AUTOMOTIVE SIDE-IMPACT SIMULATIONS AND COMPARISON OF DUMMY AND HUMAN BODY MODEL CRASH DYNAMIC RESPONSES ACCORDING TO REGULATORY STANDARDS

A Thesis by

Durga Venkata Suresh Koppisetty

Master of Technology, GITAM University, India, 2013

Bachelor of Technology, Vignan’s Institute of Information Technology, India, 2011

Submitted to the Department of Mechanical Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

July 2017
AUTOMOTIVE SIDE-IMPACT SIMULATIONS AND COMPARISON OF DUMMY AND HUMAN BODY MODEL CRASH DYNAMIC RESPONSES ACCORDING TO REGULATORY STANDARDS

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.

________________________________
Hamid M. Lankarani, Committee Chair

________________________________
Krishna Krishnan, Committee Member

________________________________
Yimesker Yihun, Committee Member
DEDICATION

To my loving parents, my sister, my brother, and my dear friends, and to my advisor, Dr. Hamid M. Lankarani
Learning gives creativity,
Creativity leads to thinking,
Thinking provides knowledge,
Knowledge makes you great.

—A. P. J. Abdul Kalam
ACKNOWLEDGEMENTS

I would like to extend my heartfelt gratitude to my advisor, Dr. Hamid M. Lankarani, Professor of Mechanical Engineering at Wichita State University, for his continuous support and patience. His guidance helped me throughout my master’s degree program. It has been a privilege to perform my duties as his Graduate Teaching Assistant, and this thesis would not have been successful without his valuable guidance.

I also thank my esteemed committee members, Dr. Krishna Krishnan and Dr. Yimesker Yihun, for their helpful comments and suggestions.

I would like to express my profound gratitude to my parents and to my siblings for their endless love and encouragement. My family is my strength and everything.

I also thank my friends and the faculty of the Department of Mechanical Engineering at Wichita State University for their constant support.
ABSTRACT

According to the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA) and the Insurance Institute for Highway Safety (IIHS), side-impact car accidents are the second leading cause of fatalities in the United States. Compared to all other accidents, side-impact crashes are quite dangerous to the occupants because of their limited ability to absorb the crash energy and less space for intrusion. NHTSA and IIHS have developed safety standards to prevent fatalities by conducting several experiments using anthropomorphic test dummies (ATDs). Although the regulations are based on the use of crash dummies, there might be differences between actual human crash performance and dummy crash performance. In recent years, technology has improved in such a way that crash scenarios can be modeled in various computational software, and human dynamic responses can be studied using active human body models, which are a combination of rigid bodies, finite elements, and kinematic joints, thus making them flexible to use in all crash test scenarios. In this research, nearside occupants were considered because they are more likely to be injured in a side-impact crash. Vehicle side-impact crash simulations were carried out using LS-DYNA finite element (FE) software, and the occupant response simulations were conducted with Mathematical Dynamic Models (MADYMO) software. Because the simulation of an entire FE model of a car and occupant is quite time consuming and expensive, a prescribed structural motion (PSM) technique was utilized and applied to the side-door panel with an occupant positioned in the driver seat of the car using the MADYMO code. Regular side-impact deformable barrier and pole test simulations were performed with belted and unbelted occupant models considering two different target vehicles—a mid-size sedan and a small compact car. Responses from dummy and human body models were compared in order to quantify the noticeable differences between the two performances in nearside-impact accidents.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Vehicle Crashworthiness</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Regulatory Standards</td>
<td>4</td>
</tr>
<tr>
<td>1.3.1</td>
<td>FMVSS Safety Regulations</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>FMVSS 214 Moving Deformable Barrier Side Impact Test</td>
<td>7</td>
</tr>
<tr>
<td>1.5</td>
<td>FMVSS 214 Rigid Pole Side Impact Test</td>
<td>8</td>
</tr>
<tr>
<td>1.6</td>
<td>IIHS Moving Deformable Barrier Side Impact Test</td>
<td>9</td>
</tr>
<tr>
<td>1.7</td>
<td>Injury Pass-Fail Criteria</td>
<td>10</td>
</tr>
<tr>
<td>1.8</td>
<td>Literature Review</td>
<td>12</td>
</tr>
<tr>
<td>1.9</td>
<td>Motivation</td>
<td>17</td>
</tr>
<tr>
<td>2.</td>
<td>OBJECTIVES AND METHODOLOGY</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Objectives</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Methodology</td>
<td>18</td>
</tr>
<tr>
<td>2.3</td>
<td>Computational Tools</td>
<td>20</td>
</tr>
<tr>
<td>2.3.1</td>
<td>LS-DYNA</td>
<td>20</td>
</tr>
<tr>
<td>2.3.2</td>
<td>HyperView</td>
<td>21</td>
</tr>
<tr>
<td>2.3.3</td>
<td>MADYMO</td>
<td>22</td>
</tr>
<tr>
<td>3.</td>
<td>COMPUTATIONAL METHODOLOGY</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>LS-DYNA Finite Element Models</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>MADYMO Interior Vehicle Model</td>
<td>28</td>
</tr>
<tr>
<td>3.3</td>
<td>Modeling Details of ES-2re Dummy</td>
<td>29</td>
</tr>
<tr>
<td>3.4</td>
<td>Modeling Details of Human Body Model</td>
<td>32</td>
</tr>
<tr>
<td>3.5</td>
<td>Modeling of Finite Element Restraining Belt</td>
<td>36</td>
</tr>
<tr>
<td>3.6</td>
<td>Vehicle and Occupant Modeling</td>
<td>37</td>
</tr>
<tr>
<td>3.6.1</td>
<td>Vehicle and ES-2re Dummy Modeling</td>
<td>37</td>
</tr>
<tr>
<td>3.6.2</td>
<td>Vehicle and Human Body Model Modeling</td>
<td>39</td>
</tr>
<tr>
<td>3.7</td>
<td>Prescribed Structural Motion</td>
<td>40</td>
</tr>
<tr>
<td>4.</td>
<td>DUMMY AND HUMAN BODY MODEL RESPONSES IN FMVSS 214 MOVING DEFORMABLE BARRIER SIDE-IMPACT TEST FOR TYPICAL MID-SIZE SEDAN AND SMALL-SIZE COMPACT CAR</td>
<td>43</td>
</tr>
<tr>
<td>4.1</td>
<td>Typical Mid-Size Sedan</td>
<td>43</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Finite Element Simulation</td>
<td>44</td>
</tr>
<tr>
<td>4.1.2</td>
<td>ES-2re Dummy Responses</td>
<td>48</td>
</tr>
</tbody>
</table>

viii
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.3</td>
<td>Human Body Model Responses</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Comparison of Results</td>
</tr>
<tr>
<td>4.1.5</td>
<td>PSM Results</td>
</tr>
<tr>
<td>4.2</td>
<td>Small-Size Compact Car</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Finite Element Simulation</td>
</tr>
<tr>
<td>4.2.2</td>
<td>ES-2re Dummy Responses</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Human Body Model Responses</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Comparison of Results</td>
</tr>
<tr>
<td>4.2.5</td>
<td>PSM Results</td>
</tr>
<tr>
<td>5.1</td>
<td>Typical Mid-Size Sedan</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Finite Element Simulation</td>
</tr>
<tr>
<td>5.1.2</td>
<td>ES-2re Dummy Responses</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Human Body Model Responses</td>
</tr>
<tr>
<td>5.1.4</td>
<td>Comparison of Results</td>
</tr>
<tr>
<td>5.1.5</td>
<td>PSM Results</td>
</tr>
<tr>
<td>5.2</td>
<td>Small-Size Compact Car</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Finite Element Simulation</td>
</tr>
<tr>
<td>5.2.2</td>
<td>ES-2re Dummy Responses</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Human Body Model Responses</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Comparison of Results</td>
</tr>
<tr>
<td>5.2.5</td>
<td>PSM Results</td>
</tr>
<tr>
<td>6.1</td>
<td>Typical Mid-Size Sedan</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Finite Element Simulation</td>
</tr>
<tr>
<td>6.1.2</td>
<td>ES-2re Dummy Responses</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Human Body Model Responses</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Comparison of Results</td>
</tr>
<tr>
<td>6.1.5</td>
<td>PSM Results</td>
</tr>
<tr>
<td>6.2</td>
<td>Small-Size Compact Car</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Finite Element Simulation</td>
</tr>
<tr>
<td>6.2.2</td>
<td>ES-2re Dummy Responses</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Human Body Model Responses</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2.4 Comparison of Results</td>
<td>127</td>
</tr>
<tr>
<td>6.2.5 PSM Results</td>
<td>133</td>
</tr>
<tr>
<td>7. OVERALL COMPARISON OF DUMMY AND HUMAN BODY MODEL SIDE-IMPACT RESULTS</td>
<td>137</td>
</tr>
<tr>
<td>7.1 Comparison for Occupants of Mid-Size Sedan</td>
<td>137</td>
</tr>
<tr>
<td>7.2 Comparison for Occupants of Small-Size Compact Car</td>
<td>139</td>
</tr>
<tr>
<td>8. CONCLUSIONS AND RECOMMENDATIONS</td>
<td>144</td>
</tr>
<tr>
<td>8.1 Conclusions</td>
<td>144</td>
</tr>
<tr>
<td>8.2 Recommendations</td>
<td>147</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>148</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>1.1</td>
<td>2014 FARS DATA FOR U.S.</td>
</tr>
<tr>
<td>3.1</td>
<td>FINITE ELEMENT MODEL SUMMARY OF CAR MODELS</td>
</tr>
<tr>
<td>3.2</td>
<td>FINITE ELEMENT MODEL SUMMARY OF MOVING DEFORMABLE BARRIERS AND RIGID POLE</td>
</tr>
<tr>
<td>4.1</td>
<td>TTI VALUES FOR DIFFERENT FMVSS 214 MDB SIDE-IMPACT TEST SCENERIOS—MID-SIZE SEDAN</td>
</tr>
<tr>
<td>4.2</td>
<td>TTI VALUES FOR DIFFERENT FMVSS 214 MDB SIDE-IMPACT TEST SCENERIOS—SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>5.1</td>
<td>TTI VALUES FOR DIFFERENT FMVSS 214 RIGID POLE SIDE-IMPACT TEST SCENERIOS—MID-SIZE SEDAN</td>
</tr>
<tr>
<td>5.2</td>
<td>TTI VALUES FOR DIFFERENT FMVSS 214 RIGID POLE SIDE-IMPACT TEST SCENERIOS—SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>6.1</td>
<td>TTI VALUES FOR DIFFERENT IIHS MDB SIDE-IMPACT TEST SCENERIOS—MID-SIZE SEDAN</td>
</tr>
<tr>
<td>6.2</td>
<td>TTI VALUES FOR DIFFERENT IIHS MDB SIDE-IMPACT TEST SCENERIOS—SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>7.1</td>
<td>COMPARISON OF OVERALL TEST RESULTS—MID-SIZE SEDAN</td>
</tr>
<tr>
<td>7.2</td>
<td>COMPARISON OF OVERALL TEST RESULTS—SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>7.3</td>
<td>COMPARISON OF FMVSS 214 MDB SIDE-IMPACT TEST RESULTS—MID-SIZE SEDAN VS SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>7.4</td>
<td>COMPARISON OF FMVSS 214 RIGID POLE SIDE-IMPACT TEST RESULTS—MID-SIZE SEDAN VS SMALL-SIZE COMPACT CAR</td>
</tr>
<tr>
<td>7.5</td>
<td>COMPARISON OF IIHS MDB SIDE-IMPACT TEST RESULTS—MID-SIZE SEDAN VS SMALL-SIZE COMPACT CAR</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Fatalities by vehicle occupant, 2006–2015</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Type of crashes occurred in 2015</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Car safety regulations</td>
<td>5</td>
</tr>
<tr>
<td>1.4</td>
<td>Different vehicle safety standard tests</td>
<td>6</td>
</tr>
<tr>
<td>1.5</td>
<td>FMVSS 214 moving deformable barrier side-impact test setup</td>
<td>7</td>
</tr>
<tr>
<td>1.6</td>
<td>FMVSS 214 rigid pole side-impact test setup</td>
<td>8</td>
</tr>
<tr>
<td>1.7</td>
<td>IIHS moving deformable barrier side-impact test setup</td>
<td>9</td>
</tr>
<tr>
<td>1.8</td>
<td>IIHS moving deformable barrier cart</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Methodology</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>LS-DYNA solving process</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>Elements used in LS-DYNA</td>
<td>20</td>
</tr>
<tr>
<td>2.4</td>
<td>MADYMO working structure</td>
<td>22</td>
</tr>
<tr>
<td>2.5</td>
<td>Examples of different multi-body systems</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Multi-body systems with forces and contacts</td>
<td>24</td>
</tr>
<tr>
<td>3.1</td>
<td>Ford Taurus mid-size sedan FE model</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>Toyota Yaris small-size compact car FE model</td>
<td>25</td>
</tr>
<tr>
<td>3.3</td>
<td>NHTSA moving deformable barrier FE model</td>
<td>27</td>
</tr>
<tr>
<td>3.4</td>
<td>IIHS moving deformable barrier FE model</td>
<td>27</td>
</tr>
<tr>
<td>3.5</td>
<td>NHTSA rigid pole FE model</td>
<td>27</td>
</tr>
<tr>
<td>3.6</td>
<td>Model of car vehicle interior compartment</td>
<td>28</td>
</tr>
<tr>
<td>3.7</td>
<td>EuroSID real crash test dummy</td>
<td>30</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.8</td>
<td>ES-2re ellipsoid dummy model</td>
<td>30</td>
</tr>
<tr>
<td>3.9</td>
<td>ES-2re thorax assembly</td>
<td>30</td>
</tr>
<tr>
<td>3.10</td>
<td>ES-2re rib extension assembly</td>
<td>30</td>
</tr>
<tr>
<td>3.11</td>
<td>ES-2re ellipsoid dummy parts</td>
<td>31</td>
</tr>
<tr>
<td>3.12</td>
<td>Human skeletal system</td>
<td>32</td>
</tr>
<tr>
<td>3.13</td>
<td>Vertebral column</td>
<td>32</td>
</tr>
<tr>
<td>3.14</td>
<td>Large male, mid-size male, and small female human facet occupant models</td>
<td>33</td>
</tr>
<tr>
<td>3.15</td>
<td>50&lt;sup&gt;th&lt;/sup&gt; percentile human male facet model</td>
<td>34</td>
</tr>
<tr>
<td>3.16</td>
<td>Joint positions of HBM</td>
<td>35</td>
</tr>
<tr>
<td>3.17</td>
<td>HBM in reference position</td>
<td>35</td>
</tr>
<tr>
<td>3.18</td>
<td>Spine and neck assemblies of HBM</td>
<td>35</td>
</tr>
<tr>
<td>3.19</td>
<td>Flexible bodies of thorax and abdomen and rigid vertebral bodies</td>
<td>36</td>
</tr>
<tr>
<td>3.20</td>
<td>Three-point hybrid restraining belt system</td>
<td>37</td>
</tr>
<tr>
<td>3.21</td>
<td>Model of vehicle and ES-2re dummy</td>
<td>38</td>
</tr>
<tr>
<td>3.22</td>
<td>Model of ES-2re dummy with seatbelt</td>
<td>38</td>
</tr>
<tr>
<td>3.23</td>
<td>Model of vehicle and HBM</td>
<td>39</td>
</tr>
<tr>
<td>3.24</td>
<td>Model of HBM with seatbelt</td>
<td>39</td>
</tr>
<tr>
<td>3.25</td>
<td>LS-DYNA finite element vehicle model</td>
<td>41</td>
</tr>
<tr>
<td>3.26</td>
<td>Finite element model of trimmed side-door panel with driver seat</td>
<td>41</td>
</tr>
<tr>
<td>3.27</td>
<td>HyperView capturing vehicle structure nodal displacements</td>
<td>42</td>
</tr>
<tr>
<td>3.28</td>
<td>Trimmed FE model: (a) with ES-2re dummy and (b) with human body model</td>
<td>42</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>FE model setup of Ford Taurus mid-size sedan and FMVSS 214 moving deformable barrier</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Simulation of Ford Taurus mid-size sedan FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Dynamic response of rear seat right sill of mid-size sedan from this study and from NCAC and NHTSA test simulations</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Dynamic response of mid-size sedan driver seat X-, Y-, and Z-accelerations from LS-DYNA FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Intrusion of mid-size sedan B-pillar: (a) before crash and (b) after crash</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td>Crash profile of Ford Taurus mid-size sedan: (a) before FMVSS 214 MDB side-impact test and (b) after FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>ES-2re dummy responses in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>ES-2re dummy responses in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.9</td>
<td>Human body model responses in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.10</td>
<td>Human body model responses in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.11</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.12</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.13</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.14</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.15</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.16</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.17</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.18</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.19</td>
<td>MADYMO configuration tree of ES-2re dummy and HBM with upper and lower rib rigid bodies and T12 spine rigid body</td>
<td></td>
</tr>
<tr>
<td>4.20</td>
<td>Ford Taurus mid-size sedan without seatbelt for ES-2re dummy and HBM responses in FMVSS 214 MDB side-impact test using PSM method</td>
<td></td>
</tr>
<tr>
<td>4.21</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
<td></td>
</tr>
<tr>
<td>4.22</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
<td></td>
</tr>
<tr>
<td>4.23</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
<td></td>
</tr>
<tr>
<td>4.24</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB test using PSM method</td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td>FE model setup of Toyota Yaris small-size compact car and FMVSS 214 moving deformable barrier</td>
<td></td>
</tr>
<tr>
<td>4.26</td>
<td>Simulation of Toyota Yaris small-size compact car FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.27</td>
<td>Dynamic response of small-size compact car driver seat X-, Y-, and Z-accelerations from LS-DYNA FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>4.28</td>
<td>Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in FMVSS 214 MDB side-impact test</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.29</td>
<td>Crash profile of Toyota Yaris small-size compact car: (a) before and (b) after (right) the FMVSS 214 MDB side-impact test</td>
<td>64</td>
</tr>
<tr>
<td>4.30</td>
<td>ES-2re dummy responses in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>65</td>
</tr>
<tr>
<td>4.31</td>
<td>ES-2re dummy responses in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>65</td>
</tr>
<tr>
<td>4.32</td>
<td>Human body model responses in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>66</td>
</tr>
<tr>
<td>4.33</td>
<td>Human body model responses in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>66</td>
</tr>
<tr>
<td>4.34</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>67</td>
</tr>
<tr>
<td>4.35</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>67</td>
</tr>
<tr>
<td>4.36</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>68</td>
</tr>
<tr>
<td>4.37</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>68</td>
</tr>
<tr>
<td>4.38</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>69</td>
</tr>
<tr>
<td>4.39</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>69</td>
</tr>
<tr>
<td>4.40</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test</td>
<td>70</td>
</tr>
<tr>
<td>4.41</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test</td>
<td>71</td>
</tr>
<tr>
<td>4.42</td>
<td>Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in FMVSS 214 MDB side-impact test using PSM method</td>
<td>72</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.43</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
</tr>
<tr>
<td>4.44</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
</tr>
<tr>
<td>4.45</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
</tr>
<tr>
<td>4.46</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test using PSM method</td>
</tr>
<tr>
<td>5.1</td>
<td>FE model setup of Ford Taurus mid-size sedan and FMVSS 214 rigid pole</td>
</tr>
<tr>
<td>5.2</td>
<td>Simulation of Ford Taurus mid-size sedan FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.3</td>
<td>Dynamic response of mid-size sedan driver seat X-, Y-, and Z-accelerations in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.4</td>
<td>Intrusion of mid-size sedan B-pillar: (a) before crash and (b) after crash in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.5</td>
<td>Crash profile of Ford Taurus mid-size sedan: (a) before and (b) after FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.6</td>
<td>ES-2re dummy responses in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.7</td>
<td>ES-2re dummy responses in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.8</td>
<td>Human body model responses in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.9</td>
<td>Human body model responses in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>5.10</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.11</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.12</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.13</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.14</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.15</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.16</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.17</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.18</td>
<td>Ford Taurus mid-size sedan without seatbelt ES-2re dummy and HBM responses in FMVSS 214 rigid pole test using PSM method</td>
</tr>
<tr>
<td>5.19</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole test using PSM method</td>
</tr>
<tr>
<td>5.20</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole test using PSM method</td>
</tr>
<tr>
<td>5.21</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole test using PSM method</td>
</tr>
<tr>
<td>5.22</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole test using PSM method</td>
</tr>
<tr>
<td>5.23</td>
<td>FE model setup of Toyota Yaris small-size compact car and FMVSS 214 rigid pole</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>5.24</td>
<td>Simulation of Toyota Yaris small-size compact car FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.25</td>
<td>Dynamic response of small-size compact car seat Y-acceleration in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.26</td>
<td>Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.27</td>
<td>Crash profile of Toyota Yaris small-size compact car: (a) before and (b) after FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.28</td>
<td>ES-2re dummy responses in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.29</td>
<td>ES-2re dummy responses in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.30</td>
<td>Human body model responses in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.31</td>
<td>Human body model responses in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.32</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.33</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.34</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.35</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.36</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
<tr>
<td>5.37</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.38</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test</td>
<td>100</td>
</tr>
<tr>
<td>5.39</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test</td>
<td>100</td>
</tr>
<tr>
<td>5.40</td>
<td>Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in FMVSS 214 rigid pole test using PSM method</td>
<td>102</td>
</tr>
<tr>
<td>5.41</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method</td>
<td>103</td>
</tr>
<tr>
<td>5.42</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method</td>
<td>104</td>
</tr>
<tr>
<td>5.43</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method</td>
<td>104</td>
</tr>
<tr>
<td>5.44</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method</td>
<td>105</td>
</tr>
<tr>
<td>6.1</td>
<td>FE model setup of Ford Taurus mid-size sedan and IIHS moving deformable barrier</td>
<td>107</td>
</tr>
<tr>
<td>6.2</td>
<td>Simulation of Ford Taurus mid-size sedan IIHS MDB side-impact test</td>
<td>107</td>
</tr>
<tr>
<td>6.3</td>
<td>Dynamic response of mid-size sedan driver seat Y-acceleration in IIHS MDB side-impact test</td>
<td>108</td>
</tr>
<tr>
<td>6.4</td>
<td>Intrusion of mid-size sedan B-pillar: (a) before crash and (b) after crash in IIHS MDB side-impact test</td>
<td>108</td>
</tr>
<tr>
<td>6.5</td>
<td>Crash profile of mid-size sedan: (a) before and (b) after IIHS MDB side-impact test</td>
<td>109</td>
</tr>
<tr>
<td>6.6</td>
<td>ES-2re dummy responses in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>110</td>
</tr>
<tr>
<td>6.7</td>
<td>ES-2re dummy responses in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>110</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.8</td>
<td>Human body model responses in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>111</td>
</tr>
<tr>
<td>6.9</td>
<td>Human body model responses in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>111</td>
</tr>
<tr>
<td>6.10</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>112</td>
</tr>
<tr>
<td>6.11</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>112</td>
</tr>
<tr>
<td>6.12</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>113</td>
</tr>
<tr>
<td>6.13</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>113</td>
</tr>
<tr>
<td>6.14</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>114</td>
</tr>
<tr>
<td>6.15</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>115</td>
</tr>
<tr>
<td>6.16</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test</td>
<td>116</td>
</tr>
<tr>
<td>6.17</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in IIHS MDB side-impact test</td>
<td>116</td>
</tr>
<tr>
<td>6.18</td>
<td>Ford Taurus mid-size sedan without seatbelt ES-2re dummy and HBM responses in IIHS MDB side-impact test using PSM method</td>
<td>118</td>
</tr>
<tr>
<td>6.19</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method</td>
<td>119</td>
</tr>
<tr>
<td>6.20</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method</td>
<td>120</td>
</tr>
<tr>
<td>6.21</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method</td>
<td>120</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>6.22</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method</td>
<td>121</td>
</tr>
<tr>
<td>6.23</td>
<td>FE model setup of Toyota Yaris small-size compact car and IIHS moving deformable barrier</td>
<td>122</td>
</tr>
<tr>
<td>6.24</td>
<td>Simulation of Toyota Yaris small-size compact car IIHS MDB side-impact test</td>
<td>123</td>
</tr>
<tr>
<td>6.25</td>
<td>Dynamic response of small-size compact car driver seat Y-acceleration from LS-DYNA IIHS MDB side-impact test</td>
<td>124</td>
</tr>
<tr>
<td>6.26</td>
<td>Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in the IIHS MDB side-impact test</td>
<td>124</td>
</tr>
<tr>
<td>6.27</td>
<td>Crash profile of small-size compact car: (a) before and (b) after IIHS MDB side-impact test</td>
<td>124</td>
</tr>
<tr>
<td>6.28</td>
<td>ES-2re dummy responses in small-size compact car without seatbelt in IIHS MDB side-impact test</td>
<td>125</td>
</tr>
<tr>
<td>6.29</td>
<td>ES-2re dummy responses in small-size compact car with seatbelt in IIHS MDB side-impact test</td>
<td>125</td>
</tr>
<tr>
<td>6.30</td>
<td>Human body model responses in small-size compact car without seatbelt in IIHS MDB side-impact test</td>
<td>126</td>
</tr>
<tr>
<td>6.31</td>
<td>Human body model responses in small-size compact car with seatbelt in IIHS MDB side-impact test</td>
<td>126</td>
</tr>
<tr>
<td>6.32</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test</td>
<td>127</td>
</tr>
<tr>
<td>6.33</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test</td>
<td>128</td>
</tr>
<tr>
<td>6.34</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test</td>
<td>128</td>
</tr>
<tr>
<td>6.35</td>
<td>Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test</td>
<td>129</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>6.36</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test ........................................130</td>
<td></td>
</tr>
<tr>
<td>6.37</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test ........................................130</td>
<td></td>
</tr>
<tr>
<td>6.38</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test ........................................131</td>
<td></td>
</tr>
<tr>
<td>6.39</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test ........................................132</td>
<td></td>
</tr>
<tr>
<td>6.40</td>
<td>Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in IIHS MDB side-impact test using PSM method ........................................133</td>
<td></td>
</tr>
<tr>
<td>6.41</td>
<td>Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test using PSM method ........134</td>
<td></td>
</tr>
<tr>
<td>6.43</td>
<td>Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test using PSM method ..........135</td>
<td></td>
</tr>
<tr>
<td>6.44</td>
<td>Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test using PSM method ..........136</td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APF</td>
<td>Abdominal Peak Force</td>
</tr>
<tr>
<td>ATD</td>
<td>Anthropomorphic Test Dummy</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer-Aided Engineering</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>DFR</td>
<td>Driver Fatality Ratio</td>
</tr>
<tr>
<td>ES-2re</td>
<td>EuroSID-2 Rib Extension</td>
</tr>
<tr>
<td>FARS</td>
<td>Fatality Analysis Reporting System</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>FMVSS</td>
<td>Federal Motor Vehicle Safety Standards</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>GWU</td>
<td>George Washington University</td>
</tr>
<tr>
<td>HIC</td>
<td>Head Injury Criterion</td>
</tr>
<tr>
<td>HBM</td>
<td>Human Body Model</td>
</tr>
<tr>
<td>IIHS</td>
<td>Insurance Institute for Highway Safety</td>
</tr>
<tr>
<td>LTV</td>
<td>Light Transport Vehicle</td>
</tr>
<tr>
<td>MADYMO</td>
<td>Mathematical Dynamic Model</td>
</tr>
<tr>
<td>MDB</td>
<td>Moving Deformable Barrier</td>
</tr>
<tr>
<td>NCAC</td>
<td>National Crash Analysis Center</td>
</tr>
<tr>
<td>NCAP</td>
<td>New Car Assessment Program</td>
</tr>
<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety Administration</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>PMHS</td>
<td>Post-Mortem Human Subject</td>
</tr>
<tr>
<td>PSM</td>
<td>Prescribed Structural Motion</td>
</tr>
<tr>
<td>PSPF</td>
<td>Pubic Symphysis Peak Force</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SI</td>
<td>Severity Index</td>
</tr>
<tr>
<td>SID</td>
<td>Side-Impact Dummy</td>
</tr>
<tr>
<td>SUV</td>
<td>Sport Utility Vehicle</td>
</tr>
<tr>
<td>THUMS</td>
<td>Total Human Model for Safety</td>
</tr>
<tr>
<td>TNO</td>
<td>The Netherlands Organisation</td>
</tr>
<tr>
<td>TTI</td>
<td>Thorax Trauma Index</td>
</tr>
<tr>
<td>USSID</td>
<td>U.S. Side-Impact Dummy</td>
</tr>
<tr>
<td>VC</td>
<td>Viscous Criterion</td>
</tr>
<tr>
<td>WSTC</td>
<td>Wayne State Tolerance Curve</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 Background

