ANALYSIS OF PASSENGER SAFETY FOR THOSE ON SIDE-FACING SEATS IN LIGHT RAIL VEHICLES

A Thesis by

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LIGHT RAIL VEHICLES: SIDE FACING SEATS ANALYSIS

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my wife
To my family

Honesty is the best policy.

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ABSTRACT

Major metropolitan areas throughout the United States provide Light Rail Transit (LRT) services. What distinguishes the light rail system is that it operates on city streets with grade crossings within city limits. Consequently, the injury rates of the light rail systems are higher than for example the heavy rail systems. Light rail vehicles have different types of seats arrangements as: forward-facing seats, aft-facing seats, side-facing seats, and so forth. Although, side-facing seats are not the most common type of seats, they represent more than 17% of total number of current LRV seats.

Different side-facing seats configurations are analyzed in this thesis and the current level of safety is evaluated for different occupant sizes, as well as different crash scenarios. To evaluate the current level of safety, a multi-body model of a current LRV interior is built. The injuries are quantified by comparing the simulations results with the current Federal Motor Vehicle Safety Standard (FMVSS) limits.

Overall, the level of safety for a typical head-on crash scenario, where one LRV is stationary and the other is traveling at 20 mph, is acceptable when barrier or aft-facing seats are placed at the end of the side-facing seats. The remaining configurations analyzed do not provide the sufficient level of protection, in particular when there is head to head contact between occupants.

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LIST OF ABBREVIATIONS / NOMENCLATURE

LRT	Light Rail Transit
LRV	Light Rail Vehicle
TCRP	Transit Cooperative Research Program
NTD	National Transit Database
FTA	Federal Transit Administration
USDOT	United States Department of Transportation
CEM	Crash Energy Management
FMVSS	Federal Motor Vehicle Safety Standard
ATD	Anthropomorphic Test Dummy

CHAPTER ONE

INTRODUCTION

This thesis is part of the "*Crashworthiness Evaluation of Light Rail Vehicles Interiors*" [1]. Project conducted at the Computational Mechanic Laboratory at the National Institution for Aviation Research at Wichita State University and founded by the Federal Transit Administration (FTA).

Nowadays, most important metropolitan areas throughout the United States provide Light Rail Transit (LRT) services. The majority of the Light Rail Vehicles (LRV) on those cities operates within the city limits. Almost all the mainline track length available in the United States can be divided into two types of environments: (1) semi-exclusive right-of-way and (2) exclusive right-of-way.

According to the Transit Cooperative Research Program (TCRP) report 69 "*Light Rail Service: Pedestrian and Vehicular Safety*" published in 2001 [2], more than 75 percent of the total mainline track length fall under the category of semi-exclusive right-of-way with LRV speeds greater than 35 mph (55 kmh), nevertheless, only 13 percent of the average annual total accidents occur at these higher speed segments. In contrast, 87 percent of the LRV accidents occur on city streets where the LRV shares the street with other vehicles as cars, trucks, buses, etc. From the accidents occur on city streets, 62 percent of involved motor vehicles and 38 percent of the cases involve cyclists or pedestrians [2].

According to the "*Transit Safety & Security Statistics & Analysis 2003 Annual Report*" [3], light rail systems have higher injury rates on a per passenger-mile basis than heavy rail and commuter rail. This is the result of the high number of grade crossings that can be found on the

light rail transit systems. Occupant safety during a crash accident depends on two major components:

1) Configuration and severity of the accident
2) Degree of crashworthiness engineered in the overall vehicle designs for all the vehicles involved on the accident

Due to the impact, sudden acceleration or deceleration of the vehicle, or mechanical damage to the vehicle structure can occur. As a result of these accelerations or damages, occupants can be injured or killed. The two major mechanisms that cause these injuries are described below:

1) Primary collision of the vehicle against another vehicle or obstacle. There are two main possible results: (a) occupant compartment crush and consequent reduction of survival space or (b) 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) at some time following the initiation of the primary collision.

Due to the low speed of LRVs operating within city limits (below 35 mph (55 kph)) [2], as well as the higher mass when compared to the others vehicles sharing the road, the most part of passenger injuries occur from collisions stemming from secondary impacts with interior surfaces as seats, grab-handles, poles, etc. or other passengers, rather than reduction of survival space or penetrations of the compartment. Data from the National Transit Database (NTD) (2002-2005) indicate an average of 4,433 injuries and fatalities in U.S. heavy rail transit systems per year, 1,625 injuries and fatalities in commuter rail systems, and 605 injuries and fatalities in

light rail transit systems [3]. Nonetheless, this data does not distinguish between injuries and fatalities of pedestrians, occupants of rail vehicles, or occupants of other motor vehicles. Hence, the severity of injuries and fatalities caused by secondary impacts in light rail transit vehicles are unidentified.

Current LRVs interiors have a large variety of seating configurations (See Figure 1). The most common seating configurations are:

1) Unidirectional Forward Facing Seats
2) Unidirectional Rear Facing Seats
3) Seating Facing each other
4) Side Facing Seats or Lateral Facing Seats

Figure 1. Example LRV interior layout

1.1 Objectives

The main objective of this thesis is to identify the injury mechanisms to LRV passengers seated on side facing seats and to propose future areas of research that will improve the level of safety for this type of seating configuration.

Thirty-seven different configurations of side-facing seats are analyzed, where different seat arrangements, occupant sizes, number of passengers, and crash scenarios are considered.

All the work will be done using computational techniques, in particular multi-body technique, in order to reduce costs and increase the number of cases studied.

1.1.1 Methodology

In order to quantify the current level of safety for passengers traveling in side facing seats from an objective point of view the following steps are followed:

1) Current service conditions and therefore impact conditions for light rail vehicles are studied by the literature review.
2) Once the most common light rail services conditions are determined, a complete interior survey analysis is conducted so type of seats and their percentage are defined.
3) Using the most common impact conditions and some of the information from the interior survey four crash scenarios are analyzed (See Table 1). Two different types of LRVs, one minivan, and a bus transit bus are used.

TABLE 1

LRV CRASH SCENARIOS ANALYZED

Bullet	Target
LRV (1) – 20 mph	Mini Van – 0 mph
LRV (1) – 20 mph	Mass Tran. Bus – 0 mph
LRV (1) – 20 mph	LRV (1) – 0 mph
LRV (2) – 20 mph	LRV (2) – 0 mph

4) Using the worst-case scenario from the analysis above the detailed analysis for the passengers seated on side-facing seats is conducted. This analysis will be divided into three phases:

1. *Euro-SID analysis*. On this analysis the specific injury values that are common to side impacts are studied. In order to properly evaluate these injuries the Euro-SID Anthropomorphic Test Dummy (ATD) is used. This ATD represents a 50th percentile human and was developed specifically for analysis of side facing impacts.

2. *Exit velocity analysis*. According to the interior survey, up to six passengers can be seated on current side-facing seats. Prior to the complete analysis, the worst seated position from the injuries and the impact velocity point of view is established.

3. *Complete side-facing seats analysis*. Using the worst seating position from the previous study, different side-facing seats arrangements are evaluated.

The next figure summarizes the steps followed:

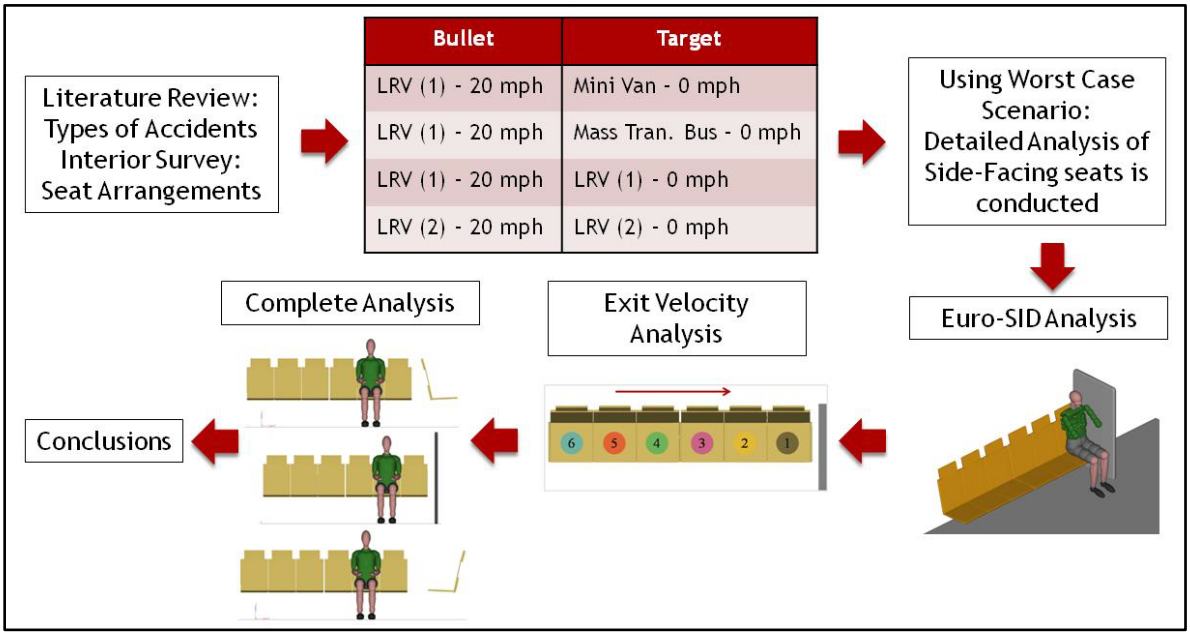


Figure 2. Methodology

In order to evaluate the level of injuries, the federal motor vehicle safety standards 208 "Occupant Crash Protection" and 214 "Side Impact Protection" are used as reference. The following table summarizes all the injury values used for normalize the result through the entire thesis.

TABLE 2

INJURY VALUES LIMITS - FMVSS 208 AND 214

Injury Criterion Performance Limits (ICPL's)	**50th %ile**	**95th %ile**	**5th %ile**	
			In-Position	**Out-of-Position**
HIC (15 Max)	*700*	*700*	*700*	
Trauma Thoracic Index TTI in G´s	*85*	*N.A.*	*N.A.*	
Viscous Criteria (m/s)	*1.0*	*N.A.*	*N.A.*	
Rib Deflection (mm)	*42*	*N.A.*	*N.A.*	
Chest Res. Acc (3 ms) in G's	*60*	*60*	*60*	
Chest Deflection (mm)	*63*	*63*	*52*	
Femur Load (N)	*10000*	*10000*	*6805*	
Neck Peak Tension (N)	*4170*	*4170*	*2620*	*2070*
Neck Peak Compression (N)	*4000*	*4000*	*2520*	
Neck Criteria N_{ij}	*1*	*1*	*1*	
Neck Flexion (Nm)	*190*	*190*	*95*	
Neck Extension (Nm)	*57*	*57*	*28*	38
Neck Shear (N)	*3100*	*3100*	*1950*	
Pelvis Max. Acceleration in G´s	*130*	*N.A.*	*N.A.*	

N.A. Not applicable

Figure 3 shows the most common neck injury mechanisms.

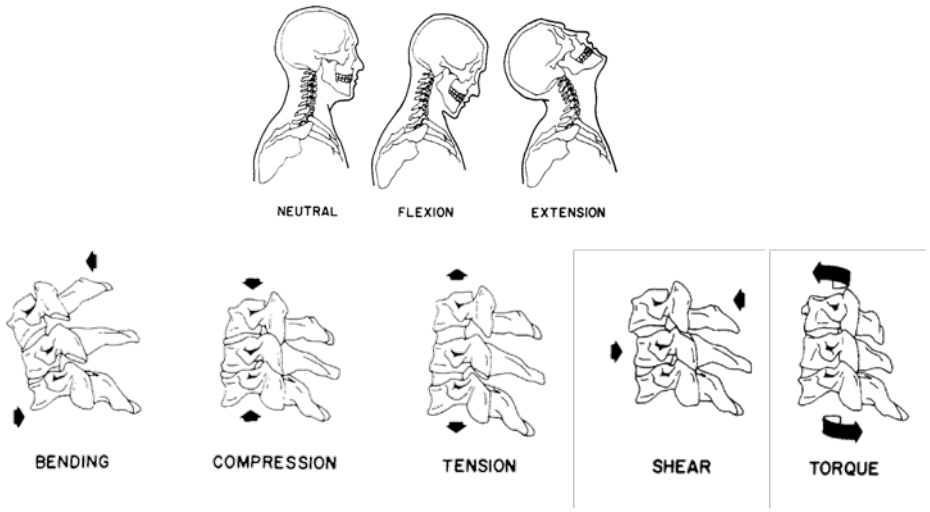


Figure 3. Neck injuries mechanisms [4]

As it was mention before, the entire analysis is conducted using multi-body techniques, in particular MADYMO code. Four numerical vATD databases are used. For the first analysis the Euro-SID 50th percentile ATD is used. For the remaining analysis the hybrid III 50th, 5th, and 95th are used. All these vATDs belong to the multi-body code database of MADYMO. The following figure shows a picture of all these vATDs.

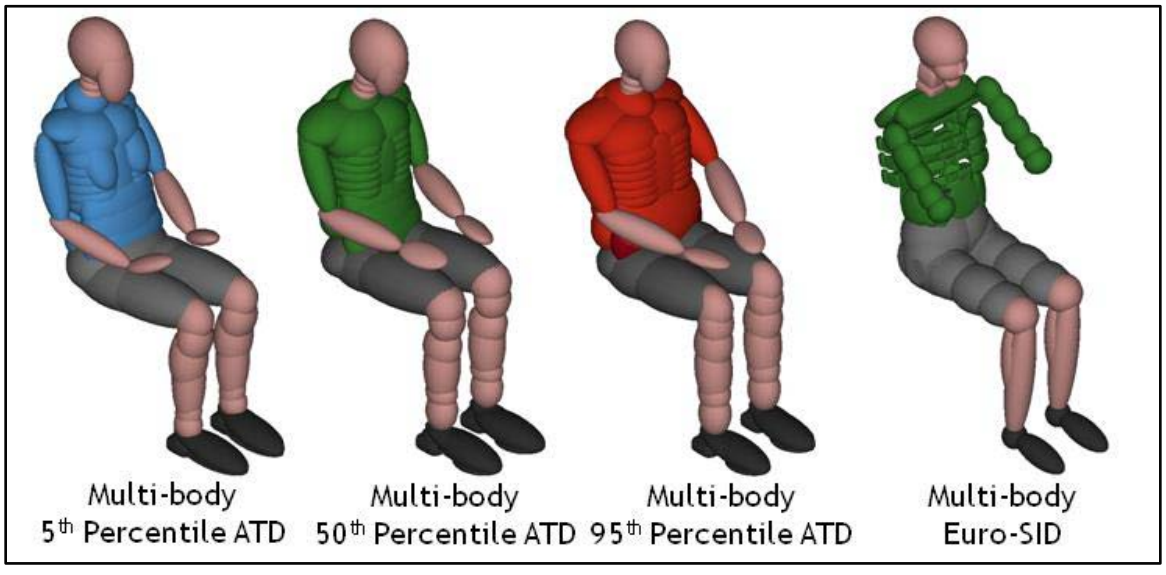


Figure 4. vATDs database

CHAPTER TWO

LITERATURE REVIEW FOR LIGHT RAIL VEHICLES

This section includes a summary of all the relevant LRV statistical data used for this research (Other reports and sources used for this research are shown in reference section). As seen in the following sections, the data available in some of these sources is not as complete as might be expected. The principal reports and surveys used to obtain the statistical data are:

1) *"Crashworthiness Evaluation of Light Rail Vehicle Interiors"* [1]

The interior layout and characteristics like size, weight, length, and maximum capacity for the majority of the current LRV fleet of the United States of America are analyzed. In addition, based on a LRV statistics studies, a reference collision scenario was identified. This collision scenario was used to conduct a detailed analysis of the current level of safety for the passengers traveling in the most common seats arrangements found in the current LRV fleet.

2) TCRP Report 69 - "*Light Rail Service: Pedestrian and Vehicular Safety*" [2]

This report provides documentation and the results of a study to improve the safety of light rail transit (LRT) in semi-exclusive rights-of-way where light rail vehicles (LRVs) operate at speeds greater than 35 mph through street crossings and pedestrian pathways. Data related to this project is presented in Chapter 2 of the report. This chapter presents an overview of the 11 LRT systems studied from U.S.A. and Canada, and summarizes the accident information. The data was collected from different time frames depending on the LRT system. It's also important to note that the data does not show any information about the type of accident, only if the accident was between the LRV and a vehicle, pedestrian, or cyclist.

3) *"Transit Safety & Security Statistics & Analysis 2003 Annual Report"* [3]

This report has information about the number of accidents for different mass transportation systems including light rail vehicles. In it there is information regarding 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. Nearly all data discussed in this report is from 1996 to 2003; nevertheless, some of the data has been updated through 2007 with information available at the Transit Safety and Security Web page [3].

4) TCRP Report 17 – *"Integration of Light Rail Transit into City Streets"* [5]

This report addresses the safety and operating experience of light rail transit (LRT) systems operating in shared (on-street or mall) rights-of-way 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: (1) accident statistics from the Federal Transit Administration (FTA) Section 15 Report for 1992, and (2) the multiyear accident information obtained from each system, including the highest-accident locations.

5) *"2008 Public Transportation Fact Book"* (Part 1 and Part 2) [6]

The Public Transportation Fact Book presents statistics describing the entire United States transit industry from 1995 to 2006, with additional detail and overview presentations for 2006. Definitions of reported data items are also included. 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 is more focused on the number of passengers and the capacity of the transport systems (including Light Rail Transit Systems) than in the type and number of accidents.

6) *"Passive Safety of Tramways for Europe"* [7]

Based on a LRV statistics study reference collision scenarios were identified. The study also includes an evaluation of their consequences in terms of material damage, injuries, and fatalities as applied to city LRV operations in Europe. An assessment of acceptable risk has also 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 1777 km. This represents about 30% of the total network length of EU operators (5121 km). In this study a total of 59,000 accidents with 7,600 casualties were reported from 21 European operators in the last 10 years. Using the data from these 21 operators, typical conditions for city tram crashes were obtained.

2.1 Summary – Data Literature Review

Throughout the last 10 years the total number of passengers, as well as LRV vehicles, has increased approximately 50% (See Figure 5). Still, as shown in Figure 6 and Figure 7, light rail passengers only represent 4.1 % of the total unlinked passenger trips if all modes are taken into account, and only 3.6% of total passenger miles by mode. It is interesting to note that while the total number of passengers and vehicles increased, Figure 8 and Figure 9, the number of

incidents remained relatively stable, Figure 10. In contrast, as shown in Figure 11 and Figure 12, while the number of incidents has been constant during this period, the number of collisions and derailments didn't experience that stability, whit a higher number of collision and derailments during the last decade.

As shown in Figure 13, the number of fatalities has increased during last decade. On the other hand, as shown in Figure 14, while the number of fatalities has increased, the number of injuries has actually been reduced during the last several years. It is important to mention that the decrease of injuries is directly associated with the revision of the NTD to coincide with other United States Department of Transportation (USDOT) modes. Therefore, the decrease in the number of people injured in LRV crashes could not be directly comparable with previous years.

Hence, according to this information it can be assumed that the number of incidents reported is similar through the last years, but the magnitude of them is larger, resulting in higher fatalities.

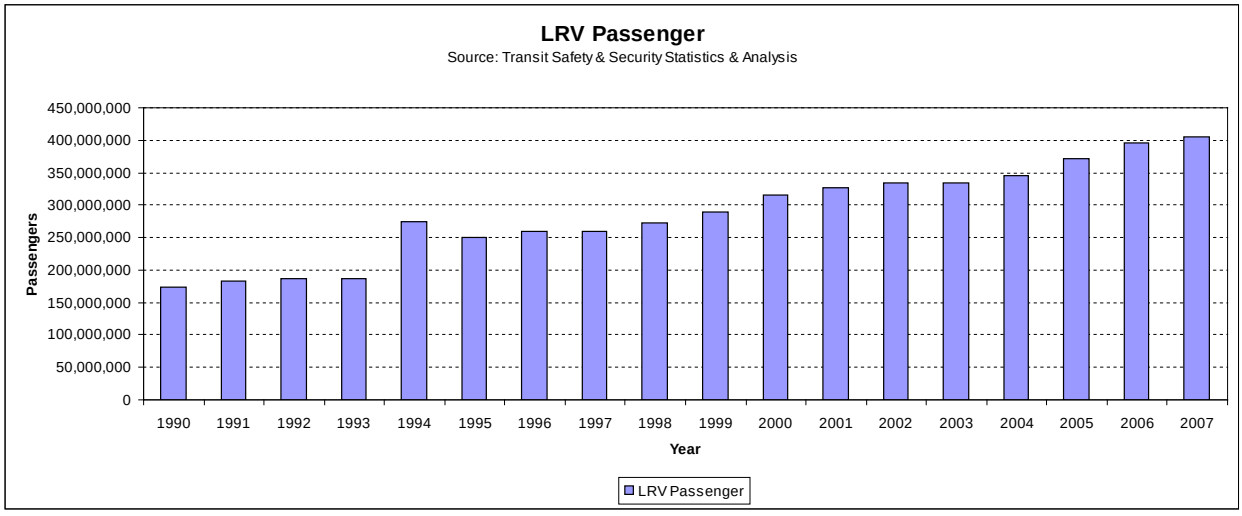


Figure 5. LRV passengers from 1990 to 2007 [1]

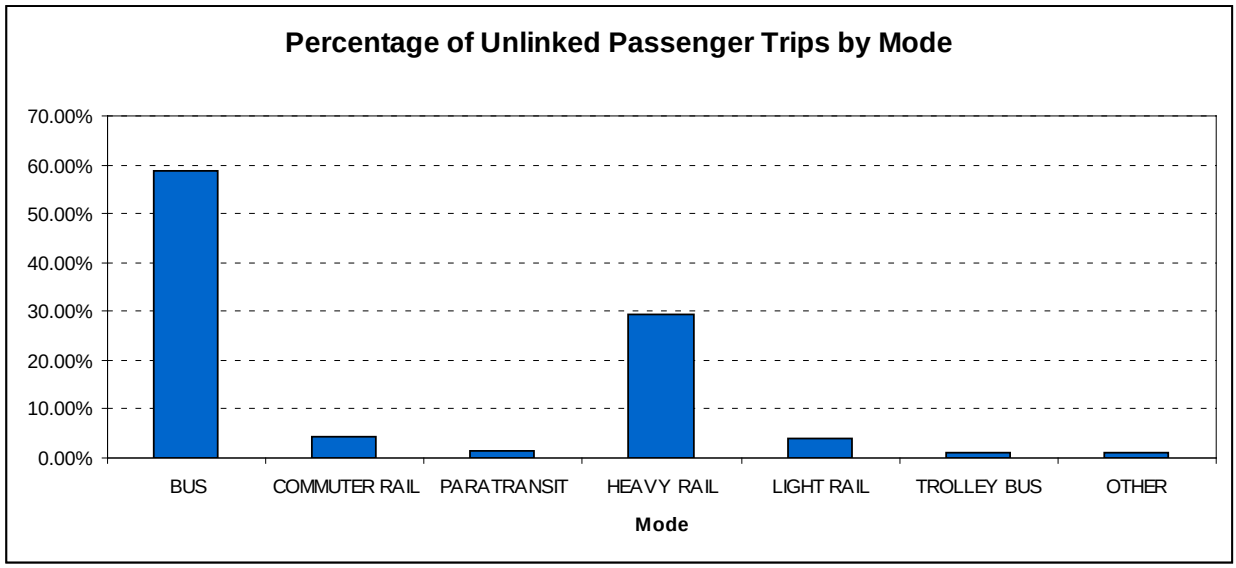


Figure 6. Percentage of unlinked passenger trips by mode [1]

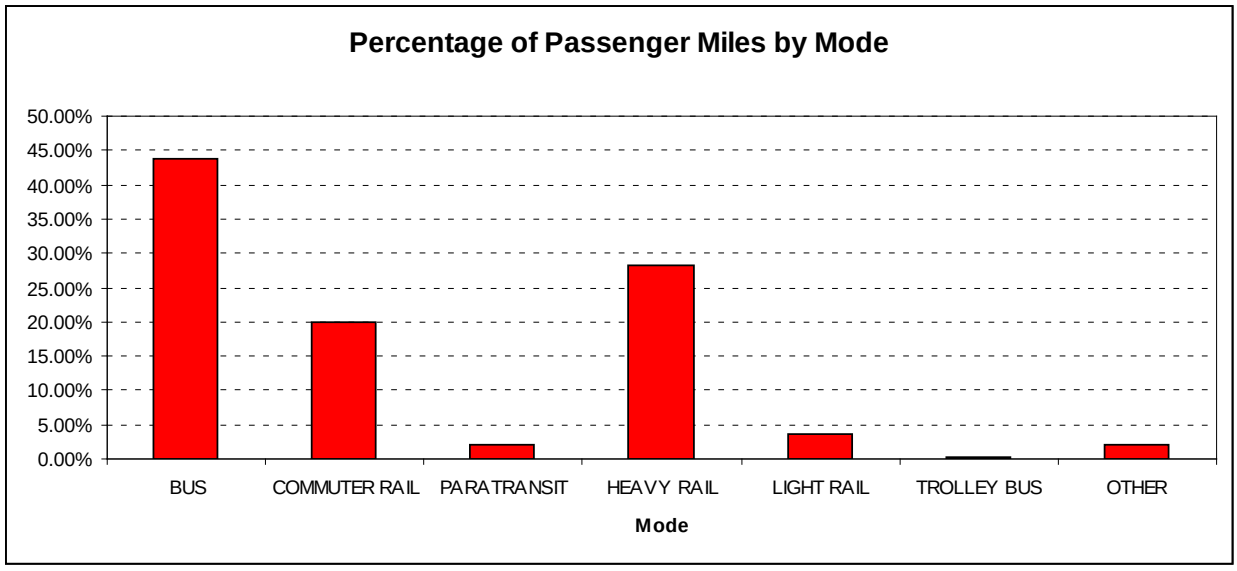


Figure 7. Percentage of passenger miles by mode [1]

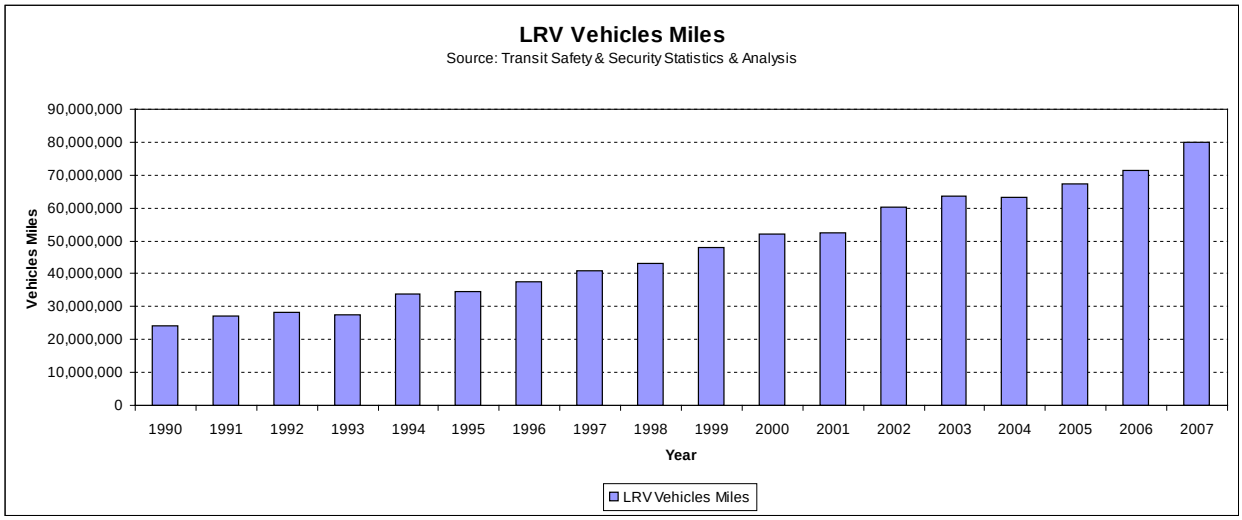


Figure 8. LRV Vehicles - Miles from 1990 to 2007 [1]

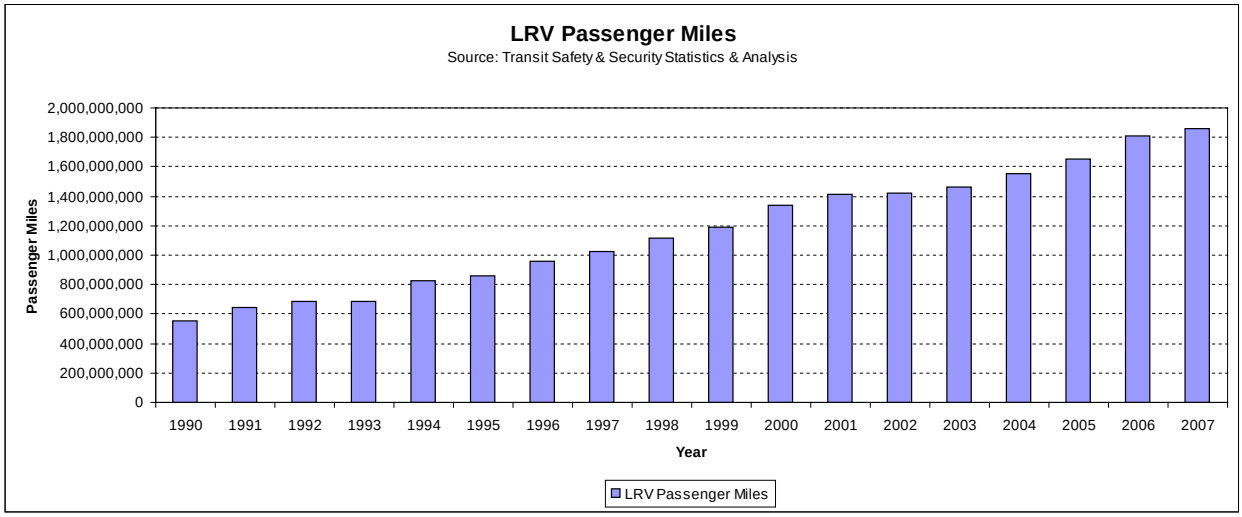


Figure 9. LRV Passengers – Miles from 1990 to 2007 [1]

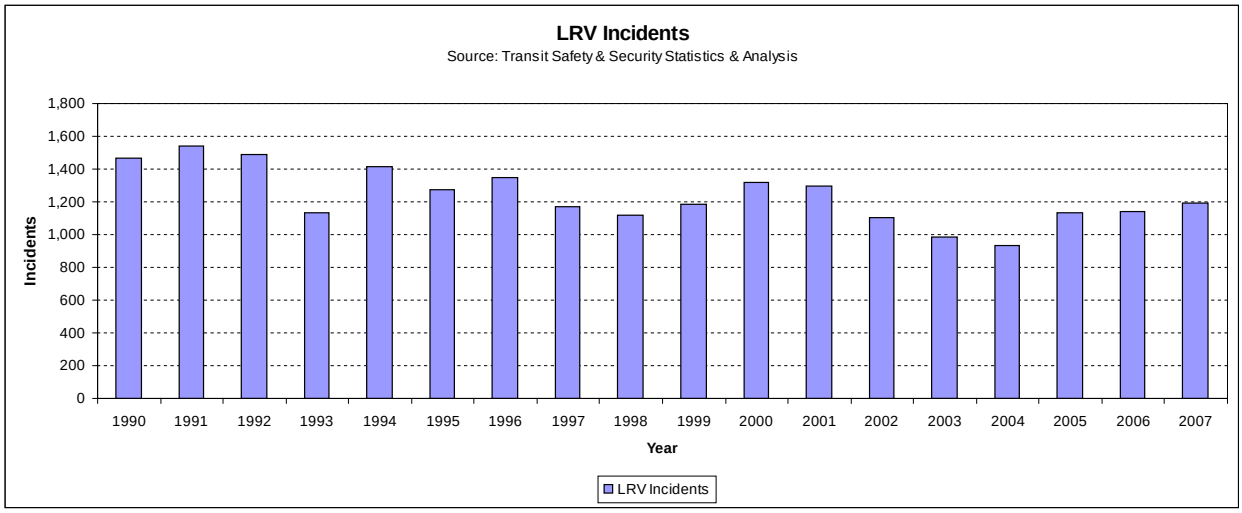


Figure 10. LRV reported incidents from 1990 to 2007 [1]

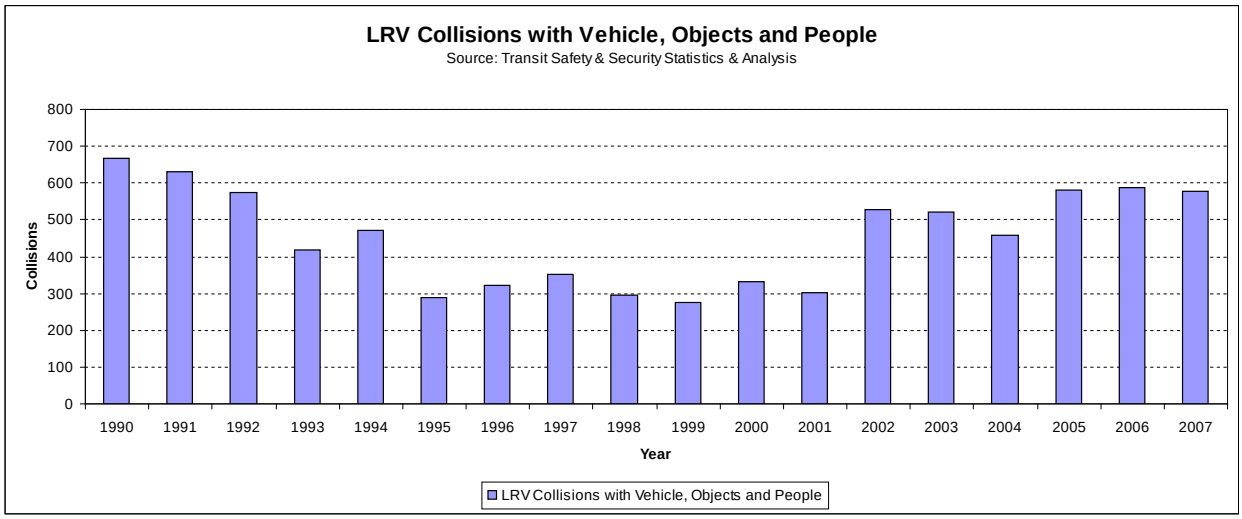


Figure 11. LRV reported collisions from 1990 to 2007 [1]

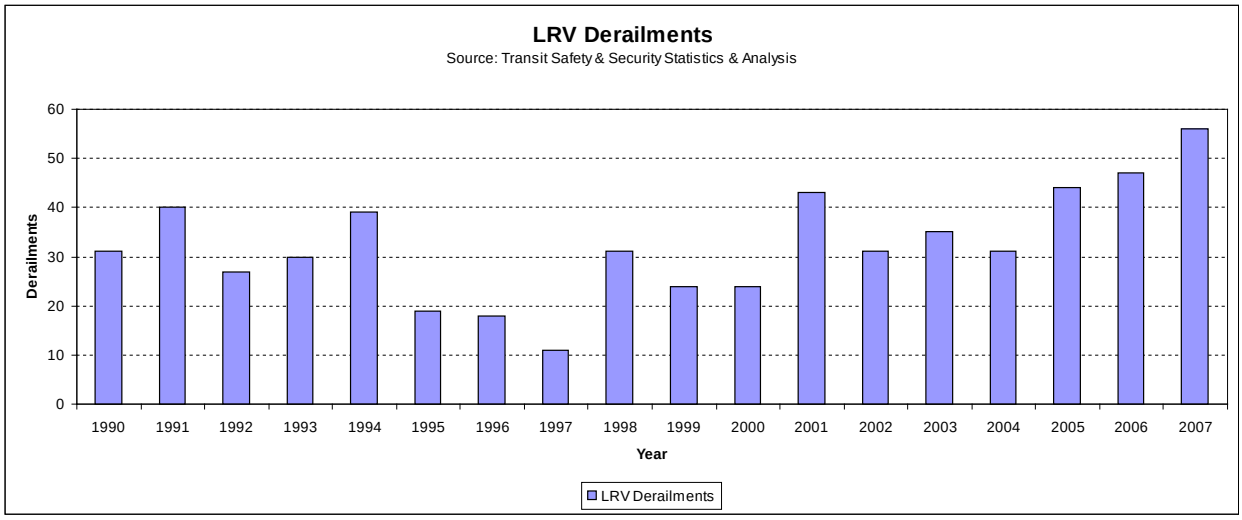


Figure 12. LRV reported derailments from 1990 to 2007 [1]

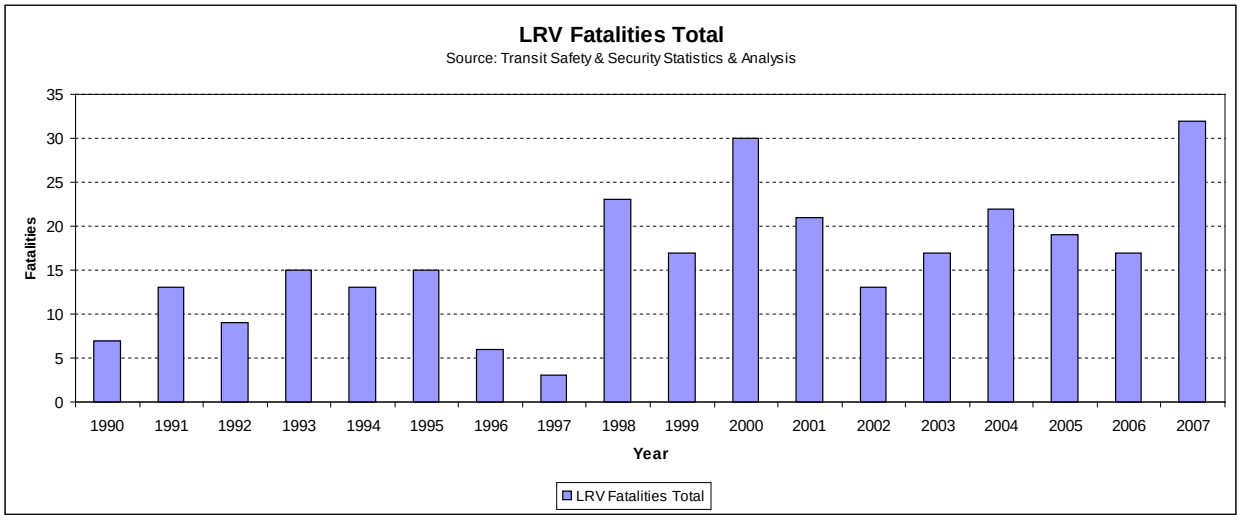


Figure 13. LRV reported fatalities from 1990 to 2007 [1]

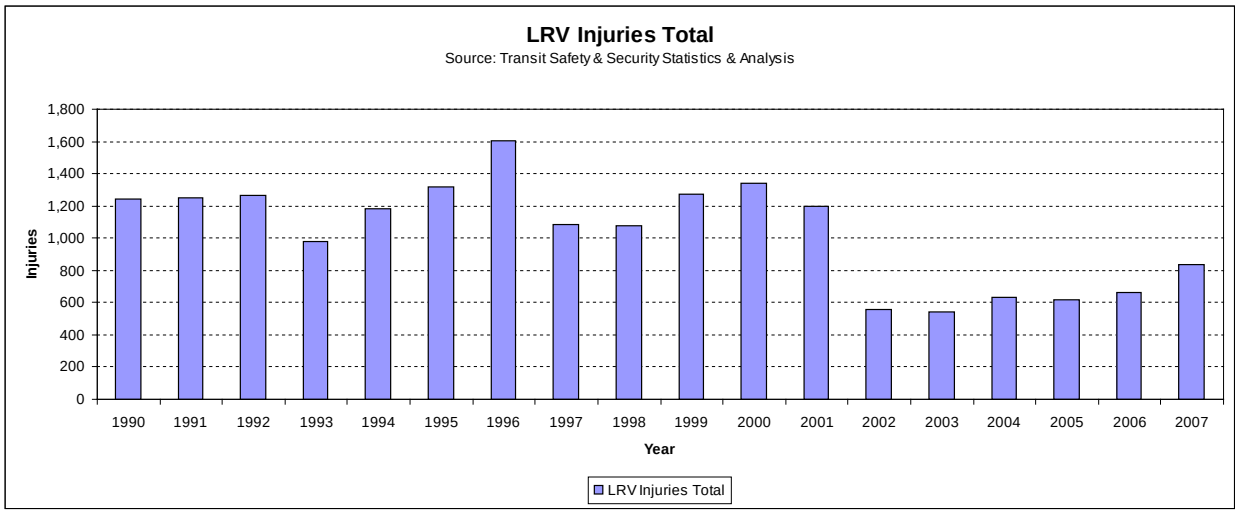


Figure 14. LRV reported injuries from 1990 to 2007 [1]

After reviewing the available information through the different agencies, it can be stated that there is a significant lack of current data for LRV accidents as most data published is confined to the mid 80's to late 90's. Available data is considered incomplete for the purpose of this research because of lack of exact injury and fatality data. Furthermore, different criteria were used to classify the types of accidents that occurred making the classification even more complex or unfeasible. Nevertheless, two useful papers [2,5] were found that aid in understanding the principal characteristics and conditions of LRV accidents.

