EVALUATION OF STRUCTURAL DAMAGE OF A SMALL CAR COLLISION UNDER FMVSS SIDE IMPACT REGULATIONS AND COMPARISON OF INJURY RESPONSE WHEN THE DRIVER'S SEAT IS DISPLACED LATERALLY INWARD

A Thesis by

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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 dear parents, my sisters and my brother, who have always supported me in all ways and encouraged me in every aspect

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ABSTRACT

Safety of the car occupant is given foremost importance by the consumers, federal regulatory agencies, and automobile manufacturers. Many techniques and new technologies are proposed every year and implemented for the enhancements of the safety and crashworthiness of the vehicles. More efforts are still needed to make the cars safer, which in turn reduces the risk of fatal injuries to the occupants. In this study, a typical compact-sized sedan model is analyzed for the Federal Motor Vehicle Safety Standards (FMVSS) 214 Moving Deformable Barrier (MDB) and, Side Pole impact collisions, via numerical simulations. In particular, the effect of placement of the driver's seat laterally inward is investigated.

A methodology is presented in this thesis to examine the structural damage experienced by the car when it is engaged in side collision with a rigid pole and the MDB barrier, and also to assess the injuries sustained by the driver in both scenarios. In order to delay the contact, a seat position is modified to provide during a side impact with an additional 18mm clearance between the seat and struck door. The National Crash Analysis Center (NCAC)'s Toyota Yaris finite element (FE) model have been utilized in this thesis to analyze the structural side impact responses of this compact sedan. The EuroSID-2re 50th percentile adult male side impact crash test dummy has been as the car occupant. The critical injury parameters of the dummy and the vehicle deformation are evaluated and compared.

This study indicates that a small inward lateral displacement of the driver's seat towards the interior of the car can significantly reduce the potential injuries to the occupant. This is due to the fact that most of the energy of impact is absorbed by the vehicle side structure instead of the seat structure and the occupant.

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LIST OF ABBREVIATIONS

ANSA	Automatic Net Generation for Structural Analysis
CAD	Computer Aided Design
CAE	Computer Aided Engineering
DFR	Driver Fatality Ratio
FMVSS	Federal Motor Vehicle Safety Standards
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
GSI	Gadd Severity Index
HIC	Head Injury Criteria
IIHS	Insurance Institute for Highway Safety
MDB	Moving Deformable Barrier
MADYMO	Mathematical Dynamic Model
NCAC	National Crash Analysis Center
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
SID	Side Impact Dummy
TTI	Thoracic Trauma Index
WSTC	Wayne State Tolerance Curve

CHAPTER 1

INTRODUCTION

1.1 Background

Crashworthiness is the ability of the vehicle structure to reduce the injuries caused to the occupant during an impact. Different criteria are used to assess crashworthiness, which includes deformation patterns of the vehicle structure, acceleration experienced by the vehicle and probability of injury for dummies in the event of the crash [1].

Generally on roads, occupants travelling in various types of vehicles are injured or killed in different types of crashes such as frontal, side, rear, rollovers and many others. Each type of crashes has different distributions of crash severities, causes and risk of injuries to the occupant for a given type of vehicle. The second most severe type of automobile impacts in the United States are the side impacts that result in serious head and pelvic injuries and fatalities to the occupant. Side impact crashes are quite dangerous, since there is not enough room between the occupant of the vehicle and the impact surface to dissipate the impact energy, leading occupants to injuries and for fatalities. The side impact crashes mainly involve impacts between passenger cars and light trucks and also the vehicle striking fixed tree or a rigid pole. The two main categories of side impact test regulatory configurations are the moving deformable barrier (MDB) test and side pole test. The MDB test simulates the 'car-to-car' side collision and the side pole simulates the 'car-to-narrow object' collision [2].

Passenger vehicle occupant deaths represented 64 percent of the 35,092 motor vehicle crash deaths in 2015 [3]. As shown in Figure 1.1, a total of 22,543 passenger vehicle occupants died in 2015, 26 percent fewer than in 1975. As pickups and SUVs have become more popular, the distribution of vehicle types in fatal crashes has changed. Car occupant deaths have declined

49 percent since 1975, while pickup occupant deaths have risen 22 percent and SUV occupant deaths are 10 times as high [3].

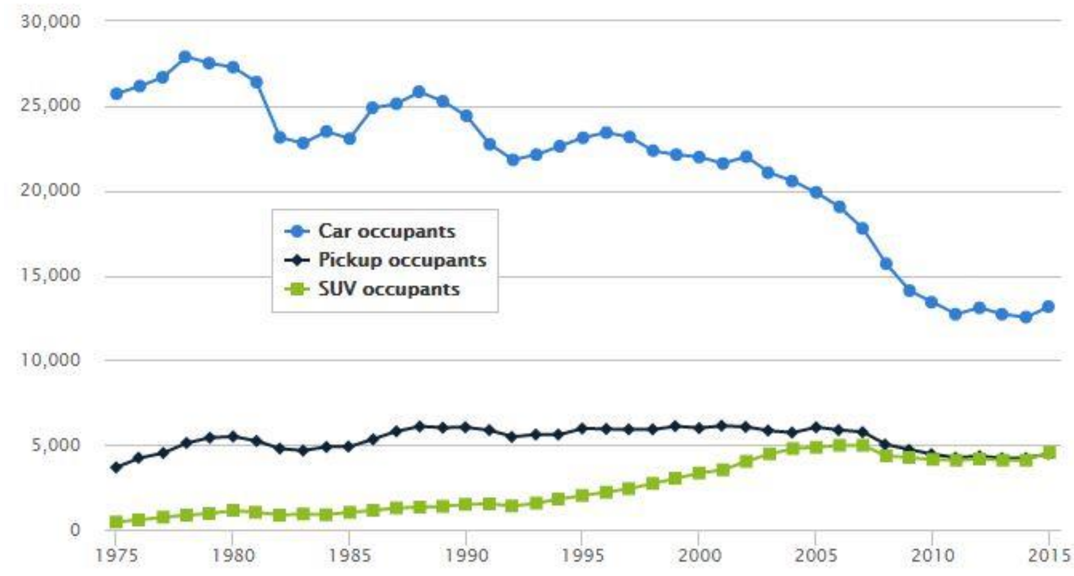

Figure 1.1 Passenger Vehicle Occupant Deaths by Vehicle Type, 1975-2015
IIHS Fatality Facts 2015 [3]

A total of 16,484 passenger vehicle drivers died in 2015, 6 percent more than in 2014 and 15 percent fewer than in 1975 as shown in Figure 1.1. Fifty-eight percent of passenger vehicle driver deaths in 2015 were car drivers, 21 percent were pickup drivers, and 19 percent were SUV drivers. Considering total passenger vehicle occupant deaths in 2015 frontal impacts accounted for 54 percent and side impact accounted for as much as 25 percent of passenger vehicle occupant deaths.

The passenger vehicle occupant deaths in single-vehicle crashes by impact point and vehicle type, multiple-vehicle crashes by impact point and vehicle type and passenger vehicle occupant deaths in all crashes by impact point and vehicle type is distributed according to the survey by International Institute for highway safety (IIHS) as shown in Tables 1.1, through 1.3. Forty-two percent of car occupant deaths has occurred in single-vehicle crashes in the year 2015 and fifty-eight percent occurred in multiple-vehicle crashes in 2015 [3].

Table 1.1 Passenger Vehicle Occupant Deaths in Single-Vehicle Crashes, 2015 [3]

Passenger vehicle occupant deaths in single-vehicle crashes by impact point and vehicle type, 2015

Point of initial impact	Car occupants		Pickup occupants		SUV occupants		All occupants	
	Number	%	Number	%	Number	%	Number	%
Frontal	2,956	54	1,278	49	1,131	44	5,470	50
Side	1,070	19	380	14	323	13	1,793	17
Rear	106	2	30	1	35	1	171	2
Other (mostly rollover)	1,364	25	943	36	1,060	42	3,424	32
All*	5,496	100	2,631	100	2,549	100	10,858	100

Total includes other and/or unknowns

Table 1.2 Passenger Vehicle Occupant Deaths in Multiple-Vehicle Crashes, 2015 [3]

Passenger vehicle occupant deaths in multiple-vehicle crashes by impact point and vehicle type, 2015

Point of initial impact	Car occupants		Pickup occupants		SUV occupants		All occupants	
	Number	%	Number	%	Number	%	Number	%
Frontal	4,112	54	1,179	64	1,184	59	6,598	56
Side	2,713	35	486	26	564	28	3,800	33
Rear	708	9	131	7	180	9	1,044	9
Other (mostly rollover)	128	2	40	2	68	3	243	2
All*	7,661	100	1,836	100	1,996	100	11,685	100

Total includes other and/or unknowns

Table 1.3 Passenger Vehicle Occupant Deaths in All Crashes,
2015 [3]

Passenger vehicle occupant deaths in all crashes by impact point and vehicle type, 2015

Point of initial impact	Car occupants		Pickup occupants		SUV occupants		All occupants	
	Number	%	Number	%	Number	%	Number	%
Frontal	7,068	54	2,457	55	2,315	51	12,068	54
Side	3,783	29	866	19	887	20	5,593	25
Rear	814	6	161	4	215	5	1,215	5
Other (mostly rollover)	1,492	11	983	22	1,128	25	3,667	16
All*	13,157	100	4,467	100	4,545	100	22,543	100

Total includes other and/or unknowns

Side impact collisions with roadside objects are responsible for many injuries and deaths on highways in the United States. Thirty-eight percent of single-vehicle side impact crash deaths occur when the vehicle strikes fixed narrow objects like trees or pole on the dead occupant's side of vehicle [3]. Nearly half of all fixed-object impacts are into roadside objects like trees and pole. In Sweden, around 25% of car occupant killed on Swedish roads collide with a fixed object [3]. When compared with other crashes, side impact crash is a much difficult problem for protection of occupants because of close proximity between the occupant and the intruding surface. Many safety standards and tests have been amended by various agencies such as the National Highway Traffic Safety Administration (NHTSA) and the Insurance Institute for Highway Safety (IIHS) to assure automotive crashworthiness and occupant safety. Full compliance with the regulations is mandatory for all automobile manufacturers [2].

1.2 NHTSA/Crashworthiness

The U.S. Department of Transportation initiated National Highway Traffic Safety Administration (NHTSA) under Highway Safety Act of 1970 [19]. The NHTSA is a successor to the National Highway Safety Bureau, to conduct safety programs under the National Traffic and Motor Vehicle Safety Act of 1966 and the Highway Safety Act of 1966. The United States Code under Title 49 outlines in Chapter 301, Motor Vehicle Safety the requirements for manufacturers and items of motor vehicles. The NHTSA also conducts various consumer programs, which are outlined in various Chapters under Title 49 established by the Motor Vehicle Information and Cost Savings Act of 1972 [19].

The major goal of NHTSA is to save lives, prevent injuries and reduce economic costs resulting from vehicle crashes. This goal is achieved by establishing and enforcing safety standards for motor vehicles manufacturers and through government awareness programs which help conduct effective local highway safety programs. NHTSA is also constantly monitors and investigates of new safety standards which help to minimize the casualties caused by the motor crashes and implements these new safety standards [19].

The NHTSA is in constant investigation of safety defects in motor vehicles, formulates and enforces fuel economy standards, helps of government and local organization to minimize the risk of drunk drivers. Sets the standard and promote the use of child safety seats and seat belts, establish vehicle anti-theft regulations. In order to bring effective safety improvements NHTSA conducts research on driver behavior and traffic safety.

1.3 Motivation

The increase in population or usage of automobile vehicles has caused significant traffic related issues. Mechanical failures in automobiles, careless driving by drivers, heavy traffic, etc. have been the main causes of increase in car accidents. Accidents are unpredictable which invokes car occupant safety, and this remained most important issue in modern society. Hence, the NHTSA commenced research on crashworthiness and occupant safety to improve the occupant factor of safety. Much research has been conducted to make occupant safer in automobile accidents. Safety measures such as energy absorbing steering column, airbags, sensors, side door beams, bumpers, etc. has been the outcomes of such research. The improvements in safety research has led to the control in death rate and occupant injuries, although occupant fatalities are still occurring.

In traffic accidents, two leading causes of death and injuries are frontal and side impact collisions in which side on crashes took second place in the world. Especially, side impact crashes are the more dangerous due to the short distance between occupant and car structure [4].

Numerical modeling and simulations, such as finite element (FE) analysis, has shown that the potential for injury in a side impact is principally related to the interaction between the struck door and the occupant. In side impact collisions, the major objective is the crash energy management and the reduction of the velocity with which the occupant is impacted. In order to delay the contact, a seat position is modified in this study with an additional 18mm clearance between the seat and the struck door. Utilizing the computational FE modeling and analysis can help in the development of the preventive measures for occupant safety which motivated to do the current research.

1.4 Literature Review

A survey of literature shows a number of sources devoted to the computational modeling and analysis of side impact accidents. A sample of these related to this thesis has been reviewed here.

Sheshadri [5] developed a composite polymer tube and a side impact beam to replace the present beam in the side door of the vehicle and recorded the injuries sustained by the occupant and concluded that the new side beam with the use of carbon\epoxy with a significant orientation and thickness may present more energy absorption in side impact collisions when compared with the present steel beam which leads to decrease in displacement and acceleration of the car [5]. Also, the occupant injuries such as chest and head injuries reduced drastically with the proposed side beam.

In another study conducted by Papa [6], the estimation of aggressivity and driver fatality ratio for side impact crashes were made using computational modeling and analysis. The main objective was to study the fatality ratios in target car and also to observe intrusions in bullet car. There were 6 different cases in which bullet cars kept varying while the target car was dodge neon. From the analysis the author concluded that with an increase in weight and size of car the impact effect on passengers decreases.

Figure 1.2 Side Impact car-to-car collision [6]

It would be of interest to learn how the different target cars at different intrusion locations of bullet and target cars and different ways of combining accelerations and intrusions can effect the results on the prediction of Driver Fatality Ratio (DFR) in side impact accidents [6]. In the design stage of a car, the DFR estimate from computational FE models can be used to make changes on the structures for improvements in DFR. By reconstructing side impact crash using computational nonlinear finite element models of bullet and target cars, estimates of DFR for a fleet of car accident can be made.

Siruvole [2] evaluated the occupant response of US DOT-SID and structural damage on mid-size car model and he simulated the newly proposed pole test under FMVSS 214 and observed that vehicle intrusion in pole test is larger than the actual side impact test [2].

Coxon, et al. [7] reviewed a range of crash tests which are under development to assess side impact protection [7]. From the pole test program results on SUV's they made it clear that side airbags with supporting structures provided good protection against collisions with narrow objects like trees and poles etc.

Olivares [8] designed a sliding seat mechanism to delay the contact and to provide during a side impact with an additional 15 to 30 cm clearance between the seat and the struck door [8].

From this study it was found that delaying the occupant's contact with the encroaching door can decrease the energy transferred from the door to the occupant. To avoid any contact between the occupant and the door a linear actuator was placed under the seat which will move the driver or passenger front seat towards the interior of the car. The sliding seat system designed in this thesis provides occupant enough distance from the door to avoid any serious upper torso or head injuries during a side impact.

Reka [9] developed a sliding seat component to translate the vehicle seat backwards, allowing an increase in deceleration distance of the torso in order to prevent whiplash injuries in rear-end collision. The sliding motion of the seat is triggered by a sensor which is activated by a sudden change in vehicle acceleration, followed by the impact force exerted by the occupant on the seat back which was needed to activate the system. From this study it was found that with the new seat slide, there is a beneficial influence on the occupant kinematics for the impact speeds of 15 mph and 25 mph. By implementing the new seat slide it was observed that the relative acceleration between the head and torso is reduced in each case which is considered to be the main reason for whiplash injury [9].

Niederer, et al. [10] developed a new seat slide to prevent whiplash injury in the case of a rear-end impact, the device allows the vehicle seat to slide backwards while damping this motion. To activate the device a trigger system was used which detects an acceleration threshold. The tests were conducted to mimic the rear-end collisions with a delta-V of 16 km/h and the results indicated beneficial influence on occupant kinematics. When comparing the standard seat with the new damping seat slide it was shown that Neck Injury Criterion (NIC) was reduced. From this study, it was inferred that besides the head restraint and the recliner that are used in other whiplash protection systems, the seat slide has the potential to prevent whiplash injury.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

2.1 Objectives

The aim of this study is to investigate whether moving a seat inward by a small distance can improve the occupant survivability in side impact crashes. To achieve this goal, following objectives are identified:

- To evaluate the dynamic performance of a typical newer model sedan compact car, as per FMVSS 214 MDB and Side Pole test standards using finite element (FE) modeling and analysis.
- To compare and evaluate the intrusion of B-pillar by utilizing IIHS side impact rating system for potential injuries to the occupants.
- To examine the resulting injury parameters of Euro SID-IIre on a representative newer sedan model, and comparing injury values when the driver's seat is displaced laterally inward towards console.
- To compare and review the critical occupant injury parameters and kinematics, in order to assess the effect of moving the driver's seat laterally inward.

2.2 General Methodology

In this research, the Toyota Yaris 2010 finite element (FE) model has been utilized to analyze the structural side impact responses of this compact car. The Euro SID-IIre 50^{th} percentile adult male side impact crash test dummy is used as an occupant which is placed inside the car using ANSA and it is positioned at driver's seat. This study evaluates the structural damage which happens to the car when it collides with a rigid pole and impacted by a barrier and also the injuries caused to the occupant on driver's seat and then in order to reduce the injury caused to the occupant because of the intrusion of the pole into the vehicle side structure and when the vehicle is impacted by barrier, the position of the seat is changed by displacing the seat 18 mm in towards the passenger side and then injuries caused to the occupant in both the scenarios are evaluated. According to the pole test under FMVSS 214 side impact regulation, the virtual simulations have been evaluated. The critical injury parameters of the dummy and the vehicle deformation are reported and evaluated defending the requirement for the pole test. The LS-Dyna is the non-linear FE software used for analysis. Rigid pole is modeled in CATIA and preprocessing is done using Hypermesh and ANSA. The car's intrusion due to pole and barrier is calculated between the doors and accelerations are analyzed at different locations.

Figure 2.1 depicts the general methodology carried out in this research in the form of a diagram.

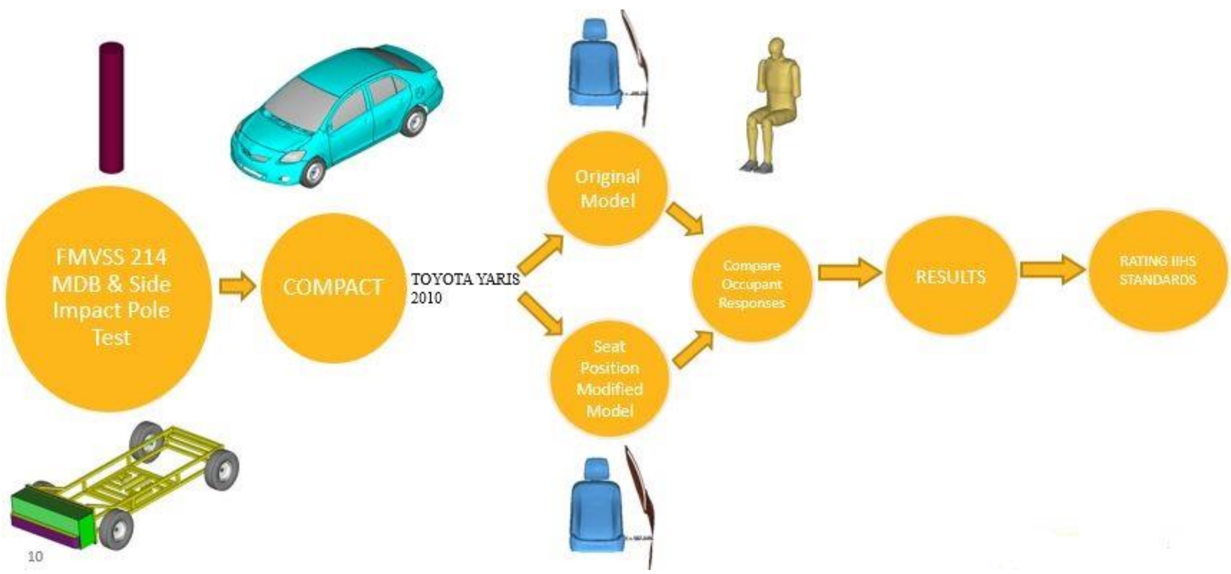

Figure 2.1 General Methodology

2.3 Federal Motor Vehicle Safety Standard (FMVSS 214)

Side impact protection requirements were amended in 1990 under the Federal Motor Vehicle Safety Standard (FMVSS 214) to guarantee the occupant protection in a crash test that simulates a serious perpendicular collision, as shown in Figure 2.2. Since the side impact caused 33 percent of fatal injuries in 1993 to passenger car occupants, it was manifested to new passenger car models during the year 1994 to 1997 [11]. It is among the most critical and promising safety regulation circulated by the National Highway Traffic Safety Administration (NHTSA).

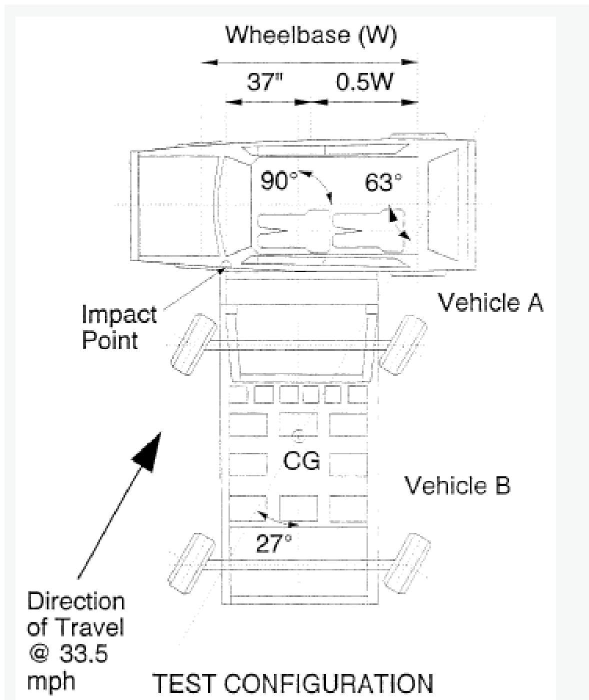

Figure 2.2 FMVSS 214 Test Configuration [11]

The present FMVSS 214 is the outcome of many years of research to manufacture the passenger vehicle less susceptible to Side Impacts, and mainly to reduce casualty to the nearside occupant during the vehicle struck by another vehicle near door area, which is primary responsible for the majority of side-impact casualties. With the combined effort from the United States and international communities, the NHTSA developed few methodologies [11]:

- A test methodology to determine the severity of intersection collision between two vehicles using a Moving Deformable Barrier (MDB).
- Thoracic Trauma Index (TTI), which finds the intensity of thoracic injuries when

occupant's torsos contact the interior side member of a car.

- A Side Impact Dummy (SID) on which Thoracic Trauma Index (TTI) can be determined with required accuracy while performing Side Impact Tests. This injury score found is called Thoracic Trauma Index TTI (d).
- The Thoracic Trauma Index TTI (d) up to 90 in 2-door cars and 85 in 4- door cars is allowed under new FMVSS 214.

The Government Performance and Results Act of 1993 and Executive Order 12866 mandates that all automobile manufacturers and agencies to evaluate their existing programs and regulations [11]. The main objective of this evaluation is to determine the actual benefits – lives saved, injuries avoided, and damages prevented – and the feasibility of safety equipment installed in production vehicles in connection with a rule [11].

2.4 Side Impact Pole Test

Designing automobiles with improved protection to vehicle occupants in side impact collisions has become an important area of concern in safety research. One of which is the side impact crashes into fixed narrow obstacles like trees, utility poles, supports, etc.

In the 214 regulations, the MDB does not demonstrate the worst-case scenario since there is too much sill loading and pillar loading. The newly proposed side impact pole test by NHTSA is more favorable since the area subjected to impact is much narrower when compared to the MDB tests. Therefore, greater crash energy is concentrated on the driver's side and transmitted onto the occupant.

In this test procedure, the vehicle is propelled sideways at an approach angle of 75 degrees with a speed of 20 mph into a fixed rigid pole [12]. As the pole is relatively narrow, there is major penetration into the side of the car thereby affecting the occupant severely on the driver's seat.

Figure 2.3 Side Impact Model of Toyota Yaris Car as per Side Pole Test

As shown in Figure 2.3, the pole is set to align with the occupant or the driver's head, so that the worst-case scenario can be obtained where the occupant's body strikes the inner door and the driver's head strikes the pole.

Figure 2.4 shows a sample side impact pole crash scenario in real world accidents. As can be seen, the impact intrusion into the car is quite significant. The objective of this side impact pole test is to evaluate the hazardous injuries caused to the occupant and the structural damage, which is the vehicle intrusion experienced by the vehicle which is not seen in the common side impact testing.

(a) (b)

Figure 2.4 (a) A Side Pole Crash. (b) Vehicle Intrusion After the Impact [12]

2.5 Driver Seat Position and Relocation

In this study the driver's seat is displaced laterally in towards the passenger seat to delay the contact and to provide 2 cm clearance between the seat and struck door. The original and modified seat positions are shown in Figure 2.5. The ANSA pre-processing tool is used to relocate the driver's seat position considering the relative position of seats available in guidelines for seating assemblies in ECER-17 and 21 regulations.