Over the years, vehicular accidents have been the major cause of loss of lives. According to the World Health Organization (WHO), thirty-one percent of traffic deaths in the entire world occurred to car occupants [1]. According to 2015 Fatality Analysis Reporting System (FARS) data, more than 35,092 people were involved in fatal accidents, and approximately 2,443,000 people suffered from subsequent injuries. Over the span from 2014 to 2015, fatalities increased by 7.5% and injuries by 4.5%. The FARS also published fatalities by person type from 2006 to 2015, reporting that most accidents occur to passenger occupants followed by light-truck occupants, motorcyclists, and non-occupants. Figure 1.1 illustrates the significant change in percentage of passenger car occupants from 42% to 36% between those years [2]. Safety systems installed in cars play a major role in protecting occupants from fatalities.

For the year 2014, FARS published a complete report of fatalities by person type. Table 1.1 summarizes this information for the total number of fatalities (32,675) by person type, including the number of vehicle occupants, motorcyclists, nonmotorists, and other unknown
persons. Out of 22,276 vehicle occupant deaths, 16,454 were drivers and 5,751 were passengers. As can be seen, the majority of persons killed in crashes were drivers [4].

TABLE 1.1


<table>
<thead>
<tr>
<th>Person Type</th>
<th>Number of Persons Killed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Occupants</strong></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>16,454</td>
</tr>
<tr>
<td>Passenger</td>
<td>5,751</td>
</tr>
<tr>
<td>Unknown Occupant</td>
<td>71</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>22,276</strong></td>
</tr>
<tr>
<td><strong>Motorcyclists</strong></td>
<td></td>
</tr>
<tr>
<td>Motorcyclist</td>
<td>4,586</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>4,586</strong></td>
</tr>
<tr>
<td><strong>Nonmotorists</strong></td>
<td></td>
</tr>
<tr>
<td>Pedestrian</td>
<td>4,884</td>
</tr>
<tr>
<td>Pedalcyclist</td>
<td>726</td>
</tr>
<tr>
<td>Other Unknown</td>
<td>203</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>5,813</strong></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>32,675</strong></td>
</tr>
</tbody>
</table>

To prevent these kind of fatalities, it is of utmost importance for automobile manufacturers to improve vehicle safety, making it the number one priority. To protect the occupants from various kinds of accidents, the National Highway Traffic Safety Administration (NHTSA) introduced many mandatory safety standards which are known as the Federal Motor Vehicle Safety Standards (FMVSS). Various other organizations have conducted a considerable amount of research to study vehicle crashworthiness and vehicle safety [3]. Since 1930, extensive studies to investigate the nature of crashes, impact loading, vehicle structural design, and safety systems have been
conducted. It is very important to understand the safety features of a car through the standard ratings before driving it.

1.2 Vehicle Crashworthiness

Vehicle crashworthiness is defined as “the measure of the vehicle’s structural ability to plastically deform and yet maintain a sufficient survival space for its occupants in crashes involving deceleration loads.” Abnormal operating conditions that lead a vehicle to impact with another vehicle or with stationary obstacles sets the vehicle structure to impact forces and deformations. If the forces generated exceed the absorbing capability of the structure, then occupants may be injured or suffer fatalities. The energy from the crash pulse must be absorbed by the vehicle structure in the form of deformations, and at the same time, the restraint system must provide room to reduce the transmission of crash loads to the vehicle occupants. Vehicle crashworthiness also deals with the maintenance of structural integrity and crash deceleration pulse, in order to be under the human tolerance limits [3].

According to NHTSA and IIHS, side-impact crashes are considered the second leading cause of road fatalities. Figure 1.2 illustrates different crashes that occurred in 2015.

![Figure 1.2. Type of crashes occurred in 2015 [5]](image)
As can be seen, almost 54% of overall fatalities were the result of frontal crashes, thus becoming the major leading cause of fatalities. However, occupants involved in frontal crashes can be protected using airbags, restraint systems, etc., but when it comes to side impacts, the crumple zone is smaller, making it difficult to protect occupants.

Depending upon the location of impact, vehicular collisions are classified into frontal collision, side-impact collision, and rear collision. In this study, side-impact crash simulations involving dummy and human body models were performed to evaluate the differences.

1.3 Regulatory Standards

In recent years, a great deal of research on occupant safety and structural integrity of the vehicle has been conducted. NHTSA and various other organizations have played a major role in this research. NHTSA was formed in the year 1970 to reduce the number of road accident deaths and injuries, and increase occupant protection by establishing a safety act. In 1978, using a speed of 35 mph, frontal impact crash testing was established, and in 1996, side-impact testing was established. During that time, NHTSA proposed several regulation standards to provide safety to occupants. All vehicles that are ready to be introduced into the market must undergo these regulatory standard tests with appropriate dummies placed in the vehicles. Responses from the vehicles and dummies are then used to evaluate the injury parameters. Vehicles are rated according to the safety evaluation of the dummies and vehicle structural crashworthiness. An overall five-star rating is used, where five stars indicates the safest, and one star indicates the least safe. Typically, ratings are specified for a car in frontal, side, and rollover testing. NHTSA has established regulations that consider almost every aspect of the vehicle that may cause injury to occupants in the case of an accident. Some of the Federal Motor Vehicle Safety Standards are shown in Figure 1.3.
1.3.1 FMVSS Safety Regulations

Several regulations have been established in the interest of occupant safety. Figure 1.4 represents some of the safety standard tests developed by NHTSA [8, 9, 10]. Almost all parts of a car have defined regulations, some of which are listed below [7]:

- FMVSS 201 Interior Impact Occupant Protection
- FMVSS 202 Head Restraints
- FMVSS 203 Driver Protection from Steering Wheel
- FMVSS 205 Glazing Materials
- FMVSS 207 Seating Systems
- FMVSS 208 Frontal Impact Occupant Protection
- FMVSS 209 Seatbelt Assemblies
- FMVSS 213  Child Restraint Systems
- FMVSS 214  Side-Impact Occupant Protection
- FMVSS 216  Roof Crush Resistance
- FMVSS 217  Bus Emergency Exits
- FMVSS 220  School Bus Rollover Protection
- FMVSS 222  School Bus Passenger Seating and Crash Protection
- FMVSS 224  Rear Impact Occupant Protection

Figure 1.4. Different vehicle safety standard tests
1.4 FMVSS 214 Moving Deformable Barrier Side Impact Test

The FMVSS 214 dynamic side-impact protection—moving deformable barrier (MDB) test was developed to prevent occupant head, thorax, abdomen, and pelvic injuries caused by another vehicle in a side-impact crash. This test comprises a stationary vehicle with a EuroSID-2 rib extension (ES-2re) 50th percentile male dummy in the driver seat and a side-impact dummy (SID-II) 5th percentile female dummy in the rear passenger seat [12]. A moving deformable barrier representing the other vehicle travels at 54 kmph (33.5 mph) with its wheels at a 27-degree crab angle. Figure 1.5 shows the complete test setup of this FMVSS 214 MDB test regulation. An MDB impacts the stationary vehicle, whereby the crash energy dissipates through the side-door panel, causing both dummies to impact with the side door panel. Equipment installed in the vehicle and in the dummies captures the responses, and data obtained are further processed with different Society of Automotive Engineers (SAE) filters. After processing the signals, the data are used to evaluate the dummy injury criteria, and the corresponding safety ratings are issued for that vehicle.

Figure 1.5. FMVSS 214 moving deformable barrier side-impact test setup [11, 12]
1.5 FMVSS 214 Rigid Pole Side Impact Test

The FMVSS 214 rigid pole side-impact test was developed to protect the occupant from crashing into narrow objects like trees, poles, etc. In this test, a car moving at 32.2 kmph (20 mph) at an angle of 75 degrees crashes into a fixed rigid pole that is 254 mm (10 in) in diameter, as shown in Figure 1.6. The moving car has a 50\textsuperscript{th} percentile ES-2re male dummy in the driver seat and a 5\textsuperscript{th} percentile SID-II female dummy in the rear seat. Responses from the vehicle and the dummies are then filtered to evaluate the injury criteria [13].

![Diagram of FMVSS 214 rigid pole side-impact test setup](image)

Figure 1.6. FMVSS 214 rigid pole side-impact test setup [13]
1.6 IIHS Moving Deformable Barrier Side Impact Test

The Insurance Institute for Highway Safety (IIHS) is another organization that evaluates a vehicle for side-impact occupant protection. In this test regulation, an MDB crashes into a stationary vehicle at 90 degrees going at 50 kmph (31.06 mph), as shown in Figure 1.7. The stationary vehicle has two 5th percentile SID-II female dummies seated in the driver and rear passenger seats [14]. The MDB in the IIHS test, as shown in Figure 1.8, is different from the one in the FMVSS 214 MDB test because it represents the latest sport utility vehicle (SUV), whereas the FMVSS 214 MDB barrier represents a regular sedan.