In regard to the results observed in the TCRP Report 17 – "*Integration of Light Rail Transit into City Streets"* [5], most accidents occur when the LRV is traveling in a shared right-of-way scenario. 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 15, 92 % 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 % of the total mainline track miles (See Figure 16). During the time frame studied, 50% of accidents involved an automobile, 36%

involved a truck or bus, and 11% involved pedestrians. Examining all available data for the metro systems reported in TRCP Report 17 [5], most of the accidents involved an automobile. Moreover, almost half of these accidents (47%) involved a vehicle turning in front of the LRV as shown in Table 3.

TCRP Report 69 - "*Light Rail Service: Pedestrian and Vehicular Safety*" [2] is a continuation of the TRCP 17 [5] 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% 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 [2]. Table 4 and Table 5 indicates that while 77% 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% of the total accidents occurred at crossings along these sections of track (Figure 17). 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 Figure 18, Figure 19 and Figure 20), collisions at these crossings tend to be more severe than those at lower speed LRV crossings.

As shown in Figure 19 and Figure 20, 19% of the total collisions between LRVs and motor vehicles at crossings along right-of-ways where LRVs operate at speeds greater than 55

km/h (35 mph) resulted in fatalities, while only 1% of the collisions at crossings where the LRV travels at lower speeds (below 35 mph) resulted in fatalities. On the contrary, as shown in Figure 21 and Figure 22, LRV-pedestrian collisions did not show that large difference, with 29% of the higher speed collisions resulting in fatalities compared with only 18% for the lower speed collisions.

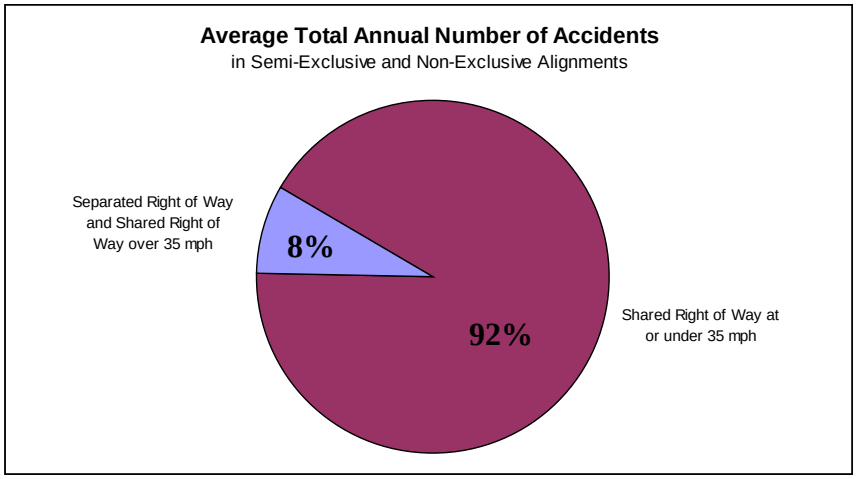


Figure 15. Average total annual number of accidents [5]

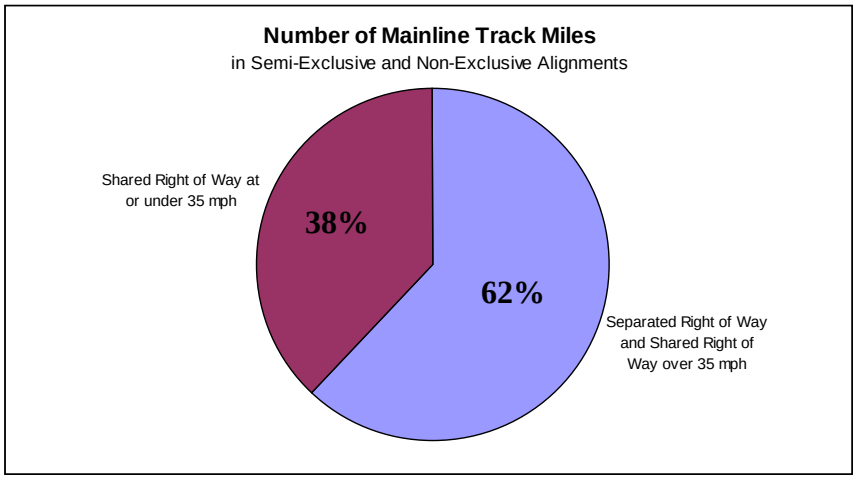


Figure 16. Mainline track miles in percentage by alignment type and velocity [5]

TABLE 3

ACCIDENTS SUMMARY FOR LRT SYSTEMS SURVEYED [5]

LRT System Period No. of Years	BALTIMORE 4/92-7/94 2.3		BOSTON 7/89-8/93 4.2		BUFFALO 2/85-11/93 8.8		CALGARY 5/81-12/93 12.7		LOS ANGELES 7/90-6/94 4.0		PORTLAND 7/86-6/94 8.0		SACRAMENTO 11/86-2/92 6.3		SAN DIEGO 7/81-6/94 13.0		SAN FRANCISCO 1/86-12/93 8.0		SAN JOSE 7/87-12/93 6.5		ALL SYSTEMS	
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	86%	--	38%	0	0%	206	73%	129	56%	76	41%	--	59%	298	85%	--	27%	106	64%	1350	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	27%	31	13%	27	15%	--	3%	54	15%	--	2%	10	6%	241	9%
Total	64	100%	97 (d)	100%	10	100%	285	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 Mille	1.16		1.98		0.09		0.64		1.35		0.85		0.77		0.41		3.12		0.73		1.11	
Mainline Track Miles 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		3.0		4.2		1.7		2.9	

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

TABLE 4

SUMMARY OF ACCIDENT EXPERIENCE AT LRT CROSSINGS IN PERCENTAGE (THROUGH 1996) [2]

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
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 (c)	20.8	1%	26%	100%	74%
Sacramento	20.5	11%	73%	89%	27%
Saint Louis	0.5	100%	100%	0%	0%
San Diego	28.5	21%	89%	79%	11%
San Jose (c)	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 rights-of-way where LRVs travel at speeds less than 55 km/h account for accidents through 1994.

TABLE 5

SUMMARY OF ACCIDENT EXPERIENCE AT LRT CROSSINGS (THROUGH 1996) [2]

LRT System	Average Total Accidents (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)		
		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	0.04	29.0	21	1.38
Calgary	12.2	5.1	20	0.26	7.1	13	0.55
Dallas	6.0	2.0	22	0.09	4.0	14	0.29
Denver	34.0	0.5	2	0.25	33.5	29	1.16
Edmonton	1.7	1.7	8	0.21	d	d	d
Los Angeles	50.7	10.7	28	0.38	40.0	56	0.71
Portland (e)	20.8	0.1	4	0.03	20.7	74	0.28
Sacramento	20.5	2.2	14	0.16	18.3	62	0.30
Saint Louis	0.5	0.5	11	0.05	d	d	d
San Diego	28.5	5.9	43	0.14	22.6	42	0.54
San Jose (e)	25.2	0.2	3	0.07	25.0	59	0.42
Average	20.9	2.7	16	0.17	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 indicates 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 at San Diego LRT system along semi-exclusive right-of-way, 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 for about 0.5 years (North line to Old Town and East line extension to Santee). The total number of crossing-years is thus (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 has been in operation for a total of 17 years. Therefore, the total number of crossings-years per year (or average annual LRT crossings-years) is 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-way 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 rights-of-way where LRVs travel at speeds less than 55 km/h account for accidents through 1994.

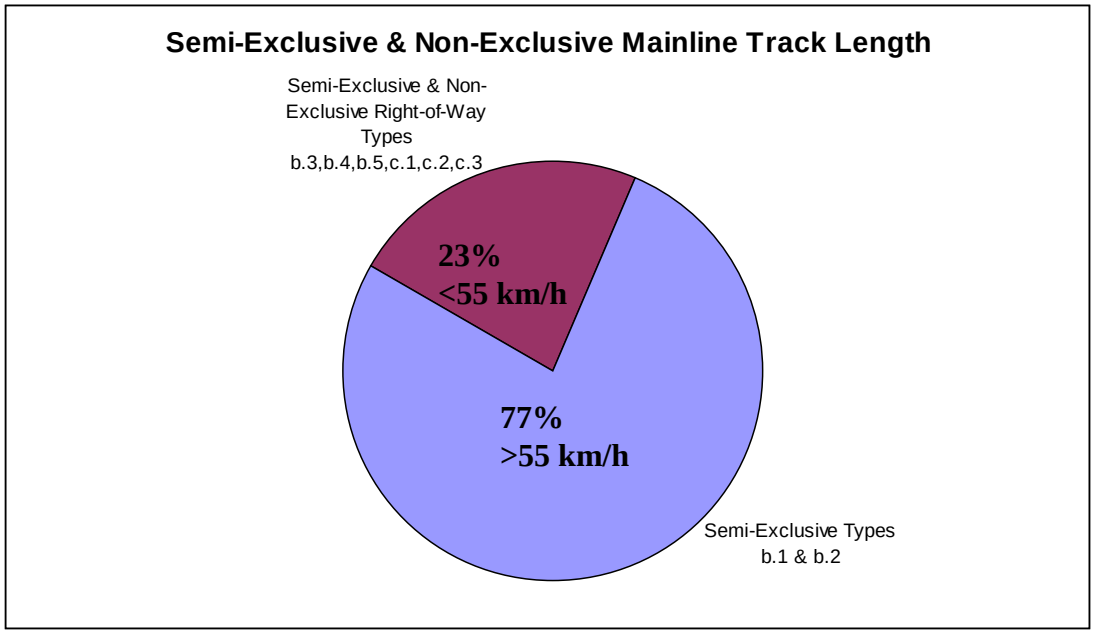


Figure 17. Semi-exclusive and Non-exclusive mainline track length [2]

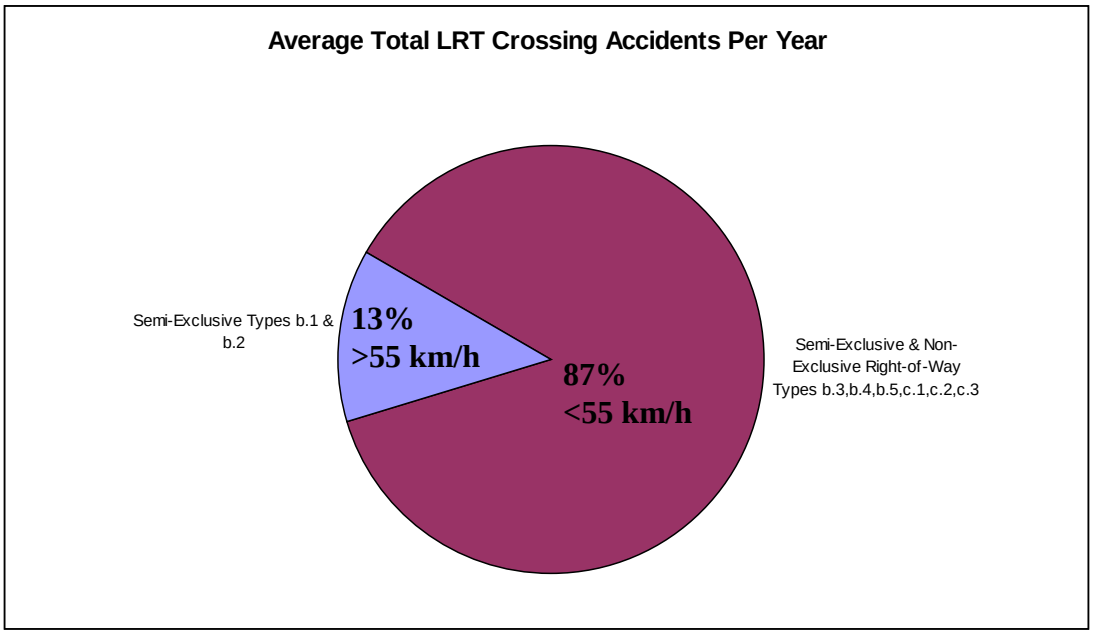


Figure 18. Average total LRV Crossing accidents per year comparison [2]

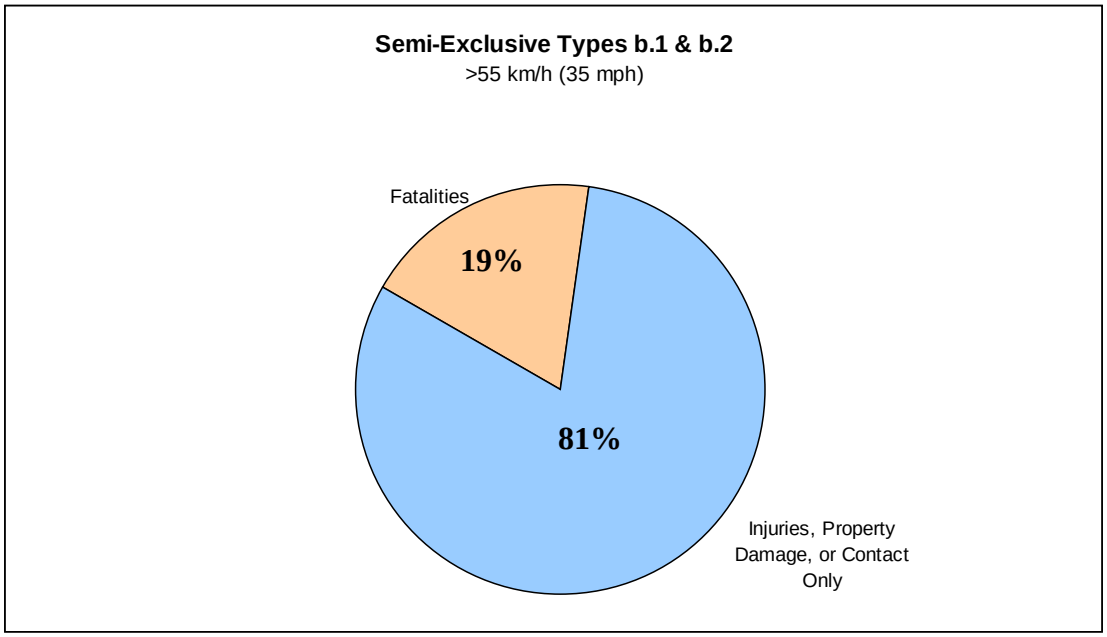


Figure 19. Collision severity LRV traveling above 35 mph [2]

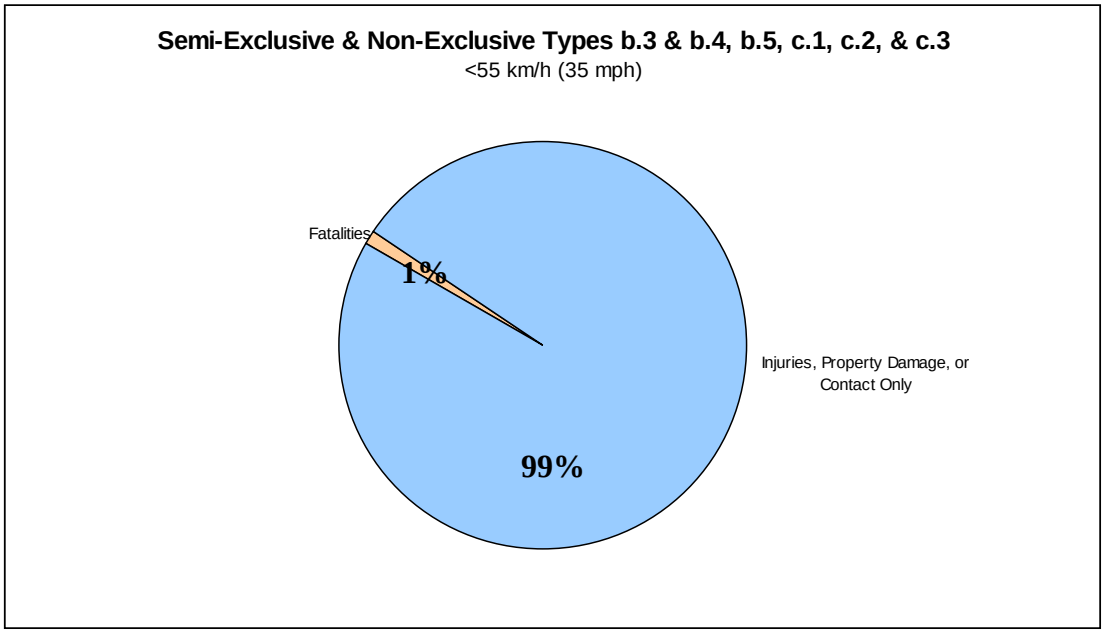


Figure 20. Collision severity LRV traveling below 35 mph [2]

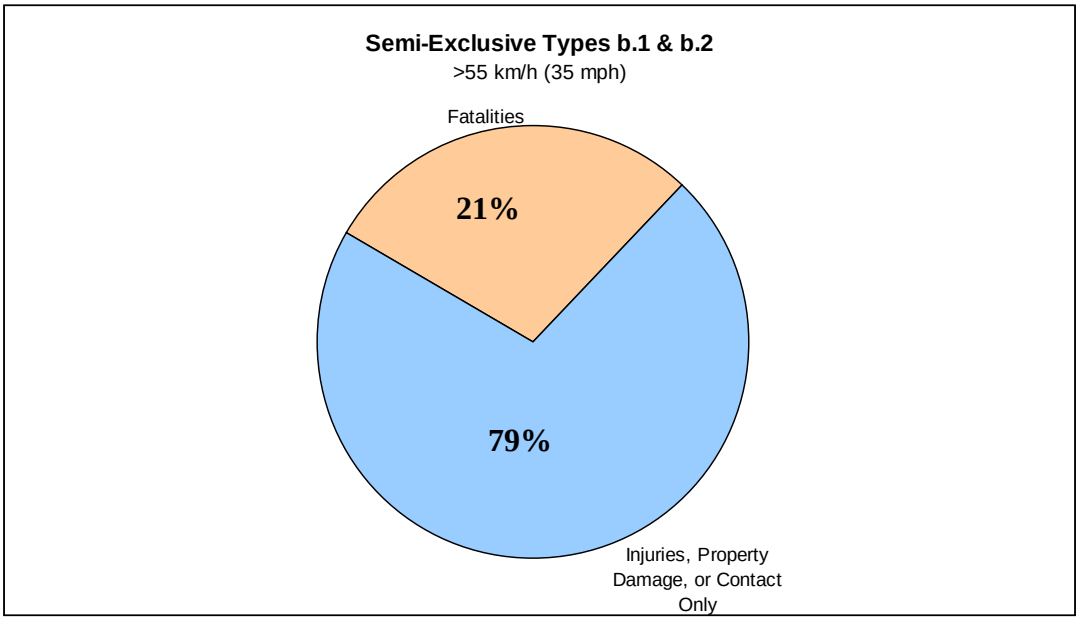


Figure 21. Pedestrian collision severity LRV traveling above 35 mph [2]

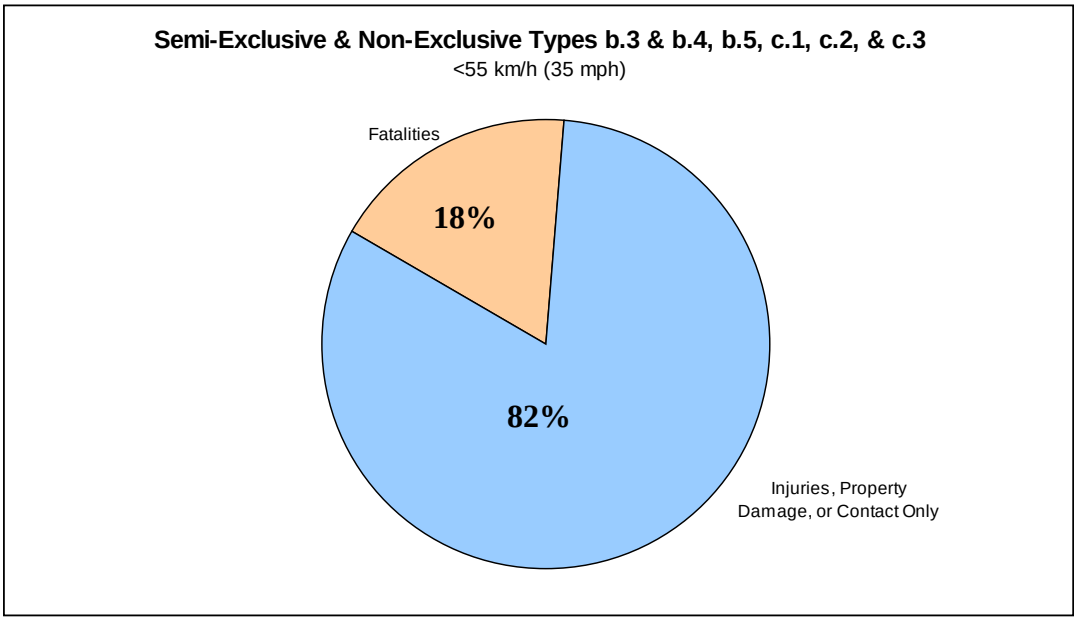


Figure 22. Pedestrian collision severity LRV traveling below 35 mph [2]

The analysis on collision severity shown from Figure 19 through Figure 22 is based on data provided by only three LRT systems: Denver, Edmonton, and Los Angeles. According to the research team, the data provided by the other LRT systems did not classify accidents by severity in enough detail to include them in this analysis [2].

Summarizing, it is possible to conclude that:

- The majority of the 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 [2].
- In 1994, most accidents involved a vehicle (approximately 86%). From those accidents, 50% involved an automobile and only 11% involved pedestrians [5].
- In the majority of the cities studied, the most common type of collision involves vehicles turning in front of a LRV or during a left-hand turn [5,8].
- Of the total accidents for all surveyed systems, 92% occurred in shared right-of-ways where LRVs operate under 35 mph, even though this type of right-of-way comprises only 38% of the total mainline track miles [5].
- Although only 13% of the total accidents occur at tracks where the LRV goes above 35 mph, this type of track represents 77% of the total track length [5].
- Under conditions when the LRV operates above 35 mph, 19% of the accidents at crossings ended in a fatality. On the contrary, only 1% of the accidents at crossings where the LRV operates below 35 mph ended in a fatality.
- Occasionally, LRVs suffered rear-end collisions when stopped [8].

CHAPTER THREE

ANALYSIS U.S. LIGHT RAIL VEHICLE FLEET SURVEY

This section presents a general overview of the United States LRV fleet and some of its main characteristics. At this time there are 25 light rail transit agencies operating in the U.S. Table 6 shows the name and its location for each agency.

TABLE 6

U.S. TRANSIT AGENCIES WITH LRVs IN SERVICE [1]

Location	**Agency**
Baltimore, MD	**MTA**
Boston, MA	**MBTA**
Buffalo, NY	**NFTA**
Camden, NJ	**NJ Transit**
Charlotte, NC	**LYNX**
Cleveland, OH	**GC RTA**
Dallas, TX	**DART**
Denver, CO	**RTD**
Houston, TX	**MetroRail**
Hudson-Bergen, NJ	**NJ Transit**
Los Angeles, CA	**LACMTA**
Minneapolis/St. Paul Min	**Metro Transit**
Newark, NJ	**NJ Transit**
Oceanside, CA	**SPRINTER**
Philadelphia, PA	**SEPTA**
Phoenix, AZ	**Valley Metro**
Pittsburgh, PA	**The T.**
Portland, OR	**Trimet MAX**
Sacramento, CA	**RT**
Saint Louis, MO	**Metro**
Salt Lake City,	**TRAX**
San Diego, CA	**SDMTS**
Sand Francisco, CA	**MUNI METRO**
San Jose, CA	**VTA**
Seattle/Tacoma, WA	**Sound Transit**

LRVs analyzed on this thesis will be classified in three categories. These categories will be defined according to the proportion of low floor area available. Low floor means that the level of the LRV's floor is at the same level of the platform ground.

1) Category 1 is referred to as 100% high-floor LRV. This category includes all the LRVs with a percentage of low floors below 50%. This is a typical model of LRV prior to 1990. This category of LRV is still in service and some companies continue to have them manufactured.
2) Category 2 is referred to as 70% low-floor LRV. In general, this category includes LRVs with a percentage of low floors between 50% and 75%. The majority of new LRVs orders on the U.S. fell in this category. It is important to mention that most of the new LRVs are equipped with Crash Energy Management (CEM).
3) Category 3 is referred to as 100% low-floor LRV. Although this category is not found in the U.S., it is very common in Europe. The entire vehicle has low floors with low-level entrances throughout the vehicle. Henceforth, Category 2 is referred to as low floor since there are not any Category 3 LRVs in the U.S.

Figure 23, Figure 24, and Figure 25 show one example for each one of the categories explained above.

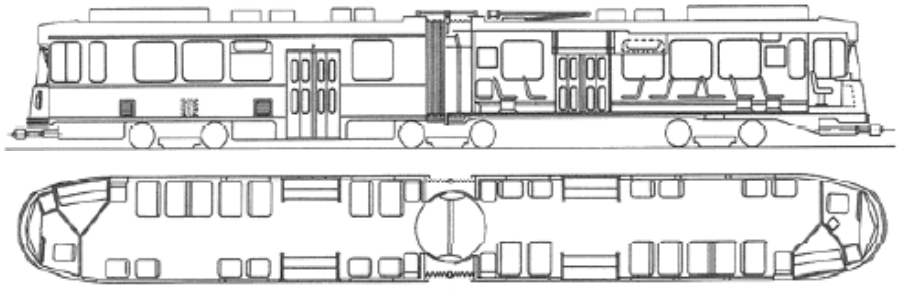


Figure 23. Example LRV category 1 - 100% high floor [9]

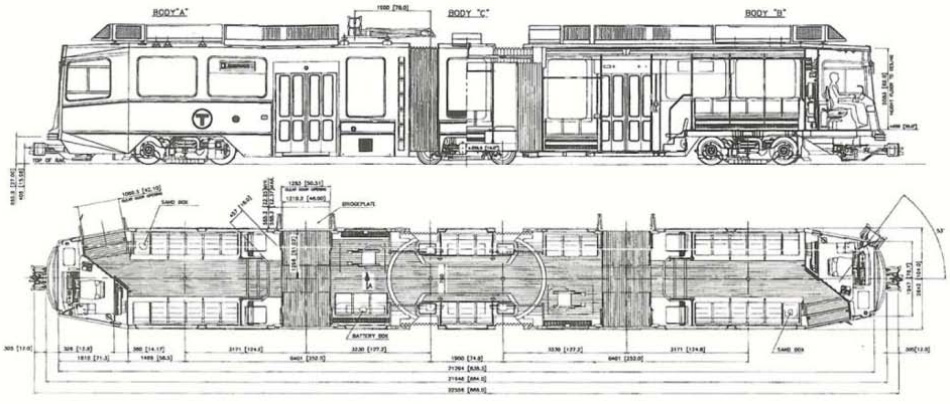


Figure 24. Example LRV category 2 - 70% low floor [9]

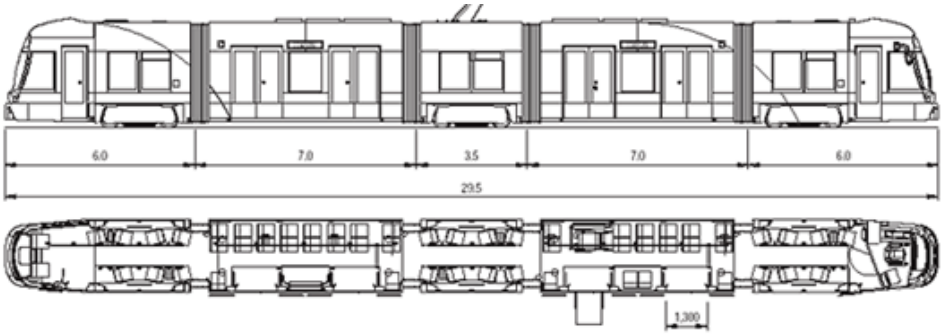


Figure 25. Example LRV category 3 - 100% low floor [9]

3.1 LRV Transit Agencies and Manufacturers Overview

Table 7 shows a list of the U.S. LRV fleet information by manufacturer. The U.S. fleet is divided in: manufacturer, transit agency, and category. Category 1 identifies a high-floor LRV and category 2 identifies a low-floor LRV. At the moment of this research no category 3 or 100% low floor LRVs were available in the current U.S. LRV fleet [9].

TABLE 7

U.S. LRV FLEET INFORMATION BY MANUFACTURER [1]

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

N.A. Not Available
*Note: Reference Not Found
**Note: Outlier data was not used for further configuration analyses

TABLE 7 (Continue) [1]

U.S. LRV Models Studied					
Make	**Category**	**Car Total**	**Model**	**Car Total**	**Agency**
Siemens	2	158	S70	16	Charlotte, NC
			S70	18	Houston, TX
			SD660 Type 2 & 3	79	Portland, OR
			S70 Type 4	22	Portland, OR
			SD70	11	San Diego, CA
			DMU	12	Oceanside, CA**
Stadler GTWDiesel	2	20	Sadler Diesel	20	Camden, NJ
Other	1	159	St Louis Car PCII	18	Philadelphia, PA*
			Kawasaki K-Car	141	Philadelphia, PA
NipponSharyo	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	N.A.	28	Pittsburgh, PA
			N.A.	40	Sacramento, CA
Škoda	2	10	N.A.	3	Seattle/Tacoma, WA
			N.A.	7	Portland, OR
TOTAL		2005		2005	

N.A. Not Available
*Note: Reference Not Found
**Note: Outlier data was not used for further configuration analyses

At the present, there are approximately 2005 LRVs operating in the United States. This number is subject to change as agencies develop new light rail lines while overhauling and replacing existing LRVs. Refurbishing old cars generally extends the operational life of the

LRV while at the same time improves the accessibility for occupants with reduced mobility. This is achieved by changing the 100% high floor layouts of the old cars to a new layout where some sections of low floor are added.

The distribution of the LRV fleet by manufacturer is shown in Figure 26. As shown, the three biggest suppliers are Siemens, Kinkisharyo, and Ansaldo Breda. These three companies produce roughly 76% of the LRVs in the U.S. market.

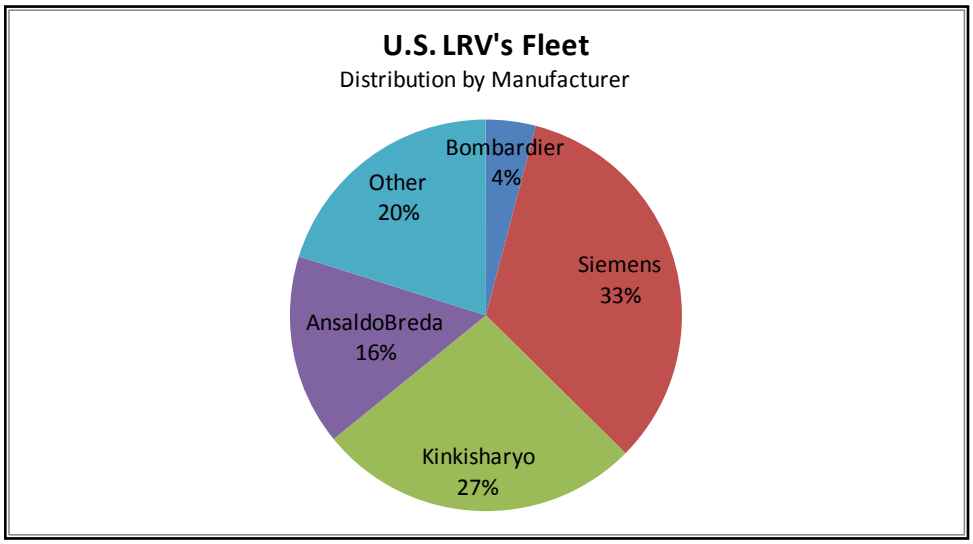


Figure 26. LRV fleet by manufacturer [1]

3.2 U.S. Fleet Summary

At the present, the United States fleet has 2005 LRVs and 25 transit agencies (See Table 7). This fleet is operating with approximately 66% of high floor, category 1 LRVs. The remaining 34% of the fleet is mostly 70% low floor, category 2 LRVs (See Figure 27). Category 1 and category 2 LRVs can be very similar except for the percentage of low-floor. Usually both categories have two cars connected through one articulation [9].

Category 2 is then divided into two subcategories: LRVs with and without CEM (62% with and 38% without). This is better illustrated in Figure 28 (Percentages are taken from a total of 2005 LRV units).

New LRV orders in the U.S. have a tendency to be low floor cars (Category 2) with two articulations (See Figure 29, two main cars connected through a small car with one articulation on each side). The majority of these new LRVs are being ordered with CEM.

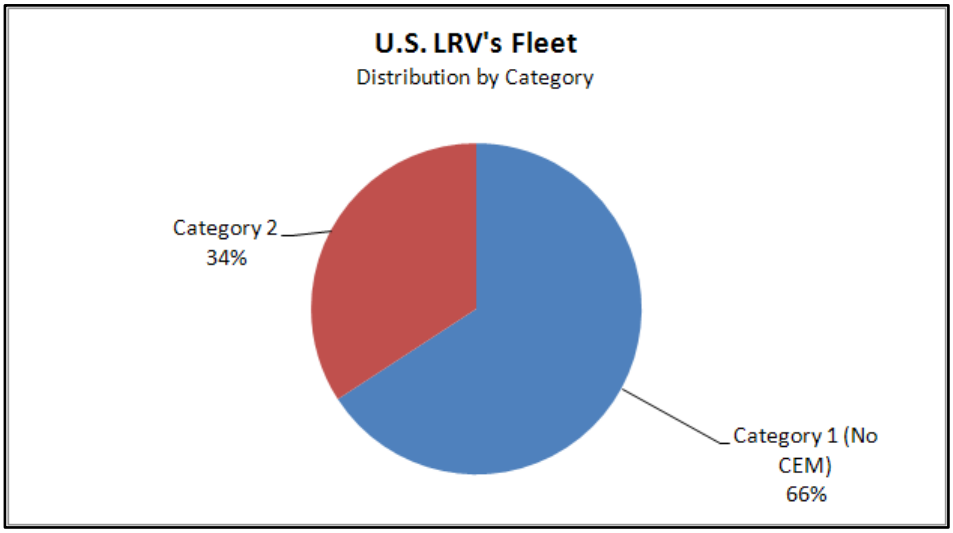


Figure 27. Composition of the U.S. LRV fleet by category [1]

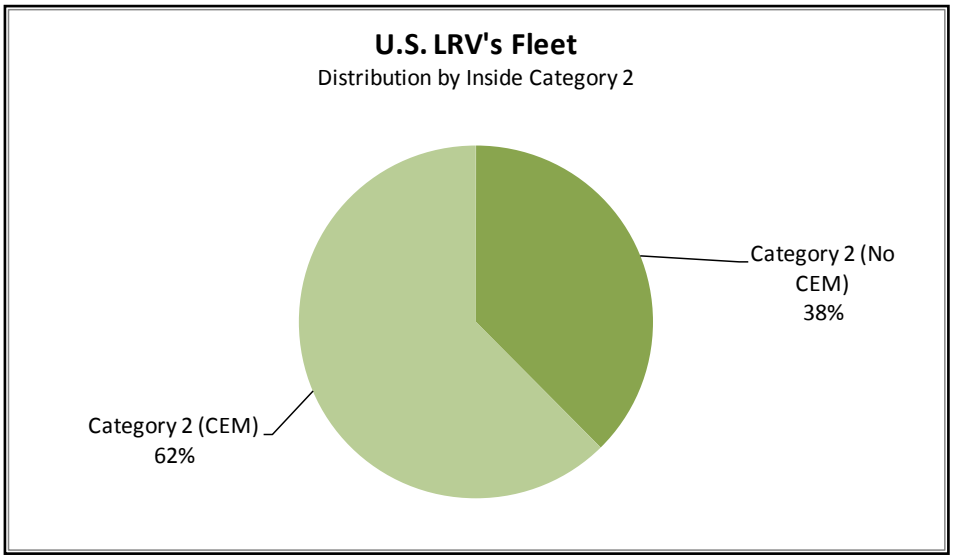


Figure 28. Composition of the U.S. LRV fleet for category 2 [1]

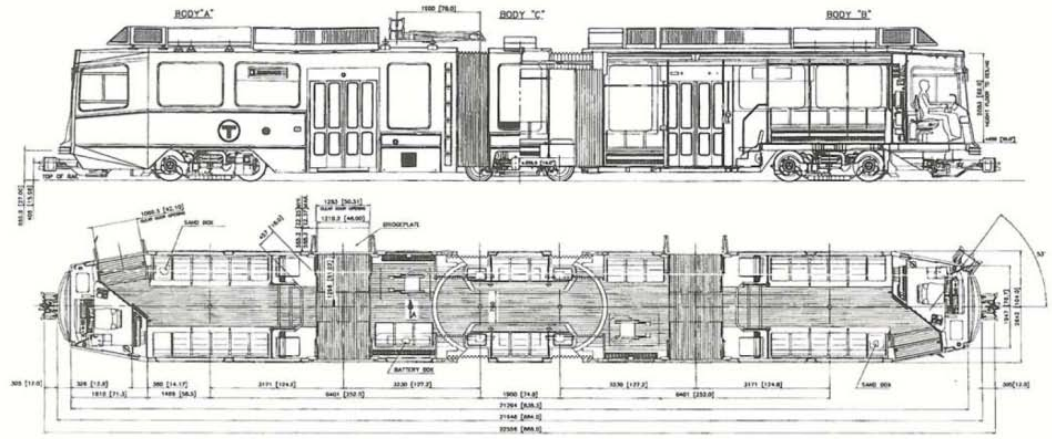


Figure 29. Sample LRV category 2 (2-articulations) [9]

3.3 Light Rail Vehicle Fleet Characteristics Survey

To properly analyze LRV passenger safety, it is important to study and categorize the LRV interiors. 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 analyzed. The majority of the differences found in the current LRV layouts are due to the varying necessities of the operating agency.

