monument
10	5th	In side-facing seat next to aft-facing seat
11	50th	In side facing seat next to forward-facing seat

Normalized injury values of the 11 occupants show that the region where most of the injuries were found was the neck. Also, one occupant (#2) suffered high chest acceleration due to impact with the front seat.

For those occupants seated on an aft-facing seat (#1 and #8), high neck extensions moments were recorded (Figure 6-19). However, for both occupants, this value is below half of the limit established by the FMVSS 208.

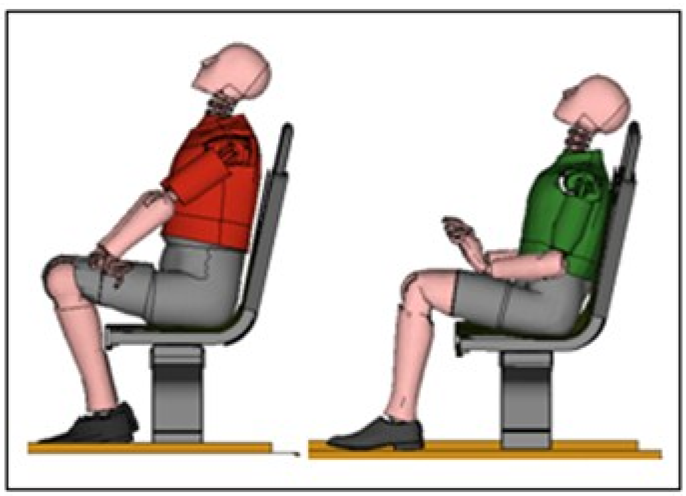


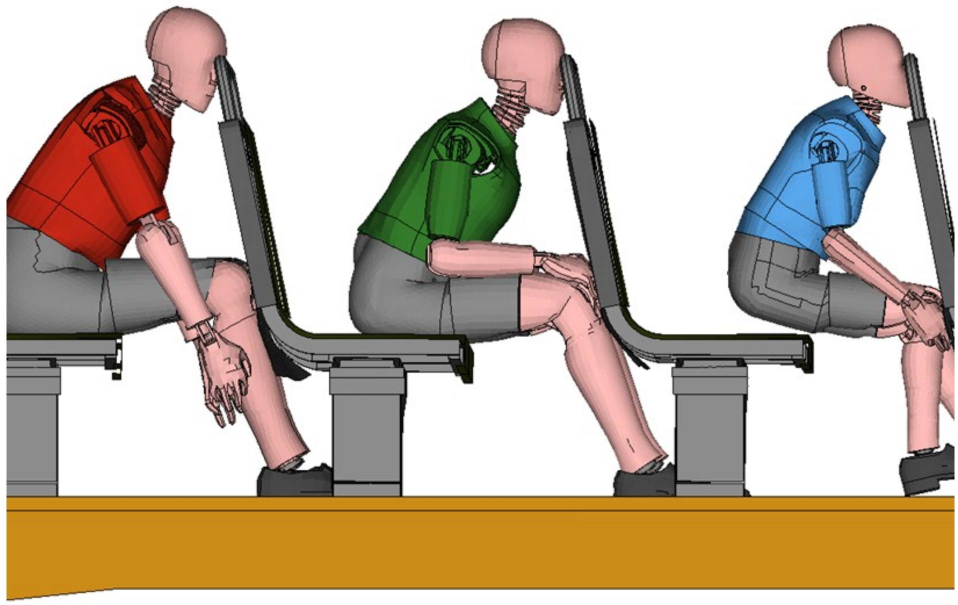
Figure 6-19

Instant of Maximum Neck Extension for Occupants #1 and #8

The occupants seated on the forward-facing seats (#2, #3, and #7) had different level of injuries depending on their sizes. Occupant #2, which is a 5th percentile ATD, had a very large neck extension because of the impact with the handrail. This occupant also had high chest acceleration due to this impact. Occupant #3 had the same problem with its neck extension. Nevertheless, all remaining injury values are very low. On the other hand, occupant #7 had low injury values because of its larger size. Figure 6-20 shows the instant where the maximum extension moment is recorded for each one of these occupants.

Figure 6-20

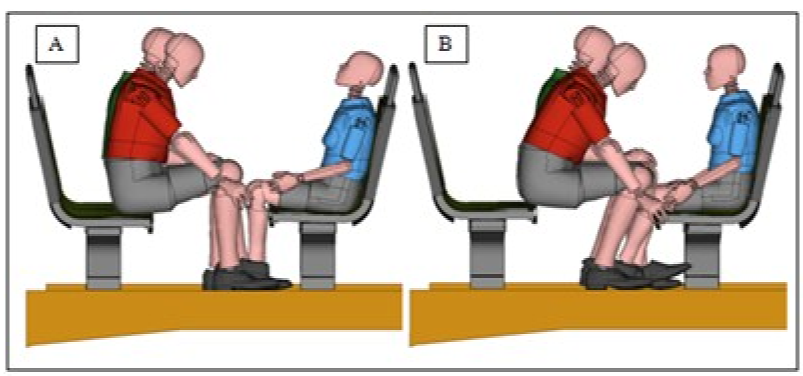
Instant of Maximum Neck Extension for Occupants #2, #3, and #7



For those occupants seated on facing seats, only occupant #4 had some high injury values. Nonetheless, these values always were below 0.5 of the limits established by the FMVSS 208. The higher injury value can be found for the neck extension. Once more, this is because occupant #4 was seated on an aft-facing seat. For this occupant, higher femur forces also can be observed, due to the direct contact with the legs of occupant #6. Figure 6-21 shows the instant of maximum neck and femur forces for occupant #4.

Figure 6-21

Instant of Maximum Neck Extension (A) and Femur Forces (B) for Occupant #4



Occupant #5 suffered high femur forces because of the impact with the empty facing seat (Figure 6-22). Although all the injury values were low, higher neck injuries could be expected once the occupant impacts the front seat back.

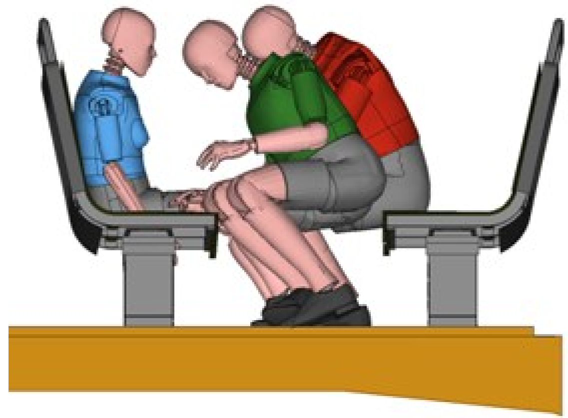


Figure 6-22

Moment of High Femur Forces for Occupant #5

Occupant #9 was seated in a forward-facing seat without any monument directly ahead. Since this is a very singular position, the occupant started moving forward until it hit the floor ahead. For this occupant, high neck injury values as well as higher femur forces can be observed (Figure 6-23).

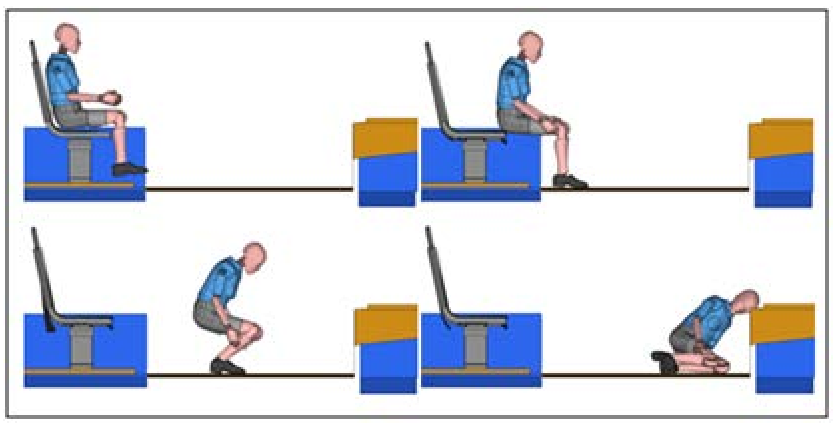


Figure 6-23

Kinematics Progression of Occupant #9 at 0 ms, 250 ms, 500 ms, and 750 ms Impact Moments (left to right, respectively)

Occupants #10 and #11 seated on side-facing seats had smaller injury values—all below 0.25. Thus, the probability of being badly injured in these seats is very small. It is important to mention that even though the injury values for occupant #10 were small, higher values should be expected in the case of a head-to-head impact between occupants.

A summary of all normalized injury values is shown in Figure 6-24. The kinematics progression at various impact conditions is shown in Figures 6-25 and 6-26

Figure 6-24

Normalized Injury Values of ATD Occupants in Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph

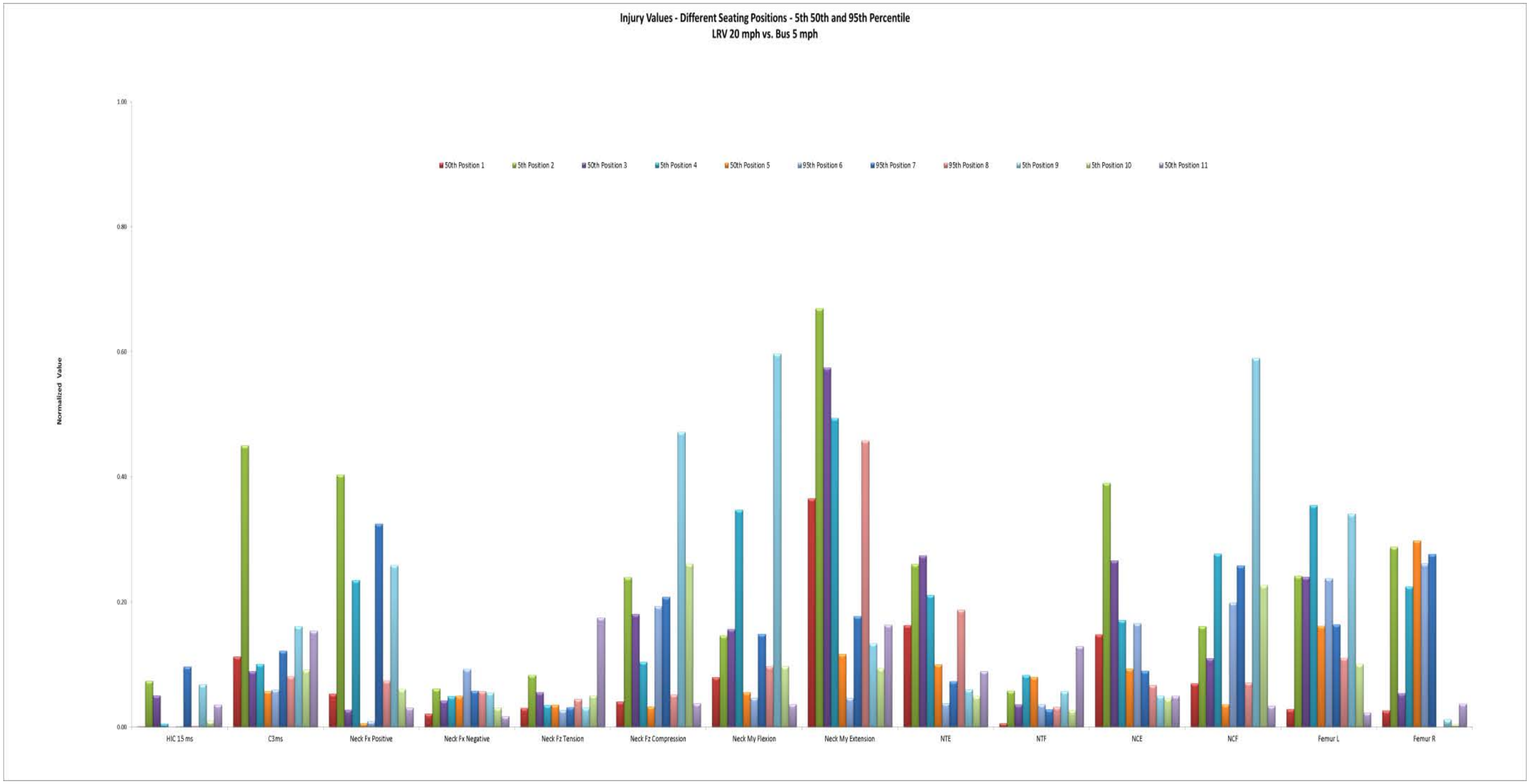


Figure 6-25

Kinematics Progression of ATD Occupants during Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph—0 to 350 ms Impact Moment

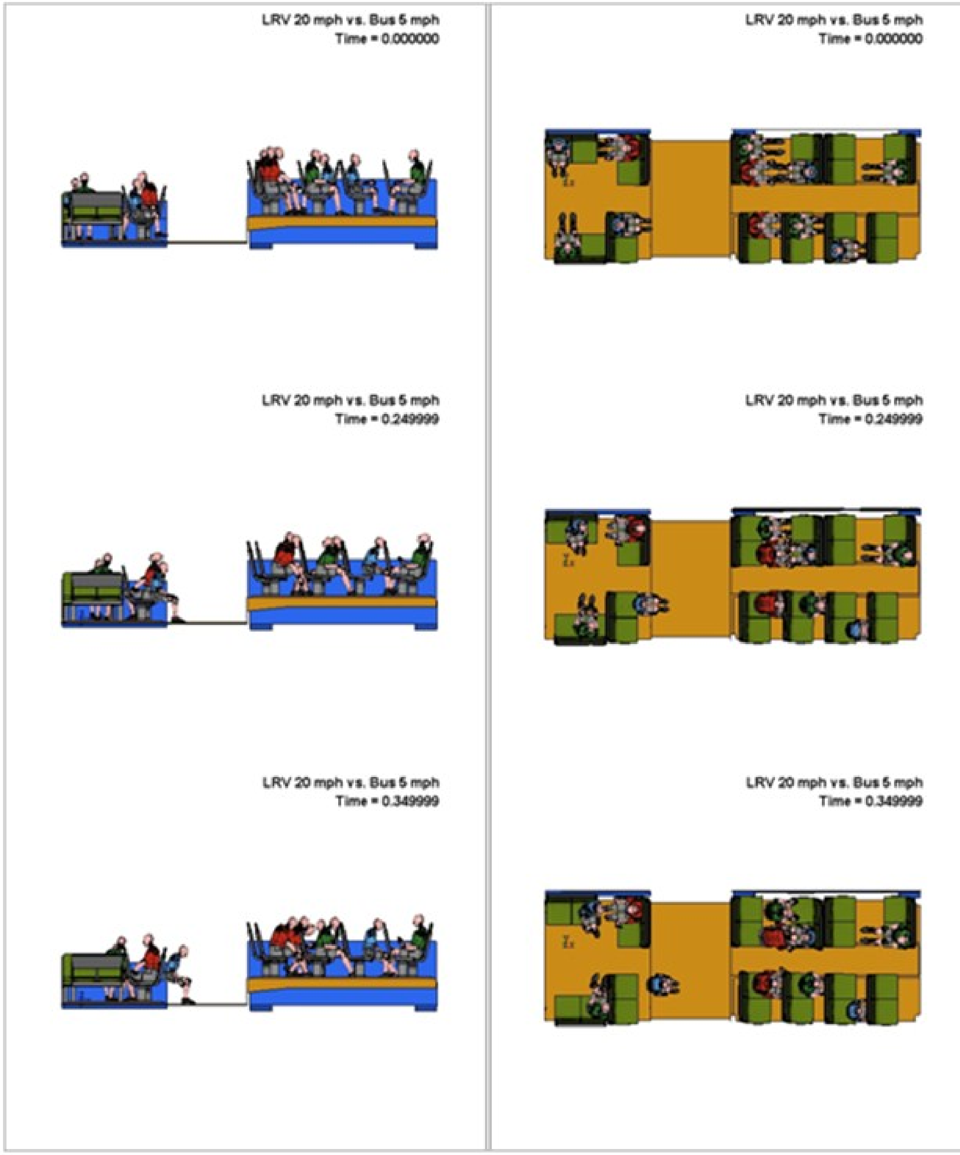
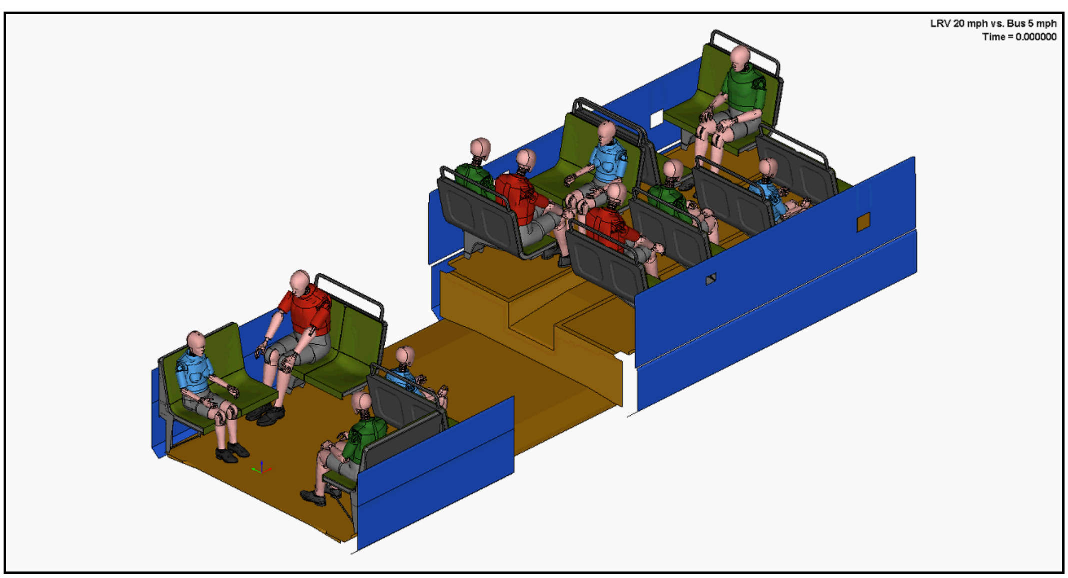


Figure 6-26

Kinematics Progression of ATD Occupants during Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph - 450 to 750 ms Impact Moment



Video 6-2

Low Energy 90 Degree LRV vs. Bus Collision Scenario – Passenger Kinematics

Operator Injuries Analysis

This section analyzes the injury values obtained for the operator in an LRV. Usually, in this type of mass transit transportation system, operators are unrestrained. Hence, in case of severe impact, some injuries can be expected due to impact with the interior cabin. Some types of injuries that can be expected for operators are lacerations or strikes in different body regions. These injuries can be due to impact with an interior part of the cabin or because of the reduction of the survival space.

For the case studied in this section (LRV at 20 mph impacting a mass transit bus perpendicularly traveling at 5 mph), no intrusions were observed on the LRV cabin (Figure 6-11).

The results shown in this section were obtained from a simplified FE model, representative of a typical interior cabin with the operator's console, operator's seat, and main structural parts (Figure 6-27). All interior panels were modeled using plastic material properties; however, aluminum was used for the main console.

The operator seat is a representative seat of a current LRV seat. It is important to notice that this type of seat does not have any type of restraint system. For this analysis, a 50th percentile ATD was used as the operator of the LRV.

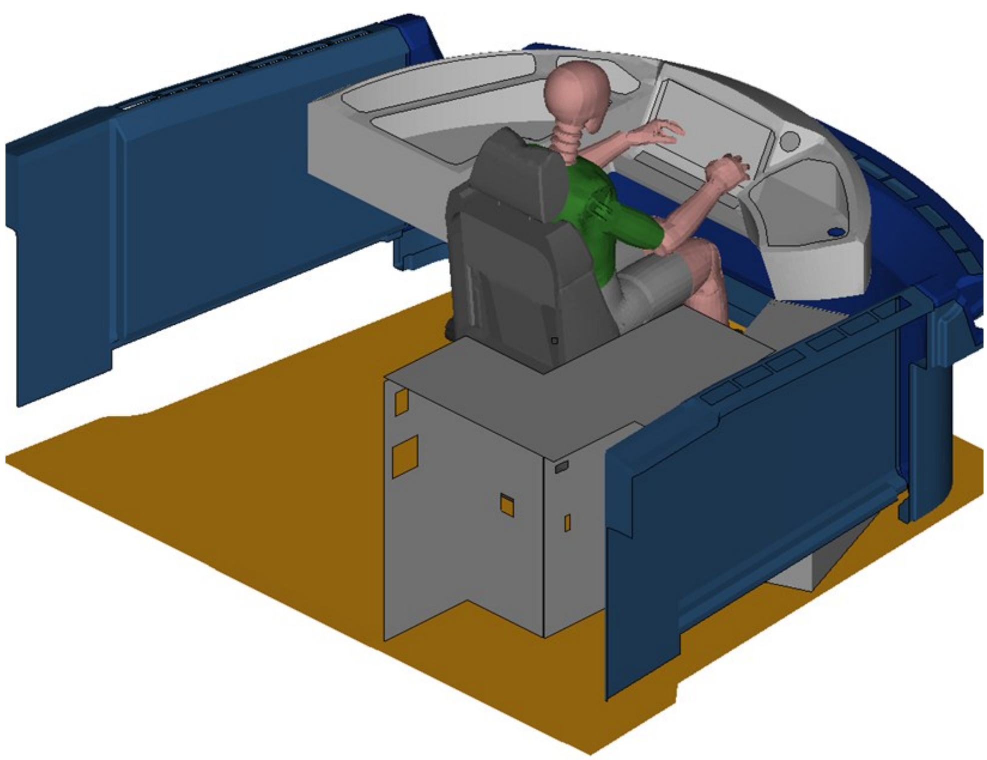


Figure 6-27

ATD Operator's Cabin Setup during Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph

The acceleration pulse obtained from the complete LRV and mass transit bus simulation (Figure 6-17) was applied to the cabin's floor.

Figure 6-28 shows the normalized injury values recorded for the operator involved in this crash scenario. As can be seen, only higher femur forces were observed, due to the impact of the operator and the front part structure. Figure 6-29 shows the moment of impact and therefore the moment where the maximum femur loads were recorded (operator's console is shown as transparent, so the contact between the knees and the structure can be observed).

Figure 6-28

Normalized Injury Values of Operator during Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph

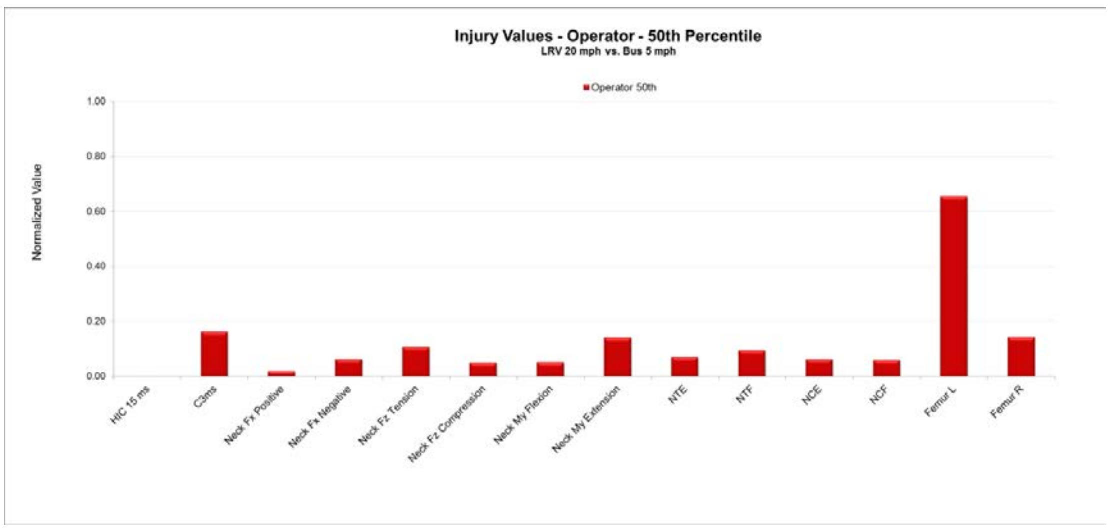
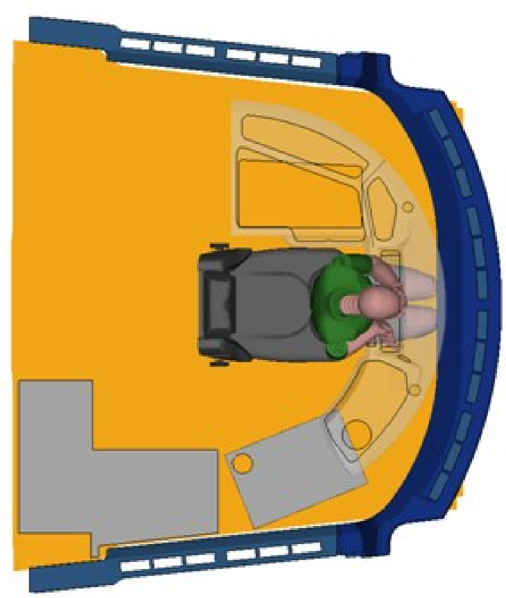


Figure 6-29

Instant of Maximum Femur Forces on Operator during Low-Energy, 90-Degree Impact at 272 ms Impact Moment



The kinematics progression of the impact at various impact moments is shown in Figure 6-30 and Figure 6-31.