The gap available between seat and console was measured which came around 21mm. To take leverage of the available gap, we moved the seat in y-direction by this available distance. Option used in ANSA was "Translate" option. Entire seat was moved, and adjustment was done at mounting point for simulation. After successful lateral displacement of seat in y-direction, contact check has been done to make sure it doesn't affect the simulation results.

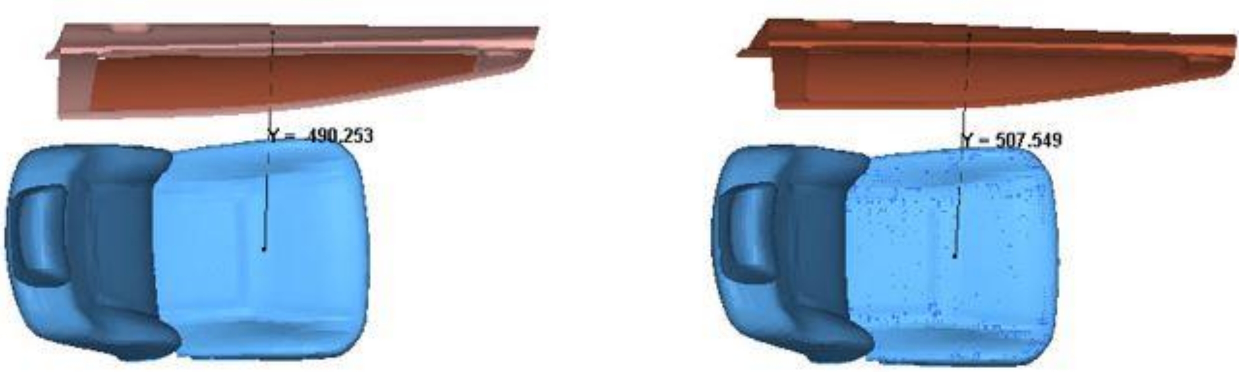

Figure 2.5 Seats in Original and Modified Positions

2.6 Computer Aided Engineering Tools

Due to increasing cost on conducting real-world crash simulations, the CAE tools are widely used in the auto industry. As a result, automakers have reduced product development cost and time while improving safety, comfort, and durability of the vehicles they produce. The predictive capability of CAE tools has progressed to the point where much of the design verification is now done using computer simulations rather than physical prototype testing. Tools used in this study are briefly explained below.

2.6.1 CATIA V5

The CATIA V5 is geometric modeling software developed by Dassault Systems. It is the leading commercial computer program used in product development solutions for wide variety of industries, such as aerospace, automotive, electrical, electronic etc. which provides greater flexibility in modeling of the irregular contours.

CATIA V5 is the only solution capable addressing the complete product development process, from product concept specifications through product-in-service, in a fully integrated an associative manner. It facilitates the true collaborative engineering across the multi-disciplinary extended enterprise, including style from design, mechanical design and equipment and systems engineering, managing digital mock-up, machining, analysis, and simulation.

2.6.2 HYPERMESH

The Hypermesh is a finite element modeler used to perform a variety of CAD/CAE tasks including modeling, meshing, and post processing for FEM solvers LSDYNA, NASTRAN, ABAQUS, etc. Hypermesh can be directly used to access the geometric models from leading design software's like CATIA, Pro-E etc. With use of many highly advanced tools presented in Hypermesh helps to overcome the FEM challenges, including many topological irregularities multi body contacts and others. This has the ability to import geometry from any CAD system and various data exchange standards.

Hypermesh provided with rich set of tools made it possible to achieve a required mesh quality with the different meshing techniques starting from completely automatic solid meshing to thorough node and element creation and editing. It also provided with different types of loads and constraints, which can be applied to either geometric model or to analysis model. The various visualization tools help to find much critical information, including maximum and minimum values, contour plots which shows trends and correlations. Imaging features such as graphics shading, multiple light sources, local view manipulation and many other sophisticated visualization tools help to speed and improve results evaluation. It is also possible export result images and animation videos in many standard forms which help to present in reports.

2.6.3 ANSA

ANSA is a multidisciplinary CAE pre-processing system that integrates functionality for full-model build up, from CAD data to ready to run solver input file for numerous analysis codes. Its rich automated functionality provides a uniquely productive modelling environment. ANSA is computer -aided engineering tool for Finite Element Analysis and CFD analysis widely used in automotive industry. It is developed by the BETA CAE Systems S.A., Greece. In the United States, it is distributed by Beta CAE Systems, USA, based in Farmington Hills, Michigan. ANSA stands for 'Automatic Net Generation for Structural Analysis'. ANSA has broadly six menus which are used to do various activities those are: TOPO MESH VMESH DECK-SOLVER MORPH HBLOCK.

ANSA maintains the association between CAD geometry and the FE mesh. This means that the FE meshes are better representations of their geometric parents. Also, it is easy to maintain and update any changes in the geometry by simply reworking the updated area instead of recreating the FE from scratch. It carries several proprietary algorithms for meshing suitable for both CFD and structural models. ANSA is the user's preference due to its wide range of features and tools that meet their needs. The list of productive and versatile features is long and the alternative tasks and processes to be completed using them are countless.

2.6.4 LS-DYNA

LS-DYNA is a general purpose transient dynamic finite element program capable of simulating complex real-world problems. It is optimized for shared and distributed memory UNIX, Linux, and Windows based, platforms. It is an explicit 3-D finite element program for analyzing the large deformation dynamic response of the elastic and inelastic solids and structures. The program is extensively used by many top automobile, aerospace and research organizations. A wide range of material types and interfaces enable the efficient mathematical modeling of many engineering problems.

The LS-DYNA contains more than one hundred and fifty material models including metallic, non-metallic and composite models which enable to define any material in the real world. The contact capabilities such as contact between deformable bodies, between deformable and rigid bodies provided in LS-DYNA can solve any contact problems which very useful in crash testing. The important functional areas of LS-DYNA include:

- Crashworthiness simulations: automobiles, airplanes, trains, ships, etc.,
- Occupant safety analyses: LS-DYNA integrated with MADYMO used for dummy interaction with airbag, seat belts, foam padding, etc.,
- Simulation of bird strike on aircraft structures,
- Analysis and optimization of metal forming process,
- Biomedical applications.

LS-DYNA computes on different machines including supercomputers, leading UNIX machines, and Massively Parallel Processing (MPP) machines. Computer configuration depends on processing time and problem size. Super computers and MPP takes the advantage of multiple processes when the code is highly efficient.

2.6.5 META POST

META is a thriving multi-purpose post-processor meeting diverging needs from various CAE disciplines. It owes its success to its impressive performance, innovative features and capabilities of interaction between animations, plots, videos, reports and other objects. META provides a broad range of functionality that can successfully address even the most demanding post processing requirements for structural and CFD analyses. It supports results from all popular solvers used in structural analysis as well as CFD results from Fluent and OpenFOAM. Post-processing work is accelerated significantly through a multiple window environment with window dependent model attributes and smart functionality for the fast handling of entities visibility.

CHAPTER 3

MODEL DEVELOPMENT AND ANALYSIS

Federal Motor Vehicle Safety Standard (FMVSS 214) is the Federal regulation in the US for side impact protection developed by the National Highway Traffic Safety Administration (NHTSA). NHTSA also developed a mathematical model for the simulation of side impacts. The mathematical model simulates the responses of the MDB and the struck car. The impact energy from the MDB is transferred to the struck vehicle through the pillars and the door sections.

3.1 Vehicle Modeling

The finite element model of the vehicle is generally developed by reverse engineering process that virtually generates vehicles. These models are accurate enough to analyze different crash test configurations and to predict the vehicle and occupant behaviors in various crash scenarios. Such a design leads to minimize the time and the cost of the testing process and helps in making effective safety decisions.

The general procedures the researchers use to generate FE vehicle model are [11]:

- Apply tape over the vehicle surrounding the entire body of vehicle to get an accurate representation of the geometries.
- Digitize every component using a seven-degree-of-freedom coordinate measuring machine.
- Disassemble all the vehicle components.
- Collect the mass and the material thickness data for vehicle and individual parts.
- Identify all the parts and connections.

- Conduct center-of-gravity calculations.
- Execute material property tests for component strength.
- Create a computerized “mesh” grid of the vehicle using advanced computer codes.
- Reconnect all parts accurately, including spot welds, rigid body constraints, joints, springs and dampers.

Table 3.1 depicts the finite element summary of Toyota Yaris FE model. The FE model has 917 parts which represents the different parts of the vehicle. The table also summarizes number of nodes, different type of elements and also different types of connections present in the car.

Table 3.1 Model Summary of Toyota Yaris Car [13]

Number of Parts	917
Number of Nodes	1,480,422
Number of Shells	1,250,424
Number of Beams	4,738
Number of Solids	258,887
Beam Element Connections	4,425
Nodal Rigid Body Connections	727
Extra Node Set Connections	20
Rigid Body Connections	2
Spotweld Connections	4,107
Joint Connections	39

The Toyota Yaris model, which is used in this thesis, is a four-door passenger sedan which is developed by National Crash Analysis Center [13].

Table 3.2 Model Description of Toyota Yaris Car [13]

Model	Toyota Yaris
Year	2010
Class	Compact Car
Weight (kg)	1100
Wheel Base (mm)	2538
Total No. of Elements	1,514,068

Figure 3.1 shows the Finite element model of the Toyota Yaris car, and Table 3.2 shows the specifications of the vehicle model.

Figure 3.1 Finite Element Model of Toyota Yaris [13]

The car model has 917 parts, which represent different vehicle parts. The parts are joined by rigid body constrained options and spot weld. The contacts between different parts are modeled as single surface sliding interface (AUTOMATIC_SINGLE_SURFACE).

3.2 Rigid Pole Modeling

As shown in Figure 3.2, the rigid pole is constructed using the Finite Element Preprocessor software Hypermesh. The cross section of the pole is meshed using rigid hexa elements. The pole is place just outside the driver's door and aligned with driver's head. It measures 254mm (10 inches) in diameter and 100 mm above ground to above roofline. It is constrained in all degrees of freedom to simulate the rigid pole. Table 3.3 shows the material properties of the rigid pole which is given to the pole in hypermesh.

Figure 3.2 Finite Element Model of Rigid Pole

Table 3.3 Material Properties of the Rigid Pole

Density	7.8E-09 kg/mm^3
Young's Modulus	2E+05 KN/mm^2
Poisson Ratio	0.30

3.3 Occupant Modeling (EuroSID-IIre FE Model)

As shown in Figure 3.3, the vehicle occupant used in this thesis is the EuroSID-IIre finite element model side impact dummy is been developed by Livermore Software Technology Corporation (LSTC) and DYNAmore GmbH [14]. The model is based on the EuroSID 2 rib extensions (ES-IIre) 50th percentile adult male side impact crash test dummy according to the code of Federal Regulations, Title 49, Part 572, Subpart U. It has been validated to the certification tests described in the regulation [14]. Figure 3.3 summarizes the types of mesh element used in occupant modeling.

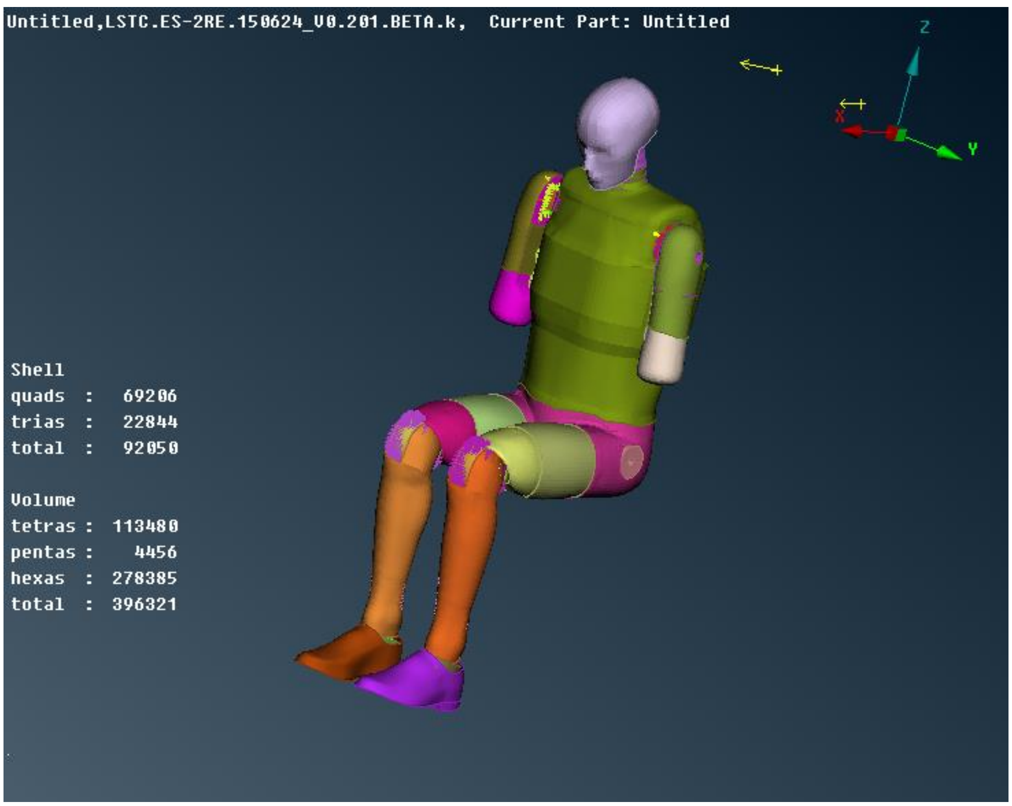

Figure 3.3 EuroSID-IIre Side Impact Dummy

The LSTC EuroSID-IIre finite element model has been delivered in the units of mm, ms, kg and it is converted into different unit system, as tons, mm and second.

Table 3.4 Numbering Scheme of Original EuroSID-IIre Dummy Model [14]

Component	Min ID	Max ID	Total number
Nodes	10001	437100	427088
Solids	11000	312155	301156
Beams	10000	10169	79
Shells	10200	30850	20651
Discrete elements	10500	10511	12
Accelerometer	1	17	17
Set parts	21	42	15
Parts	1	1057	315
Materials	1	64	64
Sections	1	261	261
Joints	1	19	19
Joint stiffness	1	11	11
Contacts	1	8	7
Local coordinate systems	1	31	31
Load curves/tables	1001	1019	15
Time history nodes	10001	10029	17
Time history elements	10000	10013	9

The numbering scheme of original model is shown in Table 3.4, which summarizes various components such as number of accelerometer present in the model, total number of nodes present in the FE model, different type of elements present in the model and also the total number of time history nodes present in the model which are used in evaluation of results. The mesh of the finite element model of the EuroSID-IIre was developed by LSTC utilizing the TrueGrid meshing software.

The mass of the major parts in the model are listed in Table 3.5.

Table 3.5 Mass of the Parts in the EuroSID-IIre Dummy Model [14]

Part	Specification (Kg)	Mass in Kg
Head	4.0 ±0.2	4.144
Neck	1.0 ±0.05	1.041
Thorax	22.4 ±1.0	21.335
Arm, Left	1.3 ±0.1	1.269
Arm, Right	1.3 ±0.1	1.380
Abdomen	5.0 ±0.25	5.317
Pelvis	12.0 ±0.6	11.712
Leg, Left	12.7 ±0.6	13.069
Leg, Right	12.7 ±0.6	13.069
Total	72.4 ±1.2	72.338

3.4 Moving Deformable Barrier (MDB) Modeling

The mass and geometry of the MDB defined in FMVSS 214 (Side Impact) represents the general U.S vehicles, as shown in Figure 3.4. The impact angle represents the most common side impact. The relative speed and direction of the MDB and the target vehicle is considered the threshold for severe injury in actual crashes.

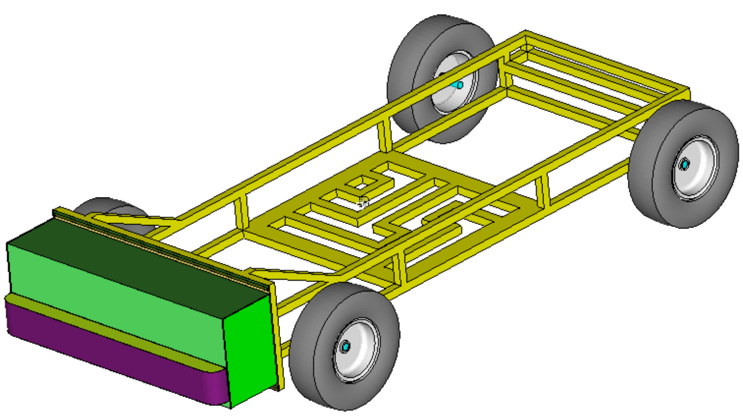

Figure 3.4 Finite Element Model of Moving Deformable Barrier [15]

The MDB face assembly includes a bumper constructed of honeycomb 1690+/-103 kPa sandwiched between 3.2 mm thick aluminum plates. The thickness of the honeycomb structure is 381mm.

Table 3.6 summarizes total number of parts, number of nodes and type of elements present in the model of the moving deformable barrier.

Table 3.6 Model Summary of Moving Deformable Barrier (FMVSS 214) [15]

Number of Parts	29
Number of Nodes	160988
Number of Quad Elements	33330
Number of Hexa Elements	114417

The bumper is a flexion member and develops flexion strength based on the material properties of the front and back plates.

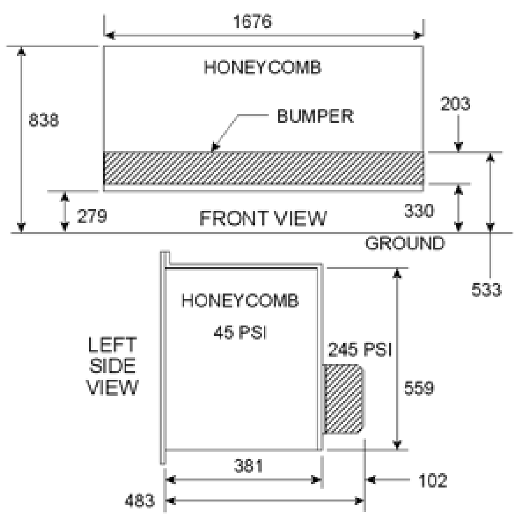

Figure 3.5 Moving Deformable Barrier Face [11]

Figures 3.5 and 3.6 show the moving deformable barrier (MDB) and its dimensions, which is used as the impactor or the bullet vehicle in the regulatory test. The impact face of the barrier is made from aluminum honeycomb structure. The bottom edge distance of MDB from ground is 279 mm.

The extending part of the barrier, which represents a bumper, is 330 mm from ground. The total mass of the MDB is 1367 kg. For defining material model in LS- DYNA for honeycomb structure of the barrier face, MAT_HONEYCOMB card has been defined.

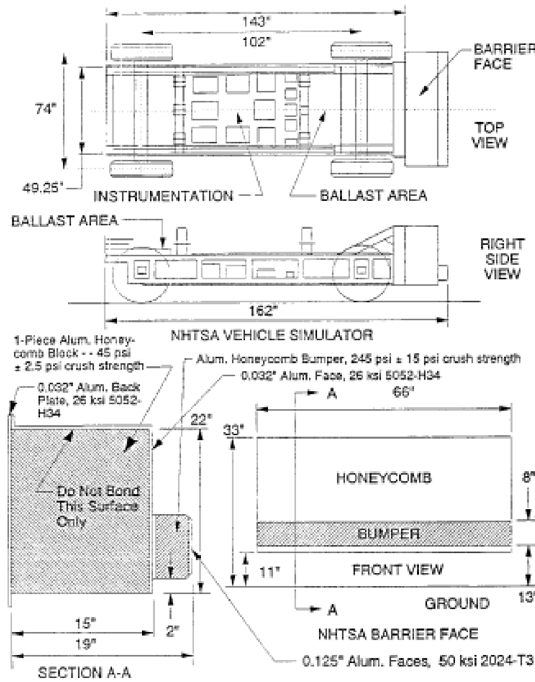

Figure 3.6 Dimensions of Moving Deformable Barrier [11]

3.5 Driver Seat Position and Its Lateral Displacement

As shown in Figure 3.7, In this study the driver's seat is displaced laterally inward to delay the contact and to provide 2 cm clearance between the seat and struck door. This is illustrated in Figure 3.7. The ANSA pre-processing tool is used to relocate the driver's seat position considering the relative position of seats available in guidelines for seating assemblies in ECER-17 and ECER-21 regulations. We are not exactly following regulation (ECER-17 and ECER-21) as our load case is little bit different from the conventional one. As our point of interest is to see the differences in injuries, considering the relative distance between seat and console.

The gap available between seat and console was measured which came around 21mm. To take leverage of the available gap, we moved the seat in y-direction by this available distance. Theory behind this experiment was the application of a mechanism which can move the seat in y-direction by available distance, to reduce the injuries to the occupant.

The option “Translate” was used in ANSA. The entire seat was moved, and adjustment was made at mounting point for simulation. After successful lateral displacement of seat in lateral y-direction, contact check has been done to make sure it does not affect the simulation results.

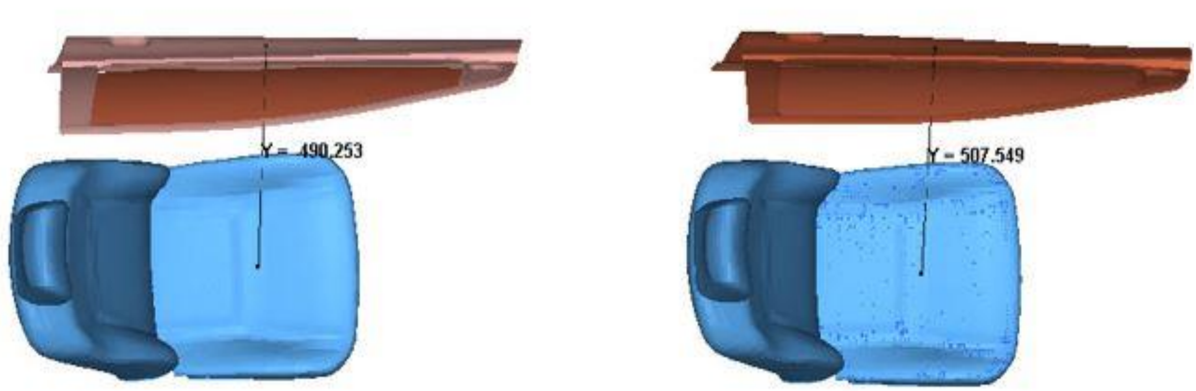

Figure 3.7 Seats in Original and Modified Positions

CHAPTER 4

SIMULATION RESULTS FOR FMVSS 214 SIDE IMPACT MDB TEST

For the FMVSS 214 as defined in MDB test, the test vehicle is stationary and the line of action of the Moving Deformable Barrier makes an angle of 63 degrees with the test vehicles centerline. This condition is shown in Figure 4.1, the longitudinal centerline of the moving deformable barrier is perpendicular to the longitudinal centerline of the test vehicle when the barrier strikes the test vehicle. In a test in which the test vehicle is to be struck on its left side, all wheels of the moving deformable barrier are positioned angle of 27 degrees to right of the centerline of the moving deformable barrier. The full side impact model is carried out in LS-DYNA for 0.2 seconds.

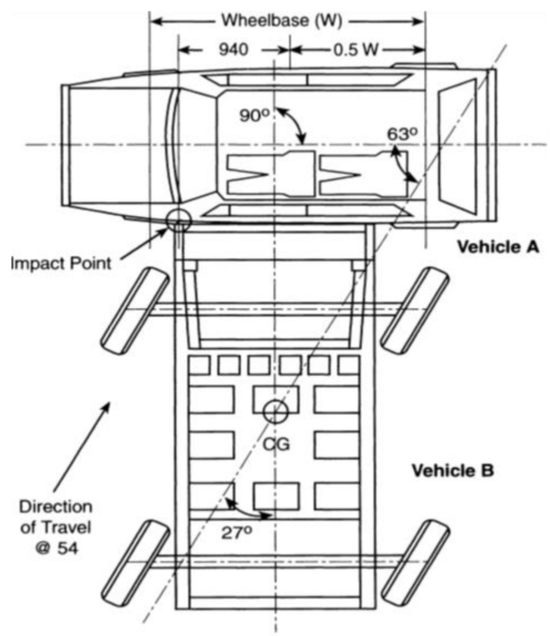

Figure 4.1 FMVSS 214 Test Configuration [11]

4.1 Simulation Results

The Toyota Yaris car with current and modified seat is impacted by Moving Deformable Barrier for two simulations according to FMVSS 214 side impact regulation. Figure 4.2 shows the setup of finite element model of the side impact test. According to FMVSS 214, the moving deformable barrier hits the driver side of the stationary vehicle at an angle of 27 degrees with the longitudinal axis of the barrier at a speed of 33.5 mph (53.9 km/h).