All data presented in this section was analyzed in order to define the most representative type of seats that are found in the current fleet of LRVs. Later in the paper this information is used to analyze typical injuries observed when using some of these types of seats, in particular the side-facing seats. The results and conclusions obtained from these models are shown in section 4 *"LRV Crash Conditions Definition"* and section 5 *"LRV Crashworthiness evaluation – Side-Facing Seats"*.

3.3.1 United States LRV Fleet Studied

Interior and exterior data was not found for all U.S. agencies and LRV models but data that was found is analyzed in this section. As mentioned before, there are approximately 2005

LRV units distributed throughout the different U.S. Transit agencies. Information was found for 1925 of these units. Nevertheless, the level of information for each LRV model was different. No information regarding the main characteristics was available for 68 units. In addition, there were 12 units considered outliers because of their very different size and weight. Hence, a total of 80 units were not studied. Figure 30 illustrates the units studied and their distribution by the categories aforementioned.

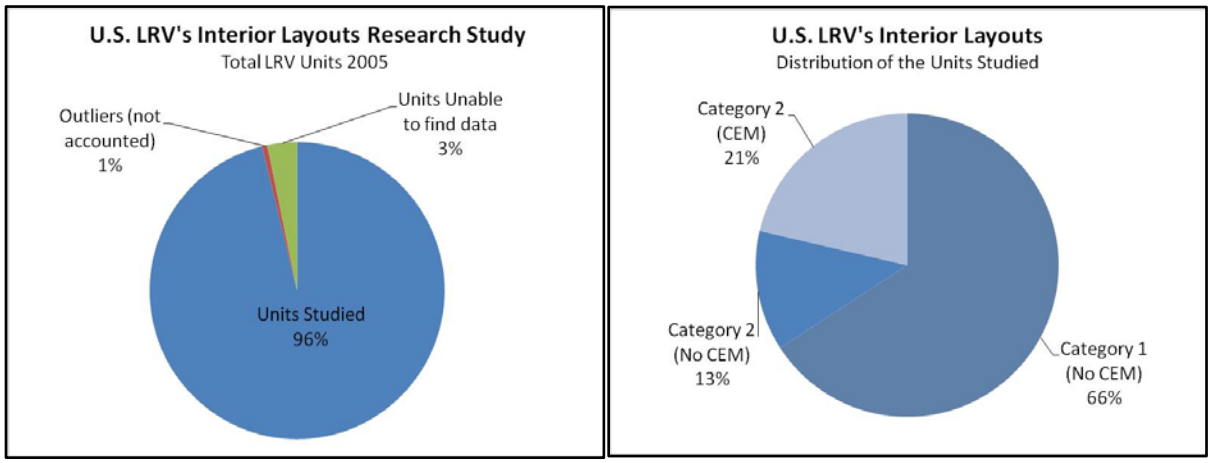


Figure 30. LRV study of interior layouts for U.S. fleet [1]

3.3.2 Average Results for Main Characteristics and Interior Layouts

A summary of all data gathered for the available LRVs is summarized in this section. The data is interpreted in two distinct ways, biased and unbiased. The biased or average biased results are presented based on the number of units per agency compared to the total number studied, i.e., a model with more units would have more weight. The unbiased results or average are presented where each LRV model receives equal weight independently of the number of units available for that particular model.

Figure 31 shows the average of the main characteristics analyzed for the aforementioned LRVs. According to the biased data, on average, a current LRV has a total of 63 seats with a

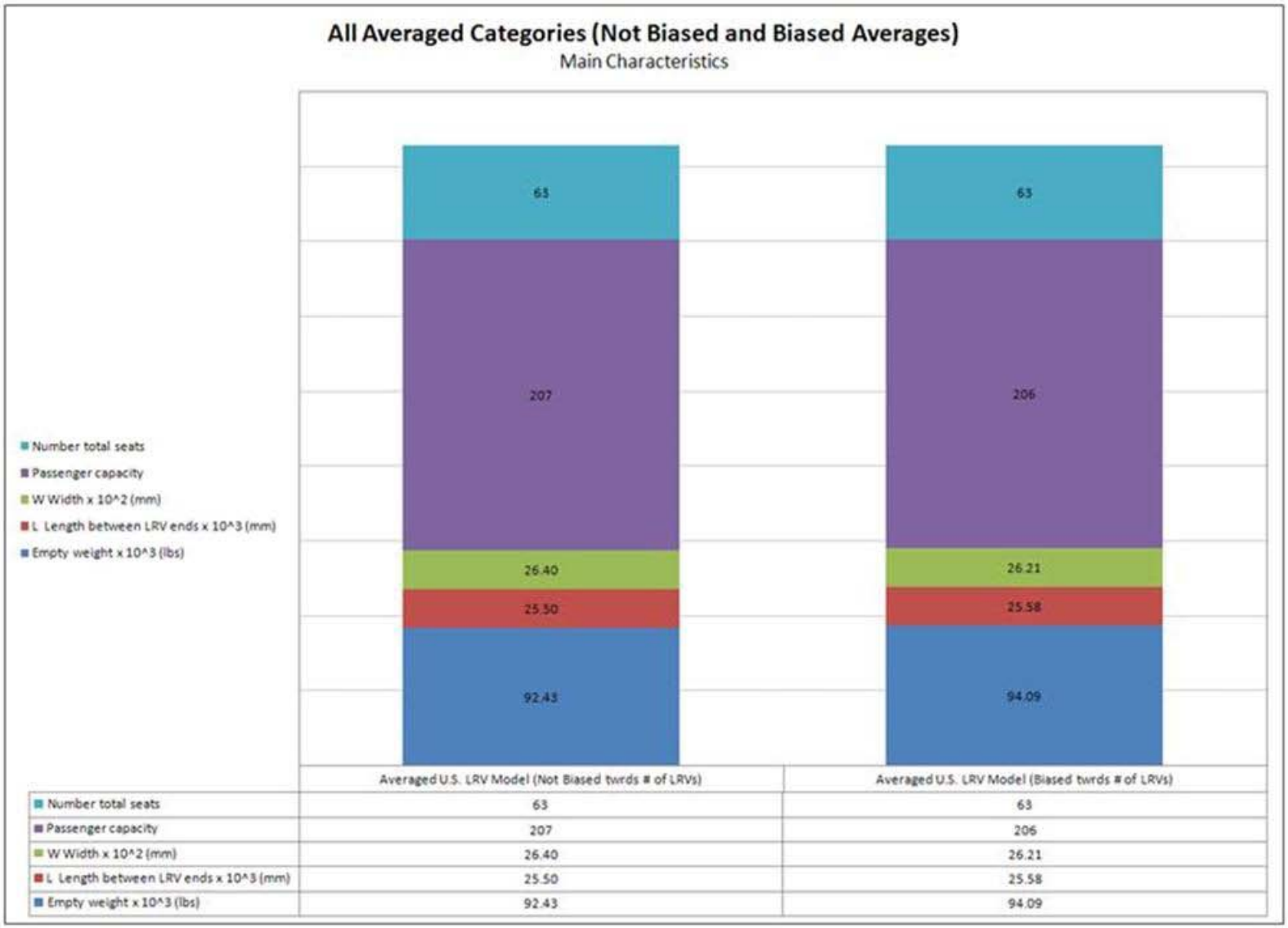
capacity of approximately 206 passengers. The biased average dimensions are: 2.62 meters for the width and 25.58 meters for the length. The average empty weight is 42,678 kg (94,090 lbs).

When comparing to the unbiased results, the main differences are found in overall passenger capacity and empty weight. Without consider the number of LRVs available for each model, there is a passenger capacity of 207 and an average empty weight of 41,925 kg. In other words, there are more LRVs in use with less passenger capacity and larger weight.

Figure 32 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 side-facing seats. This type of seat configuration is more common when taken into consideration all the units available.

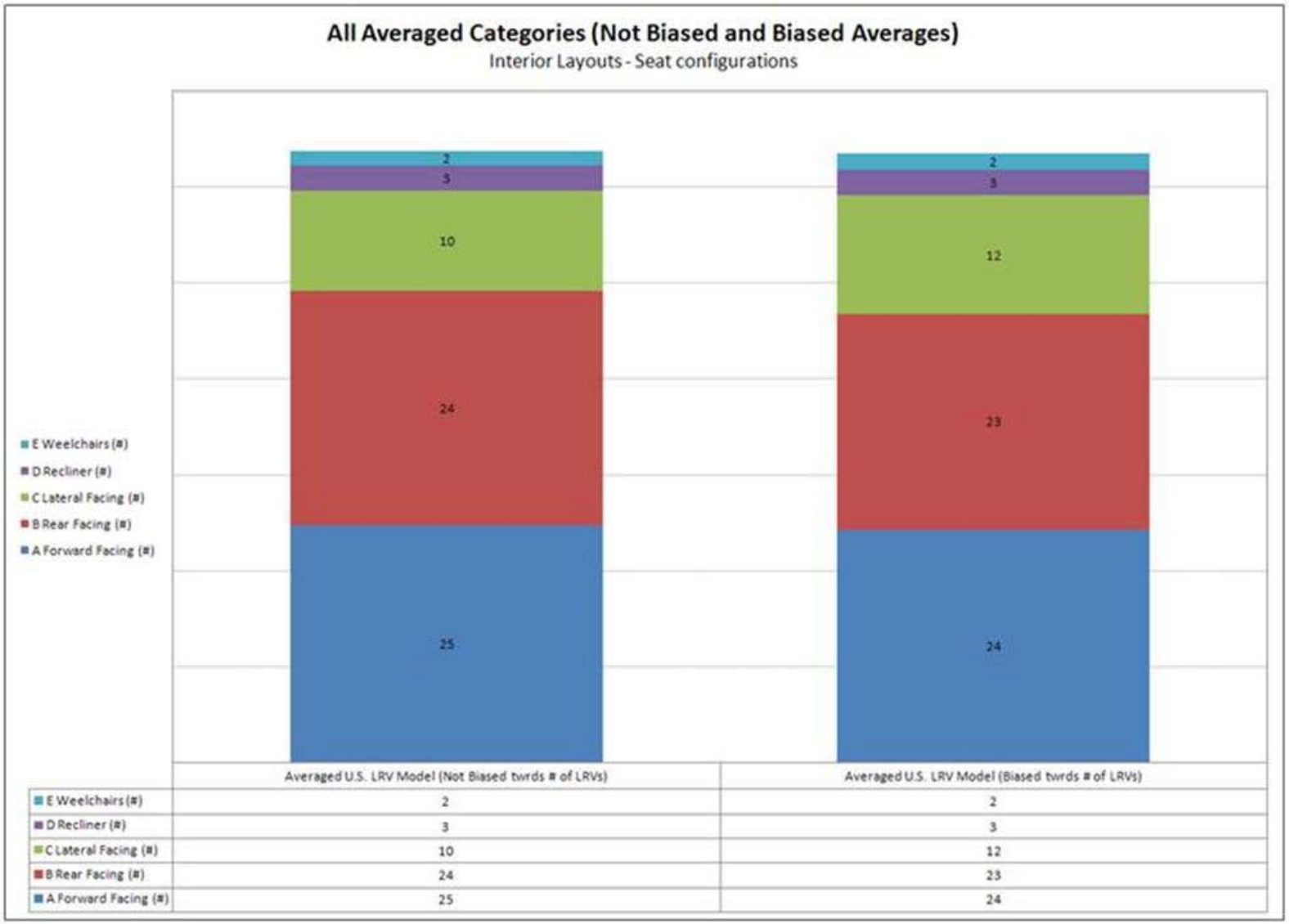
Overall, it is possible to conclude that the forward-facing seats and rear-facing seats are the most commonly used seating arrangements on current LRVs. In fact, most existing LRVs are produced with two main cars attached through articulations to a middle small car. This arrangement results in most current LRVs being symmetric (Figure 23, Figure 24). As a result of this symmetry, the average number of forward and rear-facing seats is very similar.

The third most used type of seating arrangement is side-facing seat. Side-facing seats account for approximately 17% of total LRV seating. Finally, on average, there are two available places for wheelchairs. Usually, most of these spaces share room with recliner seats, which can be folded and stored in order to make room for the wheelchair. A more detailed survey of existing LRV interiors is discussed in the following section.



	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 31. Main characteristic averages [1]



	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

Figure 32. Interior layout averages [1]

3.3.3 LRV Specific Interior Survey

This section contains a more specific survey of the possible seats arrangements found in current LRVs. According to all the layouts studied, a total of thirteen types of seating configurations were defined [9]. The different types of seat arrangements analyzed are shown in Table 8. The number of seats for each configuration as well as the percentage with respect the total number of seats of this configuration is also shown in this table. The same results are also shown in a bar chart format (See Figure 33. Percentage of seat configurations for total number of LRVs [1]).

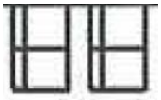
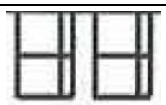
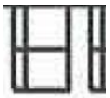
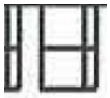
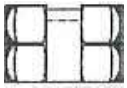
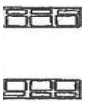
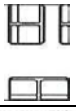
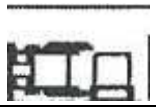
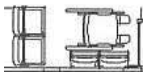
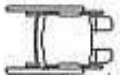
The total number of seats studied is 113,822. This number takes into account the number of LRVs that exist with that specific interior layout. For example, if the Siemens LRV from Los Angeles has 24 forward-facing seats and there are 59 LRVs with that layout, a total of 1416 forward-facing seats are counted for this model.

From Table 8 and Figure 33 is possible to observe 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 about 74% of the total, being the percentage for each individual configuration 22%, 18%, 19%, and 15% respectively.

Although side-facing seats are not the most used type of seats on the current LRVs according to this study, they still represent a large percentage of the current LRVs seats. The main objective of this thesis is to evaluate the principal types of injuries found in passengers traveling on this type of seats.

TABLE 8

INTERIOR SURVEY - PERCENTAGE OF SEATS PER CONFIGURATION [1]

Type of Configuration		Total #Seats	Percentage
Unidirectional Forward facing seats (1)		25196	22.1%
Unidirectional Rear facing seats (2)		19998	17.6%
Forward facing seats Monument (3)		8888	7.8%
Rear facing seats Monument (4)		8044	7.1%
Seat facing each other (5)		21904	19.2%
Lateral Seat facing each other (6)		17057	15.0%
Single Seat Forward & Rear (7)		4734	4.2%
Lateral seat facing forward/rear double seat (8)		1713	1.5%
Lateral seat facing wheel chair (9)		1096	1.0%
Lateral facing rear/forward single seat (10)		862	0.8%
Forward & Rear Seat facing wheelchair (11)		2268	2%
Seat at the end of the Tram (12)		796	0.7%
Wheelchair (13)		1266	1.1%

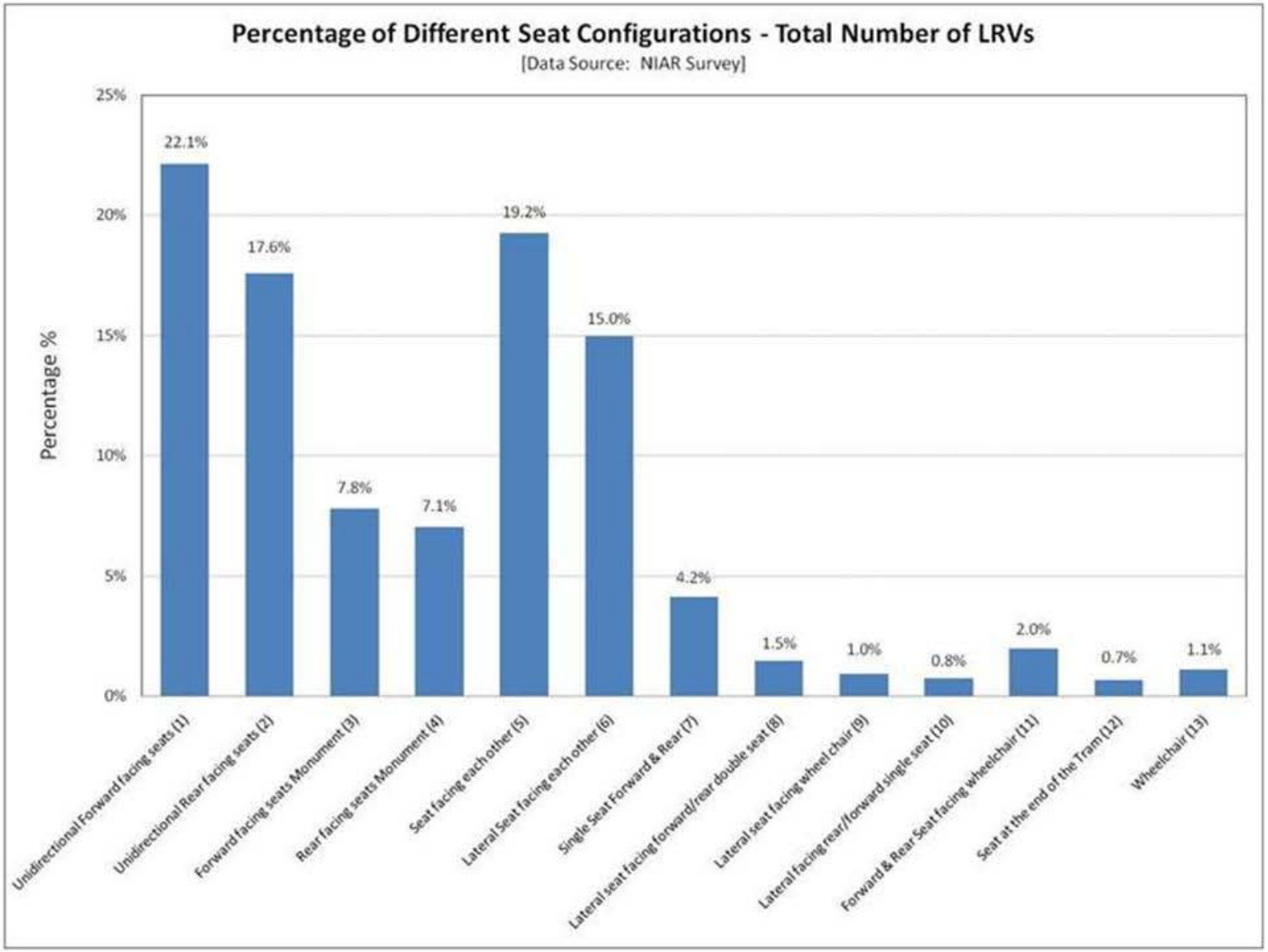


Figure 33. Percentage of seat configurations for total number of LRVs [1]

CHAPTER FOUR

LRV CRASH CONDITIONS DEFINITION

In this section, four crash conditions are evaluated in order to understand the level of injuries in the different crash scenarios. From this analysis, the worst-case scenario will be determined and used for the side facing seats analysis.

Two different computational techniques were used to analyze these crash scenarios. These techniques are Multi-Body (MB) and Finite Elements (FE). For the main part of this thesis the multi-body technique was used. The most important feature of this technique is that it uses very little computational time and still returns very accurate results. This means that many different types of crash scenarios can be completed accurately in a short amount of time.

Due to the similarities between current LRVs and bus seats characteristics, as well as seat arrangements (See Figure 34), a dynamic test performed at National Institute of Aviation Research (NIAR) was used to validate the multi-body model used for this thesis.

Figure 34. LRV interior vs. Bus interior

The dynamic test represented an accident between one mass transit bus traveling at 20 mph with another similar mass transit bus stationary (0 mph). The maximum level of deceleration recorded for this type of accident was 11 g's.

4.1 Multi-body Models

Although a detailed explanation of the validation can be found in the appendix, this section shows the main characteristics of the seats used for this analysis. Two seats were used for this analysis:

- Double seat (Figure 35): This seat represents a typical semi-rigid seat and is used in most mass transportation systems. This model can be used to represent forward-facing seats, rear-facing seats, and any combination of those like seat facing each other.

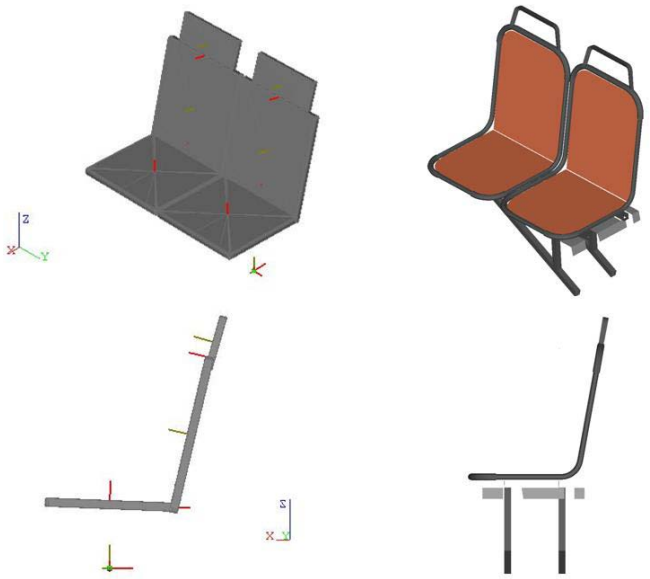


Figure 35. Double seat – Multi-body and FE model [1]

- Triple seat (Figure 36): Although it is most often used for side facing seats, it can also be found in certain special configurations such as the row of seats at the end of some LRVs. The main characteristics defined for this type of seats remain identical to the double seat. Usually, triple seats are manufactured using the same parts used for double seats, and therefore similar performance can be expected.

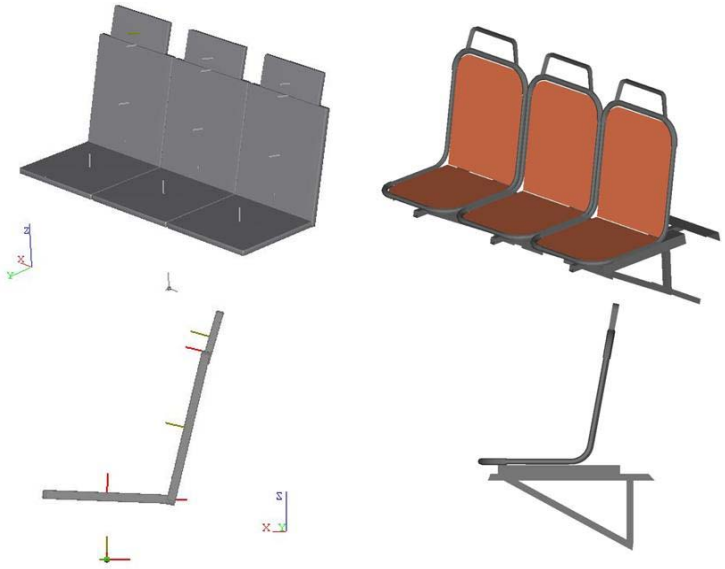


Figure 36. Triple seat – Multi-body and FE model [1]

The layout survey presented in section 3.3.3 *LRV Specific Interior Survey* shows all the different configurations found. One of these configurations is the side-facing seat with a barrier monument. This barrier can be found on either side of the side-facing seat. With the intention of representing this configuration, a generic multi-body model was created to represent this barrier (Figure 37). Although, this barrier was not used for the analysis presented in this section, it will be used for most of the cases studied in the following sections.

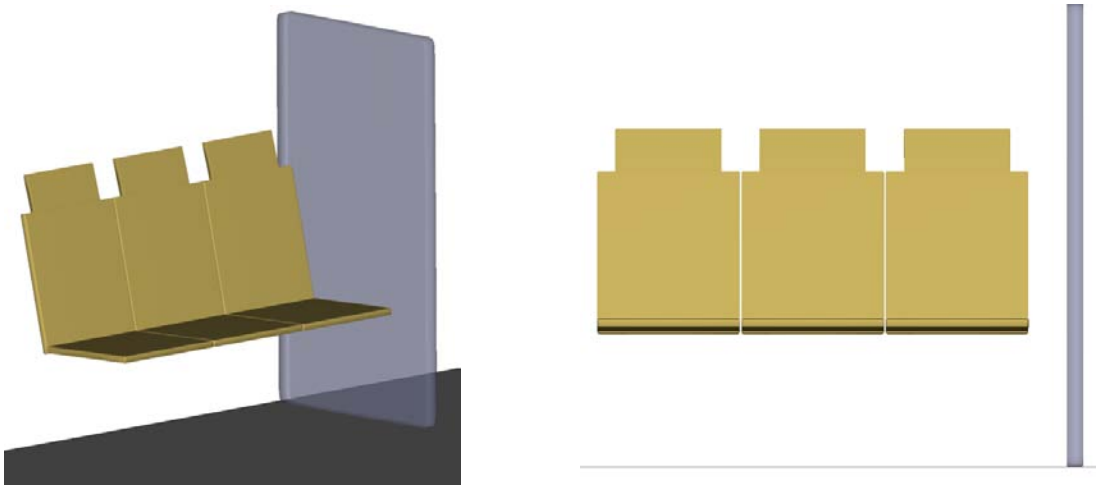


Figure 37. Multi-body barrier model [1]

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. In order to represent this type of constraint the multi-body barrier is attached to the LRV structure by a bracket joint. This type of joint does not have any degrees of freedom, and therefore no rotations or translations are allowed on the barrier.

The main dimensions of the barrier are:

- Barrier Height: 1400 mm
- Barrier Length: 760 mm
- Barrier Width: 50 mm

After defining how the barrier is attached to the LRV structure, the contact properties need to be defined. This parameter is very important since it will determine the stiffness of the barrier, and therefore the level of injuries (Figure 38). This property was obtained directly from the validation model shown in the appendix.

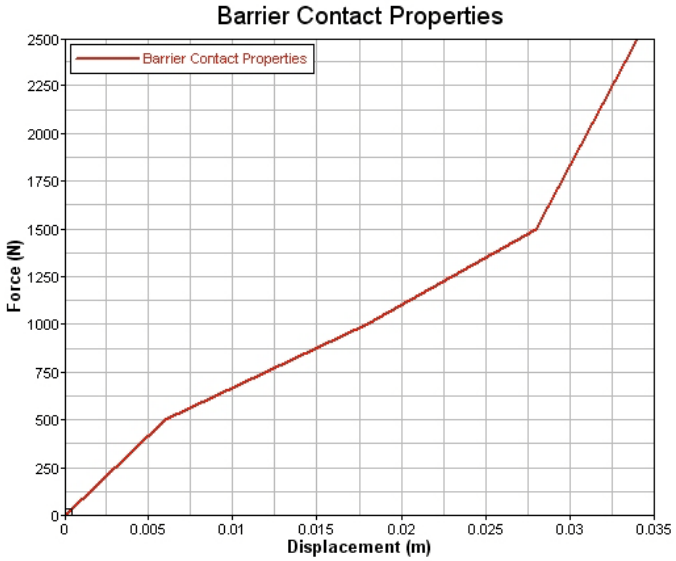


Figure 38. Barrier contact stiffness [1]

4.2 Preliminary Evaluation for Low, Mid, and High Energy Level Impact Conditions

Once the seat models were validated using the dynamic sled test, the injury levels from four different energy level conditions were evaluated for a typical forward facing seat LRV layout:

- LRV 20 mph vs. LRV 0 mph (LRV type N - High Energy)
- LRV 20 mph vs. Bus 0 mph (LRV type N - Medium Energy)
- LRV 20 mph vs. Mini Van 0 mph (LRV type N - Low Energy)
- LRV 20 mph vs. 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. This LRV represents a category 2 LRV without CEM. It has two cars attached through one articulation at the center. The LRV is symmetric, with a total of 96 seats (See Figure 39).

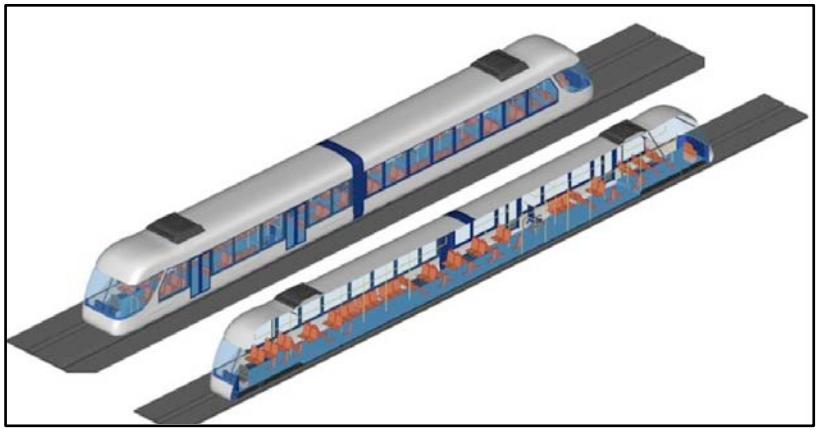


Figure 39. NIAR generic LRV (type N) [1]

LRV type 0 represents a category 2 LRV with CEM. It has two main cars attached through a center car with two articulations (See Figure 40). The acceleration pulse used for the analysis of this LRV can be found in "Develop of Crash Energy Management Performance Requirements for Light-Rail Vehicles" [10].

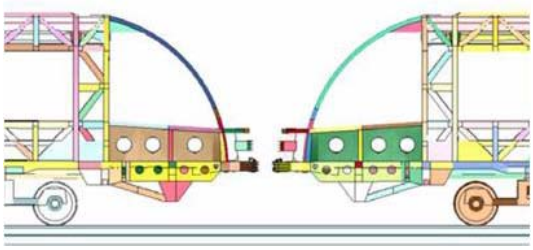


Figure 40. LRV type 0 [10]

The 95th, 50th, and 5th percentile occupants were used for the evaluation in this thesis. These ATDs represent the most of the range of sizes of the U.S. current population. In order to quantify the severity of the injuries the FMVSS 208 injury criterion was used (Table 2). Figure 41 shows the model used for all impact conditions studied on this section.

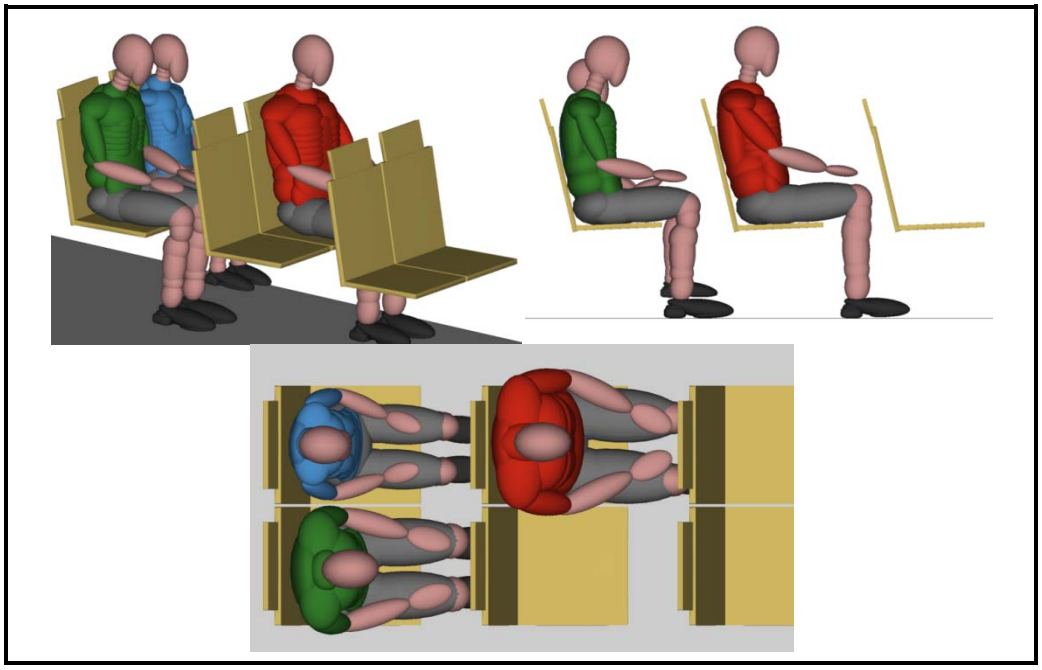


Figure 41. Multi-body model for low, mid, and high energy level impact conditions [1]

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

4.2.1 LRV 20 mph vs. Mini Van 0 mph (LRV type N - Low Energy)

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 vehicles, LRV weights 42 tons and minivan about 2 tons, the change in velocity for the LRV is very small when compared to the change in velocity for the minivan. Consequently, 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, as well as the kinematics of the impact (Figure 42). The first spike on the acceleration plot illustrates the point at which the LRV strikes the mini-van. Observe that after this initial spike the acceleration remains very low (less than 2 g's in the x-direction).

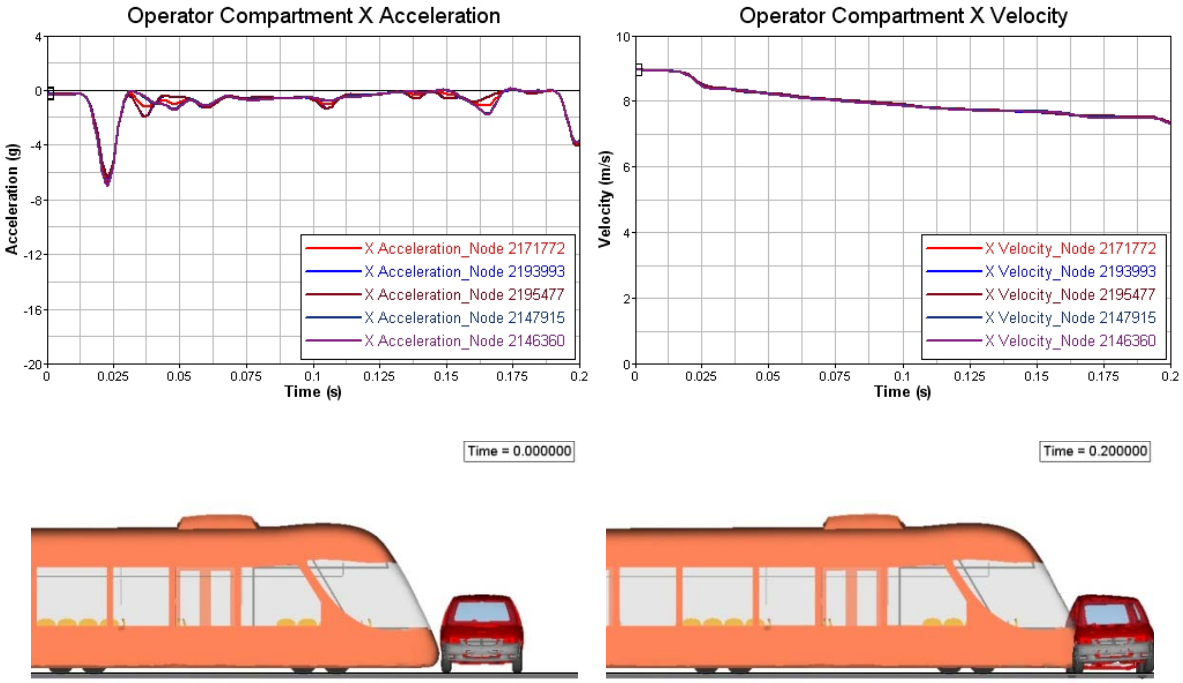


Figure 42. Acceleration pulse - low energy crash scenario (LRV type N 20 mph vs. mini-van 0 mph) [1]

The acceleration pulse obtained using the FE model shown in Figure 42 was used in the Multi-body model shown before (See Figure 41), in order to evaluate possible injuries.

Because of the low acceleration pulse, no contact between occupants and seats was observed. Hence, the injuries observed are much lower than current FMVSS 208 limits.

4.2.2 LRV 20 mph vs. Bus 0 mph (LRV type N - Medium Energy)

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 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 in order to obtain an acceleration pulse. The acceleration pulse is then used in the multi-body model to analyze passenger injuries. The acceleration pulse on the compartment is shown in Figure 43.

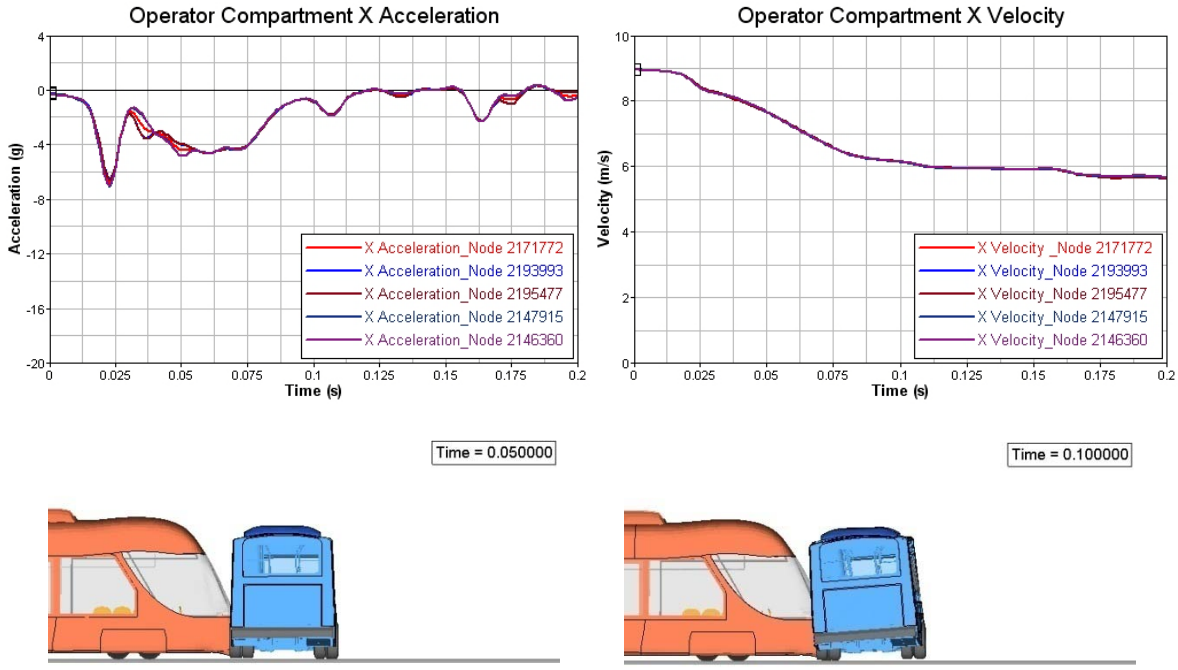


Figure 43. Acceleration pulse- mid energy crash scenario (LRV type N 20 mph vs. bus 0 mph) [1]

Notice that the acceleration pulse profile is similar to the one obtained for the low-energy scenario. Nonetheless, the average acceleration in the x-direction is approximately double that obtained for the low-energy impact condition.

Observe that with an increase in the target vehicle mass, the change in velocity for the LRV increases and therefore higher occupant injuries are observed. Since seats are designed for average sized occupants, low injury values are observed for the 50th percentile ATD. On the contrary, the largest injury values are observed for the 5th percentile ATD. Overall, most of the injuries are below current FMVSS limits, although some high injuries can be observed for the neck region.

4.2.3 LRV 20 mph vs. LRV 0 mph (LRV type N – High Energy)

This crash scenario represents a collision between a LRV type N traveling at 20 mph and another LRV type N stationary (0 mph). This scenario represents a high-energy collision due to the equal mass of both vehicles (approx. 42 tons). Hence, this type of crash will be considered as the worst-case scenario.

Again, the acceleration pulse for this crash scenario is obtained using the FE model. The following plots show the acceleration and velocity of the operator compartment in the x-direction (Figure 44).

