PROTECTION OF OCCUPANTS IN CAR SIDE IMPACT CRASHES WITH AN EXTERNAL INFLATABLE UPPER TORSO RESTRAINT SYSTEM

A Thesis by

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PROTECTION OF OCCUPANTS IN CAR SIDE IMPACT CRASHES WITH AN INFLATABLE UPPER TORSO RESTRAINT SYSTEM

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

Hamid Lankarani, Committee Chair

We have read this thesis and
Recommend its acceptance:

Krishna Krishnan, Committee Member

Ramazan Asmathulu, Committee Member
DEDICATION

To my family and friends.
ACKNOWLEDGEMENTS

It is a precious opportunity, I feel, to convey my gratitude to all the people who were important to the successful realization of my thesis. Every one of you has directly or indirectly helped in this success. I thank you from the bottom of my heart.

First, I thank my advisor Dr. Hamid Lankarani for his advice, supervision, and guidance throughout my studies at Wichita State University. Above all, he provided me with unflinching encouragement and support in various ways. He is a good human being whom I would always admire for the rest of my life. “Dr. Hamid Lankarani, I thank you once again for all your patience in guiding me.”

I also thank Dr. Krishna Krishnan and Dr. Ramazan Asmathulu for taking time in reviewing and providing valuable suggestions on my thesis work.

Important person behind what I am today are my parents. They strongly believe in me more than I ever do in myself. They inspired me in many ways. My dad, mom and sister have always foregone their pleasures in educating me and fulfilling my desires. The affection my family showed on me all the time never let me feel alone. There are no words to express my gratitude towards my family. I thank God for giving me such a wonderful, loving family.
ABSTRACT

Passenger vehicles in today’s world are more crashworthy than they used to be. Significant improvements have been done in the recent years to improve protection for occupants in the passenger vehicle; most of it was done in frontal crashes and only a small amount of improvement has been observed in side impact crashes.

Thus, making it necessary, to do significant research on side impact crashes. Side impact standard FMVSS 214 was established to be used as a base for studying injury parameters during side impacts. But, this standard does not take into account the severities of Neck injury.

Neck injuries, used to associate with front and rear side crashes can be life altering. Neck injuries are even given lowest ratings on the Abbreviated Injury Scale (AIS) 1. Recent studies show the importance of neck injury during side impacts, leading to need for immediate need to study the effect of neck injuries on occupants in passenger vehicles.

In this study, to address the above concern effort has been made to improve neck injury protection during side impacts, using FMVSS 214 standard as the basis to study the effect of airbag on restraint system in improving occupant protection from neck injuries. Two different dummy models US-DoT SID (according to FMVSS 214 standard) and Hybrid III 50% dummy have been used for the study, and the results show improvement in Neck Injury Criterion (NIC) commonly used to assess neck injuries along with improvement in Head injury criterion (HIC) commonly used to evaluate head injuries with the use of airbag on restraint system.
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</tr>
<tr>
<td>1.2</td>
<td>Passenger vehicle occupant deaths in multiple-vehicle crashes by impact point and Vehicle type, 2006.</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Passenger vehicle occupant deaths in all crashes by impact point and vehicle type, 2006.</td>
<td>3</td>
</tr>
<tr>
<td>1.4</td>
<td>Different side impact test procedures used</td>
<td>5</td>
</tr>
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<td>4.1</td>
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<tr>
<td>4.2</td>
<td>Components of barrier</td>
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<tr>
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<td>88</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety Administration</td>
<td></td>
</tr>
<tr>
<td>FMVSS</td>
<td>Federal Motor Vehicle Safety Standard</td>
<td></td>
</tr>
<tr>
<td>NCAC</td>
<td>National Crash Analysis Center</td>
<td></td>
</tr>
<tr>
<td>IIHS</td>
<td>Insurance Institute for Highway Standard</td>
<td></td>
</tr>
<tr>
<td>MBD</td>
<td>Moving Deformable Barrier</td>
<td></td>
</tr>
<tr>
<td>HIC</td>
<td>Head Injury Criterion</td>
<td></td>
</tr>
<tr>
<td>NIC</td>
<td>Neck Injury Criterion</td>
<td></td>
</tr>
<tr>
<td>TTI</td>
<td>Thoracic Trauma Index</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

1.1 Introduction

Crashworthiness is the ability of the structure to reduce the injury of its occupants during an impact, which is dependent on the nature of the impact and the vehicle involved[12]. Different criteria are used to assess crashworthiness, which includes deformation patterns of the vehicle structure, acceleration experienced by the vehicle and the probability of injury for dummies in the event of the crash.

Several vehicles undergo crashes, according to the survey by International institute for highway safety (IIHS) there were a total of 30,476 passenger vehicle occupant deaths in the year 2006 which is nearly the same as in 1975, but the distribution of vehicle types among these crashes has changed where SUV occupant death alone rose by as much as 10 times.

Figure 1.1 Passenger vehicle occupant deaths by vehicle type, 1975-2006

IIHS fatality facts 2006 [10].
Several improvements have been made to passenger vehicles to make them more crashworthy, specifically in frontal crashes. As the passenger protection improves during frontal crashes, relative importance for protection in side impacts increases. Considering from 1975 to 2000 though driver deaths rates per million cars registered reduced by as much as 47 percent most of this improvement was in frontal crashes which accounts for as much as 52 percent where as only 24 percent improvement in protection was observed during Side impact scenario, which calls for the need of improved crashworthiness for automobiles during side impact.

![Diagram](image.png)

Figure 1.2 IIHS fatality facts 2006 [10].

Considering total passenger vehicle occupant deaths in 2006 frontal impacts accounted for 49 percent and side impact accounted for as much as 29 percent.
The passenger vehicle occupant deaths in single, multi is distributed according to the survey by International Institute for highway safety (IIHS) as shown below

### Table 1.1 Passenger vehicle occupant deaths in single-vehicle crashes by impact point and vehicle type, 2006

<table>
<thead>
<tr>
<th>Point of principal impact</th>
<th>Car occupants</th>
<th>Pickup occupants</th>
<th>SUV occupants</th>
<th>All occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num</td>
<td>%</td>
<td>Num</td>
<td>%</td>
</tr>
<tr>
<td>Frontal</td>
<td>4,073</td>
<td>50</td>
<td>1,708</td>
<td>46</td>
</tr>
<tr>
<td>Side</td>
<td>2,032</td>
<td>25</td>
<td>574</td>
<td>16</td>
</tr>
<tr>
<td>Rear</td>
<td>263</td>
<td>3</td>
<td>55</td>
<td>1</td>
</tr>
<tr>
<td>Other (mostly rollover)</td>
<td>1,822</td>
<td>22</td>
<td>1,343</td>
<td>36</td>
</tr>
<tr>
<td>All*</td>
<td>8,190</td>
<td>100</td>
<td>3,680</td>
<td>100</td>
</tr>
</tbody>
</table>