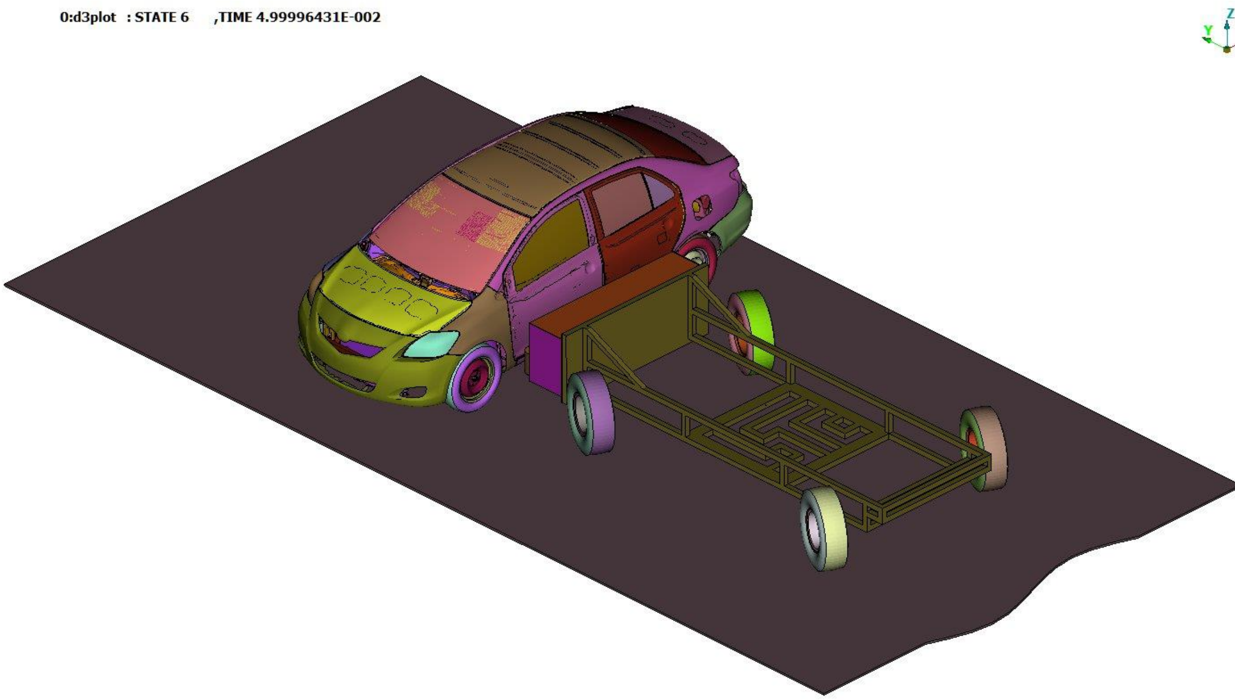

Figure 4.2 Side Impact Model of Toyota Yaris Car as per FMVSS 214

The full side impact model is carried out in the LS-DYNA for 0.2 seconds. The accelerometers are placed at eight locations in the vehicle. Time history nodes are defined for evaluation of results and the contacts are defined by geometric interface. Initial velocity card is defined in LS-DYNA and velocity is given to the moving deformable barrier. The distance between the vehicle and the barrier is kept to be minimal in order to minimize the simulation time. Figures 4.3(a, b, c, d, e, f, g, h) shows the side impact analysis which was carried on Toyota Yaris according to FMVSS 214 side impact standards. The simulation of the side impact test at different time intervals is shown in Figures 4.3(a-through h).

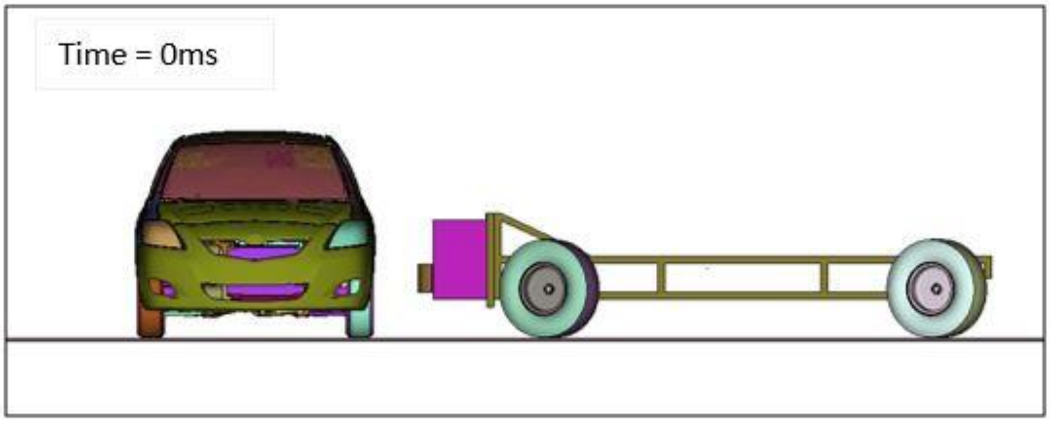

Figure 4.3(a) FMVSS Side Impact MDB Test on Toyota Yaris at 0ms

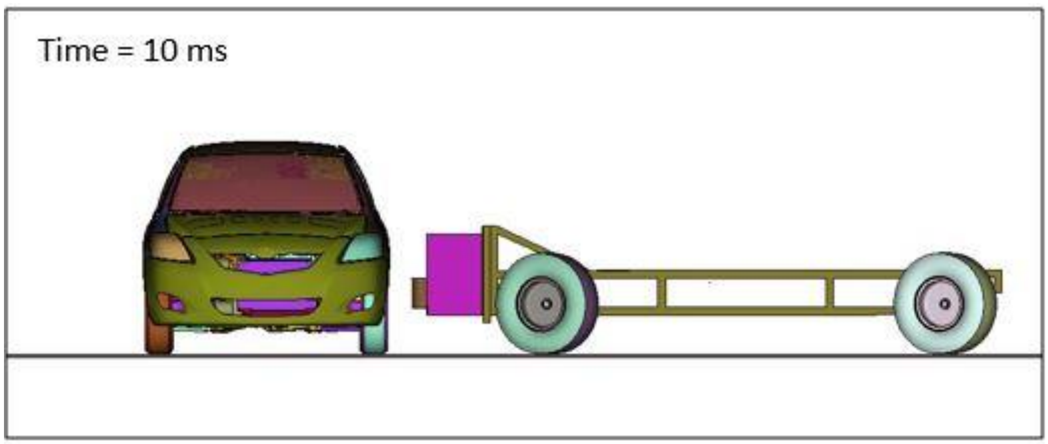

Figure 4.3(b) FMVSS Side Impact MDB Test on Toyota Yaris at 10ms

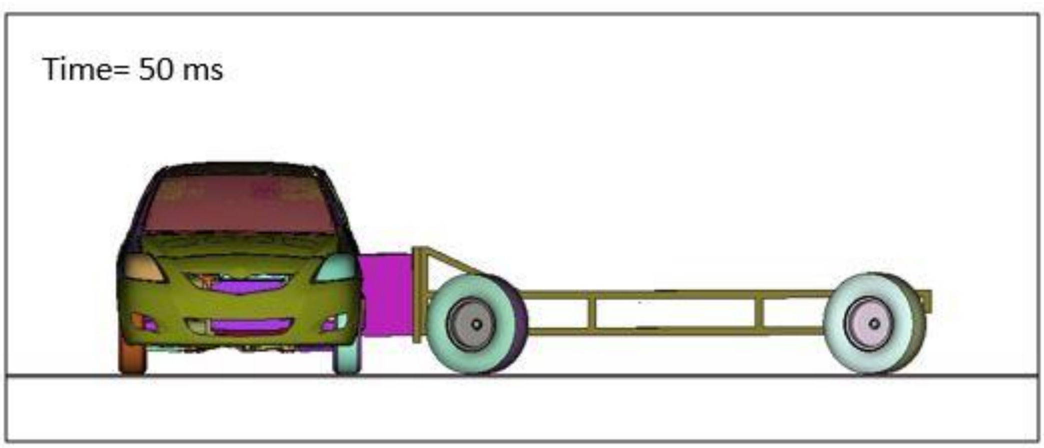

Figure 4.3(c) FMVSS Side Impact MDB Test on Toyota Yaris at 50ms

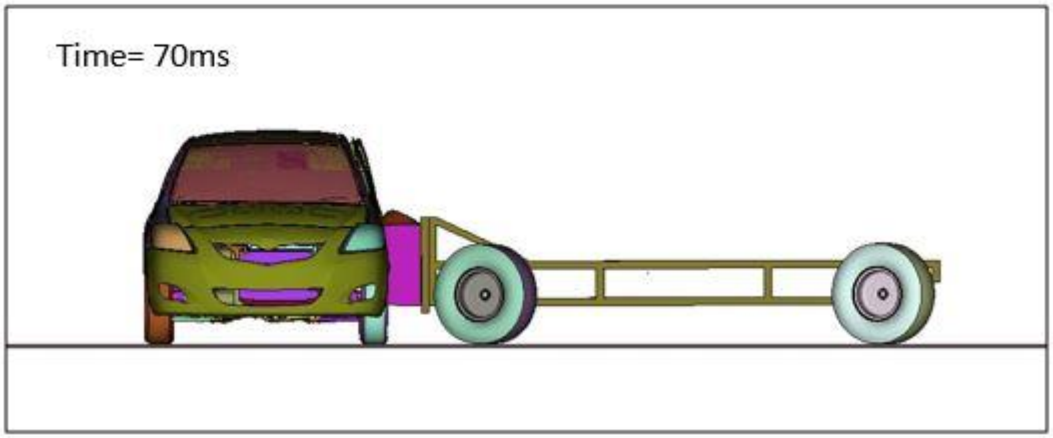

Figure 4.3(d) FMVSS Side Impact MDB Test on Toyota Yaris at 70ms

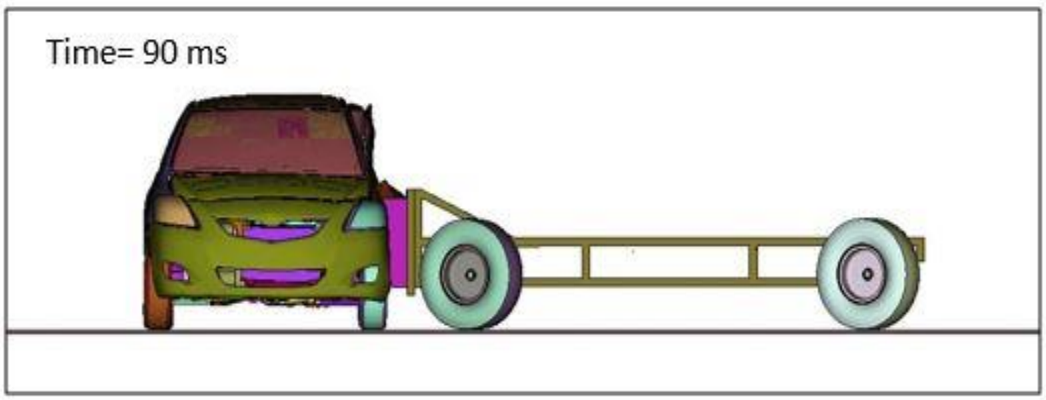

Figure 4.3(e) FMVSS Side Impact MDB Test on Toyota Yaris at 90ms

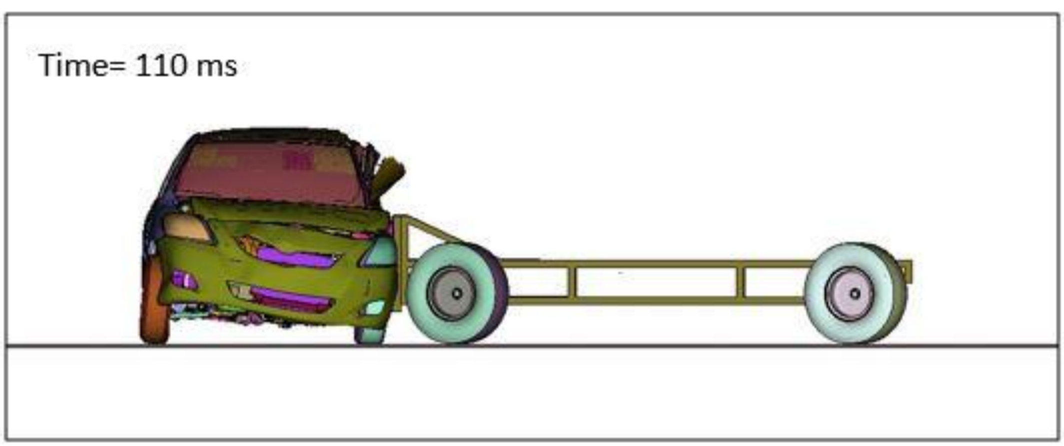

Figure 4.3(f) FMVSS Side Impact MDB Test on Toyota Yaris at 110ms

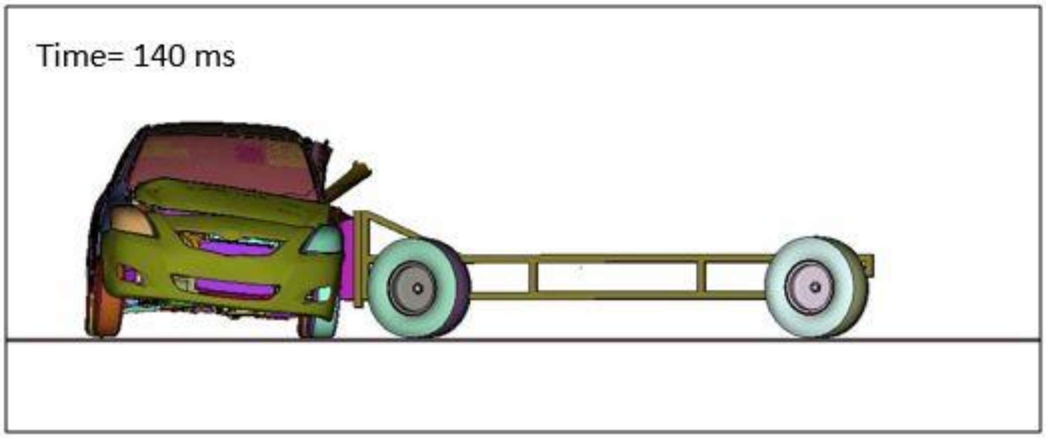

Figure 4.3(g) FMVSS Side Impact MDB Test on Toyota Yaris at 140ms

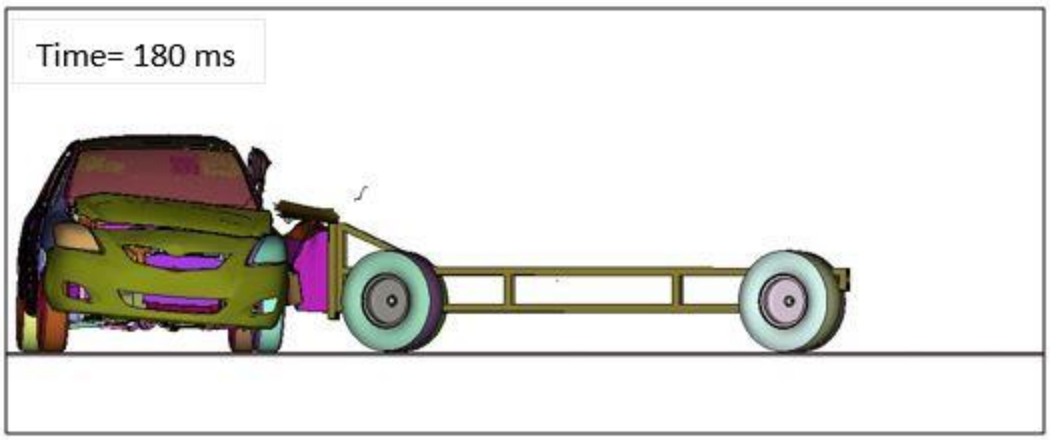

Figure 4.3(h) FMVSS Side Impact MDB Test on Toyota Yaris at 180ms

From this simulation, as shown in Figures 4.3 (a, b, c, d, e, f, g, h), it can be observed that there is uniform vehicle intrusion in the MDB impact as the front surface of the honeycomb structure of the moving deformable barrier is uniformly distributed. The MDB impacts the vehicle and damages the side structure of the vehicle and passes all its energy on to the side door which is transmitted to the occupant. Moreover, in this side impact regulation, the vehicle is thrown away from the moving deformable barrier. The simulations of the occupant behavior are shown in the next section.

4.2 Occupant Response with Current Seat Position Simulation results

Side impact MDB test with EuroSID-IIre dummy as an occupant in original seat position was simulated as shown in Figures 4.4 (a,b,c,d,e,f,g,h,i,j). The Figures show the occupant dynamic behavior at different time intervals.