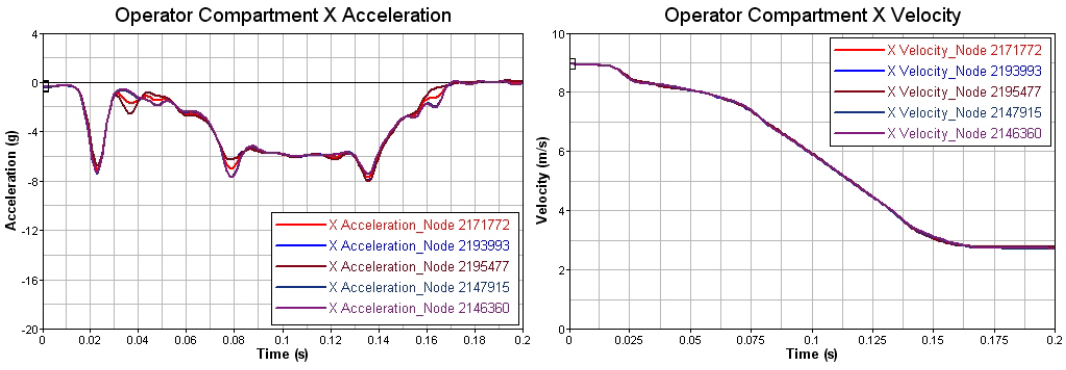


Figure 44. Acceleration pulse- high energy crash scenario (LRV type N 20 mph vs. LRV type N 0 mph) [1]

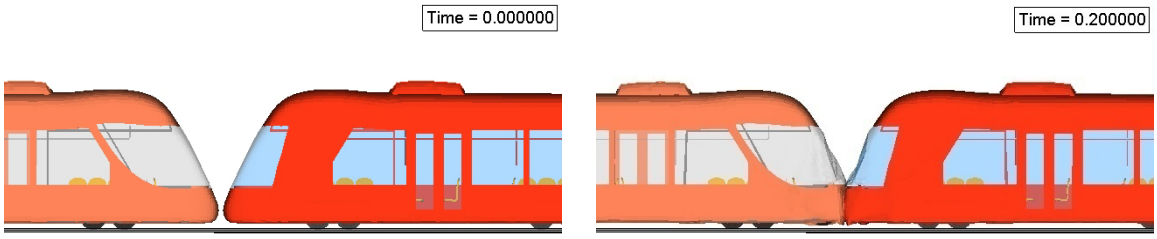


Figure 45. Kinematics – high-energy crash scenario (LRV type N 20 mph vs. LRV type N 0 mph) [1]

This acceleration pulse is then used in the multi-body model to analyze passenger injuries. High injury values for the neck and femur regions were found for the 5th and 95th percentile passengers. This impact condition shows that the current seats are designed for the 50th percentile, since this is the only passenger with all the injury values below the acceptable limits. However, values for the neck region were relatively large compared to the other case scenarios.

Due to the severity of the acceleration pulse and the resulting injuries, this crash scenario was also 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 41. The results for this configuration show that all the injury values, independently of the position and occupant size, are very small when compared to current FMVSS limits.

4.2.4 LRV 20 mph vs. LRV 0 mph (LRV type 0 – High Energy)

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). As the last case scenario, this one also represents a high-energy collision due to the equal mass of both vehicles. Likewise, this collision scenario can also be considered a worst-case scenario.

Due to differences in structural design between LRV type 0 and type N, the acceleration pulse recorded is slightly different. The LRV type 0 is designed using the Crash Energy

Management approach and therefore, the acceleration pulse obtained is slightly 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 46. This acceleration profile was provided directly by the authors of the research: “Develop of Crash Energy Management Performance Requirements for Light-Rail Vehicles" [10]. As before, this pulse was used as an input for the multi-body simulation in order to analyze the level of injuries.

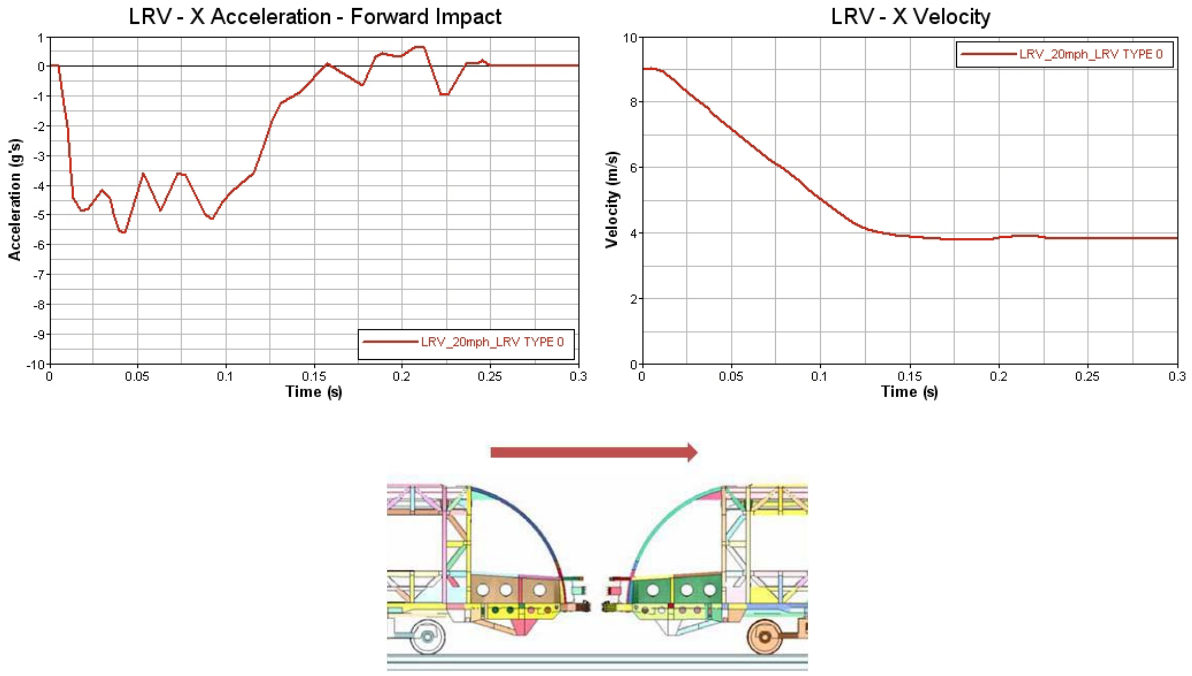


Figure 46. Acceleration pulse - high-energy crash scenario (LRV type 0 (20 mph) vs. LRV type 0 (0 mph)) [10]

Similar conclusions as the ones obtained for the LRV type N higher energy crash scenario can be drawn. Most of the injuries occur to the neck region due to the direct or indirect impact with the headrest. Again, the 50th percentile ATD sustains injuries that are below the current FMVSS 208 limits.

4.2.5 Summary for Low, Mid and High Energy Level 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, the injury values are high. Thus, both rear impact scenarios analyzed in this section have low levels of injuries and are a good approach in order to reduce the level of injuries during a high-energy crash scenario.

In accordance with the results shown in sections 4.2.3 and 4.2.4, neck moments and shear forces are the most common type of injury. Femur forces could also exceed the injury criteria limits for the 5^{th} percentile ATD for the high-energy crash scenario.

The injuries sustained in the neck region are directly associated with the height and stiffness of the seat headrest and seatback. In order to improve the safety of occupants independently of the size, 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 5^{th} percentile ATD are related to the stiffness of the seat back. Some new padding materials could be used on the knee impact region in order to improve safety.

CHAPTER FIVE

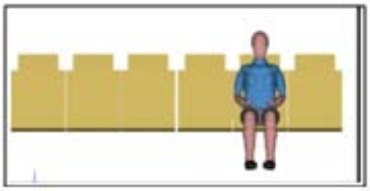
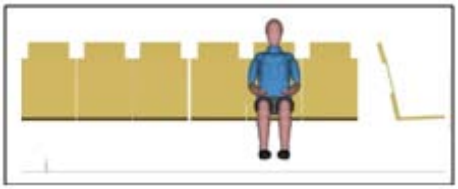
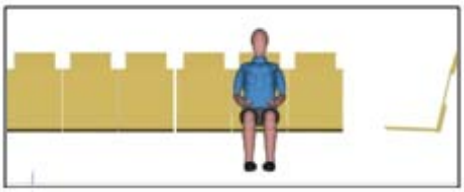
LRV INTERIOR CRASHWORTHINESS EVALUATION – SIDE FACING SEATS

So far, the number of side-facing seats available in the current LRVs fleet has been computed (around 17% of the total). Furthermore, an analysis was done in order to establish the worst crash scenario. According to this analysis, the highest injuries are expected for a collision between one LRV traveling at 20 mph and another stationary.

This section analyzes the different types and levels of injuries that passengers seated on side-facing seats can suffer depending on the seat configuration, as well as occupancy. A summary of the configurations analyzed on this section is shown on Table 9.

TABLE 9

SUMMARY OF SIDE FACING SEATS ARRANGEMENTS ANALYZED

Seat Arrangement. – 1 Side Facing Seat vs. Barrier	
Seat Arrangement. – 2 Side Facing Seat vs. Fwd Facing Seat	
Seat Arrangement. – 3 Side Facing Seat vs. Aft Facing Seat	

The following figure shows and example of current interior side-facing seats arrangements. Scheme #1 shows side-facing seats close to aft or forward-facing seats depending on the traveling direction. Something similar is shown in scheme #2, but with only one side-

facing seats. Scheme #3 and #4 are very similar with respect to the configuration and the number of seats. However, in scheme #3 it is possible to observe that the seat pans have a small curvature while the seats in scheme #4 are completely flat. These different types of seat pan will be studied later in this section.

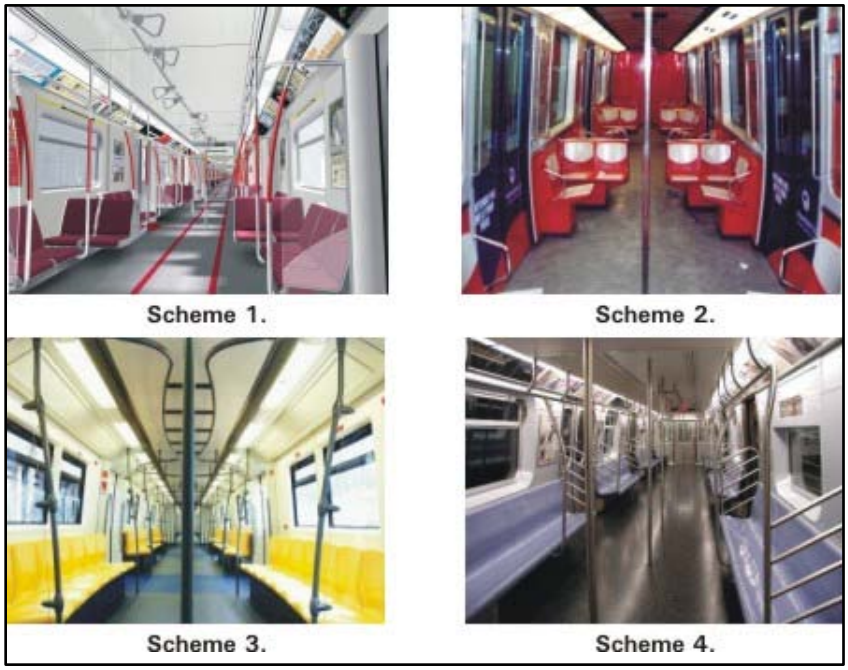


Figure 47. Example of side-facing seats arrangements

As mention before (see chapter four), only for those impacts of high-energy injuries are expected. Consequently, the LRV 20 mph vs. LRV 0 mph acceleration pulse with the LRV Type 0 is used for all the analysis presented in this section. The severity of the injuries is quantified by the FMVSS 208 injury criterion presented in Table 2.

5.1 Side Facing Seats Analysis

According to the analysis done in section 3.3.3. *"LRV Specific Interior Survey"*, the fourth type of configuration most often used in the current fleet of U.S. LRVs is the side-facing seat or lateral-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 (See Figure 48). This is very useful for those LRVs operating in high use regions such metropolitan areas.

Figure 48. Example of side-facing seats

In order to evaluate the safety for this type of seating, the high impact acceleration pulse obtained from the analysis done in section 4.2.4 LRV 20 mph vs. LEV 0 mph (LRV type 0 – High Energy) is used.

Due to the longitudinal position of this type of seating with respect the LRV main body, the results obtained from this analysis can be used for both frontal and rear impacts.

The analysis for this type of seating is divided into three different parts:

1) Euro-SID ATD Analysis: Initially this type of ATD is used to determine what type of injuries are expected from the side impact point of view and the possibility of using different types of ATDs for the remaining analysis.
2) Exit Velocity Analysis: Due to the different number of seats in side-facing seats arrangements, a study is conducted to analyze the relative velocity of the passenger in relation to the seated position (Figure 49).

3) Current LRV Layout Analysis: Using the worst case scenario from the aforementioned study, a complete analysis will be done evaluating:

   a. The representative side facing seat layouts (Figure 49. Side-facing seats with barrier and Figure 50. Forward-, lateral-, and aft-facing seats)

   b. The occupant-to-occupant interactions for typical side facing seat layouts studied in the previous section.

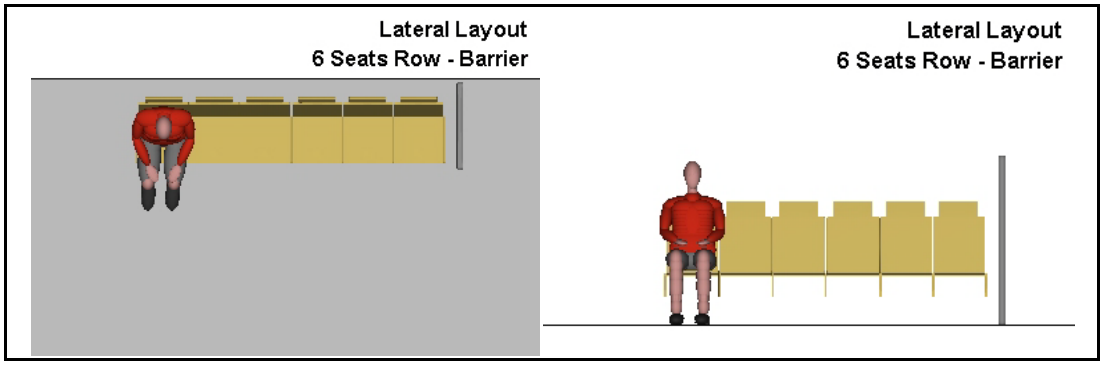


Figure 49. Side-facing seats with barrier [1]

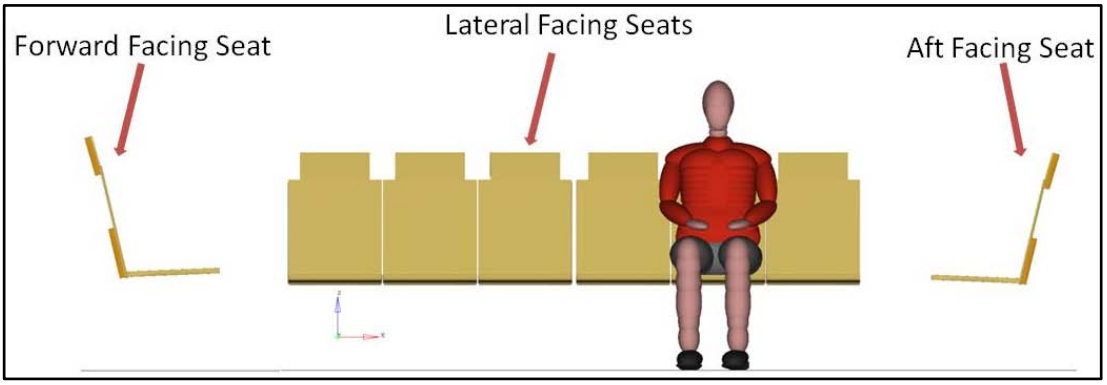


Figure 50. Forward-, lateral-, and aft-facing seats [1]

5.1.1 Euro-SID Analysis

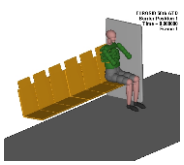
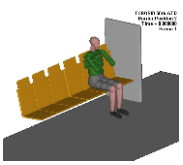
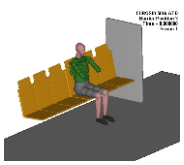
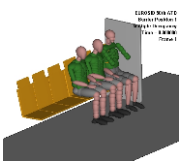
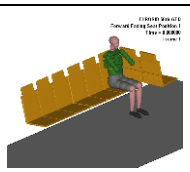
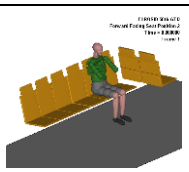
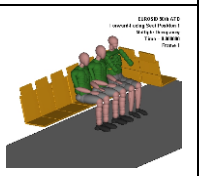
The European Side Impact Dummy (Euro-SID) was developed for tests in vehicles subjected to side impacts. The Euro-SID represents a 50th percentile adult male. One of the major differences with respect the hybrid III ATDs is that it has a special thorax region where

different sensors can be used for measure the rib deflections and accelerations at different positions around the thorax height.

This ATD was used in order to determine the level of injuries for those specific of side impacts as: Thoracic Trauma Index (TTI), Viscous Criteria (VS), and rib deflection. In order to analyze these injuries seven different configurations were analyzed. Table 10 shows the eight configurations analyzed.

TABLE 10

EURO-SID ANALYSIS CONFIGURATIONS

	Pos. 1	Pos. 2	Pos. 3	Pos 1. 3 Occupants
Seat Arrangement. – 1 Side-Facing Seat vs. Barrier				
Seat Arrangement. – 2 Side-Facing Seat vs. Fwd-Facing Seat				

All injury values were normalized with respect to the current FMVSS limits in order to facilitate the comprehension of the results. Figure 53 shows the injury values obtained for configurations 1 and 2. All injury values recorded are below limits, including the injury values that are specific of the side impact analysis as TTI, VC, and rib deflection. Although all injuries are below limits, the TTI and the rib deflection results show higher values than those desired in order to be completely safe.

It is interesting to notice that while higher values are observed for the neck region once the occupant is seated farther from the monument (barrier or forward facing seat), the opposite occurs to the thorax region. The closer the occupant is to the monument (barrier or forward

facing seat), the higher the injury values for TTI, VC, and rib deflection are. This was expected since these types of injuries are more related with diffusions. The kinematics for the two worst conditions are shown in Figure 51 and Figure 52.

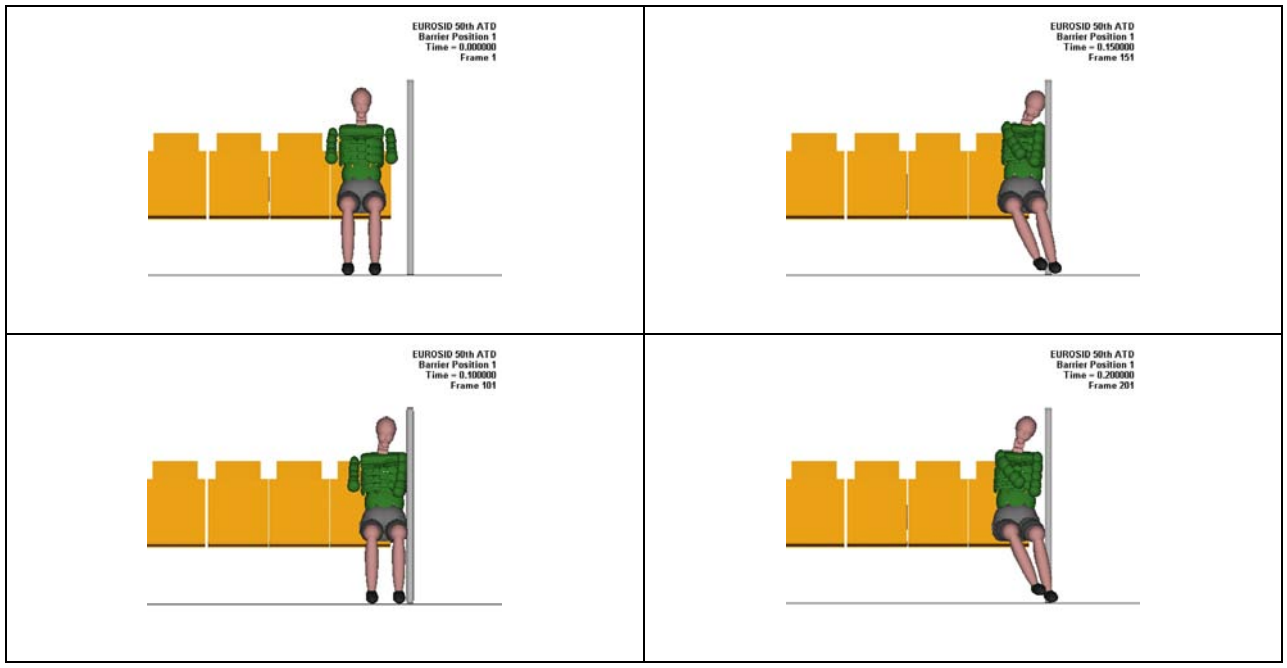


Figure 51. Kinematics Euro-SID analysis – position 1 with barrier (0ms to 200ms)

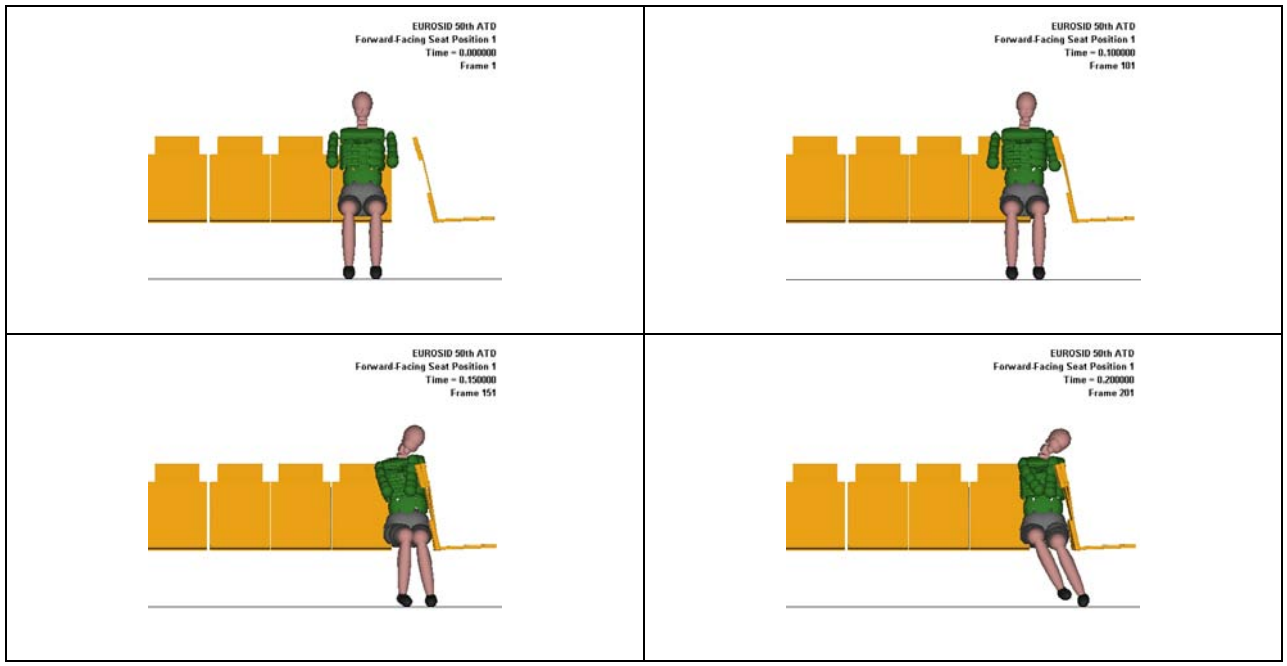


Figure 52. Kinematics Euro-SID analysis – position 1 with forward-facing seat (0ms to 200ms)

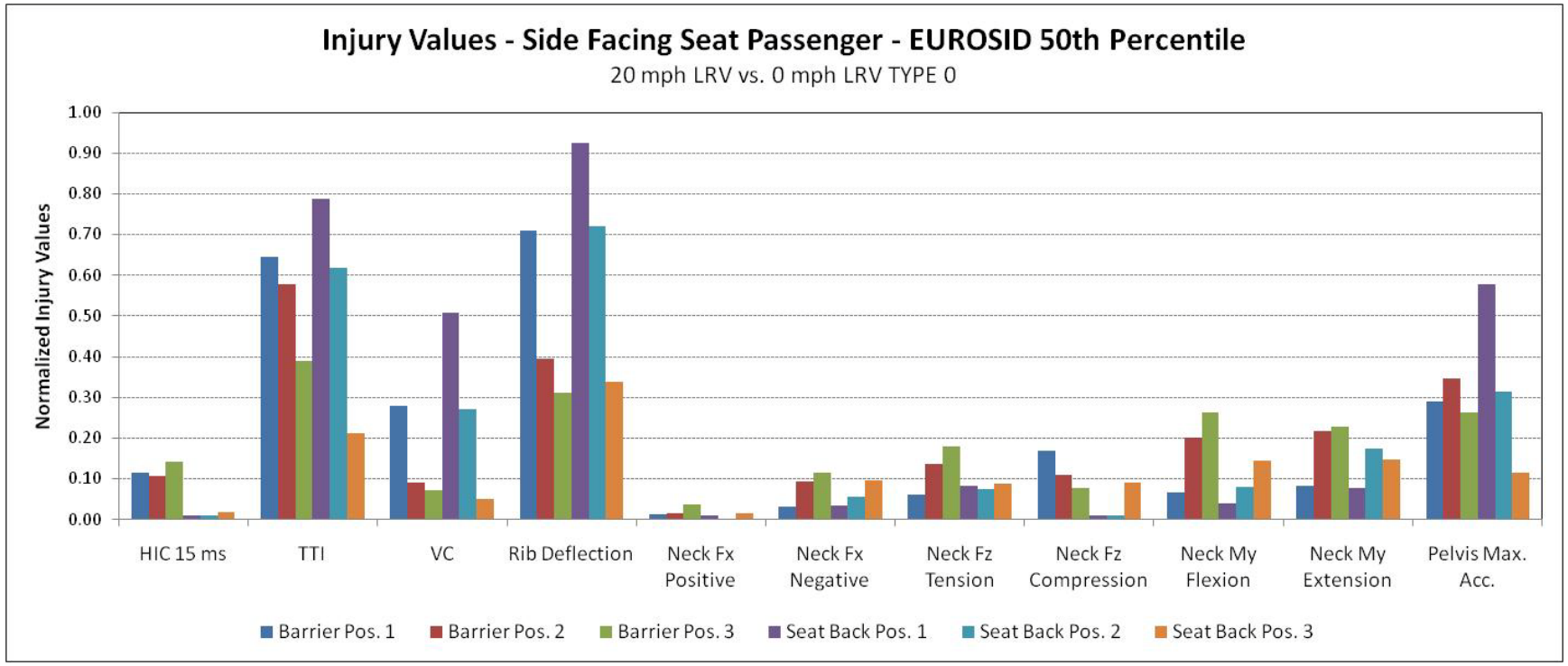


Figure 53. Euro-SID analysis – injury values for position 1, 2, and 3 for barrier and forward-facing seat configurations

To finalize this analysis two more configurations with multiple occupants are analyzed. On these models three occupants are seated on the side-facing seat. The first one, and closest to the monument, is the Euro-SID. The second one, which is seated on the following seat, is a Hybrid III 50th percentile. The third and last is another Hybrid III 50th percentile seated on the following seat. Figure 54 shows the initial setup for both configurations: barrier and forward-facing seat.

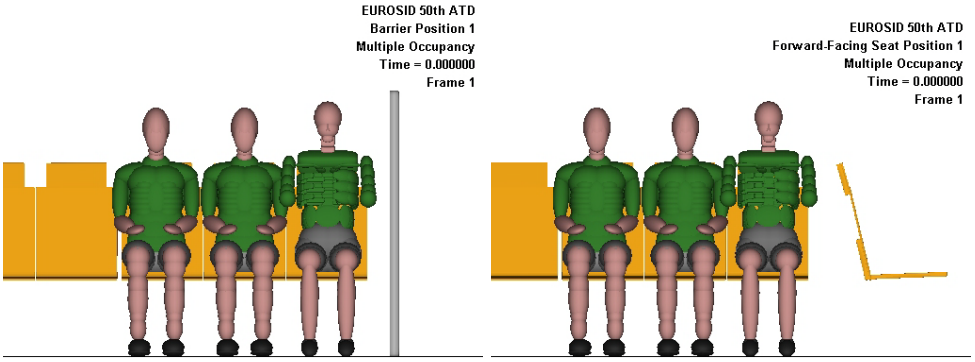


Figure 54. Euro-SID analysis - multiple occupants setup

Figure 55 shows the injury values for this analysis. The suspect of interest in this analysis is the Euro-SID. A left side Euro-SID is used for this analysis, thus similar results to those found for the configurations where the Euro-SID is seated alone are found. TTI values remained in the range of 65 to 75% when compared to the current limits. Pelvis maximum acceleration is a little bit larger as a result of the contact between occupants, though the values are still low when compared to the current limits. The remaining injury values are very low when compared to the current limits except for the rib deflection. According to the results obtained higher rib deflections are expected for the occupant seated close to a barrier when other occupants are seated next to it. The larger compression of the chest is due to the force applied by the other two occupants when pushing the occupant towards the barrier. At the present, same analyses are being conducted using right side Euro-SID to complete this study.

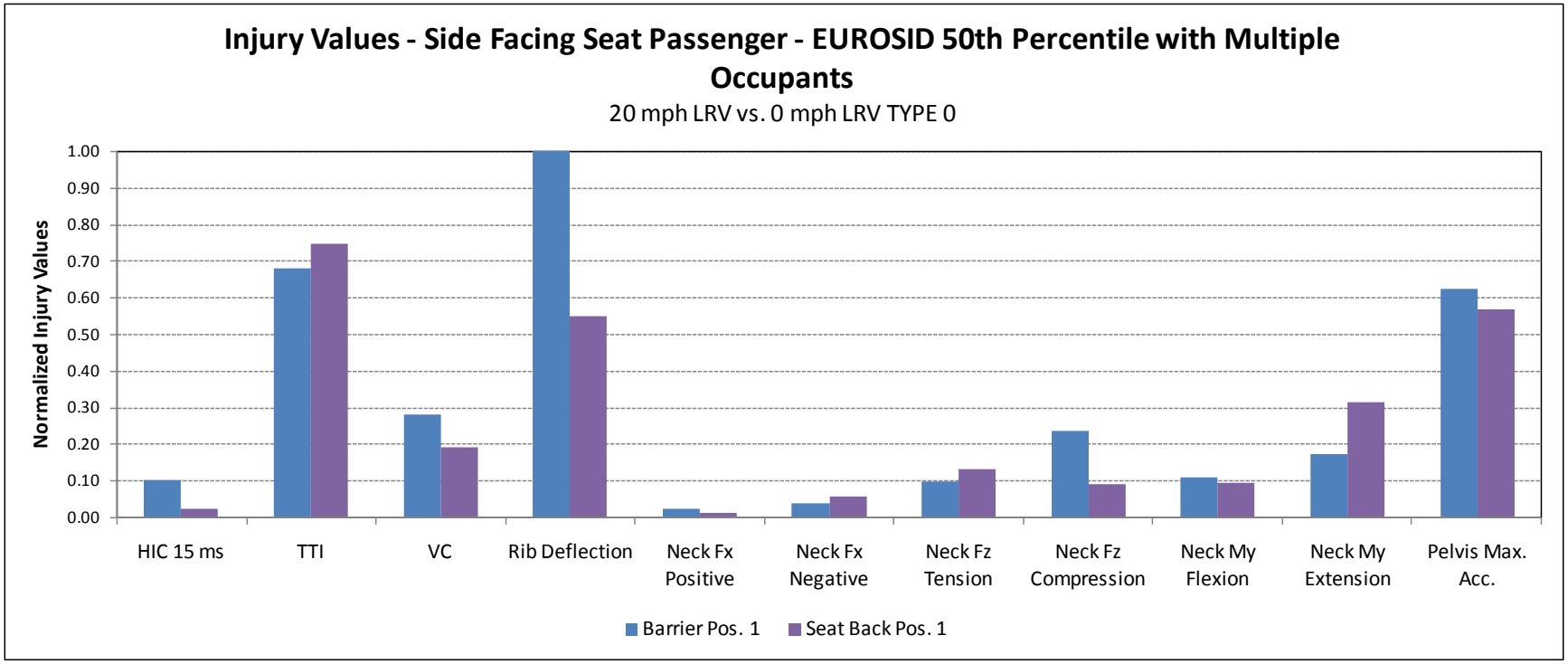


Figure 55. Euro-SID multiple occupants analysis – injury values

The kinematics of the moment of impact for the barrier configuration are shown in Figure 56. In addition, Figure 57 shows the kinematics for the forward-facing seat configuration.

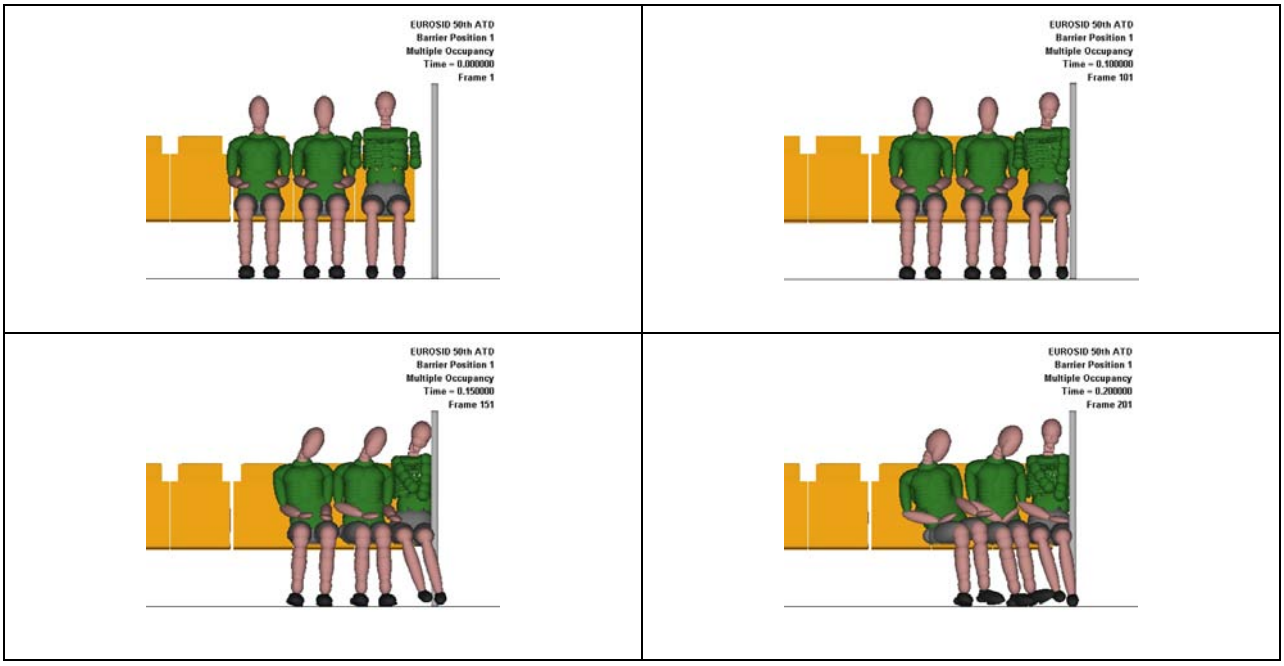


Figure 56. Kinematics Euro-SID multiple occupants analysis barrier (0ms to 200ms)

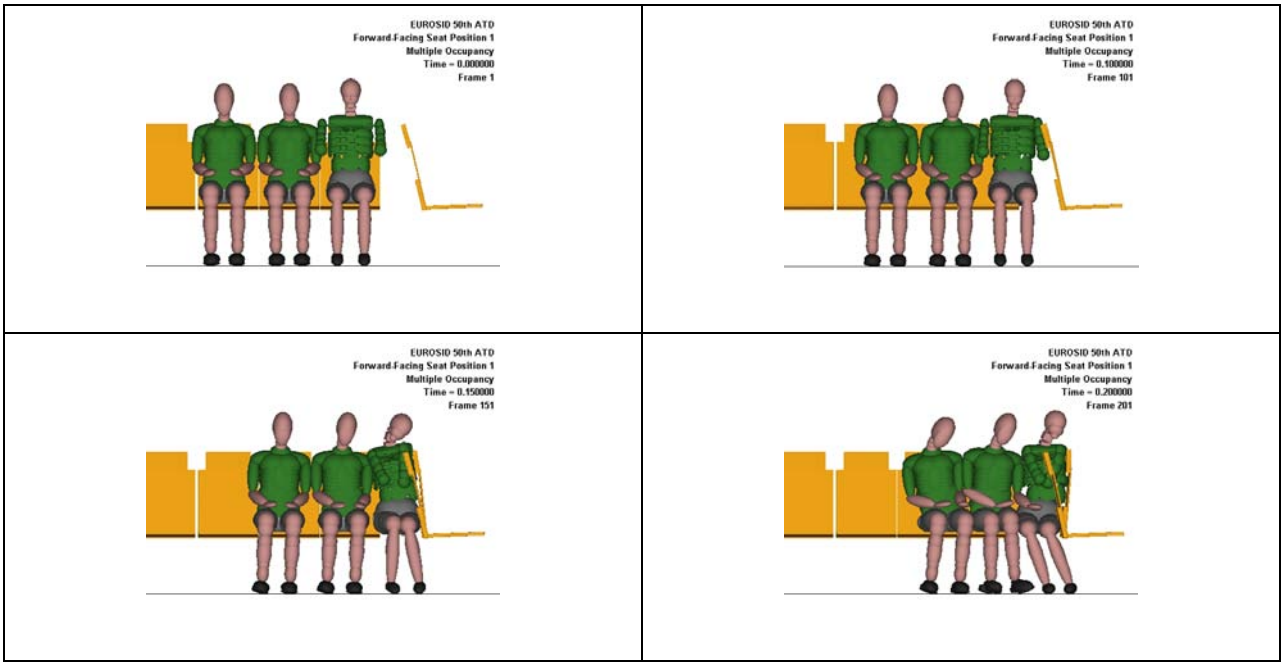


Figure 57. Kinematics Euro-SID multiple occupants analysis forward-facing seat (0ms to 200ms)

5.1.2 Exit Velocity Analysis

According to all layouts available for analysis (section 3.3.3. *"LRV Specific Interior Survey"*), the number of side-facing seats usually varies from one to six seats. From a total of 11 LRVs types where side-facing seats were found, the following distribution was obtained:

- Six of them (54.5%) have a row with three seats
- The other 5 LRVs (45.5%) have a varying number of lateral facing seats per row ranging from only one seating position to six

Figure 58 throughout Figure 61 show some examples of LRV interiors where different numbers of side facing seats can be found:

- Six lateral facing seats:

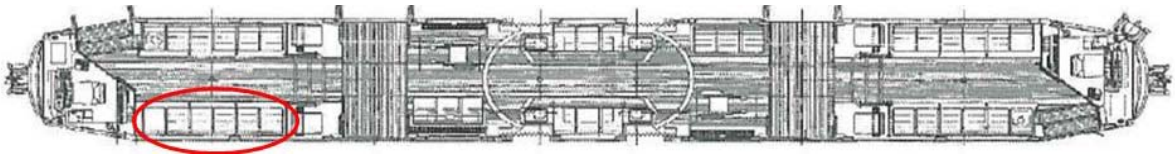


Figure 58. Six side-facing seats configuration [9]

- Five and two lateral facing seats:

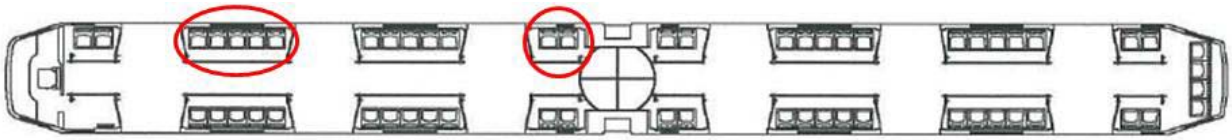


Figure 59. Five and two side-facing seat configurations [9]

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

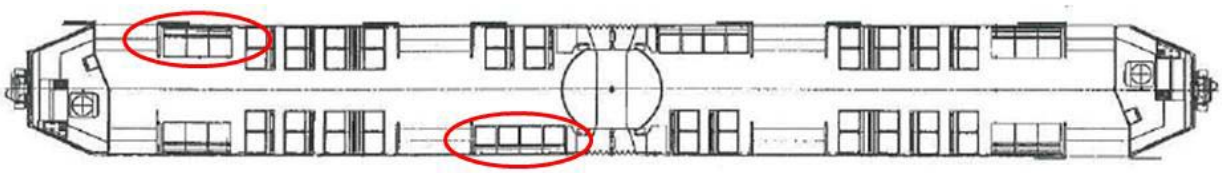


Figure 60. Three and four side-facing seat configurations [9]

- One lateral facing seat:

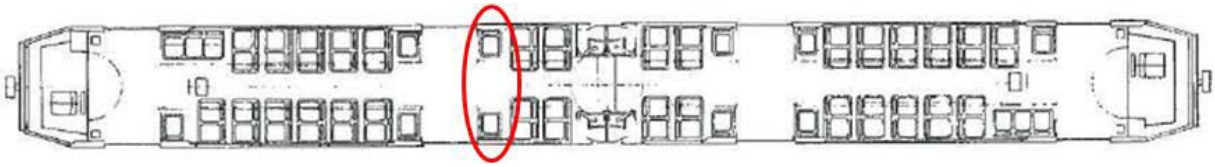


Figure 61. Single side-facing seat configuration [9]

The maximum exit velocity for the occupant is evaluated according to occupant seating position. Exit velocity is defined as the impact velocity of the ATD with the barrier (Figure 62). The exit velocity for the six positions is compared. The worst-case scenario will be defined as the seating position that shows the largest impact velocity. The Hybrid III 5th, 50th, and 95th percentile ATDs are used for this analysis.