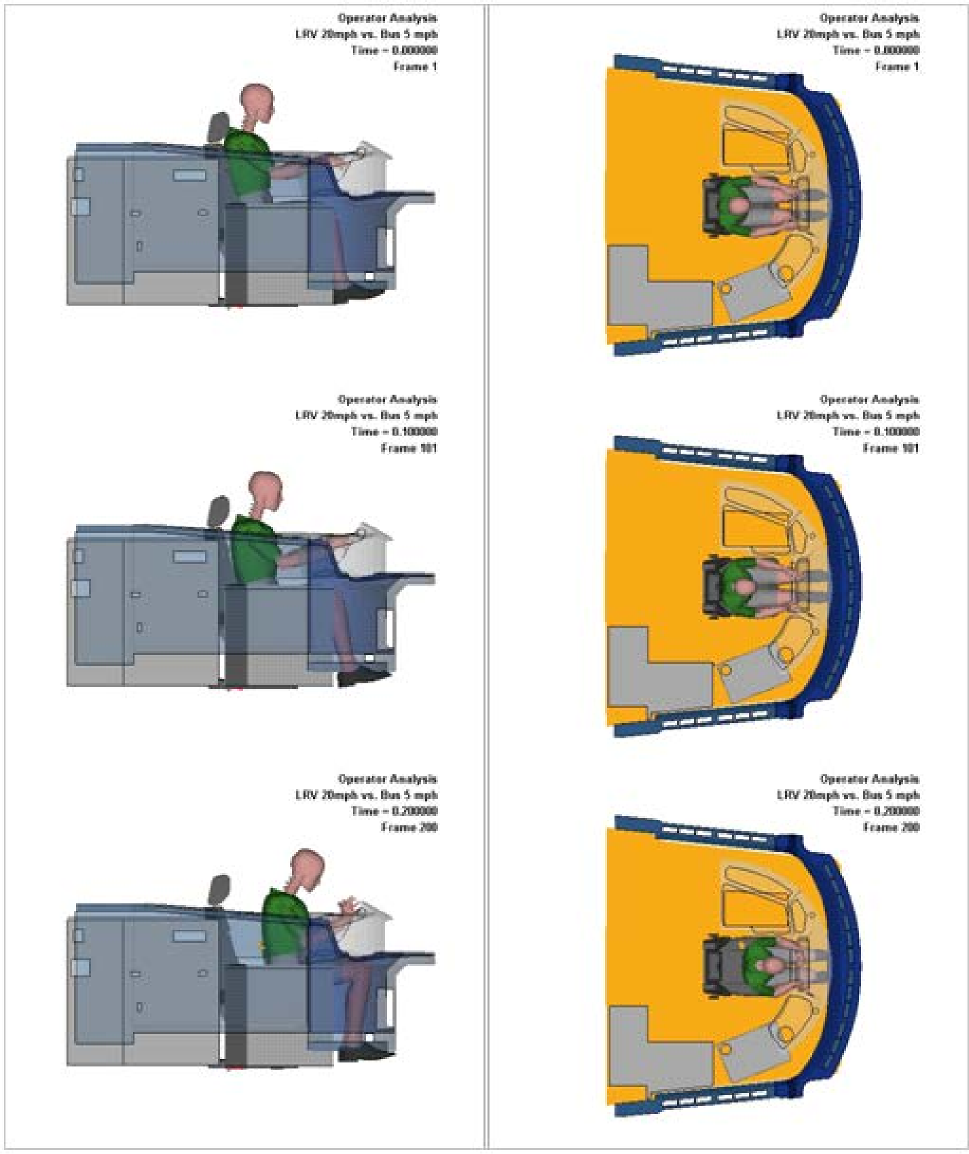
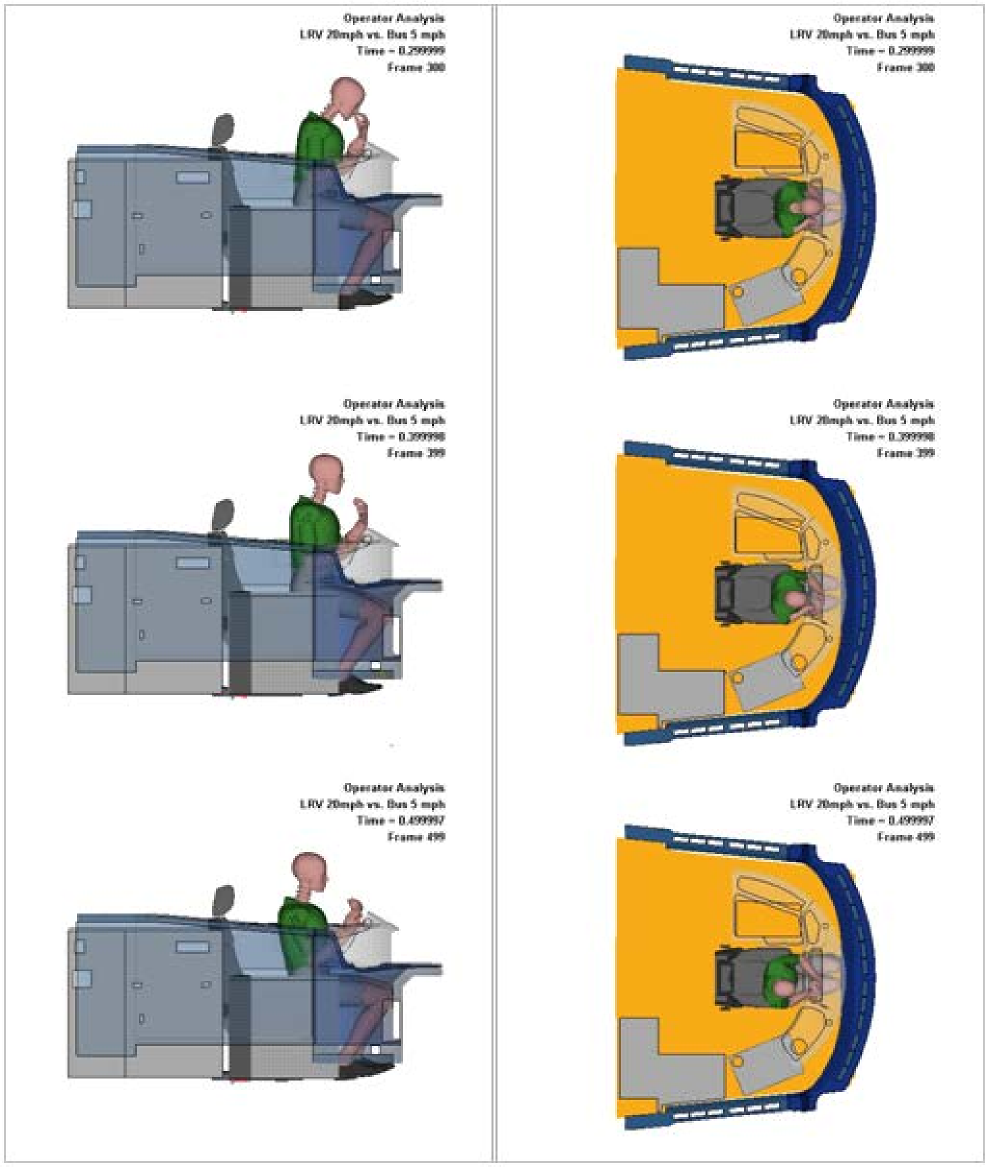


Figure 6-30

Kinematics Progression of ATD Operator during Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph—0 to 200 ms Impact Moment

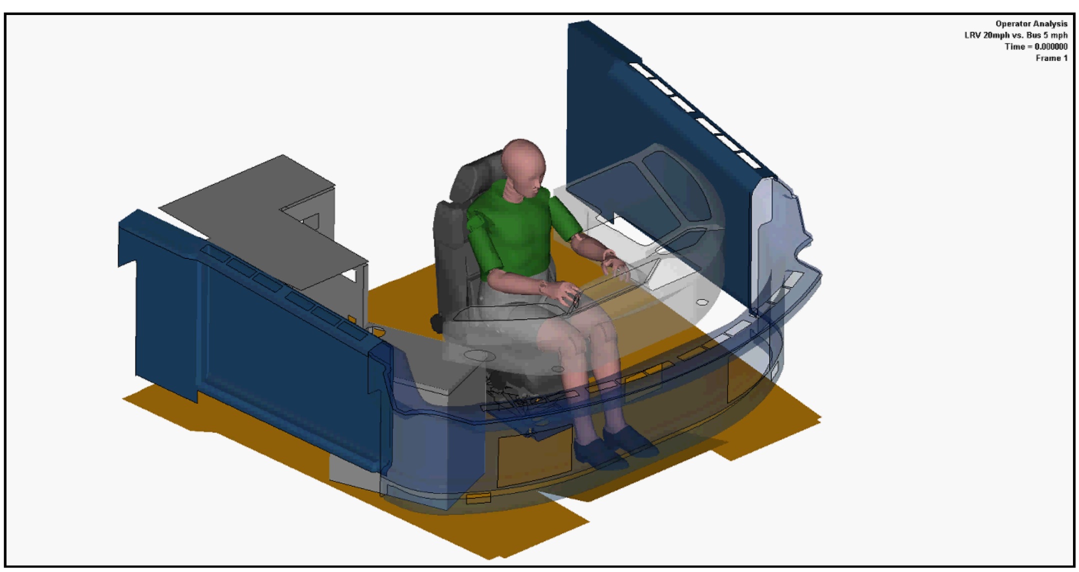
Figure 6-31

ATD Operator Kinematics Progression in Low-Energy, 90-Degree Impact of LRV at 20 mph and Mass Transit Bus at 5 mph—300 to 500 ms Impact Moment



Video 6-3

Low Energy 90 Degree LRV vs. Bus Collision Scenario – Operator Kinematics

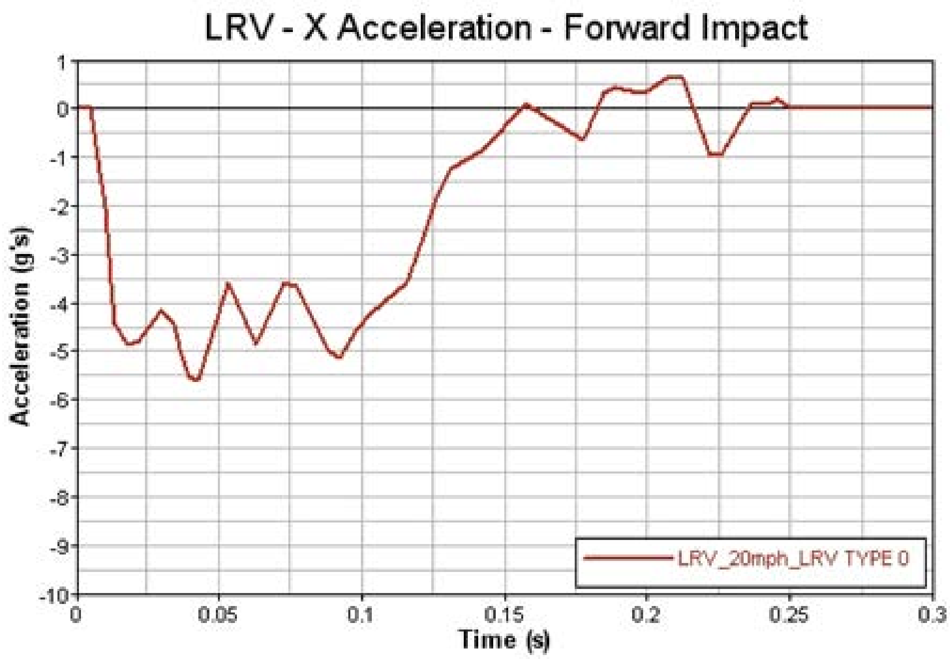


High-Energy Impact Analysis—LRV at 20 mph and LRV at 0 mph

Because the acceleration profile for this type of accident was available from Section 4, a simplified version of the LRV FE model was used. The acceleration pulse used is shown in Figure 6-32. It corresponds to the collision between one LRV traveling at 20 mph while another one is stopped (0 mph).

Figure 6-32

Acceleration Pulse of High-Energy Impact of LRV at 20 mph and LRV at 0 mph



Occupant Injuries Analysis

The interior arrangement shown in Figure 6-33 was used for this analysis. The acceleration pulse was applied to the floor in the longitudinal direction. To facilitate the comparison between different energy levels due to impact, the same arrangement of seats and occupants was used for both low- and high-energy impacts. Table 6-3 shows the ATD numeration as well as its position on the aforementioned configuration.

Figure 6-33

Seat Layout and Occupant Arrangement for High-Energy Impact Condition

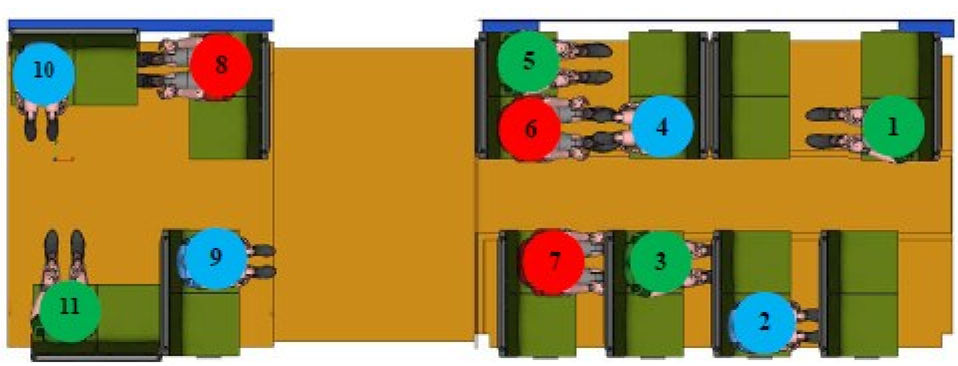


Table 6-3

Positions of ATDs during High-Energy Impact

ATD Number	Percentile ATD	Position
1	50th	In aft-facing seat across from empty facing seat
2	5th	In forward-facing seat
3	50th	In forward-facing seat
4	5th	In aft-facing seat across from facing seat with ATD
5	50th	In forward-facing seat across from empty facing seat
6	95th	In forward-facing seat across from facing seat with ATD
7	95th	In forward-facing seat
8	95th	In aft-facing seat across from side-facing seat
9	5th	In forward-facing seat across from monument
10	5th	In side-facing seat next to aft-facing seat
11	50th	In side-facing seat next to forward-facing seat

Normalized injury values for the 11 occupants shows that the region where most of the injuries can be found is the neck. One occupant (#2) also suffered high chest acceleration due to impact with the front seat.

Again, as for the low-energy pulse, occupants seated on an aft-facing seat (#1 and #8) had high neck extensions moments (Figure 6-34). This value is above the FMVSS 208 limit for occupant #8 and below the limit for occupant #1. The difference between these two values can be explained primarily by the difference in mass as well as size of both occupants' heads. The inboard and outboard positions can also affect the way the seat deforms and therefore the kinematics of the movement. Occupant #8 was seated at the inboard position, and therefore less deformation was observed on the seat.

Occupants seated on forward-facing seats (#2, #3, and #7) had different level of injuries depending on their sizes. Occupant #2 had a very large neck extension due to impact with the handrail. As in the low-energy condition, this occupant also had very high chest acceleration as a result of this impact. For this impact condition, it is important to notice that the femur forces were higher. Occupant #3 also had high neck extension. As a result of the combination of high neck extension and high tension and compression loads, the NTE and NCE injury values are also high.

Occupant #7, as a result of its different size and mass, deformed the seat ahead more than occupants #2 and #3. Thus, the injury mechanism was different. For this occupant, the higher injury value was observed for the neck Fx force because of the large head angle prior to impact with the handrail. Figure 6-35 shows occupants at the instant of maximum femur forces, and Figure 6-36 shows occupants at the instant of maximum neck extension.

Figure 6-34

Instant of Maximum Neck Extension for Occupants #1 and #8

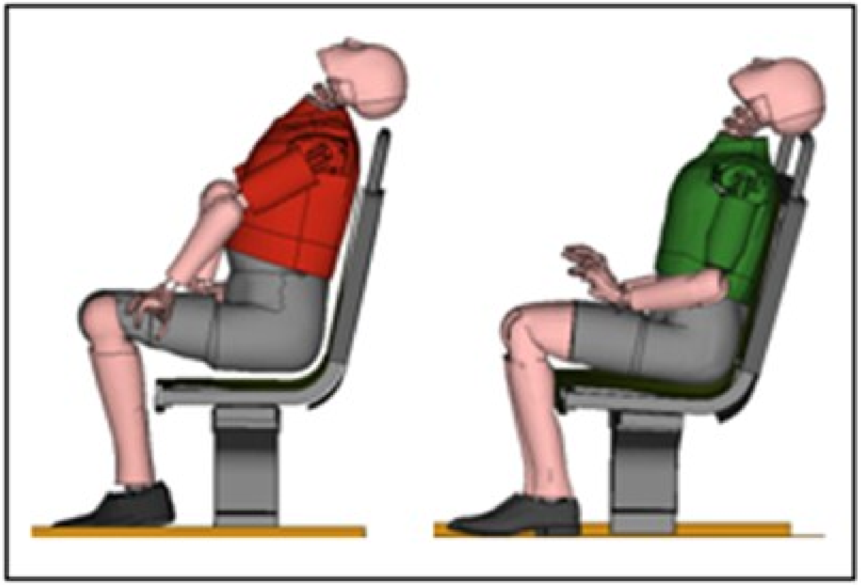


Figure 6-35

Instant of Maximum Femur Forces for Occupants #2, #3, and #7

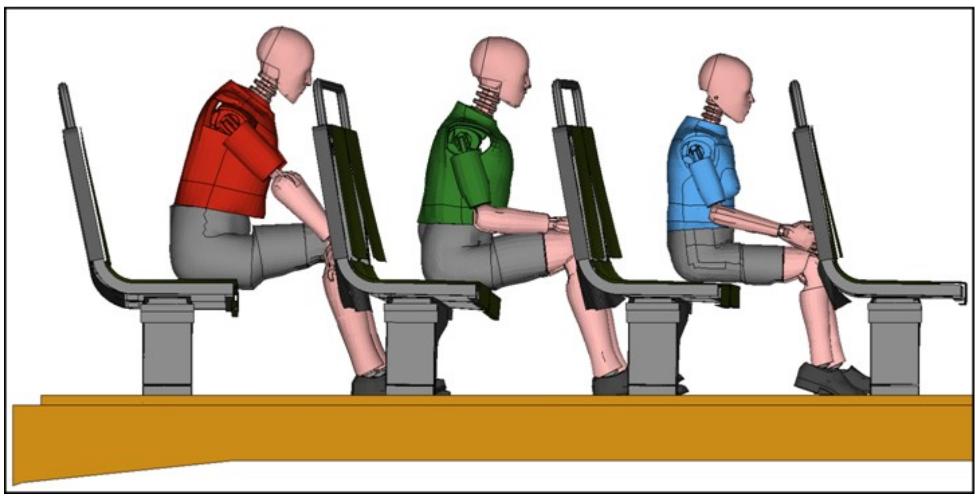
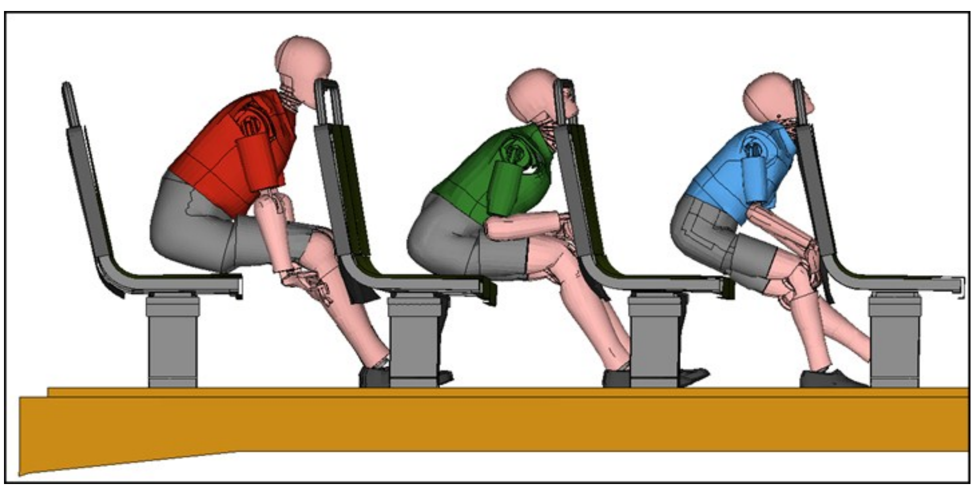


Figure 6-36

Instant of Maximum Neck Extension for Occupants #2, #3, and #7



For occupants seated on facing seats (#4, #5 and #6), only occupant #6 had low injury values. Occupant #4 had a high neck extension because of the aft-facing seat. At the same time, high femur forces can be observed on occupants #4 and #6 because of the direct impact between their low extremities (Figure 6-37).

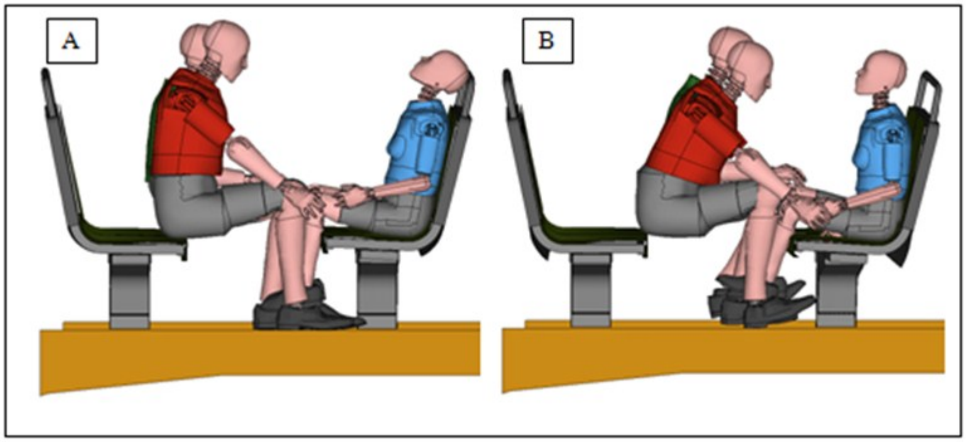


Figure 6-37

Instant of Maximum Neck Extension (A) and Femur Forces (B) for Occupant #4

For this high-energy impact, occupant #5 impacted the facing seat in front of it. Consequently, high injury values were observed for neck extension and neck compression (Figure 6-38). Also, femur forces were higher than those obtained during the low-energy impact.

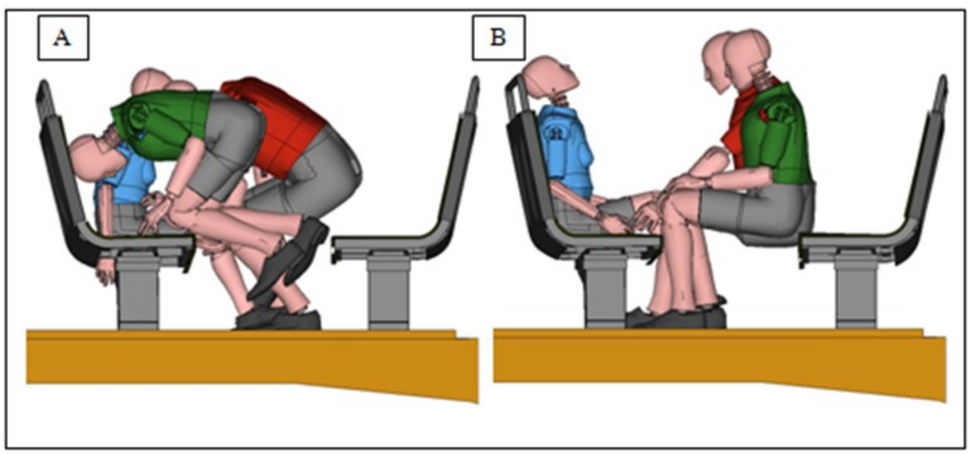


Figure 6-38

Instant of Maximum Neck Extension and Compression (A) and Femur Forces (B) for Occupant #5

Occupant #9 was seated in a forward-facing seat without any monument directly ahead of it. Because of the high velocity of the occupant in the moment of impact, the occupant seated in this position moves quickly toward the seat and floor ahead and, thus, higher femur forces can be observed. At the same time, high chest acceleration also is observed. During the rebound, after impacting the floor ahead, high injury values on the neck region can be expected. Figure 6-39 shows the kinematics progression for this occupant; notice the occupant position at the same instant when compared with the low-energy impact (Figure 6-23).