![Figure 1.7. IIHS moving deformable barrier side-impact test setup [14]](image)

![Figure 1.8. IIHS moving deformable barrier cart [14]](image)
1.7 Injury Pass-Fail Criteria

Head Injury Criterion

Head injuries are the leading cause of death and disability as the result of most automobile crashes. It is of utmost important to protect the head from potential injuries using airbags, restraint systems, etc. Previously, the severity of the injuries was calculated using the severity index (SI), which is based on the Wayne State Tolerance Curve (WSTC). Head injury criterion (HIC) was first proposed by Versace in 1971 using the average acceleration, which is related to the WSTC. HIC36 is used to evaluate head injuries in a side impact and should not exceed 1000 for both the ES-2re and SID-II dummies [15, 16]. HIC36 is expressed as

\[
HIC36 = \max \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1)
\]  

(1.1)

where \( a(t) \) is the resultant head acceleration in G’s, and \( t_1 \) and \( t_2 \) are the initial and final time intervals, respectively, where the HIC attains a maximum value, and \( (t_2 - t_1) \leq 36 \text{ m sec.} \)

Viscous Criterion

After head injuries, thorax injuries are very serious injuries. Viscous criterion (VC) is also known as soft tissue criterion or (velocity of compression) as the vital organs of the human body are covered by these soft tissues [15]. VC is defined as the product of the velocity of thorax deformation \( V(t) \) and the thorax instantaneous compression function \( C(t) \) [15, 16]:

\[
V \ast C = V(t) \ast C(t)
\]

\[
VC = \frac{d[D(t)]}{dt} \ast \frac{D(t)}{b}
\]  

(1.2)

where \( V(t) \) is the velocity of deformation, \( C(t) \) is the instantaneous compression function, and parameter \( b \) represents the torso thickness. The tolerance level of the viscous criterion in a side impact should not reach 1 m/s.
**Thorax Trauma Index**

In the case of a side impact, the thorax of the occupant impacts the side-door panel of the car, which results in a blunt trauma. To understand thorax injuries, the thorax trauma index (TTI) was developed after conducting several cadaver tests [15, 16, 17]. The TTI is a chest acceleration-based criterion, and the TTI for a human is expressed as

\[
TTI = 1.4 \times \text{Age} + 0.5(RIB_y + T12_y)(M/M_{std})
\]

(1.3)

where Age is the age (in years) of the test object, \(RIB_y\) is the maximum absolute value of the lateral acceleration (g) of the 4\(^{th}\) and 8\(^{th}\) ribs on the struck side, \(T12_y\) is the maximum lateral acceleration (g) of the 12\(^{th}\) thoracic vertebrae, \(M\) represents the test object mass (Kg), and \(M_{std}\) represents the standard mass of 75 Kg [15, 16]. When using a 50\(^{th}\) percentile Hybrid III dummy in testing, the mass ratio and age can be omitted, and TTI is expressed as

\[
TTI(d) = 0.5(RIB_y + T12_y)
\]

(1.4)

According to FMVSS 214, the TTI should be less than 85 g for four-door passenger vehicles, whereas it should be less than 90 g for two-door passenger vehicles.

**Rib Deflection**

When evaluating injury criteria in a side-impact crash test, it is necessary to acquire rib deflections (mm) to identify rib fractures. Maximum deflection of all ribs is considered in side impacts. For ES-2re and SID-II dummies, this is the maximum of three rib deflections. According to FMVSS 214, the maximum rib deflection should not exceed 44 mm [15, 16].

**Abdominal Peak Force**

The abdominal region consists of the lower rib cage, liver, kidneys, and intestines, thus making it a crucial area in which to evaluate the injury criteria. It is very difficult to interpret the injury mechanisms and biomechanical responses in the abdominal area. Abdominal peak forces
(APFs) are acquired through the deformations and penetrations of the abdominal organs. According to FMVSS 214, the injury parameter is set as 2.5 kN internal force [15, 16, 35].

**Pubic Symphysis Peak Force**

The pubic symphysis peak force (PSPF) represents the lower extremities injury criterion. In side-impact dummies, the left and right halves of the pelvic bone are connected by a load cell at the pubic symphysis where the lateral forces are recorded. The measured pubic force is referred to as the pubic symphysis peak force and according to FMVSS 214, the maximum PSPF should not exceed 6 kN internal force [15].

**Pelvic Acceleration**

The pelvic region consists of the hip joint, iliac wings, sacrum, and pubic rami. The possibilities of pelvic fractures are greater in side impacts. The pubic rami fracture, acetabulum fracture, and hip dislocation are the most commonly caused injuries in a lateral impact. Lateral acceleration from the pelvic region can be utilized to determine whether there are fractures in the pelvic region. According to FMVSS 214, the peak pelvic acceleration (peak lateral sacrum acceleration) shall not exceed 130 g [18].

**1.8 Literature Review**

Since their implementation, FMVSS 214 side-impact regulations have saved many lives. Much research has been carried out and many new technologies that save time and cost are emerging. The safety of the occupant and crashworthiness of the vehicle are among the mostly researched topics.

Van Ratingen evaluated the EuroSID-2 side-impact dummy by conducting full-body pendulum tests and Heidelberg sled tests. Following the evaluation of test results, it was concluded that values for the ES-2 dummy were higher than those for the ES-1 dummy, particularly rib
deflections and viscous criterion. Evaluation results also proved that the biofidelity of the ES-2 dummy was improved from the ES-1 dummy and also met certification standards [19].

Watson et al. studied vehicle dynamics and occupant response trends in side-impact crash tests. They investigated New Car Assessment Program (NCAP) side-impact test data and developed velocity profiles for an LS-DYNA simplified side-impact sled setup. The U.S. side-impact dummy (USSID) and the ES-2re dummy are used in finite element (FE) simulations to study the potential for injury. The USSID dummy showed maximum injury when the differential velocity was greatest between the seat and the door, whereas the ES-2re dummy showed higher injury value when there was the largest velocity between the door and the seat [20].

Rupp et al. performed lateral impact tests with a WorldSID mid-size male dummy at different test velocities. Thorax, abdomen, iliac wing, greater trochanter, and mid-thigh responses were measured from near-side sled tests. Responses were then compared to cadaver tests conducted using the same input conditions as those of the WorldSID tests. Results showed that the WorldSID abdomen and pelvis are stiffer and less sensitive than that of the cadaver [21].

Yoganandan et al. conducted studies on post-mortem human subjects (PMHSs) to design and evaluate side-impact dummies. Lateral, anterior, and posterior oblique sled tests were conducted on PMHSs to obtain chest and abdomen deflections. In pure lateral sled tests, thorax deflections did not change, but abdominal deflections showed greater values in high-speed versus low-speed tests. In anterior tests, peak deflections observed at the upper-thorax level, mid- and lower-thorax levels which were similar to those in the pure lateral tests. In posterior sled tests, because of the change in the sled angle and airbag, results were varied. Finally, deflections and injuries from all the tests were recorded to evaluate the side-impact dummies [22].
Lankarani et al. modeled the occupant response on side-facing aircraft seats to study the nature of crash injuries. Side-facing-seat impact sled tests were conducted using a side-impact dummy as the occupant and a Hybrid II dummy as the second occupant. A three-point belt restraint system was used during impact testing. Injury criteria such as pelvic acceleration, thorax trauma index, viscous criteria, and rib deflection were measured and calculated. Results were compared to mathematical simulation models, and it was concluded that the SID has the capability of measuring only some of the injury criteria [23].

Liu et al. developed finite element models (FEMs) of 5th and 50th percentile WorldSID dummies to predict the occupant injuries in side-impact collisions. These models were validated with physical dummies of the same type using standard laboratory tests. Advanced technologies such as laser scanning, fine meshing, and better material (shape memory) cards were used in FE modeling of dummies. The FMVSS 214 regulation test was conducted on both dummies, and injury criteria were calculated. The FE results were validated with physical tests, and the FE dummy models predicted injuries that were nearly the same as in the actual physical tests [24].

Campbell et al. studied side-impact crash conditions using a detailed human body model and a side-impact crash model. The human body model was developed and validated with PMHS test data. FMVSS 214 and IIHS side-impact tests were conducted to study the effects of the door-to-occupant safety, door-velocity profile, and seat foam properties. Results showed that the viscous criterion injury was controlled by the door-velocity profile, and the thoracic trauma was controlled by the seat foam properties [25].

Mundal et al. created a new development process to improve quality and reduce development times. An FEM of a side-impact sled test was designed and validated in computer-aided engineering (CAE). Vehicle dynamics from a regular CAE crash test simulation was used
and attached to the newly developed sled test setup. Additionally, a folded pelvis-thorax bag was installed in the door panel and attached to the newly developed sled test setup. Validation results from real sled tests and CAE tests showed closer values [26].

Teng et al. developed finite element side-impact models to simulate the full-scale crash test and the regular sled test. According to FMVSS 214, a full-scale FE side-impact test was conducted using the USSID seated in the driver seat. A simple FE sled test was conducted using the velocity response from the earlier full-scale side-impact test. The pelvis and TTI results obtained were 78 g and 114.7 g, respectively, which are under the injury limits in the full-scale tests. However, in the sled test, the pelvis and TTI results were calculated as 76 g and 100 g, respectively. Responses from both the full-scale and sled test predicted similar injuries [27].

Hallman et al. examined the effect of the closer-proximity torso air bag on injury metrics in a side-impact sled test. PMHS sled test results were analyzed to evaluate thoracic injuries with rigid and air bag boundary conditions. A computational simulation was performed using a Mathematical Dynamic Models (MADYMO) human body model against a rigid wall. Simulations were carried out with and without an air bag. The results here demonstrated that the air bag affected the viscous criterion in close-proximity boundary conditions [28].

Kent et al. studied side-impact thoracic injury criteria using a MADYMO human body model. This study was carried out by conducting 36 near-side-impact simulations using a 50th percentile male human body model. This model was seated on a rigid seat next to a deformable wall. Three door V (t) profiles with three different pad moduli and peak velocities were applied to the deformable wall. The pad modulus, door-to-occupant offset, and V (t) profile affected the thoracic injury criteria. Chest deflection, TTI, and VC showed sensitivity with the change in pad modulus [29].
Bosma et al. implemented an efficient design process to meet side-impact requirements using BASIS sled testing and MADYMO prescribed structural motion (PSM) simulations. A BASIS sled test was developed by The Netherlands Organisation (TNO) for applied research. This test consists of a restraint system, seat, and trimmed side-door panel. The MADYMO PSM simulation was used to save time and cost. Final results demonstrated that MADYMO PSM simulation and BASIS sled test methods are cost effective and central processing unit (CPU) efficient [30].

Tay studied the impact injury biomechanics of vehicle occupants and developed a new technology for the passive safety of vehicles in side-impact accidents. High-energy absorption material properties were used to perform a numerical simulation in the side-door panels. The materials showed reduced intrusion by 29%. In another case study, a pre-deployment algorithm of the side airbags was developed and successfully implemented, showing reduced injury to the dummy [31].

Moradi examined impact dynamics and crash energy management by applying stereo mechanics, contact mechanics, and various FEM methods. Results indicated that contact detection and contact force play a major role in FE and multi-body system analysis [32].

Siruvole studied the critical injury parameters and vehicle structural damage in the FMVSS 214 regulation. Simulations were conducted using an LS-DYNA-MADYMO coupling technique, and results showed that vehicle intrusion in the FMVSS 214 rigid pole test is large when compared to the FMVSS 214 MDB test [33].

Tay et al. studied the driver fatality ratio (DFR) of light transport vehicles (LTVs). Simulations were conducted by striking LTVs over a passenger car. The main parameters considered in this study were intrusion, deceleration, and stiffness ratios. Results were then
compared with actual DFR statistics, indicating good agreement in terms of intrusion and acceleration [34].

Bhaskaran et al. evaluated the potential injuries in side-facing seats in a civil aircraft by applying the automotive side-impact test concept. Various side-impact injury criteria were evaluated by applying 16 g acceleration. Hybrid III, SID-H3 dummies were used in this study, and suitable injury criteria were recognized [35].

1.9 Motivation

The advancement in computational numerical methods has led to the development of several computational numerical dummy models. Using these dummy models, the dynamic behavior can be observed in various automotive crash-related scenarios. Many regulatory standard tests have been developed in order to protect vehicle occupants, pedestrians, etc. These tests are conducted in safe environment with a real vehicle, anthropomorphic test dummies (ATDs), and considerable equipment. The complete test setup needs considerable time and effort, and the equipment involved should be precise. Using computer models makes it easy to model the test setup and requires less CPU time to generate results. These computer models can be modified to a specific purpose and can be used in almost every situation.

Newer computer models such as the Total Human Model for Safety (THUMS) [40] and the MADYMO human body model represent humans in every aspect. These models consist of bones, organs, muscles, flesh, skin, etc., and can be used to study human injuries in detail. Replacing numerical dummy models with these human body models in automotive crash testing would provide greater in-depth knowledge of the dynamic behavior of the human and safety-related problems. In this research, various side-impact safety regulations were considered to compare the ES-2re dummy and human body model dynamic responses.
CHAPTER 2
OBJECTIVES AND METHODOLOGY

2.1 Objectives

The main aim of this study was to examine the occupant responses and injury potential in different side-impact regulations using the ES-2re dummy and MADYMO human body model. The ultimate goal here was to quantify such differences between the ES-2re model and the HBM in a side-impact scenario using different computational software. To achieve this goal, the following objectives were identified:

- To perform crash analysis on a typical mid-size sedan and a small-size compact car according to the FMVSS 214 dynamic side-impact regulations and IIHS side-impact regulations.
- To model and analyze the side-impact crash scenarios in MADYMO software using the ES-2re dummy and HBM, especially in the driver seat.
- To evaluate and distinguish the injury parameters for both the ES-2re and human body models.
- To perform prescribed structural motion (PSM) for both car models with ES-2re and HBM dummies seated in the driver seat.

2.2 Methodology

This thesis work was entirely developed using computational software, such as LS-DYNA, HyperMesh, and MADYMO. First, the modeling of the side-impact crash scenario according to FMVSS 214 and the IIHS regulations were done using FE software LS-DYNA. The driver seat responses from LS-DYNA were then applied to a similar vehicle environment with a seated dummy using MADYMO. The same was applied for the human body model, and the differences
between the responses were studied. Finally, the FEM vehicle was imported into MADYMO, and the side-door panel was trimmed along with the driver seat. Nodal displacements from the LS-DYNA software were applied to the trimmed side-door panel. The responses were studied further to distinguish differences between the ES-2re dummy and the HBM. The complete methodology is shown in the Figure 2.1.

Figure 2.1. Methodology
2.3 Computational Tools

2.3.1 LS-DYNA

LS-DYNA is a finite element code developed for the study of static and dynamic loads of structures. It is used to perform both explicit and implicit analysis, employing spatial discretization and a contact-impact-based algorithm to solve nonlinear problems. Using LS-DYNA, structures can be discretized into their different elements, such as springs, dampers, membranes, shells, solids, trusses, bricks, and seatbelt elements. Figures 2.2 and 2.3 correspond, respectively, to the LS-DYNA solving process and different LS-DYNA elements, which are defined by a set of nodes [41].

![TIME INTEGRATION LOOP](image)

**Figure 2.2.** LS-DYNA solving process [41]  **Figure 2.3.** Elements used in LS-DYNA [41]

The contact-impact algorithm identifies the interface as slave and master surfaces. In structural analysis or impact analysis, the surfaces are supposed to slide on one another, and the contact-impact algorithm ensures that the surfaces are not penetrating each other by using the concept of master and slave surfaces. This problem can be defined in the LS-PrePost graphical user interface (GUI) using keyword manager for materials, contacts, time step, outputs, etc. The
simulation files and output result files can be processed using different filters such as SAE, FIR etc., to reduce the noise in the plots. Figure 2.2 explains the time integration loop process of the LS-DYNA solver [41], which is defined as follows:

- Start or define the problem.
- Apply force boundary conditions.
- Process the elements.
- Process discrete elements.
- Process contact interfaces.
- Apply kinematics and update the accelerations.
- Process kinematic-based contacts and rigid walls.
- Write the output.
- Update the velocities.
- Update displacements and new geometry.
- Update current time.
- Check for end termination.

2.3.2 **HyperView**

HyperView, developed by Altair HyperWorks, is a high-performance post-processing tool used for finite element analysis (FEA), computer fluid dynamics, multi-body system simulations, and engineering data. HyperView has a user-friendly graphical interface, where the XY plotting tool, unit conversion, and simulation animations are very simple to process. In this research, HyperView was used for the post processing of LS-DYNA results as well as for PSM. Using HyperView, nodal displacements of the vehicle side panel were obtained from LS-DYNA crash simulations [42].
2.3.3 MADYMO

Mathematical Dynamic Models software is a multi-body simulation software used to study the dynamic behavior of vehicle collisions and assess occupant injury criteria. It is also used to study the effect of restraint systems such as seatbelts and airbags on occupants. Figure 2.4 shows the basic working structure of MADYMO. Multi-body models and finite element models along with restraint systems can be combined for simulation in this software.

![MADYMO working structure](image)

**Figure 2.4. MADYMO working structure [43]**

MADYMO provides a wide range of databases consisting of multi-body dummies, human body models, belt systems, airbag models, and validated test models. It has a wide range of applications, such as coupling with other software, prescribed structural motion, accident reconstruction, etc. In general, MADYMO is known for multi-body simulations involving multi-body models and finite element structures. To model a multi-body system, all the multi-body systems and finite element structures must be included in a single input data file. A multi-body system is a system of bodies connected to each other by a kinematic joint. A multi-body system can be a dummy, vehicle steering column, knee bolster, or even restraint system. Some examples of multi-body systems are shown in Figure 2.5.
Figure 2.5. Examples of different multi-body systems [43]

Finite element models that are typically used in MADYMO are airbags, knee bolster, and seatbelts. MADYMO also accepts FE structures from other finite element analysis packages. MADYMO also has a database of human body models that are modeled using FE techniques. When there is a system involving a multi-body model and an FE model, the interaction between both surfaces is carried out by the supports and contacts, which eventually results in forces and torques.

Defining the contacts between the surfaces is a crucial step in the dynamic simulation setup. MADYMO provides contact interaction models such as the elastic contact model and kinematic contact model. The elastic contact model allows the contact surfaces to penetrate each other, whereas the kinematic contact model does not allow penetrations to take place. The kinematic contact model is primarily used when an FE model is in contact with an ellipsoid model.
Contact between the finite element surface and the multi-body surface is defined in such a way that a slave surface is defined by FE surface, whereas the master surface is defined by the multi-body ellipsoids. The contact between FE surfaces is defined by the same concept, except both master and slave surfaces are defined by a group of FE groups. Figure 2.6 shows the different forces and contacts acting on a system of bodies.

![Figure 2.6. Multi-body systems with forces and contacts][1]

To complete a MADYMO model setup, initial conditions and boundary conditions must be specified. Initial conditions, such as input velocity, initial displacements, time step, and end time etc., must be defined in the model setup file. Correspondingly, boundary conditions, such as prescribed structural motion, contacts, and loads, must be defined in the same input setup file. Geometrical properties and material properties can be easily defined in the MADYMO workspace.

Results from the simulation are printed on different data files. Output-like forces, torque, accelerations, velocities, relative displacements, injury peak values, and animation files can be obtained after submitting the input file to the MADYMO solver [43]. The MADPost post processor is used for post processing and extracting all results.

---

[1]: image.png
CHAPTER 3

COMPUTATIONAL METHODOLOGY

3.1 LS-DYNA Finite Element Models

In this research, finite element analysis was carried out to analyze different side-impact test conditions. This research focused on the crash analysis of two different-sized cars. The FE car models and barrier models acquired from the NHTSA website [44] are developed and validated by the National Crash Analysis Center (NCAC). The first car model used in this study was a 2001 Ford Taurus passenger sedan, and the second car model was a 2010 Toyota Yaris passenger sedan. Both cars were developed through the process of reverse engineering at the NCAC of George Washington University (GWU). Figures 3.1 and 3.2 show the FE models of both car models [44].