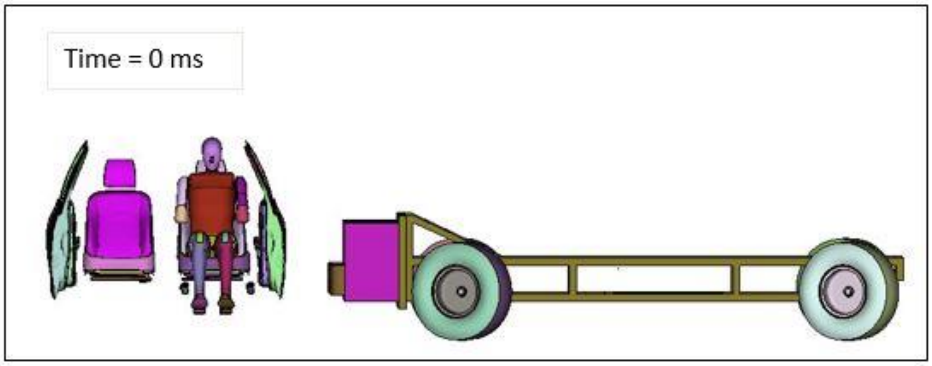

Figure 4.4(a) Occupant Response with Current Seat Position at 0ms

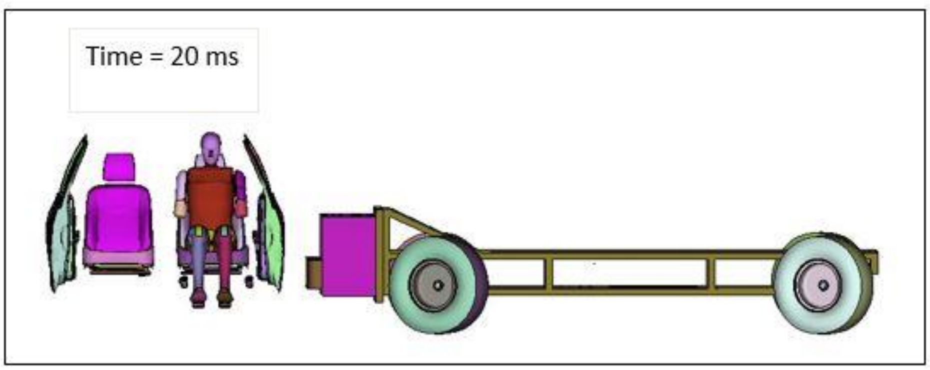

Figure 4.4(b) Occupant Response with Current Seat Position at 20ms

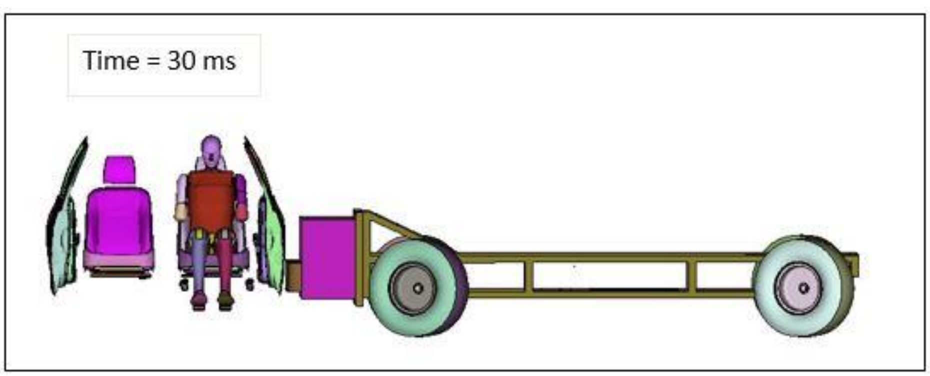

Figure 4.4(c) Occupant Response with Current Seat Position at 30ms

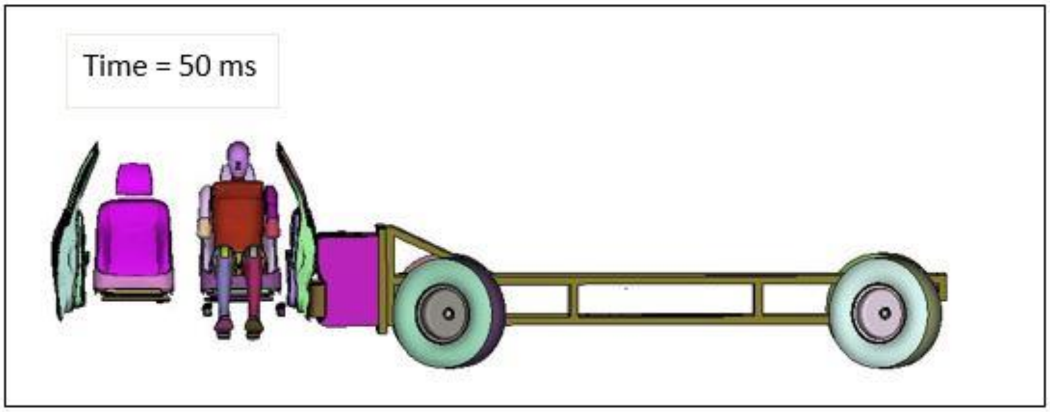

Figure 4.4(d) Occupant Response with Current Seat Position at 50ms

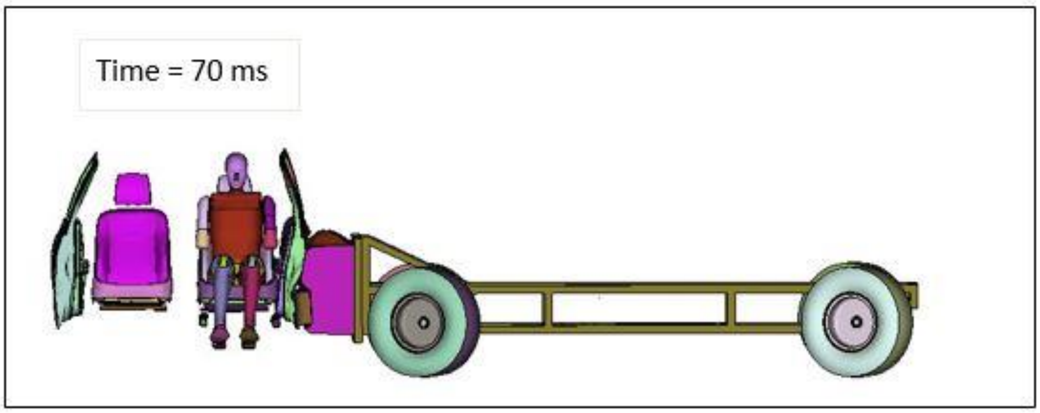

Figure 4.4(e) Occupant Response with Current Seat Position at 70ms

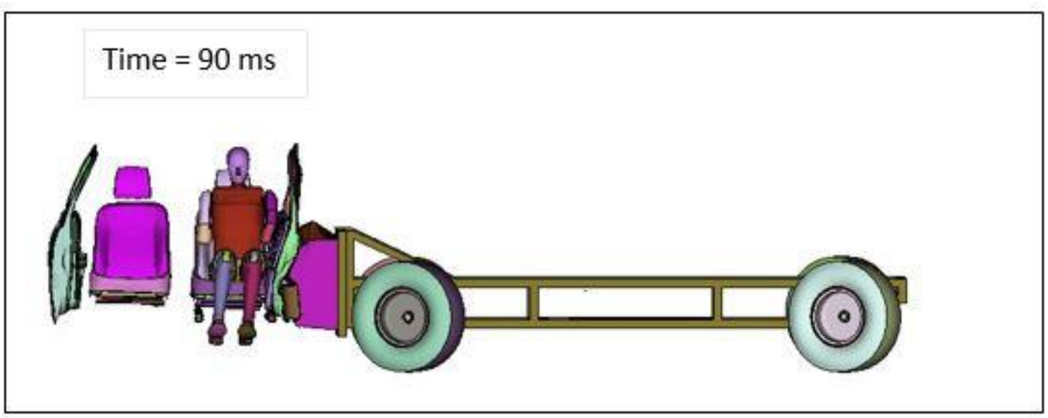

Figure 4.4(f) Occupant Response with Current Seat Position at 90ms

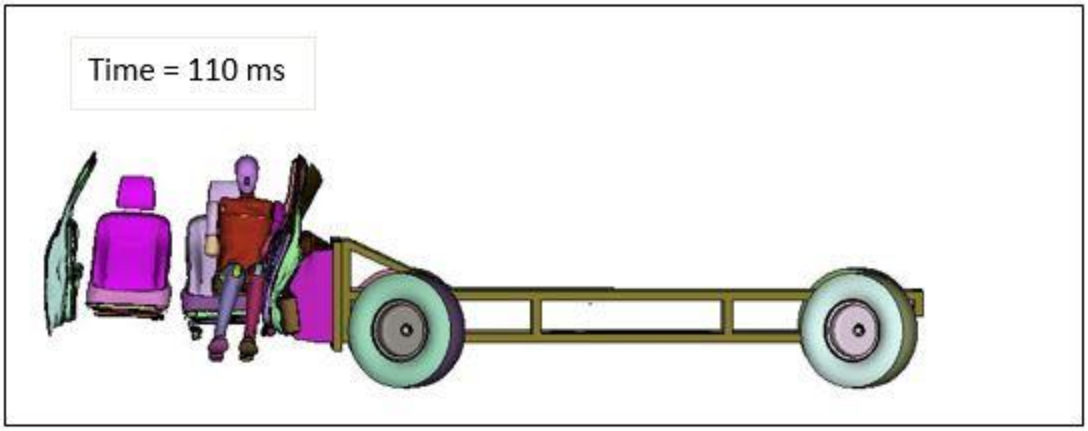

Figure 4.4(g) Occupant Response with Current Seat Position at 110ms

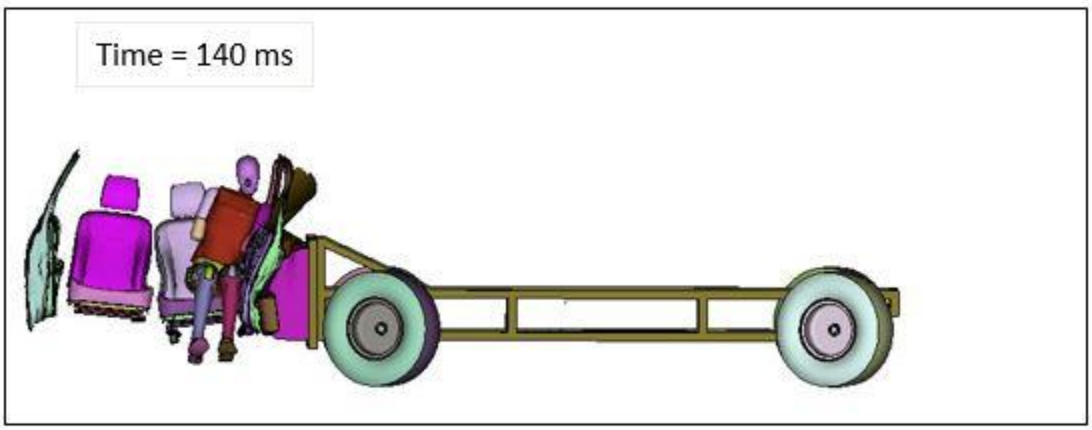

Figure 4.4(h) Occupant Response with Current Seat Position at 140ms

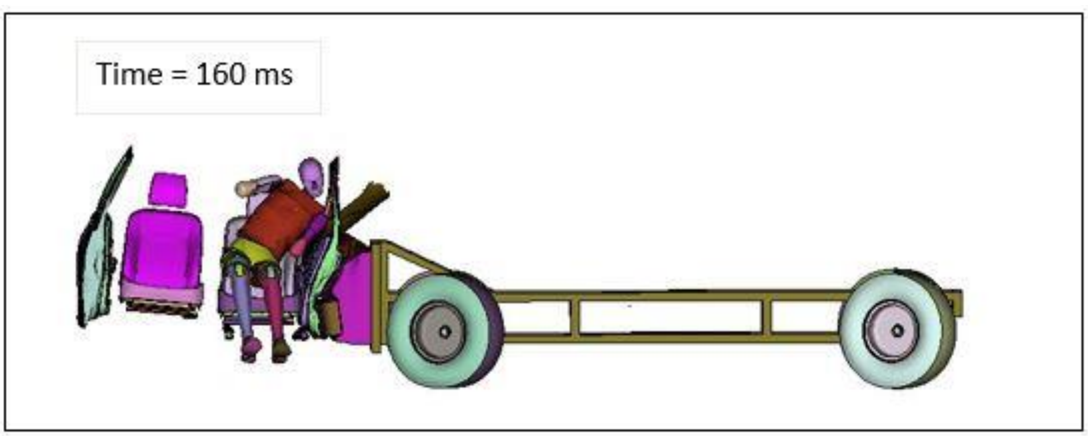

Figure 4.4(i) Occupant Response with Current Seat Position at 160ms

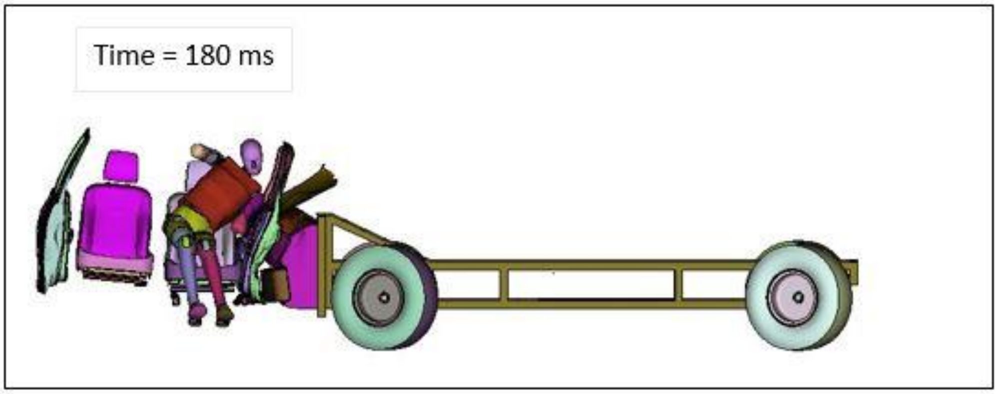

Figure 4.4(j) Occupant Response with Current Seat Position at 180ms

From the simulations, the occupant dynamic response in the side impact regulation can be observed. It is seen that the occupant is thrown away from the impactor. The struck door impacts the dummy at shoulder and hip area.

4.3 Occupant Response with Modified Seat Position Simulation results

Side impact MDB test with EuroSID-IIre dummy as an occupant is placed in modified seat position was simulated as shown in Figures 4.5(a,b,c,d,e,f,g,h,i,j). The dummy was positioned inside the car by using ANSA. Figures 4.5(a,b,c,d,e,f,g,h,i,j) show the occupant dynamic behavior at different time intervals.

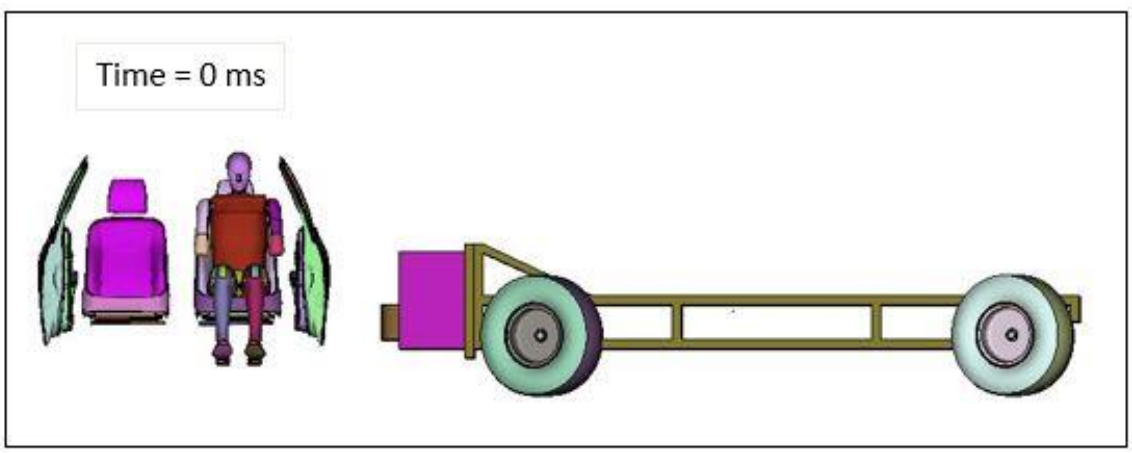

Figure 4.5(a) Occupant Response with Modified Seat Position at 0ms

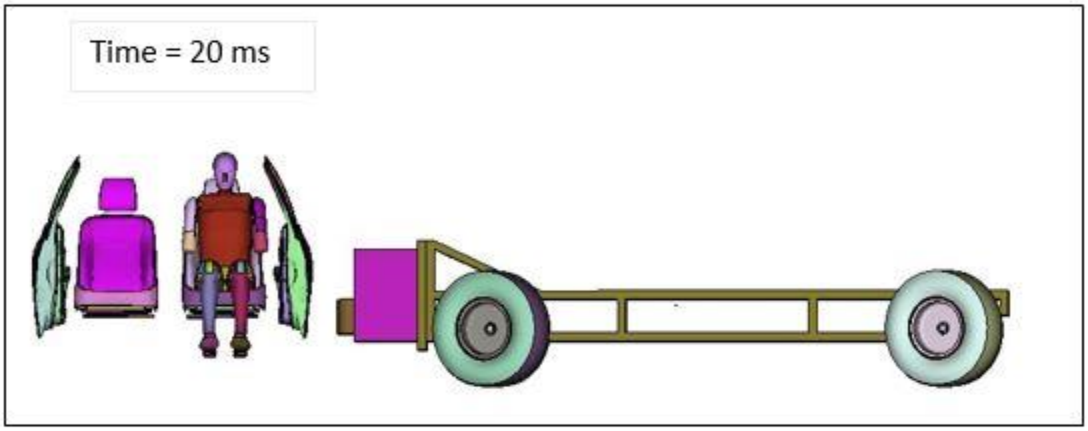

Figure 4.5(b) Occupant Response with Modified Seat Position at 20ms

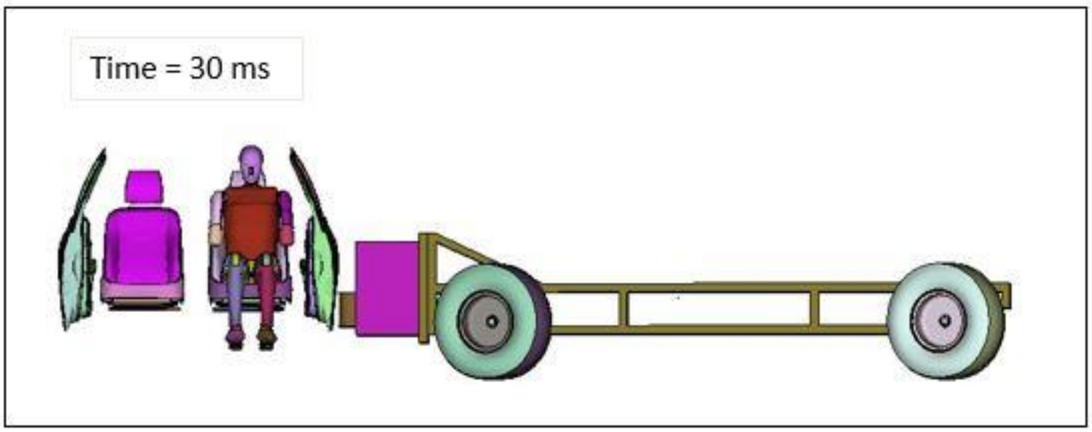

Figure 4.5(c) Occupant Response with Modified Seat Position at 30ms

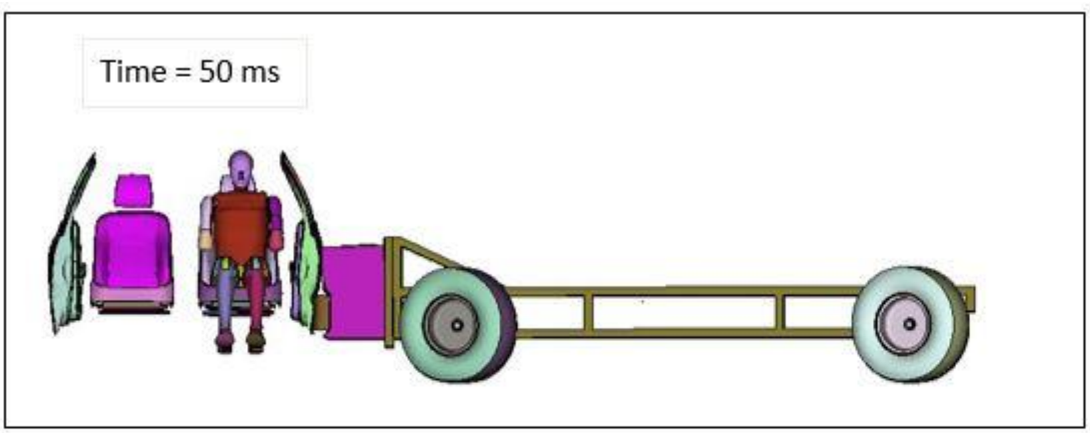

Figure 4.5(d) Occupant Response with Modified Seat Position at 50ms

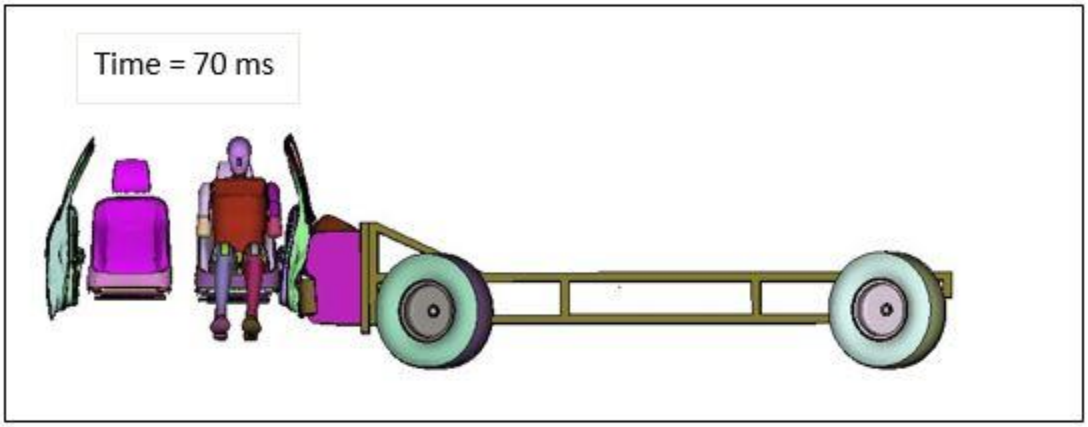

Figure 4.5(e) Occupant Response with Modified Seat Position at 70ms

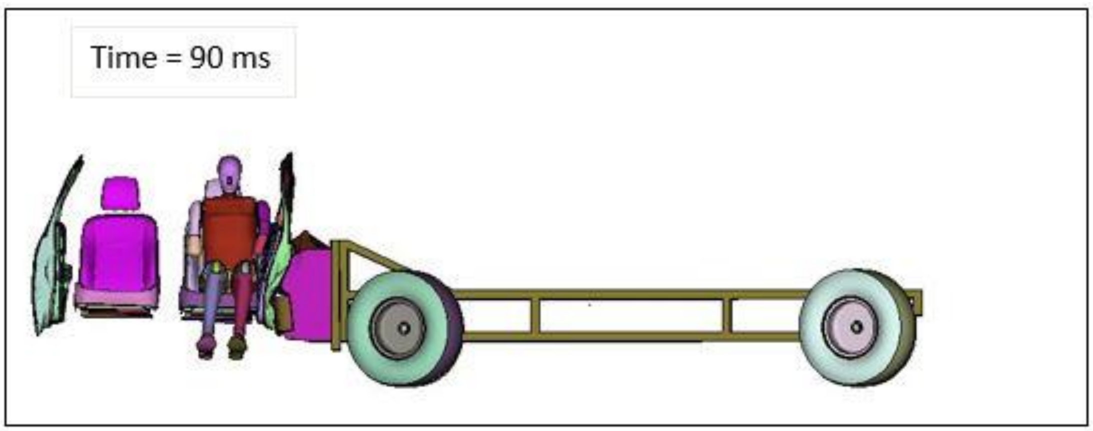

Figure 4.5(f) Occupant Response with Modified Seat Position at 90ms

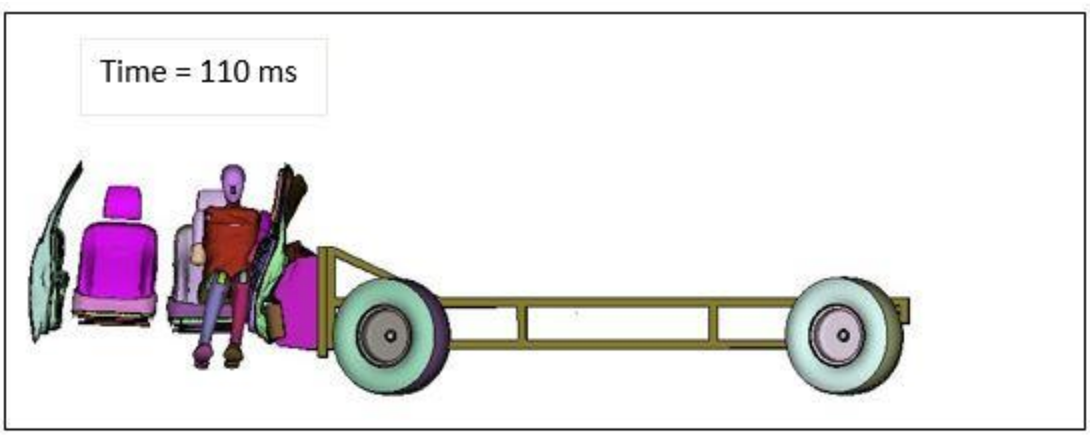

Figure 4.5(g) Occupant Response with Modified Seat Position at 110ms

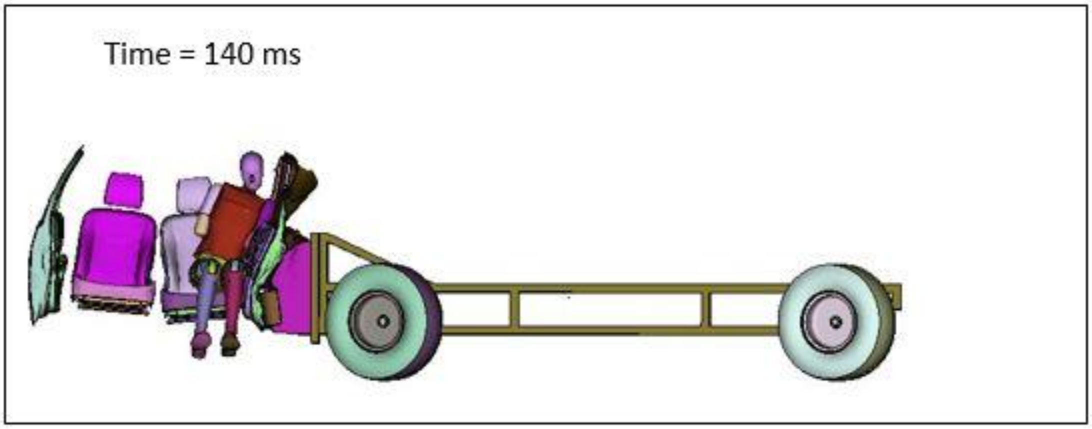

Figure 4.5(h) Occupant Response with Modified Seat Position at 140ms

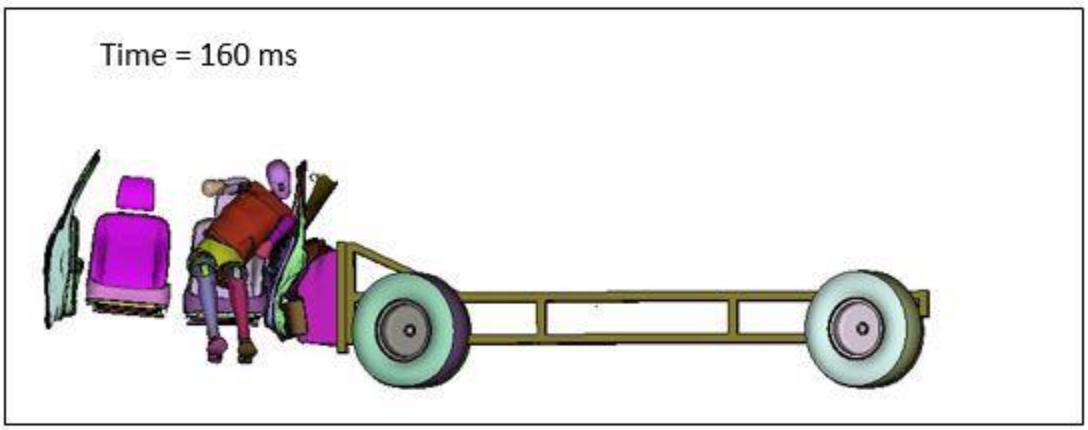

Figure 4.5(i) Occupant Response with Modified Seat Position at 160ms

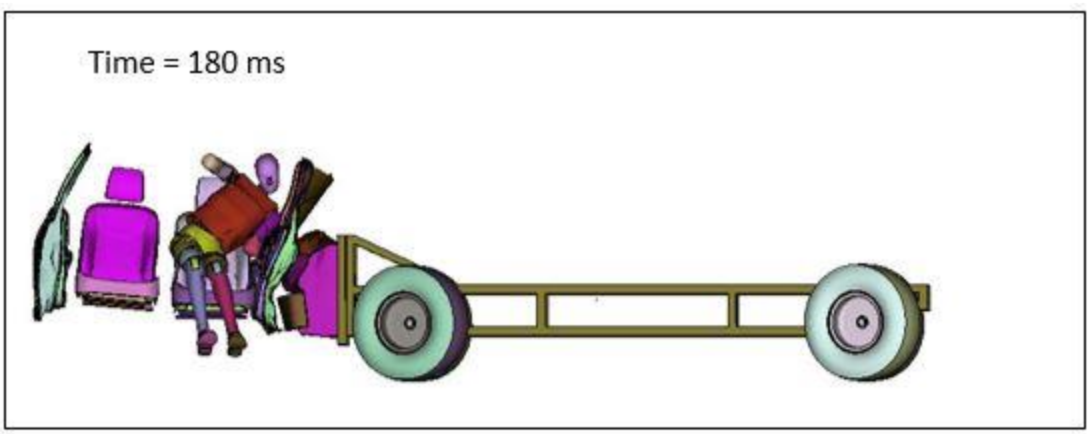

Figure 4.5(j) Occupant Response with Modified Seat Position at 180ms

From these simulations, the occupant dynamic response in the side impact regulation can be observed. It can be seen that due to the modification of the seat as the seat's position has been changed, the interaction between the vehicle door and the dummy is reduced. This suggests that the force of the barrier impacting the door and the load exerted on the occupant is decreased, which reduces the injuries sustained by the driver.

4.4 Door Intrusions for FMVSS 214 MDB Test

The door intrusion is measured by selecting a node at the center of the door. It is basically the distance between the driver side door and passenger side door, and it is measured before the simulation and post simulation.

The door intrusions when the car is impacted by a moving deformable barrier for both current seat position and the modified seat position according to FMVSS 214 side impact regulation, is listed in Table 4.1. As shown, the movement of the seat inward reduces the door intrusion by about 1.3 cm or about 0.7%.

Table 4.1 Intrusion of Door for MDB Test

	Distance between Door Pre-Simulation (cm)	**Distance between Door Post Simulation (cm)**	**Door Intrusion (cm)**	**Percentage of Intrusion (%)**
Current Seat Position	168.6	140.7	**27.9**	**16.5**
Modified Seat Position	168.6	142	**26.6**	**15.8**

4.5 B-Pillar Intrusions for FMVSS 214 MDB Test

The B-Pillar intrusion is measured by selecting a random node at the center of the B-Pillar. It is basically the distance between the driver side B-Pillar and passenger side B-Pillar and it is measured from the pre-simulation and the post simulation.

The B-pillar intrusions when the vehicle is impacted by a moving deformable barrier according to FMVSS 214 side impact regulation are listed in Table 4.2. As shown, the movement of the seat inward reduces the B-pillar intrusion by 1.9 cm or about 1.4%.

Table 4.2 Intrusion of B-pillar for MDB Test

	Distance between B-pillar Pre-Simulation (cm)	**Distance between B-pillar Post Simulation (cm)**	**Door Intrusion (cm)**	**Percentage of Intrusion (%)**
Current Seat Position	137.5	116.8	**20.7**	**15.1**
Modified Seat Position	137.5	118.7	**18.8**	**13.7**

4.6 Occupant Dynamic Responses

The responses of the occupant in each scenario has been recorded and the acceleration response for critical dummy injury parts has been compared for the current seat and modified seat positions according to the FMVSS 214 side impact test regulation. It has been observed that there is reduction in values obtained. Significant bending and torsion has been observed in the occupant.