*Total includes other and/or unknowns

### Table 1.2 Passenger vehicle occupant deaths in multiple-vehicle crashes by impact point and vehicle type, 2006

<table>
<thead>
<tr>
<th>Point of principal impact</th>
<th>Car occupants</th>
<th>Pickup occupants</th>
<th>SUV occupants</th>
<th>All occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num</td>
<td>%</td>
<td>Num</td>
<td>%</td>
</tr>
<tr>
<td>Frontal</td>
<td>5,337</td>
<td>50</td>
<td>1,399</td>
<td>62</td>
</tr>
<tr>
<td>Side</td>
<td>4,472</td>
<td>42</td>
<td>612</td>
<td>27</td>
</tr>
<tr>
<td>Rear</td>
<td>623</td>
<td>6</td>
<td>149</td>
<td>7</td>
</tr>
<tr>
<td>Other (mostly rollover)</td>
<td>322</td>
<td>3</td>
<td>104</td>
<td>5</td>
</tr>
<tr>
<td>All*</td>
<td>10,754</td>
<td>100</td>
<td>2,264</td>
<td>100</td>
</tr>
</tbody>
</table>

*Total includes other and/or unknowns

### Table 1.3 Passenger vehicle occupant deaths in all crashes by impact point and vehicle type, 2006

<table>
<thead>
<tr>
<th>Point of principal impact</th>
<th>Car occupants</th>
<th>Pickup occupants</th>
<th>SUV occupants</th>
<th>All occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num</td>
<td>%</td>
<td>Num</td>
<td>%</td>
</tr>
<tr>
<td>Frontal</td>
<td>9,424</td>
<td>50</td>
<td>3,111</td>
<td>52</td>
</tr>
<tr>
<td>Side</td>
<td>6,512</td>
<td>34</td>
<td>1,186</td>
<td>20</td>
</tr>
<tr>
<td>Rear</td>
<td>887</td>
<td>5</td>
<td>204</td>
<td>3</td>
</tr>
<tr>
<td>Other (mostly rollover)</td>
<td>2,145</td>
<td>11</td>
<td>1,448</td>
<td>24</td>
</tr>
<tr>
<td>All*</td>
<td>18,968</td>
<td>100</td>
<td>5,949</td>
<td>100</td>
</tr>
</tbody>
</table>

*Total includes other and/or unknowns
1.2 Literature Review

Side impact of passenger vehicles has been studied for its importance as the second major type of impact generally occurring in real time scenarios only after frontal crashes. Different injury parameters have been devised by the automotive industry to study the effect of side impact and improve the crashworthiness of the vehicle. Though several studies have been done, neck injury has not been given much importance during side impact scenarios. Neck injury which can be disabling and even life altering is given the lowest rating on the abbreviated injury scale of 1 [1]. It was studied that several factors affect the likelihood of experiencing neck injury [2]. These include

- Impact Factors

Type of contact has a major role in the severity of the neck injury. It can occur in every kind of impact with frontal impact registering 38% of its total cases followed by rear and side impacts with 16 and 12 % respectively. Literature shows that neck injury as a result of rear impact take longer time to heal than any other type of impact [3].

- Human Factors

Gender is considered as an important factor influencing neck injury, were females experience twice as many injuries compared to their male counterpart. Along with gender, age plays an important role, as the age increases so is the rate of neck injury with adolescents having less neck injuries that adults.

Simon Lewis, Eren Semercigil, Brain Fildes did a study on real world side impact accidents taken from the Monash University accident research center database. The results from the study provided an introduction of neck injuries showing that, there is a common angle of impact that results in neck injury from side impacts. They also
identified that the occupants age and head contact with the interior of the vehicle played an important role in affecting neck injury.

Future directions for further understanding neck injuries include investigating aging and gender effects on neck injury by studying certain age groups. Effect of different kind of restraint systems can be studied and ways to reduce neck injuries can be established. Effect of angle of impact and improvement of crashworthiness under such conditions can be taken into considerations.

1.3 Test Standard

Several different test procedures are used to assess occupant safety during side impact scenario. Regulatory procedures used in the United States include FMVSS 214 (deformable barrier side impact) and FMVSS 201 (pole side impact) and the LINCAP/SINCAP. European ECE R95 and Euro NCAP test procedures are used in most other regions. All these test procedures differ in impact speed, type of barrier and the crash test dummy used. Test procedures used for different standards are summarized in the following table.

<table>
<thead>
<tr>
<th>Test protocol</th>
<th>Barrier type</th>
<th>Barrier mass</th>
<th>Impact velocity</th>
<th>Impact angle</th>
<th>Crash dummy</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMVSS201</td>
<td>Rigid Pole</td>
<td>1370 kg</td>
<td>18 mph</td>
<td>90°</td>
<td>SID-HIII</td>
</tr>
<tr>
<td>FMVSS214</td>
<td>MDB</td>
<td>1370 kg</td>
<td>33.5 mph</td>
<td>63°</td>
<td>US DoT-SID</td>
</tr>
<tr>
<td>US LINCAP</td>
<td>MDB</td>
<td>1370 kg</td>
<td>38.5 mph</td>
<td>63°</td>
<td>US DoT-SID</td>
</tr>
<tr>
<td>IIHS-SUV</td>
<td>MDB</td>
<td>1500 kg</td>
<td>30 mph</td>
<td>90°</td>
<td>SID-IIs</td>
</tr>
<tr>
<td>ECE R95</td>
<td>MDB</td>
<td>950 kg</td>
<td>50 km/h</td>
<td>90°</td>
<td>EuroSID-1</td>
</tr>
<tr>
<td>EuroNCAP</td>
<td>MDB</td>
<td>950 kg</td>
<td>50 km/h</td>
<td>90°</td>
<td>ES-2</td>
</tr>
</tbody>
</table>

Table 1.4 Different side impact test procedures used [20].
1.4 FMVSS 214

Federal vehicle motor safety standard 214 was introduced in 1990 to improve passenger protection during dynamic test simulating a severe right angle collision at 33.5mph crash test, which was introduced into new passenger vehicles during 1994-1997. This test basically involves a MDB Moving deformable barrier hitting the side of the vehicle in which the SID Side Impact Dummies are seated at the near side of the Impact point. Thoracic Trauma Index, TTI is measured on the Dummies at the near side of impact point.

According to NHTSA FMVSS 214 development included

- Test configuration simulating a severe collision between two passenger vehicles using a moving deformable barrier (MDB).
- Prediction of severity of thoracic injuries during contact with car interior using Thoracic Trauma Index (TTI).
- A Side Impact Dummy on which TTI could be measured reliably.
- Technologies that significantly reduce TTI such as
  - Structure modifications like stronger sills, pillars, rail roofs, seats and cross-members, to reduce intrusion.
  - Padding capable of absorbing great amount of energy.

This test was evaluated in two phases

Phase 1 is a statistical analysis of relationships between front seat TTI and fatality risk in actual side impact on highway.
Phase 2 is a statistical comparison of side impact fatality and injury rates in cars produced immediately after verses the once immediately before the implementation of the standard FMVSS 214.

1.5 Objective

The subject involving research on Side impacts has received less emphasis compared to frontal impact injury protection. Attention is now shifting to side impact injury protection as frontal impact protection is in a good state. Occupant protection sitting on the near side of the impact poses several difficulties such as

- Minimal crush distance to control the forces of crash.
- Deformation of the vehicle and its penetration into the occupant compartment.
- Partial ejection of the occupant through the side windows involving interaction with outside objects.
- Finally, difficulty in adequately restraining the occupant by conventional restraint system.