![Figure 3.1. Ford Taurus mid-size sedan FE model [39]](image1)

![Figure 3.2. Toyota Yaris small-size compact car FE model [45]](image2)

These NCAP models were validated and compared with actual NHTSA crash tests. The details of these FE models are shown in Table 3.1. NHTSA’s moving deformable barrier model was used to complete the setup, and Figure 3.3 depicts the FE model of that barrier. Car models were provided with the material properties, interior contacts, and added masses. The masses of a Hybrid III 50\(^{th}\) percentile dummy, 5\(^{th}\) percentile passenger dummy, and luggage were also included in the FE model file.
<table>
<thead>
<tr>
<th>Details</th>
<th>Ford Taurus</th>
<th>Toyota Yaris</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of parts</td>
<td>802</td>
<td>917</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>921,793</td>
<td>1,480,422</td>
</tr>
<tr>
<td>Number of shells</td>
<td>838,880</td>
<td>1,250,424</td>
</tr>
<tr>
<td>Number of beams</td>
<td>10</td>
<td>4,738</td>
</tr>
<tr>
<td>Number of solids</td>
<td>134,449</td>
<td>258,887</td>
</tr>
<tr>
<td>Nodal rigid body connections</td>
<td>1,930</td>
<td>727</td>
</tr>
<tr>
<td>Extra node set connections</td>
<td>53</td>
<td>20</td>
</tr>
<tr>
<td>Rigid body connections</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Spotweld connections</td>
<td>5,557</td>
<td>4,107</td>
</tr>
<tr>
<td>Joint connections</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>Total number of elements</td>
<td>973,351</td>
<td>1,514,068</td>
</tr>
</tbody>
</table>

The moving deformable barrier has 63 parts, 54,582 nodes, and 57,032 elements. A rigid pole was also acquired from NHTSA’s FE model database to test the vehicle in a side-impact rigid pole test regulation. This rigid pole was modeled according to the FMVSS 214 standard with a diameter of 254 ± 3 mm [13]. In this study, LS-PrePost was used to model and analyze the side-impact crash scenarios. LS-DYNA was used to execute the side-impact test simulations. All interior contacts were predefined, and the new contacts between the vehicle and MDB, vehicle and rigid pole, etc., were defined using the LS-PrePost keyword manager. The initial conditions and termination time should be defined according to the standard unit system followed by LS-DYNA. Figure 3.3 represents the FE model of NHTSA moving deformable barrier, Figure 3.4 represents the IIHS MDB, and Figure 3.5 represents the rigid pole used in the side-impact test.
Table 3.2 summarizes the total number of elements, parts, and nodes of the barriers and rigid pole. The material properties for all FE models were predefined in the files provided. The difference between FMVSS 214 MDB and IIHS MDB can be observed from Figures 3.3. and 3.4.

TABLE 3.2

<table>
<thead>
<tr>
<th>Details</th>
<th>NHTSA MDB</th>
<th>IIHS MDB</th>
<th>Rigid Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>54,581</td>
<td>58,160</td>
<td>2,136</td>
</tr>
<tr>
<td>Number of parts</td>
<td>63</td>
<td>66</td>
<td>5</td>
</tr>
<tr>
<td>Total number of elements</td>
<td>57,032</td>
<td>60,420</td>
<td>1830</td>
</tr>
</tbody>
</table>
3.2 MADYMO Interior Vehicle Model

A simple vehicle interior compartment was used to model the side-impact setup and is provided in the three-dimensional database of the MADYMO 7.6 package. This interior consists of an A-pillar, windscreen, airbag, steering wheel, seat system, vehicle floor, knee bolster, toe board, accelerator, and brake. Figure 3.6 illustrates the MADYMO vehicle interior compartment.

![Diagram of car vehicle interior compartments]

Figure 3.6. Model of car vehicle interior compartments

To complete the side-impact setup, a bulkhead/side wall was modeled to resemble a side-door panel and placed next to the left side of the seat. The idea behind this design was to determine how the dummy and HBM behave when impacting with the plane rigid side-door panel. The bulkhead was locked to the vehicle compartment model to complete the side-impact test setup. This same model setup is used for all regulatory sled tests.
3.3 Modeling Details of ES-2re Dummy

The injuries most likely to occur in a side-impact collision are head, thorax, abdomen, and pelvic fractures. To protect the occupant from these injuries considerable research has taken place, which is how the concept of a side-impact dummy came into existence. This anthropomorphic test dummy consists of three rib structures that are specifically designed to measure the thorax deflections and forces. Over time, there has been many design modifications, and a new version EuroSID-2re, which is still in use, was developed.

According to FMVSS 214, an ES-2re dummy must be used in the regulation crash test and, prior to actual testing, must undergo different time-consuming calibration tests. Computational mathematical models of dummies were developed by the TASS International Company’s MADYMO for several kinds of crash simulations. These dummy models are validated in a similar to that of regular physical dummies. Figure 3.7 shows the real crash test dummy, and Figure 3.8 shows the mathematical ellipsoid model of the ES-2re dummy in different configurations. Figure 3.9 shows the thorax assembly consisting of upper-, mid-, and lower-rib structures with extensions. The rib extensions shown in Figure 3.10 are supported by an extension guide assembly to improve the contact interaction between the seat and dummy.

Figure 3.11 shows different part assemblies of an ES-2re ellipsoid dummy. The head of the ellipsoid dummy was designed with an accelerometer and a neck load cell to acquire head responses. The head is connected to the torso with a neck assembly which consists of six bodies. Figure 3.11(a) represents the head-neck assembly of the ES-2re ellipsoid dummy. Figure 3.11(b) corresponds to the shoulder box assembly, which was designed with a clavicle box, U-type spring, shoulder load cells, and elastic cords. The U-type spring was modelled with multiple revolute joints, which help the shoulder assembly to behave visually realistically in a side-impact crash.
The ES-2re dummy does not have lower arms, in order to avoid the disturbance in repeatability.

The arm shown in Figure 3.11(c) is modelled with rigid bodies and spherical joints. The abdomen assembly shown in Figure 3.11(d) consists of a drum, T12 load cell, and three impact side-load cells. Figures 3.11(e) and (f) show the thorax single rib structure and thorax assembly, respectively.

Figure 3.11(g) shows the pelvic assembly, which consists of a pubic load cell, sacrum block, and iliac wing. The pubic cell in the pelvic assembly joins the left and right pelvic bodies. Figures 3.11(h) and (i) represent the leg assembly and jacket, respectively.

Figure 3.7. EuroSID real crash test dummy [17]  Figure 3.8. ES-2re ellipsoid dummy model [36]

Figure 3.9. ES-2re thorax assembly [36]  Figure 3.10. ES-2re rib extension assembly [36]
The ellipsoid model of the ES-2re dummy consists of 217 bodies, 29 joint restraints, and 188 kinematic restraints. These models are predefined with side-impact injury criteria plus 35 other MADYMO outputs. The body parts of these multi-body-based models are designed with ellipsoid surfaces resembling the real ES-2re hardware dummy. Load cells are installed as rigid bodies throughout different locations of the dummy to gather output responses in a crash simulation [36]. ES-2re dummy corresponds to a 50th percentile adult male with a mass of 72 kg (158.8 lbs) and is generally used in automotive regulatory tests.
3.4 Modeling Details of Human Body Model

The human body is comprised of organs and a nervous system, which are supported by 206 bones. The modeling of bones is an important task in human body modeling. The skeleton system is complicated in design because of its complex shape and size. The major bones of the human skeletal system are the skull, clavicle, humerus, sternum, ribs, vertebral column, pelvis, femur, tibia and fibula shown in Figure 3.12. The vertebral column, shown in Figure 3.13, consists of cervical bones (C1–C7), thoracic vertebrae (T1–T12), lumbar vertebrae (L1–L5), sacrum (S1–S5), and coccyx. The ribcage consists of seven true ribs and four false ribs. The sternum is located at the center of the ribcage and connects the left and right side of the ribs [37].

Figure 3.12. Human skeletal system [37]  Figure 3.13. Vertebral column [37]
In this research, the MADYMO human body model was considered to distinguish the differences between a regular dummy and a human body, like the mathematical model. MADYMO HDMs are designed for different kinds of impact, such as frontal, lateral, rear, vertical, and rollover scenarios. These human body models are different from regular dummies in terms of biofidelity, scalability, posture adjustment, post fracture modelling, and muscle activity [38]. In Figure 3.14, the large male represents the 95th percentile, the mid-size male represents the 50th percentile, and the 5th percentile represents a small female model.

![Figure 3.14. Large male, mid-size male, and small female human facet occupant models [38]](image)

MADYMO software also has child facet human body models in its database, alongside ellipsoid dummy models. Child human body models can be created by scaling down a male human body model using MADYMO scaler utility. Mechanical properties like mass, inertia, stiffness, and contacts can be easily defined using MADYMO. The standing height of a 50th percentile human male model was measured as 1.74 m, whereas the weight of the model was defined as 75.7 kg.
The human body model was designed and modelled with 92 bodies. Figure 3.15 represents a 50\textsuperscript{th} percentile human male facet model in a sitting position [38].

![Figure 3.15. 50\textsuperscript{th} percentile human male facet model [38]](image)

**Spine and Neck**

All joint positions of the HBM are shown in Figure 3.16 from top to bottom of the human body model shown in Figure 3.16 [38]. The spine and neck assemblies of a human body model are designed with ellipsoid bodies, which can be seen in Figure 3.18. The neck bodies (C7–T1) connects the head to the thoracic region (L5–T1), and the thoracic region is connected to the pelvic region. These ellipsoid bodies are modelled to produce a biofidelic response under different loading conditions. These bodies are connected by free joints with translational and rotational resistance using the concept of non-linear lumped-joint resistance models.
Thorax and Abdomen

The thorax and abdomen are the two significant regions where impact loading causes deformation. The thorax and abdomen are constructed with four flexible bodies, each represented
in Figure 3.19. Each flexible body can be deformed in three predefined modes (one frontal and two lateral) [38].

Figure 3.19. Flexible bodies of thorax and abdomen and rigid vertebral bodies (green dots)

**Pelvis and Skin**

The pelvis of the human body model was modelled by facet FEM parts and was used to create a contact between skin and a seatbelt. The pelvis provides a realistic response under impact loading conditions and is shown in Figure 3.19. The skin of the model was created with triangular finite elements with the property of a null material. The skin has different contact characteristics at different parts of the model [38].

**3.5 Modeling of Finite Element Restraining Belt**

This research employed a hybrid three-point restraining belt system consisting of a combination of lap belt and shoulder belt, as shown in Figure 3.20. These hybrid belts were modelled with truss or membrane finite elements in order to provide multi-directional belt slip.
Retractor, pretensioner, and load limiters were used to obtain a realistic behavior of the belt system [43].

![Figure 3.20. Three-point hybrid restraining belt system [43]](image)

The hybrid belt can slide over the occupant’s body surfaces with the defined Coulomb friction. The belt system was created using a belt-fitting module of MADYMO, or XMADgie. The ends of the belts were tied to the retractor, pretensioner, and load limiters because they are fixed to the vehicle model. Suitable contacts were defined between the belts and occupant models to restrain the model from impact under crash-loading conditions.

3.6 Vehicle and Occupant Modeling

3.6.1 Vehicle and ES-2re Dummy Modeling

This study was performed by considering Heidelberg stationary sled testing, where an occupant is impacted against a stationary rigid surface. The car interior compartment was acquired from the MADYMO database and it consisted of a driver seat, steering wheel, windshield, knee bolster, and toe panel. The model was then designed according to side-impact conditions. A
bulkhead structure was modeled as a side panel and placed on the left side of the driver seat, as shown in the Figure 3.21. An ES-2re dummy was imported from the MADYMO dummy database and positioned in a sitting posture. The complete setup with seatbelt is presented in Figure 3.22. Contacts (CONTACT.MB_MB) were defined between the bulkhead and dummy head, left arm, jacket, pelvis, femur, tibia, and shoes. A hybrid three-point belt system was added to the same setup, in order to study the occupant response with a seatbelt.

The following contacts were defined between the ES-2re dummy and the vehicle:

- Dummy legs and knee bolster
- Dummy shoes and vehicle floor
- Dummy shoes and accelerator
- Dummy shoes and brake
- Dummy and seatback

Figure 3.21. Model of vehicle and ES-2re dummy [46]

Figure 3.22. Model of ES-2re dummy with seatbelt [46]
• Dummy and bottom seat
• Dummy pelvis and lap belt
• Dummy jacket and shoulder belt

3.6.2 Vehicle and Human Body Model Modeling

The main objective of this study was to study the differences between a regular ES-2re dummy and a human body model. A 50th percentile human male model was imported from the MADYMO human body model database. This HBM is seated on a frictionless seat in the vehicle interior compartment, as shown in the Figure 3.23. Since the HBM’s skin is modeled with finite elements, it was difficult to define contacts. Therefore, the model was further grouped into individual parts by defining GROUP_FE under the system model in MADYMO. The arms of the HBM were raised to a driving position. Similar to the ES-2re dummy, contacts were defined between the stationary sled and the human head, left arm, jacket, pelvis, femur, tibia, and shoes. In order to study the response of the same system with a seatbelt, a three-point hybrid restraint belt system was added to the setup. Figure 3.24 illustrates the HBM seated in the vehicle compartment with a seatbelt. CONTACT.MB_FE was used because of the finite element part groups.
The following contacts were defined between the human body model and the vehicle:

- Human legs and knee bolster
- Human shoes and vehicle floor
- Human shoes and accelerator
- Human shoes and brake
- Human and seatback
- Human and bottom seat
- Human pelvis and lap belt
- Human jacket and shoulder belt
- Human lower arms and steering wheel

3.7 Prescribed Structural Motion

Prescribed structural motion is a method of applying nodal structural displacements to a finite element structure when its surrounding environment is negligible on the deformation. This method is used in automobile industries to design and optimize occupant restraint systems. When a particular motion of the joint or part is needed when performing dynamic analysis, it is more convenient to apply nodal displacements to the finite element in order for it to behave in a certain way. This method allows for a faster analysis by not disturbing its neighboring elements.

In this study, PSM was used to produce a crash profile of a vehicle and to use an occupant model in the driver seat to study the response characteristics. The crash nodal displacements were acquired from the LS-DYNA crash analysis model and defined into a separate file known as the PSM file. MADYMO was used to study the occupant kinematics using the PSM method. MADYMO accepts the nodal displacement file by defining MOTION.STRUCT.DISPLACEMENT in the simulation setup file.
The first step in the PSM method is achieved by trimming down the FE vehicle model shown in Figure 3.25 to a simple side-door panel with a driver seat, as shown in Figure 3.26. The main objective here was to apply structural displacement on the side-door panel by keeping a dummy model in the driver seat at the same time.

Figure 3.25. LS-DYNA finite element vehicle model

Figure 3.26. Finite element model of trimmed side-door panel with driver seat

The main challenge was to apply material properties to the vehicle side-door panel. Therefore, a reference side-impact reference file was used to model this trimmed structure. The nodal displacements were captured using HyperView. The trimmed model was then imported into MADYMO workspace to apply nodal displacements. PSM was defined to particular parts over a particular time in order to provide a crash profile. A dummy was placed in the driver seat, and the
PSM for the driver seat was applied. Contacts must be applied so that the dummy interacts with the vehicle structure. Figure 3.27 represents process of capturing the PSM file, which is then exported to MADYMO for the simulation where the dummy kinematics along with crash profile can be studied.

Figure 3.27. HyperView capturing vehicle structure nodal displacements

Figure 3.28 represents the imported models of the FE trimmed model. These models were imported into MADYMO, and the occupant models were positioned in the driver seats.

Figure 3.28. Trimmed FE model: (a) with ES-2re dummy and (b) with human body model
CHAPTER 4

DUMMY AND HUMAN BODY MODEL RESPONSES IN FMVSS 214 MOVING DEFORMABLE BARRIER SIDE-IMPACT TEST FOR TYPICAL MID-SIZE SEDAN AND SMALL-SIZE COMPACT CAR

This chapter examines the differences between dummy and human model responses in FMVSS 214 moving deformable barrier side-impact tests. Injury criteria including HIC, rib deflection, pelvis acceleration, VC, and TTI for both the dummy and human were obtained. Results between the ES-2re dummy and human body model were compared.

4.1 Typical Mid-Size Sedan

In this study, a 2001 Ford Taurus was used to represent a mid-size passenger sedan. NCAC finite element models from the NHTSA database were used to model the side-impact test setup, as shown in Figure 4.1. The moving deformable barrier used in this study was also accessed from the NHTSA database [44]. In order to study the dummy and human body model responses, the FMVSS 214 moving deformable barrier side-impact test protocol was used to model the entire test setup [12].

Figure 4.1. FE model setup of Ford Taurus mid-size sedan and FMVSS 214 moving deformable barrier
4.1.1 Finite Element Simulation

The entire crash test simulation setup was modeled using LS-DYNA PrePost. The moving deformable barrier was positioned at the vehicle model using the wheelbase calculation (940 + 0.5 W), according to the FMVSS 214 regulation [12]. The Ford Taurus model was placed in a stationary position while the MDB was positioned to strike the stationary vehicle model at a speed of 33.5 mph, according to the FMVSS 214 side-impact regulation. The wheels of the MDB model were aligned at a 27-degree crab angle, and the entire setup is shown in Figure 4.1. An initial velocity of 33.5 mph was defined to the MDB in order for it to move forward and impact the stationary vehicle, as shown in Figure 4.1. Contacts were defined between the vehicle model and the MDB using the keyword manager from LS-DYNA. Figure 4.2 illustrates the simulation results.

Figure 4.2. Simulation of Ford Taurus mid-size sedan FRMVSS 214 MDB side-impact test
Due to factors such as contacts, crab angle, penetrations, etc., it is very important to check the accuracy of the simulation with a standard test or simulation. The simulation in this study was validated against a similar test simulation performed by the NCAC [39]. To check the accuracy of the simulation results, the nodal accelerations and velocities of the right sill rear seat were validated with data from the NCAC and NHTSA [39]. Test simulation results are shown in Figure 4.3.

![Rear Seat Right Sill](image)

(a) Rear Seat Right Sill Y-Acceleration

![Rear Seat Right Sill](image)

(b) Rear Seat Right Sill Y-Velocity

Figure 4.3. Dynamic response of rear seat right sill of mid-size sedan from this study and from NCAC and NHTSA test simulations [39]
From the LS-DYNA results shown in Figure 4.3, it can be seen that the velocity and acceleration data of the rear seat right sill are in good agreement with the NHTSA test 3263 and NCAC test simulation [39]. Peak values of the Y-acceleration of the right sill are quite similar for all three sets of test data. Similar to the Y-acceleration of the right sill, the Y velocity from this study is in closer proximity. Based on these validation results, it can be assumed that the vehicle model analysis is efficient.

After the validation, the acceleration pulses of the driver seat were obtained. Figure 4.4 represents the X-, Y-, and Z-acceleration pulses of the driver seat node. These pulses were further utilized as input for the MADYMO side-impact sled tests. The intrusion of the vehicle was measured at the vehicle’s B-pillar to check the effect of the MDB on the vehicle. An intrusion of 301.32 mm was measured after the crash with the MDB. Figure 4.5 illustrates before and after crash results of the vehicle’s B-pillar.