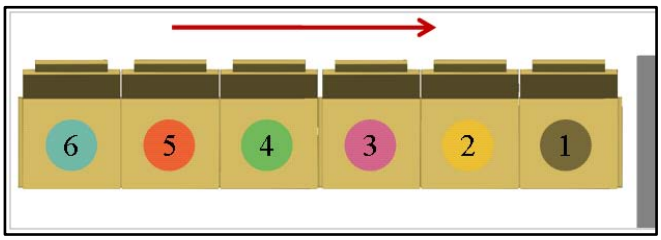


Figure 62. Side-facing seats – exit velocity analysis

The setup model used for this section was shown previously in Figure 49. The velocity of the passenger is recorded during the entire event for each one of the six positions. The results are shown in Figure 63.

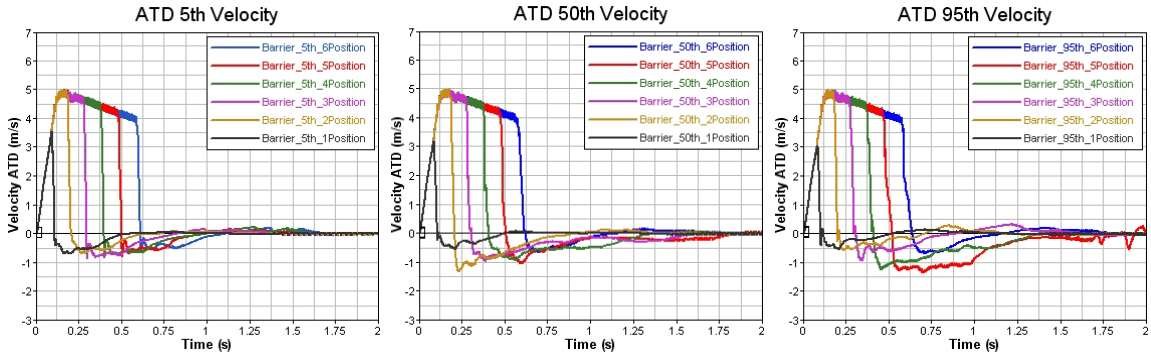


Figure 63. Side-facing seats – exit velocity for 5th, 50th, and 95th percentile ATDs [1]

As expected, all occupants show similar behavior. The passenger seated in the first seating position has the smaller 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 seating position has the highest impact velocity. In this position the occupant has enough time to build the maximum relative velocity due to the acceleration pulse just prior to impacting with the barrier.

In seating positions three through six, the passenger reaches the maximum relative velocity, but as a result of friction and contact with the seat pan the impact velocity is reduced before impacting with the barrier. For this analysis the coefficient of friction between the ATDs and the seats was defined as 0.2.

Figure 64 summarizes these results. This bar chart shows the impact velocity as a function of the distance between the centerline of the seat pan and the barrier in meters.

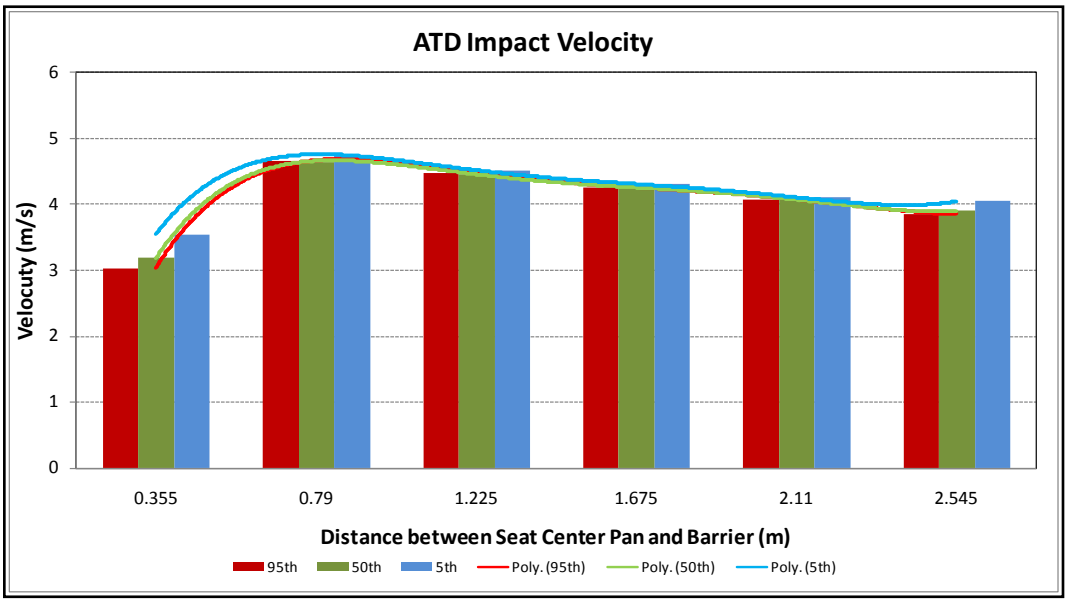


Figure 64. Side-facing seats – ATD impact velocity analysis results [1]

The equations for these results are:

95^{th} $y = 0.7918x^5 - 6.7958x^4 + 22.549x^3 - 35.986x^2 + 27x - 2.9252$ (5.1)

50^{th} $y = 0.8595x^5 - 7.1839x^4 + 23.19x^3 - 35.967x2 + 26.213x - 2.511$ (5.2)

5^{th} $y = 0.8803x^5 - 7.152x^4 + 22.478x^3 - 33.967x^2 + 24.04x - 1.6007$ (5.3)

The variable x (m) represents the distance between the center of the seat pan and the barrier (distance (1) in Figure 65) and y (m/s) is the exit velocity. If the velocity of impact is desired, x needs to be corrected by the following (distance (2) in Figure 65):

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

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

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

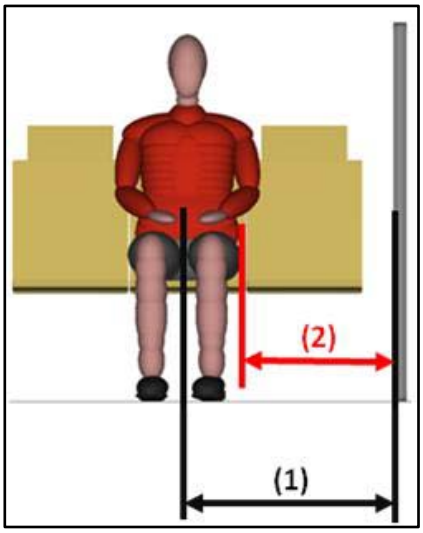


Figure 65. Side-facing seats – distance between occupant and barrier [1]

The injury values for the entire series of simulations done in this analysis are shown in the following figures. The worst injury values for the 5^{th} and 50^{th} percentile ATDs were obtained when they were seated in the second position (See Figure 66 and Figure 67 respectively). In contrast, for the 95^{th} percentile the worst injury values were observed when seated in position number three (See Figure 68).

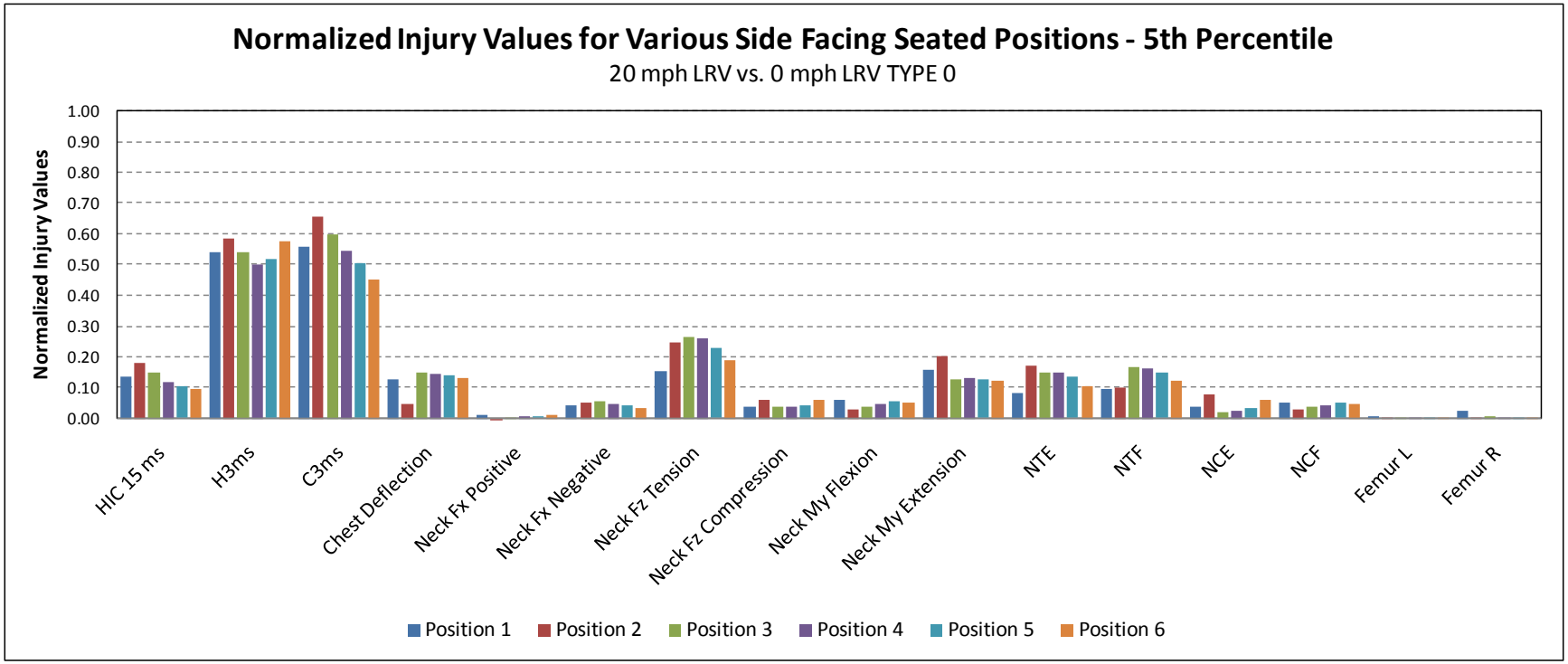


Figure 66. Injury values for 5th percentile ATD – exit velocity analysis [1]

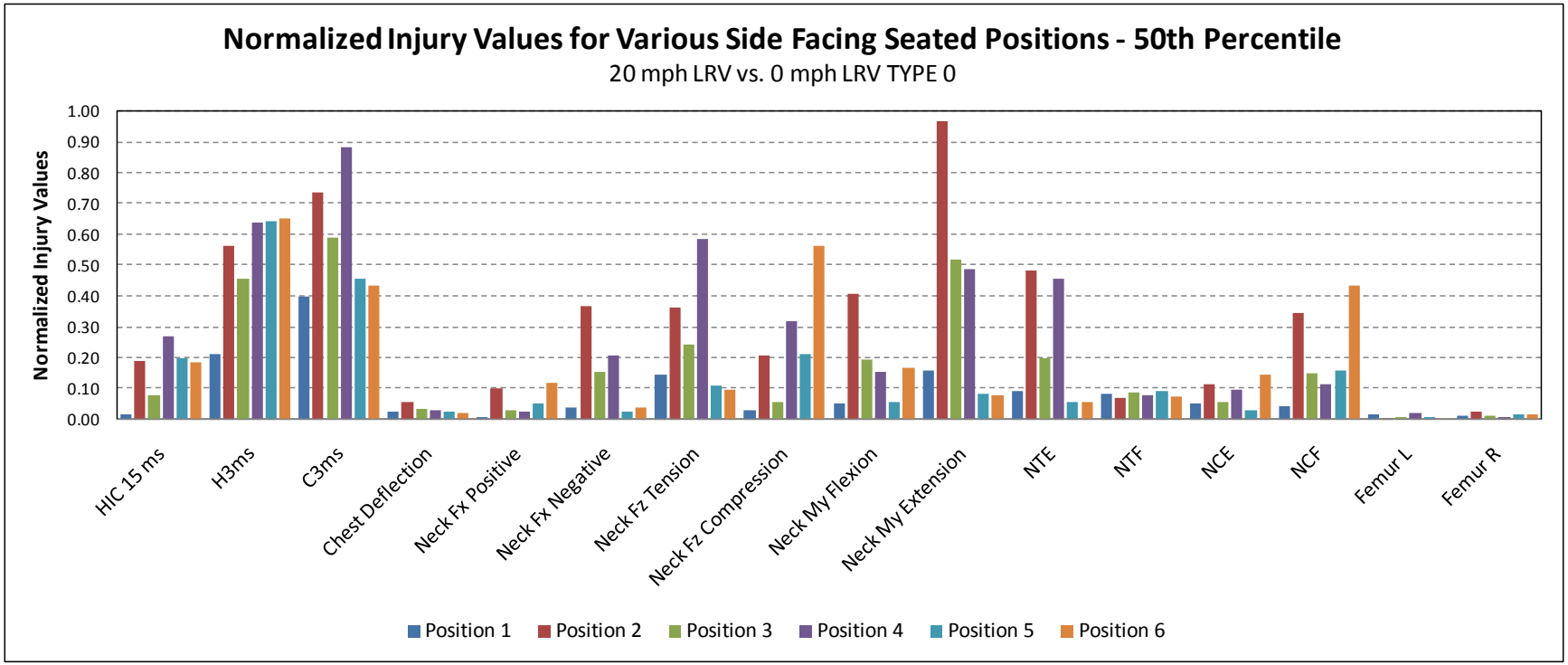


Figure 67. Injury values for 50th percentile ATD – exit velocity analysis [1]

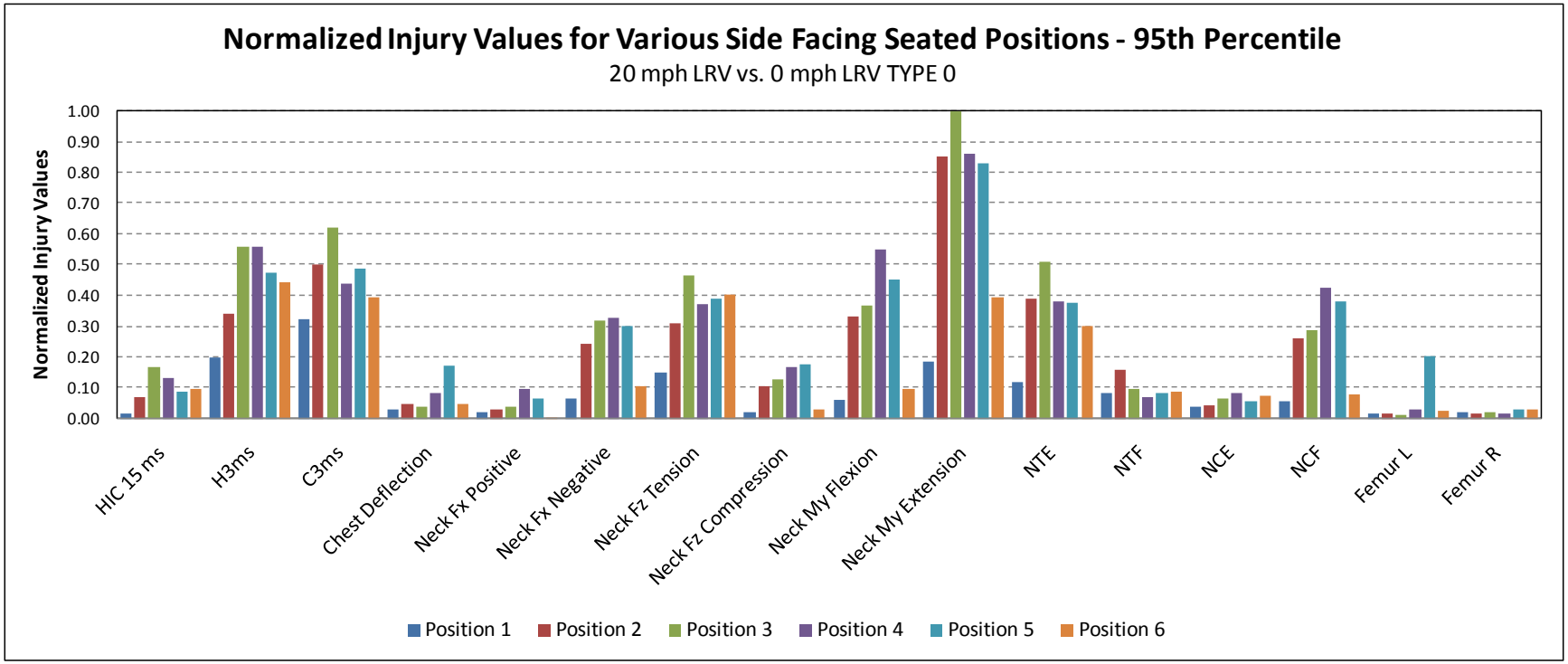


Figure 68. Injury values for 95th percentile ATD – exit velocity analysis [1]

To summarize, it is possible to state that the maximum impact velocity for the passengers traveling in a side facing seats is the one corresponding to the second seating position. 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, so the impact occurs with the maximum energy. Hence, in general, the worst injuries can be expected for occupants seated on this position. Even though the maximum velocity reached by passenger is the same when sitting in positions three through six, the impact velocity is smaller due to the friction with seat surfaces.

Therefore, the complete analysis for the side facing seats conducted in the following section is done with the occupant seated on the second seating position.

5.1.3 Detailed LRV Side-Facing Seat Analysis

The most representative configurations available for side-facing seats are studied in this section. These layouts can be found in some of the current LRVs. Figure 69 shows the layout of an LRV with both side-facing seats vs. aft-facing seats and side-facing seats vs. forward-facing seats. Figure 70 shows a LRV layout where a side-facing seat vs. a barrier or monument can be observed.

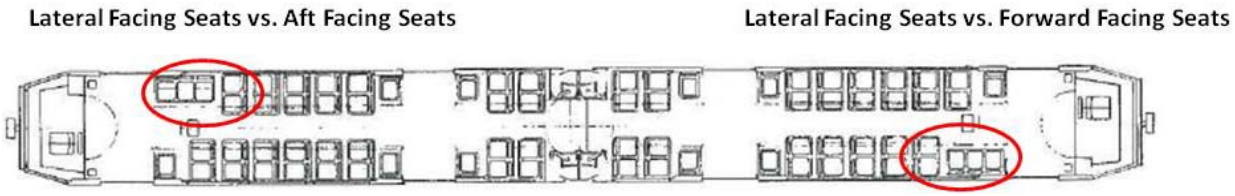


Figure 69. Side-facing seats with forward and aft-facing seat combinations [9]

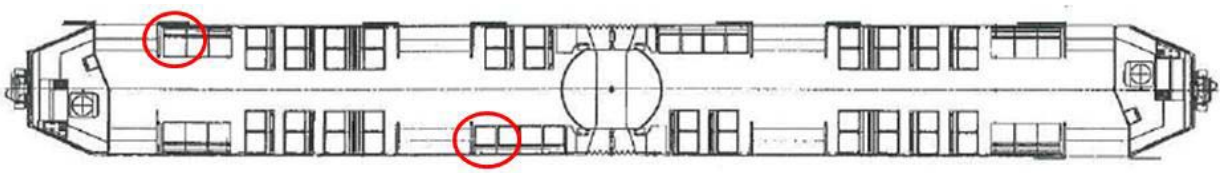


Figure 70. Side-facing seats with barrier [9]

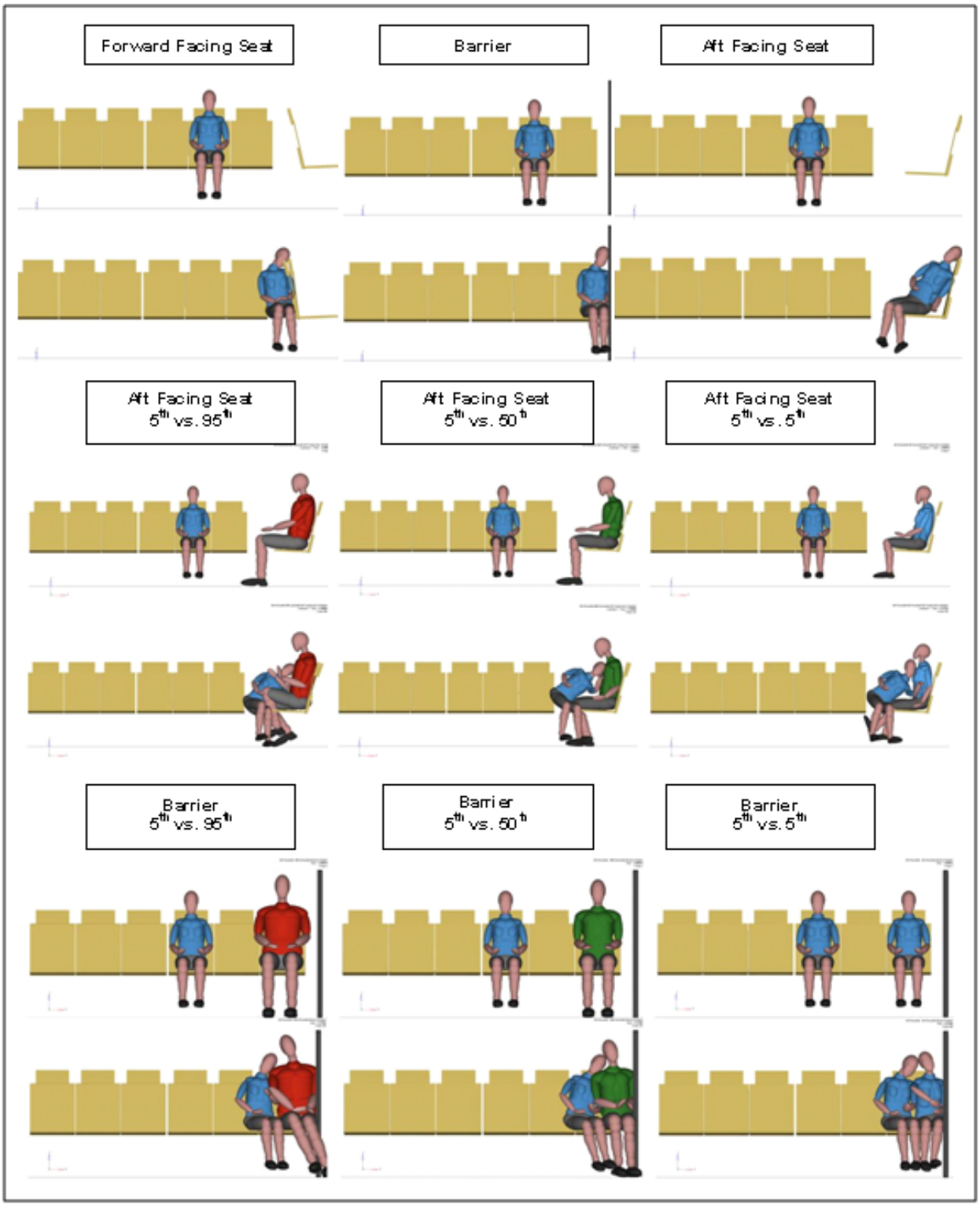
In addition, all possible seating combinations of the 5th, 50th, and 95th percentile ATDs are studied. The following table (Table 11) shows the test matrix for all the cases analyzed on this section with a total of 27 runs.

TABLE 11

TEST MATRIX – LATERAL LAYOUT ANALYSIS (27 RUNS)

Test Matrix - Lateral Layout Analysis			
Layout	**95th**	**50th**	**5th**
Barrier	X	X	X
Barrier - 95th	X	X	X
Barrier -50th	X	X	X
Barrier - 5th	X	X	X
Forward Facing Seat - Empty	X	X	X
Forward Facing Seat - 95th	X	X	X
Forward Facing Seat - 50th	X	X	X
Forward Facing Seat - 5th	X	X	X
Rear Facing Seat	X	X	X

The kinematics of all these configurations are shown in figures 71, 76, and 81. The injury values are summarize by percentile, as well as scenario, and are shown in figures 72, 73, 74, and 75 for the 5th percentile, figures 77, 78, 79, and 80 for the 50th percentile, and figures 82, 83, 84, and 85 for the 95th percentile.



Notes: Red 95th Percentile, Green 50th Percentile, and Blue 5th Percentile

Figure 71. Kinematics – 5th percentile - side-facing seats - all possible combinations [1]

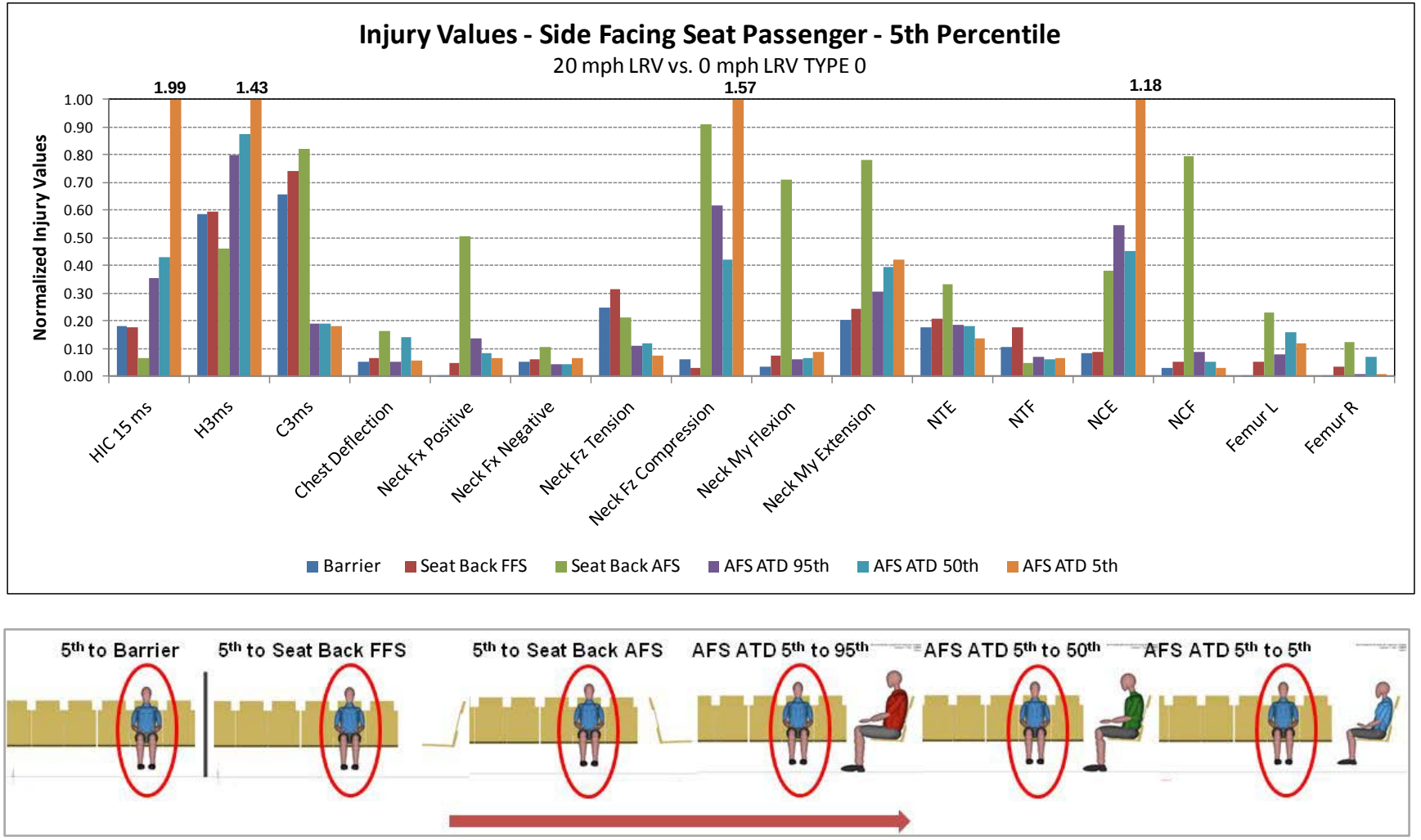


Figure 72. Normalized injury values – side-facing seats – 5th Percentile [1]

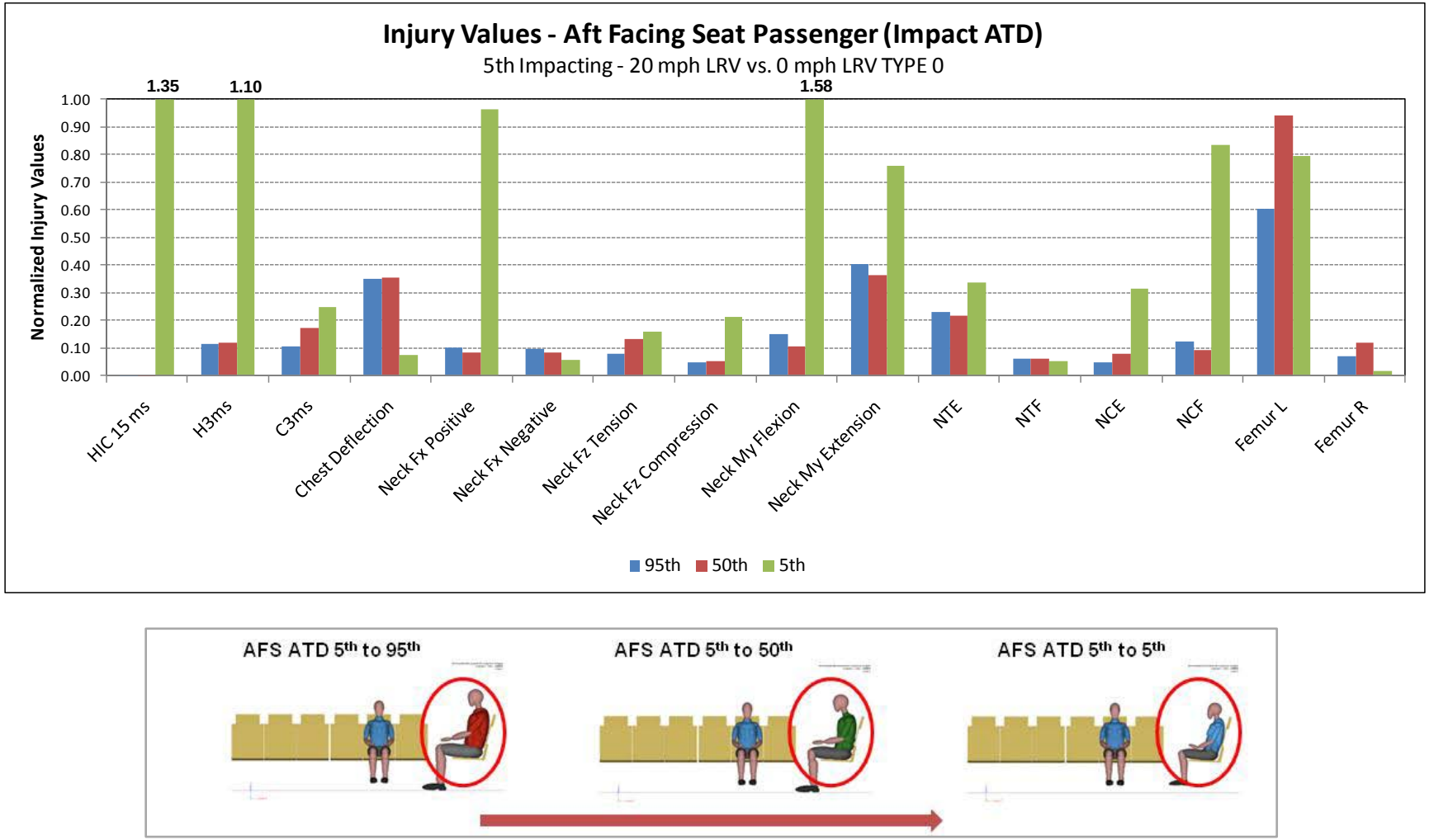
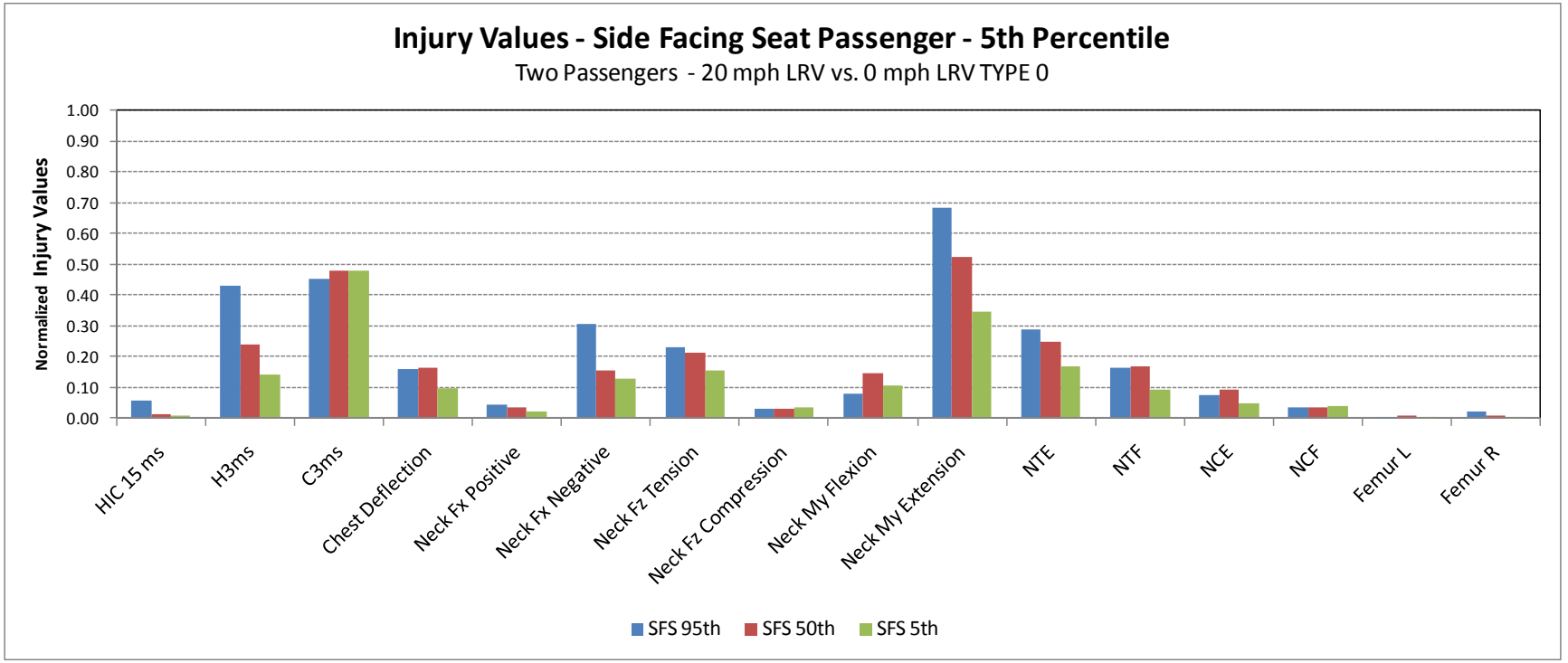


Figure 73. Normalized injury values – side-facing seats – impact ATD [1]



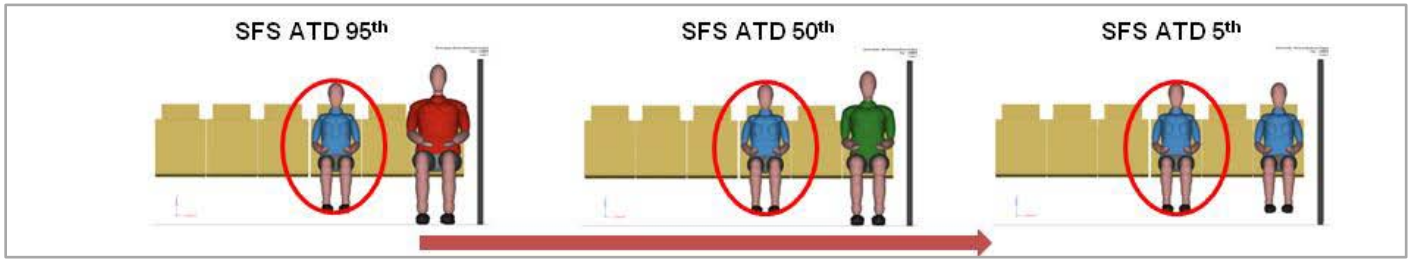
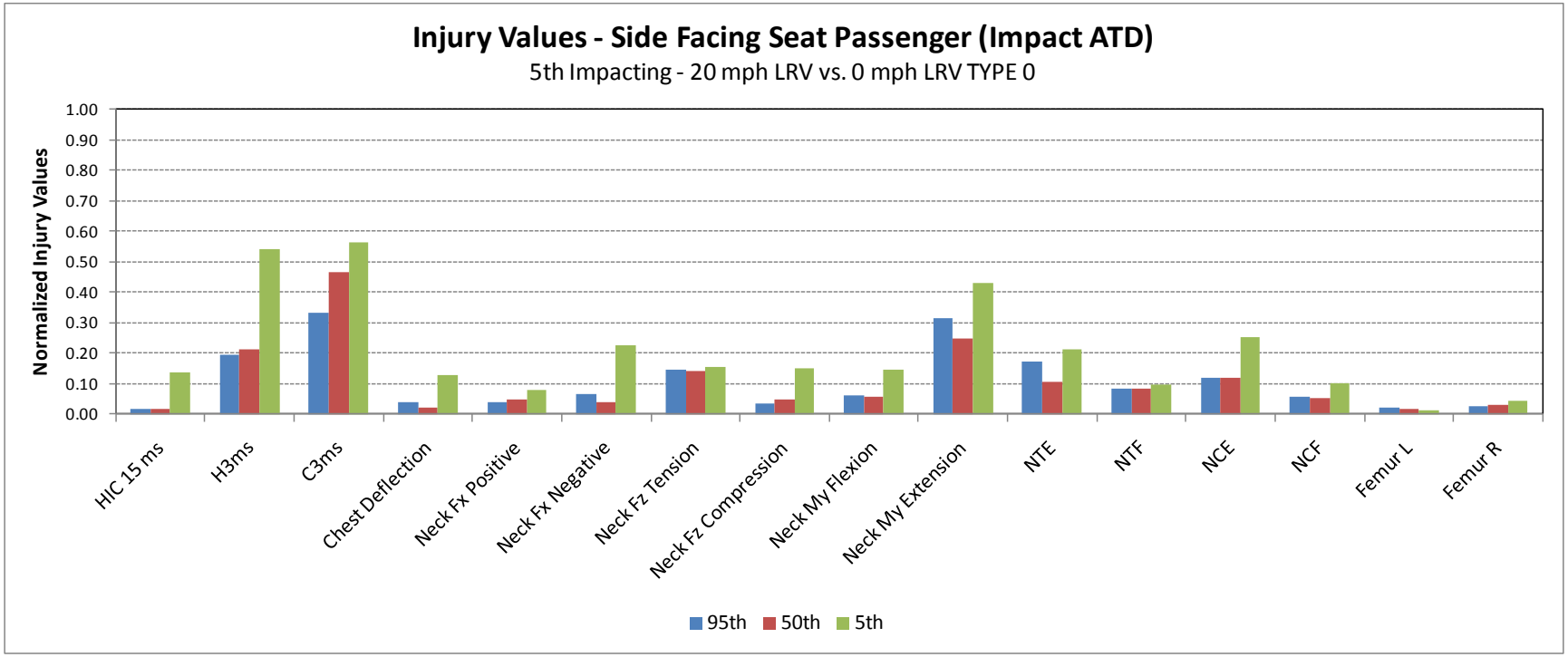