Thus considerable research needs to be done to improve occupant protection during Side impacts. The objective of this thesis Thus, is to use the existing FMVSS 214 side impact standard and implement the concept of inflatable seat belts in order to improve the overall protection for the occupant in the passenger vehicle and there by contributing to the field of crashworthiness and to mankind, by saving lives or at least reduce the severity of the injury occurred during a side impact analysis.
CHAPTER II

INJURY BIOMECHANICS

2.1 Injuries Biomechanics

Injury biomechanics describes the effect 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 a mechanism is called “injury mechanism” and the severity of the injury is identified 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 follows

0  no injury
1  minor
2  moderate
3  serious
4  severe
5  critical
6  maximum injury (causes death)
AIS is a “threat to life” ranking where the numerical values have no significance other than to designate order.

2.2 Injury Criterion

Biomechanical index of exposure severity is defined as “injury criterion”. It indicates in magnitude the potential for injury during an impact. The several reasons why injury criterion was developed were

- 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 car safety and optimization.

There are several injury parameters which are taken into account during a Side Impact Analysis.

2.3 Gadd Severity Index (GSI)

This severity index was developed to improve the utility of Wayne State Tolerance Curve (WSTC) and to provide analytical approximation to the curve. This WSTC is the relation between effective acceleration vs. duration which is basically a boundary established to separate the “skull fracture” zone from the “no fracture zone”, which was developed by Wayne State University.

![Wayne State Tolerance Curve (WSTC)](image-url)

Figure 2.1 Wayne State Tolerance Curve (WSTC) [18].
The head acceleration as a function of time for a head impact is used in the severity index formulation to determine the severity of the impact has exceeded the limit of WSTC. So, if the value is greater than 1000 it is in the fracture region, like wise if the value is less than 1000 it is in the no fracture region.

2.4 Head Injury Criterion (HIC)

In response to the relationship between Gadd Severity Index and Wayne State Tolerance Curve NHTSA devised a new parameter in 1972 called the HIC, which was revised several times after that. The formulation for HIC goes as[18]

\[
HIC = \max_{0 \leq t_1 \leq t_2 \leq TE} \left\{ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t) \, dt \right\}^{2.5} (t_2 - t_1)
\]

Where ‘R (t)’ is a result of head acceleration

\[ t_2 - t_1 \leq TE \]

A value of 1000 is specified for HIC as concussion tolerance level, for practical reasons the maximum time interval for HIC values was set to 36ms which was further reduced to 16ms so as to restrict the use of HIC to hard head impacts. There are some limitations to HIC which include

- HIC does no consider angular motion of the head which causes head injury while just considering linear acceleration.
- The time duration for the impact is limited as HIC is only valid for hard contact.
- WSTC is the basis for HIC, which was just derived from subjects loaded in anterior-posterior direction only.
2.5 Neck Injury Criterion – FORWARD (NIC_FORWARD)

Peak forces and moments often assess neck injury at upper and lower neck at that location. The element NIC_FORWARD is a measure of injury due to load transferred through head and neck interface. It consists of three components.

- The fore/aft neck shear force Fx,
- Neck axial force,
- Neck bending moment about a lateral axis at head and neck interface.

This criterion is applied to bracket joint constraint load signals. In this criterion axial force, the component of constraint force in the joint ζ-direction is used, as fore/aft shear force Fx, the component of the constraint force in the joint η-direction is used as bending moment, the component of the constraint moment My, about the joint η-axis is used. The moment My formulation goes as

\[ M_y = M_y - e F_x \]

where ‘e’ is the distance between joint in the positive joint ζ-direction and the occipital condyle.

The neck axial force and shear force should not exceed the values in the curves where as the bending moment must not exceed 57Nm in extension.

![Figure 2.2 Neck extension and shear force extension criteria.][18]
2.6 3ms (CONTIGUOUS_3MS, CUMULATIVE_3MS)

After head and the neck the most crucial part is the Thorax, which consists of twelve thoracic vertebrae, the sternum and twelve pairs of ribs. Linear acceleration in the center of gravity of the upper thorax of 60g for 3 ms or longer is taken as the tolerance level for chest injury.

CONTINGUOUS_3MS injury criterion is calculated by tracing resultant linear acceleration using time window with a width of 3ms, where as CUMULATIVE_3MS injury criterion is the highest acceleration exceeded during at least 3ms.

2.7 Thoracic Trauma Index (TTI)

TTI was proposed in 1984 to calculate the probability of serious injury to hard thorax due to blunt lateral impact. TTI is the acceleration of the lower thoracic spine and the ribs, which also incorporates the age, and weight of the human model. The tests required to derive the formulation of TTI was based cadaver tests which showed the injuries to the thorax including the ribs and its internal organs is strongly related to the average of the peak lateral acceleration experienced by the impacted side of the rib cage and lower thoracic spine. TTI formulation goes as[18]

\[
TTI = 1.4 \times \text{AGE} + 0.5 \times \left( \text{RIB}_g \times T12_g \right) \times \text{MASS/MSTD}
\]

Where: \( \text{AGE} \) = age of the subject in years

\( \text{RIB}_g \) = maximum absolute value of acceleration in g’s of the 4\text{th} and 8\text{th} rib on struck side , in lateral direction

\( T12_g \) = maximum absolute acceleration value in g’s of the 12\text{th} thoracic vertebra, in lateral direction
MASS = test subject mass in kg and MSTD = standard mass of 75 kg

TTI can also be used without using the specific age for dummies which is called TTI(d), this was defined for 50th percentile dummies with a mass of 75 kg, which goes as[18]

$$TTI(d) = 0.5^\dagger (\text{RIB}_g + \text{TIL}_g)$$

According to FMVSS 214 standard the TTI(d) level should not exceed 85 g for 4 door passenger cars and 90 g for 2 door passenger cars.

### 2.8 Viscous Injury Response (VC)

Acceleration of ribs and the spine used for TTI criterion do not address the injury mechanism at high velocity rates of soft tissues therefore it is critical to understand the mechanism of soft tissue injury. Viscous Injury Response is used to address such injuries under high impact velocities. VC is the maximum value of time function formed by product of instantaneous compression function (C) and the velocity of deformation (V)[18].

$$VC = SF \cdot \max \left( \frac{dD(t)}{dt} \cdot \frac{D(t)}{SZ} \right)$$

Where D(t) is a deflection and SZ is a prescribed size (half torso thickness for side impacts) SF is the scale factor dependent on dummy.
CHAPTER III

COMPUTATIONAL TOOLS

3.1 Computational Tools

Computational tools give us a unique advantage in generating efficient design along with cost effective techniques, they provide a distinct advantage such as:

- Generating detailed analysis prior to building first prototype
- Minimizing number of prototypes and testing needed for product development
- Significant reduction in development costs and time
- Finally, optimizing product performance.

Several computational tools have been used in the process of the thesis, they are:

3.2 Pre/Post processors

Finite element modeling of seat belt and positioning for Dodge caravan and the barrier have been done using Hypermesh, where as collecting the accelerometer data for obtaining the pulse was done using LS-prepost.

3.2.1 Hypermesh

Altair Hypermesh is a high performance finite element pre processor, which allows engineers to analyze product design performance in a highly interactive and visual environment[14]. The user interface of Hypermesh is easy to learn and supports a number of finite element and CAD geometry model file formats. Thereby, helping in increasing efficiency and interoperability. Efficient manipulation of geometry and meshing high complex models can be done using Hypermesh. Functionality of Hypermesh includes
model control using extensive meshing, morphing technology and automatic generation of mid surface for complex designs.