![Driver Seat Accelerations](image)

Figure 4.4. Dynamic response of mid-size sedan driver seat X-, Y-, and Z-accelerations from LS-DYNA FMVSS-214 side-impact test
Figure 4.5. Intrusion of mid-size sedan B-pillar: (a) before crash and (b) after crash

Figure 4.6 represents before and after simulations of the FMVSS 214 MDB side-impact test involving a typical mid-size sedan. The MDB impacts with the car, and the crush profile can be seen afterward.

Figure 4.6. Crash profile of Ford Taurus mid-size sedan: (a) before FMVSS 214 MDB side-impact test and (b) after FMVSS 214 MDB side-impact test
4.1.2 ES-2re Dummy Responses

The acceleration pulse acquired from the driver seat was applied as input for the MADYMO sled test. Acceleration was applied to the ES-2re dummy occupant model in the lateral direction so that the occupant impacted the sled. All contacts were defined between the dummy and the vehicle sled system as CONTACT.MB_MB. A restraint belt system was also added to the vehicle to study the dummy response with and without a seatbelt. Figures 4.7 and 4.8 illustrate the simulation of a dummy impacting a rigid sled in the lateral direction with and without a belt system. The shoulder belt slipped onto the dummy, while the lap belt kept the dummy in the seat, and the dummy moved in the lateral direction, thereby impacting its torso with the sled.

Figure 4.7. ES-2re dummy responses in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.8. ES-2re dummy responses in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test
4.1.3 Human Body Model Responses

The human body model was seated on the rigid seat with arms raised to expose the thorax region to the rigid sled. The acceleration pulse was applied to the human body model to impact the sled laterally. Since the HBM was designed with both rigid and flexible bodies, it behaved realistically when the body moved toward the sled. Figures 4.9 and 4.10 depict the HBM response in a side-impact scenario without and with a seatbelt. All contacts between the HBM and vehicle system were defined as CONTACT.MB_FE, and the skin of the facet HBM was modeled with finite elements. It is important to define certain parts of the HBM as GROUP_FE, particularly when defining the contact between the seatbelt and the HBM skin.

![Figure 4.9](image1.png)

**Figure 4.9.** Human body model responses in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test

![Figure 4.10](image2.png)

**Figure 4.10.** Human body model responses in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test
From Figure 4.10, it can be seen that the shoulder belt has slipped over the human body, while the lap belt kept the human in contact with the seat. The human body model exhibited flexibility when impacted with the sled, and the upper torso bent smoothly at $t = 0.08$ sec. This is because of the design of vertebrae having different kinematic joints. The human neck behaves the same way as the spine vertebrae, showing biofidelity in comparison to regular hybrid models.

4.1.4 Comparison of Results

A side-impact sled test was performed on both occupant models using the acceleration pulse acquired from the driver seat of a standard LS-DYNA test. These tests were conducted with and without a restraint belt system, as illustrated previously in Figures 4.7 to 4.10. MADYMO output was plotted for both scenarios. Results were compared in order to understand the dynamic behavior and injuries for cases with and without a seatbelt.

**Rib Deflection**

Ribs play a major role in the protection of the human chest, heart, and lungs. Rib deflection measure is one of the important criteria in evaluating a side-impact dummy. According to the FMVSS 214 regulation, rib deflection should not exceed 44 mm. If it does, then the occupant may suffer severe chest injury. Chest injuries usually occur at sudden high-speed decelerations.

Rib deflection is calculated from the relative displacement of upper and lower ribs from the T12 spine. The injury criteria limit developed for rib deflection is 44 mm. Figures 4.11 and 4.12 represent the rib deflection plots of the ES-2re dummy and the human body model. For the model without seatbelt, the peak values were 49.41 mm for the ES-2re dummy and 63.19 mm for the human body model. For the model with the seatbelt, the peak values were 53.20 mm for the ES-2re dummy and 69.40 mm for the human body model. These values obtained are above the tolerance limit of 44 mm; therefore, both the ES-2re dummy and the human body model suffer
severe injuries. Both plots follow the same trend; no such significant difference between the models with and without seatbelts was observed.

Figure 4.11. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.12. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test
Head Injury Criterion

Head injury that occurs when the head hits a rigid plane or hard surface is one of the most severe causes of car fatalities. Since this study involved a sled test, HIC was used to calculate whether the occupant suffered any kind of head injury. After performing the simulation in MADYMO, the output from the head resultant acceleration was plotted against time for both the ES-2re dummy and the human body model without and with a seatbelt, as shown in Figures 4.13 and 4.14, respectively. From both plots, it can be seen that the ES-2re dummy exhibits larger acceleration (g) values, and the HBM produces smaller acceleration forces. Peak values of 1,250 g’s were produced by the ES-2re dummies in both tests, without and with a seatbelt. The HBM produced 480 g and 450 g in both tests, respectively. Without a seatbelt, the HIC for the ES-2re dummy was 216 and for the HBM was 186. With a seatbelt, the HIC for the ES-2re dummy was 214 and for the HBM was 185. The effect of the seatbelt was considerably less in this type of sled test, indicating that the occupant may not suffer head injuries with this type of impact.

Figure 4.13. Comparison of head injury criteria for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test
Figure 4.14. Comparison of head injury criteria for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test

Pelvic Acceleration

According to the FMVSS 214 safety regulation, pelvic acceleration in the lateral direction should not exceed 130 g. Pelvic acceleration was plotted for both the ES-2re dummy and HBM. Tests were conducted for both scenarios of without and with a seatbelt. The seatbelt plays a key role in restraining the occupant from moving towards the impact surface. Many factors such as friction between belts and body surfaces, belt material properties, prescribed motion of joints, and dummy position are involved. Figure 4.15 represents the pelvic accelerations for occupant models without a seatbelt, where it can be seen that the peak acceleration was observed at 126 g for the human body model and 113 g for the ES-2re model.

When the occupant models were restrained with a seatbelt, pelvic accelerations were reduced to 112 g for the HBM and 73 g for the ES-2re dummy, as shown in Figure 4.16. Therefore, the human body model may suffer pelvic injury when it is not restrained with a seatbelt as the
value is near to 130 g, whereas the ES-2re dummy might not be affected. The restraint system plays a major role in protecting the pelvis from injuries.

Figure 4.15. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.16. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test
Viscous Criterion

Viscous criterion predicts the thoracic injuries by measuring the product of the relative velocity of chest and relative displacement or compression of chest. MADYMO dummies were predefined with VC parameters before using them in the simulation. According to the FMVSS 214 safety regulation, VC should not exceed 1 m/s. After simulations, results were obtained for without and with seatbelt scenarios. Figure 4.17 shows the viscous criteria for the ES-2re dummy and HBM. Peak values obtained were 1.4 m/s for the ES-2re dummy and 0.96 m/s for the HBM, indicating that the ES-2re dummy may suffer thoracic injury without a restraint system, whereas the HBM is very near the VC injury limit.

Figure 4.18 shows the VC values for both occupant models with the seatbelt installed. As shown, the values increased, with peak values of 1.17 m/s for the ES-2re dummy and 1.09 m/s for the HBM. The seatbelt restraint system affects the chest by pushing it back towards the seat in order to keep the dummy in position.

Figure 4.17. Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test
Figure 4.18. Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 MDB side-impact test

**Thorax Trauma Index**

The TTI is calculated using the chest-based accelerations. Accelerations from the ribs of the ES-2re dummy and the human body model were obtained from the simulations.

Figure 4.19. MADYMO configuration tree of ES-2re dummy and HBM with upper and lower rib rigid bodies and T12 spine rigid body
It is important to identify the rigid bodies on the rib structure for HBM. ES-2re dummies are specifically designed for side impacts, whereas the human body models are designed for multi-purpose impacts. Rigid bodies at the 4th and 8th ribs on the struck side were considered for the TTI calculation of the TTI. These are shown in Figure 4.19. Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 safety regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles.

Table 4.1 shows the thorax trauma index values for the ES-2re dummy and the human body model for different MDB test scenarios involving a sedan. It can be seen that the ES-2re dummy is protected when a restraint system is installed, and the human body model is affected by the seatbelt in both cases. However, the human body model may suffer thoracic injuries.

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re dummy without seatbelt</td>
<td>121</td>
</tr>
<tr>
<td>ES-2re dummy with seatbelt</td>
<td>76</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>132</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>100</td>
</tr>
</tbody>
</table>

### 4.1.5 PSM Results

Prescribed structural motion was applied to the trimmed side-door panel of a Ford Taurus with the respective occupant model seated in the driver seat. Results are shown in Figure 4.20. The crush behavior observed through PSM was exactly the same as for the FE method, and the results were plotted. There are certain limitations with this method. As it follows the nodal displacements of
the FE model, the behaviors of the occupant models are different. This approach was used to check the efficiency of the PSM method and also the occupant model behavior in a real crash scenario.

The same method was followed throughout this research, and the results were plotted

<table>
<thead>
<tr>
<th></th>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0 msec</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>t = 25 msec</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>t = 50 msec</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>t = 75 msec</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Figure 4.20. Ford Taurus mid-size sedan without seatbelt for ES-2re dummy and HBM responses in FMVSS 214 MDB side-impact test using PSM method
**Rib Deflection**

Rib deflection results were obtained from the occupant models. As shown in Figure 4.21, rib deflection for the ES-2re dummy crossed the limits of 44 mm; however, rib deflection for the HBM was within limits. Maximum values obtained were 51 mm for the ES-2re dummy and 38 mm for the HBM. As shown, the ES-2re dummy crossed the injury limit and may suffer potential injuries. The plot also shows differences in both occupant models behavior and signal sensitivity.

![Figure 4.21. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method](image)

**Head Injury Criterion**

The head accelerations were found be small because there was no physical contact between the occupant head and the car door panel. As shown in Figure 4.22, the head acceleration reaches 375 g for the HBM and 143 g for the ES-2re dummy. These values are under the limits of HIC, and there are no potential head injuries. An HIC value of 170 was obtained from the formula for both occupant models, indicating that both models are safe with no potential injuries.
Figure 4.22. Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method

Pelvic Acceleration

The maximum values observed in the pelvic acceleration were 225 g’s for the human body model and 155 g’s for the ES-2re dummy. As shown in Figure 4.23, pelvic accelerations crossed the injury limit of 130 g, indicating that both occupant models may suffer potential injuries.

Figure 4.23. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method
**Viscous Criterion**

Viscous criterion is one of the major injury parameters relating to chest injuries. Figure 4.24 shows that the viscous criterion obtained are 1.6 m/s for the ES-2re dummy and 1.45 m/s for the HBM, indicating that both occupant models may suffer injuries because there is no restraint system to protect them.

![Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 MDB side-impact test using PSM method](image)

**Thorax Trauma Index**

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 safety regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI was 133 g for the ES-2re dummy and 95 g for the human body model. Since the TTI crossed over 85 g, there might be potential injuries for both kinds of occupant models.
4.2 Small-Size Compact Car

4.2.1 Finite Element Simulation

A small-size compact car was also considered to study crash and occupant responses. An NCAC finite element model of a Toyota Yaris was acquired from the NHTSA database [44], and a FMVSS 214 MDB crash setup was modeled in LS-PrePost. The main objective of this part of the study was to investigate ES-2re dummy and human body model responses in a small-size compact car.

The moving deformable barrier was positioned in the vehicle model using the wheelbase calculation of 940 + 0.5 W, according to the FMVSS 214 regulation. The Toyota Yaris model was placed in a stationary position, while the MDB was positioned to strike the stationary vehicle model at a speed of 33.5 mph, according to the FMVSS 214 side-impact regulation. The wheels of the MDB model were aligned at a 27-degree crab angle, and the entire setup is shown in the Figure 4.25. An initial velocity of 33.5 mph was assigned to the MDB to move forward and impact the stationary vehicle, as shown in Figure 4.25.

Figure 4.25. FE model setup of Toyota Yaris small-size compact car and FMVSS 214 moving deformable barrier
Contacts between the vehicle model and the MDB were defined using the keyword manager from LS-DYNA. The crash test simulation was performed, and Figure 4.26 illustrates the simulation results.

![Simulation of Toyota Yaris small-size compact car FMVSS 214 MDB side-impact test](image)

Figure 4.26. Simulation of Toyota Yaris small-size compact car FMVSS 214 MDB side-impact test

The X-, Y-, and Z-acceleration pulses of the driver seat node are shown in Figure 4.27. These pulses were further utilized as input for the MADYMO side-impact sled tests. Intrusions of the vehicle’s B-pillar were measured to check the effect of the moving deformable barrier on the vehicle. An intrusion of 150.05 mm was measured after the crash with the MDB. Figure 4.28 illustrates before and after crash results of the vehicle’s B-pillar, and Figure 4.29 shows the crash profile before and after the FMVSS 214 MDB side-impact crash.
Figure 4.27. Dynamic response of small-size compact car diver seat X-, Y-, and Z-accelerations from LS-DYNA FMVSS 214 MDB side-impact test

Figure 4.28. Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in FMVSS 214 MDB side-impact test

Figure 4.29. Crash profile of Toyota Yaris small-size compact car: (a) before and (b) after the FMVSS 214 MDB side-impact test
4.2.2 ES-2re Dummy Responses

The crash pulse from the LS-DYNA was applied to the occupant model in the lateral direction to the MADYMO sled test setup with proper contacts defined. Figures 4.30 and 4.31 show ES-2re dummy responses without and with seatbelts, respectively. Output from MADYMO software was studied for these responses.

Figure 4.30. ES-2re dummy responses in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.31. ES-2re dummy responses in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test

4.2.3 Human Body Model Responses

The same crash pulse was applied to this model to study responses. Figures 4.32 and 4.33 show responses of the human body model without and with seatbelts, respectively. Output from the MADYMO software was studied for these responses.
4.2.4 Comparison of Results

Results were compared in order to understand the dynamic behavior and injuries for the cases with and without restraint seatbelts.

Rib Deflection

Side-impact sled tests were performed on both the occupant models using the acceleration pulse of the Toyata Yaris. According to the FMVSS 214 safety regulation, rib deflection should not exceed 44 mm. Results for these tests without and with a seatbelt are shown in Figures 4.34 and 4.35, respectively. For models without a seatbelt, the peak values obtained were 45.26 mm for the ES-2re dummy and 57.44 mm for the human body model. For models with a seatbelt, the peak
values were 49.49 mm for the ES-2re dummy and 68.44 mm for the human body model. All values exceeded the regulation limit, indicating that both occupant models might suffer severe injuries.

Figure 4.34. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.35. Comparison of rib deflection for ES-2re dummy and HBM HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test
Head Injury Criterion

Head injury criterion was calculated using the head resultant acceleration. Figures 4.36 and 4.37 show that the maximum values for the models without a seatbelt were 912 g for the ES-2re dummy and 361 g for the human body model. When a seatbelt was installed, the peak values were 993 g for the ES-2re dummy and 332 g for the human body model. All HIC values did not exceed the regulation injury limit of 1000, indicating no potential injuries to both occupant models.

Figure 4.36. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.37. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test
Pelvic Acceleration

Figure 4.38 shows peak acceleration at 92 g for the ES-2re dummy and 221 g for the human body model without a seatbelt. When the occupant models were restrained with a seatbelt, the pelvic accelerations were reduced to 68 g for the ES-2re dummy and 87 g for the human body model, as shown in Figure 4.39.

Figure 4.38. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test

Figure 4.39. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test
The HBM may suffer pelvic injury when it is not restrained with a seatbelt, whereas the ES-2re dummy might not be affected. The restraint system plays a major role in protecting the pelvis from injuries. There are no injuries for both the ES-2re dummy and Human body model occupants when they are restrained by a seatbelt.

**Viscous Criterion**

According to the FMVSS 214 safety regulation, VC should not exceed 1 m/s. Figure 4.40 shows VC for the ES-2re dummy and the human body model without a seatbelt. The peak values obtained were 0.9 m/s for the ES-2re dummy and 0.7 m/s for the HBM. Both occupants did not exceed the injury limit. Figure 4.41 represents VC for the ES-2re dummy and the HBM with a seatbelt. Peak values obtained were 0.9 m/s for the ES-2re dummy and 0.75 m/s for the HBM. From Figures 4.40 and 4.41, it can be seen that the behavior of both models is approximately the same and is the best fit. When the seatbelt is added to the system, the plots are closer, as shown in Figure 4.41.

![Figure 4.40](image)

Figure 4.40. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test
Figure 4.41. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 MDB side-impact test

Thorax Trauma Index

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. The values for the ES-2re dummy and human body model for different MDB test scenerios involving a small car were calculated using the standard formula, as shown in Table 4.2. It can be seen that the ES-2re dummy is protected when a restraint system is installed. Both occupant models were under the injury limit, except for the ES-2re dummy without a seatbelt, which crossed the injury limit of 85 g and thereby potentially suffered injuries.

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re dummy without seatbelt</td>
<td>89</td>
</tr>
<tr>
<td>ES-2re dummy with seatbelt</td>
<td>42</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>59</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>45</td>
</tr>
</tbody>
</table>
4.2.5 PSM Results

Figure 4.42 shows the ES-2re dummy and human body model responses in an FMVSS 214 MDB side-impact test using the PSM method.

<table>
<thead>
<tr>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="t = 0 msec" /></td>
<td><img src="image2" alt="t = 0 msec" /></td>
</tr>
<tr>
<td><img src="image3" alt="t = 25 msec" /></td>
<td><img src="image4" alt="t = 25 msec" /></td>
</tr>
<tr>
<td><img src="image5" alt="t = 50 msec" /></td>
<td><img src="image6" alt="t = 50 msec" /></td>
</tr>
<tr>
<td><img src="image7" alt="t = 75 msec" /></td>
<td><img src="image8" alt="t = 75 msec" /></td>
</tr>
</tbody>
</table>

Figure 4.42. Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in FMVSS 214 side-impact test using PSM method
Prescribed structural motion was applied to the trimmed side-door panel of a Toyota Yaris FE model with the respective occupant model seated in the driver seat.

**Rib Deflection**

Figure 4.43 shows that rib deflection for the ES-2re dummy without a seatbelt is within the limit of 44 mm, but rib deflection for the human body model without a seatbelt has crossed the limit. Maximum values obtained were 32 mm for the ES-2re dummy and 47 mm for HBM. From this plot, it can be seen that the HBM may suffer potential injuries.

![Figure 4.43. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 side-impact test using PSM method](image)

**Head Injury Criterion**

Data indicated that the human body model was sensitive to the head acceleration pulse. As shown in Figure 4.44, the head acceleration reached 110 g for the ES-2re dummy and 600 g for the human body model. HIC values were calculated as 168 and 176, respectively. These values are under the HIC limits and hence no potential injuries to the head.
Figure 4.44. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 side-impact test using PSM method

Pelvic Acceleration

As shown in Figure 4.45, pelvic accelerations for both occupant models crossed the injury limit of 130 g, indicating that they may suffer serious injuries. The maximum values were 210 g for the ES-2re dummy and 340 g for the human body model, which are above the limit.

Figure 4.45. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 MDB side-impact test using PSM method
Viscous Criterion

From Figure 4.46, it can be seen that the viscous criterion are 0.65 m/s for the ES-2re dummy and 0.9 m/s for the human body model. These values are very near the limit of 1 m/s, indicating that the occupant models may not suffer injuries.