Figure 74. Normalized injury values – side-facing seats (barrier) – 5th percentile [1]



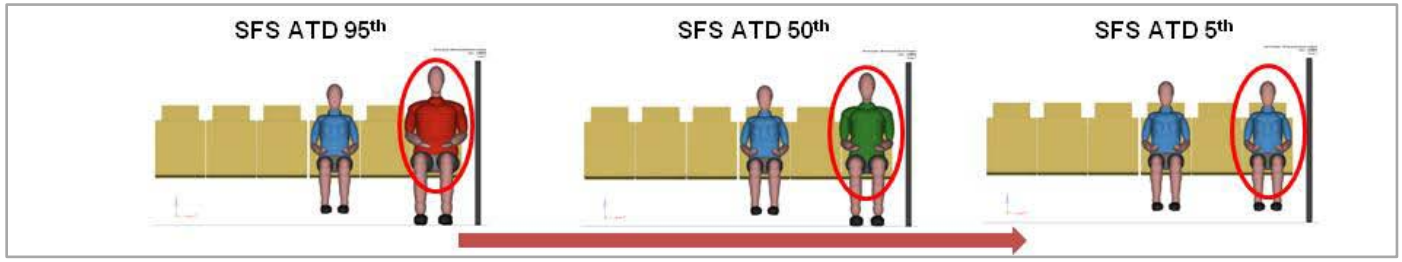
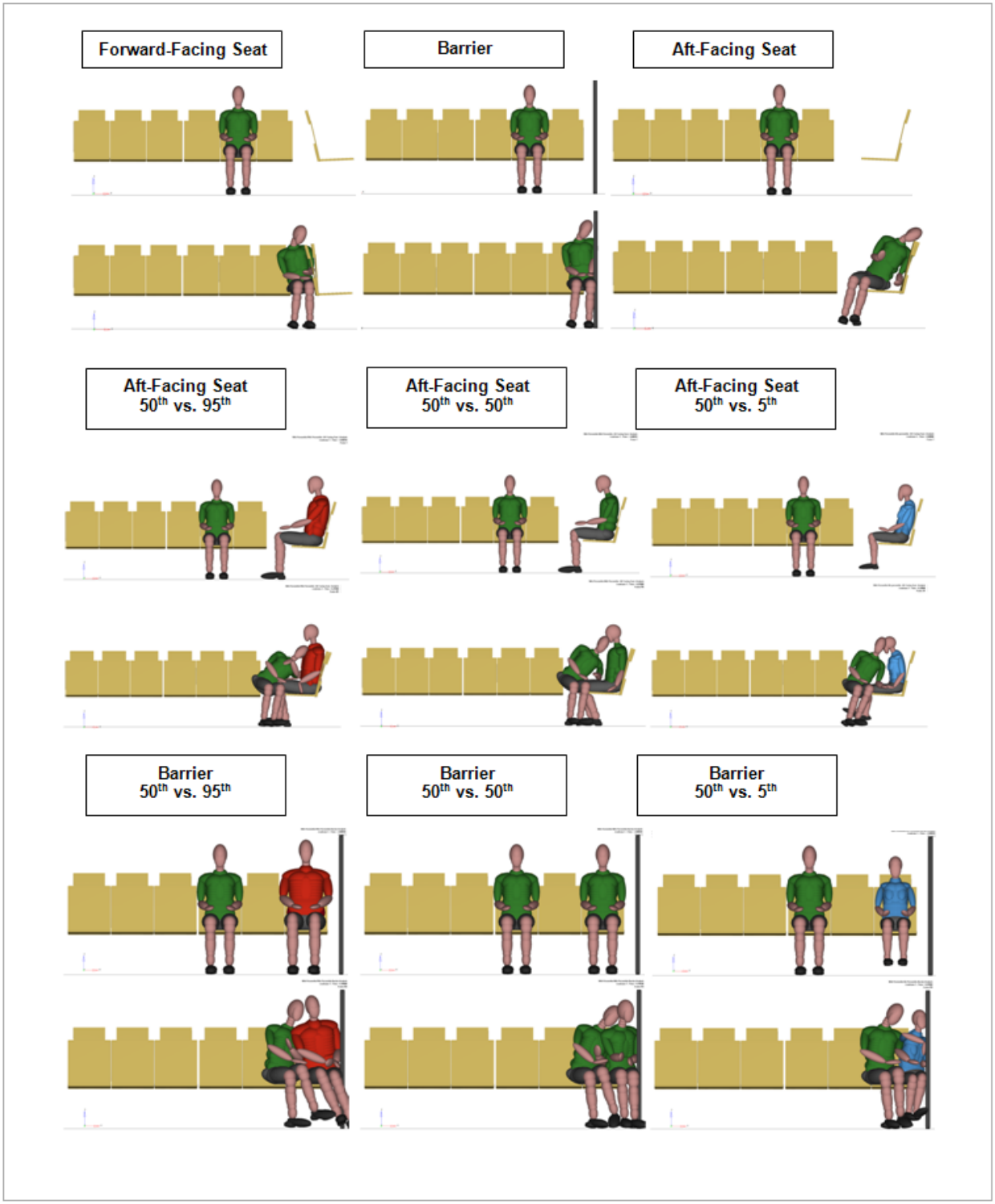
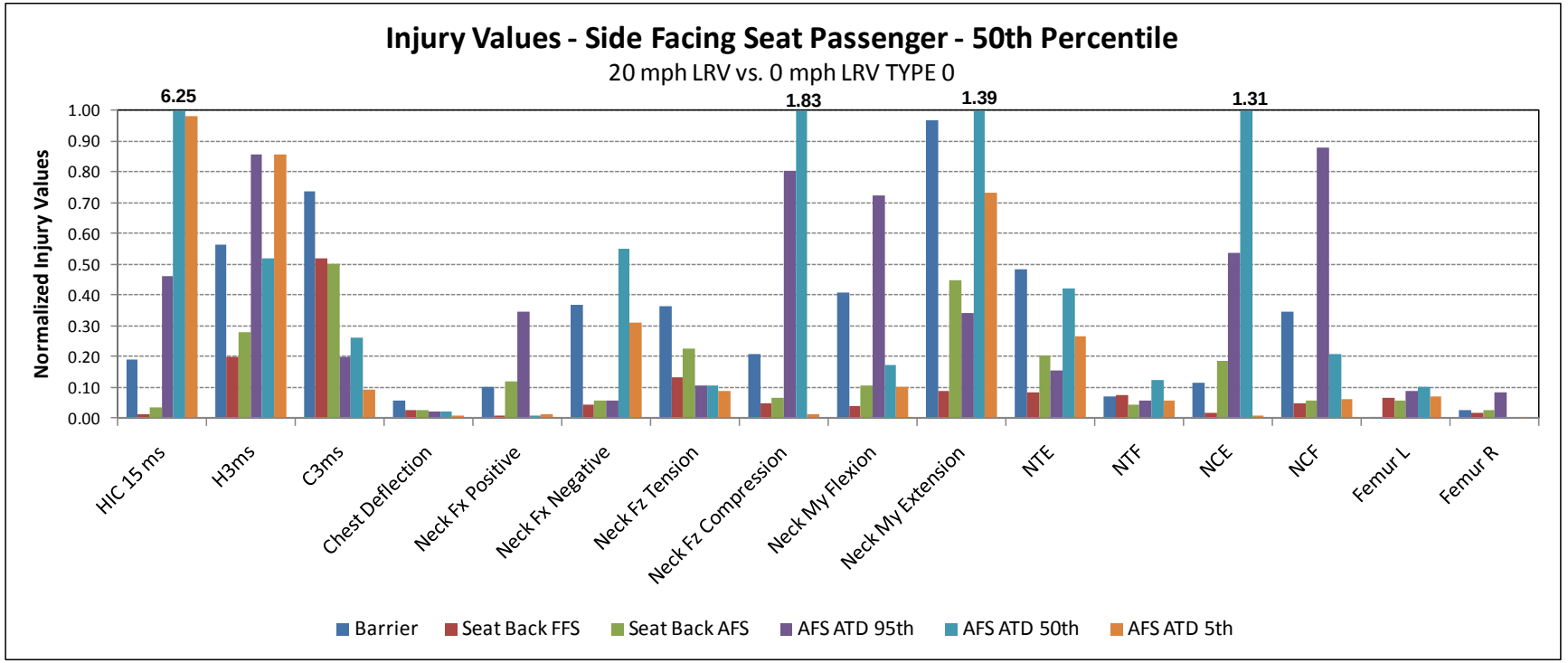


Figure 75. Normalized injury values – side-facing seats (barrier) – impact ATD [1]



Notes: Red 95th Percentile, Green 50th Percentile, and Blue 5th Percentile

Figure 76. Kinematics – 50th percentile - side-facing seats - all possible combinations [1]



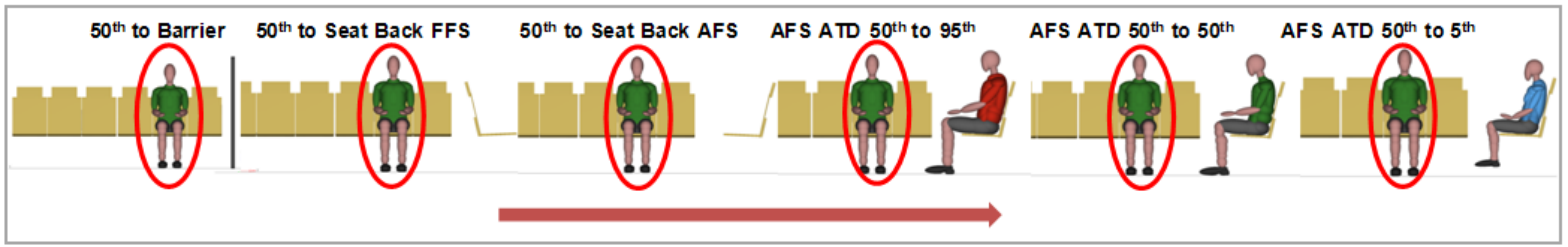
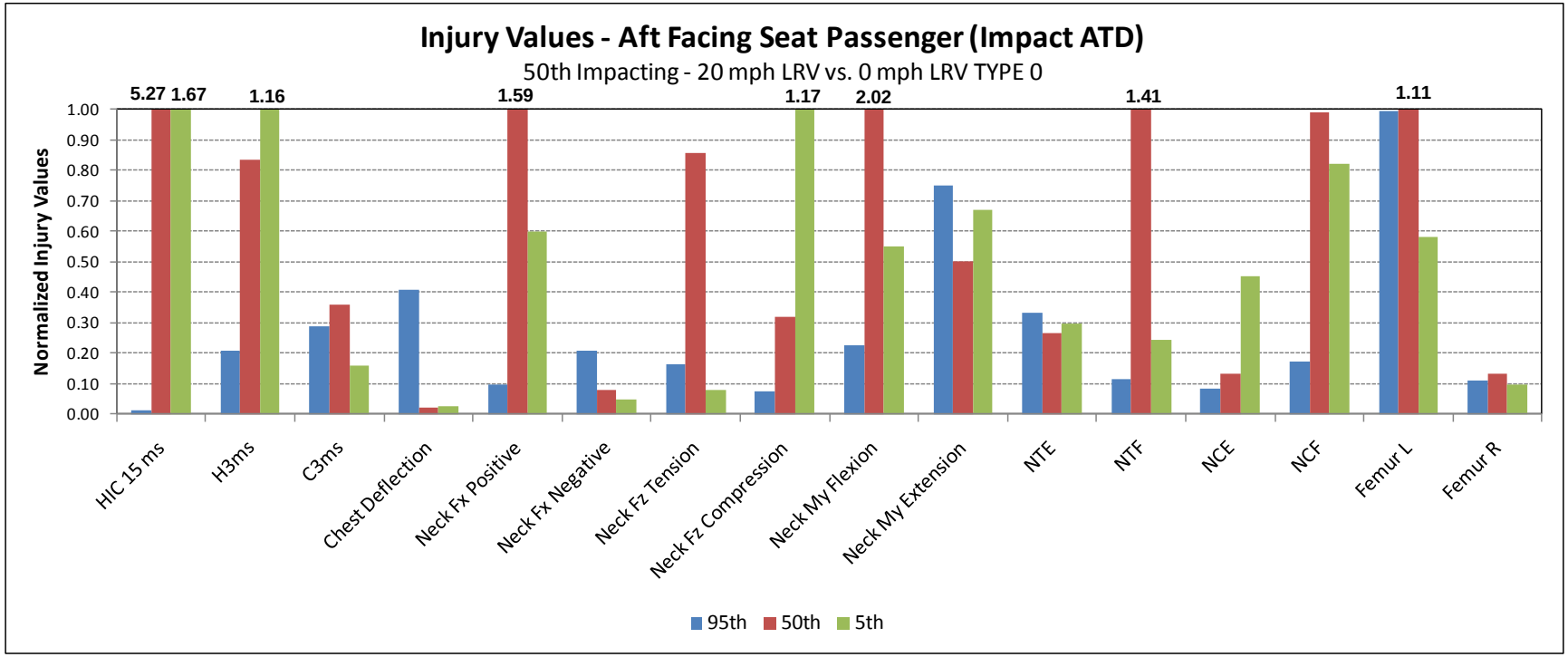


Figure 77. Normalized injury values – side-facing seats – 50th percentile ATD [1]



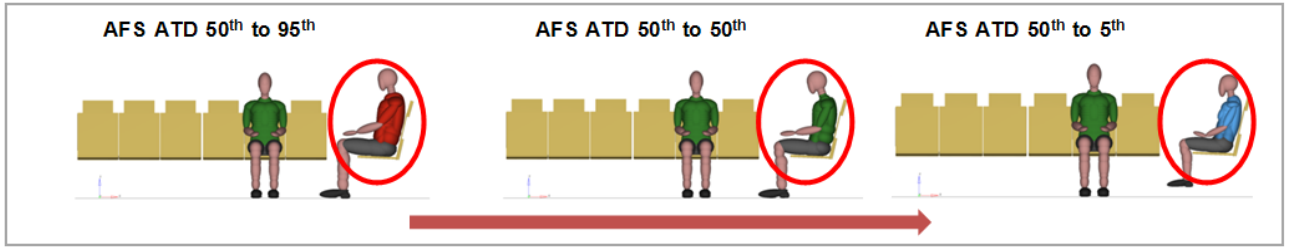
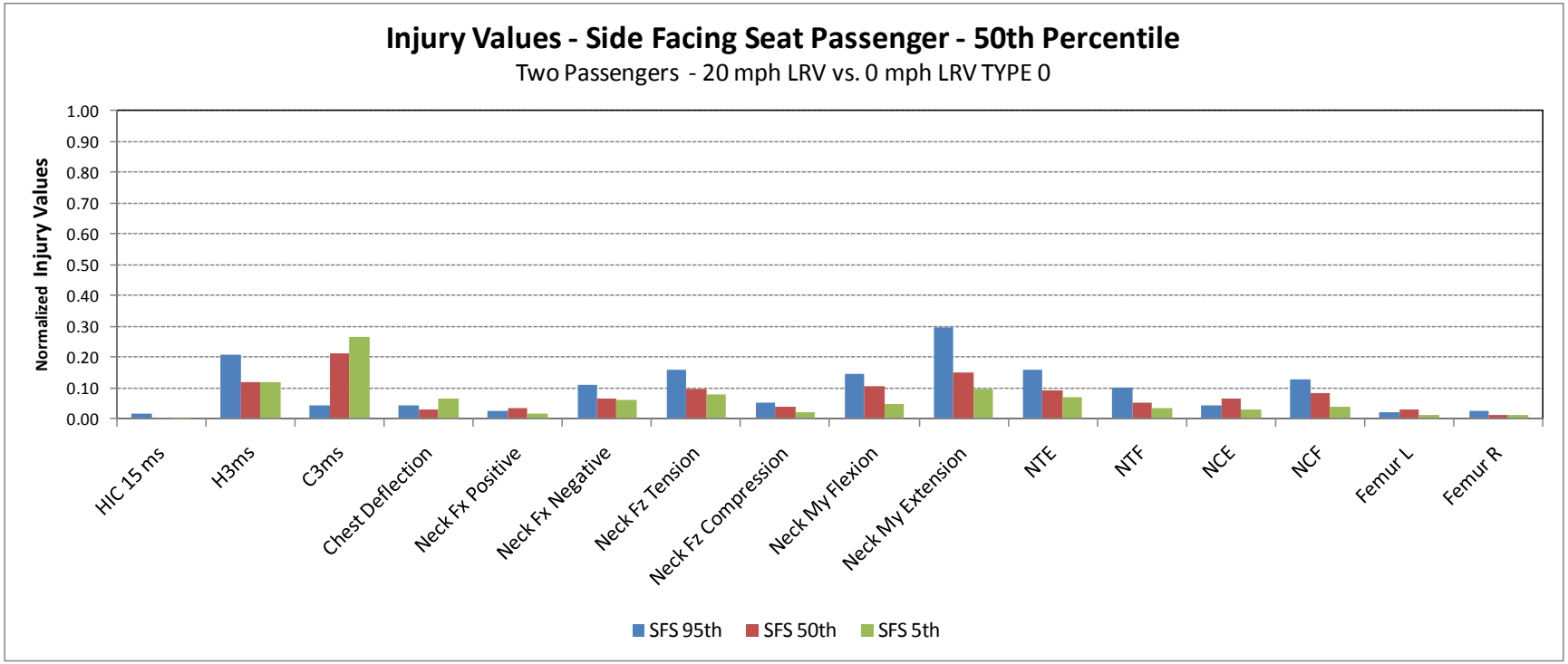


Figure 78. Normalized injury values – side-facing seats – impact ATD [1]



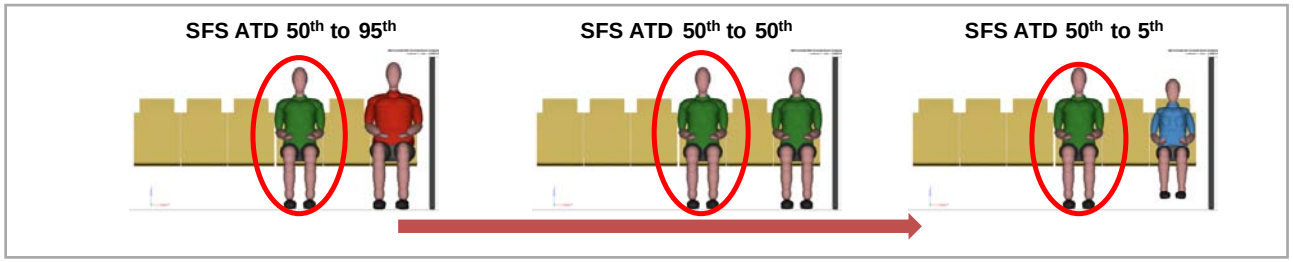


Figure 79. Normalized injury values – side-facing seats with barrier – 50th percentile ATD [1]

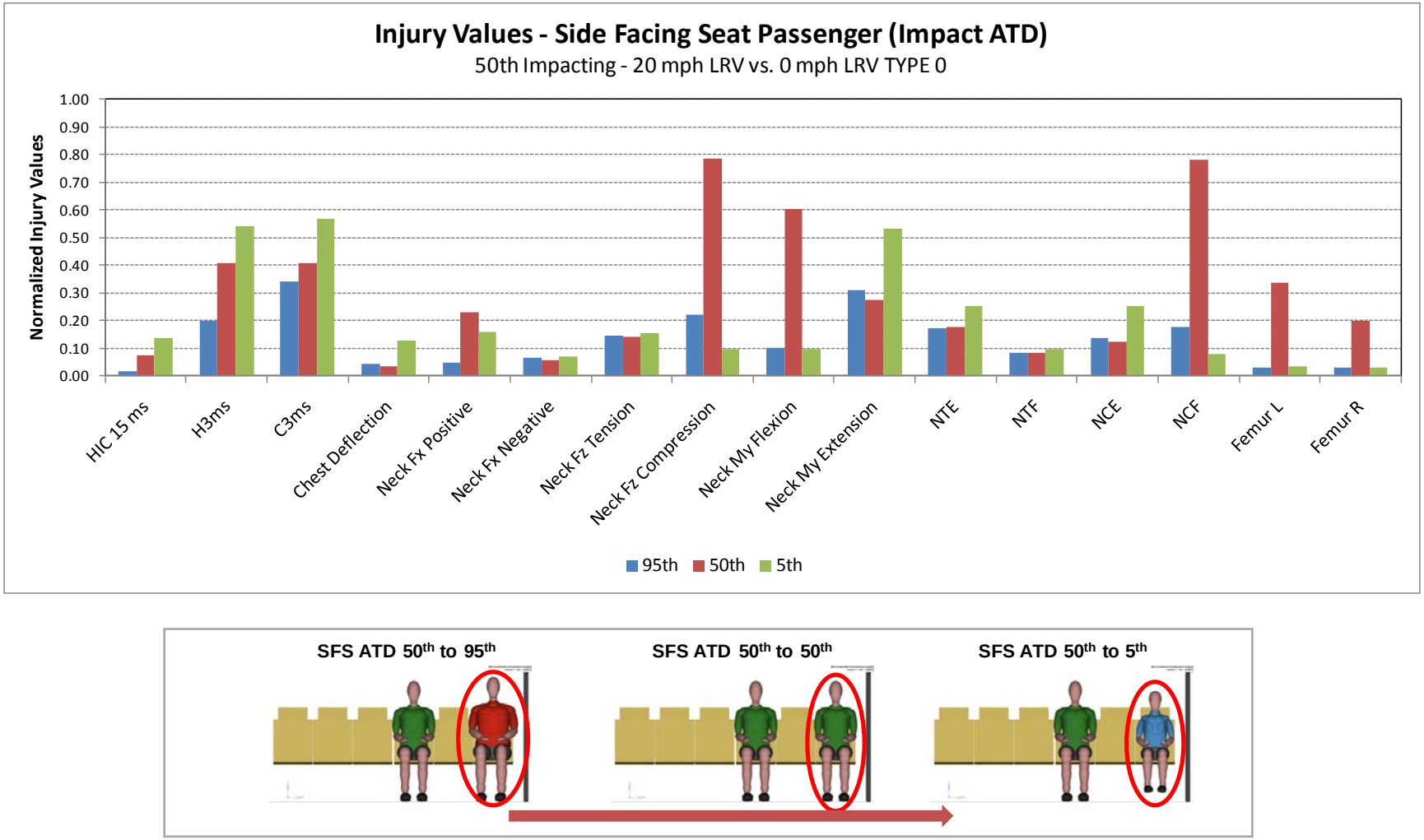
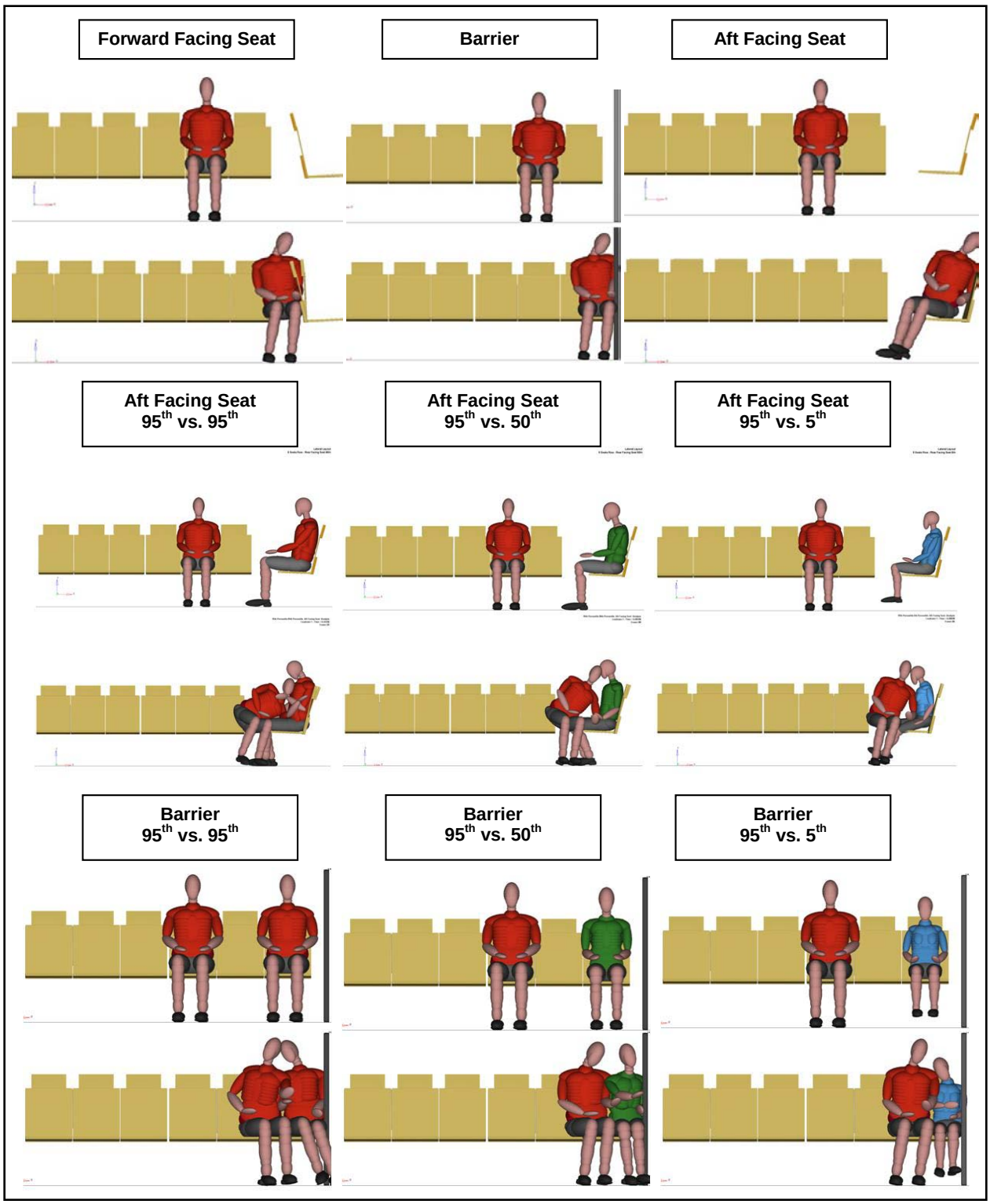
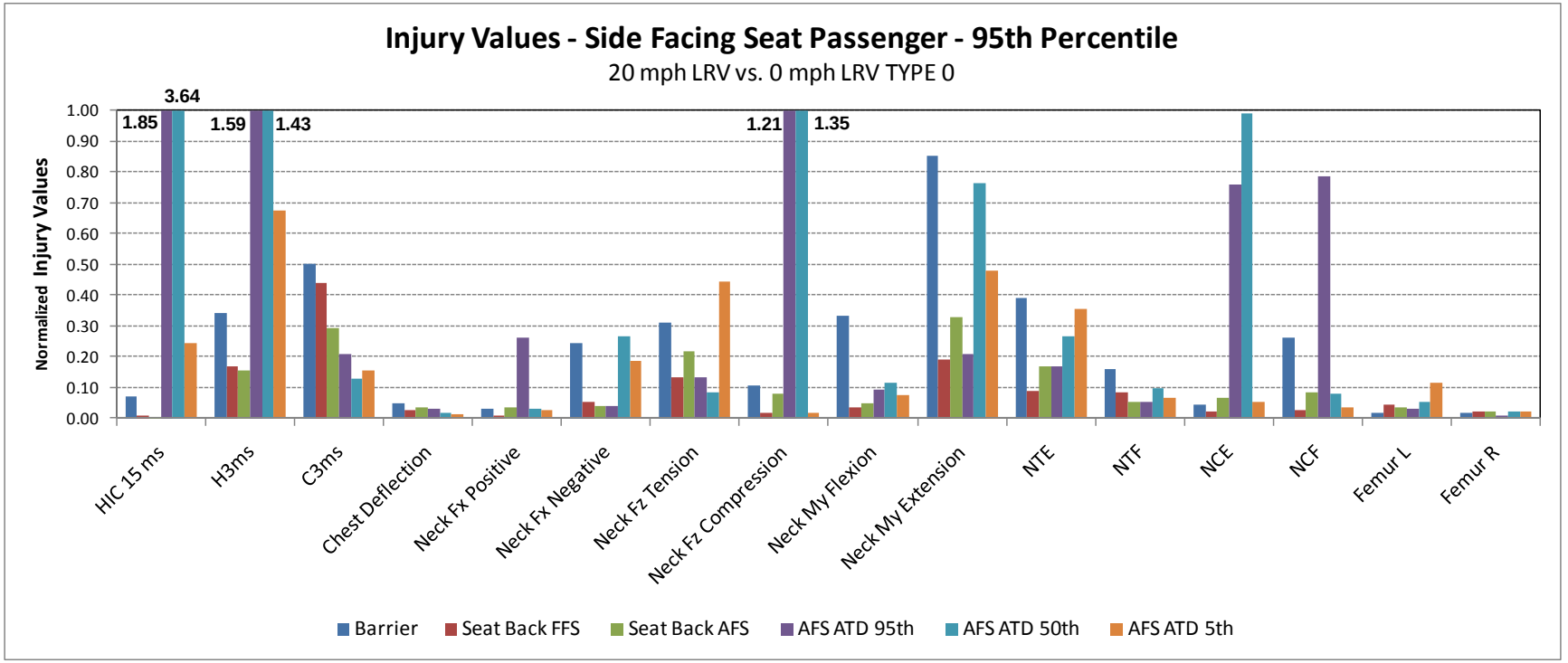


Figure 80. Normalized injury values – side-facing seat with barrier – impact ATD [1]



Notes: Red 95th Percentile, Green 50th Percentile, and Blue 5th Percentile

Figure 81. Kinematics – 95th percentile ATD - side-facing seats - all possible combinations [1]



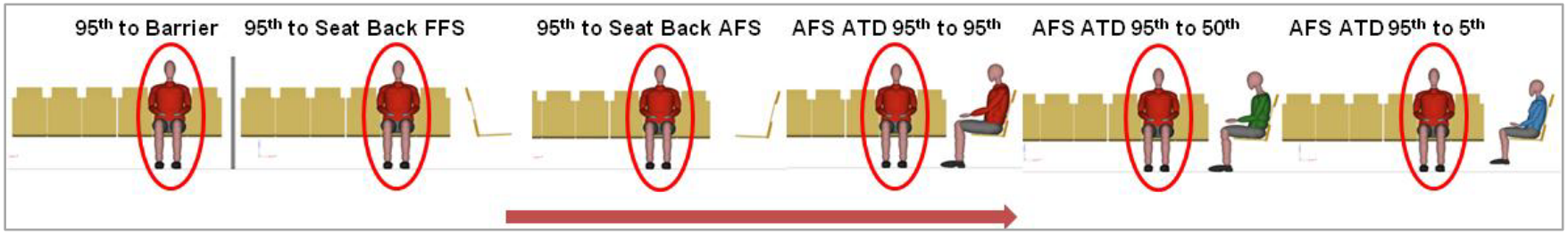


Figure 82. Normalized injury values – side-facing seats – 95th percentile ATD [1]

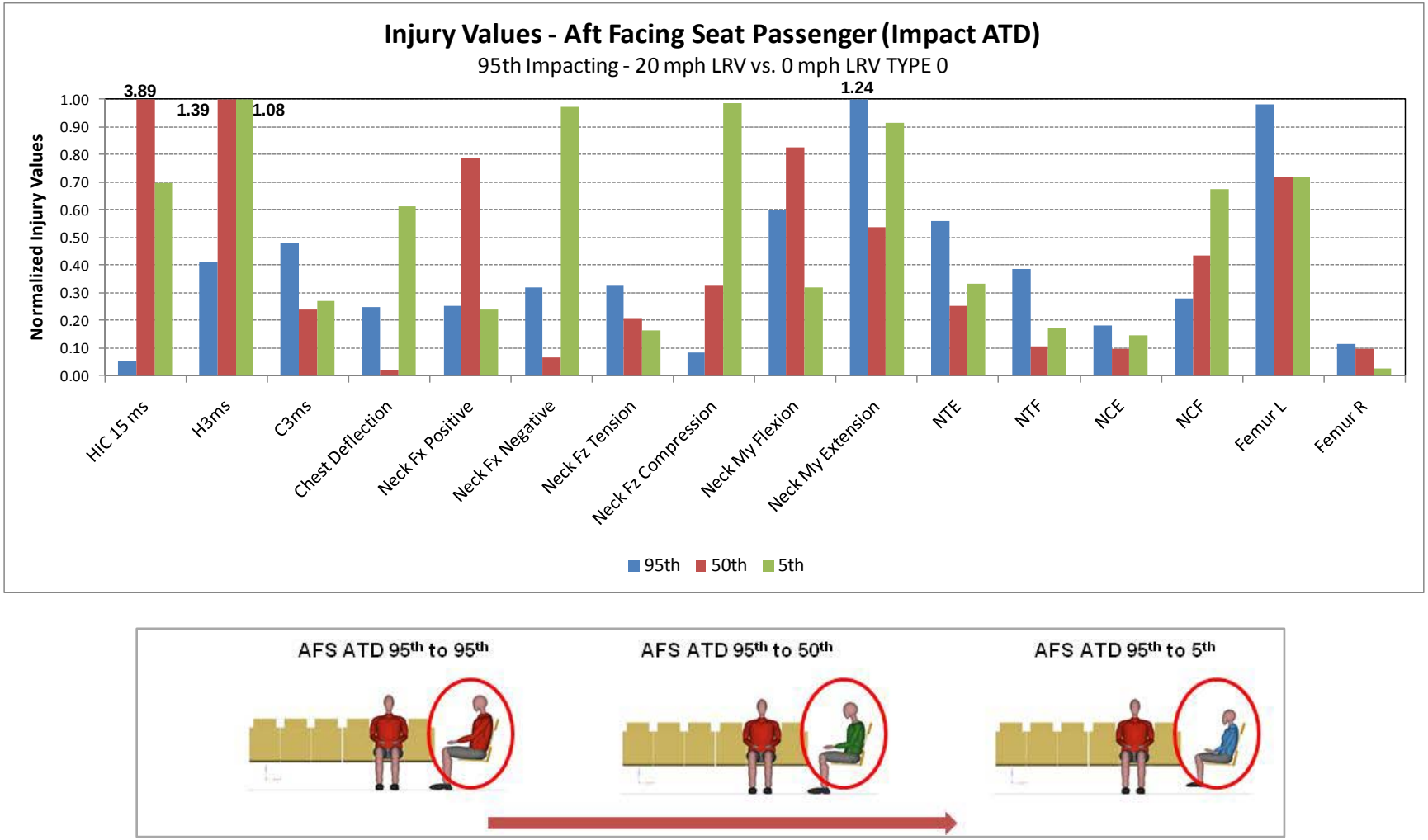
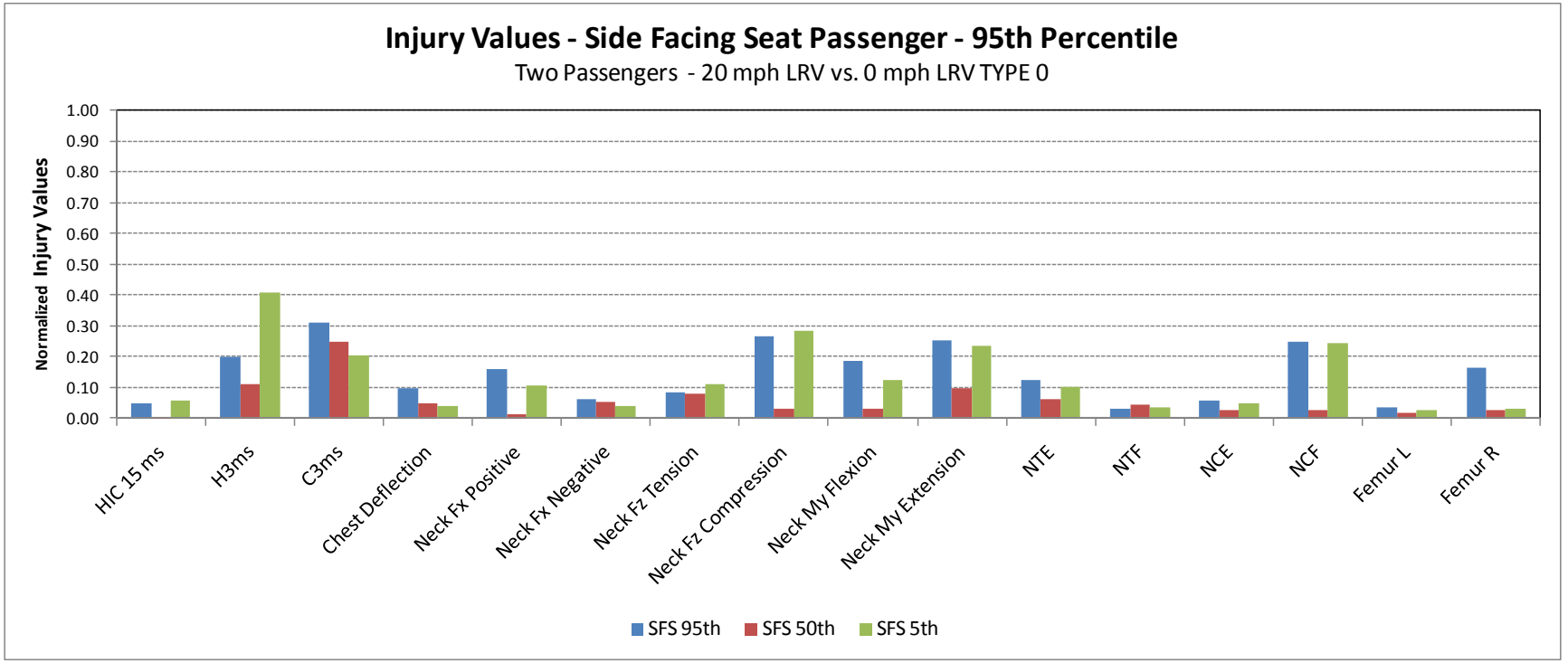