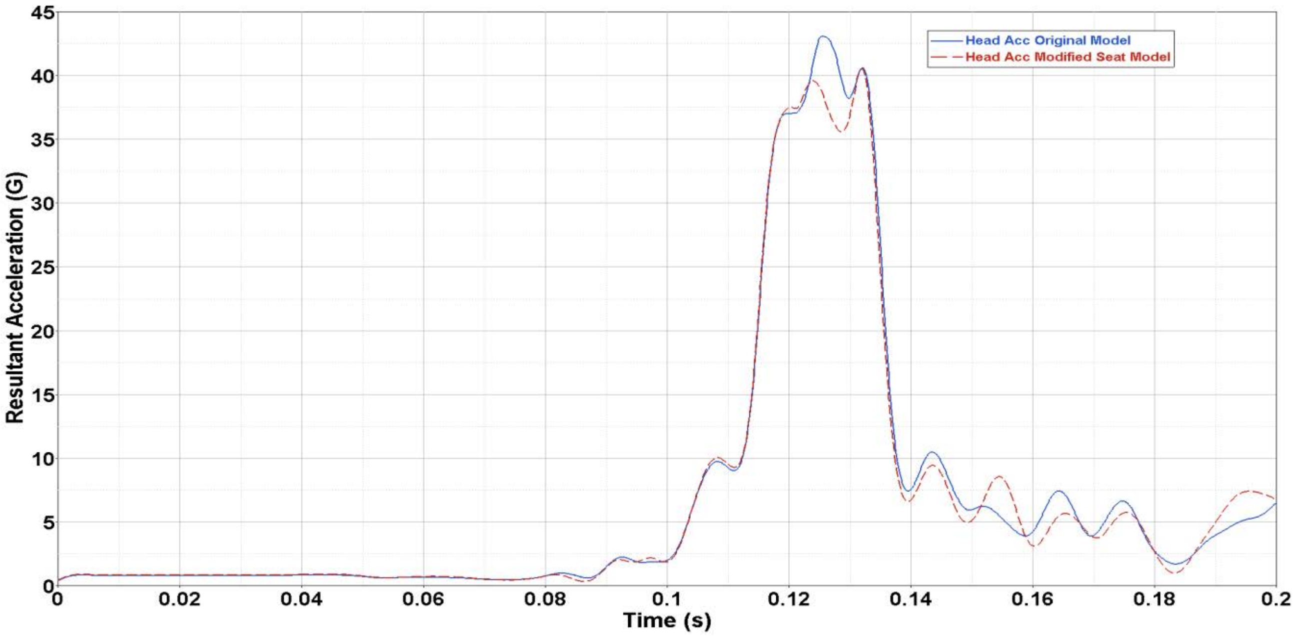

Figure 4.6 Head Acceleration Response

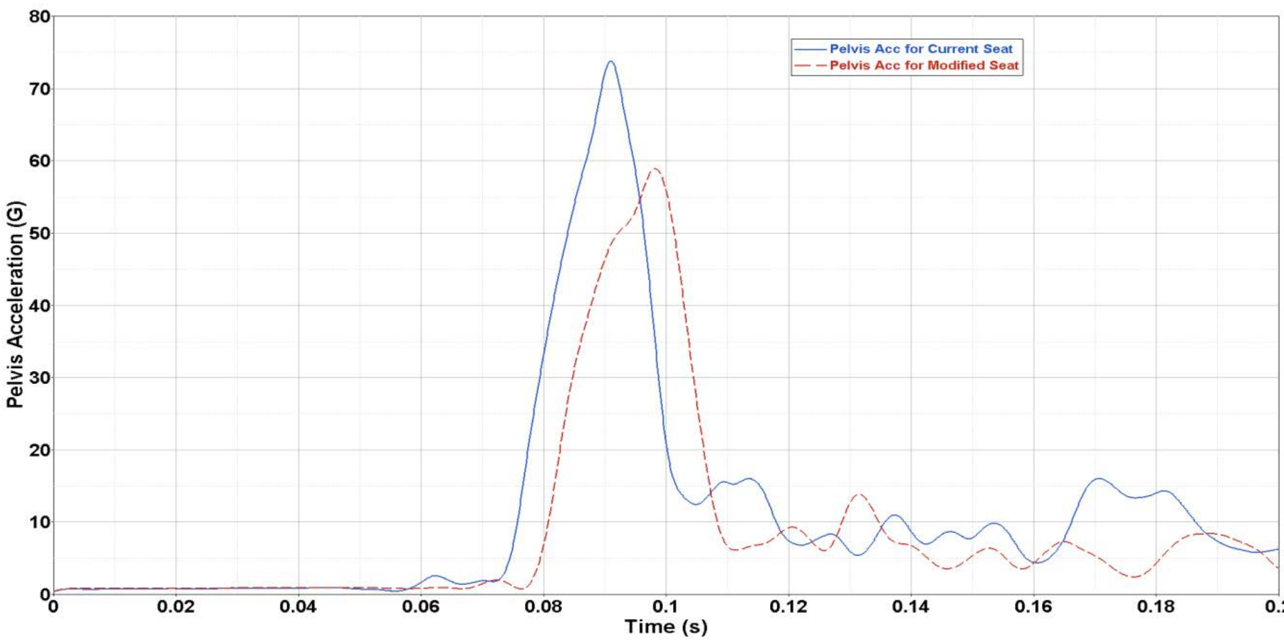

Figure 4.7 Pelvis Acceleration Response

Figures 4.6 and 4.7 show the comparison of the Head CG acceleration and the pelvis region acceleration of the driver occupant. From the graphs, it can be observed that the acceleration response are comparatively lesser for the occupant in the modified seat's position.

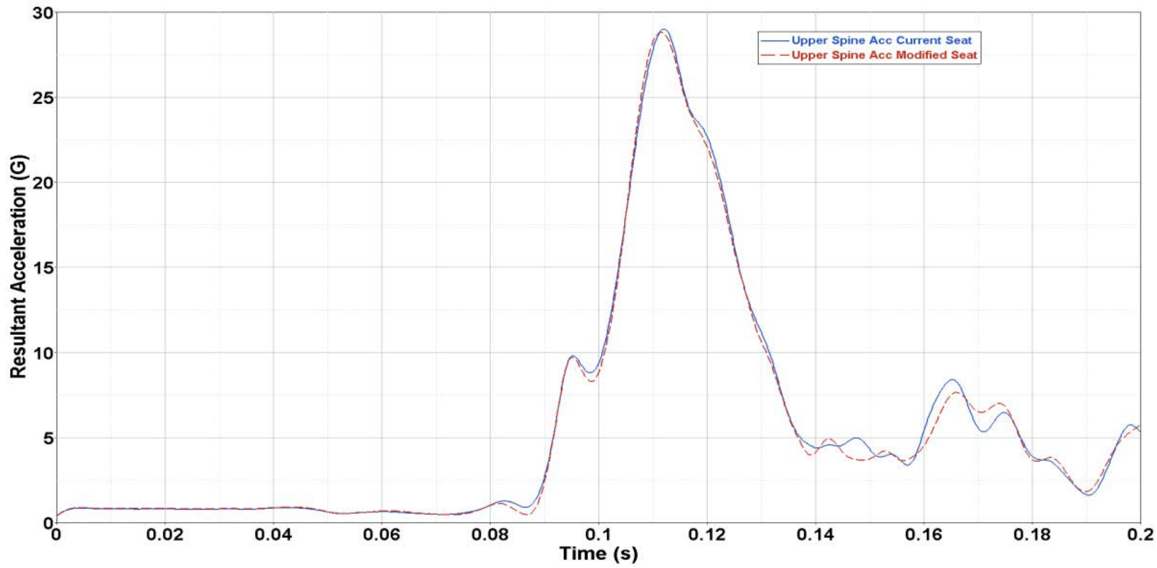

Figure 4.8 Upper Spine Acceleration Response

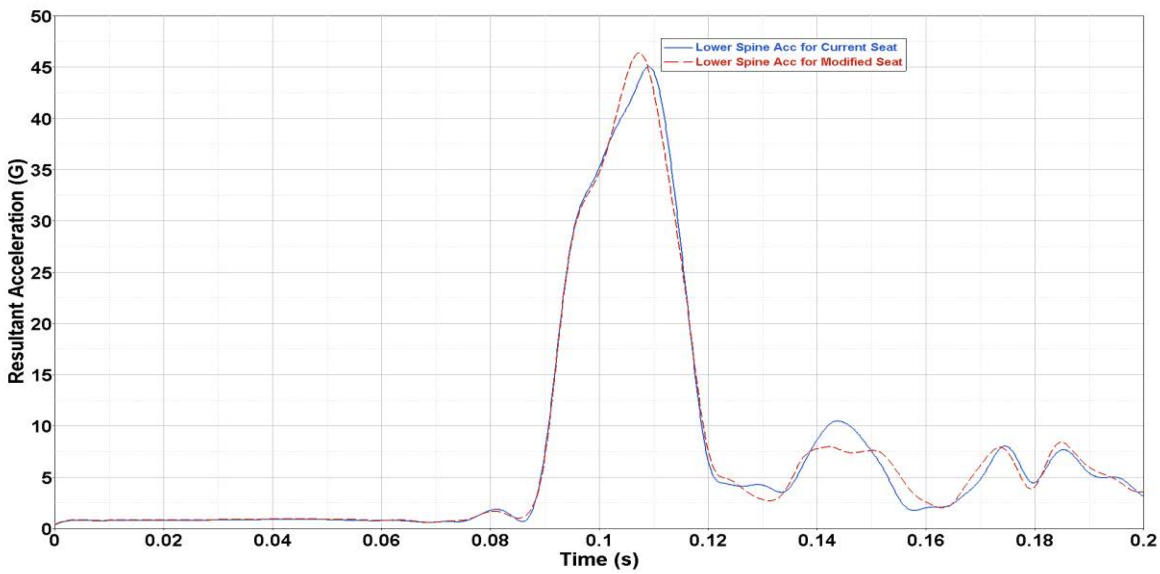

Figure 4.9 Lower Spine Acceleration Response

Figures 4.8 and 4.9 show the comparison between the upper and lower spine accelerations of the EuroSID-IIre and it can be observed that the acceleration responses of occupant in modified seat position are comparatively less when compared to the occupant in the original seat position. The reason behind the decrease in acceleration responses of the occupant is because of the relocation of the driver seat's position laterally inward for about 18 mm which reduces the velocity with which the occupant is impacted and delays the contact between the occupant and the intruding surface.

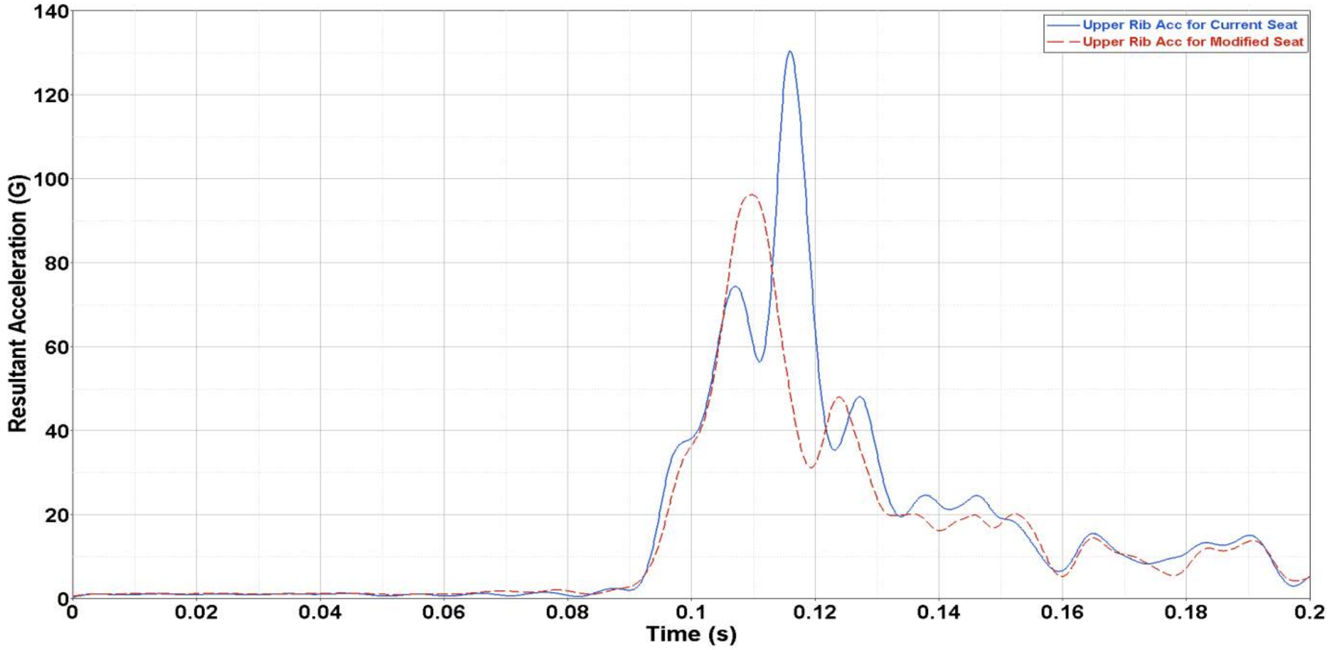

Figure 4.10 Upper Rib Acceleration Response

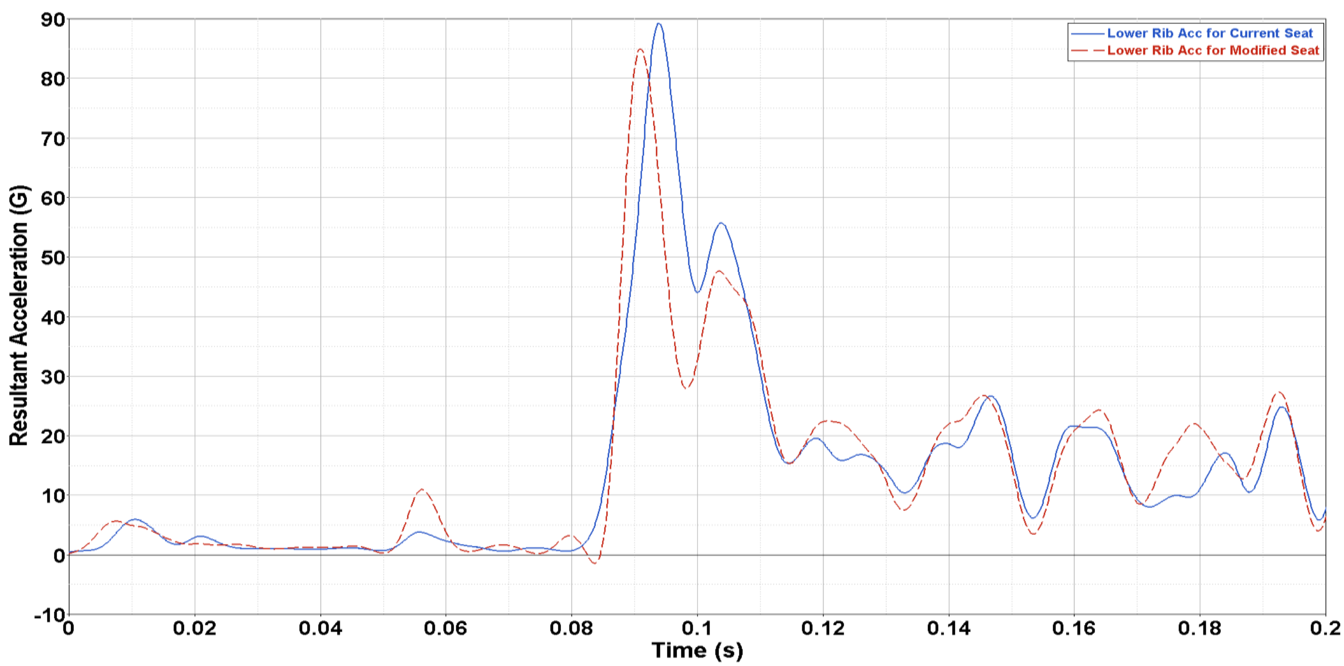

Figure 4.11 Lower Rib Acceleration Response

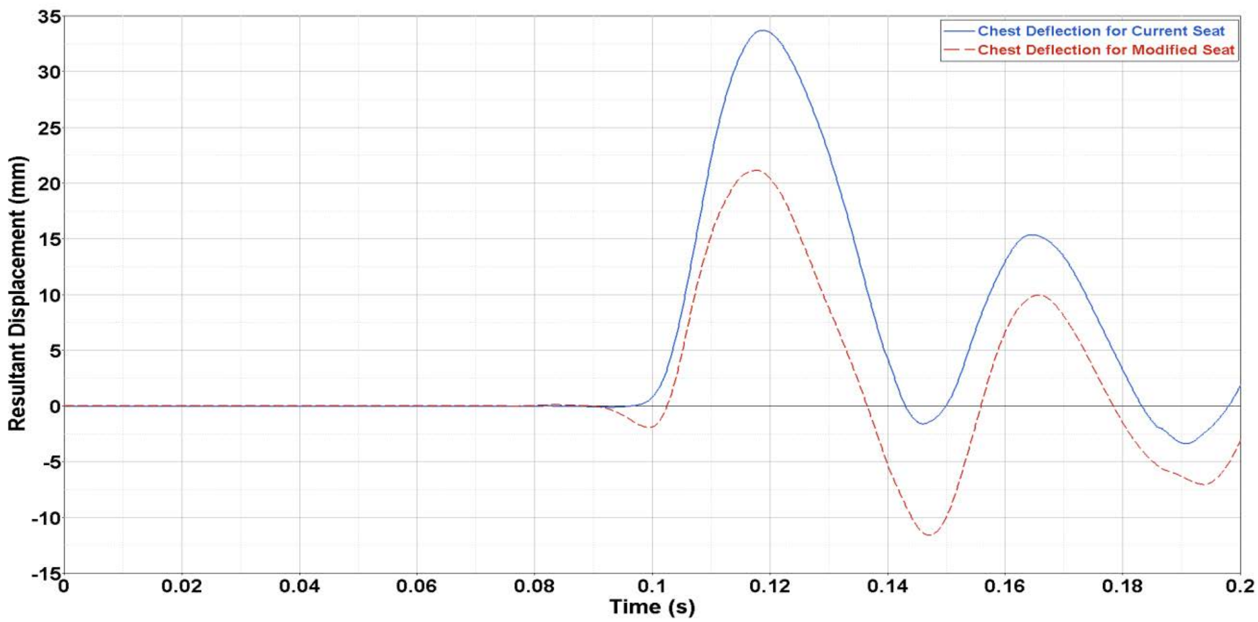

Figure 4.12 Dummy Chest Deflections

Figures 4.10, 4.11, 4.12 show the comparison the upper rib acceleration and the lower rib acceleration response and the occupant chest deflections for both the simulations. From the graphs, it can be inferred that the general acceleration response attained for the dummy in modified seat position are comparatively lower when compared to dummy in original seat position.

The injury parameters will be discussed in the following section, which are of significant importance, as they indicate the potential injuries to the occupants in the two different scenarios.

4.7 Injury Biomechanics

Injury biomechanics describes the effect of impact loads have on human body. Human body will experience mechanical and psychological changes due to such mechanical loads. If the biological system deforms beyond a limit of recoverability it experiences Injury, resulting in damage to anatomical structures and altering normal function. Such mechanisms are referred as “injury mechanism” and the intensity is recognized by the expression “injury severity”.

Injury parameter is a physical parameter that correlates well with injury severity of the body region to be examined. Many schemes have been proposed for ranking and quantifying injuries. Anatomical scales describe the injury in terms of the type of injury, its relative severity and the anatomical location. Abbreviated Injury Scale (AIS) is a widely accepted anatomical scale. AIS distinguishes the injury levels as shown in Table 4.3 [16]

Table 4.3 Abbreviated Injury Scales [16]

AIS	**Severity code**
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum Injury (virtually un-survivable)
9	Unknown

AIS is a "threat to life" ranking where the numerical values have no significance other than to designate order.

4.7.1 Injury / Pass-Fail Criteria for EuroSID-IIre

An injury criterion can be defined as a biomechanical index of exposure severity, which indicates the potential for impact induced injury by its magnitude. Several reasons why injury criterion was developed are:

- To get better understanding of injury mechanisms and the situations when they occur.
- To relate loading conditions during impacts to certain levels of AIS injury scales.
- So that the data can be used for efficient analysis of automobile safety and optimization.

The important evaluation criteria in side impact collisions with roadside objects are head and torso injuries and the amount of intrusion into the side structure. The Thoracic Trauma Index (TTI) and the Pelvis Lateral Acceleration are the main injury criteria developed by NHTSA for the body regions mentioned above. The usage of these parameters improves understanding.

The various types of injury criteria which are available for side impact occupant evaluation are shown in Table 4.4. As described in the FMVSS 214 regulation, the injury assessment of a car occupants in side impact crashes are evaluated by the two regulatory test configurations MDB and pole tests. The occupant/driver is represented by a EuroSID-IIre crash test dummy. The injury pass-fail criteria for the dummy, and chances of potential injuries to the occupant, are evaluated by a number of parameters, evaluated based on the dummy responses. These are listed in Table 4.4.

Table 4.4 Injury / Pass-Fail criteria for EuroSID-IIre [11]

Injury criteria	**Requirements**
Upper Rib Deflection (mm)	**<44**
Lower Rib Deflection (mm)	**<44**
Middle Rib Deflection (mm)	**<44**
Total Abdominal Force (N)	**2500**
Pubic Symphysis Force (N)	**6000**
Pelvis Acceleration (G's)	**<130**
TTI (g’s)	**<85**
Chest Deflection (mm)	**<44**
Lwr Spine Acceleration (G’s)	**<82**
Viscous Criteria (m/sec)	**1.0**

4.8 Injury Parameters for FMVSS 214 MDB Test

The various dummy injury parameters were evaluated for both the dummy seat positions according to FMVSS 214 side impact test.

Table 4.5 Injury Parameters for FMVSS 214 MDB Test

EuroSID-II RE Physical Responses	Requirements	Original Seat Position	Modified Seat Position
Upper Rib Deflection (mm)	<44	46	34
Lower Rib Deflection (mm)	<44	36	28
Middle Rib Deflection (mm)	<44	31	27
Total Abdominal Force (N)	2500	2636	2100
Pubic Symphysis Force (N)	6000	3717	3361
Pelvis Acceleration (G's)	<130	74	61
TTI (g's)	<85	88	71
Chest Deflection (mm)	<44	34	22
Lwr Spine Acceleration (G's)	<82	47	43
Viscous Criteria (m/sec)	1.0	0.74	0.67

It can be observed from Table 4.5 that the critical dummy injury values for dummy in modified seat position are comparatively less when compared to dummy in original seat position according to FMVSS 214 side impact regulation. For the original seat position, the Upper Rib, Thoracic Trauma Index and Chest injuries are to be exceeded in FMVSS 214 MDB test. Therefore, movement of the seat laterally inward significantly reduces the potential injuries to the occupant's Upper rib, Abdominal forces and Thoracic accelerations.

CHAPTER 5

SIMULATION RESULTS FOR SIDE IMPACT POLE TEST

Designing automobiles with improved protection to vehicle occupants in side impact collisions has become an important area of concern in safety research. One of which is the side impact crashes into fixed narrow obstacles like trees, utility poles, supports, etc.

In the FMVSS 214 regulation, MDB does not demonstrate the worst-case scenario since there is too much sill loading and pillar loading. The newly proposed test by NHTSA is more favorable since the area subjected to impact is much narrower when compared to the MDB tests. Therefore, greater crash energy is concentrated on the driver's side and transmitted onto the occupant.

Figure 5.1 Side Impact Model of Toyota Yaris Car as per Side Pole Test

This test procedure, as shown in Figure 5.1, the vehicle is propelled sideways at an approach angle of 75 degrees with a speed of 20 mph into a fixed rigid pole. As the pole is relatively narrow, there is major penetration into the side of the car thereby affecting the occupant severely on the driver's seat.

In this test, the pole is set to align with the occupant or the driver's head, so that the worst-case scenario can be obtained where the occupant's body strikes the inner door and the driver's head strikes the pole.

5.1 Impactor Modeling

As shown in Figure 5.2, the rigid pole is modelled using the Finite Element Preprocessor software Hypermesh. The cross section of the pole is meshed using rigid hexa elements. The pole is placed just outside the driver's door and aligned with the driver's head. Table 5.1 summarizes the total number of parts, nodes and hexa elements present in the rigid pole.

Table 5.1 Model Summary of Rigid Pole

Number of Parts	1
Number of Nodes	121104
Number of Hexa Elements	114400

It measures 254 mm (10 inches) in diameter and 100 mm above ground to above roofline. It is constrained in all degrees of freedom to simulate the rigid pole.

Figure 5.2 Finite Element Model of Rigid Pole

5.2 Simulation Results

The Toyota Yaris car with current and modified seat is impacted to the stationary Rigid Pole under the FMVSS 214 regulation. According to FMVSS 214 regulation, the moving car hits the stationary rigid pole at an angle of 75 degrees at a speed of 20 mph. Figures 5.3(a, b, c, d, e, f, g, h) shows the side impact analysis which was carried on Toyota Yaris according to FMVSS 214 side impact pole test standards. The simulation of the side impact pole test at different time intervals is shown in following figures.