![Graph showing comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 side-impact test using PSM method](image)

Thorax Trauma Index

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 safety regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI was 172 g for the ES-2re dummy and 196 g for the human body model. Since the TTI exceeded 85 g, this indicates that there might be potential injuries to both occupant models.
CHAPTER 5

DUMMY AND HUMAN BODY MODEL RESPONSES IN FMVSS 214 RIGID POLE SIDE-IMPACT TEST FOR TYPICAL MID-SIZE SEDAN AND SMALL-SIZE COMPACT CAR

This chapter examines the differences between the dummy and human body model responses to the FMVSS 214 rigid pole side-impact test. Injury criteria including head injury criterion, rib deflection, pelvis acceleration, viscous criterion, and thorax trauma index for both occupant models were obtained.

5.1 Typical Mid-Size Sedan

NCAC finite element models from the NHTSA were used to model the Ford Taurus mid-size sedan and FMVSS 214 rigid pole side-impact test setup. The rigid pole used in this study was accessed from NHTSA’s database [44]. In order to study the dummy and human body model responses, the FMVSS 214 rigid pole side-impact protocol was used to model the entire test setup.

5.1.1 Finite Element Simulation

The FE simulation was carried out in LS-DYNA, whereby the vehicle ran into a rigid pole at a speed of 20 mph. The model setup is shown in Figure 5.1 and simulation results in Figure 5.2.

Figure 5.1. FE model setup of Ford Taurus mid-size sedan and FMVSS 214 rigid pole
The X-, Y-, and Z-acceleration pulses of the driver seat node are shown in Figure 5.3. These pulses were further utilized as input for the MADYMO side-impact sled tests. Intrusions of the vehicle’s B-pillar were measured to check the effect of the MDB on the vehicle. An intrusion of 396.16 mm was measured after the crash with an MDB. Figure 5.4 illustrates before and after crash results of the vehicle’s B-pillar. Figure 5.5 shows the crash profile of the vehicle before and after the FMVSS 214 rigid pole side-impact test.
Figure 5.4. Intrusion of vehicle’s B-pillar: (a) before crash and (b) after crash in FMVSS 214 rigid pole side-impact test

Figure 5.5. Crash profile of Ford Taurus mid-size sedan: (a) before and (b) after FMVSS 214 rigid pole side-impact test
5.1.2 ES-2re Dummy Responses

The acceleration pulse acquired from the driver seat was applied as input for the MADYMO sled test. Acceleration was applied to the ES-2re dummy in the lateral direction so that the occupant impacted with the sled. All contacts were defined between the dummy and the vehicle sled system as CONTACT.MB_MB. A restraint belt system was also added to the vehicle to study the dummy response without and with a seatbelt. Figures 5.6 and 5.7 illustrate the simulation of the dummy impacting a rigid sled in the lateral direction without and with a restraint belt system. The shoulder belt slipped onto dummy, while the lap belt kept the dummy in the seat but moving the dummy in the lateral direction, thus impacting its torso with the sled.

![Images of ES-2re dummy responses with and without seatbelt](image1)

Figure 5.6. ES-2re dummy responses in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test

![Images of ES-2re dummy responses with seatbelt](image2)

Figure 5.7. ES-2re dummy responses in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test

79
5.1.3 **Human Body Model Responses**

The human body model was situated on the rigid seat with arms raised to expose the thorax region to the rigid sled. The acceleration pulse was applied to the HBM to impact into the sled laterally. Since the HBM was designed with both rigid and flexible bodies, it behaved realistically when the body moved towards the sled. Figures 5.8 and Figure 5.9 depict the human body model response in a side-impact scenario without and with a seatbelt. All contacts between the human body model and vehicle system were defined as CONTACT.MB_FE. It was also important to define certain parts of the human body model as GROUP_FE, particularly when defining the contact between the seatbelt and HBM skin.

![Figure 5.8. Human body model responses in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test](image)

![Figure 5.9. Human body model responses in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test](image)
5.1.4 Comparison of Results

Rib Deflection

According to the FMVSS 214 safety regulation, rib deflection should not exceed more than 44 mm. Figures 5.10 and 5.11 represent the occupant model responses in a rigid pole side-impact test without and with a seatbelt, respectively.

Figure 5.10. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test

Figure 5.11. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test
The peak deflection observed was 42 mm for the ES-2re dummy and 54 mm for the human body model without a seatbelt, as shown in Figure 5.10. Here, the HBM might suffer a severe chest injury because this value is much higher than the limit; however, the ES-2re dummy might suffer minor injuries as well. When a seatbelt was added to the system, the peak values observed were 42 mm for the ES-2re dummy and 65 mm for the HBM, as shown in Figure 5.11.

**Head Injury Criterion**

Head acceleration was found to be small in this scenario because of restraints at the shoulder and torso. Peak values were 810 g for the ES-2re dummy and 280 g for the human body model. Values without and with a seatbelt were approximately equal, as shown in the Figures 5.12 and 5.13, respectively. Without a seatbelt, HIC values were 188 for the ES-2re dummy and 175 for the HBM. With a seatbelt, HIC values were 189 for the ES-2re dummy and 174 for the HBM. The effect of a seatbelt on the HIC of occupant models was not that significant in the side impact.

![Graph showing head acceleration over time](image)

Figure 5.12. Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test
Figure 5.13. Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test

**Pelvic Acceleration**

Pelvic acceleration pulses are plotted in Figures 5.14 and 5.15 for both the ES-2re dummy and the human body model without and with seatbelts, respectively. Pulses in both models follow the trend line.

Figure 5.14. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test
Figure 5.15. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test

Without a seatbelt, the ES-2re dummy attained its peak value at 85 g and the HBM at 190 g. With a seatbelt, the peak value for the ES-2re dummy was 60 g and for the HBM was 85 g. Without a seatbelt, the HBM model crossed the limit of 130 g and may suffer injuries.

**Viscous Criterion**

According to the FMVSS 214 safety regulation, VC should not exceed 1.0 m/s. Figures 5.16 and 5.17 represents VC plots for both the ES-2re dummy and HBM in case of without seatbelt and with seatbelt respectively. In both cases the VC values are below the injury limit of 1.0 m/s. Therefore, no potential injuries occurred to the chest or thoracic region. Maximum VC values were 0.72 m/s for the ES-2re dummy and 0.68 m/s for the HBM. When a seatbelt was added, the VC criteria was further reduced to 0.68 m/s for the ES-2re dummy and 0.64 m/s for the HBM. In both the cases, there was no potential injury to the occupants, but there was a decrease in value when the seatbelt system was added.
Figure 5.16. Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test.

Figure 5.17. Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan with seatbelt in FMVSS 214 rigid pole side-impact test.
Thorax Trauma Index

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 safety regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI was calculated using the standard formula, and the values for the ES-2re dummy and HBM are tabulated in Table 5.1. As can be seen, both occupant models are protected when the restraint system is used, and injuries might not occur in this test.

TABLE 5.1

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re dummy without seatbelt</td>
<td>57</td>
</tr>
<tr>
<td>ES-2re dummy with seatbelt</td>
<td>55</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>76</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>64</td>
</tr>
</tbody>
</table>
5.1.5 PSM Results

Prescribed structural motion was applied to the trimmed side-door panel of the Ford Taurus.

Figure 5.18 shows the ES-2re dummy and HBM responses using the PSM method.

<table>
<thead>
<tr>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>t = 0 msec</td>
<td>t = 0 msec</td>
</tr>
<tr>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>t = 25 msec</td>
<td>t = 25 msec</td>
</tr>
<tr>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>t = 50 msec</td>
<td>t = 50 msec</td>
</tr>
<tr>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>t = 75 msec</td>
<td>t = 75 msec</td>
</tr>
</tbody>
</table>

Figure 5.18. Ford Taurus mid-size sedan without seatbelt ES-2re dummy and HBM responses responses in FMVSS 214 rigid pole test using PSM method
**Rib Deflection**

Rib deflection results were obtained from the occupant models, and from Figure 5.19 it can be seen that rib deflection for the ES-2re dummy crossed the limit of 44 mm, whereas the human body model was within the limit. The maximum values obtained were 53 mm for the ES-2re dummy and 28 mm for the human body models. As shown in this plot, the ES-2re dummy crossed the injury limit and may suffer potential injuries.

![Graph showing rib deflection](image)

**Figure 5.19.** Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method

**Head Injury Criterion**

In this regulation, the door panel crashes into a rigid pole. Head acceleration values were found to be small because there was no physical contact between the occupant head and the car door panel. As shown in Figure 5.20, the head acceleration reached 175 g for the ES-2re dummy and 290 g for the human body model. In the case of PSM, HIC values were 199 for the ES-2re dummy and 189 for the human body model. These values are under the HIC limit and therefore no potential injuries to the head. The difference between ellipsoid models and finite element models plays a major role in the behavior of occupant models.
Figure 5.20. Comparison of head injury criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method

**Pelvic Acceleration**

Pelvic accelerations are plotted for both occupant models in Figure 5.21. As shown, the HBM crossed the pelvic acceleration injury limit of 130 g and may suffer potential injuries. Pelvic accelerations for the ES-2re dummy are within the injury limit, and this occupant may not suffer injuries. The maximum values observed were 92 g for the ES-2re dummy and 158 g for the HBM.

Figure 5.21. Comparison of pelvic acceleration for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method
Viscous Criteria

As shown in Figure 5.22, the viscous criterion obtained for the ES-2re dummy is 0.8 m/s and 0.26 m/s for the human body model, thus indicating no potential injuries.

![Viscous Criterion Graph](image)

Figure 5.22. Comparison of viscous criterion for ES-2re dummy and HBM in mid-size sedan without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method

Thorax Trauma Index

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 safety regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI was obtained as 158 g for the ES-2re dummy and 106 g for the human body model, thus indicating very serious injuries to the occupants.
5.2 Small-Size Compact Car

NCAC finite element models from the NHTSA were used to model the Toyota Yaris small-size compact car FMVSS 214 rigid pole side-impact test setup. The fixed rigid pole used in this study was accessed from NHTSA’s database [44]. In order to study the ES-2re dummy and human body model responses, the FMVSS 214 rigid pole side-impact protocol was used to model the entire test setup.

5.2.1 Finite Element Simulation

In this test, the vehicle ran into a fixed rigid barrier at a speed of 20 mph. The vehicle at a 75-degree angle impacts the rigid pole of 254 ± 3 mm in diameter. Contacts were defined between the vehicle model and rigid pole using the keyword manager from LS-DYNA PrePost. The vehicle should contact the pole at the dummy head CG location. Figure 5.23 shows the setup of the rigid pole side-impact test setup, and Figure 5.24 illustrates the simulation results.

Figure 5.23. FE model setup of Toyota Yaris small-size compact car and FMVSS 214 rigid pole
After validation, Y-acceleration pulse of the driver seat node was obtained, as shown in Figure 5.25. The pulse was further utilized as input for the MADYMO side-impact sled tests. Intrusions of the vehicle’s B-pillar were measured to check the effect of the rigid pole on the vehicle. An intrusion of 262.91 mm was measured after the crash with the rigid pole. Figure 5.26 illustrates before and after crash results of the vehicle’s B-pillar. Figure 5.27 shows the crash profile of the vehicle before and after the FMVSS 214 rigid pole side-impact test.
Figure 5.26. Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in FMVSS 214 rigid pole side-impact test

Figure 5.27. Crash profile of Toyota Yaris small-size compact car: (a) before and (b) after FMVSS 214 rigid pole side-impact test

5.2.2 ES-2re Dummy Responses

The acceleration pulse acquired from the driver seat was applied as input for the MADYMO sled test. The acceleration was applied to the ES-2re dummy in the lateral direction so that the occupant impacted the sled. All contacts were defined between the dummy and the vehicle sled system as CONTACT.MB_MB. A restraint belt system was also added to the vehicle to study
the dummy response without and with a seatbelt. Figures 5.28 and 5.29 illustrate the simulation of the dummy impacting a rigid sled in the lateral direction without and with a restraint belt system. The shoulder belt slipped onto the dummy, while the lap belt kept the dummy in the seat, and the dummy moved in the lateral direction, impacting its torso with the sled.

Figure 5.28. ES-2re dummy responses in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test

Figure 5.29. ES-2re dummy responses in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test

5.2.3 Human Body Model Responses

The human body model was seated on the rigid seat with arms raised to expose the thorax region to the rigid sled. The acceleration pulse was applied to the HBM to impact into the sled laterally. Since the HBM was designed with both rigid bodies and flexible bodies it behaved realistically when the body moved towards the sled. Figures 5.30 and 5.31 depict the human body
model response in a side-impact scenario without and with a seatbelt. All contacts between the HBM and vehicle system were defined as CONTACT.MB_FE, and the skin of the facet HBM was modeled with finite elements. It was also important to define certain parts of the human body model as GROUP_FE, particularly when defining the contact between the HBM skin and seatbelt.

![Figure 5.30. Human body model responses in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test](image)

![Figure 5.31. Human body model responses in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test](image)

5.2.4 Comparison of Results

Rib Deflection

Results shown in Figures 5.32 and 5.33 indicate that the human body model may suffer severe injuries because the peak values exceed the injury limit of 44 mm. For the ES-2re dummy, this value was 43 mm, and for the HBM it was 51 mm without a seatbelt system. The peak values
gradually increased to 46 mm for the ES-2re dummy and 66 mm for the human body model with the added seatbelt system, which suggests that the occupant might suffer potential injuries.

**Figure 5.32.** Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test

**Figure 5.33.** Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test
Head Injury Criterion

From Figures 5.34 and 5.35, it can be seen that the head acceleration plots obtained are similar, with peak values of 300 g for the ES-2re dummy and 820 g for the human body model.

Figure 5.34. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test

Figure 5.35. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test
In the case of no seatbelt, the HIC values obtained were 188 for the ES-2re dummy and 176 for human body model. In the case with a seatbelt, the HIC was calculated as 193 for the ES-2re dummy and 175 for the HBM. These HIC values appear to be under 1000, which suggest that the occupant is would be safe from head injuries. From the simulations and resultant plots, it can be seen that the shoulder seatbelt does not restrain the occupant and allows the occupant to move and hit the side panel or pole.

**Pelvic Acceleration**

Pelvic accelerations shown in Figures 5.36 and 5.37 suggest that the seatbelt provides safe protection for the occupant. The peak values obtained without the seatbelt were 85 g for the ES-2re dummy and 240 g for the human body model, which implies an injury. After installation of the seatbelt, the pelvic acceleration was reduced to 62 g for the ES-2re dummy and 68 g for the HBM, indicating that the restraint system was effective at such low speeds.

![Figure 5.36. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test](image-url)
Figure 5.37. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test

**Viscous Criterion**

The viscous criteria obtained in this test are shown in Figures 5.38 and 5.39. According to the FMVSS 214 safety regulation, the VC should not exceed 1.0 m/s. As shown, the VC is beyond the injury limit. Therefore, there would be no potential injuries to the chest or thoracic region. Maximum values observed for the VC were 0.7 m/s for the ES-2re dummy and 0.63 m/s for the human body model. When a seatbelt was added to the sled system, the VC was slightly increased to 0.77 m/s for the ES-2re dummy and 0.67 m/s for the human body model. In both cases, there was no potential injury to the occupants, but there was a decrease in value when the seatbelt system was added. In case of without seatbelt and with seatbelt, the same trend can be observed for both the occupant models. In both the cases, the ES-2re dummy showed slightly higher values than the human body model. From the plots, human body model showed sensitivity by an early rise in VC values.
Figure 5.38. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test.

Figure 5.39. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in FMVSS 214 rigid pole side-impact test.
Thorax Trauma Index

The TTI was calculated for different rigid pole test scenarios involving a small-size compact car using the standard formula, and the values are shown in Table 5.2. It can be seen that the ES-2re dummy as well as the human body model are well protected when the restraint system is installed, and injuries might not occur in this test; however, the ES-2re dummy without a seatbelt might suffer potential injuries.

TABLE 5.2

TTI VALUES FOR DIFFERENT FMVSS 214 RIGID POLE SIDE-IMPACT TEST SCENARIOS—SMALL-SIZE COMPACT CAR

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re dummy without seatbelt</td>
<td>89</td>
</tr>
<tr>
<td>ES-2re dummy with seatbelt</td>
<td>42</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>59</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>45</td>
</tr>
</tbody>
</table>
5.2.5 PSM Results

Prescribed structural motion was applied to the trimmed side-door panel of the Toyota Yaris. Figure 5.40 shows the ES-2re dummy and HBM responses using the PSM method.

<table>
<thead>
<tr>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 0 msec</td>
<td>t = 0 msec</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 25 msec</td>
<td>t = 25 msec</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 50 msec</td>
<td>t = 50 msec</td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 75 msec</td>
<td>t = 75 msec</td>
</tr>
</tbody>
</table>

Figure 5.40. Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in FMVSS 214 rigid pole side-impact test using PSM method
The crush behavior observed through PSM as shown in Figure 5.40 was exactly the same as for the FE method. The results were plotted for various injury criteria.

**Rib Deflection**

Rib deflection results for the occupant models are shown in Figure 5.41. It can be seen that for both models, the rib deflections were within the limit of 44 mm. The maximum values obtained were 25 mm for the ES-2re dummy and 31 mm for human body models. From the plot, it can be seen that the occupant models may not suffer injuries.

![Figure 5.41. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method](image)

**Head Injury Criterion**

From Figure 5.42, it can be seen that the head acceleration reaches 190 g for the ES-2re dummy and 1100 g for the human body model. In the case of prescribed structural motion, the HIC values were 169 for the ES-2re dummy and 195 for the human body model. These values are under the limits of HIC and there are no potential injuries to the head. Rigid pole impact is one of the factors considered in the HIC criterion because the head tends to hit the rigid pole. Because there is no actual pole in PSM, the impact is not that hard, so the HIC values are not as high.
Figure 5.42. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method

**Pelvic Acceleration**

Pelvic accelerations were plotted for both occupant models. From Figure 5.43, it can be seen that the ES-2re dummy is within the injury limits and may not suffer injuries, but the human body model crosses the pelvic acceleration injury limit of 130 g and may suffer serious injuries. The maximum values observed are 127 g for the ES-2re dummy and 346 g for the HBM.

Figure 5.43. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method
**Viscous Criterion**

According to the FMVSS 214 safety regulation, VC should not exceed 1 m/s. From Figure 5.44, it can be seen that the viscous criterion obtained for the ES-2re dummy is 0.38 m/s for and for the human body model is 0.6 m/s, which indicates that there is no potential injuries to either occupant model.

![Graph showing viscous criterion for ES-2re dummy and HBM model](image)

Figure 5.44. Comparison of viscous criterion for ES-2re dummy and HBM model in small-size compact car without seatbelt in FMVSS 214 rigid pole side-impact test using PSM method

**Thorax Trauma Index**

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to the FMVSS 214 regulation, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI for the ES-2re dummy was 178 g and for the human body model was 162 g, which indicates very serious injuries to the occupants.
CHAPTER 6

DUMMY AND HUMAN BODY MODEL RESPONSES IN IIHS MOVING DEFORMABLE BARRIER SIDE-IMPACT CRASH TEST FOR TYPICAL MID-SIZE SEDAN AND SMALL-SIZE COMPACT CAR

This chapter examines the differences between ES-2re dummy and human body model responses in the Insurance Institute for Highway Safety moving deformable barrier side-impact test. Injury criteria including head injury, rib deflection, pelvis acceleration, viscous criteria, and thorax trauma index of both the ES-2re dummy and human body model were obtained. Results of both the sled tests and the PSM models were compared.