Advantages of Hypermesh are

- Hypermesh fits seamlessly with any simulation environment because of its broadest set of direct CAD and CAE interfaces coupled with user defined integrations.
- Hypermesh simplifies the modeling process of complex geometries using both automatic shell, tetra- and hexa-meshing capabilities.
- It has a flexible set of modeling tools allowing users to modify existing meshes to meet design flaws and reduce model development costs.
- Its batch mesher technology eliminates the need to perform manual geometry clean-up thus accelerating model development process.
- Easy to use graphic user interface makes it simple to learn, increasing modeling efficiency.
- Easy creation of surfaces from finite elements enabling engineers to communicate design modifications back into design environment.
- Leverage highly automated methods for model assembly that create connections such as bolts and seam welds.

Hypermesh provides direct access to a variety of CAD data formats for finite element model generation along with robust tools to mend imported geometry containing surfaces with overlaps that prevent high-quality mesh generation. Along with such distinctive advantages Hypermesh supports a host of different solver formats along with providing
flexibility to support additional solvers by the way of a complete export template language such as MADYMO, LS-DYNA, ABACUS, RADIOSS etc.

3.2.2 LS-PrePost

LS-PrePost is an advanced interactive program for preparing input data for LS-dyna and processing the results from LD-DYNA analysis[13]. Graphic user interface is easy to use and intuitive where the data and menus are designed in a logical and efficient way to minimize the number of mouse clicks and operations. LS-PrePost uses open GL graphics standard to achieve fast rendering and XY plotting.

LS-PrePost has several key pre-processing features, which include[15]

- Importing and combining multiple models to improve productivity
- Several model manipulation features such as translating, scaling, projecting and offset
- Entity creation using coordinate systems, sets, CNRBs, spot-welds, Rigid walls, Accelerometers etc.
- Special applications such as airbag folding, seatbelt fitting, dummy positioning and initial penetration check
- Automating surface meshing of IGES data and meshing of simple geometric objects.
3.3 Analysis Software

There are several Analysis Software’s in use today which have specific identity in solving specialized analysis. Some of the prominent Software’s include

- MADYMO
- LS-DYNA
- RADIOSS
- ABAQUA
- PAM-CRASH

Madymo and LS-Dyna have been used in this thesis. Where Madymo was used for occupant response and LS-Dyna was used to calculate Pulse data.

3.3.1 LS-DYNA

LS-DYNA is an advanced general-purpose multi-physics simulation software package that is actively developed by the Livermore Software Technology Corporation (LSTC)\[17\]. John O. Hallquist wrote the FEA program DYNA3D which uses explicit time integration to study nonlinear dynamic problems, which was released for public distribution in 1976. During the next few years, several companies began to develop commercial versions based on the public domain code which was released in 1978. Later when Hallquist started LSTC he continued developing his own version of the code and called it LS-DYNA.

LS-DYNA had the capabilities to solve the complications during non linear analysis such as

- Changing boundary conditions such as contact between parts that change over time
• Large deformations like crumpling of sheet metal parts
• Nonlinear materials that do not exhibit ideally elastic behavior like thermoplastic polymers were ideally handled in LS-DYNA.

A single executable file which is command line driven is used in LS-DYNA. Command shell, executable file, enough disk space and the input file are all that required to run LS-DYNA. Simple ASCII format is used for the input file and thus a text editor can be used to prepare it. Preprocessors can also be used to prepare the input file for LS-DYNA such as LS-PrePost, MSC.Patran and Hypermesh. Out of which LS-PrePost is developed by LSTC itself, which is freely distributed without a license. LS-DYNA can sole from simple linear static mechanical analysis up to advanced thermal and flow solving methods.

LS-DYNA’s applications are numerous which are not limited to any particular type of simulation. Some of the capabilities include

• Full 2D and 3D capabilities
• Nonlinear and Rigid body dynamics
• Quasi static simulations
• Thermal and fluid analysis
• Crack propagation
• Real time acoustics
• Implicit spring back

LS-DYNA has a vast library of material cards and element cards. Several different types of contacts can be used in the simulation of LS_DYNA analysis such as flexible body
contact, flexible to rigid body contact, single surface contact, eroding contact and edge-to-edge contact.

Applications

Automotive Crashworthiness and occupant safety

LS_DYNA is widely used by automobile industry to analyze vehicle designs. It is used to predict the crashworthiness of a vehicle in the event of a collision. Using LS-DYNA companies can test car designs without having to experiment using a prototype thereby making it a cost effective and an efficient procedure. LS-DYNA’s specified Automotive features include Seatbelts, sliprings, sensors, accelerometers, airbags and retractors.

Sheet metal Forming

LS-DYNA accurately predicts the deformations and stresses experienced by the metal. It supports adaptive meshing thereby increasing accuracy of the analysis. Some of the metal forming applications includes Metal stamping, hydro forming, forging and deep drawing.

Other application of LS-DYNA include Drop testing, Electronic component design, Glass forming, Earthquake engineering, failure analysis and Metal cutting.
3.3.2 Madymo

Madymo stands for Mathematical Dynamic Modeling. This software was developed by TNO automotive safety solutions (TASS)[20]. This is a leading multi dynamics solver used frequently for automobile occupant safety and injury calculations. Though MADYMO was developed to study occupant response during car crashes it can also be used to analyze collisions involving trains, airplanes, motorcycles and bicycles. It also allows calculations to be made using restraint systems such as seatbelts and airbags.

Madymo can perform the capabilities offered by multi-body and finite element techniques like in structural behavior. Madymo can be used to generate a model using just finite element models or only multi bodies or even using both with great accuracy. The basic Madymo structure looks as shown in the figure below

![Madymo Structure](image)

Figure 3.1 Madymo Structure [18]

Within the standard airbag module MADYMO offers standard force models for airbag, belts and contact between bodies and with the surroundings. For creating a MADYMO input file, we need to select the number of multi-body systems and finite
element structures to be included, like a system can consist of a multi body (dummy), deformable steering column and a restraint system. Finite element structures can be used for all the occupants of the vehicle, passenger side airbag and the knee bolster. Standard TNO models are available for using in crash testing analysis. An input file is then setup which specifies the mass distribution of the bodies, joint properties and the connections between the bodies, for finite element structures such as belt restraint systems.