Figure 83. Normalized injury values – side-facing seats – impact ATD [1]



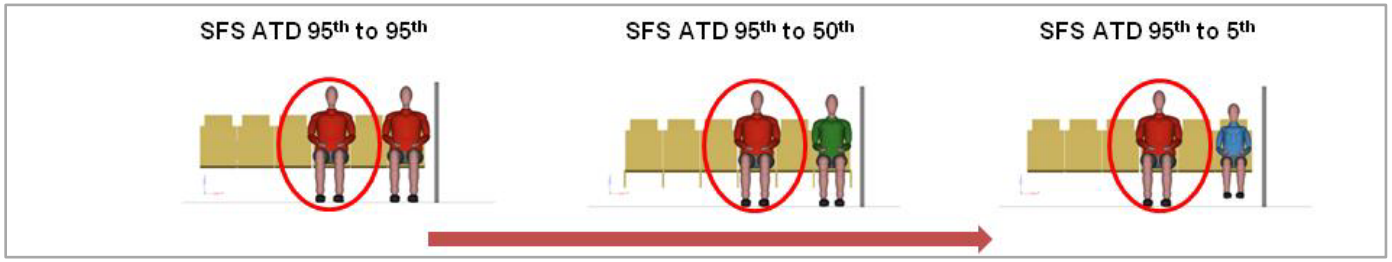
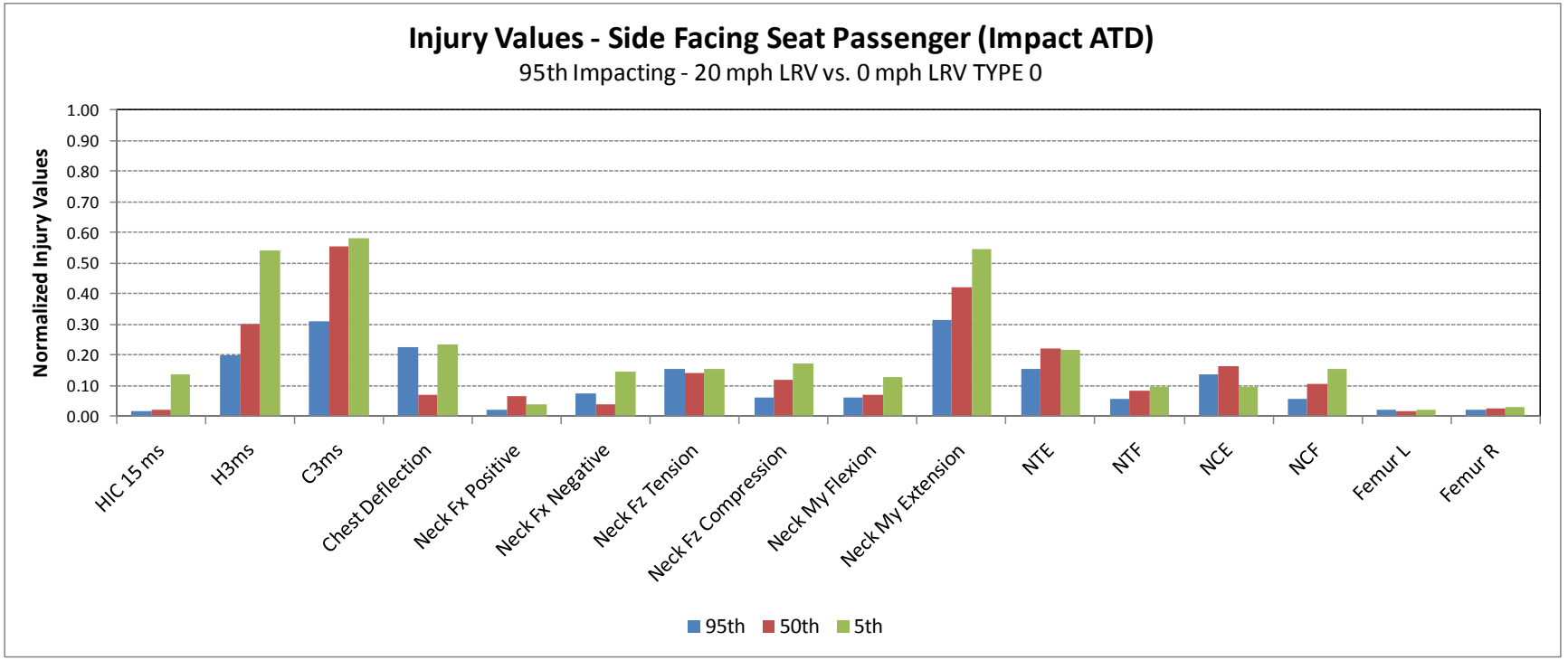


Figure 84. Normalized injury values – side-facing seats with barrier – 95th percentile ATD [1]



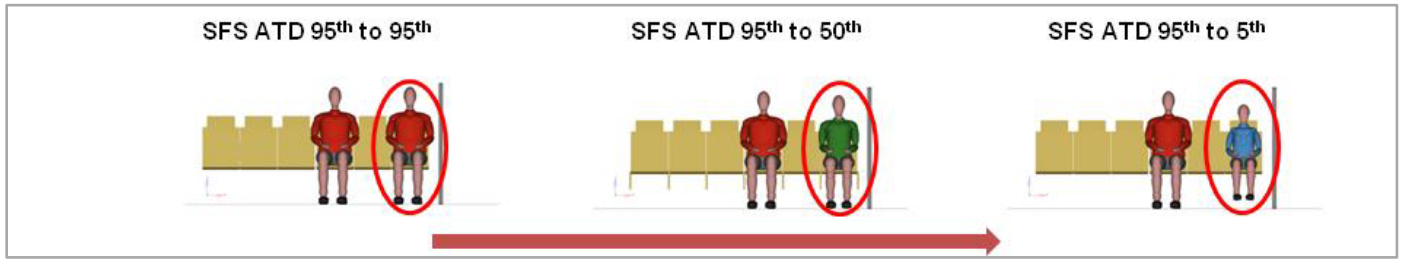


Figure 85. Normalized injury values – side-facing seat with barrier – impact ATD [1]

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

- The worst results are obtained when occupant-to-occupant contact occurs; in particular when the impact involves passengers of the same size (contact between heads is most probable).
- Although the injuries from this type of contact are generally on the neck and head regions, some injuries can occur to the lower extremities, in particular to the pelvis region, as well.
- Conditions where there is an empty aft-facing seat result in injuries that comply with current FMVSS limits. Nonetheless, the problem is that it is impossible to guarantee an empty aft-facing seat. Thus, if another passenger is seated in the aft-facing seat then the injury values are above tolerable limits.
- If only one passenger is seated on the side facing seat, the best configuration to minimize the injury values will be a row of side facing seats followed by a row of forward facing seats (See Figure 86).

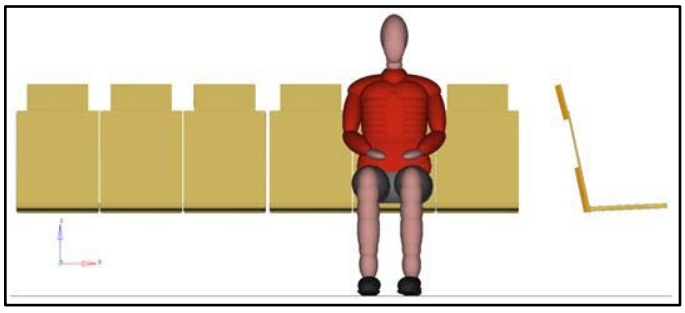


Figure 86. Safest side-facing seat configuration (only one seated passenger) [1]

- The barrier configuration gives also good results with all the injury values below the limits. Nevertheless, a separate study should be conducted in order to improve the injuries of the neck region for the 50^{th} and 95^{th} percentiles occupants.

5.1.4 Side-Facing Analysis – Screening Analysis for Dividers

This section presents the results obtained for a simple screening analysis where two simple models of dividers for the side-facing seats are used (See Figure 87).

The first configuration represents a common side-facing seat with a tall divider between each seat. The height of these dividers is 200 mm. This height is slightly larger than the height of the abdomen for an occupant that is seated.

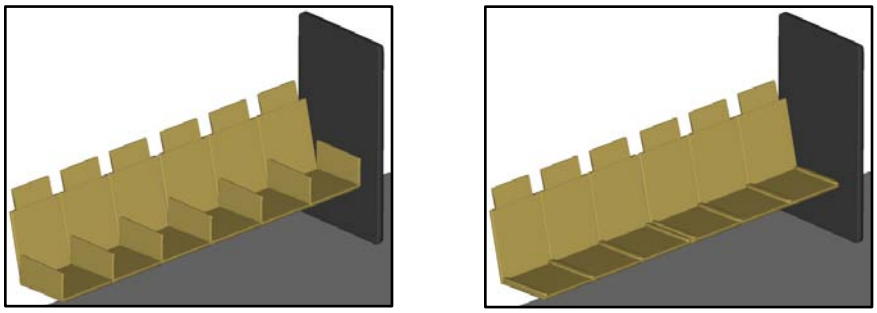


Figure 87. High and low dividers – side-facing analysis

The second configuration represents a side-facing seat with short dividers. Actually, these dividers can be analyzed as curvatures of the seat pan. The following picture (Figure 88) shows the seat pan of a side-facing seat with more detail. As is possible to observe, the seat pan has some curvature in order to prevent lateral movement of the occupant during accelerations and decelerations of the LRV. This curvature is simulated in the multi-body model by two small ellipsoids at either lateral edges of the seat pan.

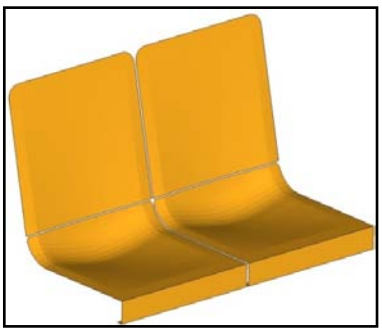


Figure 88. Side-facing seat pan curvature

The injury values observed for these models are shown in the following pages (Figure 91 and Figure 92). The results for the same configuration but without dividers are also shown for reference in Figure 93.

The kinematic for each model are shown in Figure 89 and Figure 90, respectively.

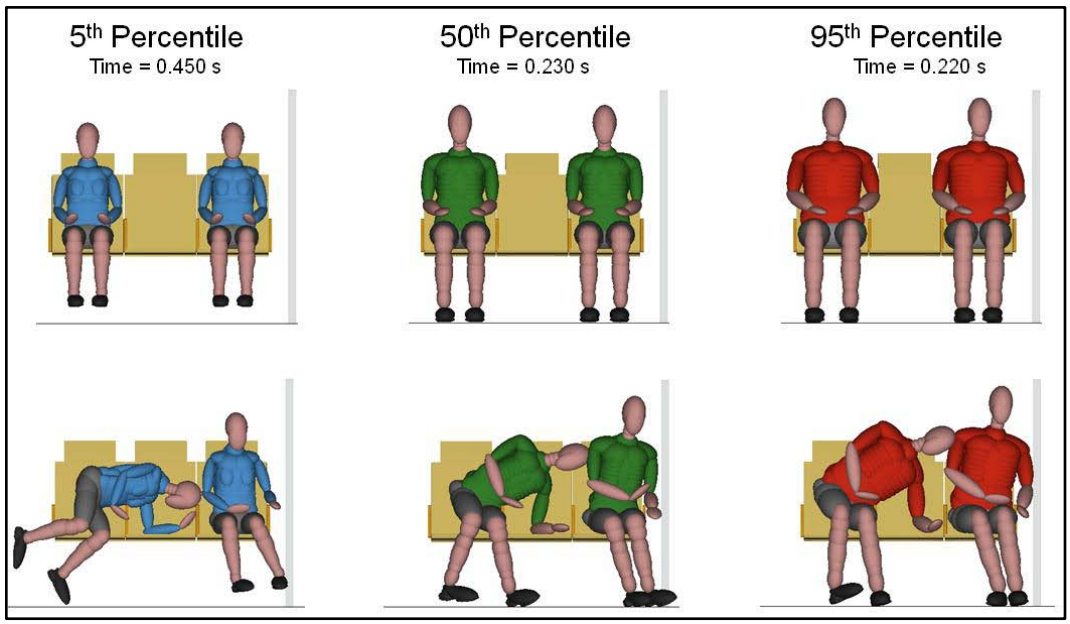


Figure 89. Side-facing seat analysis – kinematics for high dividers [1]

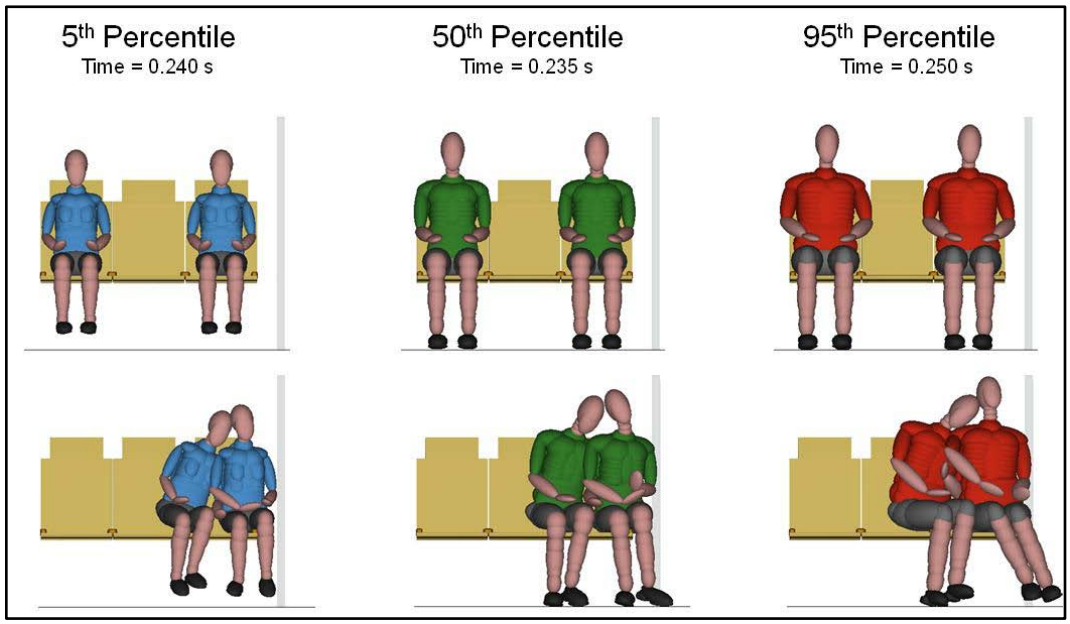


Figure 90. Side-facing seat analysis – kinematics for low dividers [1]

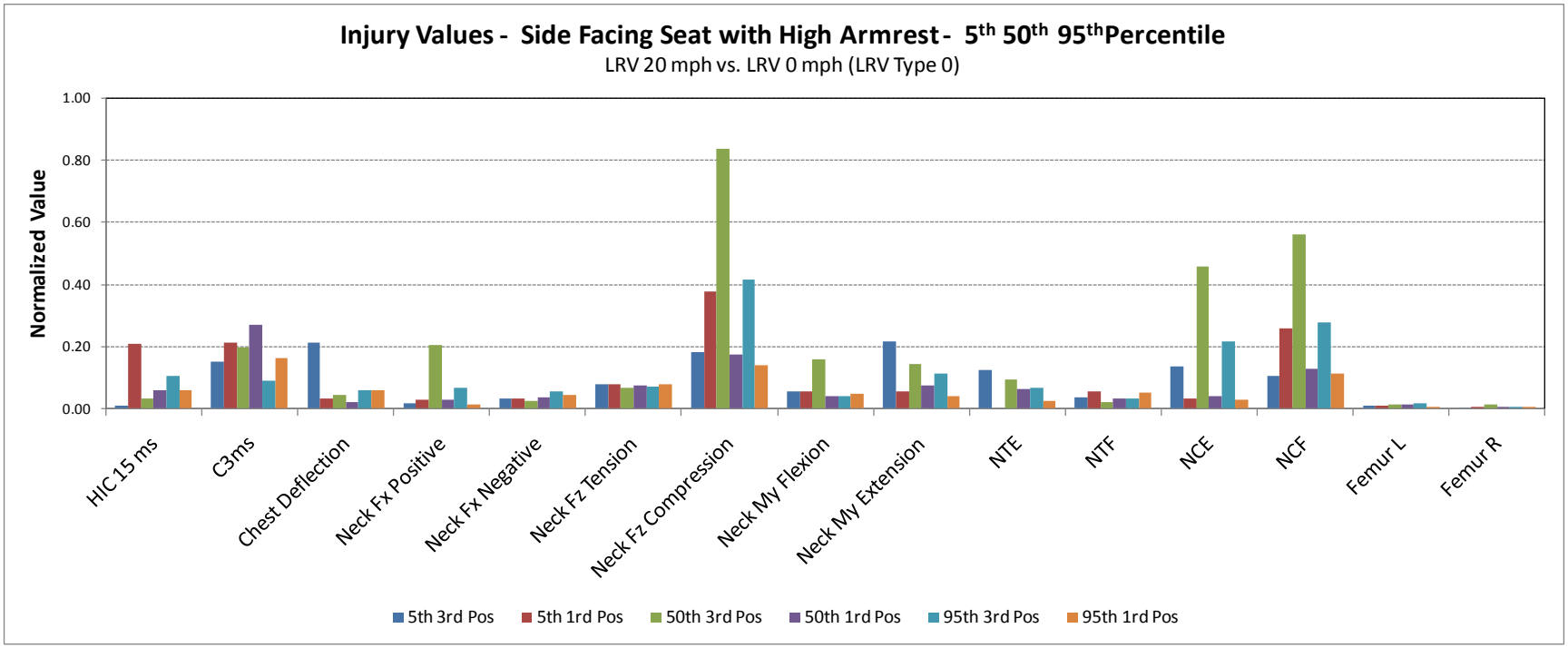


Figure 91. Side-facing seat analysis – high divider results [1]

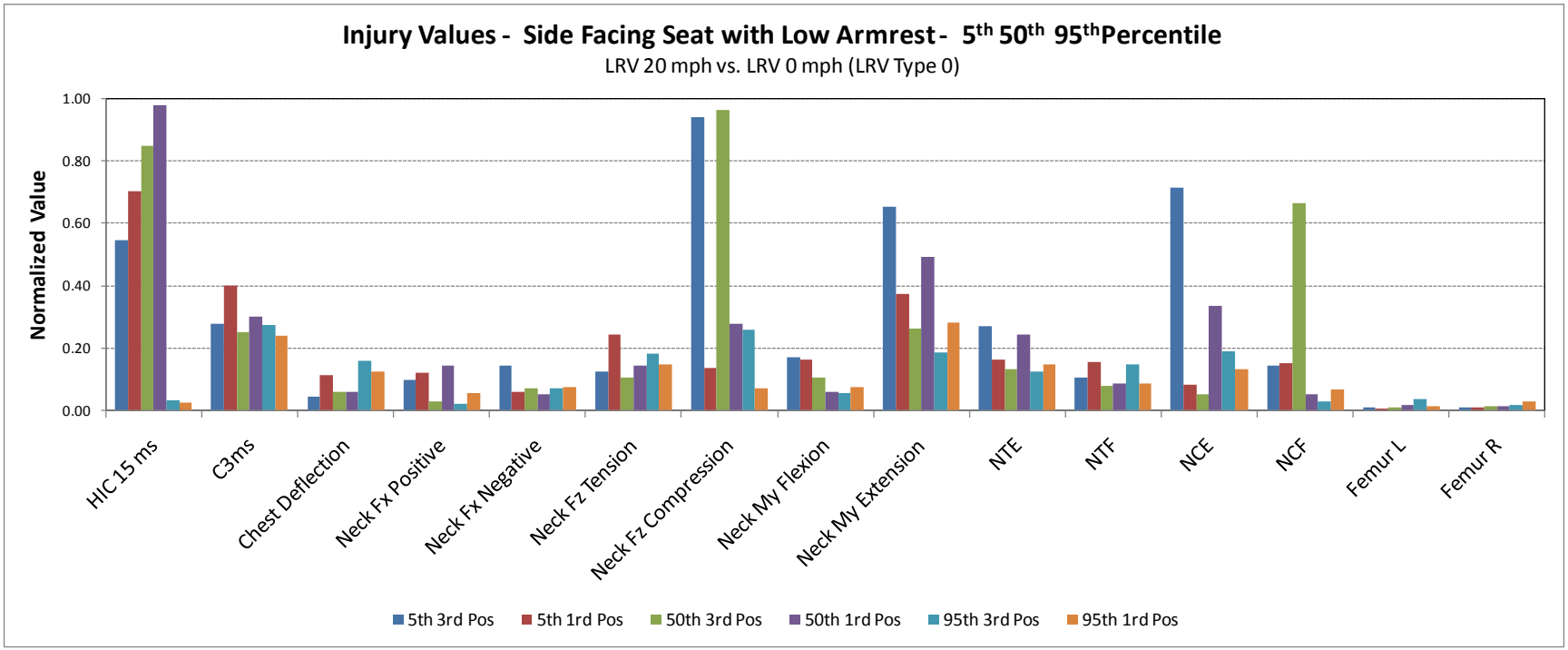


Figure 92. Side-facing seat analysis – low divider results (seat pan curvature) [1]

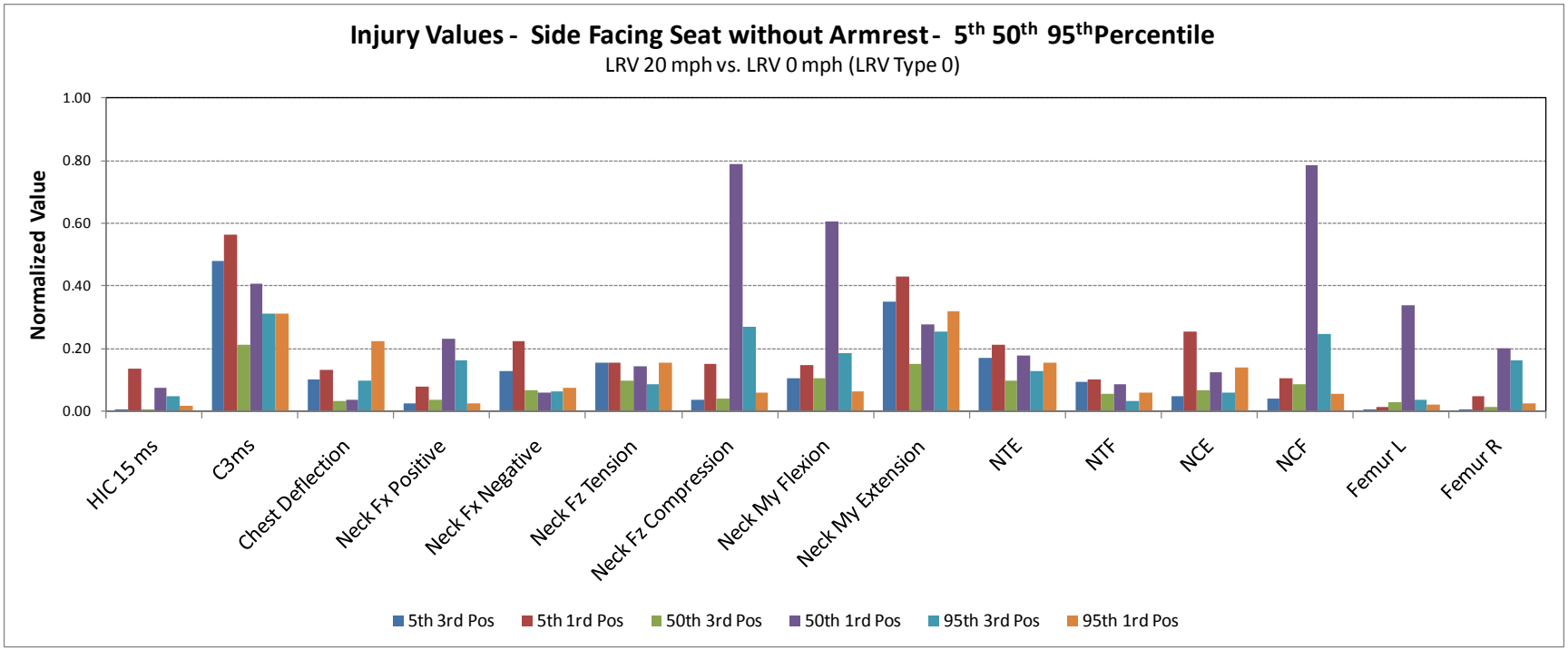


Figure 93. Side-facing seat analysis – no dividers (original results) [1]

Summarizing the results of this analysis it is possible to state:

- The use of high dividers does not seem to affect significantly the results. Thus, this type of divider could be used between seating. However, if this were desired, a more detailed analysis would be needed in order to optimize the level of safety.
- Smaller dividers, or curvatures, in the seat pans do not seem to improve the level of safety for the occupants. A change in occupant kinematics during the impact event can be observed. With these dividers a rotation is added to the occupant and the impact on the neck and head regions is more severe.
- Finally, comparing the results obtained in section 5.1.3 (side-facing seats without dividers) with the ones 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. This configuration will reduce the rotation of the body, and therefore the majority of the impact will occur between the barrier and the pelvis region. This region is not as important as the neck and head regions from an injury point of view.

CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

The LRV represents one of the safest modes of transportation [3]. In 2007, only 32 fatalities and around 800 injuries occurred in approximately 1,800,000 passenger miles traveled. It is unknown if the 32 fatalities were all passengers traveling in the LRV or if, on the contrary, some of them where pedestrians or other vehicles drivers, as those distinctions were not made in the literature reviewed. Nevertheless, in cases of high-energy impact some severe injuries could occur.

The results of this study show that because of the differences in weight between LRVs and the 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 crash scenario selected for this analysis represents the collision between two LRVs, one traveling at 20 mph and the other stationary.

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 injury mechanisms are to the neck (neck extension, flexion, shear, and compression) and femur (compression) regions, and for some special configuration chest.

After analyzing all the side-facing configurations, it is possible to conclude the following:

- The worst results are obtained when occupant-to-occupant contact occurs; in particular when the impact involves passengers of the same size (contact between heads is most probable).

- Although the injuries from this type of contact are generally on the neck and head regions, some injuries can occur to the lower extremities, in particular to the pelvis region, as well.
- Conditions where there is an empty aft-facing seat result in injuries that comply with current FMVSS limits. Nonetheless, the problem is that it is impossible to guarantee an empty aft-facing seat. Thus, if another passenger is seated in the aft-facing seat then the injury values are above tolerable limits.
- If only one passenger is seated on the side facing seat the best, configuration to minimize the injury values will be a row of side facing seats followed by a row of forward facing seats (See Figure 94).

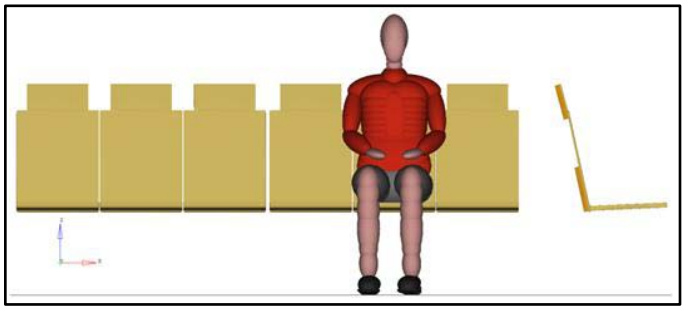


Figure 94. Safest side-facing seat configuration (only one seated passenger)

- The barrier configuration gives also good results with all the injury values below the limits. Nevertheless, a separate study should be conducted in order to improve the injuries of the neck region for the 50^{th} and 95^{th} percentiles occupants. New padding materials on the contact region could be used.
- Further studies should be conducted in order to minimize injuries due to contact between passengers.
    - For side-facing seats, an armrest could be designed. The results of an initial analysis can be found in section 5.1.4.

- If it is not possible to avoid side-facing seats with aft-facing seats, a divider between these seats should be designed.

- For configurations with side facing seats close to forward-facing seats, some studies can be done in order to minimize the injuries:
  - Addition of padding materials to the seat back of the forward-facing seats.
  - Redesign of the seat back geometry (height, seat-back angle, rotational stiffness, etc.).

- For passengers seated in side-facing seats the most common injury mechanisms are head, neck, and femur compression injuries due to passenger 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 side-facing seat, the best configuration to minimize injury values is a row of side-facing seats followed by a row of forward-facing seats. However, when more than one occupant is seated in the side-facing seat, the injury values increase. Further analysis should be done in order to improve the interaction between the occupant and seat back. In general, the seating arrangement that minimizes the risk of severe injuries for the 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.

According to the data shown in section 3.3 "*Light Rail Vehicle Fleet Characteristics 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. Current ATDs were developed for the automotive and aerospace industry. Usually, for these types of vehicles the majority of the impact condition occurs in less than 300ms.

Because of the high weight of the LRV, during normal impact conditions (see Chapter Four) the deceleration pulse has a duration of approximately 150ms and peak deceleration of only 5 g's. Thus, there are some scenarios where passengers will have enough time to tense their muscles or even change their position. For this reason, in order to be able to analyze the standing position passengers, it will be necessary to develop a new series of ATDs with an active response that is more like that of the humans they are to represent.

REFERENCES

REFERENCES

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APPENDIX

APPENDIX

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 conducted by NIAR were modeled. Plots comparing the simulation versus dynamic test are shown at the end.

Double Seat

This seat is defined as a typical semi-rigid seat. This type of seat 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: In order to simulate the dynamic behavior of the seat, this body will be able to rotate around the z-axis. A revolute joint is used to allow that movement (Red circle Figure A.1). This joint has a specific stiffness that simulates the behavior of the actual seat (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 Figure A.1). This joint has a specific stiffness that simulates the behavior of the actual seat (Figure A.2)

APPENDIX (continued)

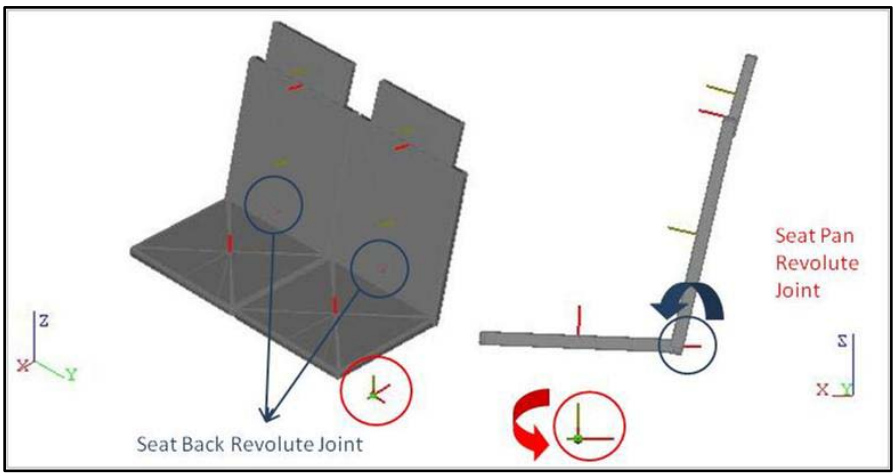

Figure A.1 Double seat – model [1]

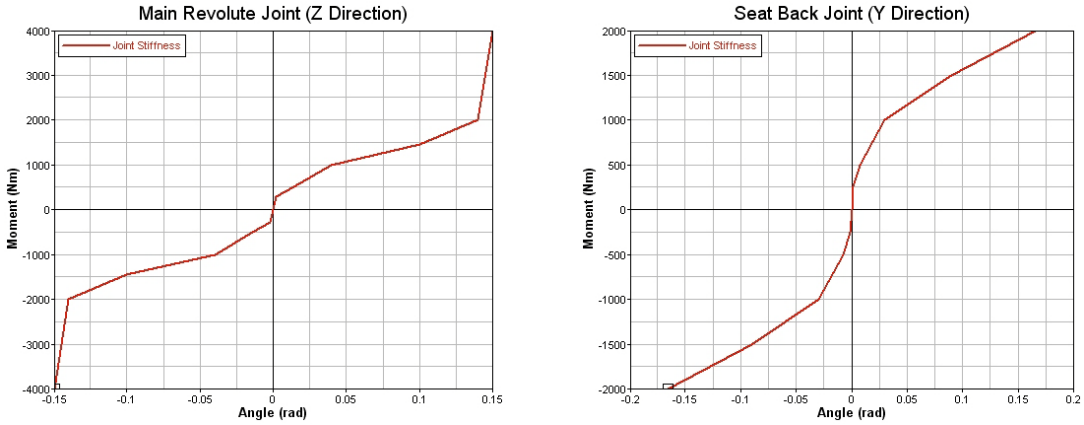

Figure A.2 Stiffness - seat pan revolute joint (z axis) and seat back revolute joint (y axis) [1]

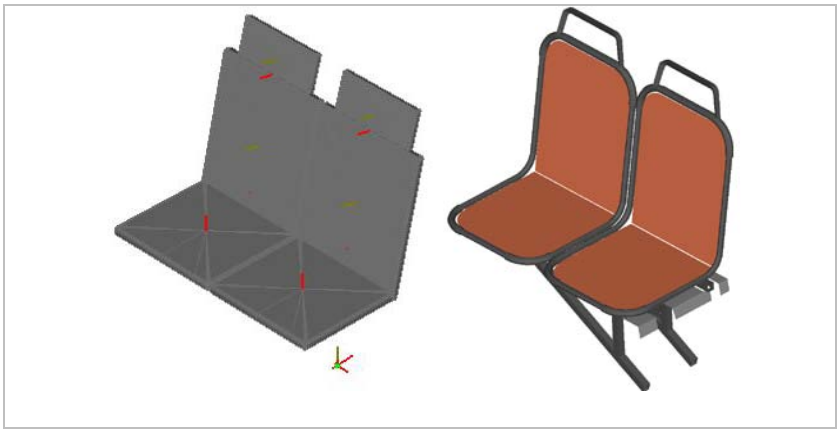

Figure A.3 Double seat – Multi-body vs. FE model [1]

The total weight of the double seat is 32 kg. This weight is distributed as follow:

- Each Seat Pan: 9 kg (Total 18 kg)
- Each Seat Backs: 6 kg (Total 12 kg)
- Each Headrests: 1 kg (Total 2 kg)

Furthermore, the main dimensions of the seat are:

- 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 the seat back are shown on the Figure A.4.

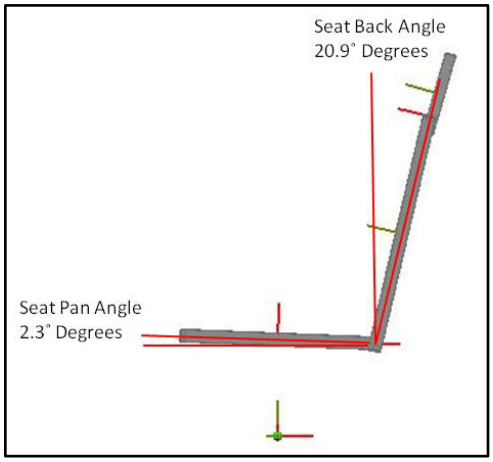

Figure A.4 Double seat – seat pan and seat back angles [1]

Finally, the contact properties between the ATD and the surfaces are defined by the following stiffness.

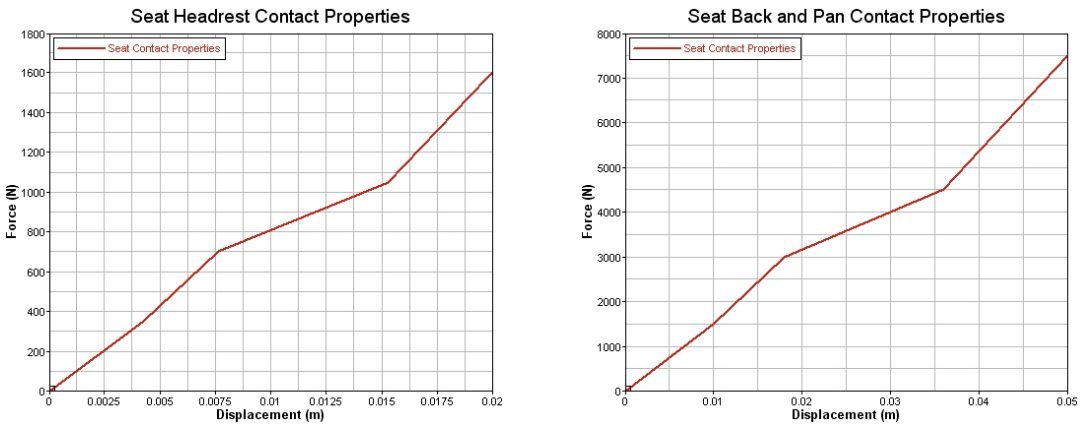

Figure A.5 Double seat – seat back and seat headrest contact stiffness [1]

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).

In order to connect these bodies the following joints are used:

- Legs – Floor Attachments: A revolute joint is used to represent this type of union. This joint allows the legs to rotate on y-axis (Red circle Figure A.6). The stiffness of this revolute joint is shown on Figure A.7.
- Main body to Legs: In order to attach the main body to the legs, a restrain Cardan is used (Blue circle Figure A.6). Although this type of restrain allows the upper body to rotate on every axis, a very high stiffness is used for x and z axis in order to avoid the rotation on these axis. The stiffness defined for the y-axis is shown on Figure A.7; this allows the main body to rotate when impacted.

APPENDIX (continued)

The total weight is 21 kg (18 kg main body and 3 kg each leg). The main dimensions are: 840 mm height, 794mm length, and 50mm width. Finally, the contact properties for the top part of the barrier and the main part are shown in Figure A.9.