6.1 Typical Mid-Size Sedan

The NCAC finite element models from the NHTSA were used to model the Ford Taurus mid-size sedan side-impact test setup. The IIHS moving deformable barrier used in this study was acquired from NHTSA database [44]. In order to study the dummy and human body model responses, the IIHS side-impact protocol was used to model the entire test setup. The MDB replicates an SUV, and when a side impact occurs, the occupant might end up hitting the barrier.

6.1.1 Finite Element Simulation

The entire setup was performed using LS-DYNA PrePost. The MDB was positioned at the vehicle model using IIHS side-impact testing protocol. The Ford Taurus model was placed in a stationary position while the MDB was positioned to strike the stationary vehicle model at a speed of 31.06 mph (50 kmph) according to the protocol. The MDB hit the stationary vehicle perpendicularly. An initial velocity of 31.06 mph was assigned to the MDB in order to move forward and impact the stationary vehicle, as shown in Figure 6.1. Contacts were defined between the vehicle model and the MDB using the keyword manager from LS-DYNA. Figure 6.2 illustrates the crash test simulation results.
Figure 6.1. FE model setup of Ford Taurus mid-size sedan and IIHS moving deformable barrier

Figure 6.2. Simulation of Ford Taurus mid-size sedan IIHS MDB side-impact test
The Y-acceleration pulse of the driver seat node is shown in Figure 6.3. This pulse was further utilized as input for the MADYMO side-impact sled tests. The intrusions of the vehicle’s B-pillar was measured to check the effect of the MDB on the vehicle. An intrusion of 323.24 mm was measured after the crash with the MDB. Figure 6.4 illustrates before and after crash results of intrusion of the vehicle B-pillar.

![Y-Acceleration Graph](image)

**Figure 6.3. Dynamic response of mid-size sedan driver seat Y-acceleration in IIHS MDB side-impact test**

![Intrusion Graph](image)

**Figure 6.4 Intrusion of mid-size sedan B-pillar: (a) before crash and (b) after crash in IIHS MDB side-impact test**
Figure 6.5. Crash profile of mid-size sedan: (a) before and (b) after IIHS MDB side-impact test

6.1.2 ES-2re Dummy Responses

The acceleration pulse acquired from the mid-size sedan driver seat was applied as an input for the MADYMO sled test. Acceleration was applied to the ES-2re dummy in the lateral direction so that the dummy impacted with the sled. All contacts were defined between the dummy and the vehicle sled system as CONTACT.MB_MB. A seatbelt restraint system was also added to the vehicle to study the dummy response with a seatbelt. Figures 6.6 and 6.7 illustrate simulation of the ES-2re dummy impacting the rigid sled in the lateral direction without and with a restraint system, respectively. In case of with seatbelt, the shoulder belt slipped onto the dummy and the lap belt kept the dummy in the seat. The dummy moved in lateral direction, impacting its torso with the sled.
6.1.3 Human Body Model Responses

The human body model was seated on the rigid seat with arms raised to expose the thorax region to the rigid sled. The acceleration pulse was applied so that the HBM impacted the sled laterally. Since the HBM was designed with both rigid and flexible bodies, it behaved realistically when the body moved towards the sled. Figures 6.8 and 6.9 depict the human body model response in a side-impact scenario without and with a seatbelt. All contacts between the HBM and the vehicle system were defined as CONTACT.MB_FE, and the skin of the facet HBM was
modeled with finite elements. It is important to define certain parts of the HBM as GROUP_FE, particularly when defining the contact between the HBM skin and the seatbelt.

Figure 6.8. Human body model responses in mid-size sedan without seatbelt in IIHS MDB side-impact test

Figure 6.9. Human body model responses in mid-size sedan with seatbelt in IIHS MDB side-impact test

6.1.4 Comparison of Results

Rib Deflection

The rib deflection peak for the human body model without a seatbelt was 49 mm as shown in Figure 6.10, slightly higher than the 44 mm marginally acceptable limit according to IIHS injury criteria. For the ES-2re dummy, the maximum rib deflection was 39 mm, which is between
acceptable and marginally acceptable. When the seatbelt was added to the system, the values were 38 mm for the ES-2re dummy and 57 mm for the HBM as shown in Figure 6.11. In both cases, there might be potential injuries.

![Figure 6.10](image1.png)

**Figure 6.10.** Comparison of rib deflection for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test

![Figure 6.11](image2.png)

**Figure 6.11.** Comparison of rib deflection for ES-2re dummy and HBM model in mid-size sedan with seatbelt in IIHS MDB side-impact test
Head Injury Criterion

Figures 6.12 and 6.13 show the results of IIHS MDB side-impact tests. Similar to other regulations, the IIHS test hits the target car at a 90-degree angle. The injury criteria is different for IIHS, but in this research, the same HIC was used to evaluate the occupant models.

![Figure 6.12. Comparison of head injury criterion for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test](image1)

Figure 6.12. Comparison of head injury criterion for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test

![Figure 6.13. Comparison of head injury criterion for ES-2re dummy and HBM model in mid-size sedan with seatbelt in IIHS MDB side-impact test](image2)

Figure 6.13. Comparison of head injury criterion for ES-2re dummy and HBM model in mid-size sedan with seatbelt in IIHS MDB side-impact test
Peak values without a seatbelt were 620 g for the ES-2re dummy and 220 g for HBM. According to IIHS criteria, an HIC value of 779 is safe. In the case of with a seatbelt, the HIC was 183 for the ES-2re dummy and 169 for the HBM and in case of nobelt 177 for ES-2re and 170 for HBM. In both cases, there would be no potential injuries.

**Pelvic Acceleration**

Pelvic acceleration was not considered in the IIHS injury criteria but was used for overall results comparison. Figures 6.14 and 6.15 show that the pelvic acceleration results for the ES-2re dummy and HBM model in the mid-size sedan without and with a seatbelt seem to be in good agreement, with peak values less than 130 g, indicating that there might not be any potential injuries to the occupant according to other standards. When a seatbelt was added to the system, accelerations of the ES-2re dummy and HBM nearly matched. The peak value without the seatbelt was 71 g for the ES-2re dummy and 109 g for the HBM. The peak value with the seatbelt was 40 g for the ES-2re dummy and 37 g for the HBM.

![Figure 6.14. Comparison of pelvic acceleration for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test](image-url)
Viscous Criterion

According to the FMVSS 214 safety regulation, VC should not exceed 1 m/s. As shown in Figure 6.16, the viscous criterion obtained without a seatbelt was 0.52 m/s for the ES-2re dummy and 0.55 m/s for the human body model, which indicates no potential injuries to the occupant models. From Figure 6.17, the viscous criterion obtained with a seatbelt was 0.56 m/s for the ES-2re dummy and and 0.38 m/s for the HBM, which again indicates no potential injuries to the occupant models. Both figures show that the curves are in a best fit for both the scenarios for both models. In both cases, the VC values are low and there are no potential injuries. In case of with seatbelt, the ES-2re dummy showed slightly higher values than the human body model and in case of without seatbelt, human body model showed higher values than the dummy. From the plots, human body model showed sensitivity by an early rise in VC values.
Figure 6.16. Comparison of viscous criterion for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test

Figure 6.17. Comparison of viscous criterion for ES-2re dummy and HBM model in mid-size sedan with seatbelt in IIHS MDB side-impact test
Thorax Trauma Index

The TTI was calculated using the standard formula, and the values for the ES-2re dummy and human body model are tabulated in Table 6.1. These values are under the injury limit of 85 g, and both occupant models are well protected in this test. The restraint system reduced the TTI values and helped in protecting the occupants.

**TABLE 6.1**

**TTI VALUES FOR DIFFERENT IIHS MDB SIDE-IMPACT TEST SCENERIOS—MID-SIZE SEDAN**

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re without seatbelt</td>
<td>56</td>
</tr>
<tr>
<td>ES-2re with seatbelt</td>
<td>40</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>49</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>39</td>
</tr>
</tbody>
</table>
6.1.5 PSM Results

Prescribed structural motion was applied to the trimmed side-door panel of the Ford Taurus mid-size sedan. Figure 6.18 shows the ES-2re dummy and HBM responses using the PSM method.

<table>
<thead>
<tr>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 0 msec</td>
<td>t = 0 msec</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 25 msec</td>
<td>t = 25 msec</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 50 msec</td>
<td>t = 50 msec</td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 75 msec</td>
<td>t = 75 msec</td>
</tr>
</tbody>
</table>

Figure 6.18. Ford Taurus mid-size sedan without seatbelt ES-2re dummy and HBM responses in IIHS MDB side-impact test using PSM method
Rib Deflection

Rib deflection results for models in the mid-size sedan IIHS MDB side-impact test were plotted for both occupant models, and from Figure 6.19 it can be seen that the maximum values were 48 mm for the ES-2re dummy and 28 mm for HBM. From the plot, it can be seen that because the ES-2re dummy has crossed the injury limit of 44 mm, it may suffer potential injuries.

Figure 6.19. Comparison of rib deflection for ES-2re dummy and HBM in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method

Head Injury Criterion

Head accelerations for models in the mid-size sedan IIHS MDB side-impact test using the PSM method were small in value, indicating no physical contact between the occupant head and the car door panel, as shown in the Figure 6.20. The head acceleration reached 100 g for the ES-2re dummy and 172 g for the HBM. In the case of PSM, the HIC was calculated as 171 for the ES-2re dummy and 167 for the HBM. These values were under the HIC limit, and there were no potential injuries to the head for both occupant models. Since the occupant models were not restrained in the seat, it is quite possible that the model could move quickly out of the seat, and there might be some differences in plots, as observed in Figure 6.20.
Pelvic Acceleration

Pelvic accelerations for both occupant models in the mid-size sedan IIHS MDB side-impact test using the PSM method are plotted in Figure 6.21. As shown, the ES-2re dummy is within the pelvic acceleration injury limit of 130 g at 118 g and may not suffer potential injuries, whereas the HBM crosses the limit at 210 g and may suffer injuries.
**Viscous Criterion**

From Figure 6.22, it can be seen that the viscous criterion for models in the mid-size sedan IIHS MDB side-impact test was 1.5 m/s for the ES-2re dummy and 1.6 m/s for the human body model, which indicates possible injuries to both occupants.

![Graph showing viscous criterion comparison](image)

**Figure 6.22. Comparison of viscous criterion for ES-2re dummy and HBM model in mid-size sedan without seatbelt in IIHS MDB side-impact test using PSM method**

**Thorax Trauma Index**

Using the TTI formula, the thorax trauma index for models in the mid-size sedan IIHS MDB side-impact test was calculated by considering the age and mass of the occupant models. According to IIHS regulations TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. TTI was obtained as 123 g for the ES-2re dummy and 67 g for the HBM, which indicates very serious injuries to the ES-2re dummy. The human body model behaved normally and is within the PSM simulation limit.
6.2 Small-Size Compact Car

The NCAC finite element models from the NHTSA were used to model the Toyota Yaris small-size compact car side-impact test setup [44]. The IIHS moving deformable barrier used in this study was acquired from NHTSA database [44]. In order to study the dummy and human body model responses, the IIHS side-impact protocol was used to model the entire test setup.

6.2.1 Finite Element Simulation

The MDB replicates an SUV, and when a side impact occurs the occupant might end up hitting the barrier. The entire setup was performed using LS-DYNA PrePost. The Toyota Yaris model was placed in a stationary position while the MDB was positioned at the vehicle model to strike the stationary vehicle model at a speed of 31.06 mph according to the IIHS side-impact protocol. The entire IIHS MDB setup was shown in Figure 6.23. The MDB was positioned at certain place by measuring the wheelbase accoeding to IIHS side impact protocol [14]. Contacts were defined between the vehicle model and the MDB using the keyword manager from LS-DYNA. Figure 6.24 illustrates the crash test simulation results.

Figure 6.23. FE model setup of Toyota Yaris small-size compact car and IIHS moving deformable barrier
In IIHS MDB side impact test, the MDB wheels are aligned straight in the direction perpendicular to the stationary car. The MDB travels at a speed of 31.06 mph and hits the stationary car as shown in Figure 6.24. The Y-acceleration pulse of the driver seat node are shown in Figure 6.25. This pulse was further utilized as input for the MADYMO side-impact sled tests. Intrusions of the vehicle’s B-pillar were measured to check the effect of the moving deformable barrier on the vehicle. An intrusion of 218.3 mm was measured after the crash with the MDB. Figure 6.26 illustrates before and after crash results of the vehicle B-pillar. Figure 6.27 shows the crash profile of Toyota Yaris small-size compact car, before and after IIHS MDB test.
Figure 6.25. Dynamic response of small-size compact car driver seat Y-acceleration from LS-DYNA IIHS MDB side-impact crash test

Figure 6.26. Intrusion of small-size compact car B-pillar: (a) before crash and (b) after crash in the IIHS MDB side-impact test

Figure 6.27. Crash profile of small-size compact car: (a) before and (b) after IIHS MDB side-impact test
6.2.2 ES-2re Dummy Responses

The acceleration pulse acquired from the driver seat was applied as input for the MADYMO sled test. The acceleration was applied to the ES-2re dummy in a lateral direction so that the occupant impacted the sled. All contacts were defined between the dummy and vehicle sled system as CONTACT.MB_MB. A seatbelt restraint system was also added to the vehicle to study the dummy response with a seatbelt. Figures 6.28 and 6.29 illustrate the simulation of a dummy impacting a rigid sled in the lateral direction without and with a restraint system. The shoulder belt slipped onto the dummy, while the lap belt kept the dummy in the seat, and the dummy moved in the lateral direction, impacting its torso with the sled.

Figure 6.28. ES-2re dummy responses in small-size compact car without seatbelt in IIHS MDB side-impact test

Figure 6.29. ES-2re dummy responses in small-size compact car with seatbelt in IIHS MDB side-impact test
6.2.3 Human Body Model Responses

The human body model was seated on the rigid seat with arms raised to expose the thorax region to the rigid sled. The acceleration pulse was applied to the human body model to impact with the sled laterally. Since the HBM was designed with both rigid and flexible bodies, it behaved realistically when the body moved towards the sled. Figures 6.30 and 6.31 depict the human body model response in a side-impact scenario without and with a seatbelt. All contacts between the HBM and vehicle system were defined as CONTACT.MB_FE, and the skin of the facet human body model was modeled with finite elements. It was also important to define certain parts of the human body model as GROUP_FE, particularly when defining the contact between the HBM skin and the seatbelt.

![Figure 6.30](image-url)

Figure 6.30. Human body model responses in small-size compact car without seatbelt in IIHS MDB side-impact test

![Figure 6.31](image-url)

Figure 6.31. Human body model responses in small-size compact car with seatbelt in IIHS MDB side-impact test
6.2.4 Comparison of Results

Rib Deflection

Rib deflection results for models in the small-size compact car IIHS MDB side-impact test are plotted in Figures 6.32 and 6.33. Peak rib deflection for the ES-2re dummy without a seatbelt attained a value of 44 mm, which is considered marginally acceptable according to the IIHS side-impact protocol. Rib deflection for the human body model was 55 mm, which is between marginal and poor.

When a seatbelt was added to the system, peak values increased. For the ES-2re dummy, the peak value was 46 mm, which is between marginal and poor, according to IIHS side-impact criteria. For the human body model, the peak value was 64 mm, which is considered poor. Therefore, both models potentially suffer injuries.

Figure 6.32. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test
Figure 6.33. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test

**Head Injury Criterion**

Figures 6.34 and 6.35 represent the head acceleration values obtained for models in the small-size compact car IIHS MDB side-impact test. Peak values without the seatbelt were 870 g for the ES-2re dummy and 340 g for human body model. On other hand, peak values with the seatbelt were 920 g for the ES-2re dummy and 320 g for the HBM.

Figure 6.34. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test
Figure 6.35. Comparison of head injury criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test

Without the seatbelt, HIC values were 191 for the ES-2re dummy and 177 for the human body model. With the seatbelt, HIC values were 194 for the ES-2re dummy and 175 for the HBM. In both the cases, the values did not exceed the injury limit. Therefore, there were no potential injuries to the occupants.

**Pelvic Acceleration**

Pelvic acceleration values obtained for models in the small-size compact car IIHS MDB side-impact test, shown in Figures 6.36 and 6.37, predict injuries to the human body model when there is no restraint system. The peak value for the ES-2re dummy without a seatbelt was 90 g, and when the seatbelt was added, this was reduced to 64 g. The peak value for the HBM was about 230 g, which exceeded the injury limit. But when a seatbelt was added, this value was reduced to 86 g, meaning the seatbelts were efficient enough to protect the occupant.
Figure 6.36. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test

Figure 6.37. Comparison of pelvic acceleration for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test
Viscous Criterion

From Figure 6.38, for models in the small-size compact car IIHS MDB side-impact test, it can be seen that without the seatbelt, the viscous criterion obtained for both occupant models was 0.83 m/s for the ES-2re dummy and 0.7 m/s for the human body model, thus indicating no potential injuries. From Figure 6.39, with the seatbelt, the viscous criterion obtained for both models was 0.8 m/s for the ES-2re dummy and 0.68 m/s for the HBM, which also indicates no potential injuries.

![Graph showing comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test](image)

Figure 6.38. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test

Both figures show that the curves are in a best fit for both scenarios for both models. In both cases, the VC values are low and there are no potential injuries. In case of without seatbelt, ES-2re dummy showed higher values than the dummy and in case of with seatbelt, the human body model showed slightly higher values than the human body model and. From the plots, human body model showed sensitivity by an early rise in VC values.
Figure 6.39. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car with seatbelt in IIHS MDB side-impact test

Thorax Trauma Index

The TTI for the ES-2re dummy and human body model in the small-size compact car IIHS MDB side-impact test was calculated using the standard formula, and the values are tabulated in Table 6.2. All values were under the injury limit, and after adding a seatbelt to the system, they were reduced. In both the cases, the occupant is safe and protected.

<table>
<thead>
<tr>
<th>Occupant Model</th>
<th>TTI (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2re without seatbelt</td>
<td>85</td>
</tr>
<tr>
<td>ES-2re with seatbelt</td>
<td>44</td>
</tr>
<tr>
<td>Human body model without seatbelt</td>
<td>54</td>
</tr>
<tr>
<td>Human body model with seatbelt</td>
<td>49</td>
</tr>
</tbody>
</table>
6.2.5 PSM Results

Prescribed structural motion was applied to the trimmed side-door panel of the Toyota Yaris small car. Figure 6.40 shows the ES-2re dummy and HBM responses using the PSM method.