Figure 3.2 Examples of systems of multi bodies with force interactions [18]

The multi-body algorithm in MADYMO yields the second time derivatives of the degrees of freedom in an explicit form. Computer operations are linear to number of bodies considering all the joints have the same number of degrees of freedom leading to an efficient algorithm. Initial state of position and velocities of the joints have to be specified in the beginning of integration. To account for joint stiffness, damping and friction several kinematic joint types along with dynamic restraints are available and can be locked and unlocked based on user defined conditions. Sensors, transformers, actuators and controllers can be used in the control module to apply loads depending on the motion of the body. The finite element module divides the actual continuum into surfaces or finite volumes. This continuum is then analyzed as a complex system.
comprising simple elements ensuring continuity between interfaces. The initial position and velocity of the nodes used to connect elements, their connectivity, element properties such as material behavior should be specified at the start of the simulation. Material modes are available for metals, fabrics and honeycomb. Different integration method can be used for equations of motions for both multi-body parts and finite element parts. To increase the efficiency finite element module can be subdivided with respect to multi body module using different time steps for each module.
CHAPTER IV
MODELING AND ANALYSIS

4.1 MODELING

4.1.1 Modeling Of Dodge Caravan

Vehicle modeling is done using reverse engineering process thereby virtually creating automobiles and trucks. These accurate models are then used to simulate several different crash scenarios and predict vehicle and occupant response. Resulting in, efficiently using research time and data in making safety decisions. The Procedure used in the generation of virtual vehicle models is [16]

- Apply tape over the entire vehicle to get accurate representation of the geometry
- Digitize every component using seven degree of freedom co-ordinate measuring machine
- Disassemble all vehicle components
- Collect mass and material thickness data for vehicle and individual parts
- Identify all 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.

The above methodology is used to determine physical data to even other devices as test dummies, child car seats, highway barriers and crash components. This procedure is used by research organizations worldwide. The Dodge Caravan used in the process is a
standard model obtained from NCAC consisting of 515 components, 339969 elements and 344725 nodes. The materials and properties of the model are set as per standards of the actual Dodge caravan.

![Dodge Caravan](image)

**Figure 4.1 Dodge Caravan**

The model consists of shell, beam, solid and discrete elements a total of 339969 elements as shown in the table below

<table>
<thead>
<tr>
<th>Component</th>
<th>Dodge Caravan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>515</td>
</tr>
<tr>
<td>Elements</td>
<td>339969</td>
</tr>
<tr>
<td>Nodes</td>
<td>344725</td>
</tr>
<tr>
<td>Weight</td>
<td>2268 (kg)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>4732x1951x1740 (mm)</td>
</tr>
</tbody>
</table>

Table 4.1 Details of Dodge Caravan
4.1.2 Barrier Modeling

The National Highway Traffic Safety Administration (NHTSA) developed a Moving Deformable Barrier (MBD) for use in full system crash testing[20]. The barrier included the development of a crushable face to simulate the stiffness of the front end of the striking vehicle. Aluminum honeycomb having crush strength of 310 ± 17 kPa (45 ± 2.5 psi) is used as the main core of the barrier face assembly. A standard procedure for certifying the crush strength of the aluminum honeycomb has been established.

The MBD face assembly consists of a bumper constructed honeycomb 1690 ± 103kPa sandwiched between 3.2 mm thick aluminum plates. The bumper is a flexion member and develops flexion strength based on the material properties of these front and back plates. As the crush strength for this honeycomb is not critical, manufacturer’s standard method for certified crush strength would be used for bumper honeycomb.

Figure 4.2 LSTC 214 Barriers[20]
The side impactor is made of two assemblies

- Face Assembly
- Bumper Assembly

Face Assembly

This is comprised of the face honeycomb, a backing plate and a face sheet

The face honeycomb has the following specifications

1.6-density 3/8” cell size 5052 material aluminum combs.

Crush Strength – 45 ± 2.5 psi

Dimensions – 15 ±0.25 T x 66 ± 0.25 W x 22 ± 0.25 L

Weight 65 Pounds

Bumper Assembly

The bumper assembly consists of a bumper honeycomb, a back plate and a face plate

Its specifications include

5.2 density ¼” cell size 3003 material aluminum honeycomb

Crush strength 245 ± 15 psi

Dimensions – 3.75 T x 65.75 W x 6.00 L

The barrier used consists of 27 components, 145163 elements and 157627 nodes as shown in the table below

<table>
<thead>
<tr>
<th>Barrier</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>27</td>
</tr>
<tr>
<td>Elements</td>
<td>145163</td>
</tr>
<tr>
<td>Nodes</td>
<td>157627</td>
</tr>
<tr>
<td>mass</td>
<td>1370 (Kg)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>4114x1879 (mm)</td>
</tr>
</tbody>
</table>

Table 4.2 Components of barrier
4.1.3 Modeling Of US DoT –SID Side Impact Dummy

The US DoT-SID is a side impact dummy that was originally adapted from the Hybrid II 50th percentile dummy[19]. This dummy is prescribed for Side Impact Analysis testing using the US regulation FMVSS 214. The neck is represented by a rigid body link that is connected to the head body and spine box by spherical joints. Flexion-torsion restraints are used between thorax-neck and neck-head interface to obtain the static and dynamic neck behavior. A rigid body and two ellipsoids representing skull and face model the head. The spine is represented by a rigid body and a fourth order hyper-ellipsoid and the ribcage is subdivided into sternum body and ten rib segment bodies. Revolute joints having stiffness and damping characteristics are used for ribcage segment body. Several such joints were used to model the thorax, jacket and arms of the side impact dummy.

Figure 4.3 US DoT-SID dummy models: ellipsoid model (left) and finite element model (right)[19].
To obtain the model of the lumbar spine a combination of a free joint and a six-dof joint restraint is used along with a Kelvin element to model the spine cable. The six-dof restraint describes the lumbar spine characteristics for combined bending, shear, compression and torsion. The pelvis is modeled as a rigid body, with ten ellipsoids attached five on each pelvis geometry. The abdomen is depicted visually by ellipsoid attached to upper lumbar spine body whose inertial properties are incorporated in the pelvis body. Each leg consists of three bodies’ femur, knee and tibia body.

Hip joints are used to connect legs to the pelvis. Femur and knee bodies are connected using revolute joints. These joints allow, “yaw” halfway in the upper legs. Knee rotation in knee and tibia joints is allowed using revolute joints. Revolute ankle joints are used to connect foot bodies to the tibia bodies. Foot and heel ellipsoid are used to model the foot geometry. Contact characteristics for the ellipsoids show compliance of feet and leg flesh. Finite element model has the same configuration of joints as that of ellipsoid model except for the thorax.

Contacts between dummy components for both ellipsoid and finite element dummy are defined between both the legs. Numerous contacts are defined in between pelvis, abdomen, lumbar spine, shoulder, thorax and arm foam for finite element dummy.
Table 4.3 The tests used for the US DoT-SID dummy models are as shown [19]