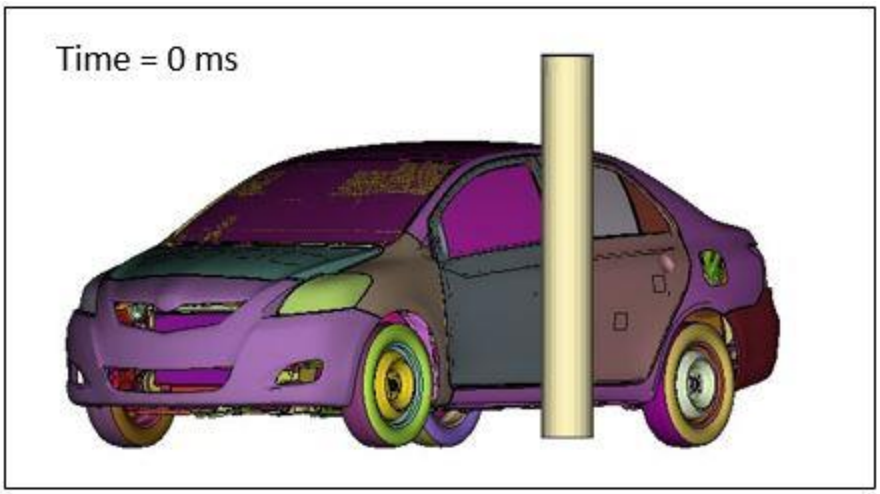

Figure 5.3(a) FMVSS Side Impact Pole Test on Toyota Yaris at 0ms

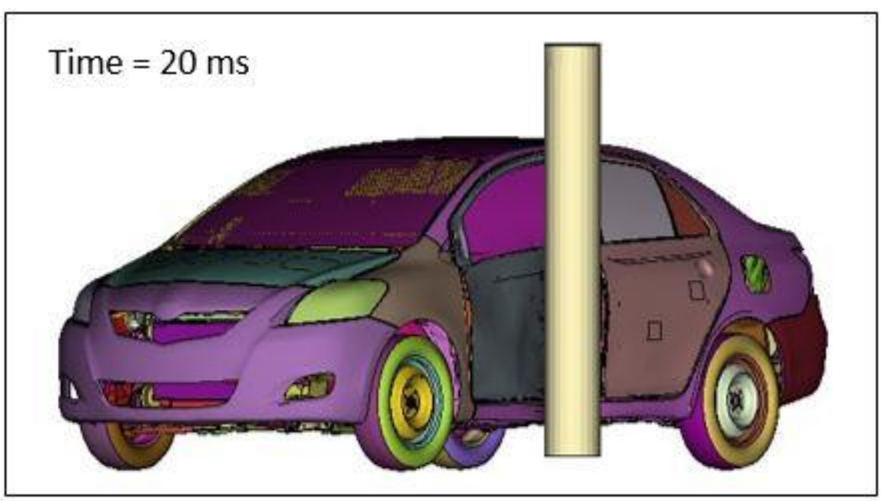

Figure 5.3(b) FMVSS Side Impact Pole Test on Toyota Yaris at 20ms

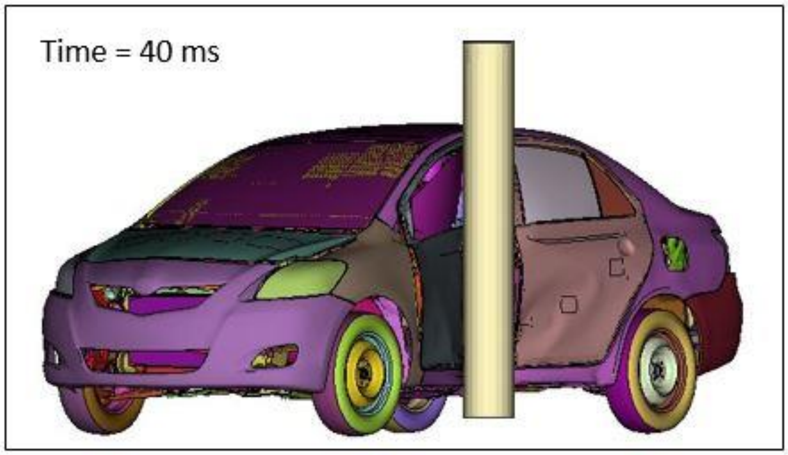

Figure 5.3(c) FMVSS Side Impact Pole Test on Toyota Yaris at 40ms

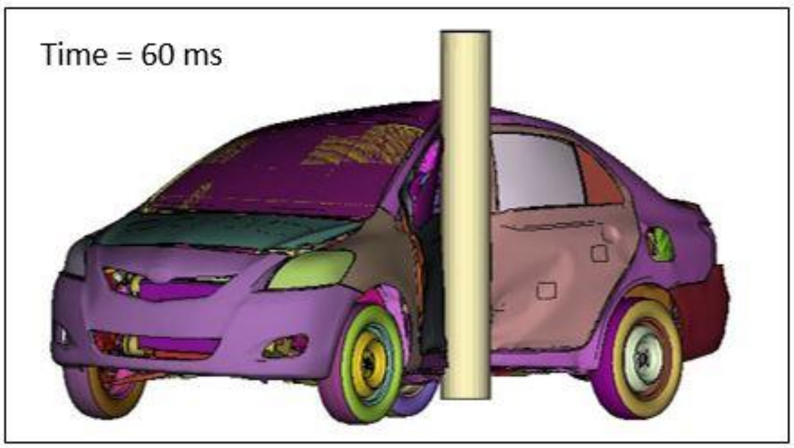

Figure 5.3(d) FMVSS Side Impact Pole Test on Toyota Yaris at 60ms

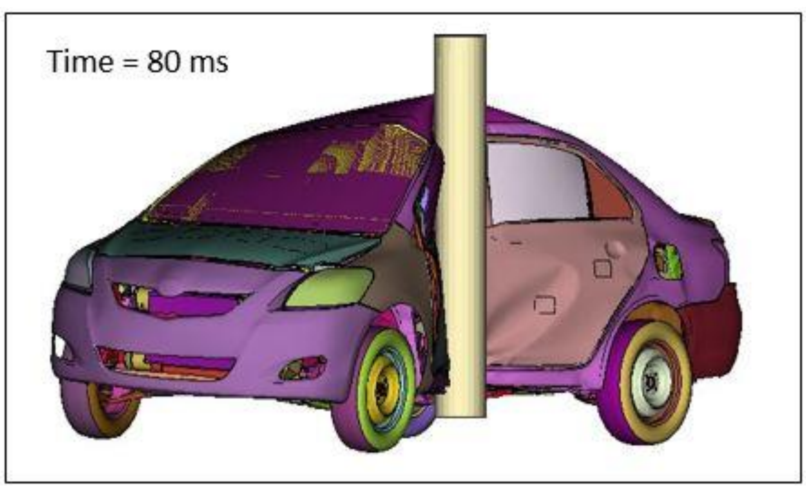

Figure 5.3(e) FMVSS Side Impact Pole Test on Toyota Yaris at 80ms

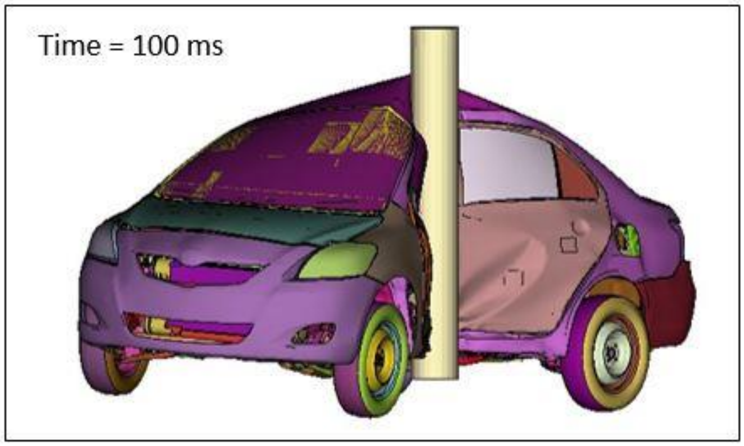

Figure 5.3(f) FMVSS Side Impact Pole Test on Toyota Yaris at 100ms

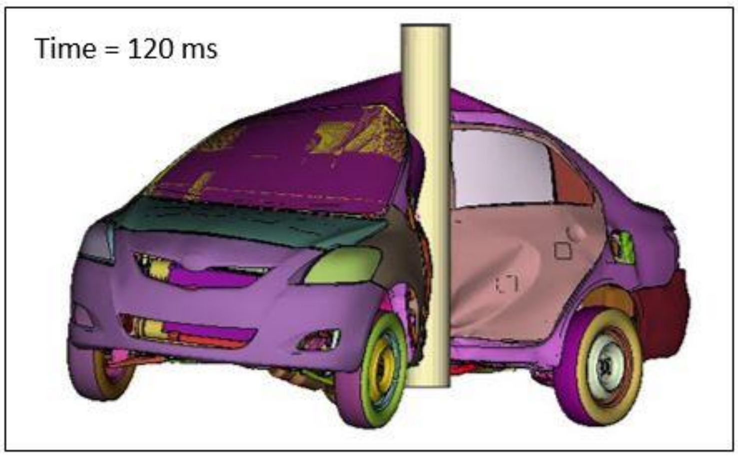

Figure 5.3(g) FMVSS Side Impact Pole Test on Toyota Yaris at 120ms

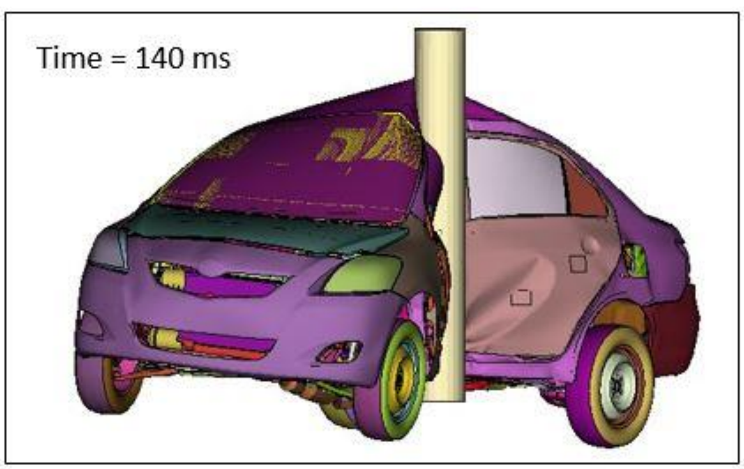

Figure 5.3(h) FMVSS Side Impact Pole Test on Toyota Yaris at 140ms

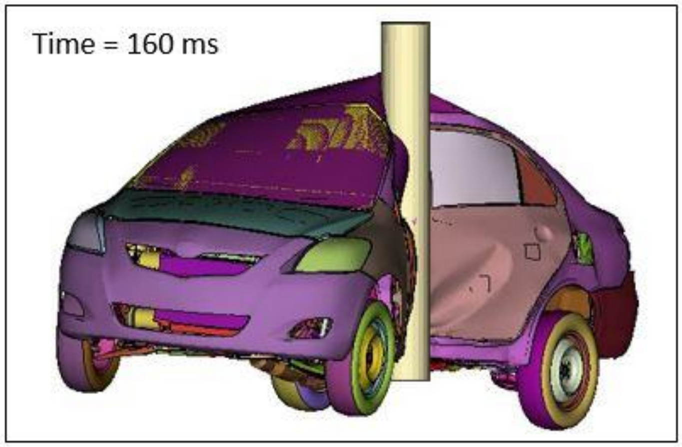

Figure 5.3(i) FMVSS Side Impact Pole Test on Toyota Yaris at 160ms

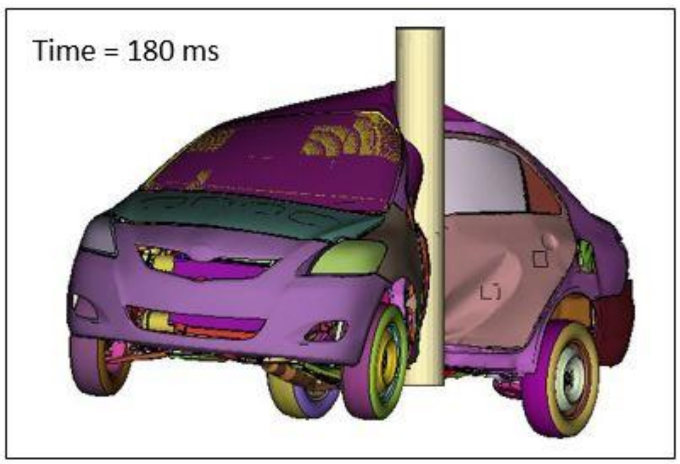

Figure 5.3(j) FMVSS Side Impact Pole Test on Toyota Yaris at 180ms

From the simulations, of the side impact pole test it can be seen that the vehicle intrusion in this test is much larger, when compared to the side impact 214 regulation with moving deformable barrier. In this pole test, the vehicle strikes the rigid pole at a velocity of 20 mph, and as the pole being narrow, the vehicle rotates about the pole. Thus, there is a point of impact involved in this crash scenario. The occupant is prone to serious injuries.

5.3 Occupant Response with Current Seat Simulation Results

Side impact Pole test with EuroSID-IIre dummy as an occupant in original seat position was simulated as shown in Figures 5.4(a,b,c,d,e,f,g,h,i,j). Following Figures shows occupant behavior at different time intervals and impact speed.

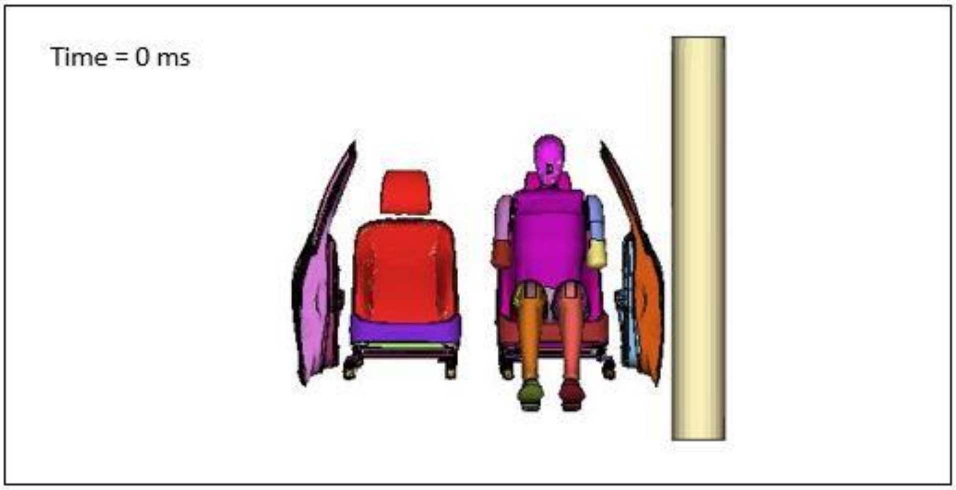

Figure 5.4(a) Occupant Response with Current Seat Position at 0ms

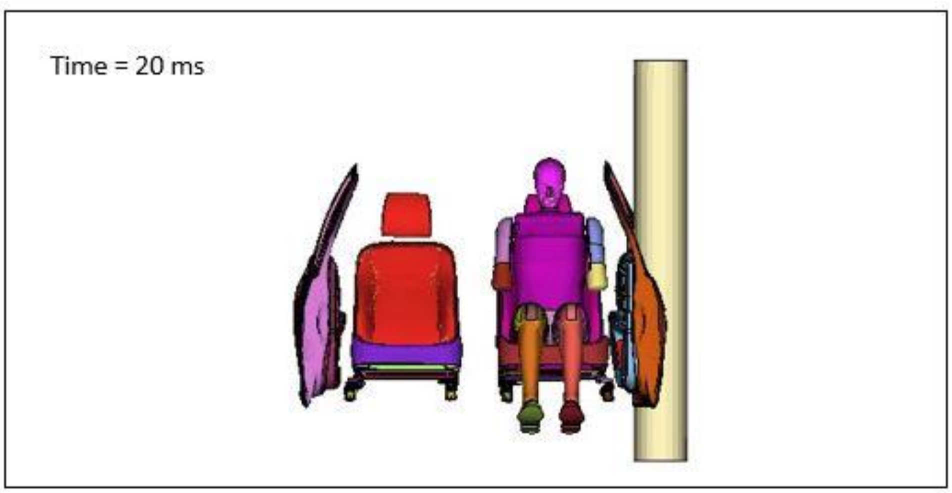

Figure 5.4(b) Occupant Response with Current Seat Position at 20ms

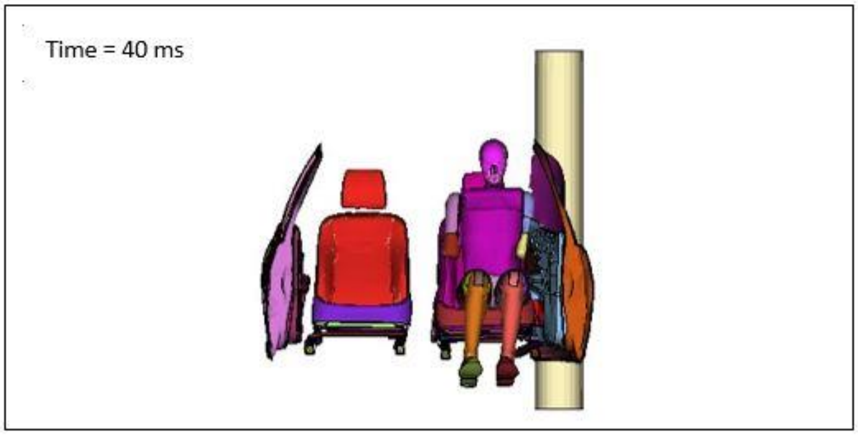

Figure 5.4(c) Occupant Response with Current Seat Position at 40ms

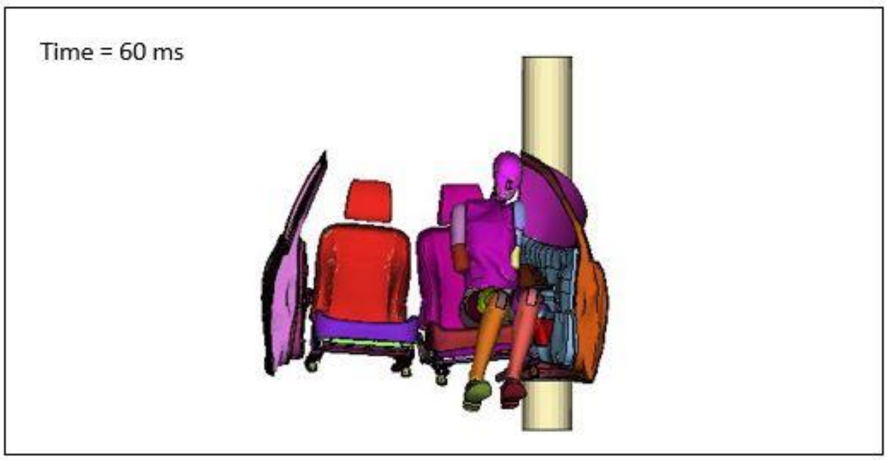

Figure 5.4(d) Occupant Response with Current Seat Position at 60ms

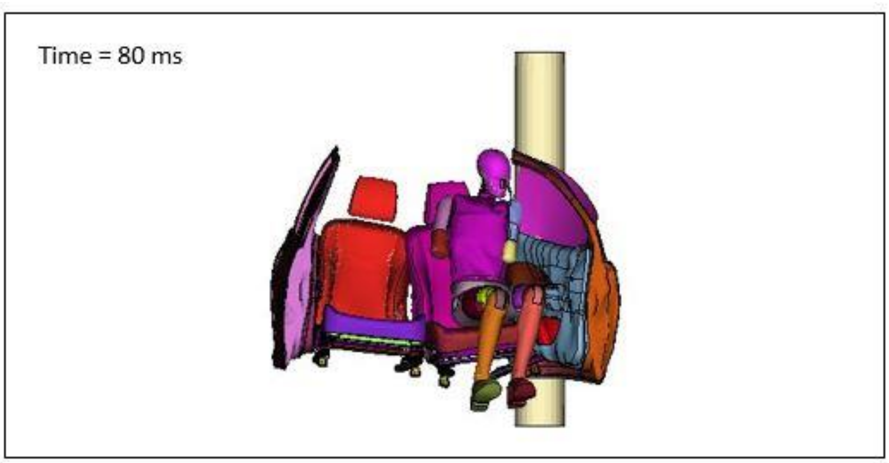

Figure 5.4(e) Occupant Response with Current Seat Position at 80ms

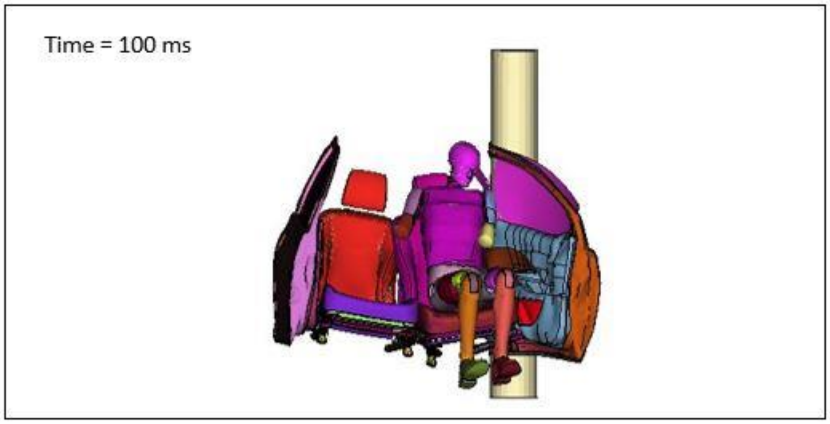

Figure 5.4(f) Occupant Response with Current Seat Position at 100ms

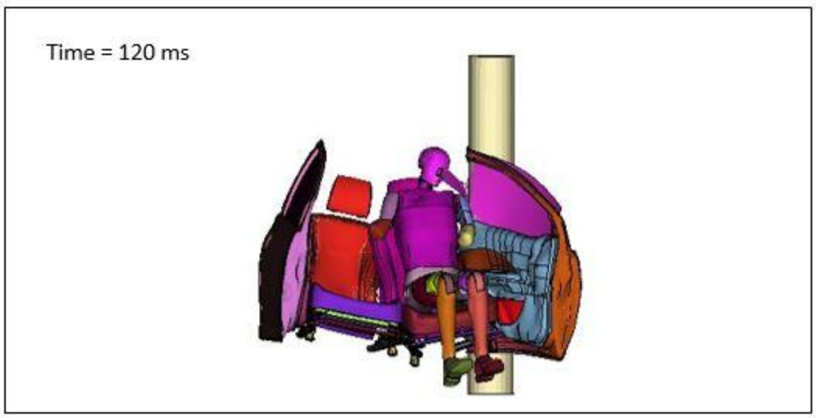

Figure 5.4(g) Occupant Response with Current Seat Position at 120ms

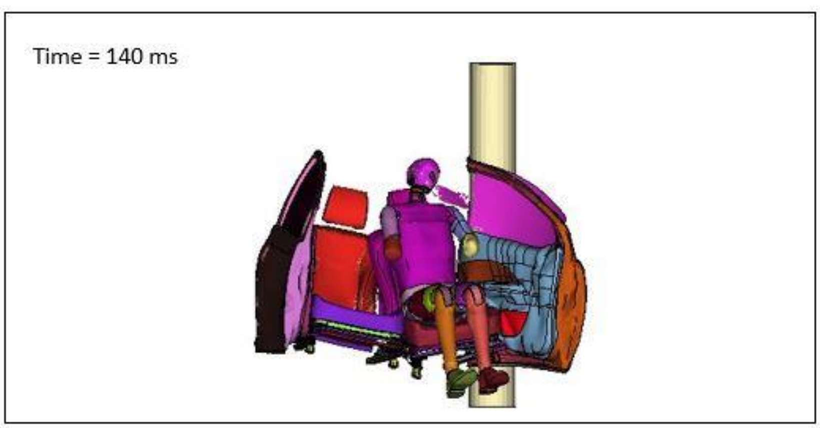

Figure 5.4(h) Occupant Response with Current Seat Position at 140ms

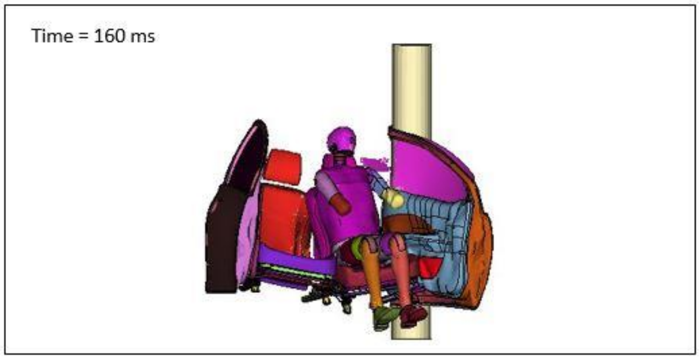

Figure 5.4(i) Occupant Response with Current Seat Position at 160ms

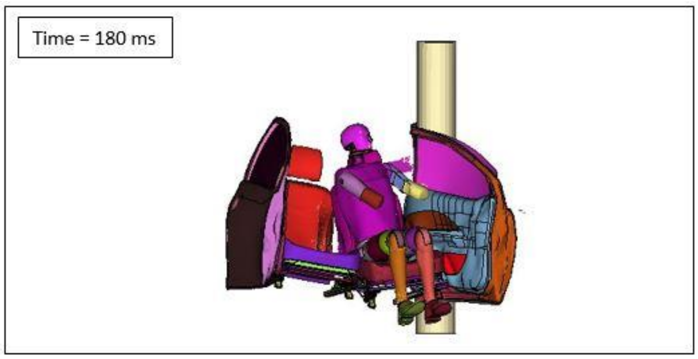

Figure 5.4(j) Occupant Response with Current Seat Position at 180ms

5.4 Occupant Response with Modified Seat Simulation Results

Side impact Pole test with EuroSID-IIre dummy as an occupant in modified seat position was simulated as shown in Figures 5.5(a,b,c,d,e,f,g,h,i,j). Following Figures shows occupant behavior at different time intervals and impact speed.