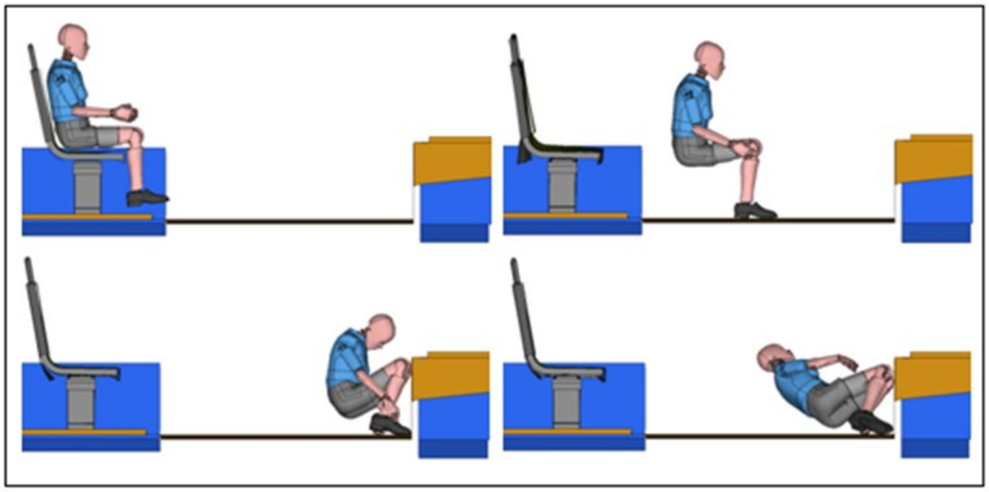


Figure 6-39

Kinematics Progression of Occupant #9 at 0 ms, 250 ms, 500 ms, and 750 ms Impact Moments (left to right, respectively)

Once again, occupants #10 and #11 had smaller injury values. They were the only occupants that had all injury values below the current FMVSS 208 limits. Nevertheless, occupant #10 had high chest acceleration (3 ms) due to impact with occupant #8. As a result, some medium values were observed for neck compression and extension.

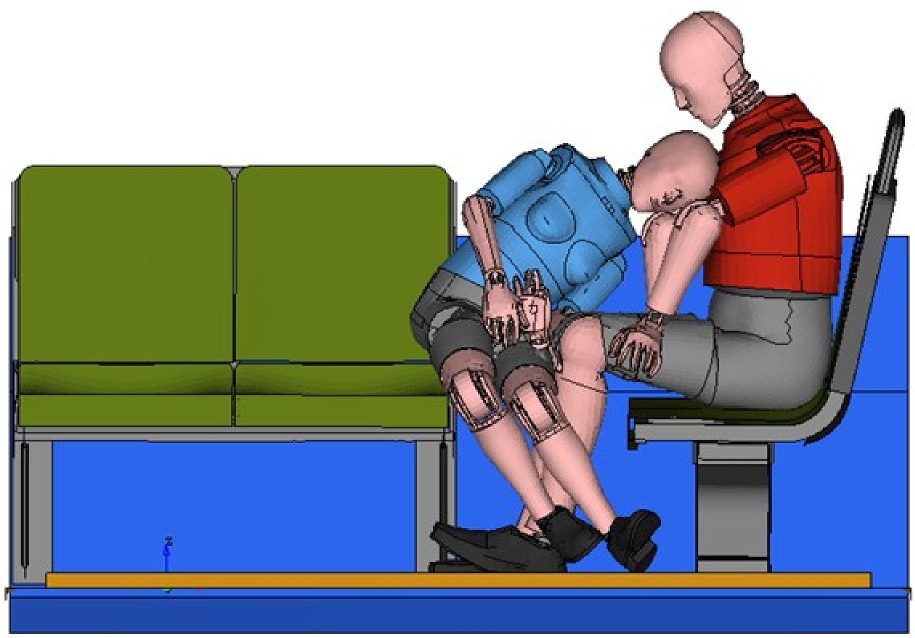


Figure 6-40

Instant of Maximum Chest Acceleration and Neck Loads for ATD Occupant #10

On the other hand, occupant #11 had the lowest injury values, as shown. It is possible to see that all injury values are below 0.25, which represents a very low probability of being injured.

A summary of all normalized injury values is shown in Figure 6-41. The kinematics progression of the impact condition is shown in Figure 6-42 and Figure 6-43

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Figure 6-41

Normalized Injury Values of ATD Occupants during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph

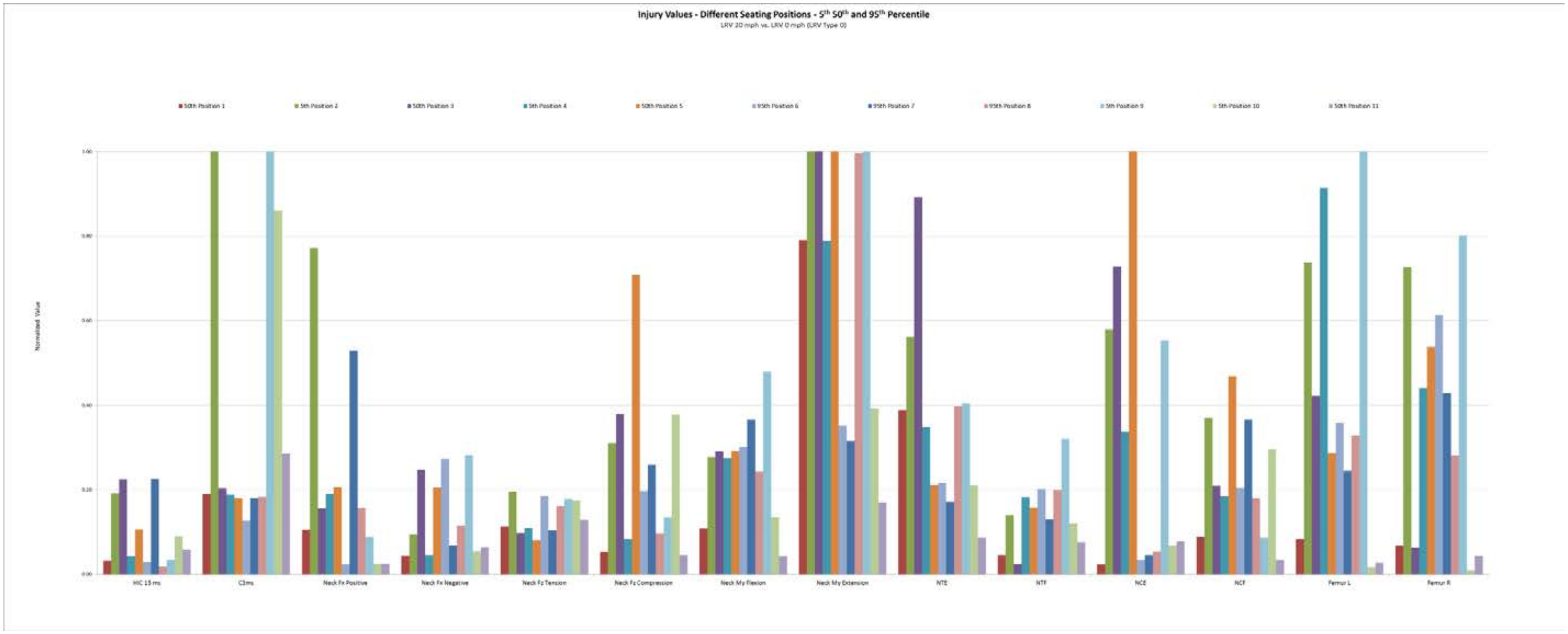
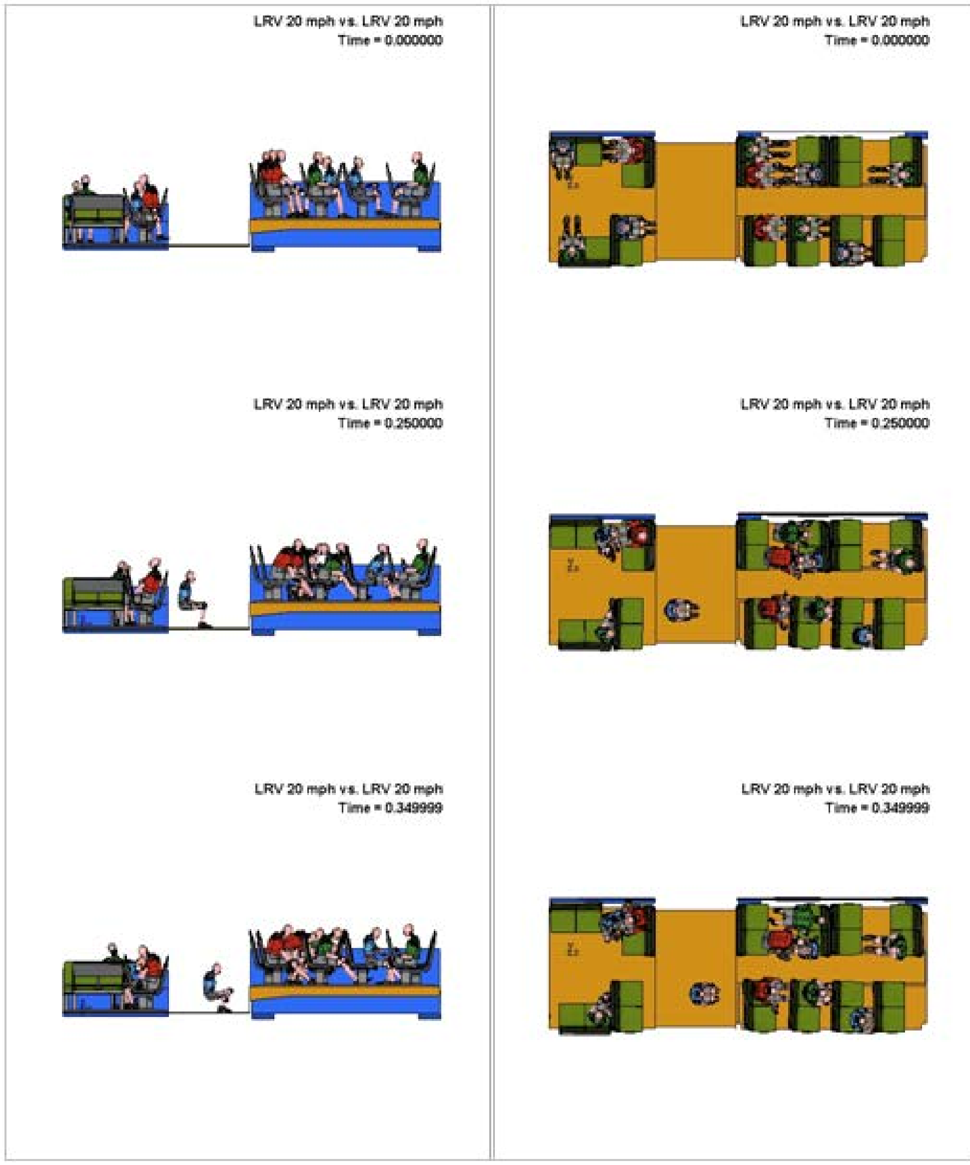


Figure 6-42

Kinematics Progression of Occupants during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph—0 to 350 ms Impact Moment



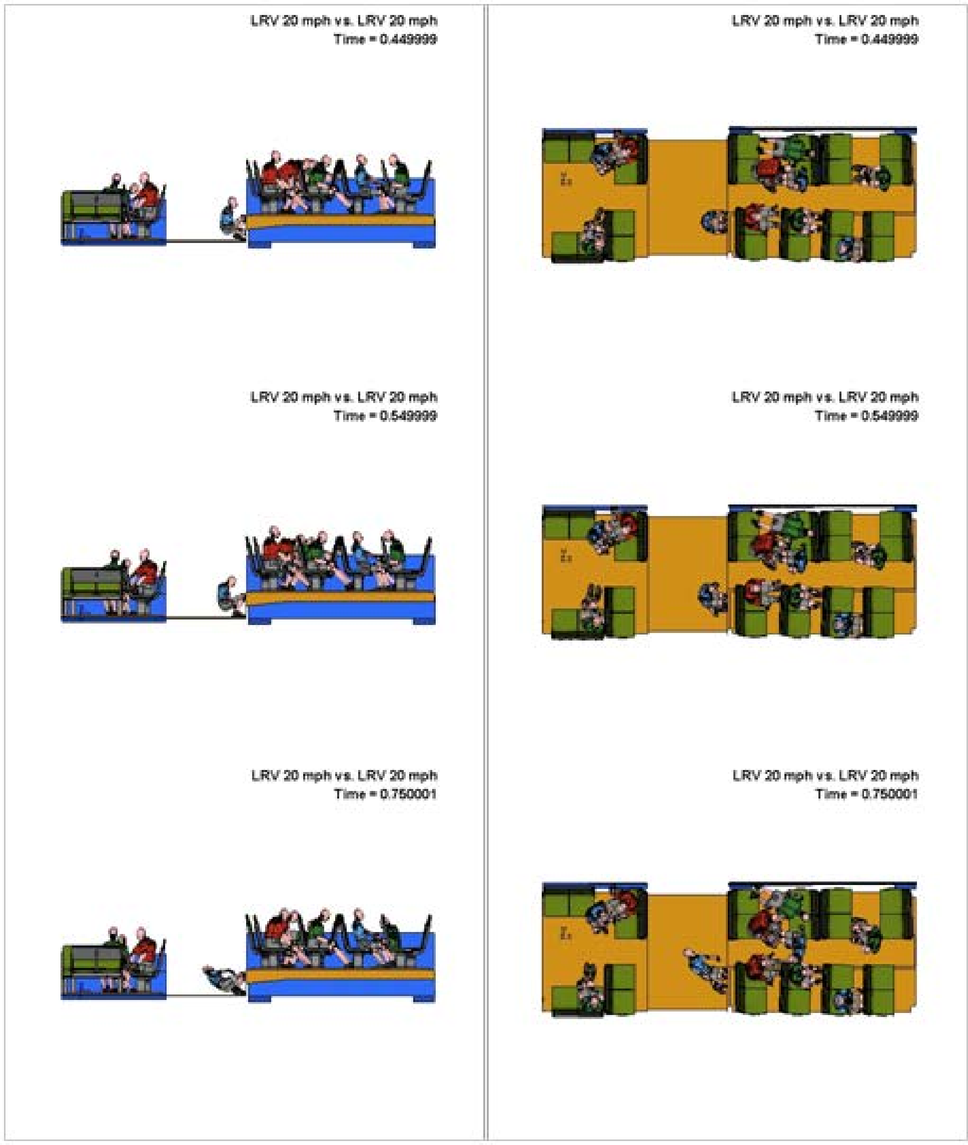
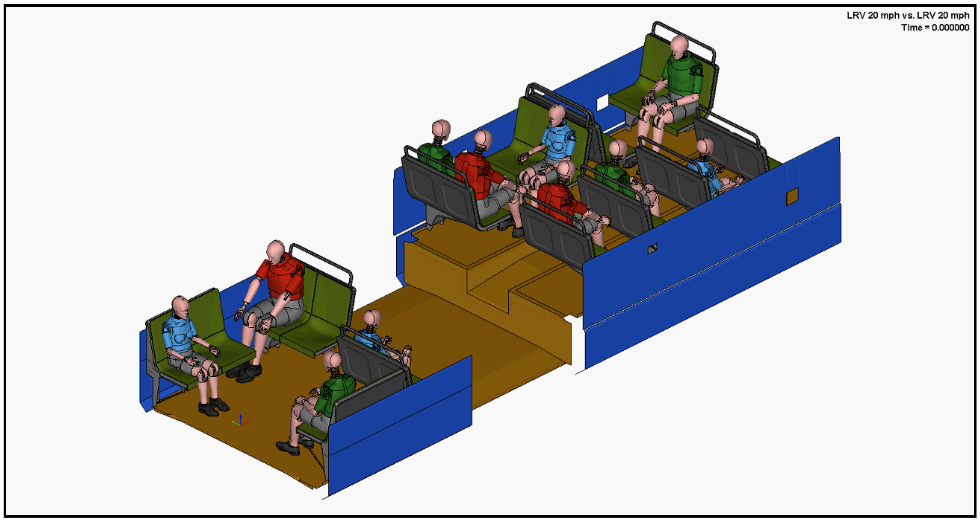


Figure 6-43

Kinematics Progression of Occupants during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph—450 to 750 ms Impact Moment

Video 6-4

High Energy LRV vs. LRV Collision Scenario – Passenger Kinematics

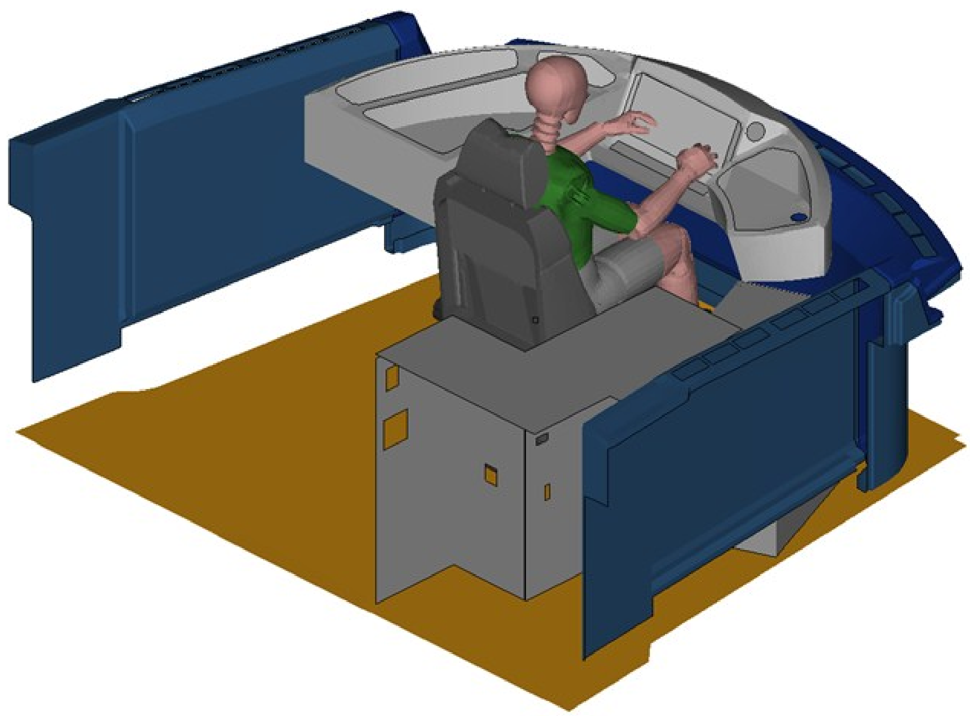


Operator Injuries Analysis

An independent analysis for the operator was completed and is described in this section. The model used was the same as that used in Section 6. The only difference is the acceleration pulse applied to the system. For this high-energy impact configuration, the same acceleration pulse used for Section 6 was used (Figure 6-32). The initial setup of the operator's cabin is shown in Figure 6-44.

Figure 6-44

Operator's Cabin Setup during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph



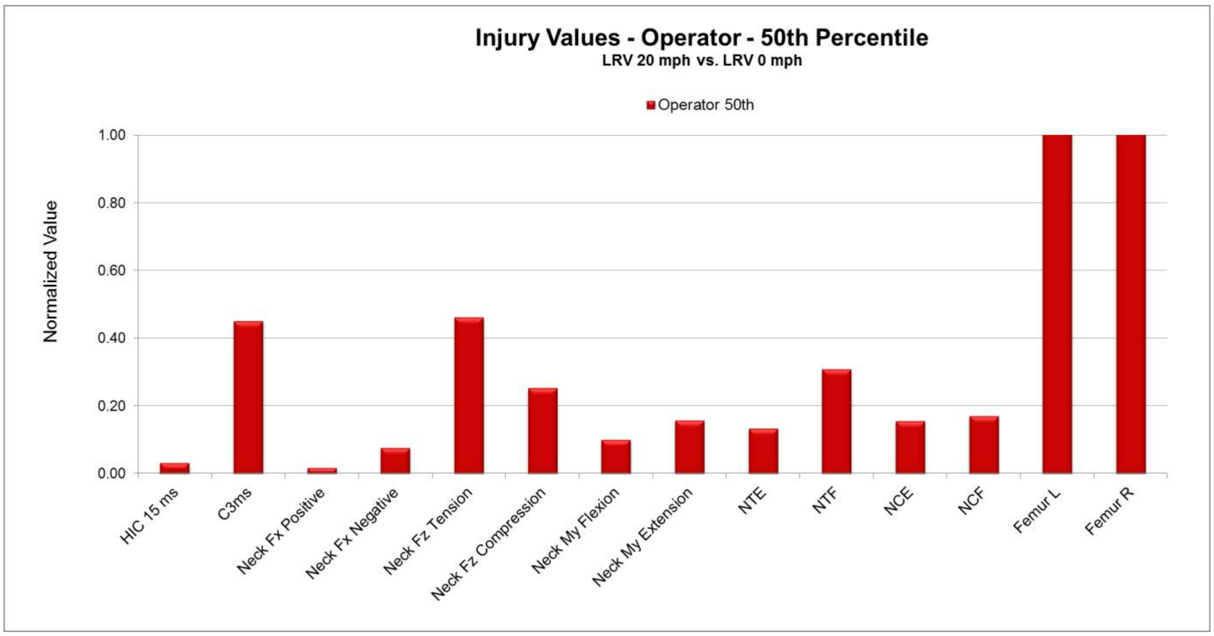
Although this is a high-energy impact, no reduction of the survival space was considered for this analysis. Consequently, the injury values observed for this model are representative of the interaction of the operator with the cabin interior only. Further analysis needs to be done to understand the injuries (if any) due to the reduction of survival space in the operator's cabin for this type of high-energy impact.

Figure 6-45 shows the normalized injury values recorded for the operator involved in this crash scenario. As can be seen, higher injury values can be observed for all parameters. The high femur loads are significant and above the current FMVSS 208 limits. The left femur force recorded was 22595 N, which is 2.26 times larger than the current limit (10000 N).

Figure 6-46 shows the moment of impact and, therefore, the moment where the maximum femur loads were recorded (operator's console is shown as transparent so the contact between the knees and the structure can be observed).

Figure 6-45

Normalized Injury Values of Operator during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph



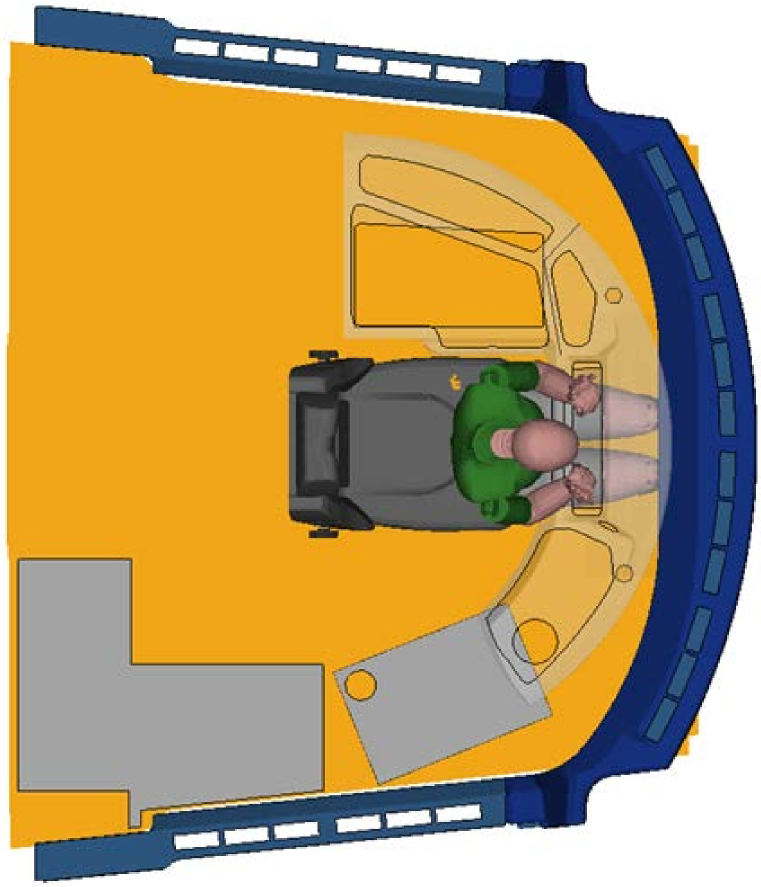


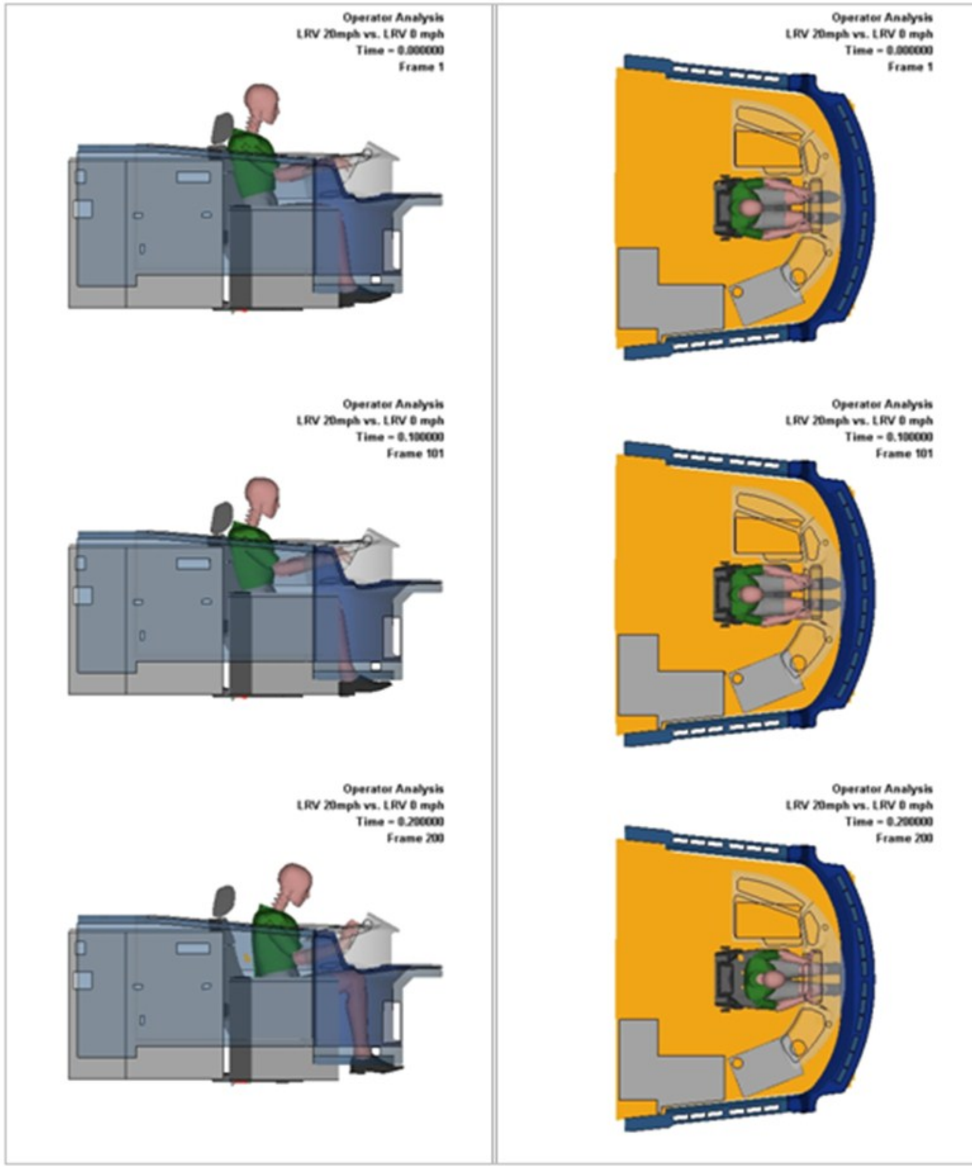
Figure 6-46

Instant of Maximum Femur Forces of Operator during High-Energy, 90-Degree Impact at 272 ms Impact Moment

The kinematics progression of this high-energy impact at various impact moments is shown in Figure 6-47 and Figure 6-48.