<table>
<thead>
<tr>
<th>Component</th>
<th>Test description</th>
<th>specifications</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Static flexion / extension</td>
<td></td>
<td>ell</td>
</tr>
<tr>
<td></td>
<td>Static lateral flexion / extension</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static oblique flexion / extension</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static torsion</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Neck</td>
<td>Dynamic impact</td>
<td>mass+velocity 4.7 kg, 3.1 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7 kg, 4.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7 kg, 6.1 m/s</td>
<td>x</td>
</tr>
<tr>
<td>Thorax</td>
<td>Static compression:</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>- free ribcage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- fixed ribcage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static chest deflection</td>
<td>mass+velocity 9.9 kg, 3.5 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Dynamic impact</td>
<td>9.9 kg, 4.5 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 6.5 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 4.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 6.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.75 kg, 4.3 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.75 kg, 8.1 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.75 kg, 10.3 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.2 kg, 6.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.2 kg, 8.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.2 kg, 10.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td>Arm &amp; Jacket</td>
<td>Dynamic impact</td>
<td>mass+velocity 9.9 kg, 1.1 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 2.2 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 3.5 m/s</td>
<td>x</td>
</tr>
<tr>
<td>Component</td>
<td>Test description</td>
<td>specifications</td>
<td>ell</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------</td>
<td>----------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Upper Torso Assembly (thorax, arms and jacket)</td>
<td>Static chest deflection</td>
<td>mass+velocity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic impact</td>
<td>9.9 kg, 4.0 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 6.0 m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 8.0 m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.2 kg, 6.0 m/s</td>
<td></td>
</tr>
<tr>
<td>Lumbar Spine</td>
<td>Static flexion/ extension</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static torsion</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static compression/ extension</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Static shear</td>
<td>mass+velocity</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>Dynamic pendulum test</td>
<td>9.9 kg, 6.9 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 4.7 m/s</td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td>Static compression</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic impact</td>
<td>mass+velocity</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 3.5 m/s</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.9 kg, 4.5 m/s</td>
<td></td>
</tr>
<tr>
<td>Upper leg</td>
<td>Hip joint:</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>static flexion/ extension</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>static adduction/ abduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Femur joint:</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>static adduction/ abduction</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Table 4.3 (continued)
4.1.4 Modeling Of Hybrid III 50\textsuperscript{th} Percentile Dummy

The Hybrid III 50\textsuperscript{th} percentile male dummy represents an average of the USA male population and is used for automotive safety restraint system. It widely accepted and used in several standards.

Figure 4.4 Hybrid III 50\textsuperscript{th} percentile Dummy model; ellipsoid model (left) and facet model (right)[19]

The neck of the dummy is represented by 5 kinematic joints located in the centers of the 4 rubber disks and on the rotation axis of the nodding joint (OC). Spherical joints and revolute joint were used to represent rubber disks and nodding joint respectively. As the US-Dot SID dummy does not have a neck region (uses a rigid link) this dummy was used
to obtain NIC during the side impact analysis. The contacts for the model are defined between head and thorax and the thorax and left and right upper leg.

4.1.5 Modeling Of Car Interior

The car interior consists of a rigid seat, with a padded head rest, foot plane mounted on the rigid sled. The dummy is placed in a realistic seat position. Foot stop plates were used to restrict the foot and lower leg movement. These plates simulate a firewall in an actual vehicle. The test environment is modeled with planes using Surface. Plane card in the xml file. The final representation of the car’s interior looks as shown in the figure below.

Figure 4.5 Car Interior in MADYMO

Simple belts can be described using Kelvin restraints. To describe a complex belt model in order to achieve the effects of slip in different directions across dummy model,
4.1.6 Three-Point Belt Modeling

Hybrid belt model which is a combination of standard belt model with finite element is used. Several examples of standard belt models used are as shown in the figure.

![Figure 4.6 Examples of applications of the belt models[20]](image)

A belt consists of a chain of belt segments interconnected by tying whose ends are called as attachment points. The model accounts for slip of belt material from segment to segment. If finite elements are used to model the belt segment the nodes on the belt can slide over the dummy so that submarining and belt rollout can be modeled. Initial belt slack, hysteresis and belt stiffness can be described in the belt model. Relative belt elongation at which rupture occurs can be defined for each belt segment.
The belt model used is a three-point hybrid belt system consisting of Finite elements. This belt system was modeled using Hypermesh in Madymo user profile, and standard characteristics of automobile seat belt have been applied to the belt model. The belt model is as shown in the figure below.

Figure 4.7 The Model of the Seat Belt
4.1.7 Airbag Modeling

Airbags like belt restraint systems belong to the vehicle interior components contributing to the safety of the passenger. Therefore it is important to model the airbags accurately to predict crash simulations accurately. Two different types of airbags have been used in the Thesis a) Elliptical airbag b) Oval airbag. Both the airbags are used on the seat belt in individual cases to improve the Head Injury Criterion of the Occupant.

Figure 4.8 Model of Oval Airbag

Figure 4.9 Model of Elliptical Airbag
Several factors affect the performance of an airbag such as mass flow rate, temperature variation with time, ambient conditions, time at which the sensors are triggered and inflator gas composition. Airbag applications require high level of accuracy during an actual crash simulation, therefore parameters such as timing and unfolding pattern are crucial and much attention should be paid to model an airbag [20].

Airbag geometry should be accurately designed which is done using defining better mesh quality. Using coarse mesh will affect the quality of the airbag during deployment. To accurately define the unfolding pattern of an airbag we first need to define a realistic initial folding configuration which is done by creating a mesh representing stress free-state geometry of the airbag and then it is folded and placed on the restraint system. As the folding process induces element distortion the airbag is relaxed via initial metric method before inflation. Example of such folding of an airbag I as shown in the figure [20].

![Fig 4.10 Folding of a passenger airbag [20]](image)

Input for an airbag plays an important role to determine its performance. Mass flow rate for the airbag plays an important role in maintaining the pressure, temperature and volume inside the airbag. Several different combinations of mass flow rate and its effect on injury parameters are considered to obtain a good result. The Mass flow rate used in the deployment of the airbag is as shown in the figure below.

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The expansion of the gas used in the airbag is considered to be isothermal thus, the temperature of the gas entering the airbag is same as the temperature of the gas exciting the airbag. The temperature variation with time for the gas is as shown in the figure below.
Physical holes are not allowed in the airbag as Madymo requires the airbag to be a closed contour. Material type HOLE is defined in the materials to take care of the outlet of the gas. Material Isolin and property type MEM3 have been used which are best suited for modeling airbag fabric. The inflator gas composition used include oxygen with a molar fraction of 0.2 and nitrogen with a molar fraction of 0.8.

4.2 FMVSS 214 Side Impact Analysis

Analysis was done according to FMVSS 214 standard using Dodge Caravan and Moving Deformable Barrier. The setup for the simulation looks as shown below.
Two different dummies have been considered in the thesis to understand the effect of having airbag on the seatbelt in preventing injuries to the occupant during Side impact analysis. The cases studied are

Using US-DoT SID

- US-DoT SID without and airbag
- US-DoT SID with oval airbag
- US-DoT SID with elliptical airbag

Using Hybrid III 50th percentile Dummy

- Hybrid III Dummy without airbag
- Hybrid III dummy with oval airbag
- Hybrid III dummy with elliptical airbag

**US-DoT SID without Airbag**

![Figure 4.14 US DoT SID without Airbag](image)

Figure 4.14 US DoT SID without Airbag
This model consists of a simple 3 point belt restraint system along with the deformed car door obtained from the FMVSS 214 analysis done using Dodge caravan and 214 moving deformable barrier.

**US-DoT SID with Oval Airbag**

This model consists of an oval airbag which is used to protect the dummy by preventing the head from impacting the door thereby reducing the injury to the occupant.

**US-DoT SID with Elliptical Airbag**
This model consists of an elliptical airbag instead of the oval airbag used in the above model. Elliptical airbag model was considered in order to evaluate the effect of the shape of the airbag on the Dummy.