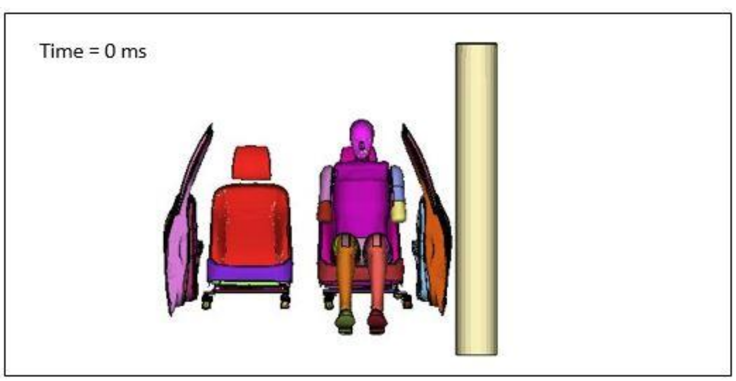

Figure 5.5(a) Occupant Response with Modified Seat Position at 0ms

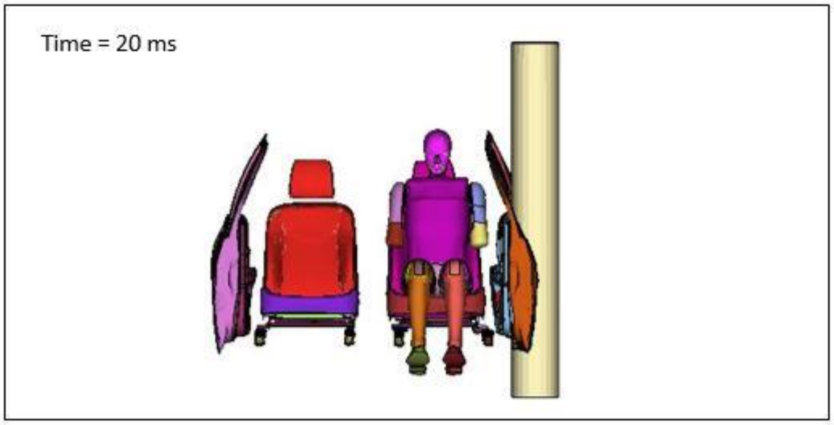

Figure 5.5(b) Occupant Response with Modified Seat Position at 20ms

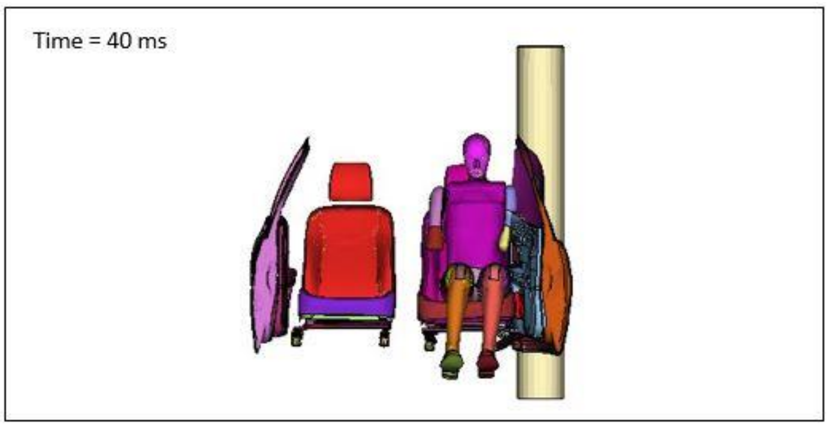

Figure 5.5(c) Occupant Response with Modified Seat Position at 40ms

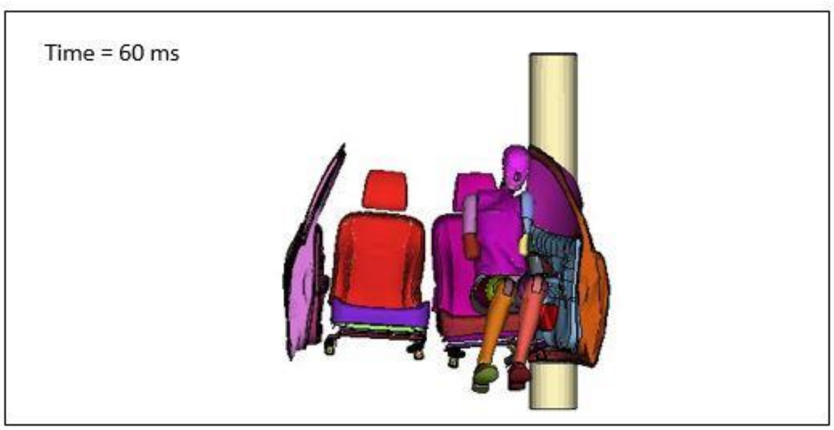

Figure 5.5(d) Occupant Response with Modified Seat Position at 60ms

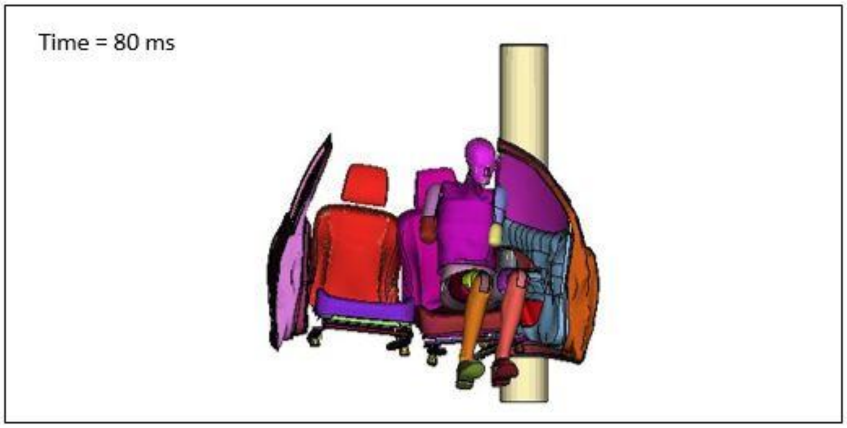

Figure 5.5(e) Occupant Response with Modified Seat Position at 80ms

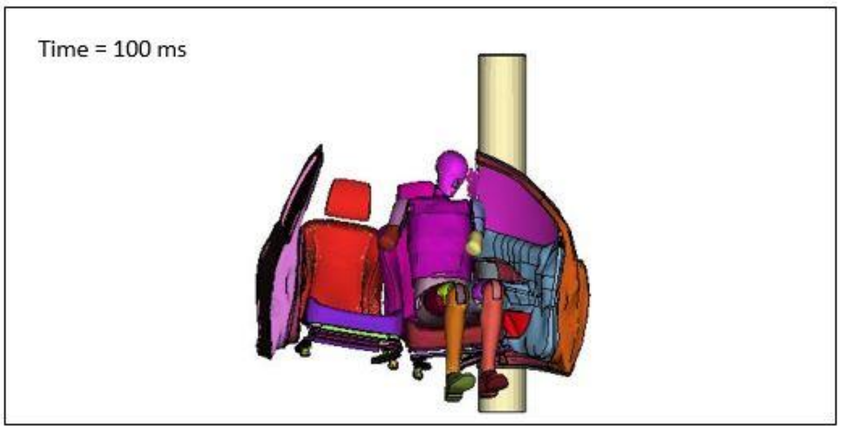

Figure 5.5(f) Occupant Response with Modified Seat Position at 100ms

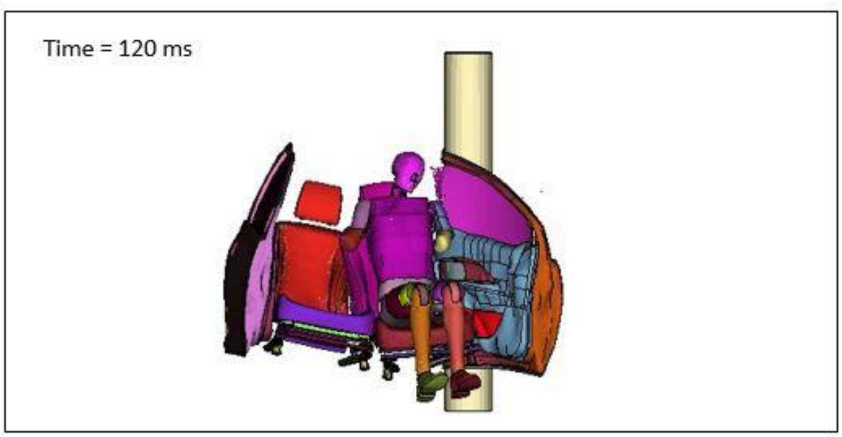

Figure 5.5(g) Occupant Response with Modified Seat Position at 120ms

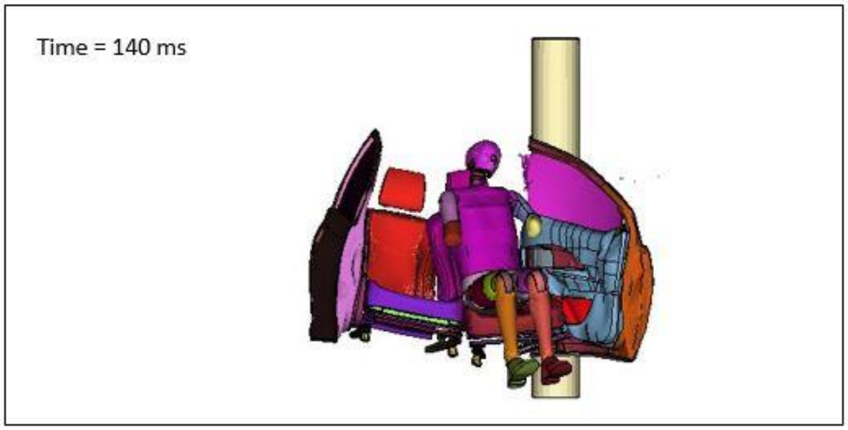

Figure 5.5(h) Occupant Response with Modified Seat Position at 140ms

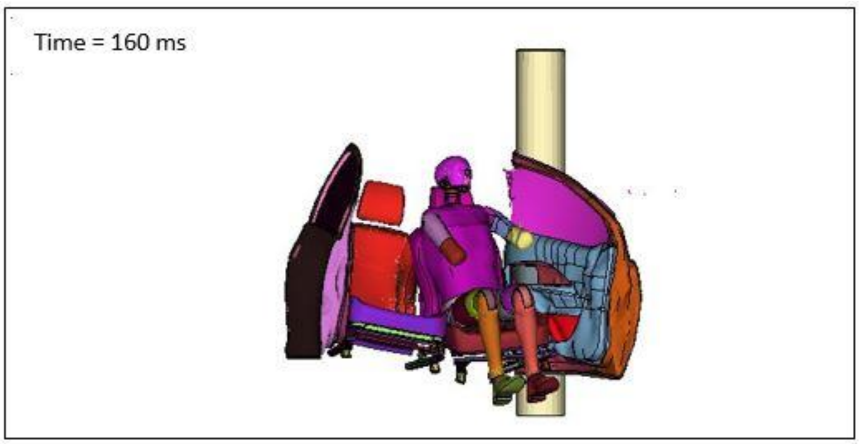

Figure 5.5(i) Occupant Response with Modified Seat Position at 160ms

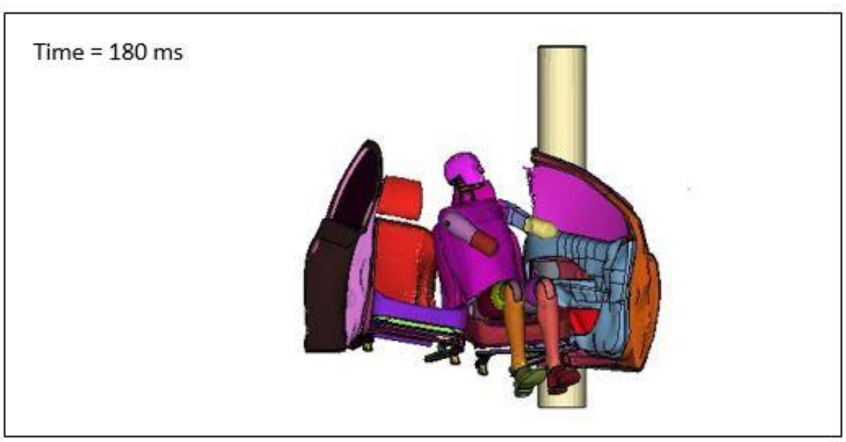

Figure 5.5(j) Occupant Response with Modified Seat Position at 180ms

From these simulations, the occupant dynamic response in the side impact pole test regulation can be observed. It can be seen that due to the modification of the seat as the seat's position has been changed the intrusion of the pole on to the door and the load exerted on the occupant is decreased which reduces the injuries happening to occupant.

5.5 Door Intrusions for FMVSS 214 Side Pole Test

The door intrusion is measured by selecting a node at the center of the door. It is basically the distance between the driver side door and passenger side door, and it is measured before the simulation and post simulation.

The door intrusions when the car hits the pole according to FMVSS 214 side impact pole test regulation as shown in Table 5.2 for both original seat position and modified seat position. It can be seen that movement of the seat laterally inward reduces the door intrusion by about 5.4 cm or about 3.2%.

Table 5.2 Intrusion of Door for FMVSS 214 Side Pole Test

	Distance between Door Pre-Simulation (cm)	**Distance between Door Post Simulation (cm)**	**Door Intrusion (cm)**	**Percentage of Intrusion (%)**
Current Seat Position	168.6	107.3	**61.3**	**36.4**
Modified Seat Position	168.6	112.7	**55.9**	**33.2**

5.6 B-Pillar Intrusions for FMVSS 214 Side Pole Test

The B-Pillar intrusion is measured by selecting a random node at the center of the B-Pillar and basically it is the distance between the driver side B-Pillar and passenger side B-Pillar and we measure it for pre-simulation and post simulation.

The B-pillar intrusions when the vehicle hits the rigid pole according to FMVSS 214 side impact pole test regulation are listed in Table 5.3 for both original and modified seat position. As shown, the movement of the seat inward reduces the B-pillar intrusion by 1.8cm or about 1.4%.

Table 5.3 Intrusion of B-pillar for FMVSS 214 Side Pole Test

	Distance between B-pillar Pre-Simulation (cm)	**Distance between B-pillar Post Simulation (cm)**	**B-pillar Intrusion (cm)**	**Percentage of Intrusion (%)**
Current Seat Position	137.5	98.6	**38.9**	**28.3**
Modified Seat Position	137.5	100.4	**37.1**	**26.9**

5.7 Occupant Dynamic Responses

The responses of the occupant in each scenario has been recorded and the acceleration response for critical dummy injury parts has been compared for the current seat and modified seat positions according to the FMVSS 214 side impact pole test regulation. It is observed that there is reduction in values obtained. Significant bending and torsion has been observed in the occupant.

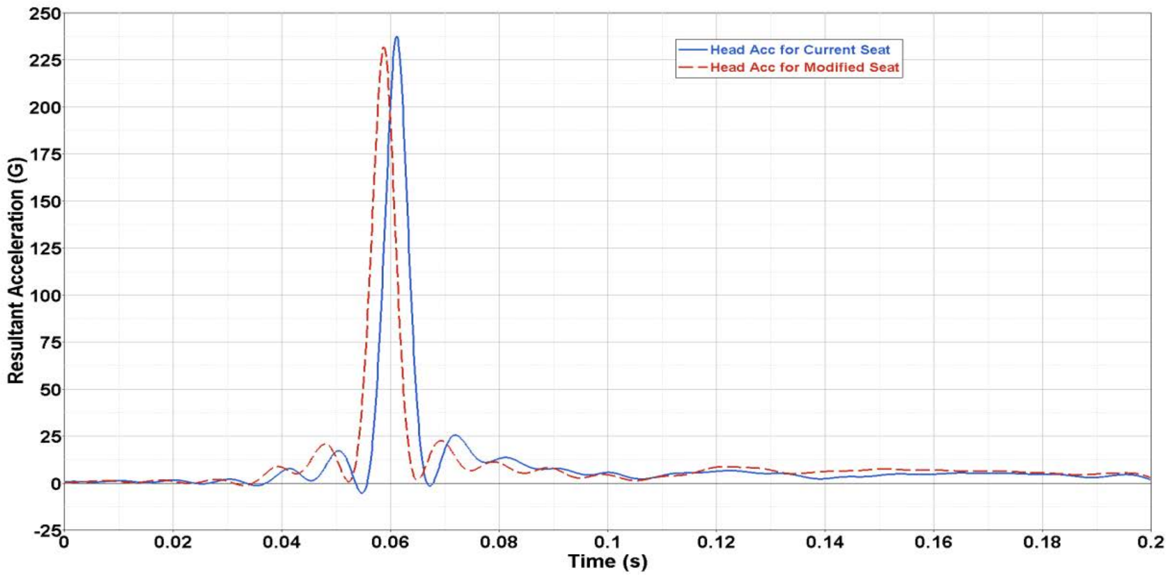

Figure 5.6 Head Acceleration Response

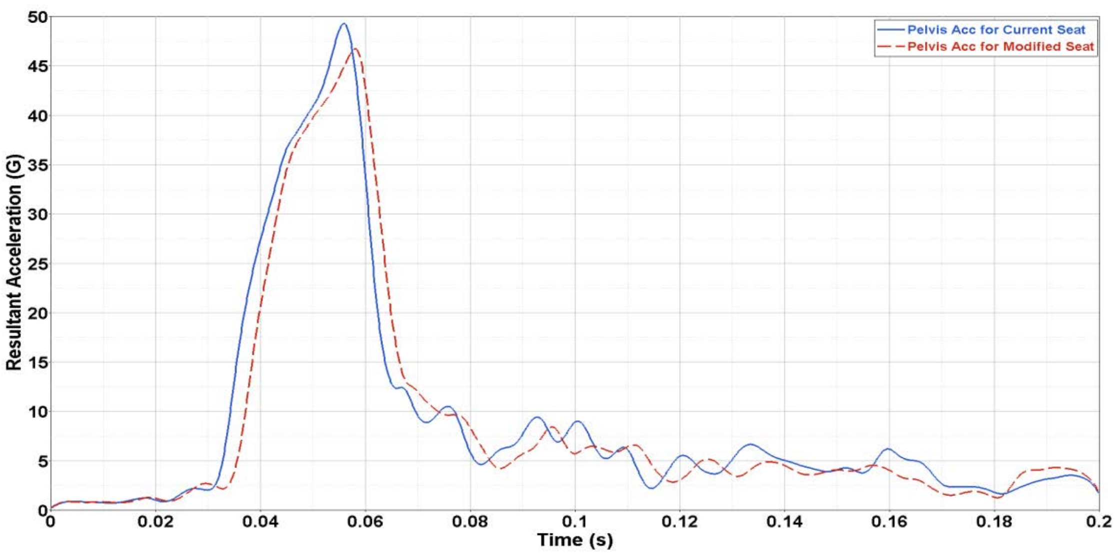

Figure 5.7 Pelvis Acceleration Response

Figures 5.6 and 5.7 shows the comparison of the Head CG acceleration and the pelvis region acceleration of the driver occupant. From the graphs, it can be observed that the acceleration response are comparatively lesser for the occupant in the modified seat's position.

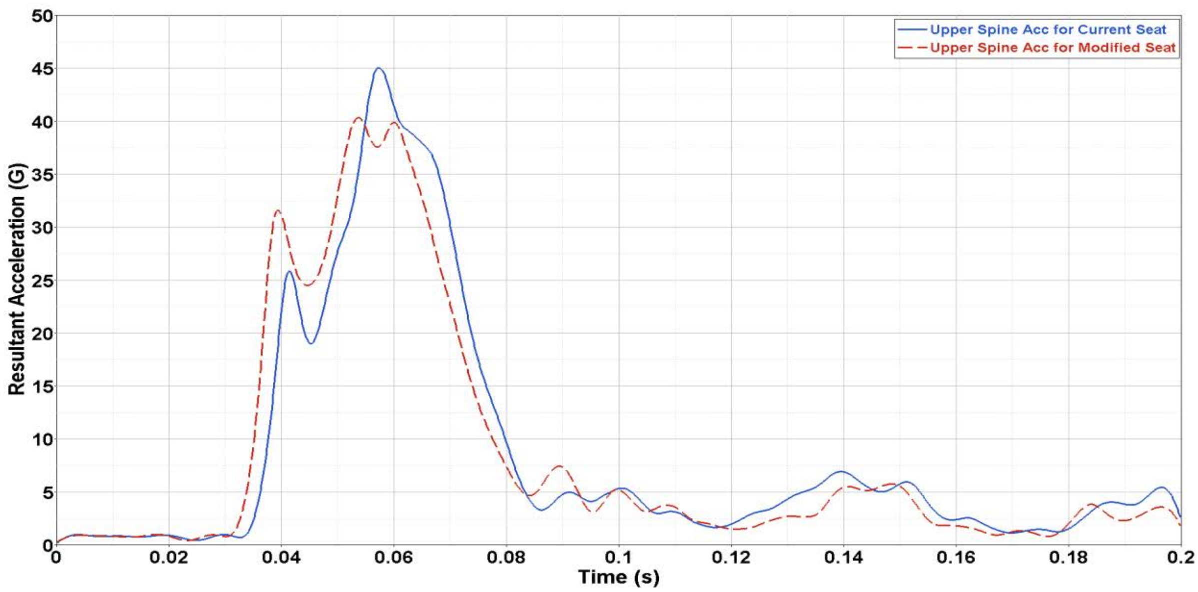

Figure 5.8 Upper Spine Acceleration Response

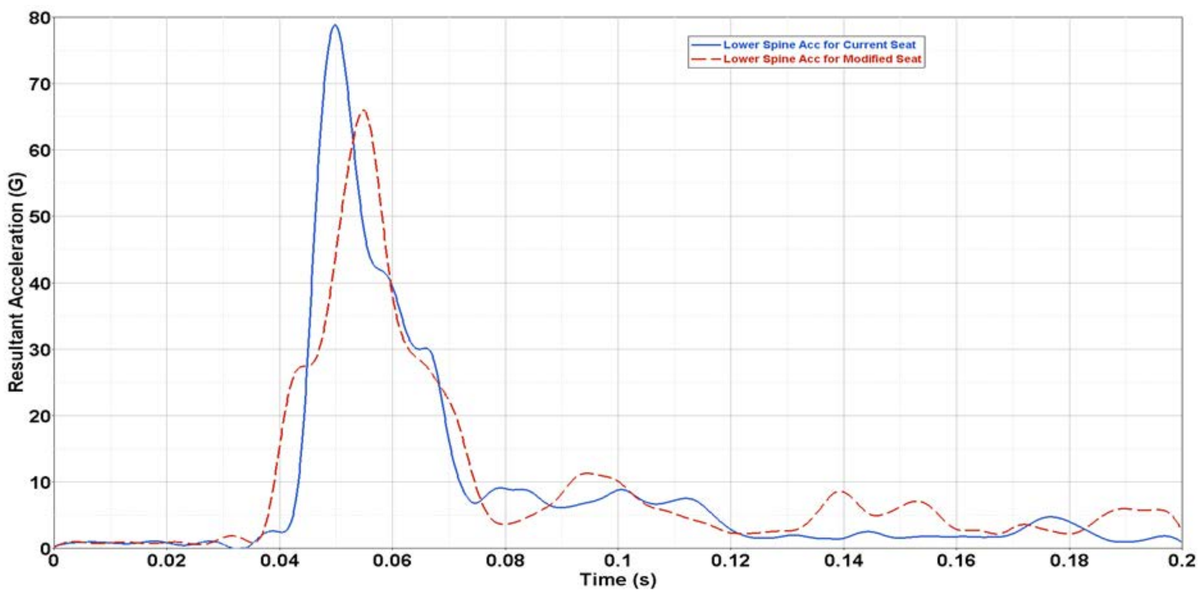

Figure 5.9 Lower Spine Acceleration Response

Figures 5.8 and 5.9 shows the comparison between the upper and lower spine accelerations and it can be seen that the acceleration response are comparatively lesser for the occupant in the modified seat's position.