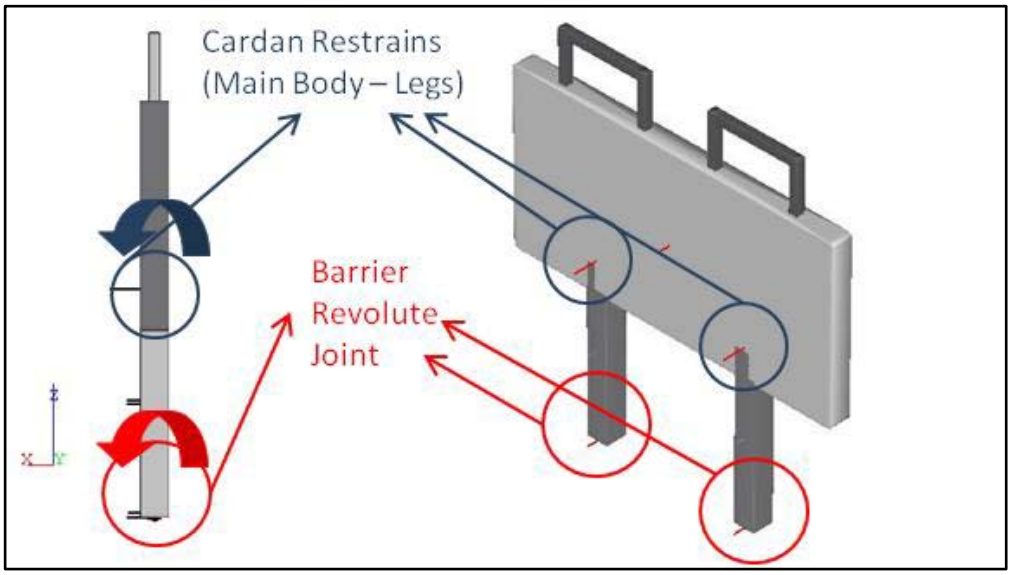

Figure A.6 Barrier – model [1]

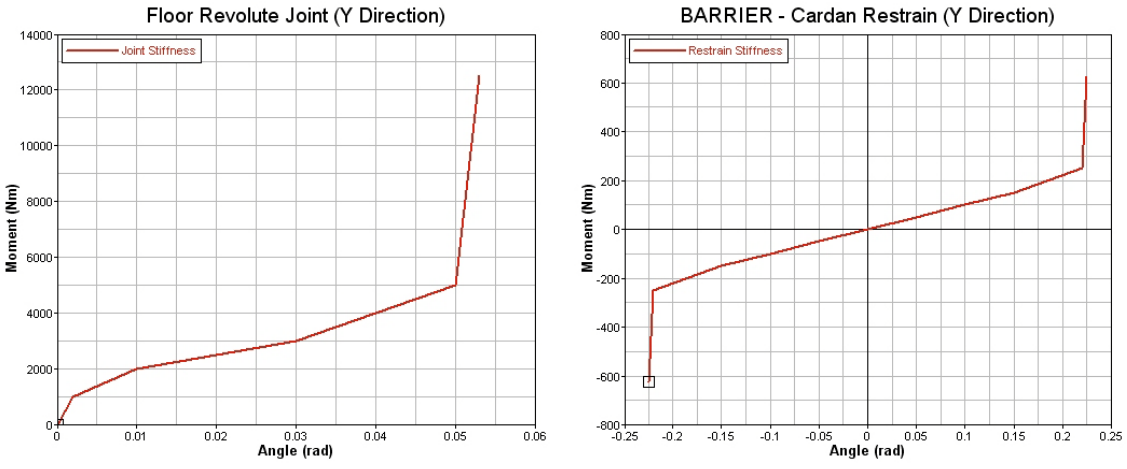

Figure A.7 Stiffness – floor-legs revolute joint and legs-body restrain cardan (y-axis) [1]

APPENDIX (continued)

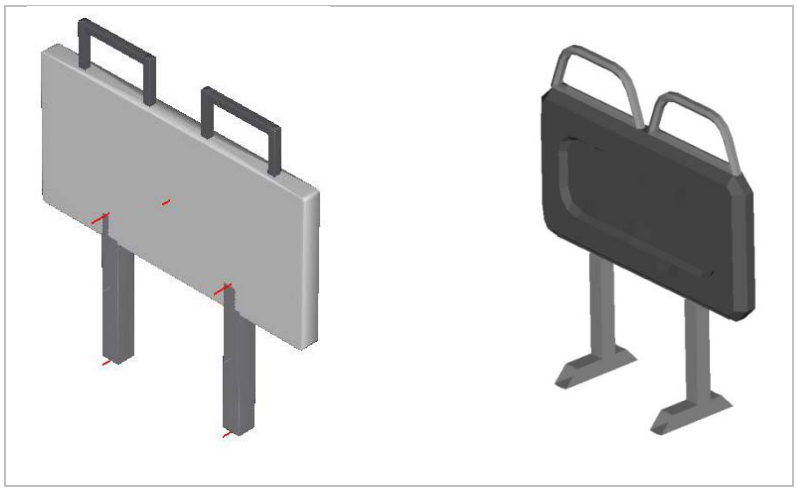

Figure A.8 Barrier – Multi-body vs. FE model [1]

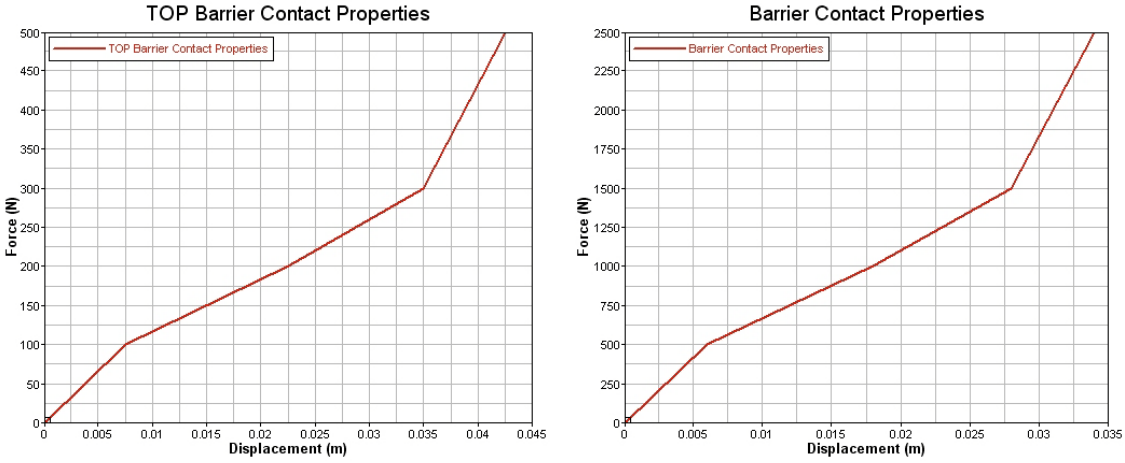

Figure A.9 Contact stiffness – barrier top and low parts [1]

APPENDIX (continued)

Validation Results – Dynamic Test 06221-8 vs. Multi-body Simulation

The dynamic test used to validate the multi-body models represents a frontal-rear impact between buses. For this test the bus is traveling at 20 mph, with the target stopped (0 mph). The validation is done using the results from this test. The pulse of the dynamic test is shown in Figure A.10.

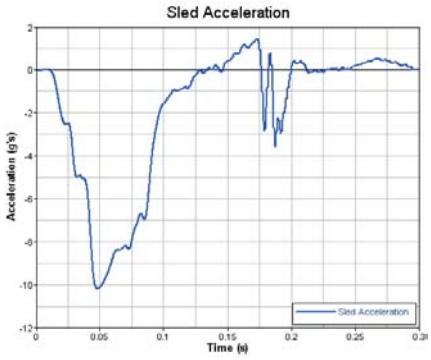

Figure A.10 Sled acceleration dynamic test 06221-8 – bus 20 mph vs. bus 0 mph [1]

The layout of this dynamic test is shown on the following page (Figure A.11). Four ATDs are used for the test:

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

Although a 50th percentile 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 seats, this ATD is not evaluated on the multi-body model. The actual distances between seats and monuments are slightly different between LRVs and buses (See red marks on Figure A.11). According to the data available, current LRVs have more space between seats.

APPENDIX (continued)

Finally, the comparison between the test and simulation results for positions one, three, and four are shown.

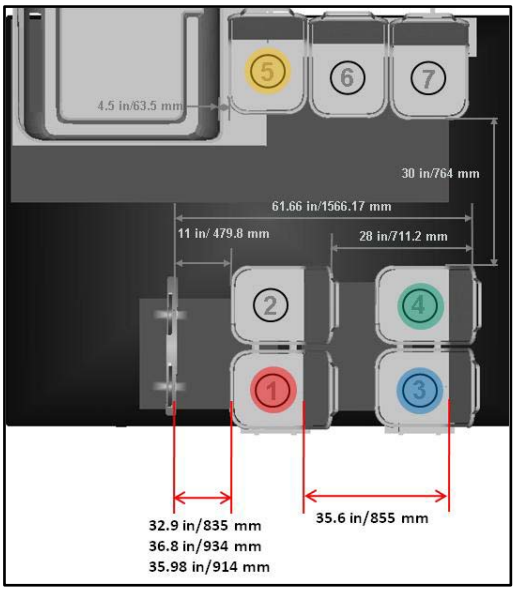

Figure A.11 Sled test 06221-8 – layout [1]

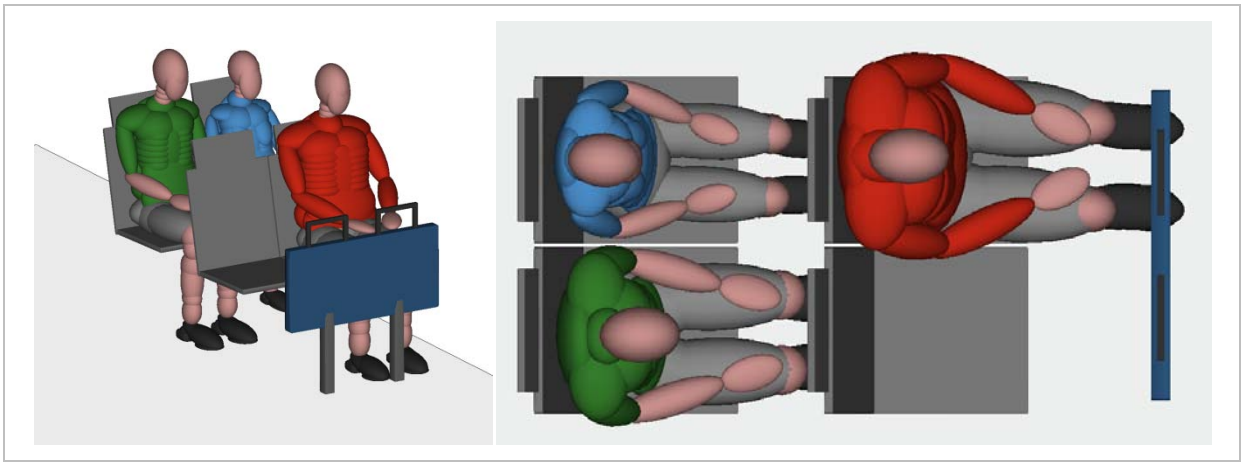

Figure A.12 Simulation – layout [1]

APPENDIX (continued)

Kinematics MB Model vs. Sled Test 06221-8

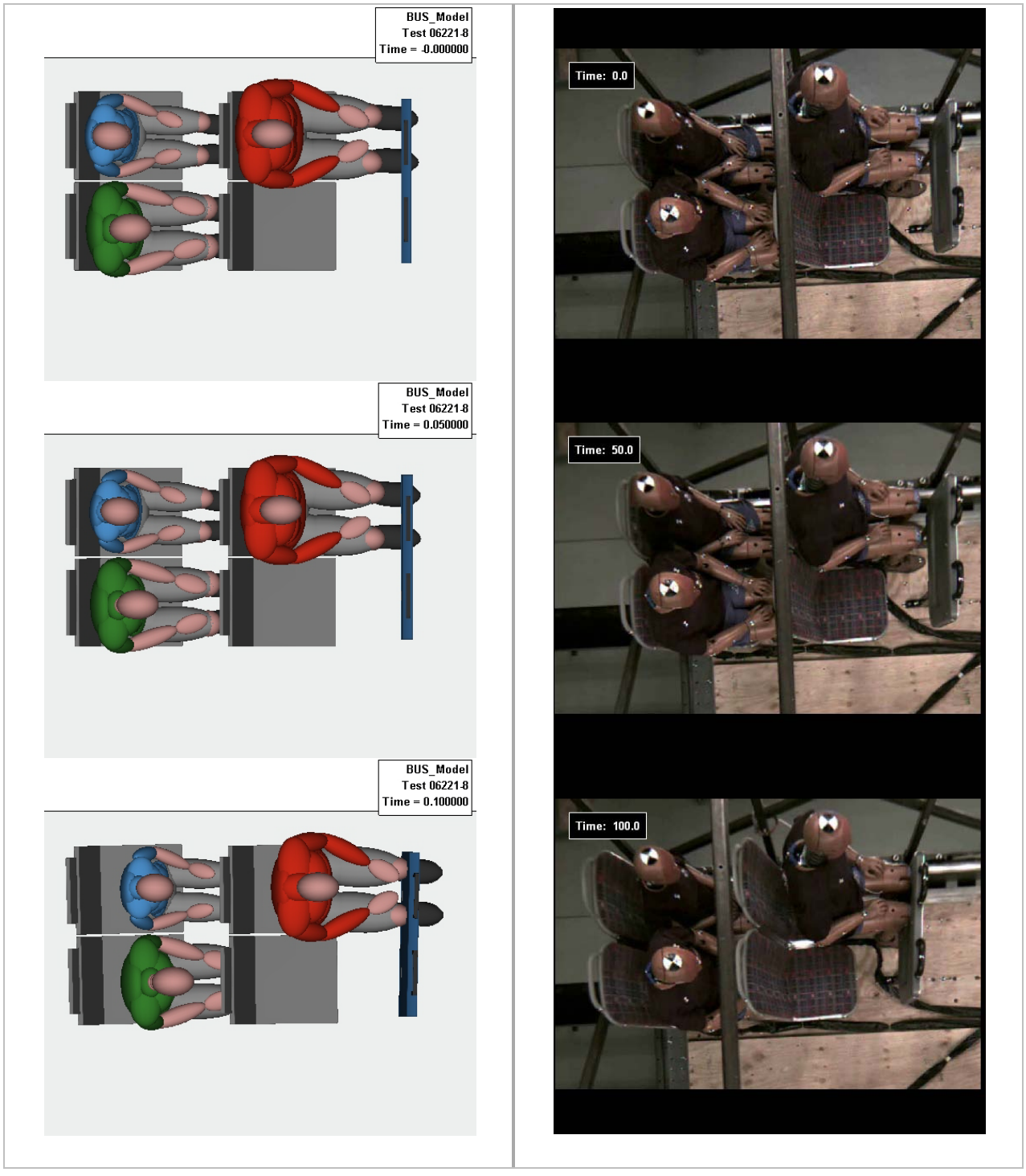

Figure A.13 Kinematics (0 to 100 ms) – simulation vs. sled test 06221-8 [1]

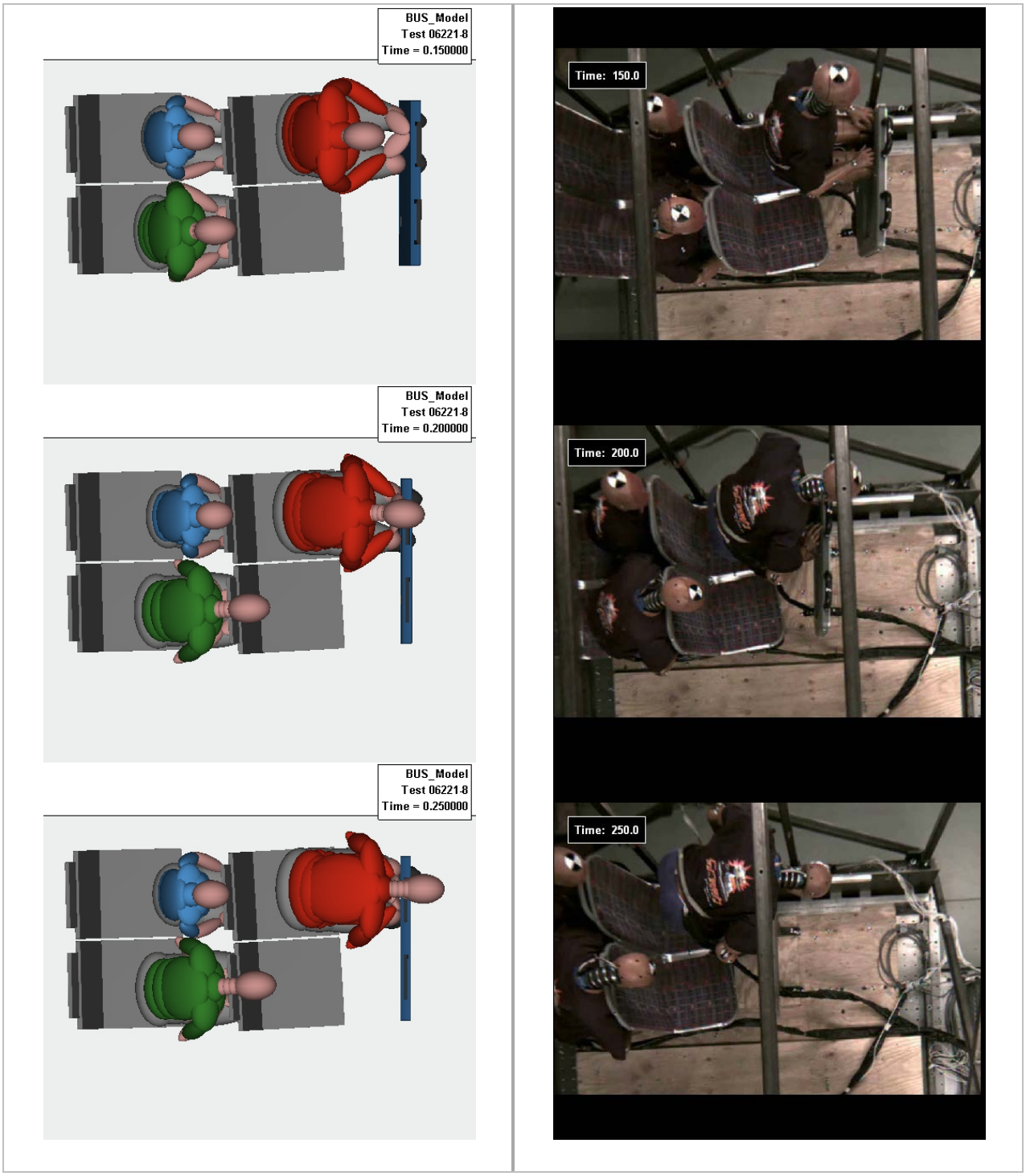

Figure A.14 Kinematics (150 to 250 ms) – simulation vs. sled test 06221-8 [1]

Position 1 – 95th percentile - Results

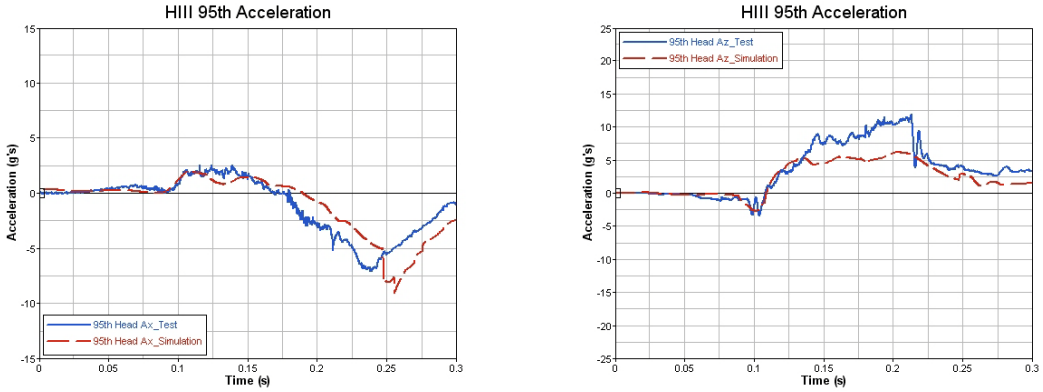

Figure A.15 Head acceleration – position 1 – 95th percentile [1]

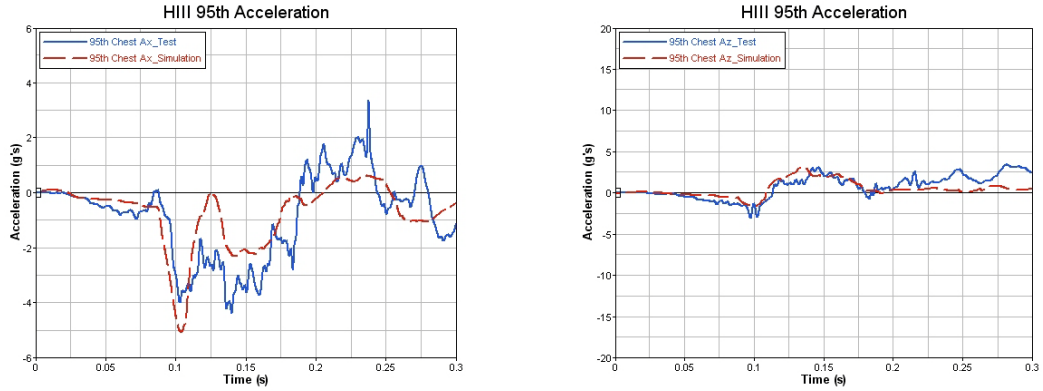

Figure A.16 Chest acceleration – position 1 – 95th percentile [1]

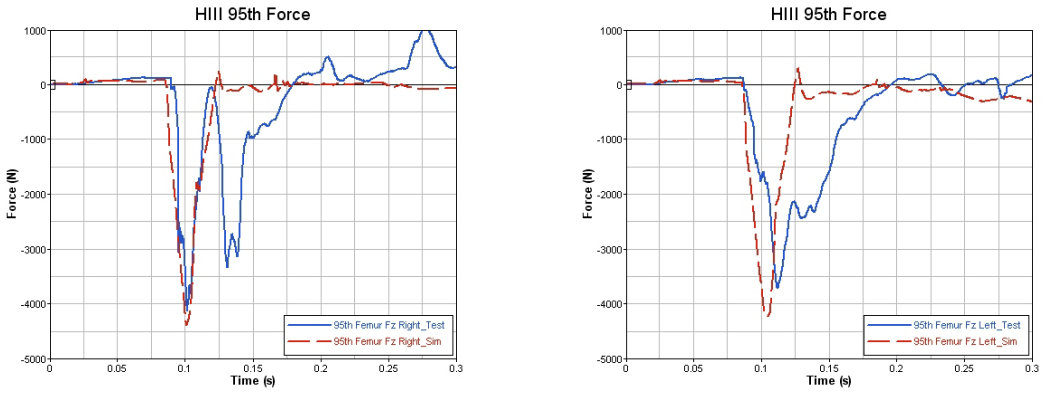

Figure A.17 Femur forces – position 1 – 95th percentile [1]

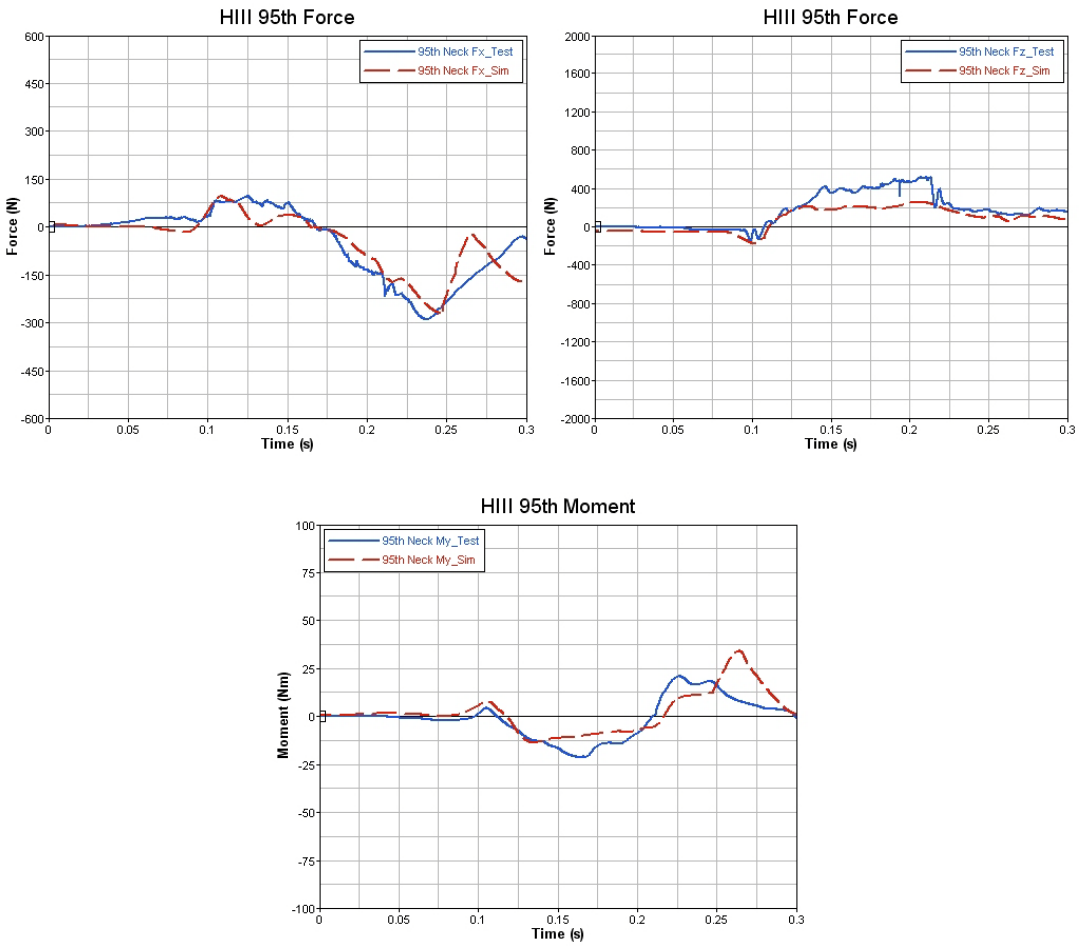

Figure A.18 Neck forces and moments – position 1 – 95th percentile [1]

Position 3 – 5th percentile - Results

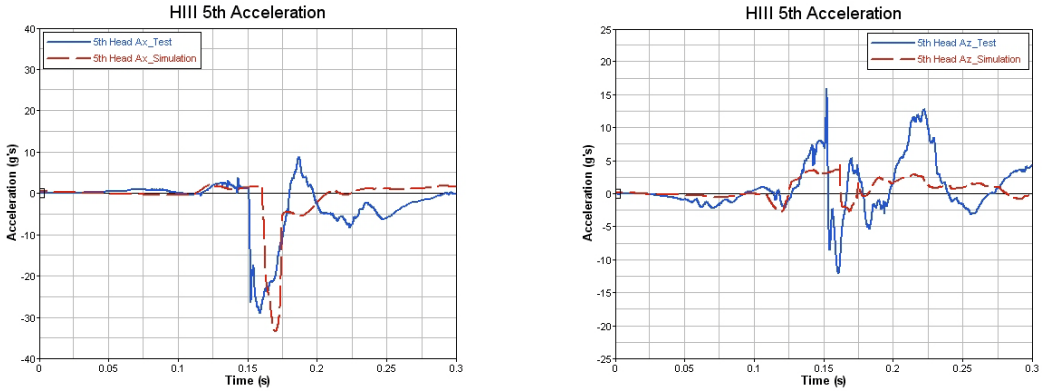

Figure A.19 Head acceleration – position 3 – 5th percentile [1]

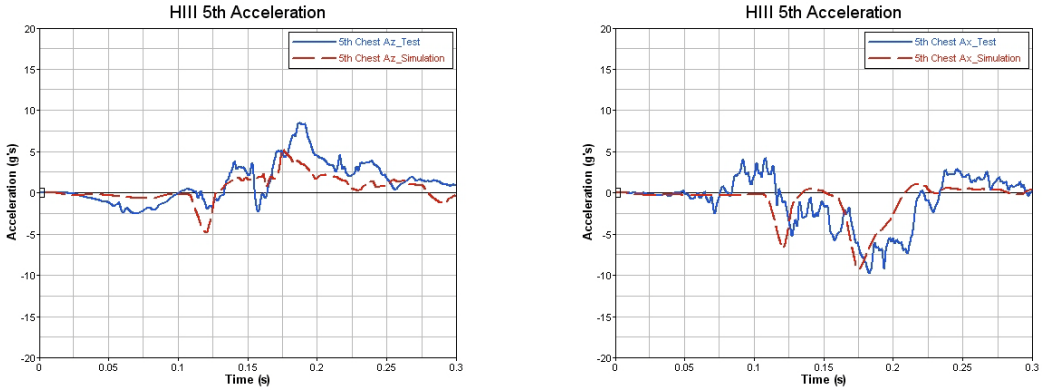

Figure A.20 Chest acceleration – position 3 – 5th percentile [1]

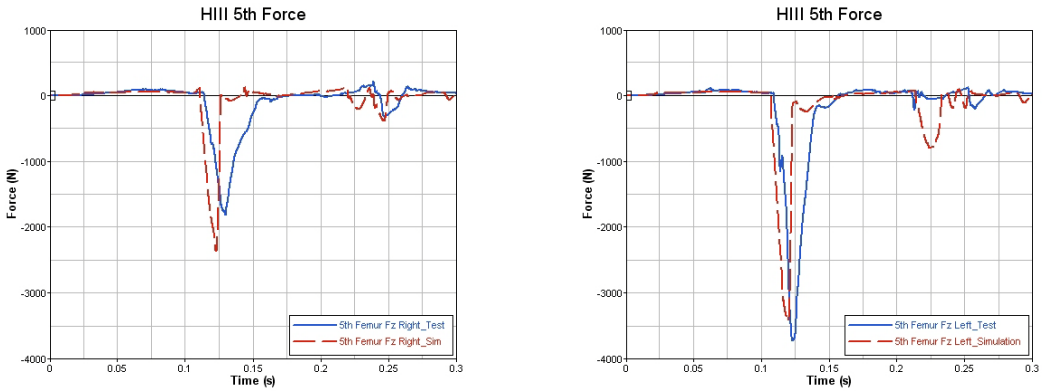

Figure A.21 Femur forces – position 3 – 5th percentile [1]

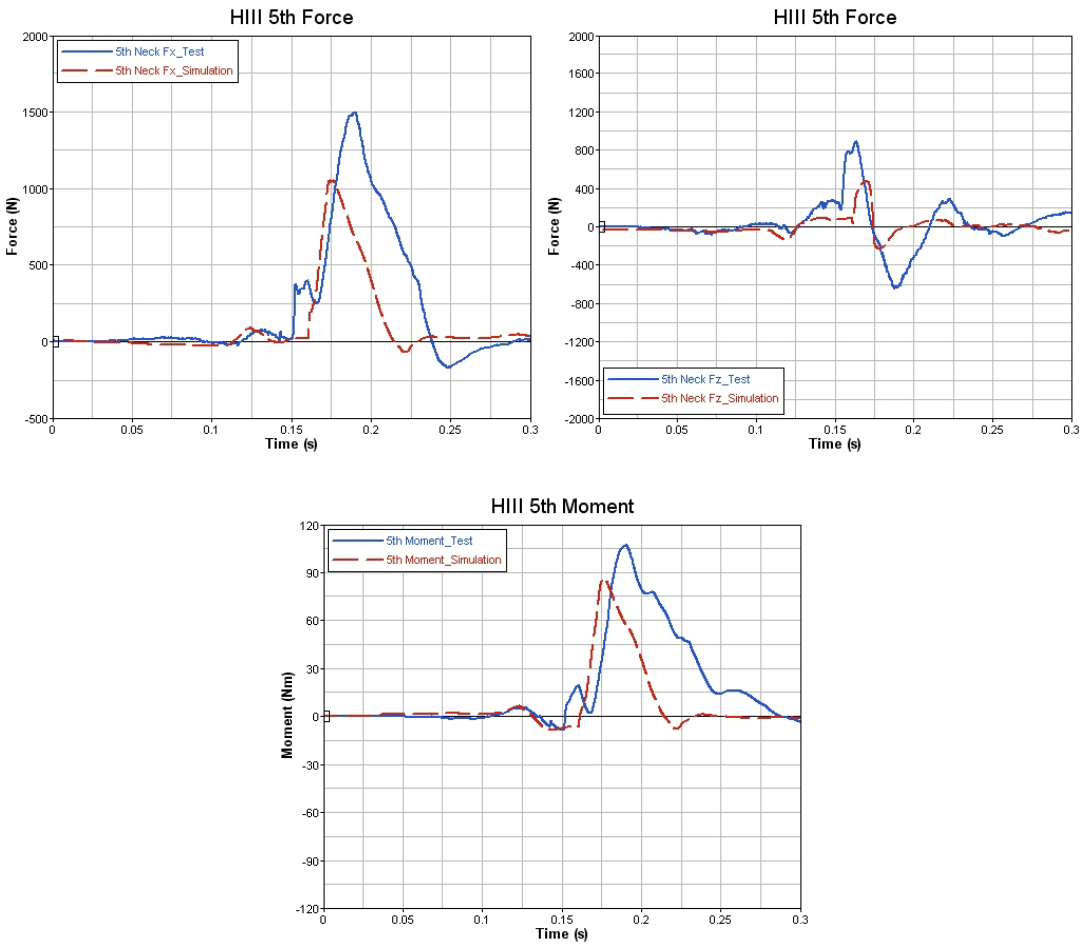

Figure A.22 Neck forces and moments – position 3 – 5th percentile [1]

Position 4 – 50th percentile - Results

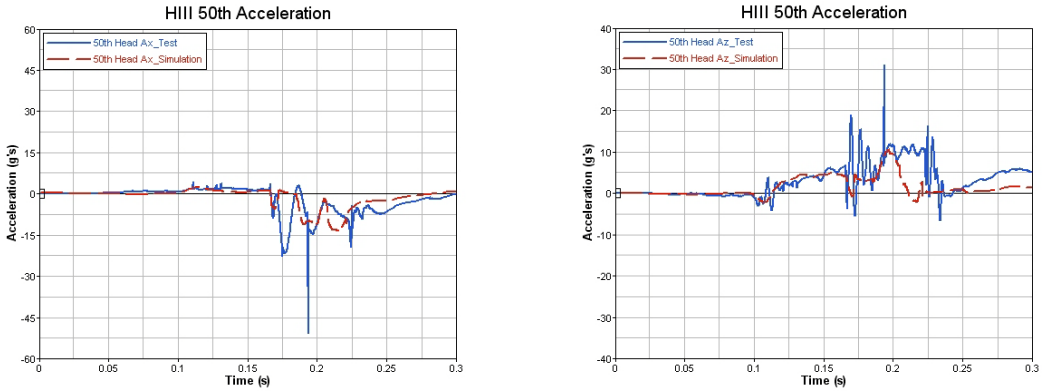

Figure A.23 Head acceleration – position 4 – 50th percentile [1]

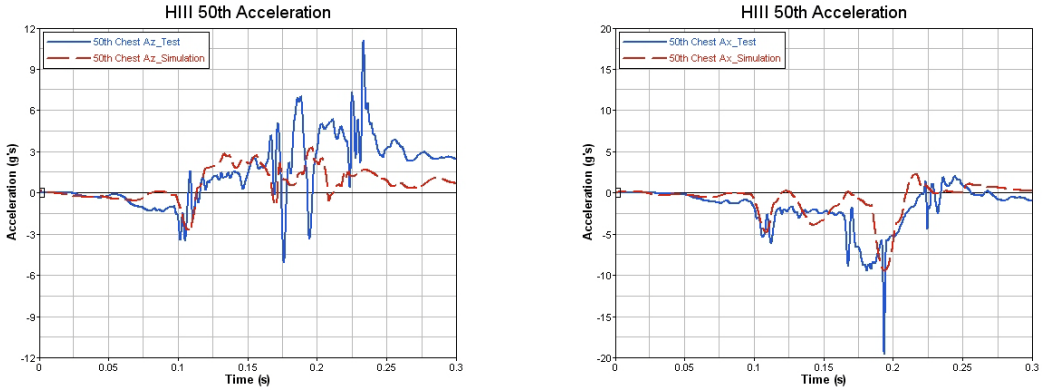

Figure A.24 Chest acceleration – position 4 – 50th percentile [1]

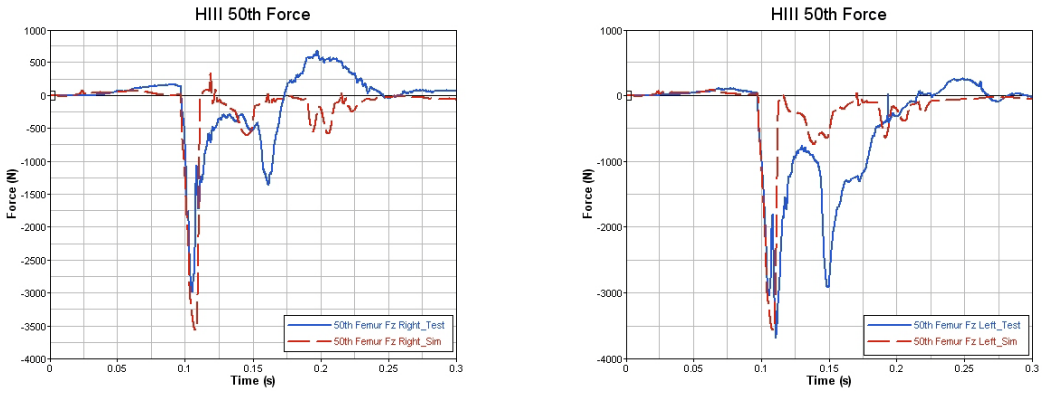

Figure A.25 Femur forces – position 4 – 50th percentile [1]

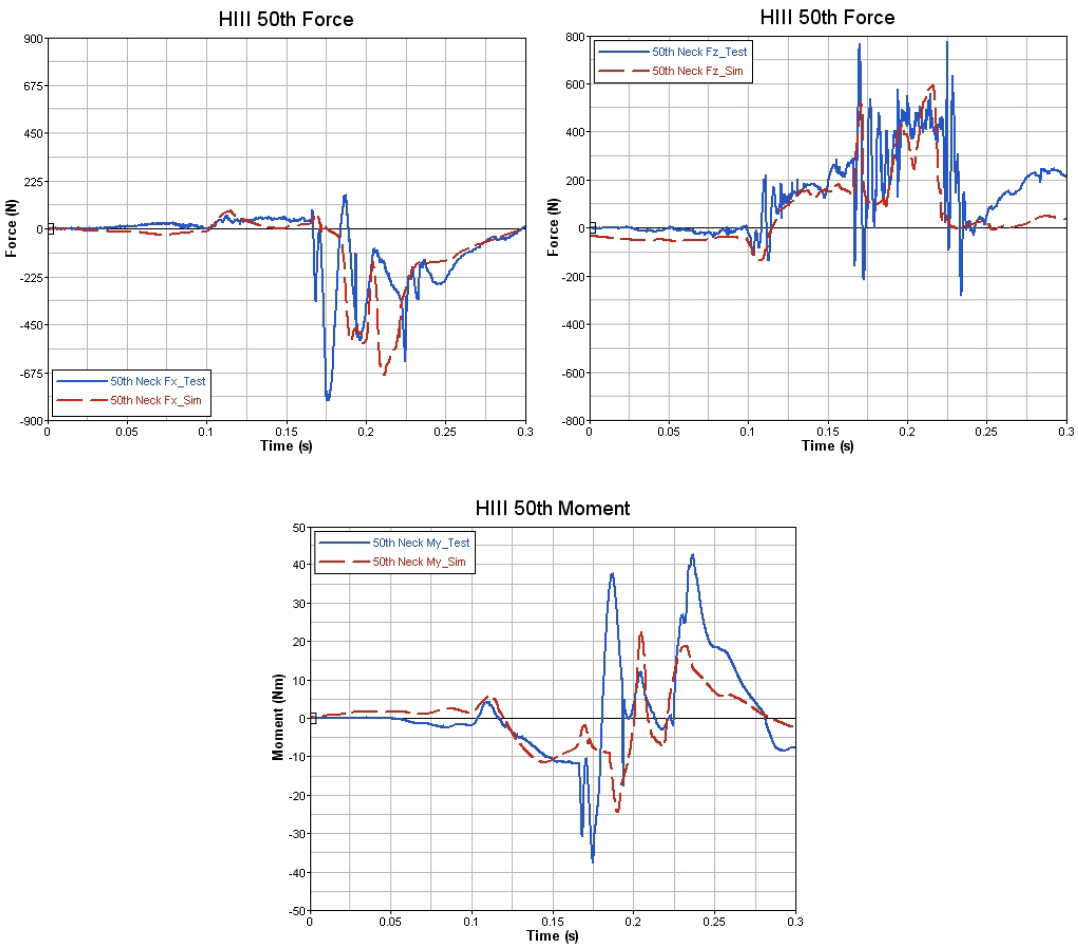

Figure A.26 Neck forces and moments – position 4 – 50th percentile [1]