Figure 6-47

Kinematics Progression of Operator during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph—0 to 200 ms Impact Moment



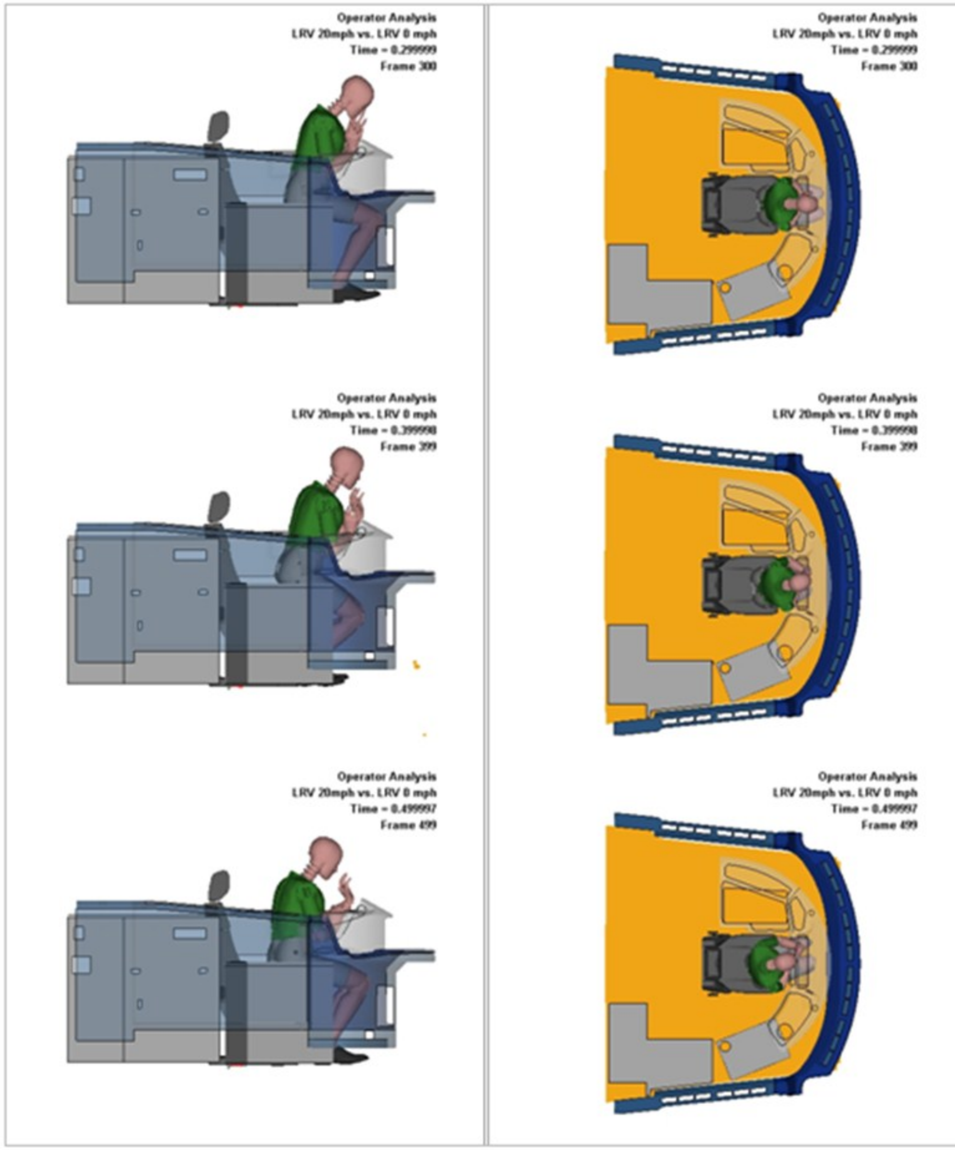
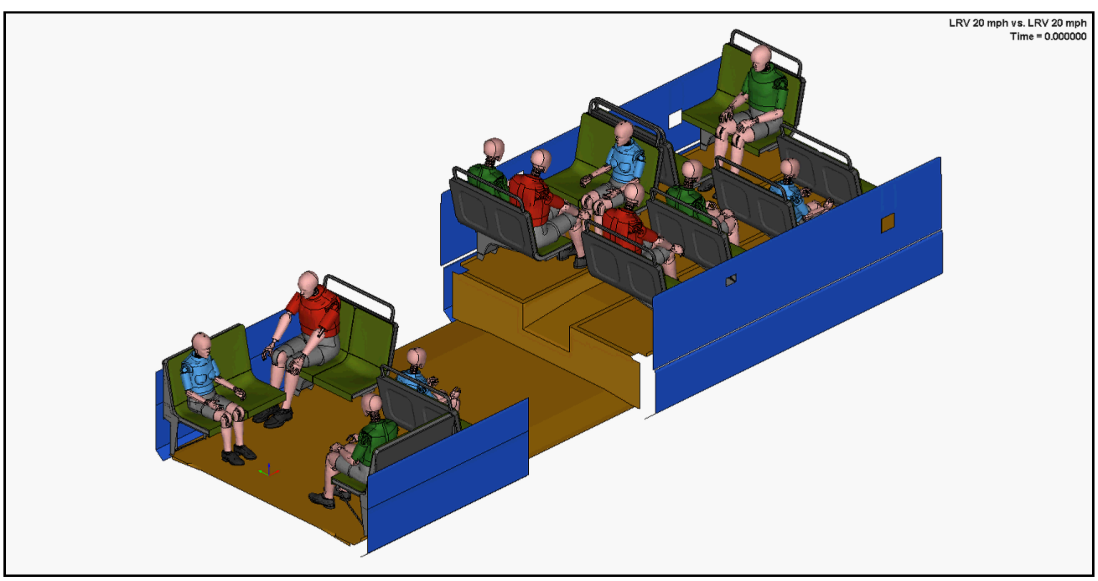


Figure 6-48

Kinematics Progression of Operator during High-Energy, 90-Degree Impact of LRV at 20 mph and LRV at 0 mph—300 to 500 ms Impact Moment



Video 6-5

High Energy LRV vs. LRV Collision Scenario – Operator Kinematics

SECTION

7

Conclusions and Future Work

The results of this study show that because of weight differences between LRVs and other vehicles with which they share the road, only collisions between LRVs and large vehicles, such as buses or trucks, seem to be hazardous for LRV occupants. Consequently, the high-impact crash scenario selected for this analysis represents the collision between two LRVs, one traveling at 20 mph and the other stationary (0 mph).

By analyzing this crash scenario, the most common and severe injury mechanisms to LRV passengers were studied. According to the results of this study, these injuries occur in the head (HIC), neck (neck extension, flexion, shear, and compression) and femur (compression) regions. The seating configurations that contribute to these injury mechanisms are the following:

- Injuries in forward-facing seat configurations are due to contacts between the head and seat backs. It should be noted that with current seat-back designs, it is difficult to maintain a consistent injury level. The interaction of an unbelted passenger with the seat yields either neck flexion or extension issues, depending on the contact area. A compartmentalization approach should be used to provide head-impact-compliant surfaces for a wide range of passenger sizes. Also, as a consequence of the type of connection between the seat and the LRV structure, it is likely that the passengers sitting inboard (by the window) will have greater injuries than those sitting outboard (by the aisle).
- For configurations where forward- and aft-facing seats are facing each other, injuries are due to contact between occupants and appear at both the head and neck regions. Injuries to the femurs also can be large if there is an interaction between passengers' legs. The size and position of the occupant does not appear to be an important factor in injuries as a result of this configuration. Because of the difficulty in managing occupant interaction, this type of seating arrangement should be avoided.
- For passengers seated in lateral-facing seats, the most common injury mechanisms are head, neck, and femur compression due to contact with passengers seated in aft-facing seats. This type of seating arrangement should be avoided in future LRVs. If only one passenger is seated in the lateral-facing seat, the best configuration to minimize injury values is a row of lateral-facing seats followed by a row of forward-facing seats. However, when more than one occupant is seated in the lateral-facing seats, the injury values increase. Further analysis should be done to improve the interaction between the occupant and seat back. In general, the seating arrangement that minimizes the risk of severe injuries for passengers in lateral-facing seats is the addition of a barrier or divider. These barriers

could be designed with padded surfaces to further reduce the risk of injuries.

- For passengers seated in a row of forward-facing seats at the back of the LRV, the most common injuries are in the head and neck regions. Also, some femur forces can be more severe than expected. It is important to mention that this study does not take into account the possibility of incursion into the cabin as a result of the collision. If this occurs, an increase in the severity of injuries can be expected. Thus, this type of seating arrangement should be avoided in future LRVs.
- Although a child seat inside an LRV is not a frequent occurrence, a simple restraint system could be used to improve child safety in case of an accident. This type of restraint system could be designed and placed in a small number of seats, so that it does not inconvenience other occupants (see Figure 5-88).
- Usually, existing LRVs have specific areas where wheelchairs can be positioned but, typically, anchor points are not available in these areas. When anchors are not used and an accident occurs, the wheelchair could jeopardize the safety of other passengers. In the future, some type of restraint system should be developed and made mandatory to improve safety.

The light rail vehicle represents one of the safest modes of transportation [2]. In 2007, only 32 fatalities and about 800 injuries occurred in approximately 1,800,000 passenger miles traveled. It is unknown if the 30 fatalities were all passengers traveling in the LRV or if, on the contrary, some of them were pedestrians or other vehicle drivers, as those distinctions were not made in the literature. Nevertheless, in cases of high-energy impact, some severe injuries could occur. According to the data shown in Section 2, subsection, "LRV Fleet Interior Survey," most passengers traveling in LRVs do so in a standing position. This type of condition was not analyzed in this paper because of the lack of muscle response in current ATDs, which were developed for the automotive and aerospace industries. Usually, for these types of vehicles, the majority of the impact occurs in less than 300 ms. Because of the low velocity of the LRV during normal impact conditions (see Section 4 which explains that the duration is approximately 150 ms and peak deceleration only 5 g's), there are some scenarios where passengers will have enough time to tense their muscles or even change their positions (see Figure 5-66). For this reason, to be able to analyze the standing positions of passengers, it will be necessary to develop a new series of ATDs with an active response that is more like that of humans they are to represent.

In accordance with the results presented in this paper, future LRVs should use the following types of seating arrangements to improve safety:

- Aft-facing seats with respect to the operator cabin should be used for both cars. According to the results, this type of configuration is less severe for occupants. In the design of aft-facing seats, designers should pay attention to the design of the head rest and the torsional stiffness of the seat back.

- Lateral-facing seats with a padded barrier or divider at both ends of the seating section will provide a good level of protection. For this type of seating, the interaction between passengers is less significant and, therefore, no severe injuries were observed.
- Forward-facing seats had good general results as well. Nonetheless, further analysis is needed to improve their design safety for every type of passenger. The Design of Experiments technique (see Appendix C) could be used to improve the current seat design.
- Configuration where the passengers are facing each other should be avoided, and side-facing configurations followed by an aft-facing seat configuration.

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APPENDIX

A

MB Seat Model Validation—NIAR Dynamic Test 06221-8 vs. Simulation

This appendix shows how the double seat model and barrier existing in the dynamic test 06221-8 done by NIAR were modeled. Plots comparing the simulation versus dynamic test are shown below.

Double Seat Model

This seat is defined as a typical semi-rigid seat. It is used in most mass transportation systems. According to the behavior of the seat during the dynamic test, it is possible to model the seat using two main rigid bodies:

- Seat Pan: This joint has a specific stiffness that simulates the behavior of the actual seat (Figure A-1). To simulate the dynamic behavior of the seat, this body will be able to rotate around the Z-axis, and a revolute joint is used to allow that movement (red circle in Figure A-2). The joint is positioned where the cantilever beam is attached to main structure (see FE model, Figure A-3)
- Seat Back: This body will be able to rotate around the Y-axis. A different revolute joint is used in the proper location. The joint is positioned between the seat back and the seat pan (blue circle in Figure A-2). This joint has a specific stiffness that simulates the behavior of the actual seat (Figure A-1)

Figure A-1

Stiffness of Seat Pan Revolute Joint (Z-Axis) and Seat Back Revolute Joint (Y-Axis)

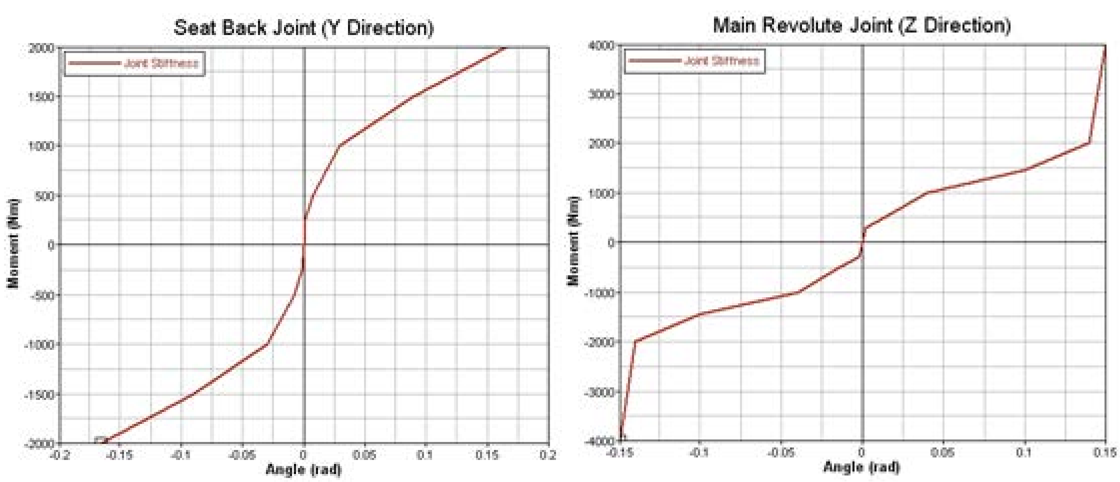


Figure A-2

Double Seat Model

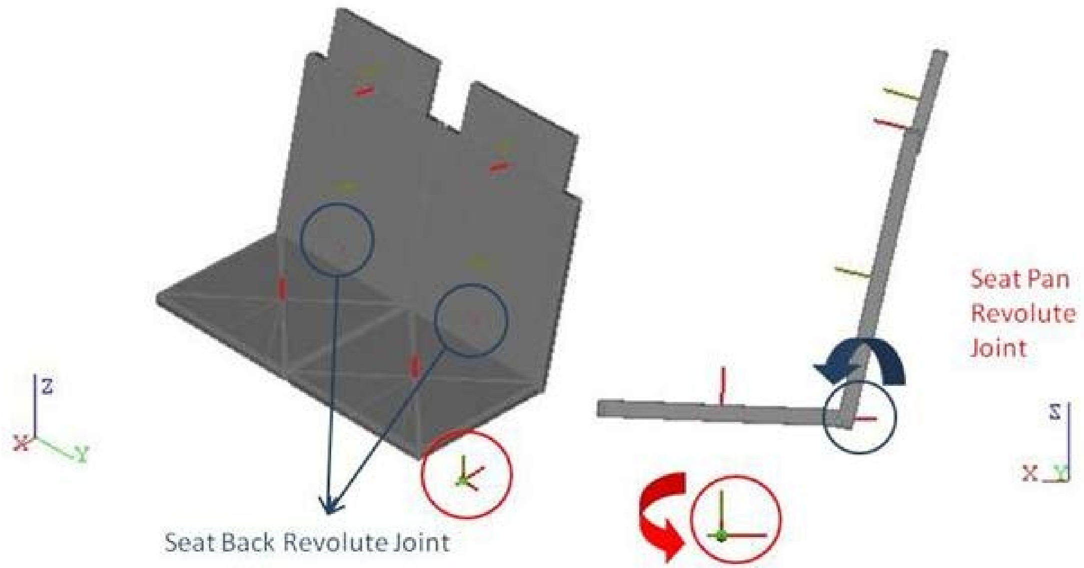
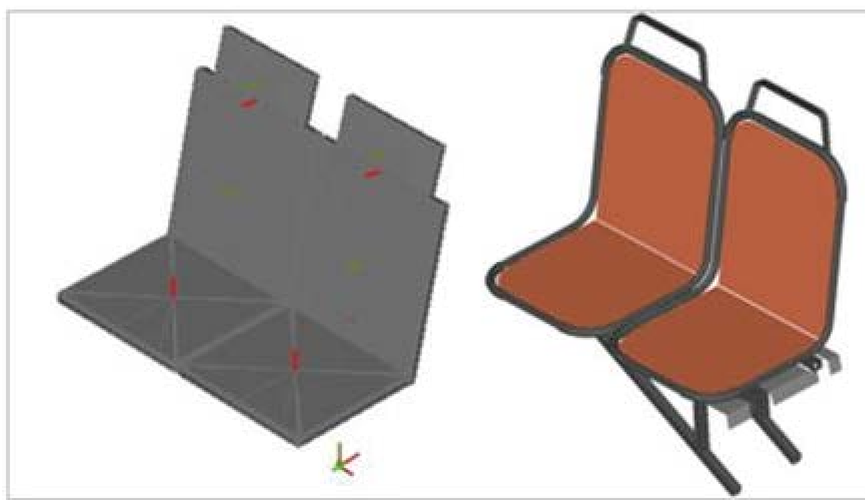


Figure A-3

Double Seat—MB Model vs. FE Model



The total weight of the double seat is 32 kg and is distributed as follows:

- Each seat pan: 9 kg (total 18 kg)
- Each seat back: 6 kg (total 12 kg)
- Each headrest: 1 kg (total 2 kg)

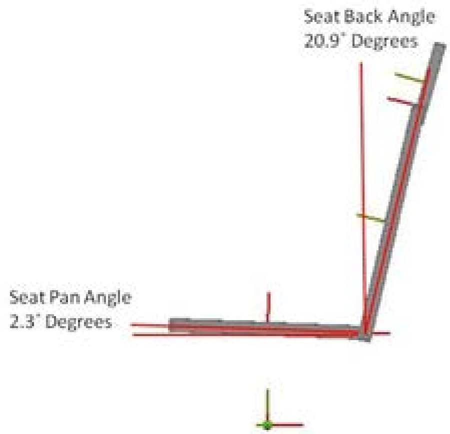
Furthermore, the main dimensions of the seat are as follows:

- Seat back height: 484 mm
- Seat headrest height: 120 mm
- Seat pan length: 390 mm
- seat width: 425 mm

The angles for the seat pan and seat back are shown in Figure A-4.

Figure A- 4

Double Seat—Seat Pan and Seat Back Angles



The contact properties between the ATD and the surfaces are defined by the stiffness shown in Figure A-5

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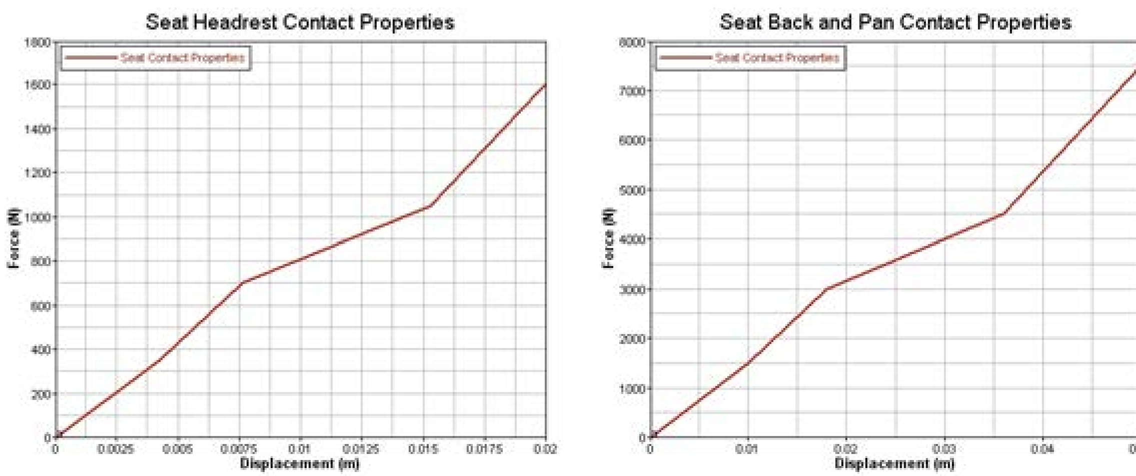
Figure A-5

Double Seat—Seat Back and Seat Headrest Contact Stiffness



Barrier Model

This barrier represents the typical semi-rigid barrier used for the dynamic tests. According to the behavior of the barrier during the dynamic test, it is possible to assume three rigid bodies (two legs and one main body).

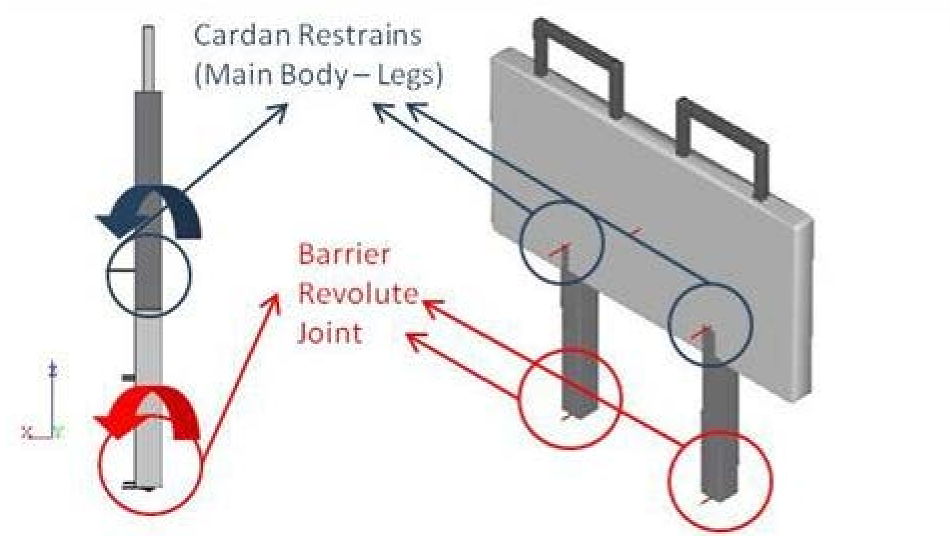
To connect these bodies, the following joints are used:

- Leg Floor Attachment: A revolute joint is used to represent this type of union. This joint allows the legs to rotate on the Y-axis (red circle in Figure A-6). The stiffness of this revolute joint is shown in Figure A-7.
- Main Body to Legs Attachment: To attach the main body to the legs, a Cardan restraint is used (blue circle in Figure A-6). Although this type of

restraint allows the upper body to rotate on every axis, a very high stiffness is used for X-axis and Z-axis to avoid the rotation on these axes. The stiffness defined for the Y-axis is shown in Figure A-7 and allows the main body to rotate when impacted.