**Hybrid III Dummy without Airbag**

![Figure 4.17 Hybrid III dummy without airbag](image)

**Hybrid III Dummy with Oval Airbag**

![Figure 4.18 Hybrid III Dummy with Oval Airbag](image)
Hybrid III Dummy with Elliptical Airbag

Figure 4.20 Hybrid III Dummy with Elliptical Airbag

The pulse obtained from the FMVSS 214 analysis is used in the above cases to study the occupant response and understand the effects of the inflatable seat belt on the dummy and its practicality.
CHAPTER V

RESULTS AND DISCUSSIONS

5.1 FMVSS 214 Analysis

Dodge caravan and FMVSS 214 moving deformable barrier were used to do the analysis according to the standard, the MBD travels at a speed of 33.5 mph at an angle of 63 degrees with a barrier mass of 1370 kg. The simulation with an increment of 0.01ms is as shown below

Figure 5.1 FMVSS Analysis of Dodge Caravan at 0.00 s

Figure 5.2 FMVSS Analysis of Dodge Caravan at 0.1 s
Figure 5.3 FMVSS Analysis of Dodge Caravan at 0.2 s

Figure 5.4 FMVSS Analysis of Dodge Caravan at 0.3 s
Figure 5.5 FMVSS Analysis of Dodge Caravan at 0.4 s

Figure 5.6 FMVSS Analysis of Dodge Caravan at 0.5 s
Figure 5.7 FMVSS Analysis of Dodge Caravan at 0.6 s

Figure 5.8 FMVSS Analysis of Dodge Caravan at 0.7 s
Figure 5.9 FMVSS Analysis of Dodge Caravan at 0.8s

Figure 5.10 FMVSS Analysis of Dodge Caravan at 0.9 s
The pulse and the deformed door are obtained from the above analysis. Pulse is in the order of 50 G’s as shown below.
The pulse is calculated at the center of gravity of the vehicle using the accelerometer to obtain the acceleration. The maximum G force obtained in the simulation is 50.9m/s^2 as shown in the chart. This pulse data is similar to the pulse data obtained from NHTSA FMVSS 214 sled test analysis. Thereby, validating the FMVSS 214 analysis.

The pulse obtained above is used in the subsequent models to evaluate the occupant response.

5.2 US-DoT SID

5.2.1 US-DoT SID without the Airbag on Restraint system

Figure 5.13 US-DoT SID without Airbag at 0 s
Figure 5.14 US-DoT SID without Airbag at 0.1 s

Figure 5.15 US-DoT SID without Airbag at 0.2 s
Figure 5.16 US-DoT SID without Airbag at 0.3 s

Figure 5.17 US-DoT SID without Airbag at 0.4 s
Figure 5.18 US-DoT SID without Airbag at 0.5 s

Figure 5.19 US-DoT SID without Airbag at 0.6 s
Figure 5.20 US-DoT SID without Airbag at 0.7 s

Figure 5.21 US-DoT SID without Airbag at 0.8 s
Figure 5.22 US-DoT SID without Airbag at 0.9 s

Figure 5.23 US-DoT SID without Airbag at 1 s
From the simulations above, the occupant response during side impact analysis can be seen, it can be observed that the occupant is thrown away resulting in heavy head impact to the Door.

5.2.2 US-DoT SID with oval airbag on the restraint system

Figure 5.24 US-DoT SID with Oval Airbag at 0 s
Figure 5.25 US-DoT SID with Oval Airbag at 0.1 s

Figure 5.26 US-DoT SID with Oval Airbag at 0.2 s
Figure 5.27 US-DoT SID with Oval Airbag at 0.3 s

Figure 5.28 US-DoT SID with Oval Airbag at 0.4 s
Figure 5.29 US-DoT SID with Oval Airbag at 0.5 s

Figure 5.30 US-DoT SID with Oval Airbag at 0.6 s
Figure 5.31 US-DoT SID with Oval Airbag at 0.7 s

Figure 5.32 US-DoT SID with Oval Airbag at 0.8 s
Figure 5.33 US-DoT SID with Oval Airbag at 0.9 s

Figure 5.34 US-DoT SID with Oval Airbag at 1 s
Above simulation shows the occupant behavior while using oval airbag on the seat belt. It can be observed that the head is not impacting the Door of the vehicle reducing the Head injury parameter.

5.2.3 US-DoT SID with elliptical airbag on the restraint system

Figure 5.35 US-DoT SID with Elliptical Airbag at 0 s
Figure 5.36 US-DoT SID with Elliptical Airbag at 0.1 s

Figure 5.37 US-DoT SID with Elliptical Airbag at 0.2 s
Figure 5.38 US-DoT SID with Elliptical Airbag at 0.3 s

Figure 5.39 US-DoT SID with Elliptical Airbag at 0.4 s
Figure 5.40 US-DoT SID with Elliptical Airbag at 0.5 s

Figure 5.41 US-DoT SID with Elliptical Airbag at 0.6 s
Figure 5.42 US-DoT SID with Elliptical Airbag at 0.7 s

Figure 5.43 US-DoT SID with Elliptical Airbag at 0.8 s
Figure 5.44 US-DoT SID with Elliptical Airbag at 0.9 s

Figure 5.45 US-DoT SID with Elliptical Airbag at 1 s
Occupant response during side impact analysis using elliptical airbag can be seen above. It can be seen that the head is restrained from hitting the door but a lot of neck bending can be observed.

5.3 Hybrid III Dummy

5.3.1 Hybrid III Dummy without the Airbag on restraint system

![Figure 5.46 Hybrid III Dummy without airbag at 0 s](image)

Figure 5.46 Hybrid III Dummy without airbag at 0 s

![Figure 5.47 Hybrid III Dummy without airbag at 0.1 s](image)

Figure 5.47 Hybrid III Dummy without airbag at 0.1 s
Figure 5.48 Hybrid III Dummy without airbag at 0.2 s

Figure 5.49 Hybrid III Dummy without airbag at 0.3 s
Figure 5.50 Hybrid III Dummy without airbag at 0.4 s

Figure 5.51 Hybrid III Dummy without airbag at 0.5 s
Figure 5.52 Hybrid III Dummy without airbag at 0.6 s

Figure 5.53 Hybrid III Dummy without airbag at 0.7 s
Figure 5.54 Hybrid III Dummy without airbag at 0.8 s

Figure 5.55 Hybrid III Dummy without airbag at 0.9 s
5.3.2 Hybrid III Dummy With Oval Airbag on the Restraint System

Figure 5.56 Hybrid III Dummy without airbag at 1 s

Figure 5.57 Hybrid III Dummy with Oval airbag at 0 s
Figure 5.58 Hybrid III Dummy with Oval airbag at 0.1 s

Figure 5.59 Hybrid III Dummy with Oval airbag at 0.2 s
Figure 5.60 Hybrid III Dummy with Oval airbag at 0.3 s

Figure 5.61 Hybrid III Dummy with Oval airbag at 0.4 s
Figure 5.62 Hybrid III Dummy with Oval airbag at 0.5 s

Figure 5.63 Hybrid III Dummy with Oval airbag at 0.6 s
Figure 5.64 Hybrid III Dummy with Oval airbag at 0.7 s

Figure 5.65 Hybrid III Dummy with Oval airbag at 0.8 s
Figure 5.66 Hybrid III Dummy with Oval airbag at 0.9 s

Figure 5.67 Hybrid III Dummy with Oval airbag at 1 s
5.3.3 Hybrid III Dummy with Elliptical Airbag on the Restraint System