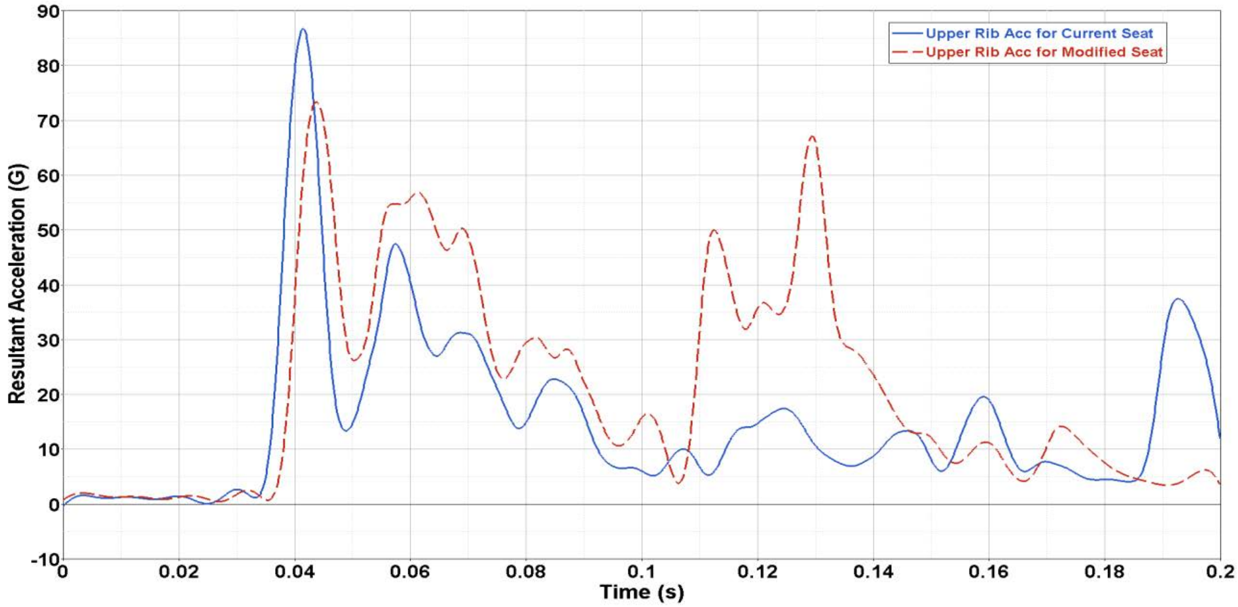

Figure 5.10 Upper Rib Acceleration Response

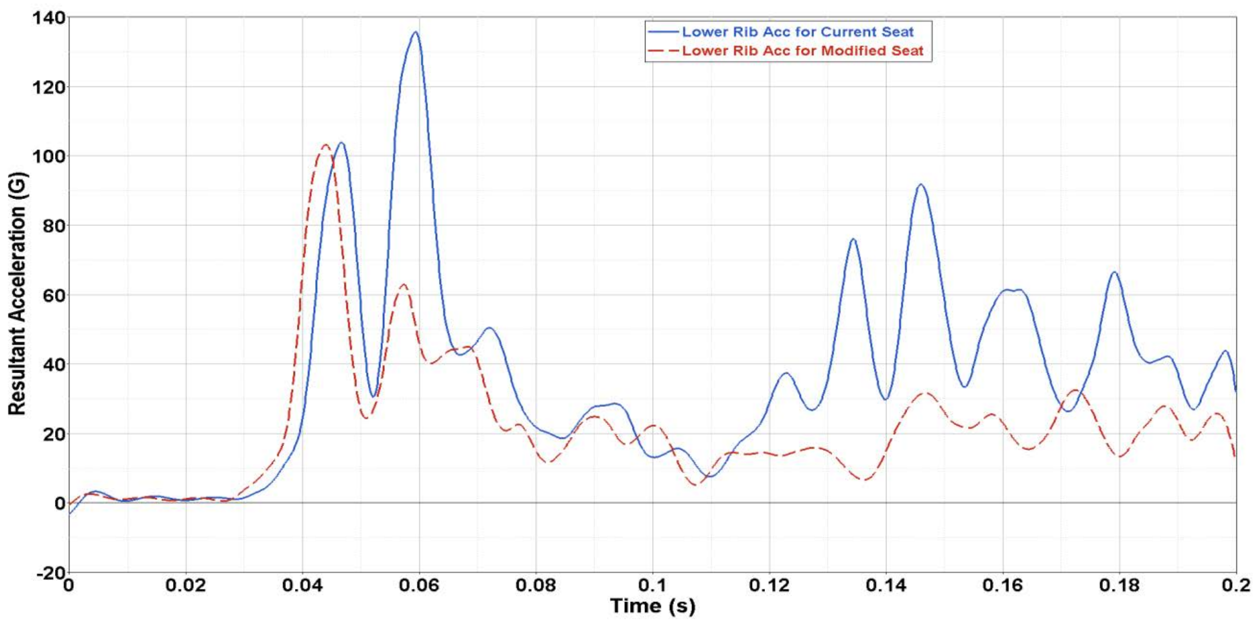

Figure 5.11 Lower Rib Acceleration Response

Figures 5.10 and 5.11 show the comparison of the upper rib acceleration and the lower rib acceleration response for both the simulations. The reason behind the decrease in acceleration responses of the occupant is because of the relocation of the driver seat's position laterally inward. for about 18 mm which reduces the velocity with which the occupant is impacted.

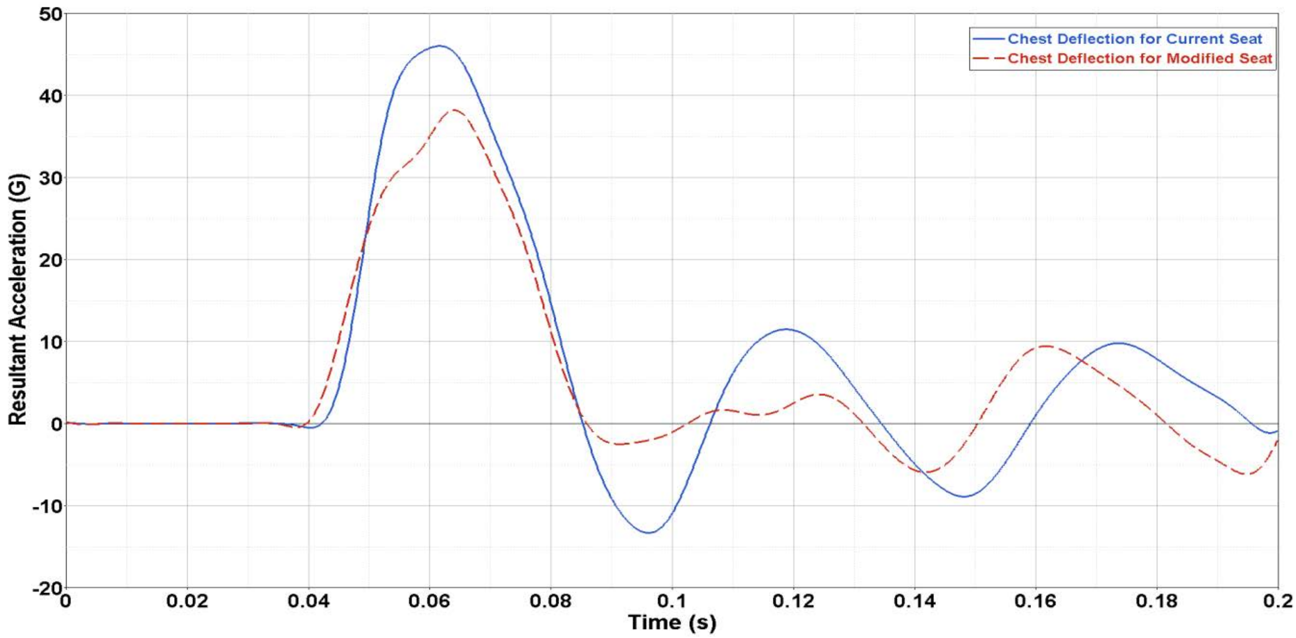

Figure 5.12 Dummy Chest Deflections

Figures 5.10, through 5.12 shows the comparison the upper rib acceleration and the lower rib acceleration response and the occupant chest deflections for both the simulations. From the graphs, it can be inferred that the general acceleration response attained for the dummy in modified seat position are comparatively lower when compared to dummy in original seat position according to FMVSS 214 side impact pole test. The decrease in acceleration responses of the occupant is because of the relocation of the driver seat's position laterally inward for about 18 mm which reduces the velocity with which the occupant is impacted and delays the contact between the occupant and the intruding surface.

The injury parameters will be discussed in the following section, which are of significant importance, as they indicate the potential injuries to the occupants in the two different scenarios.

5.8 Injury Parameters for FMVSS 214 Side Pole Test

The various dummy injury parameters evaluated for both the occupant in current seat position and in modified seat position according to FMVSS 214 side impact pole test.

Table 5.4 Injury Parameters for FMVSS 214 Side Pole Test

EuroSID-II RE Physical Responses	Requirements	Original Seat Position	Modified Seat Position
Upper Rib Deflection (mm)	<44	43	40
Lower Rib Deflection (mm)	<44	47	38
Middle Rib Deflection (mm)	<44	46	39
Total Abdominal Force (N)	2500	2854	2373
Pubic Symphysis Force (N)	6000	2646	2457
Pelvis Acceleration (G's)	<130	50	46
TTI (g's)	<85	87	78
Chest Deflection (mm)	<44	48	39
Lwr Spine Acceleration (G's)	<82	78	67
Viscous Criteria (m/sec)	1.0	0.62	0.56

From Table 5.4, it can be observed that the critical dummy injury values for dummy in modified seat position are comparatively less when compared to dummy in original seat position according to FMVSS 214 side impact pole test regulation. For the original seat position the Lower Rib, Middle Rib, Abdominal Forces, Thoracic Trauma Index and Chest injuries are to be exceeded in FMVSS 214 Pole test. Therefore, movement of the seat laterally inward significantly reduces the chances of injury to the occupant's Lower rib, Middle rib, Abdominal forces, Thoracic accelerations and the Chest deflection.

CHAPTER 6

COMPARISON OF ALL RESULTS

6.1 Comparison of all results

Table 6.1 shows the comparison of door, B-pillar intrusions and the occupant injuries for original seat position and modified seat position according to FMVSS 214 MDB test and Pole test.

Table 6.1 Comparison of all Results from MDB and Pole Test

		FMVSS 214 MDB Test		Side Pole Test	
	Requirements	Original Seat Position	Modified Seat Position	Original Seat Position	Modified Seat Position
Door Intrusion (cm)		27.9	26.6	61.3	55.9
B-Pillar Intrusion (cm)		20.7	18.8	38.9	37.1
Upper Rib Deflection (mm)	<44	46	34	43	40
Lower Rib Deflection (mm)	<44	36	28	47	38
Middle Rib Deflection (mm)	<44	31	27	46	39
Total Abdominal Force (N)	2500	2636	2100	2854	2373
Pubic Symphysis Force (N)	6000	3717	3361	2646	2457
Pelvis Acceleration (G's)	<130	74	61	50	46
TTI (g's)	<85	88	71	87	78
Chest Deflection (mm)	<44	34	22	48	39
Lower Spine Acceleration (G's)	<82	47	43	78	67
Viscous Criteria (m/s)	1.0	0.74	0.67	0.62	0.56

From Table 6.1, it can be observed that vehicle intrusion into the pole is quite larger when compared to the one from barrier test according to FMVSS 214 MDB and side impact pole test regulation. Therefore, the door and B-pillar intrusions are larger in pole test.

The movement of the driver's seat laterally inwards for MDB test has significantly reduced the potential for injuries to the occupant's Upper Rib Deflection value which exceeds the requirements it has been reduced from 46 mm to 34mm, Total Abdominal Force exceeds the requirements is been reduced from 2636 N to 2100 N and TTI (g's) has been reduced from 88g to 71g.

It can also be observed that lateral displacement of the driver's seat inwards has significantly reduced the injuries to the occupant's Lower Rib Deflection which exceeds the requirements it has been reduced from 47mm to 38mm, Middle Rib Deflection exceeds the requirements it has been reduced from 46mm to 39mm, Total Abdominal Force exceeds the injury thresholds it has been reduced from 2854 N to 2373 N, TTI (g's) value exceeds the requirements it has been reduced from 87g to 78g and also Chest Deflection exceeds the requirements it has been reduced from 48mm to 39mm. Therefore, it is observed that the movement of the seat laterally inward significantly reduces the chances of critical injuries to the occupant.

6.2 IIHS Structural Guidelines for Side Impact Ratings

The structural intrusions of the vehicles to the MDB is determined by using the IIHS's side impact rating guidelines where the intrusion of the B-pillar is measured with respect to driver seat center line as shown in the Figure 6.1 [12].

To determine the severity of the intrusion near at the driver seat area, the distance to the seat center was measured and the minimum values were compared with the IIHS side impact rating guidelines.

Boundary line	Good	Acceptable	Marginal	Poor
B-pillar to driver seat centerline distance (cm)	12.5	5.0	0.0	
Structural failures	Downgrade structural rating by one category			

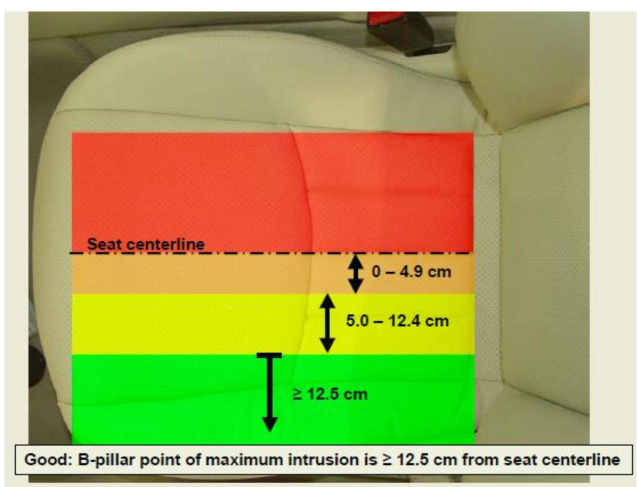

Figure 6.1 B-Pillar Intrusions Rating as per Seat Centerline [12]

6.3 B-Pillar Intrusions as per IIHS Regulation

The B-pillar intrusion with respect to seat centerline is measured by selecting a random node at the center of the B-pillar, and it is the distance between the seat centerline and driver side B-pillar after post simulation.

The minimum distance to the seat centerline in the front driver seat area recorded during the MDB and pole test of car model for 2 different tests conditions are included in the Table 6.2. Comparing the two tests, for both the FMVSS 214 MDB and Pole tests condition the FMVSS 214 side impact pole test for current and modified seat position was rated as acceptable whereas the moving deformable barrier test for current and modified seat position was rated as marginal.

Table 6.2 B-Pillar Intrusion with respect to Seat Centerline

	FMVSS 214 MDB Test		Side Pole Test	
Seat Position	Distance between Seat Centerline and B Pillar Post Simulation (cm)	Rating	Distance between Seat Centerline and B Pillar Post Simulation (cm)	Rating
Current Seat Position	11.6	Acceptable	9.2	Acceptable
Modified Seat Position	13.3	Good	13.9	Good

Overall as shown in Table 6.2, the structural damage (intrusion) of the B-Pillar for both MDB and Pole tests were evaluated according to the IIHS side impact ratings. Therefore, the rating of the car has been improved from “Acceptable” to “Good” by a minimum 2cm displacement of the driver’s seat inward for both regulatory FMVSS 214 MDB and pole tests, by mainly moving the driver’s seat laterally inward by less than 2cm.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

One objective of this study was to evaluate structural damage (intrusions) of small car and critical injury parameters of the occupant according to pole test and moving deformable barrier test in FMVSS 214 side impact regulation for a small car. Another objective of this study was to reduce the occupant injury caused due to intrusion of the pole and moving deformable barrier into the door for which driver's seat position is changed by displacing the seat by 18mm inward and then the occupant injuries are compared in both scenarios. The FMVSS 214 MDB barrier test and the pole test were simulated to examine the critical dummy injury parameters and the intrusion sustained by the vehicle in both scenarios. The occupant kinematics and injury potentials were elaborated in detail. The following conclusions have been made based on this research study.

- Movement of the driver's seat laterally inwards for MDB test has significantly reduced the chances of injuries to the occupant's Upper rib deflection which exceeded the requirements of 44mm originally, was reduced from 46 mm to 34mm. The total abdominal force which exceeded the requirements, was reduced from 2636 N to 2100 N. The TTI (g's) was also reduced from 88g to 71g.
- It is also observed that for Pole test lateral displacement of the driver's seat inwards has significantly reduced the injuries to the occupant's lower ribcage area as lower rib deflection which exceeded the requirements, it was reduced from 47mm to 38mm. The middle rib deflection which exceeded the requirements, it was reduced from 46mm to 39mm. The total abdominal force which exceeded the requirements, it was reduced from 2854 N to 2373 N. The TTI (g's) value which exceeded the requirements, it was reduced

from 87g to 78g. Finally, the chest deflection which exceeded the requirements, it was reduced from 48mm to 39mm.

- From the various simulations and results obtained, it is observed that the critical dummy injury values for occupant in modified seat position were comparatively less when compared to occupant in original seat position, according to both FMVSS 214 MDB and side impact pole test configuration. Overall the injuries to the occupant has been reduced by 10-15%.
- From the simulations, it is observed that the vehicle intrusion into the pole was quite larger when compared to the one from MDB barrier test, even though the impact velocity on the pole was smaller.
- The potential for severe injuries is higher in the pole test compared to impact with the moving deformable barrier (MDB) at smaller impact speed.
- The structural damage (intrusion) of the B-pillar for both MDB and pole tests were evaluated according to the IIHS side impact ratings. The rating has been improved from "Acceptable" to "Good" for both FMVSS 214 MDB test and for Pole test configuration.
- Overall, the study demonstrates that for a small displacement of less than 2cm in the seat position inward, the chances of injury to the occupants in side impact crashes can be significantly reduced.

7.2 Recommendations

The following are the future recommendations which can be addressed for extending the current study are offered:

- The study can be repeated on other class of vehicles such as pickup trucks, SUV's, Buses etc.

- The same study can be performed using other size occupants, including 5th Percentile female dummy in the rear seat to study the injury effects on female passengers, as also required in the FMVSS MDB test regulation.
- Similar study can be done for various other occupant positions such as passenger side, rear seat and middle back seat.
- Use of advanced restraint system such as Side-Impact Air bags (SAB) to protect the occupant during the side impact collisions can also be investigated in order to reduce occupant injuries from impacting vehicle interior by properly restraining the occupant.
- The sliding seat concept can be introduced in the vehicle to check whether it can have any significant influence on occupant kinematics and potential injuries as a result of side impact.

REFERENCES

REFERENCES

[1] Bhaghavathula, N.V.S.K., “Protection of Occupants in Car Side Impact Crashes with an External Inflatable Upper Torso Restraint System,” Master’s Thesis, Wichita State University, Wichita, December 2008.

[2] Siruvole, K.S., “Evaluation of the Occupant Response and Structural Damage According to the Newly Proposed Pole Test under Federal Motor Vehicle Safety Standard Side Impact Regulation,” Master’s Thesis, Wichita State University, Wichita, May 2007.

[3] Insurance Institute for Highway Safety, "Insurance Institute for Highway Safety, Highway Loss Data Institute," November 2016.

[4] Koneru, L.V.S.P.C., “Prediction of Accident Severity and Driver Fatality Ratios in Side Impact Accidents for Different Target and Bullet Cars Based on the FMVSS 214 and US-NCAP Test Conditions, Master’s Thesis, Wichita State University, Wichita, December 2013.

[5] Sheshadri A., “Design and Analysis of a Composite Beam for Side Impact Protection of Occupants in a Sedan,” Master’s Thesis, Wichita State University, Wichita, May 2006.

[6] Papa, A., “Estimation of Aggressivity and Driver Fatality Ratio for Side Impact Crashes,” Master’s Project, Wichita State University, 2012.

[7] Coxon, C., Paine, M., and Haley J., “Side Impacts and Improved Occupant Protection,” Department of Transport & Urban Planning, South Australia, 2004.

[8] Olivares, G., “The Retractable Steering and the Sliding Seat Safety Systems, an Alternative to Frontal and Side Airbags,” Master’s Thesis, Wichita State University, Wichita, Spring 1998.

[9] Reka, L.R., “Development of a Sliding Seat Mechanism to Prevent Whiplash Injuries in Rear-End Collision,” Master’s Thesis, Wichita State University, Wichita, May 2005.

[10] Schmitt, K.U., Muser, M., Heggendorn, P., Niederer, P., and Walz, F., “Development of a Damping Seat Slide to Reduce Whiplash Injury,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* Vol. 217(11), pp. 949-955, 2003.

[11] Federal Motor Vehicle Safety Standards (FMVSS) No. 214 “Side Impact Protection, 2005.

[12] Insurance Institute for Highway Safety, "Crashworthiness Evaluation Side Impact Crash Test Protocol (version III)", April 2004.

[13] Marzougui, D., Samaha, R.R., Cui, C., and Kan, C.D., "Extended Validation of the Finite Element Model for the 2010 Toyota Yaris Passenger Sedan," National Crash Analysis Center, The George Washington University, Ashburn, VA, July 2012.

[14] Stahlschmidt, S., D'Souza, R., Franz, U., Burger, M., Maurath, C.A., and Pathy, S., "LSTC EuroSID – 2re Finite Element Model," June 2015.

[15] National Crash Analysis Center (Retrieved 2017).

[16] "MADYMO Theory Manual Version 7.6", TASS International, 2015.

[17] Insurance Institute for Highway Safety, "Insurance Institute for Highway Safety, Highway Loss Data Institute," November 2016.

[18] LS-DYNA 970 Keyword Manual (Retrieved 2017).

[19] US NCAP regulations and crash test procedures, www.nhtsa.gov (Retrieved 2017)

[20] Tay, Y.Y., Papa, A., Koneru, L.S., Moradi, R., and Lankarani, H.M., "A Finite Element Approach Estimating Driver Fatality Ratios of a Fleet of LTVs Striking a Passenger Car Based on Vehicles' Intrusion, Acceleration, and Stiffness Ratios in Side Impact Collisions," *Journal of Mechanical Science and Technology,* Paper No. MEST-D-14-00429, Vol. 29, No. 3, pp. 1231-1242, 2015. [DOI: 10.1007/s12206-015-0237-4].

[21] Tay, Y.Y., Lim, C.S., and Lankarani, H.M., "A Finite Element Analysis of High Energy Absorption of Cellular Materials in Enhancing Passive Safety of Road Vehicles in Side Impact Accidents," *International Journal of Crashworthiness*, Paper No. IJCR.806, Vol. 19, No. 3, pp. 288-300, 2014. [DOI: 10.1080/13588265.2014.893789].

[22] Tay, Y.Y., Moradi, R., and Lankarani, H.M., "A Design-of-Experiment Method In Predicting Injuries To Out-Of-Position Occupants From Torso-Only Side-Impact Airbags," *Global Journal of Research in Engineering* - B: *Automotive Engineering*, GJRE-B, Vol. 13, Issue 2, pp. 1-14, October 2013.

[23] Setpally, R., Moradi, R., and Lankarani, H.M., "Use of Finite Element Analysis for the Prediction of Driver Fatality Ratios Based on Vehicle Intrusion Ratios in Head-on Collisions," *Journal of Applied Mathematics*, Special Issue on *Finite Element Method*, Paper No. 7401418, Vol. 4, No. 5A, pp. 56-63, May 2013. [DOI: 10.4236/am.2013.45A007].

[24] McCoy, M.L., Moradi, R., and Lankarani, H.M., "Use of Simple Finite Elements in Impact Analysis of Mechanical Systems with Stereomechanics, Wave Propagation, and Energy Method Approaches," *Journal of Mechanical Science and Technology,* Paper No. J2010-209, Vol. 25, No. 3, pp. 783-795, 2011.

[25] Hutchinson, J., Kaiser, M.J., and Lankarani, H.M., "The Head Injury Criteria Functional," *Journal of Applied Mathematics and Computation*, Elsevier Sciences, Vol. 96, Issue 1, pp. 1-16, 1998.

[26] Lankarani, H.M., Gowdy, V., DeWeese, R., Kishore, P., Murthy, A., and Satish, S., "Kinematics of SID on Side-facing Aircraft Seats," *International Journal of Crashworthiness*, Woodland Publishing, Vol. 3, No. 4, pp. 393-403, 1998.

[27] Lankarani, H.M., "Contact/Impact Dynamics Applied to Crash Analysis," Chapter in the book, **Crashworthiness of Transportation Systems: Structural Impact and Occupant Protection**, J. Ambrosio, et al. (Eds.), NATO Series E, Applied Sciences, Vol. 332, Kluwer Academic Publishers, pp. 445-473, 1996.

[28] Tay, Y.Y., Moradi, R., and Lankarani, H.M., "A Numerical Analysis of Pre-deployment Effect of Side-Impact Airbags in Reducing Occupant Injuries," 2013 ASME International Mechanical Engineering Congress and Exposition, Paper No. IMECE2013-63234, 10p, San Diego, California, November 2013.

[29] Ghati, Y., Menon. R., Olivares, G., and Lankarani, H.M., "Performance Evaluation of Child Safety Seats in Far-Side Lateral Sled Tests at Varying Speeds," 15p, 2009 Association for the Advancement of Automotive Medicine (AAAM) 53rd Annual Conference, Paper No. 9B-0338, 15p, Baltimore, Maryland, October 2009.

[30] Sasikumar, N., "Performance Comparison of Human and Dummy Models in Various Vehicle Frontal Crash Scenarios Based on Federal Regulatory Standards," Master's Thesis, Wichita State University, August 2016.

[31] Jalalpuram, R., "Evaluation and Comparison of Crashworthiness of Older and Newer Model Vehicles as Per FMVSS 214 Side Impact Test Requirements," Masters Project, Wichita State University, May 2016.

[32] Tay, Y.Y., "New Techniques and Applications in Energy-Absorbing Cellular Materials, Airbag Pre-Deployment, Injury Prediction to Out-of-Position Occupants, and Estimation of Deriver Fatality Ratio, for Enhancing Passive Safety of Road Vehicle in Side Impact Accidents," Master's Thesis, Wichita State University, May 2014.

[33] Weragoda, T.V., "Finite Element Analysis and Comparison of the Structural Integrity and Occupant Protection of an Older and a Late Model Year Compact Sedan per Current and Pre-2007 FMVSS 214 MDB and Pole Side Impact Test Requirements," Masters Project, Wichita State University, November 2013.

[34] Reddy, S., "Modeling and Analysis of a Composite B-Pillar for Side-Impact Protection of Occupants in a Sedan," Masters Thesis, Wichita State University, February 2007.

[35] Basavaraju, D., "Analysis of Composite Beams for Side Impact Protection," Masters Thesis, Wichita State University, October 2005.

[36] Mahalingam, A., "Nonlinear Finite Element Analysis of Vehicle Side Impact," Masters Thesis, Wichita State University, July 2004.

[37] Zhang, K., "Optimization of an Automobile Side Impact Door Beams and Side Airbags," Master's Thesis, Wichita State University, December 1998.

[38] Meka, B.R., "Analysis of Dynamic Test Criteria for Side-facing Aircraft Seats," Master's Thesis, Wichita State University, May 1998.

[39] Yanumula, V.S., "Validity of Door Beams in Side Impact Protection," Masters Thesis, Wichita State University, December 1996.

[40] Kumaran, P., "Scaling Laws for Development of Injury Criteria and Range of Occupant Sizes," Master's Thesis, Wichita State University, May 1994.

[41] Moradi, R., "Impact Dynamics of Mechanical Systems and Structures, and Applications in Crash Energy Management, Impulse mitigations, and Impact Injury Biomechanics," PhD Dissertation, Wichita State University, May 2012.

[42] Ma, D., "A Multibody/Finite-Element Approach for Analysis of Crash Environments," PhD Dissertation, Wichita State University, December 1993.