Figure A- 6

Barrier Model



The total weight of the barrier is 21 kg (18 kg main body and 3 kg each leg). The main dimensions are as follows:

- Barrier height: 840 mm
- Barrier length: 794 mm
- Barrier width: 50 mm

The MB vs. FE model of the barrier is shown in Figure A-8, and the contact properties for the top part of the barrier and the main part of the barrier are shown in Figure A.9.

Figure A-7

Stiffness of Floor-Legs Revolute Joint (Y-Axis) and Legs-Body Cardan Restraint (Y-Axis)

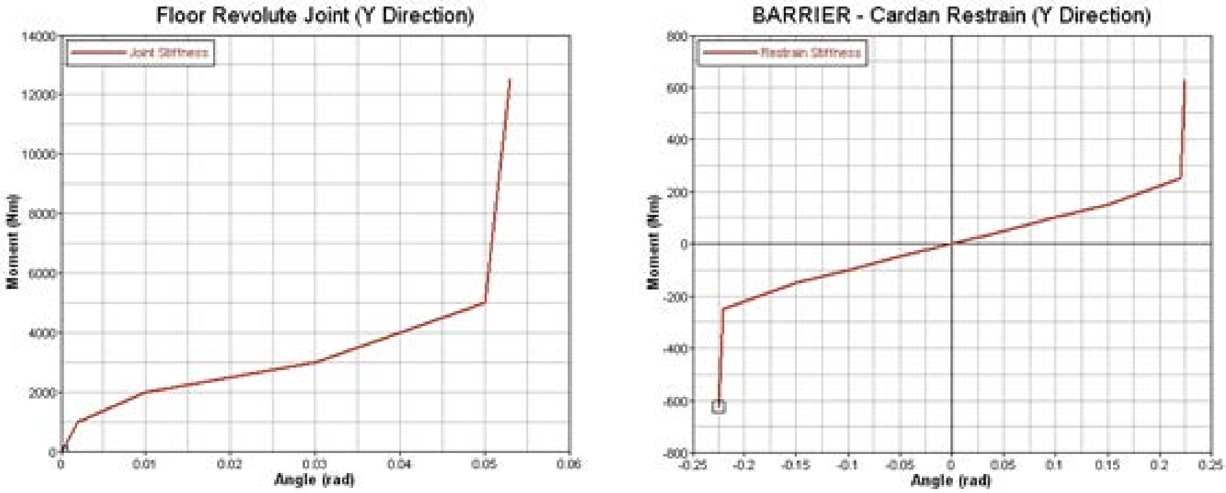


Figure A- 8

Barrier Model (left) and FE Barrier Model (right)

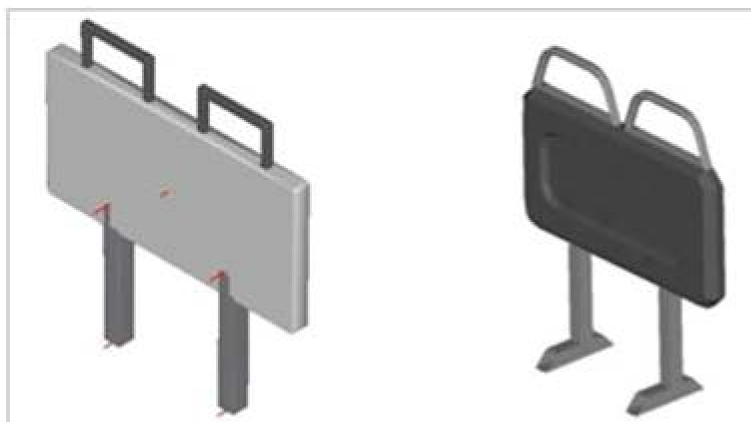
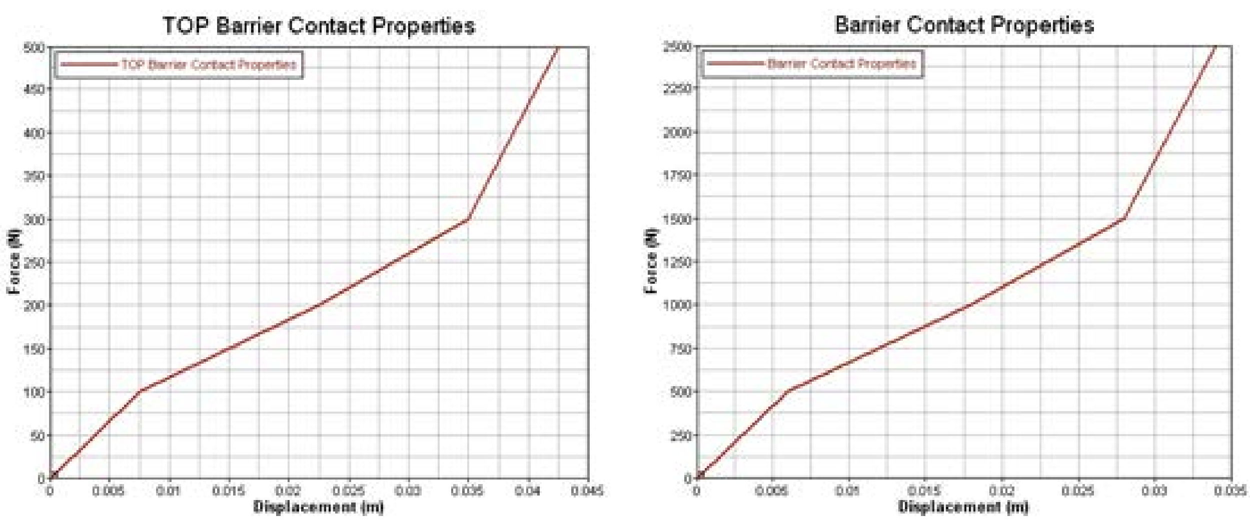


Figure A-9

Barrier Contact Stiffness Properties—Top and Bottom Parts

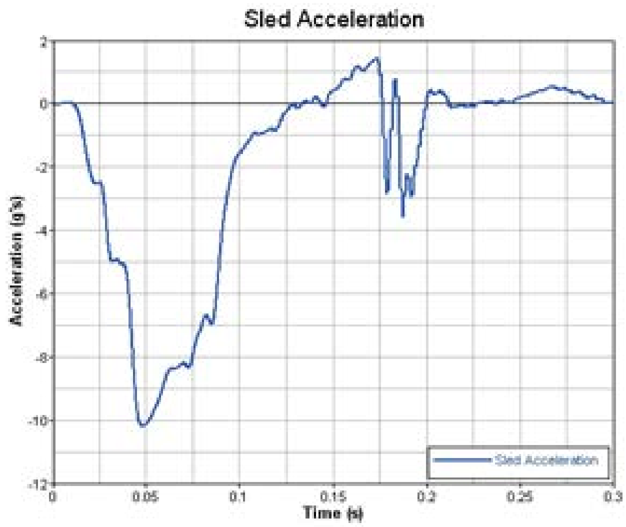


Validation Results—Dynamic Test 06221-8 vs. Multibody Simulation

The dynamic test used to validate the multibody models represents a frontal-rear impact between mass transit buses. For this test, one bus is traveling at 20 mph, while the other is stopped (0 mph). Validation is done using the results from this test. The pulse of the dynamic test is shown in Figure A-10.

Figure A- 10

Sled Acceleration Dynamic Test 06221-8 with Mass Transit Bus at 20 mph and Mass Transit Bus at 0 mph



The layout of this dynamic test, shown in Figure A-11 uses four ATDs:

- Position 1: HIII 95th percentile
- Position 3: HIII 5th percentile
- Position 4: HIII 50th percentile
- Position 5: HIII 50th percentile

Although a 50th percentile ATD is seated in the lateral-facing seat in the dynamic test, due to the differences in hardware between LRVs and buses for this type of seat, this ATD was not evaluated on the multibody model.

The actual distances between seats and monuments are slightly different between LRVs and buses (see red marks in Figure A-11). According to the data available, current LRVs have more space between seats.

Finally, the comparison between the test and simulation results for positions 1, 3, and 4 are shown.

Figure A- 11

Sled Test 06221-8 Layout

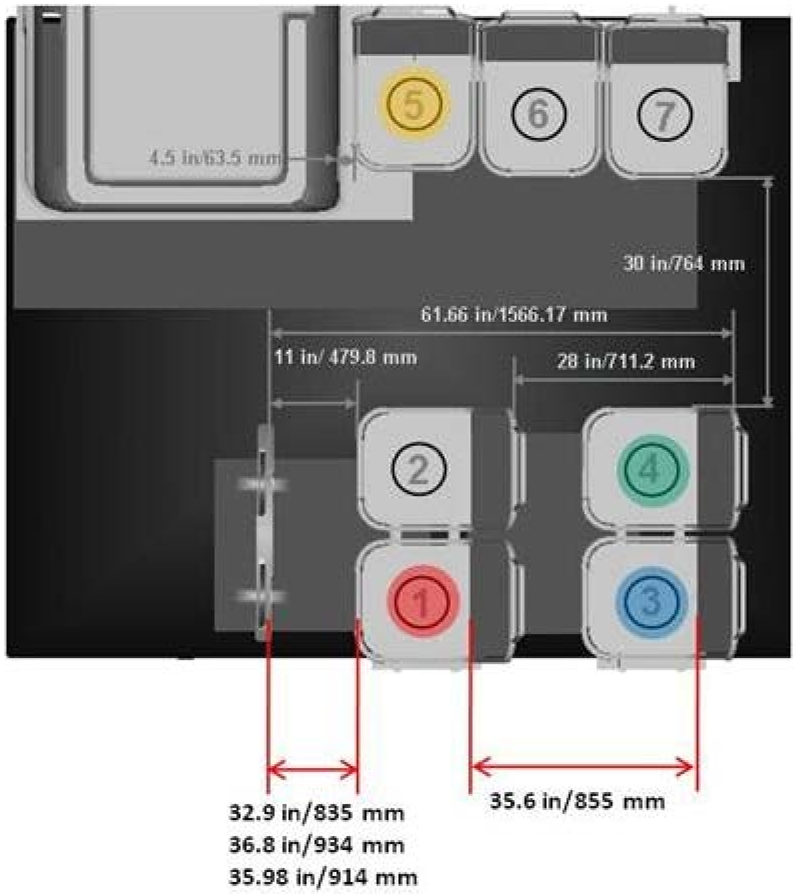
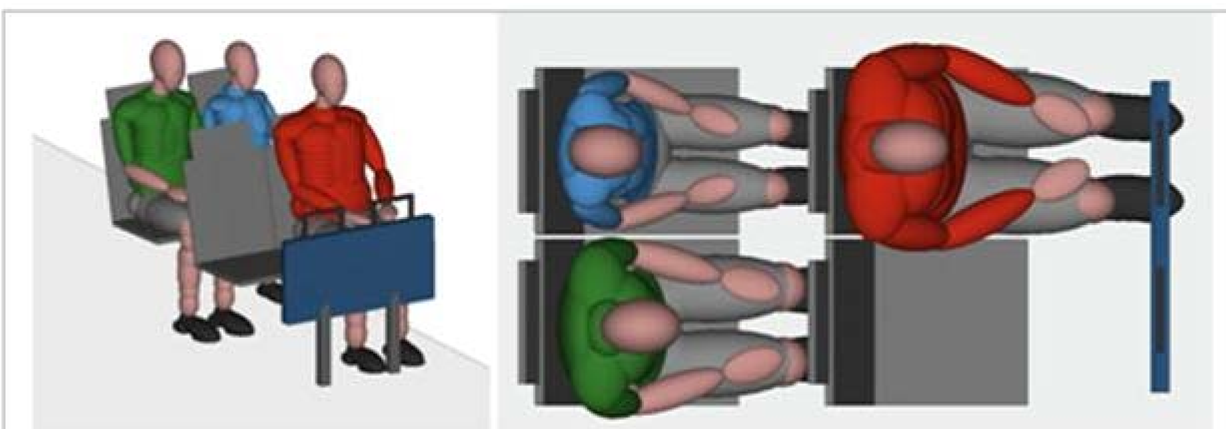


Figure A-12

Simulation Layout



Kinematics of Multibody Model vs. Sled Test 06221-8

The kinematics of the multibody model vs. the sled test 906221-8 are shown in Figure A-13 and Figure A- 14 for various impact moments.

Figure A-13

Kinematics of Simulation vs. Sled Test 06221-8—0 to 100 ms Impact Moment

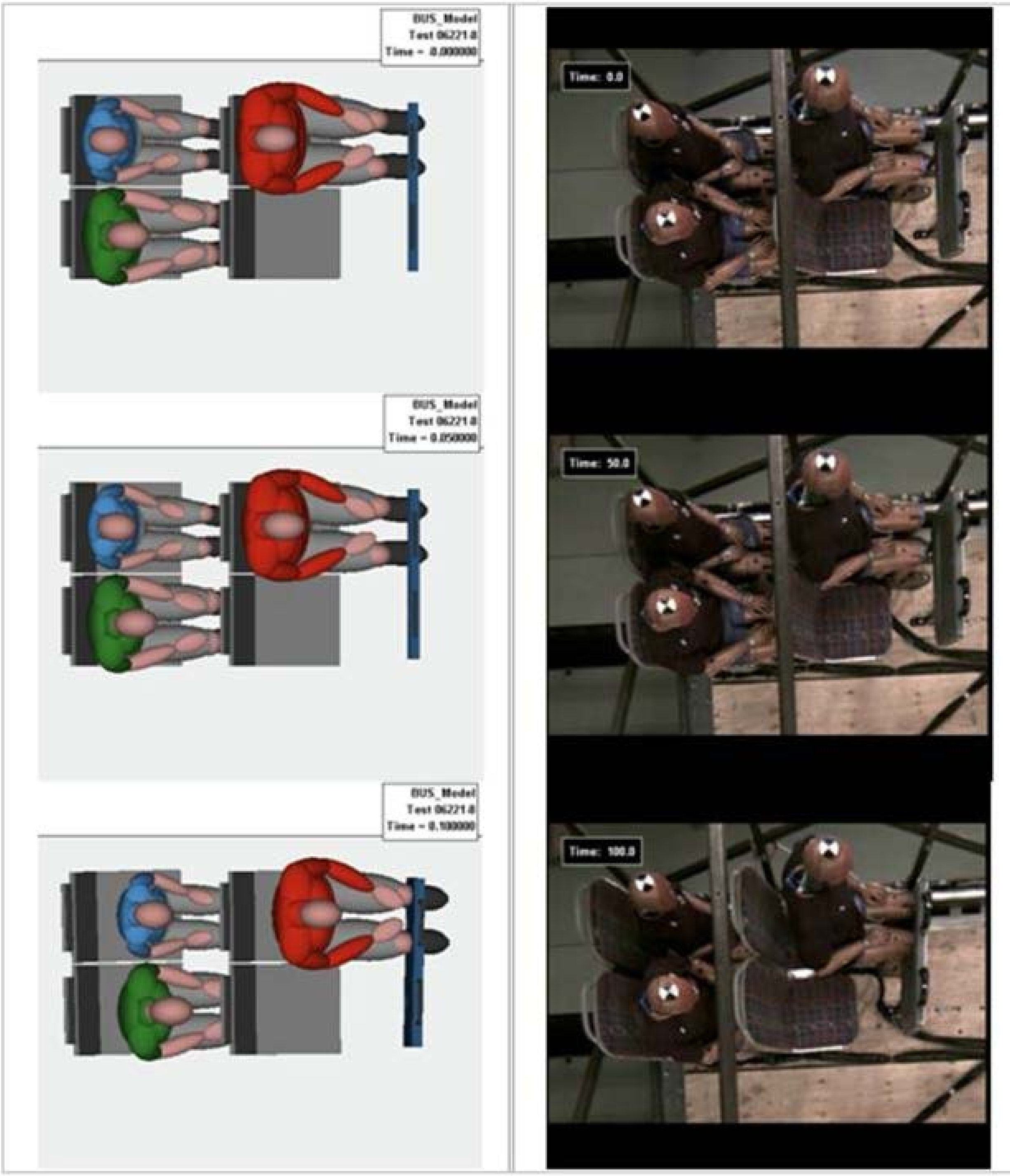
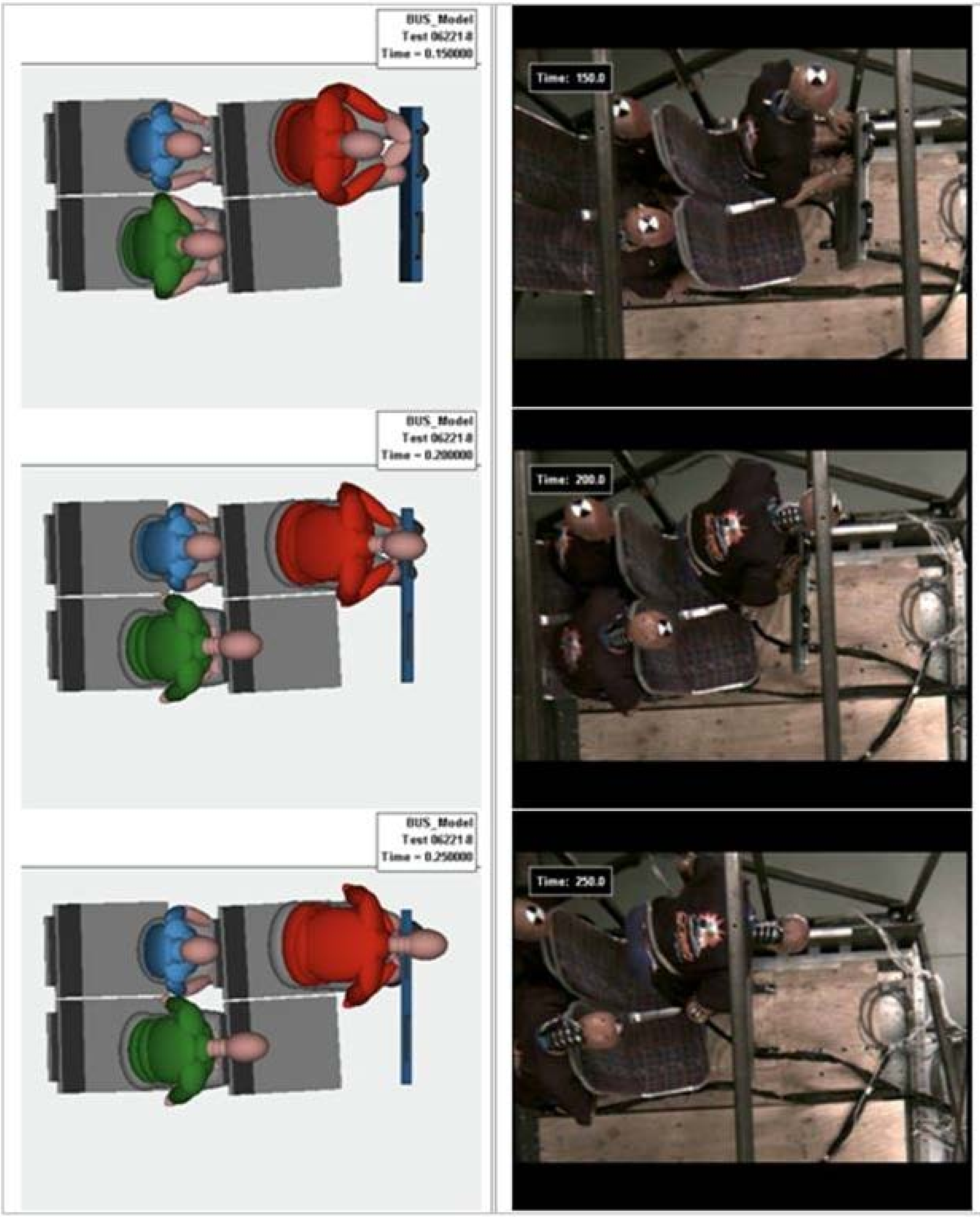


Figure A-14

Kinematics of Simulation vs. Sled Test 06221-8—150 to 250 ms Impact Moment



Position 1—95th Percentile ATD

Figures A-15 to Figure A-18 show head acceleration, chest acceleration, femur forces, and neck forces and moments, respectively, for the 95th percentile ATD in Position 1.