Figure 5.68 Hybrid III Dummy with Elliptical airbag at 0 s

Figure 5.69 Hybrid III Dummy with Elliptical airbag at 0.1 s
Figure 5.70 Hybrid III Dummy with Elliptical airbag at 0.2 s

Figure 5.71 Hybrid III Dummy with Elliptical airbag at 0.3 s
Figure 5.72 Hybrid III Dummy with Elliptical airbag at 0.4 s

Figure 5.73 Hybrid III Dummy with Elliptical airbag at 0.5 s
Figure 5.74 Hybrid III Dummy with Elliptical airbag at 0.6 s

Figure 5.75 Hybrid III Dummy with Elliptical airbag at 0.7 s
Figure 5.76 Hybrid III Dummy with Elliptical airbag at 0.8 s

Figure 5.77 Hybrid III Dummy with Elliptical airbag at 0.9 s
Figure 5.78 Hybrid III Dummy with Elliptical airbag at 1 s
5.4 OCCUPANT KINEMATICS

Occupant response to side impact analysis for all the cases have been compared below,

Head Acceleration

For US-DoT SID we get,

![Head Acceleration for US-Dot SID](image)

For Hybrid III 50\textsuperscript{th} percentile Dummy

![Head Acceleration for Hybrid III 50\textsuperscript{th} percentile Dummy](image)
It can be observed that in both the Dummies head acceleration for dummy without airbag registered high acceleration compared to their other counterparts.

**Pelvis Acceleration**

For US-DoT SID

![Pelvis Acceleration](image1)

Figure 5.81 Pelvis Acceleration for US-Dot SID

For Hybrid III 50th percentile Dummy

![Pelvis Acceleration](image2)

Figure 5.82 Pelvic Acceleration for Hybrid III 50th percentile Dummy
The difference in pelvic acceleration for both the dummies is not much. Accelerations for all the cases is less than 130 G’s. which is acceptable.

**Thorax Acceleration**

For US-DoT SID

For Hybrid III 50\textsuperscript{th} percentile Dummy

![Thorax Acceleration for US-DoT SID](image)

**Figure 5.83** Thorax Acceleration for US-Dot SID

![Thorax Acceleration for Hybrid III 50\textsuperscript{th} percentile Dummy](image)

**Figure 5.84** Thorax Acceleration for Hybrid III 50\textsuperscript{th} percentile Dummy
Similar to Pelvic acceleration, Thorax acceleration values are similar for all the cases with an average of 100 G’s.

**Chest Deflection**

For US-DoT SID

![Figure 5.85 Chest Deflection for US-Dot SID](image)

For Hybrid III 50th percentile Dummy

![Figure 5.86 Chest Deflection for Hybrid III 50th percentile Dummy](image)

Chest deflection for Hybrid III Dummy registered high values compared to US-DoT SID, but all the values are below 10mm to cause much damage.
5.5 Injury Parameters

Table 5.1 shows the results of the simulations done to evaluate the effectiveness of an external airbag on the restraint system and to compare the efficiency in reducing the injuries compared to a restraint system without an external airbag.

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Table 5.1 Dummy Injury Parameters

Neck Injury which is a serious problem during car side impacts is evaluated in the simulation and since the NIC values for the US-DoT side impact dummy cannot be calculated, Hybrid III dummy was used to calculate the neck injury values. It can be seen that the neck injury values have reduced to acceptable values with the use of both the elliptical and oval airbag.

Head injury values play an important role in the evaluation of the importance of the airbag as Side impacts can cause severe skull fracture due to limited space and intrusion of the door into the passenger compartment. HIC values in both the dummies show efficiency of the restraint system with the use of an external airbag in restraining the head of the dummy from coming in contact from the interior of the car showcasing improved protection.
Significant difference cannot be found on acceleration based injuries as both the pelvic accelerations and thoracic trauma index do not get affected with the use of an external airbag or the restraint system. It can be seen that for both the dummies the values of pelvic acceleration and TTI are below the critical limit of 130 G’s and 90 G respectively.

Cumulative 3ms for both the cases show values less than the critical limit of 70 G’s except for the Hybrid III 50th percentile dummy without an external airbag which exceeds 70 G’s.
CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

FMVSS 214 side impact evaluation test is a widely used validation technique to analyze Injuries during Side impact but the Dummy used in this test US DoT SID does not address the effect of neck bending and possible neck injuries. To address this issue Hybrid III 50th percentile dummy was used to calculate the neck injury caused during side impacts and External Airbags were used on the restraint system to improve injury protection to both Head and neck. Parametric study on two different types of dummies (US-Dot SID and Hybrid III 50th percentile dummy) during a side impact analysis by using external inflatable upper torso restraint system was done to evaluate the possible neck and head injuries. Two different types of airbags have been chosen (Oval and Elliptical shape) to test their effect in improving the neck injury parameter of the dummy. An FMVSS 214 side impact analysis was done using Dodge caravan and a Moving Deformable Barrier, and the pulse data obtained from the analysis was used in the subsequent Madymo analysis using two different dummies and airbags. Neck injury is critical during side impact analysis but the FMVSS 214 standard US-Dot Side Impact dummy does not provide neck injury data thus, Hybrid III 50th percentile dummy was used to study neck injury. With the use of airbag it was observed that there is considerable reduction in $N_{ij}$ value thereby improving occupant protection.

- The inflatable upper torso restraint system was successful in improving neck injury protection during the side impact analysis, thereby reducing $N_{ij}$ values below the critical limit which was the main aim of the study.
• Head of the dummy was restrained from hitting the deformable door, reducing the value of Head Injury Criterion (HIC) which is important in side impacts.

• Elliptical airbag was much more effective in reducing the head acceleration compared to oval airbag though both were effective in reducing the injury parameters way below critical level.

• Pelvic accelerations for both the dummies were less than 130G’s which is acceptable in all the cases.

• Lower torso restriction should be reduced as it will increase the neck bending resulting in higher injury values.

6.2 RECOMMENDATIONS

The study provided insight about neck injury and the use of inflatable upper torso restraint system in reducing neck injuries. There is still lot of research needed to be done to understand and to predict the behavior of the restraint system in various scenarios. Some of the recommendations that can be followed to improve effectiveness and efficiency of the restraint system are given below

• Hybrid III was used in the simulations to evaluate the neck injury criterion, ATD’s can be used in sled tests to validate the results obtained.

• Rigid properties were given to the deformed door and the seat to obtain data at worst case scenario, actual car interior can be designed and used to obtain better results and thereby resulting in better understanding.
• Real time test can be done using Inflatable upper torso restraint system and the results can be compared

• Dodge caravan was used to do the FMVSS 214 test, smaller cars can be used to take into effect of different boundary conditions (intrusion of the door in to the driver compartment) and better understanding of the efficiency of inflatable upper torso restraint system can be obtained.

• Different types of inflatable belt restraint systems can be used to study their effectiveness and an optimized restraint system can be developed.

• Material, combination of gases, ambient pressure and temperature can be varied for the design of airbag to get better results.

• Effect of shape of the airbag can be tested by designing various shapes and sizes of the airbag and an optimized design can be generated for improved performance.
REFERENCES
LIST OF REFERENCES


LIST OF REFERENCES (CONTINUED)


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APPENDIX
General Airbag Deck in Madymo

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General FE Belt deck in Madymo

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