Figure A-15

Head Acceleration for 95th Percentile ATD in Position 1

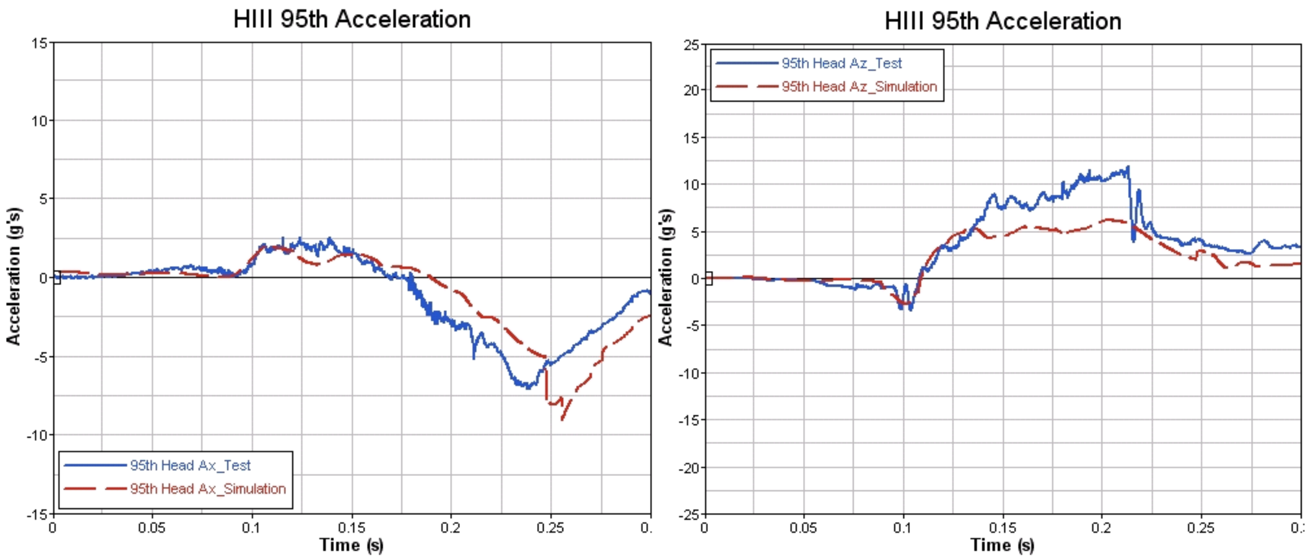


Figure A-16

Chest Acceleration for 95th Percentile ATD in Position 1

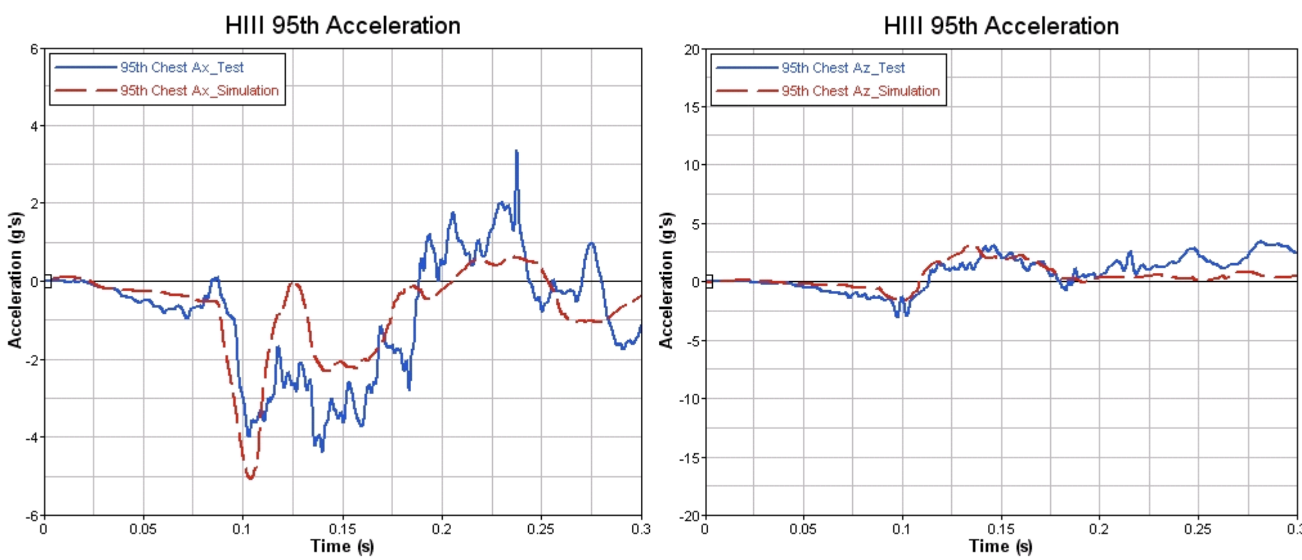


Figure A-17

Femur Forces for 95th Percentile ATD in Position I

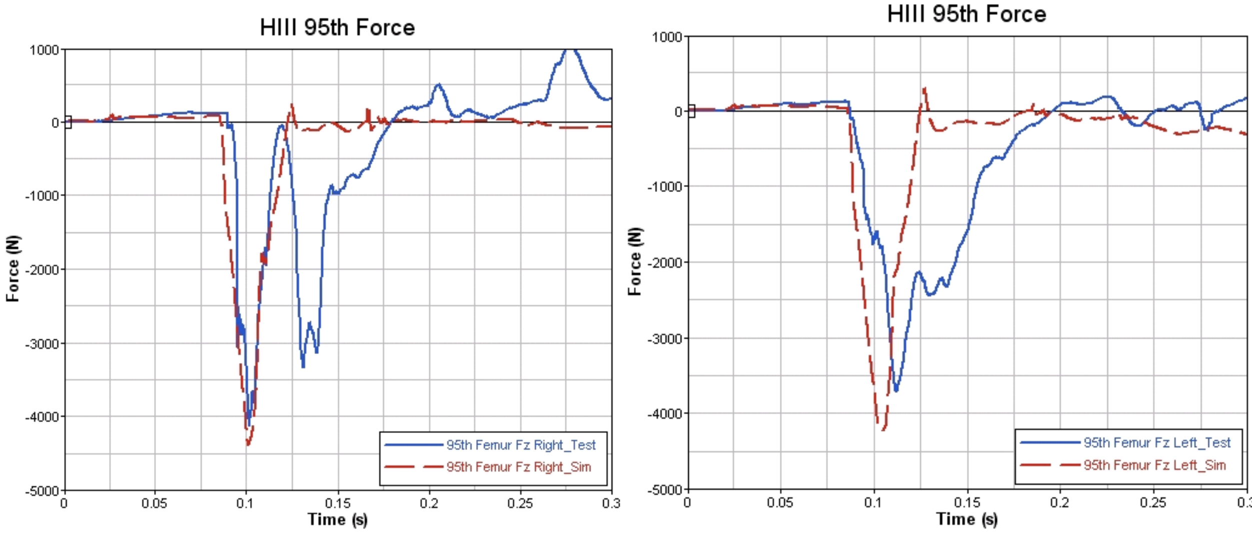
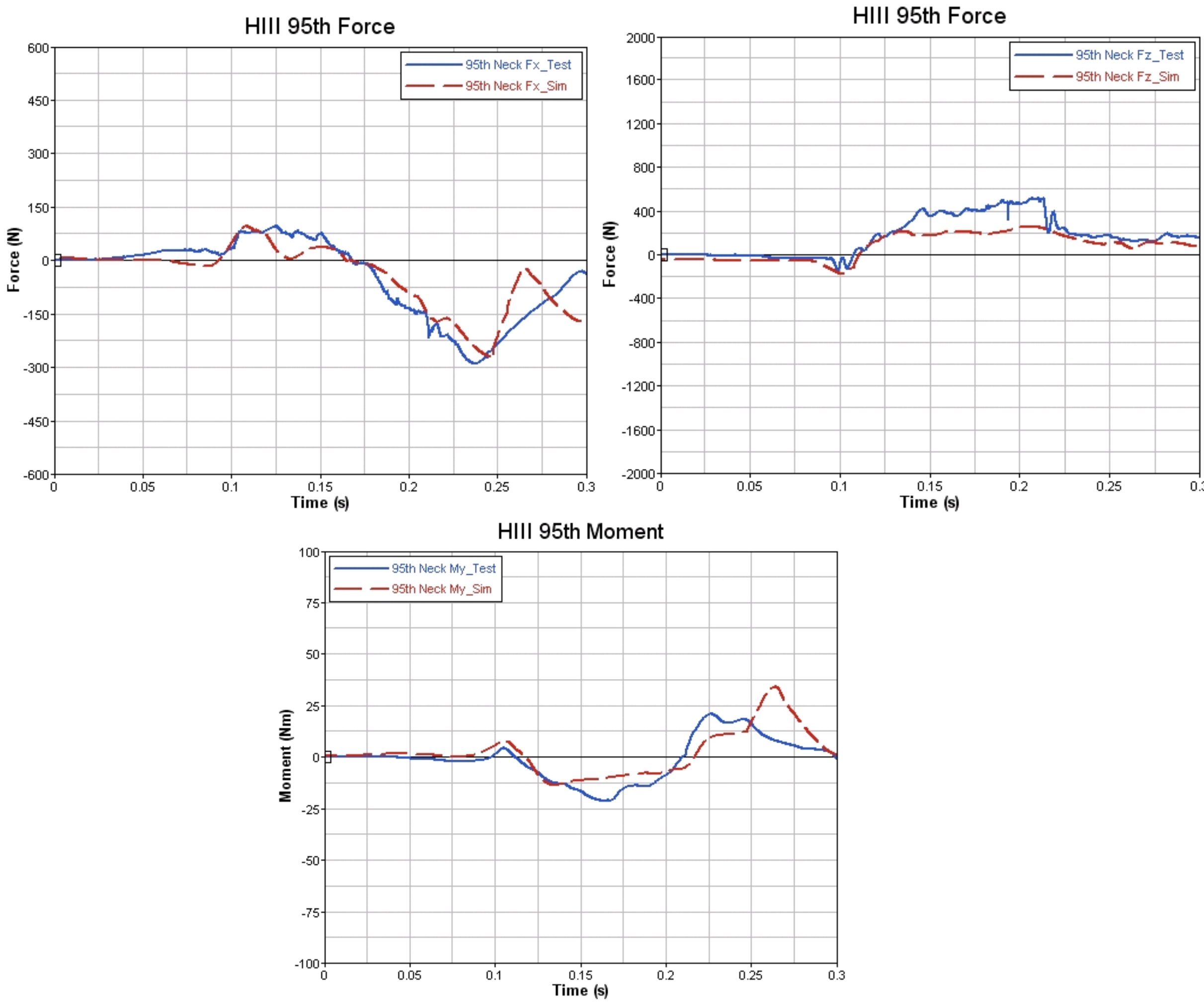


Figure A-18

Neck Forces and Moments for 95th Percentile ATD in Position I



Position 3—5th Percentile ATD

Figures A-19 to Figure A-22 show head acceleration, chest acceleration, femur forces, and neck forces and moments, respectively, for the 5th percentile ATD in Position 3.

Figure A-19

Head Acceleration for 5th Percentile ATD in Position 3

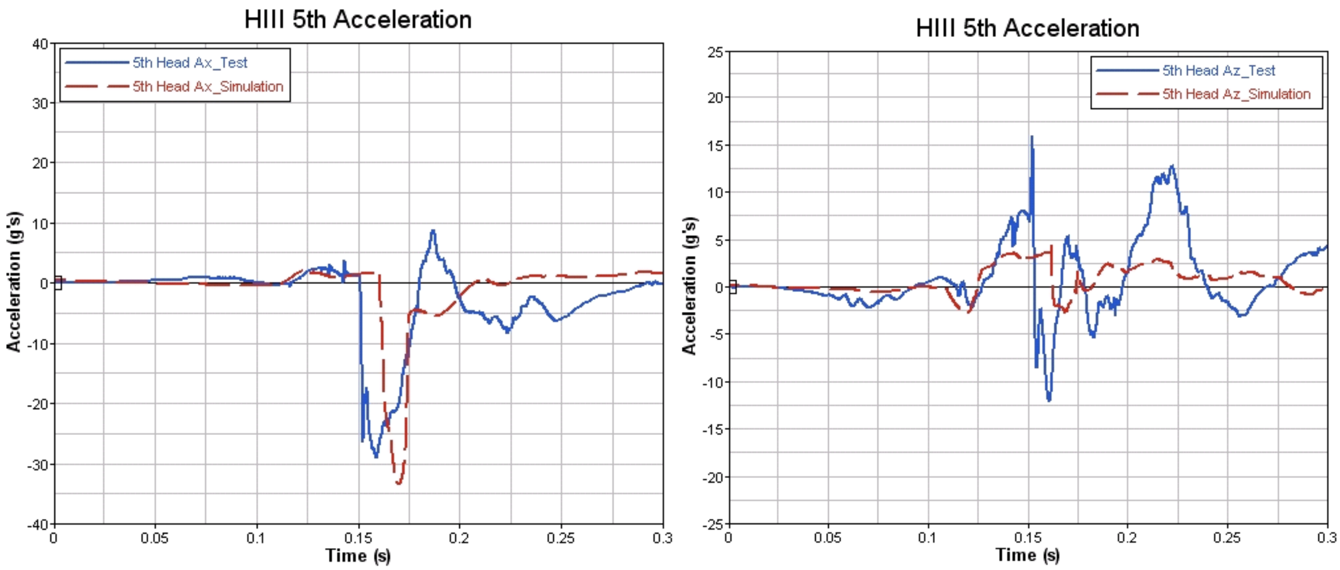


Figure A-20

Chest Acceleration for 5th Percentile ATD in Position 3

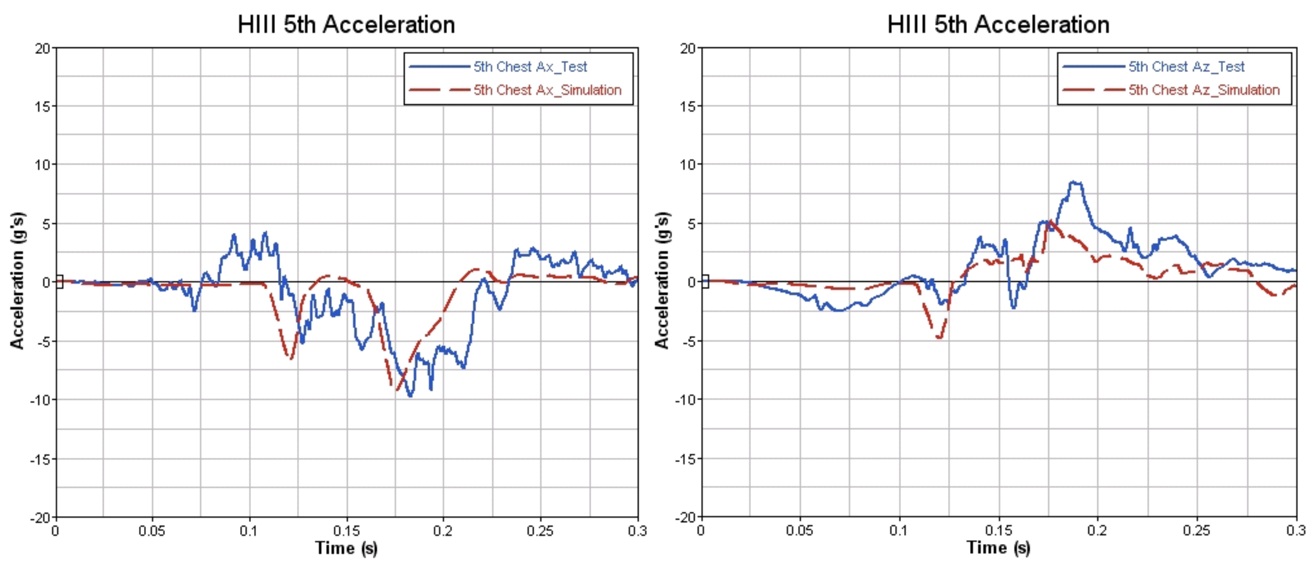


Figure A-21

Femur Forces for 5th Percentile ATD in Position 3

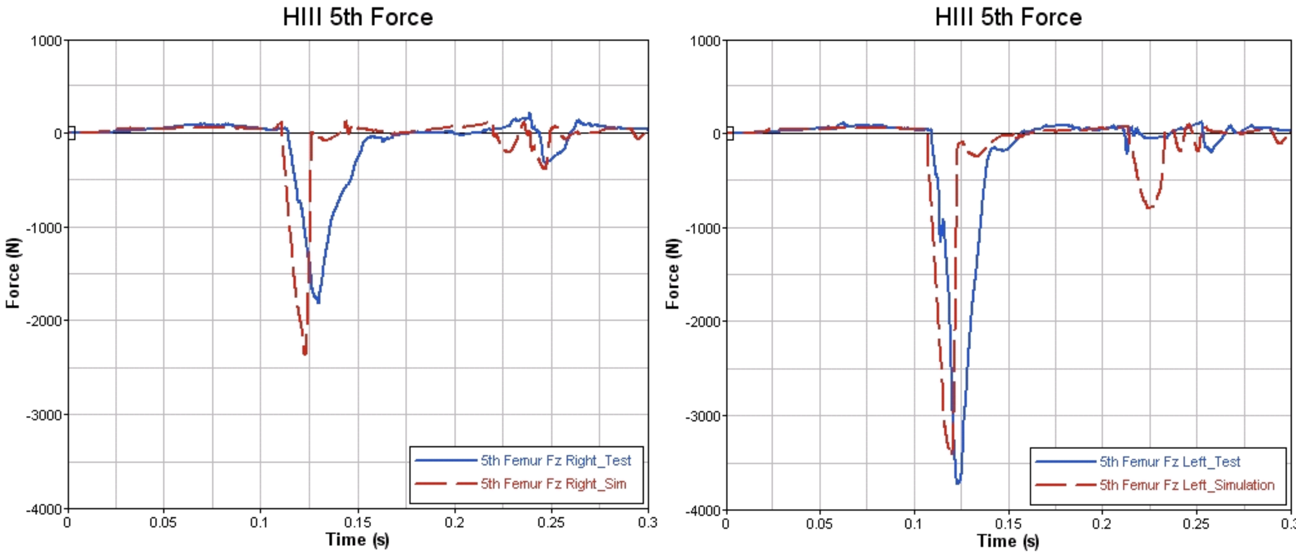
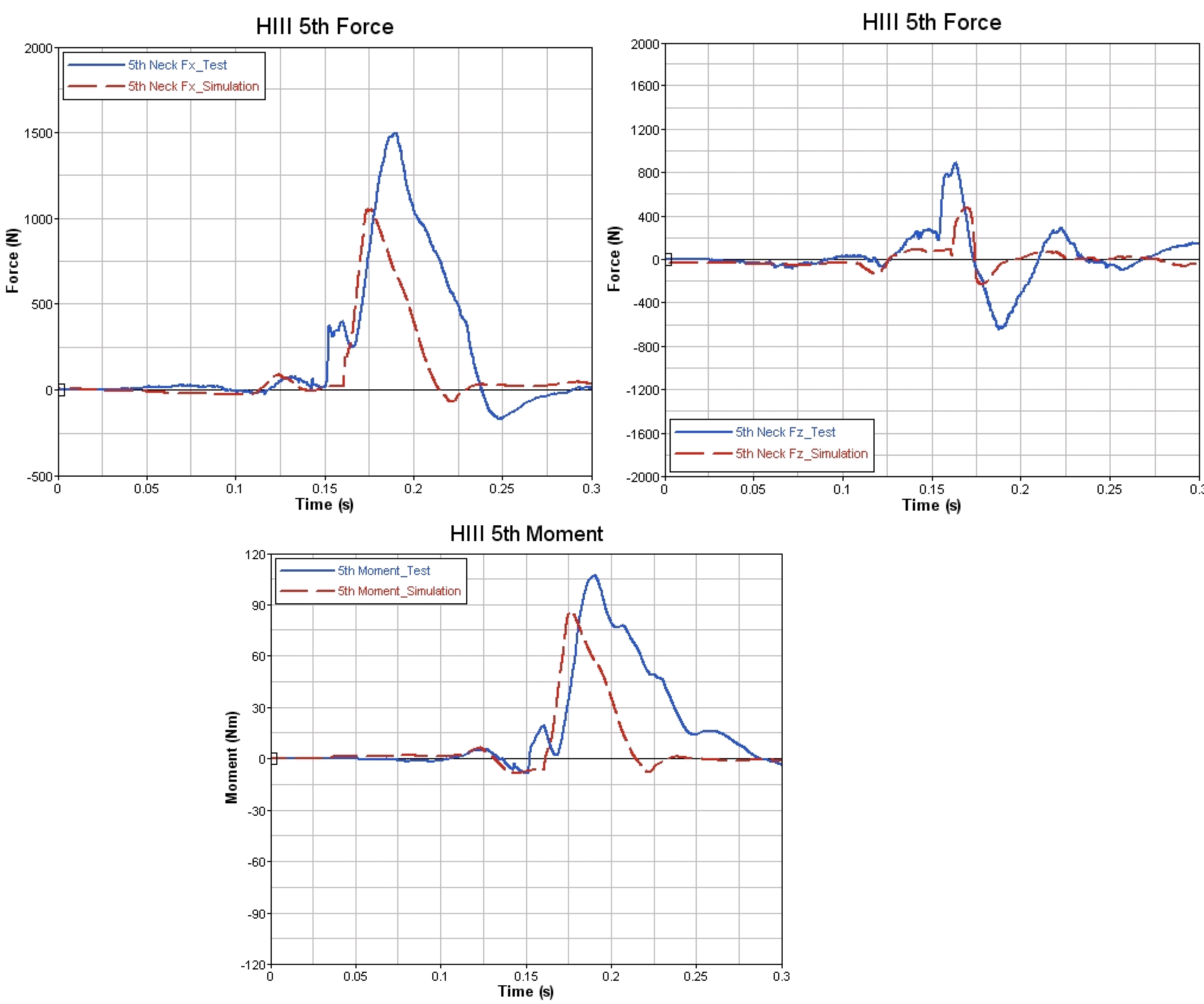


Figure A-22

Neck Forces and Moments for 5th Percentile ATD in Position 3



Position 4—50th Percentile ATD

Figures A-23 to Figure A-26 show head acceleration, chest acceleration, femur forces, and neck forces and moments, respectively, for the 50th percentile ATD in Position 4.

Figure A-23

Head Acceleration for 50th Percentile ATD in Position 4

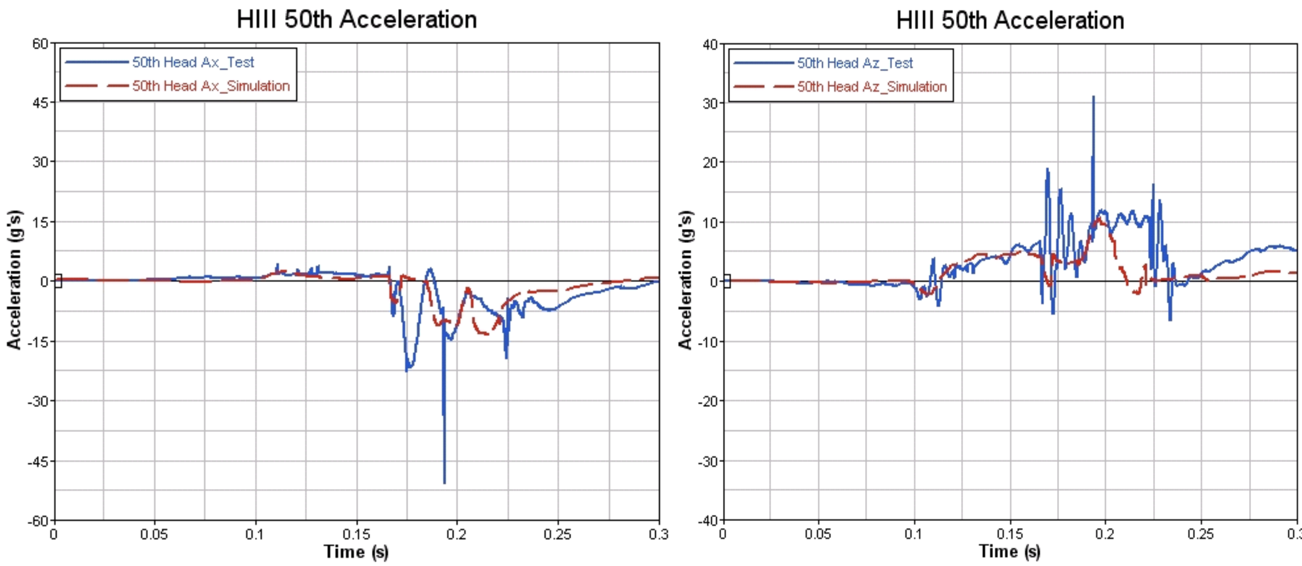


Figure A-24

Chest Acceleration for 50th Percentile ATD in Position 4

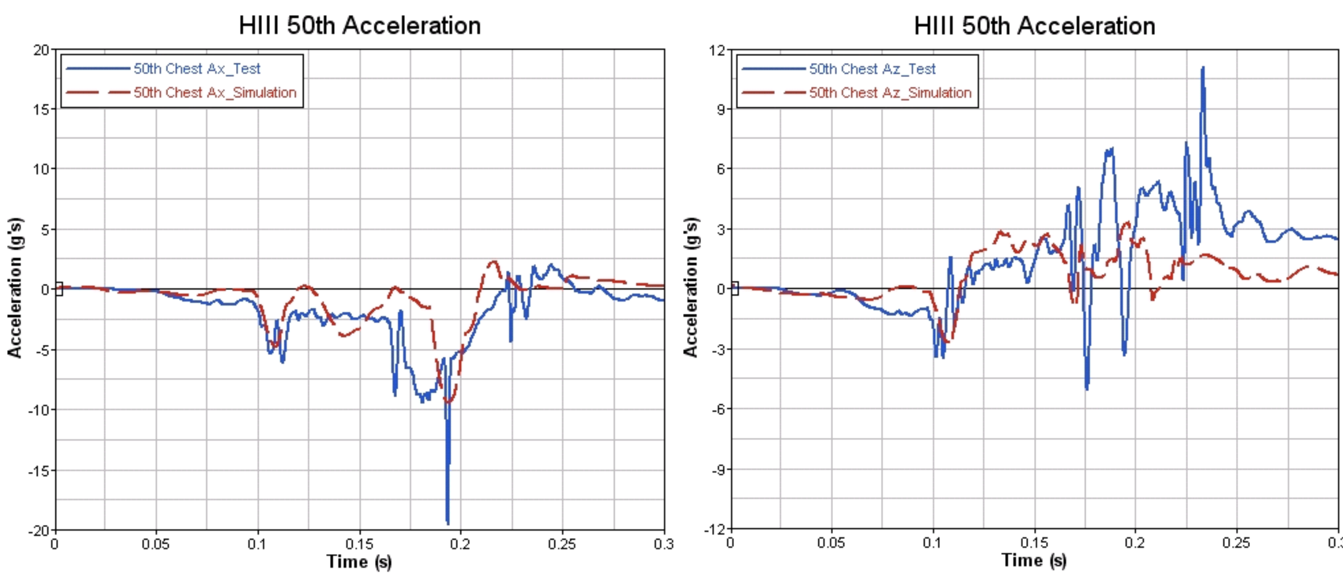
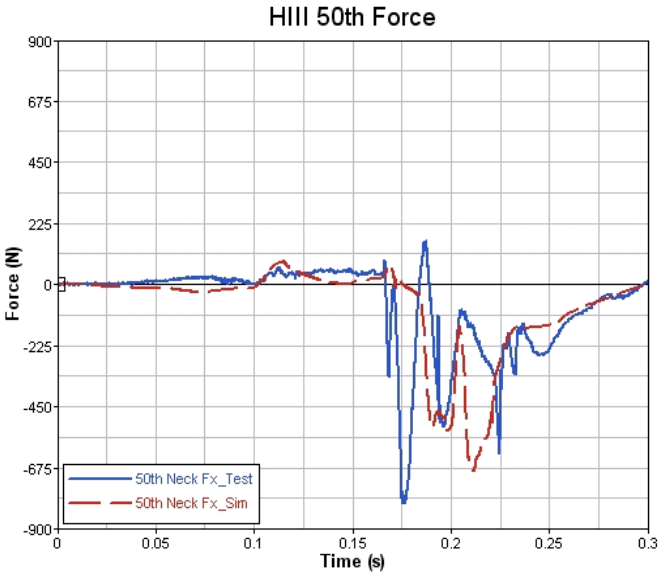
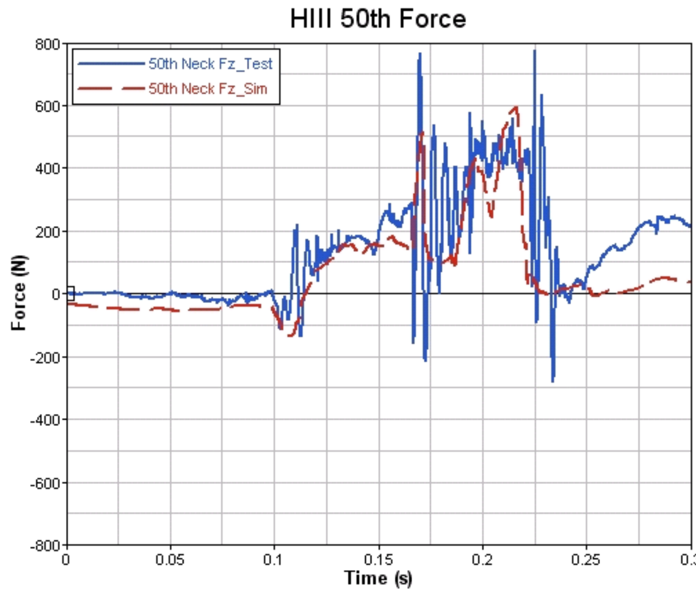
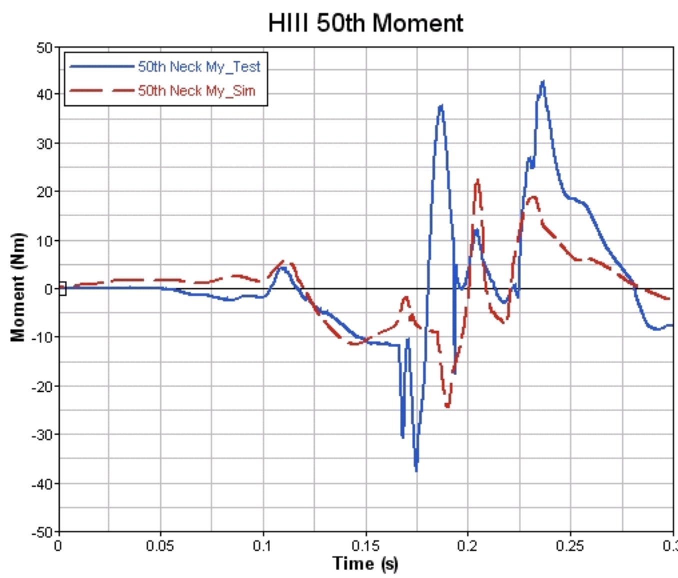


Figure A-25

Femur Forces for 50th Percentile ATD in Position 4







APPENDIX

B

Multibody Models

Two types of seats were used for the multibody model analysis:

- Double Seat (Figure B-1): This seat represents a typical semi-rigid seat and is used in most mass transportation systems to represent forward-facing seats, rear-facing seats, and other configurations of seats that face each other. Further details may be found in Appendix A.
- Triple Seat (Figure B-2): Although the triple seat is most used often for lateral facing seats, it also is used in certain special seating configurations such as the row of seats at the end of some LRVs. The main contact characteristics remain identical to the double seat (same material and thickness).

Figure B-1

Double Seat—MB Model and FE Model

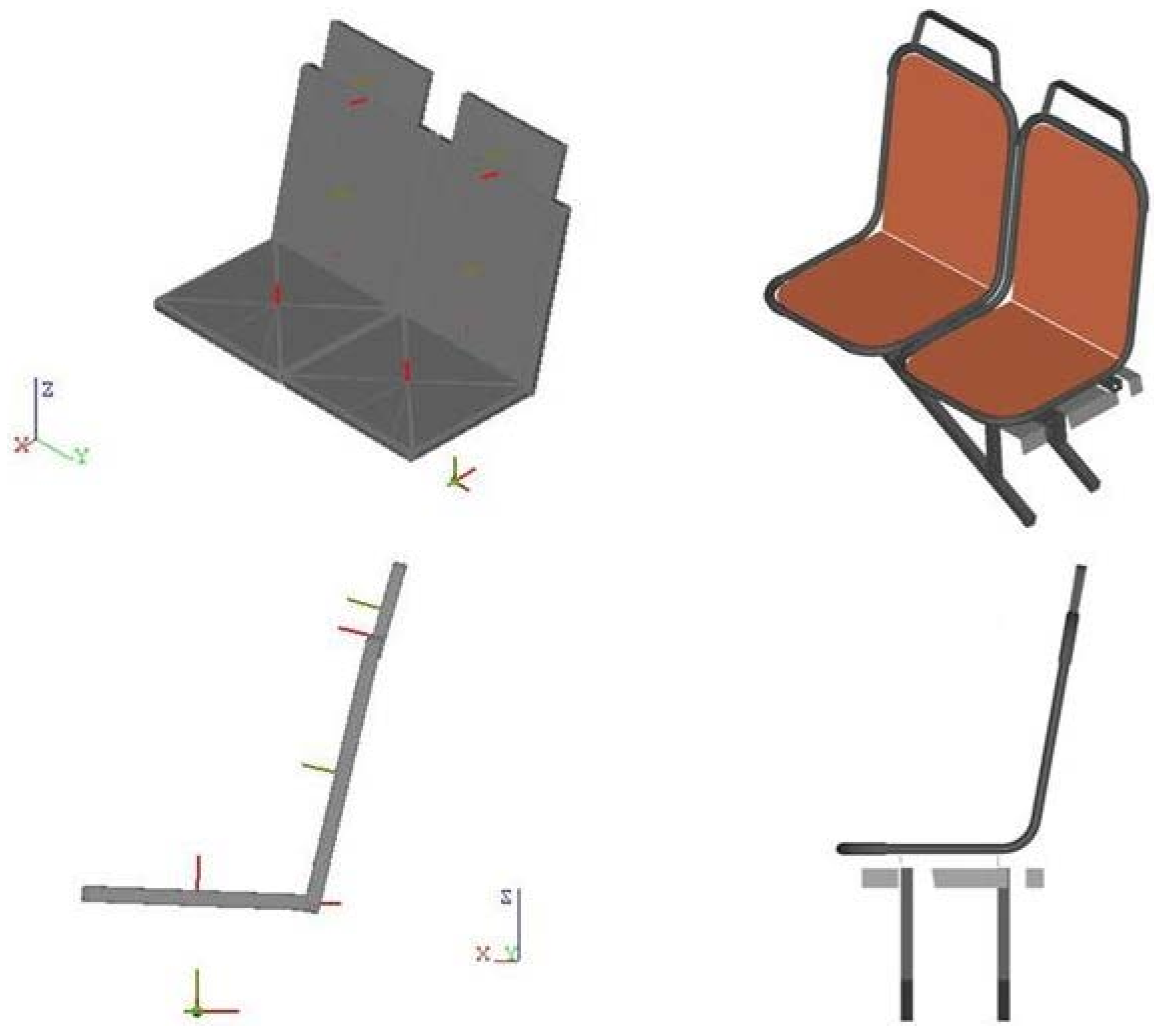
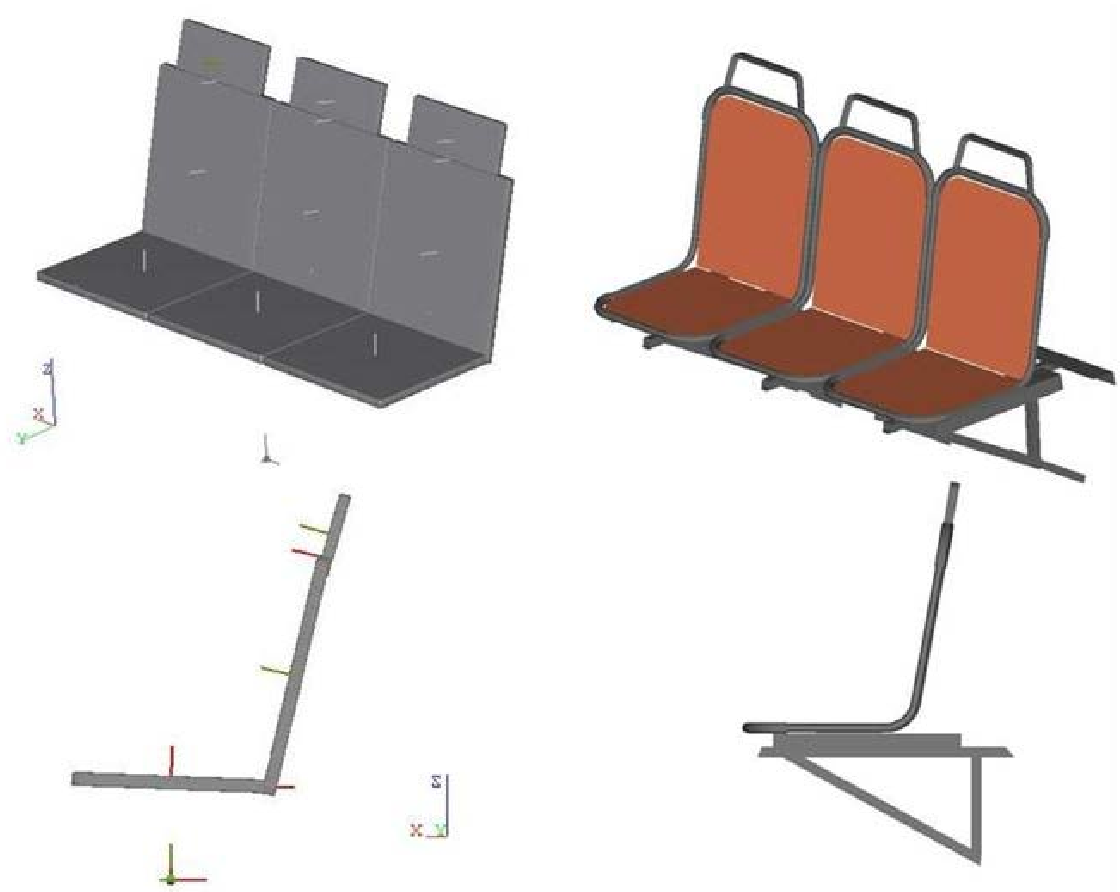


Figure B-2

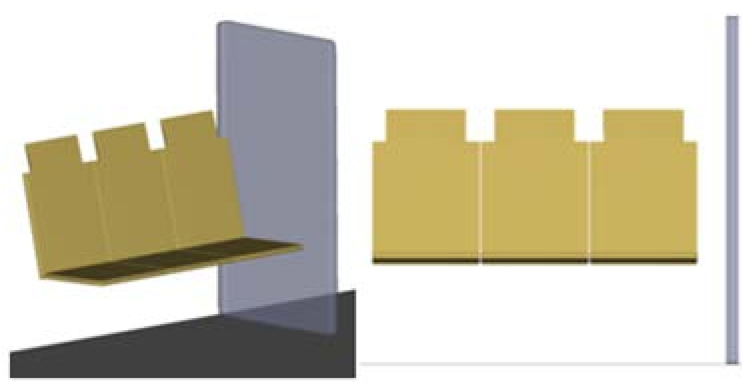
Triple Seat—MB Model and FE Model



The layout survey in the "Survey of LRV Specific Interiors" shows the different configurations. One of these configurations is the lateral-facing seat with a monument barrier. This barrier can be found on either side of the lateral-facing seat. With the intention of representing this configuration, a generic multibody model of a common barrier was created (Figure B-3).

Figure B- 3

Multibody Barrier Model



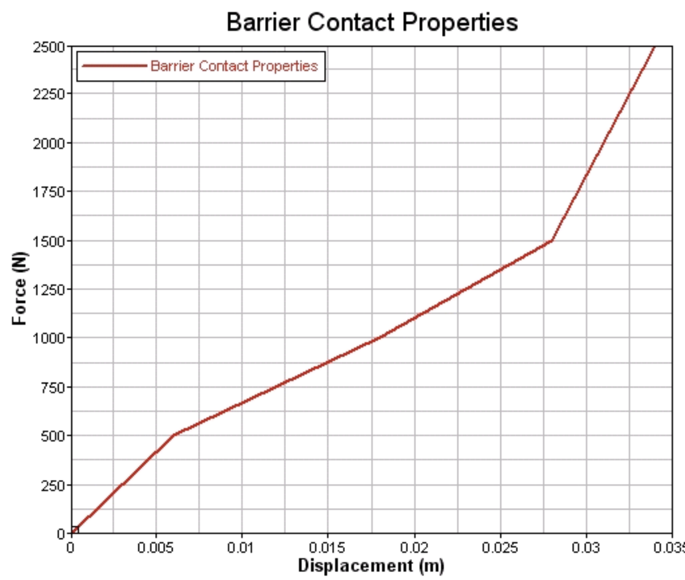
The weight of this barrier is 4 kg. This type of barrier is usually attached to the LRV at the ceiling and floor, and occasionally the outer edge is attached to the LRV wall. For this reason, in the multibody model, this barrier is attached to the LRV structure by a bracket joint. This type of joint does not have any degrees of freedom, and as a result no rotations or translations are observed. The main dimensions of the barrier are as follows:

- Barrier height: 1,400 mm
- Barrier length: 760 mm
- Barrier width: 50 mm

The most important parameter for the model of the barrier is the contact stiffness (Figure B-4). This property is obtained directly from the validation model shown inAppendix A.

Figure B- 4

Barrier Contact Stiffnes



Other models used in this section are for the wheelchair, a 3-year-old child car seat, and a 12-month-old child car seat. Although these are modeled using finite elements, they can still be combined with the multibody seats.

The wheelchair model used is a manual wheelchair (model 1800XT), as shown in Figure B-5. Its weight is 19 kg, with 136 kg of maximum weight capacity.

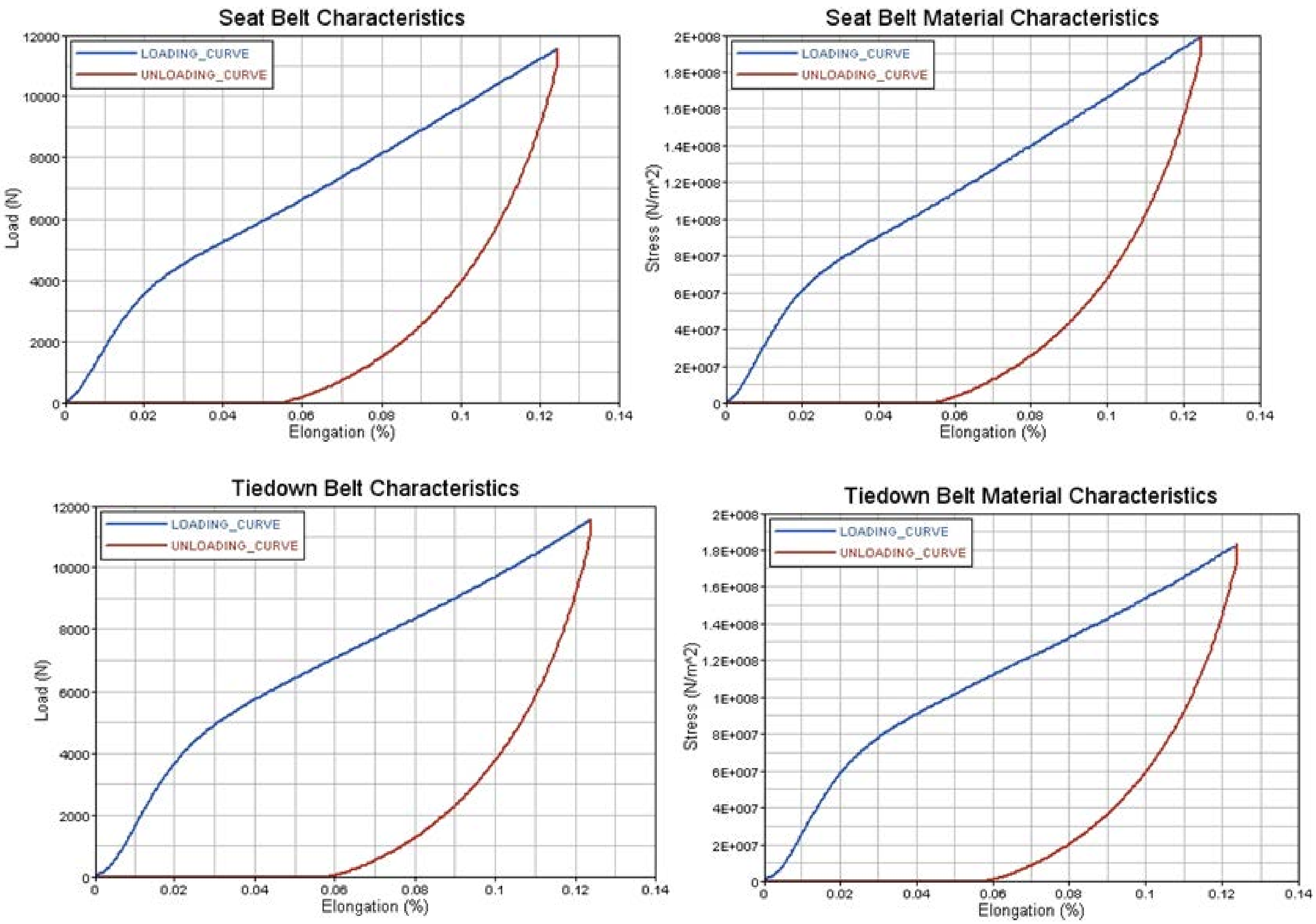
Figure B- 5

Wheelchair Model

The wheelchair model has a total of 58 parts with more than 32,000 elements. This model is used to calculate the maximum forces transmitted by the belt to the structure. The properties of the straps used are shown in Figure B-6.

Figure B-6

Wheelchair Strap Material Characterization



APPENDIX C

Design of Experiments - Overview

Design of experiments (DoE) is a common technique used in the engineering world. Usually, this technique is combined with the optimization process to improve quality or a characteristic of a product. The usual procedure for DoE and the optimization process is shown in Figure C-1.

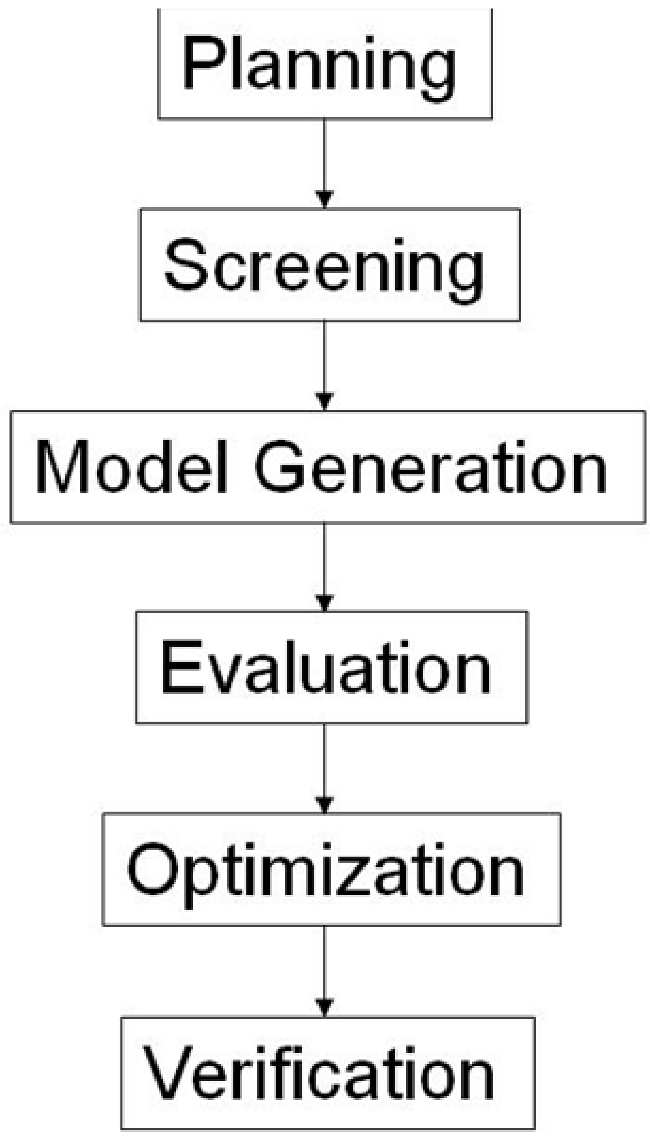


Figure C-1

Design of Experiments and Optimization Process

According to the results of this research, forward-facing seats could not provide the desired level of safety for all the different passenger sizes. The original idea was to use this design technique to improve this type of seat's safety, regardless of passenger size. This section shows an example of how the DoE technique can be used to redesign the process.

Screening *Phase*

The screening phase is the initial phase of the DoE process whereby the main factors that need to be studied are defined. Using the base model developed for this study, different parameters of the seat design can be studied to understand how they affect the safety of passengers.

For the screening phase, the following seven different factors for the inboard/outboard seated 5th, 50th, and 95th percentile ATDs were studied (see parameters in Figure C-2 and Figure C-3):

- Seat pitch (A)
- Seat back height (B)
- Seat back angle
- Seat back rotational stiffness properties
- Seat Z rotational stiffness properties
- Padding material headrest
- Padding material knee bolster

Figure C- 2

Parameters of Seat Pitch (A) and Seat Back Height (B)

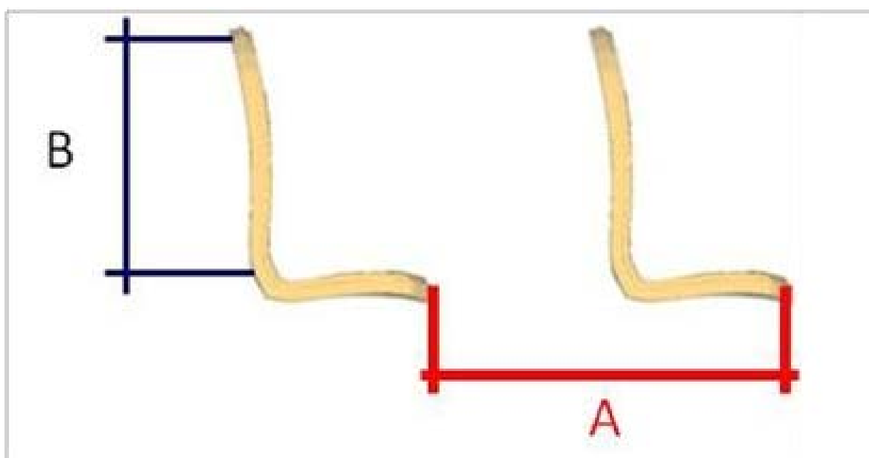
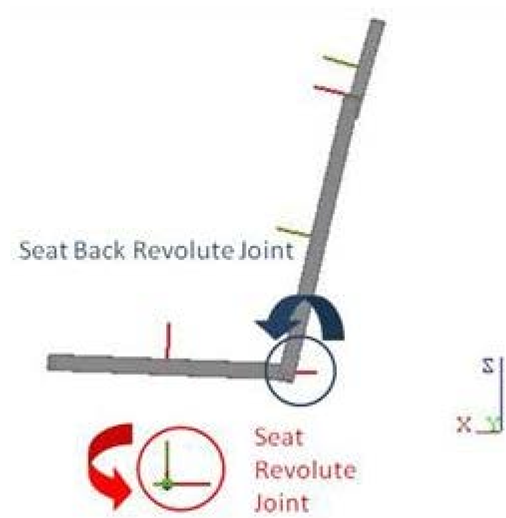


Figure C- 3

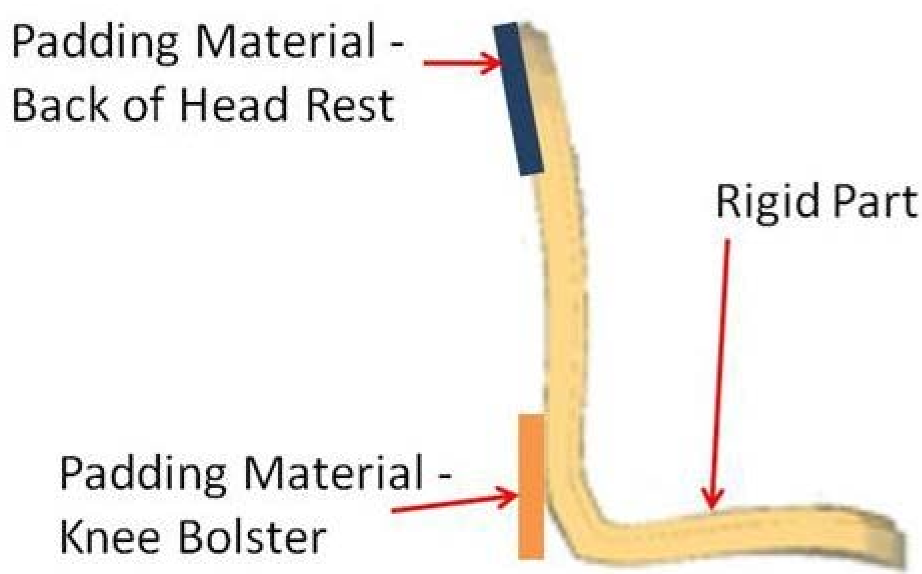
Parameters of Forward-Facing Seat Joint



Three different stiffness values were used to simulate three different padding materials. These padding materials were added to the seat headrest back and the knee bolster area (see Figure C-4).

Figure C- 4

Parameters of Padding Material of Surfaces



As a result of the seven different factors, each one with three levels (full factorial: seven factors with three levels), a total of 2,187 runs is done for each position/ATD. Thus, if the analysis is done for the 5th, 50th and 95th percentile ATDs, a total of 6,561 runs would be done for each position.

Table C-1 shows the possible range of values for the factors listed above.

Table C- 1

Design of Experiments Factors and Values

DoE Factors	Values	
Seat pitch (mm)	850	
	785	Nominal
	720	
Seat back height (mm)	670	
	632	Actual
	594	
Seat back angle (degrees)	11	
	8	Actual
	5	
Stiffness seat back (Nm vs. rad)	50%	
	0%	Actual
	-50%	
Stiffness seat rotation Z direction (Nm vs. rad)	50%	
	0%	Actual
	-50%	
Stiffness headrest material (N vs. m)	Soft (1)	
	Medium (2)	Nominal
	Hard (3)	
Stiffness knee bolster (N vs. m)	Soft (1)	
	Medium (2)	Nominal
	Hard (3)	

Example: 5th Percentile ATD in Outboard Position

Once the model is defined, the responses to be evaluated can be defined. For this model, the responses shown in Table C-2 were analyzed.

Table C- 2

Design of Experiments Responses

DoE Responses	Abbreviation
Head Injury Criteria (15 ms)	HIC15ms
Chest (3 ms) (g's)	Chest3ms
Neck Shear Force (N)	FxNegative
Neck Aft Shear Force (N)	FxPositive
Neck Tension (N)	FzTension
Neck Compression (N)	FzCompression
Neck Flexion (Nm)	MyFlexion
Neck Extension (Nm)	MyExtension
Femur Force L (N)	FemurL
Femur Force R (N)	FemurR

For this example of the 5th percentile ATD in the outboard position, some of the results are shown in Figure C-5 and Figure C-6.

Figure C-5

Flexion Response for Each Factor

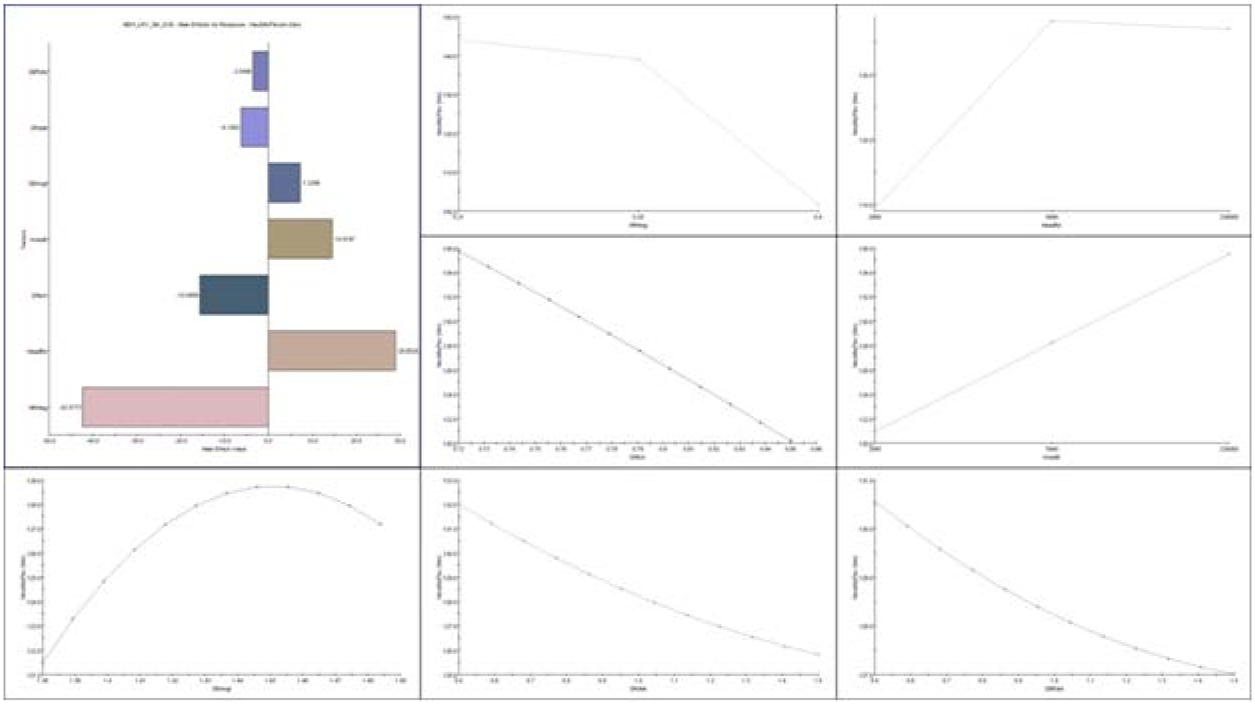
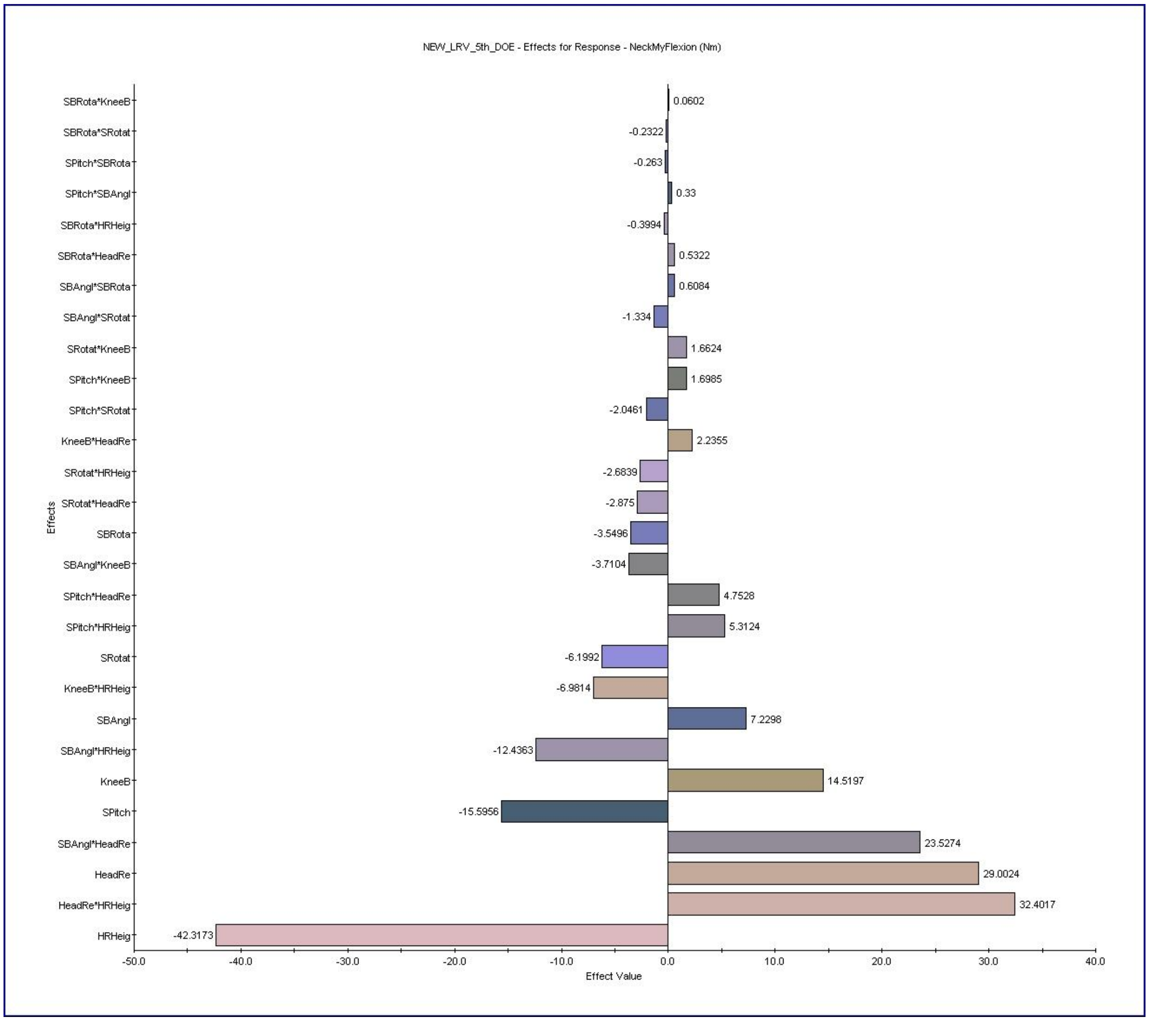


Figure C-5 shows that the height of the headrest is the most important factor to control the positive neck moment (flexion). The headrest stiffness also has a very important influence on results.

Figure C-6 shows the same results but takes into account the interaction between two different factors. This means that for flexion, the most important factor is the headrest height, but the interaction between the headrest height and its padding material is also very important for the neck flexion values obtained.

Figure C-6

Flexion Response Depending on Interaction between Factors



Optimization Example

According to the results shown in Figure 5.2, the normalized injury values obtained for the 5th percentile ATD in the outboard position were below acceptable limits, except for the neck flexion moment. This example shows the results obtained from the design of experiment once the process is optimized.

For this configuration, the seat design will be optimized to reduce the neck flexion moment and NIJ values. Table C-3 shows the values for the factors studied to reduce the aforementioned injury values. Softer padding materials and the highest headrest position should be used. The seat pitch should be 850 mm. The rotational stiffness of the seat needs to be stiffer to reduce injuries. Figure C-7 and Figure C-8 shows a comparison of the normalized injury values and seat results for the initial seat design and the new seat design. All injury values are below current FMVSS 208 limits. However, due to the decrease of some injury values, others have increased.

Table C- 3

Design of Experiments Optimized Configuration—Factors Values

DOE Parameters	To Minimize Injury Values	Original Seat
Seat Pitch (m)	0.85	0.75
Seat Back Angle (degrees)	1.4319	1.38
Stiffness Seat Back	1.5	1.0
Stiffness Seat Rotation Z-Direction	1.5	1.0
Stiffness Knee Bolster	2065	No Padding
Stiffness Headrest Material	2065	No Padding
Seat Back Height (m)	0.4	0.25

Figure C- 7

Comparison of Normalized Injury Values of Forward-Facing Seat Results for Original and Optimized 5th Percentile ATD in Outboard Position

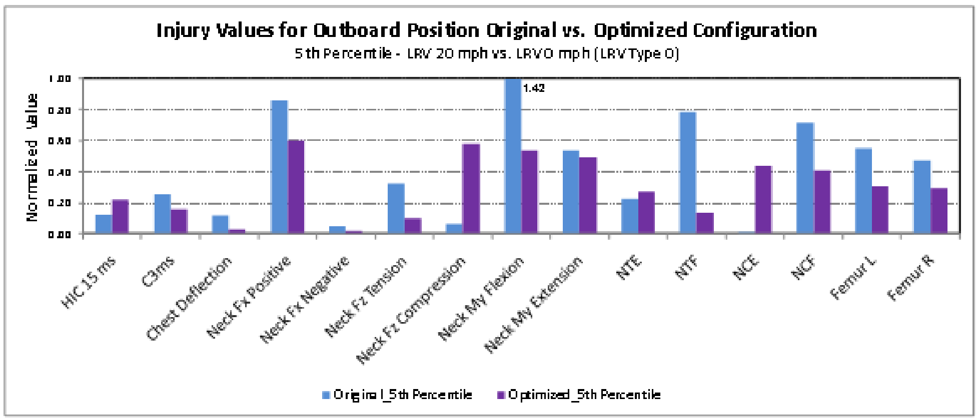
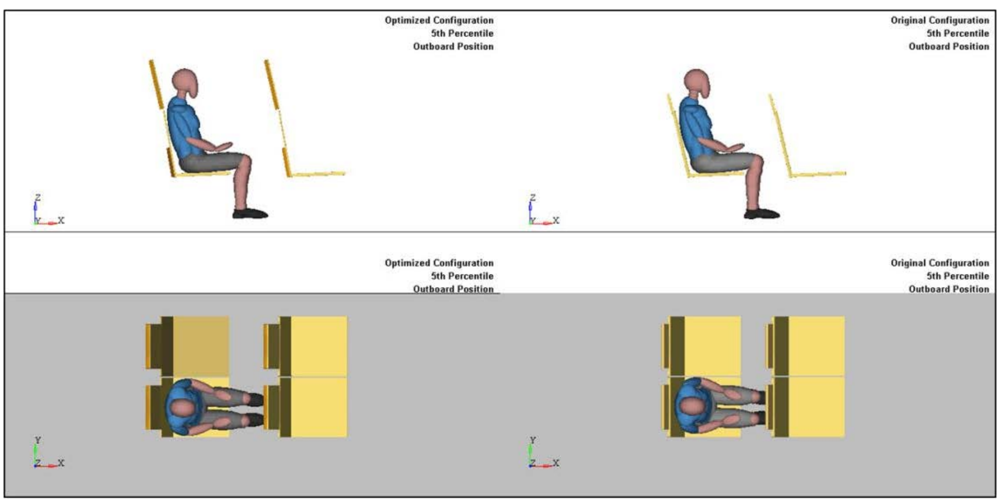


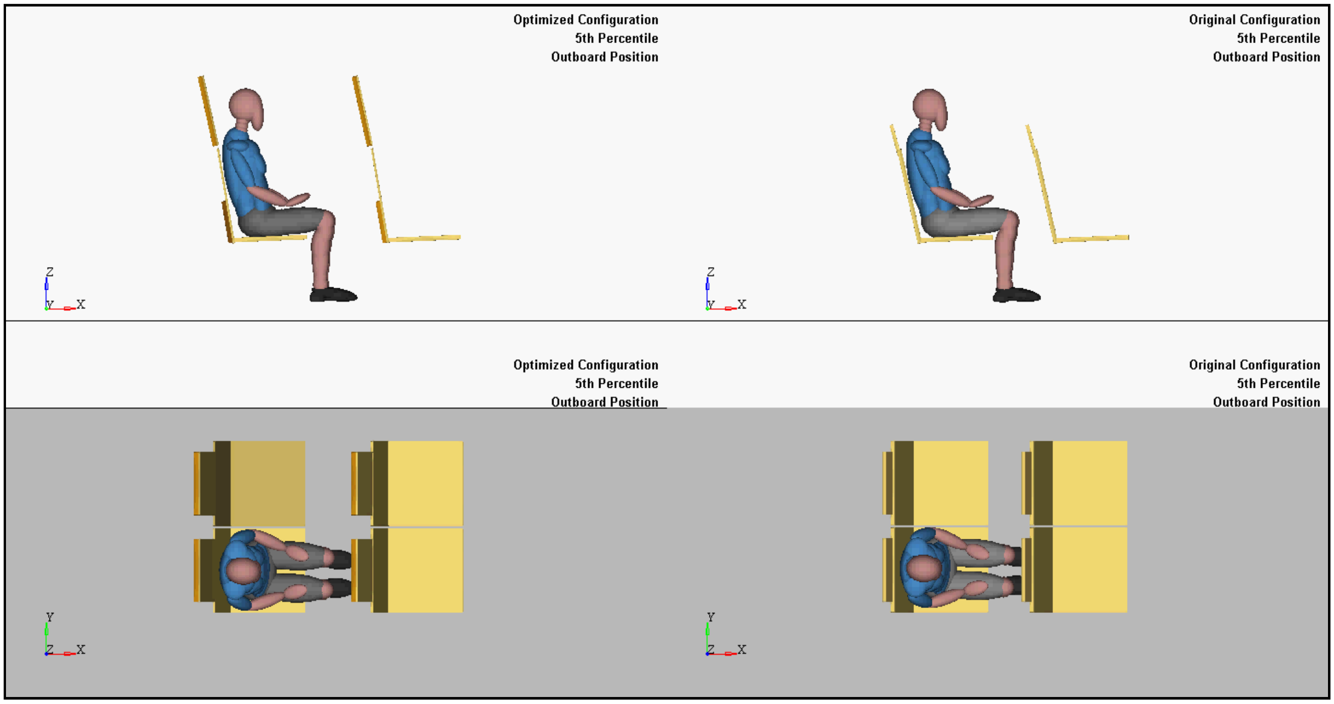
Figure C- 8

Optimized Forward-Facing Seat Results for 5th Percentile ATD in Outboard Position



Video C-1

High Energy LRV vs. LRV Optimized Forward Facing Seat Collision Scenario – 5th Percentile



It is important to stress that the results shown in this section are for the specific case of the 5th percentile ATD occupant in the outboard position. This is not applicable for other passenger sizes or positions.

For this reason, a complete design of experiments with 13,112 runs will be needed for the screening process to redesign the forward-facing seat, taking into account all types of passengers and both positions (inboard and outboard).

APPENDIX

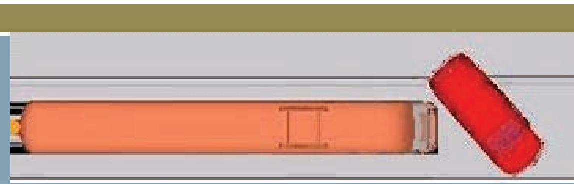
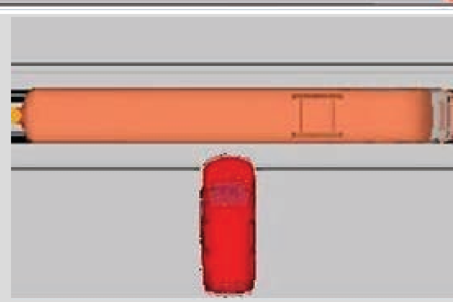
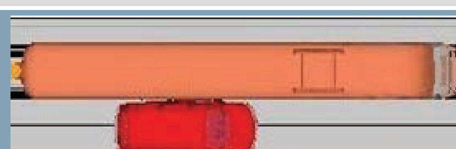
D

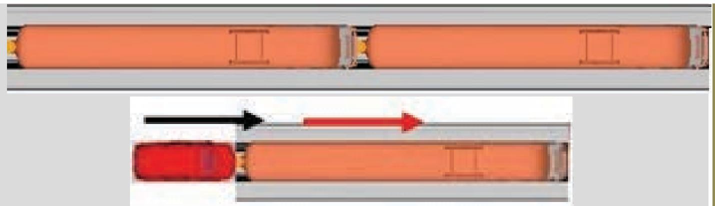
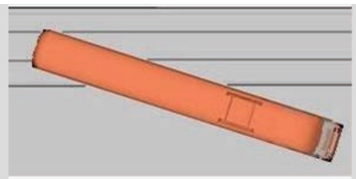
Accident Characteristics Survey

The purpose of the survey shown in Table D-1 was to gather all the available information to create a comprehensive statistical analysis of light rail vehicles. The survey requests information regarding accident conditions.

Table D-1

Accident Characteristics Survey

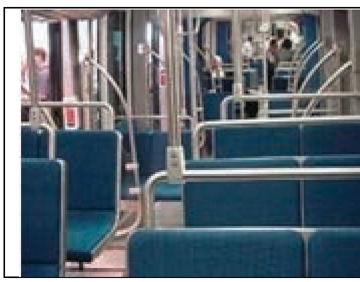
Date and Time				Answer
Location	Weather			
	Track Work			
	Other Issues			
		Exclusive right-of-way (fully grade-separated)		
	Type of Track	Semi-exclusive	Separate right-of-way	
			Shared right-of-way protected by	
			6-inch-high curbs and fences	
			Shared right-of-way protected by	
			6-inch-high curbs	
		Non-exclusive	Mixed traffic operation	
			Transit mall	
			LRV/pedestrian mall	
	Grade Crossing			
	Mall			
	Other			
Characteristics of Accident	Direction	Frontal with angle		
		Right angle		
	Direction	Sideswipe		

Date and Time				Answer
		Rear end		
		Head on		
Characteristics of Accident	Derailment after contact? (yes or no)			
		Derailment LRV alone		
	Type of Accident	With another motor vehicle	Motorcycle	
			Vehicle Sedan	
			SUV	
			Truck	
			Bus	
			LRV	
		Others	Pedestrian	
			Cyclist	
		LRV alone (derailment)		
	Velocities	LRV		
		Vehicle (if applicable)		
	Principal Cause (if known)	Exceeds velocity		
		Deteriorated infrastructure		
		Object on track		
		Human error		
		Bad weather		
	Fatalities	On board		
		On other vehicles		
		Pedestrians		
	Injuries	On board		
		On other vehicles		
		Pedestrians		
	Number of passengers on board at moment of accident			
	For injured or deceased pedestrian, when did the accident occur?	Alighting		
		Boarding		
		Struck by door		
		On board		

Layout Characteristics Survey

This study requires LRV structural data and measurements of interior layouts. An accurate description of the requirements described above may improve the passenger safety study.

- Structural data for the LRV, with emphasis on the following:
    - Make and model
    - Weight (lbs)
    - Length (in)
    - Width (in)
    - Number of articulations
    - Design buff load (lb)
    - Maximum passenger capacity
    - Percentage of the low floor area (%)
    - Distance from floor to ground (in)
- Crash energy management (CEM) systems, if equipped, and energy-absorbing capacity for each CEM element:
    - Bumpers (yes/no)
        - Energy absorbing capacity (each/kJ)
    - Cab crush design distance (in)
    - Others (if any/kJ)
- Interior layout
    - Types of seats and characteristics (dimensions, materials, etc.).
        - Forward-facing seats and number of passengers



Number of Seats	**Dimensions (inches)**	
	Seat Back	**Seat Pan**

- Rear-facing seats and number of passengers

Number of Seats	**Dimensions (inches)**	
	Seat Back	**Seat Pan**

o Side-facing seats and number of passengers

<table>
<tr><td rowspan="3"></td><td rowspan="2">Number of Seats</td><td colspan="2">Dimensions (inches)</td></tr>
<tr><td>Seat Back</td><td>Seat Pan</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

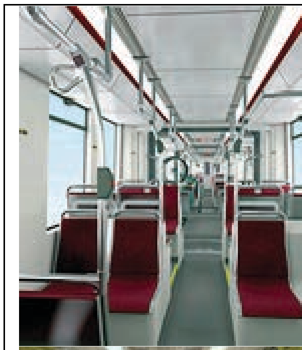
o Mixture of three types of seats and passengers (see below)

<table>
<tr><td rowspan="3"></td><td rowspan="2">Number of Seats</td><td colspan="2">Dimensions (inches)</td></tr>
<tr><td>Seat Back</td><td>Seat Pan</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

o Recliner seats

<table>
<tr><td rowspan="3"></td><td rowspan="2">Number of Seats</td><td colspan="2">Dimensions (inches)</td></tr>
<tr><td>Seat Back</td><td>Seat Pan</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

- Type of anchor points for these seats.
  - Seat attached to floor (see pictures below)



Number of Seats	Orientation
	Forward
	Rear
	Side

  - Seat attached to lateral structure (see pictures below)

Number of Seats	Orientation
	Forward
	Rear
	Side

  - Mobility device areas (type of anchor points)

Number of Seats	Type of Anchor Points	Orient-ation
		Forward
		Rear
		Side

- Types of handrails for standing passengers

	Type	Number
	Standing passenger capacity	
	A—Barrier with handrail	
	B—Floor-to-roof handrail	
	C—Seat-back handrail	
	D—Ceiling handrail	
	E—Attachment for ceiling handrail	
	F—Seat back-to-roof handrail	

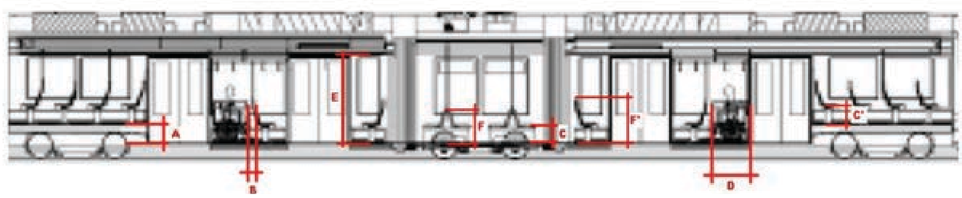
- o Space for luggage (if existent)—dimensions, position, and type of attachment (if available)

	Number of Spaces	Type of Attach-ment for Luggage	Position
			Roof
			Floor
			Shelf

Table D-2 shows the most important distances that are needed to create a detailed CAD model of the LRV. Note that some of these distances might not be applicable for all designs (for example, absence of side-facing seats).

Table D- 2

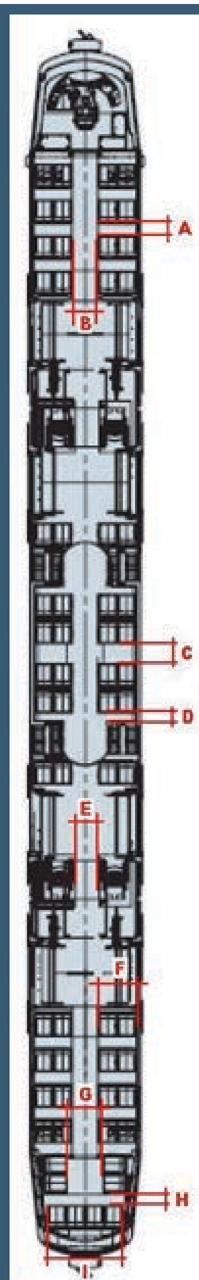
CAD Model Distances

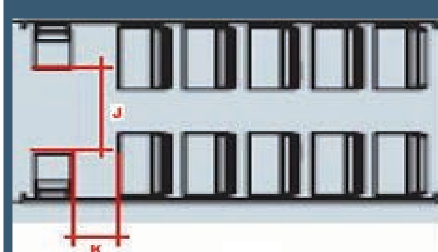


Type	Distance (inches)
A: Height of floor	
B: Gap between handicap space and regular seat	
C and C': Height of seat pan	
D: Width of handicap space	
E: Height of handrail	
F and F': Height of seat back	

Table D-2 (continued)

CAD Model Distances





Type	Distance (inches)
A: Distance between seats in same direction	
B: Aisle width between forward-facing seats	
C: Distance between seats in opposite direction	
D: Distance between seat and barrier	
E: Aisle width between wheelchairs	
F: Seat width and number of occupants	
G: Aisle width between side-facing seats	
H: Distance between side- and forward-facing seats	
I: Seat width and number of occupants for special seats configuration	
J: Distance between individual side seats	
K: Distance between side- and rear-facing seats	

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