<table>
<thead>
<tr>
<th>ES-2re Dummy</th>
<th>Human Body Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 0 msec</td>
<td>t = 0 msec</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 25 msec</td>
<td>t = 25 msec</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 50 msec</td>
<td>t = 50 msec</td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>t = 75 msec</td>
<td>t = 75 msec</td>
</tr>
</tbody>
</table>

Figure 6.40. Toyota Yaris small-size compact car without seatbelt ES-2re dummy and HBM responses in IIHS MDB side-impact test using PSM method
Rib Deflection

Rib deflection results were obtained from the occupant models in the small-size compact car IIHS MDB test using the PSM method, and from Figure 6.41, it can be seen that rib deflection for the ES-2re dummy is within the limits, whereas rib deflection for the human body model has crossed the limits of 44 mm. The maximum values obtained were 38 mm for the ES-2re dummy and 83 mm for the HBM. From this plot, the human body model crossed the injury limit and may suffer serious injuries.

![Figure 6.41. Comparison of rib deflection for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test using PSM method](image)

Head Injury Criterion

The head accelerations from the occupant models in the small-size compact car IIHS MDB side-impact test using the PSM method were small in value because there was no physical contact between the occupant head and the car door panel, as shown previously in the Figure 6.40. From Figure 6.42, it can be seen that the head acceleration reached 597 g for the ES-2re dummy and 194 g for the human body model. HIC values observed are 169 for ES-2re and 179, These values are under the HIC limits, and there are no potential head injuries.
Pelvis Acceleration

Pelvic accelerations for occupant models in the small-size compact car IIHS MDB side-impact test are plotted in Figure 6.43. As shown, the ES-2re dummy is near the pelvic acceleration injury limit and may suffer injuries, whereas the human body model crosses the limit of 130 g and may suffer serious injuries. The maximum values observed are 128 g for the ES-2re dummy and 240 g for the HBM.
Viscous Criterion

Figure 6.44 shows that the viscous criterion obtained for both models in the small-size compact car IIHS MDB side-impact test are 0.7 m/s for the ES-2re dummy and 2.3 m/s for the human body model. The ES-2re dummy VC was less than the injury limit and may not suffer injuries, whereas the HBM exceeded the injury limit of 1.0 m/s and may suffer potential injuries.

Figure 6.44. Comparison of viscous criterion for ES-2re dummy and HBM in small-size compact car without seatbelt in IIHS MDB side-impact test using PSM method

Thorax Trauma Index

Using the TTI formula, the thorax trauma index was calculated by considering the age and mass of the occupant models. According to IIHS regulations, the TTI should not exceed 85 g for four-door passenger vehicles and 90 g for two-door passenger vehicles. The TTI was 133 g for the ES-2re dummy and 151 g for the human body model, which indicates very serious injuries to both model occupants.
CHAPTER 7

OVERALL COMPARISON OF DUMMY AND HUMAN BODY MODEL
SIDE-ImpACT RESULTS

7.1 Comparison for Occupants of Mid-Size Sedan (Ford Taurus)

In the FMVSS 214 moving deformable barrier test, both the ES-2re dummy and human body model exhibited same kind of dynamic behavior in the simulations. Head injury was not a problem in this scenario as the head injury criterion values were under the injury limit of 1000. Rib deflection responses were high in this test, with most of the values exceeding the injury limit of 44 mm. Pelvis acceleration values were within the limit, except for the case of the HBM without a seatbelt. Following rib deflection, the viscous criterion and thorax trauma index values predicted the possibility of occupant fatalities. Results from the prescribed structural motion (PSM) simulations seem to be in good agreement with the regular sled tests.

In the FMVSS 214 rigid pole test, the ES-2re dummy without a seatbelt had a good set of values in terms of injury criteria. Rib deflection values were slightly higher than the injury criteria but very near the injury limit. Pelvic acceleration values were within good limits, except for the HBM without a seatbelt. TTI values were high in case of PSM method because the car panel hit the rigid pole. Compared to other regulations, the IIHS MDB tests indicated that injury responses were within good limits, with all values in the acceptable range except for PSM method values.

The pelvic accelerations and viscous criterion were reduced when a seatbelt was added to the system. Rib deflection and TTI values increased due to the restraining action of the seatbelt on the chest along with the side-impact forces. Table 7.1 summarizes the overall FMVSS 214 and IIHS side-impact test results from the simulations for a typical mid-size sedan. The values shown in red indicate that they are above the test limits.
## TABLE 7.1

**COMPARISON OF OVERALL TEST RESULTS—MID-SIZE SEDAN**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Test</th>
<th>HIC36</th>
<th>Rib Defl (mm)</th>
<th>Pelvic Acc (g)</th>
<th>TTI (g)</th>
<th>VC (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Limits</strong></td>
<td>1000</td>
<td>44</td>
<td>130</td>
<td>85</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>FMVSS 214 MDB Test</td>
<td>ES-2re dummy without belt</td>
<td>216</td>
<td>49</td>
<td>113</td>
<td>121</td>
</tr>
<tr>
<td>3</td>
<td>FMVSS 214 MDB Test</td>
<td>HBM without belt</td>
<td>186</td>
<td>63</td>
<td>126</td>
<td>76</td>
</tr>
<tr>
<td>4</td>
<td>FMVSS 214 MDB Test</td>
<td>ES-2re dummy with belt</td>
<td>214</td>
<td>53</td>
<td>73</td>
<td>132</td>
</tr>
<tr>
<td>5</td>
<td>FMVSS 214 MDB Test</td>
<td>HBM with belt</td>
<td>185</td>
<td>69</td>
<td>112</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>FMVSS 214 MDB Test</td>
<td>PSM-ES-2re dummy without belt</td>
<td>170</td>
<td>51</td>
<td>155</td>
<td>133</td>
</tr>
<tr>
<td>7</td>
<td>FMVSS 214 MDB Test</td>
<td>PSM-HBM without belt</td>
<td>170</td>
<td>38</td>
<td>225</td>
<td>95</td>
</tr>
<tr>
<td>8</td>
<td>FMVSS 214 Rigid Pole Test</td>
<td>ES-2re dummy without belt</td>
<td>188</td>
<td>42</td>
<td>85</td>
<td>57</td>
</tr>
<tr>
<td>9</td>
<td>FMVSS 214 Rigid Pole Test</td>
<td>HBM without belt</td>
<td>175</td>
<td>54</td>
<td>190</td>
<td>76</td>
</tr>
<tr>
<td>10</td>
<td>FMVSS 214 Rigid Pole Test</td>
<td>ES-2re dummy with belt</td>
<td>189</td>
<td>42</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>11</td>
<td>FMVSS 214 Rigid Pole Test</td>
<td>HBM with belt</td>
<td>174</td>
<td>65</td>
<td>85</td>
<td>64</td>
</tr>
<tr>
<td>12</td>
<td>FMVSS 214 Rigid Pole Test</td>
<td>PSM-ES-2re dummy without belt</td>
<td>199</td>
<td>53</td>
<td>92</td>
<td>158</td>
</tr>
<tr>
<td>13</td>
<td>IIHS MDB Test</td>
<td>ES-2re without belt</td>
<td>177</td>
<td>39</td>
<td>71</td>
<td>56</td>
</tr>
<tr>
<td>14</td>
<td>IIHS MDB Test</td>
<td>HBM without belt</td>
<td>170</td>
<td>49</td>
<td>109</td>
<td>49</td>
</tr>
<tr>
<td>15</td>
<td>IIHS MDB Test</td>
<td>ES-2re with belt</td>
<td>183</td>
<td>38</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>16</td>
<td>IIHS MDB Test</td>
<td>HBM with belt</td>
<td>169</td>
<td>57</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>17</td>
<td>IIHS MDB Test</td>
<td>PSM-ES-2re without belt</td>
<td>171</td>
<td>48</td>
<td>118</td>
<td>123</td>
</tr>
<tr>
<td>18</td>
<td>IIHS MDB Test</td>
<td>PSM-HBM without belt</td>
<td>167</td>
<td>28</td>
<td>210</td>
<td>67</td>
</tr>
</tbody>
</table>
7.2 Comparison for Occupants of Small-Size Compact Car (Toyota Yaris)

For the small-size compact car, the head injury criterion values were under the limit, indicating no risk of head injuries.

In the FMVSS 214 moving deformable barrier side-impact test, the human body model exhibited higher rib deflection and pelvic acceleration values than the ES-2re dummy. TTI and viscous criterion values were higher for the ES-2re dummy but very near the injury limit. When a belt system was added to the system, rib deflection values increased while pelvic acceleration values decreased. With the PSM method, the HBM exhibited extremely higher pelvic acceleration values, and the ES-2re dummy also produced higher pelvic accelerations. The TTI calculated was higher with the PSM method in comparison to the sled tests.

In the FMVSS 214 rigid pole test, rib deflections and pelvic acceleration values were high for the HBM without a seatbelt. For the ES-2re dummy, the values were high for pelvic acceleration, and all other values were in the same approximate range. With the PSM method, both occupant models had lower values and therefore might suffer injuries due to the higher TTI values. When a seatbelt was added to the system, all the injury parameters were reduced.

In the IIHS moving deformable barrier test, rib deflections were higher for both occupant models. The human body model not restrained by a seatbelt suffered higher values in terms of pelvic accelerations. When a belt was added to the setup, all parameters were reduced, except for the rib deflections. With the PSM method, the ES-2re dummy exhibited lower values under the injury limits, but the HBM showed higher injury values. The calculated viscous criterion was uniform throughout all the regulation standards. The TTI values obtained with the PSM method were high in value throughout all regulations. Table 7.2 summarizes the overall FMVSS 214 and IIHS side-impact test results for a small-size compact car.
**TABLE 7.2**

**COMPARISON OF OVERALL TEST RESULTS—SMALL-SIZE COMPACT CAR**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Test</th>
<th>HIC36</th>
<th>Rib Defl (mm)</th>
<th>Pelvic Acc (g)</th>
<th>TTI (g)</th>
<th>VC (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limits</td>
<td>1000</td>
<td>44</td>
<td>130</td>
<td>85</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>FMVSS 214 MDB Test ES-2re dummy without belt</td>
<td>192</td>
<td>45</td>
<td>92</td>
<td>89</td>
<td>0.91</td>
</tr>
<tr>
<td>20</td>
<td>FMVSS 214 MDB Test HBM without belt</td>
<td>177</td>
<td>57</td>
<td>221</td>
<td>59</td>
<td>0.77</td>
</tr>
<tr>
<td>21</td>
<td>FMVSS 214 MDB Test ES-2re dummy with belt</td>
<td>197</td>
<td>49</td>
<td>68</td>
<td>42</td>
<td>0.9</td>
</tr>
<tr>
<td>22</td>
<td>FMVSS 214 MDB Test HBM with belt</td>
<td>176</td>
<td>68</td>
<td>87</td>
<td>45</td>
<td>0.74</td>
</tr>
<tr>
<td>23</td>
<td>FMVSS 214 MDB Test PSM-ES-2re without belt</td>
<td>168</td>
<td>32</td>
<td>210</td>
<td>172</td>
<td>0.65</td>
</tr>
<tr>
<td>24</td>
<td>FMVSS 214 MDB Test PSM-HBM without belt</td>
<td>176</td>
<td>47</td>
<td>340</td>
<td>196</td>
<td>0.9</td>
</tr>
<tr>
<td>25</td>
<td>FMVSS 214 Rigid Pole Test ES-2re dummy without belt</td>
<td>188</td>
<td>43</td>
<td>85</td>
<td>89</td>
<td>0.7</td>
</tr>
<tr>
<td>26</td>
<td>FMVSS 214 Rigid Pole Test HBM without belt</td>
<td>176</td>
<td>51</td>
<td>240</td>
<td>59</td>
<td>0.63</td>
</tr>
<tr>
<td>27</td>
<td>FMVSS 214 Rigid Pole Test ES-2re dummy with belt</td>
<td>193</td>
<td>46</td>
<td>62</td>
<td>42</td>
<td>0.77</td>
</tr>
<tr>
<td>28</td>
<td>FMVSS 214 Rigid Pole Test HBM with belt</td>
<td>175</td>
<td>66</td>
<td>68</td>
<td>45</td>
<td>0.67</td>
</tr>
<tr>
<td>29</td>
<td>FMVSS 214 Rigid Pole Test PSM-ES-2re dummy without belt</td>
<td>169</td>
<td>25</td>
<td>127</td>
<td>178</td>
<td>0.38</td>
</tr>
<tr>
<td>30</td>
<td>FMVSS 214 Rigid Pole Test PSM-HBM without belt</td>
<td>195</td>
<td>31</td>
<td>346</td>
<td>162</td>
<td>0.6</td>
</tr>
<tr>
<td>31</td>
<td>IIHS MDB Test ES-2re without belt</td>
<td>191</td>
<td>44</td>
<td>90</td>
<td>85</td>
<td>0.83</td>
</tr>
<tr>
<td>32</td>
<td>IIHS MDB Test HBM without belt</td>
<td>177</td>
<td>55</td>
<td>230</td>
<td>54</td>
<td>0.7</td>
</tr>
<tr>
<td>33</td>
<td>IIHS MDB Test ES-2re with belt</td>
<td>194</td>
<td>46</td>
<td>64</td>
<td>44</td>
<td>0.82</td>
</tr>
<tr>
<td>34</td>
<td>IIHS MDB Test HBM with belt</td>
<td>175</td>
<td>64</td>
<td>86</td>
<td>49</td>
<td>0.68</td>
</tr>
<tr>
<td>35</td>
<td>IIHS MDB Test PSM-ES-2re without belt</td>
<td>169</td>
<td>38</td>
<td>128</td>
<td>133</td>
<td>0.7</td>
</tr>
<tr>
<td>36</td>
<td>IIHS MDB Test PSM-HBM without belt</td>
<td>179</td>
<td>83</td>
<td>240</td>
<td>151</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Table 7.3 summarizes the FMVSS 214 MDB test overall results comparison for a mid-size sedan (Ford Taurus) and small-size compact car (Toyota Yaris).

**Table 7.3**

**COMPARISON OF FMVSS 214 MDB OVERALL TEST RESULTS—MID-SIZE SEDAN VS SMALL-SIZE COMPACT CAR**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Test</th>
<th>HIC36</th>
<th>Rib Defl (mm)</th>
<th>Pelvis Acc (g)</th>
<th>TTI (g)</th>
<th>VC (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Limits →</strong></td>
<td>1000</td>
<td>44</td>
<td>130</td>
<td>85</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>Taurus FMVSS 214 MDB Test ES-2re dummy without belt</td>
<td>216</td>
<td>49</td>
<td>113</td>
<td>121</td>
<td>1.41</td>
</tr>
<tr>
<td>2</td>
<td>Yaris FMVSS 214 MDB Test ES-2re dummy without belt</td>
<td>192</td>
<td>45</td>
<td>92</td>
<td>89</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>Taurus FMVSS 214 MDB Test ES-2re dummy with belt</td>
<td>214</td>
<td>53</td>
<td>73</td>
<td>132</td>
<td>1.17</td>
</tr>
<tr>
<td>4</td>
<td>Yaris FMVSS 214 MDB Test ES-2re dummy with belt</td>
<td>197</td>
<td>49</td>
<td>68</td>
<td>42</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>Taurus FMVSS 214 MDB Test HBM without belt</td>
<td>186</td>
<td>63</td>
<td>126</td>
<td>76</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>Yaris FMVSS 214 MDB Test HBM without belt</td>
<td>177</td>
<td>57</td>
<td>221</td>
<td>59</td>
<td>0.77</td>
</tr>
<tr>
<td>7</td>
<td>Taurus FMVSS 214 MDB Test HBM with belt</td>
<td>185</td>
<td>69</td>
<td>112</td>
<td>100</td>
<td>1.09</td>
</tr>
<tr>
<td>8</td>
<td>Yaris FMVSS 214 MDB Test HBM with belt</td>
<td>176</td>
<td>68</td>
<td>87</td>
<td>45</td>
<td>0.74</td>
</tr>
<tr>
<td>9</td>
<td>Taurus FMVSS 214 MDB Test PSM-ES-2re dummy without belt</td>
<td>170</td>
<td>51</td>
<td>155</td>
<td>133</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>Yaris FMVSS 214 MDB Test PSM-ES-2re dummy without belt</td>
<td>168</td>
<td>32</td>
<td>210</td>
<td>172</td>
<td>0.65</td>
</tr>
<tr>
<td>11</td>
<td>Taurus FMVSS 214 MDB Test PSM-HBM without belt</td>
<td>170</td>
<td>38</td>
<td>225</td>
<td>95</td>
<td>1.4</td>
</tr>
<tr>
<td>12</td>
<td>Yaris FMVSS 214 MDB Test PSM-HBM without belt</td>
<td>176</td>
<td>47</td>
<td>340</td>
<td>196</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Table 7.4 summarizes the FMVSS 214 rigid pole test overall results comparison of a mid-size sedan (Ford Taurus) and small-size compact car (Toyota Yaris).

TABLE 7.4

COMPARISON OF FMVSS 214 RIGID POLE SIDE-IMPACT TEST RESULTS—MID-SIZE SEDAN VS SMALL-SIZE COMPACT CAR

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Test</th>
<th>HIC36</th>
<th>Rib Defl (mm)</th>
<th>Pelvis Acc (g)</th>
<th>TTI (g)</th>
<th>VC (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Limits</strong></td>
<td>1000</td>
<td>44</td>
<td>130</td>
<td>85</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>Taurus FMVSS 214 Rigid Pole Test ES-2re dummy without belt</td>
<td>188</td>
<td>42</td>
<td>85</td>
<td>57</td>
<td>0.72</td>
</tr>
<tr>
<td>2</td>
<td>Yaris FMVSS 214 Rigid Pole Test ES-2re dummy without belt</td>
<td>188</td>
<td>43</td>
<td>85</td>
<td>89</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Taurus FMVSS 214 Rigid Pole Test ES-2re dummy with belt</td>
<td>189</td>
<td>42</td>
<td>60</td>
<td>55</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>Yaris FMVSS 214 Rigid Pole Test ES-2re dummy with belt</td>
<td>193</td>
<td>46</td>
<td>62</td>
<td>42</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td><strong>Limits</strong></td>
<td>175</td>
<td>54</td>
<td>190</td>
<td>76</td>
<td>0.68</td>
</tr>
<tr>
<td>5</td>
<td>Taurus FMVSS 214 Rigid Pole Test HBM without belt</td>
<td>176</td>
<td>51</td>
<td>240</td>
<td>59</td>
<td>0.63</td>
</tr>
<tr>
<td>6</td>
<td>Yaris FMVSS 214 Rigid Pole Test HBM without belt</td>
<td>174</td>
<td>65</td>
<td>85</td>
<td>64</td>
<td>0.64</td>
</tr>
<tr>
<td>7</td>
<td>Taurus FMVSS 214 Rigid Pole Test HBM with belt</td>
<td>175</td>
<td>66</td>
<td>68</td>
<td>45</td>
<td>0.67</td>
</tr>
<tr>
<td>8</td>
<td>Yaris FMVSS 214 Rigid Pole Test HBM with belt</td>
<td>199</td>
<td>53</td>
<td>92</td>
<td>158</td>
<td>0.8</td>
</tr>
<tr>
<td>9</td>
<td>Taurus FMVSS 214 Rigid Pole Test PSM-ES-2re dummy without belt</td>
<td>169</td>
<td>25</td>
<td>127</td>
<td>178</td>
<td>0.38</td>
</tr>
<tr>
<td>10</td>
<td>Yaris FMVSS 214 Rigid Pole Test PSM-ES-2re dummy without belt</td>
<td>189</td>
<td>28</td>
<td>158</td>
<td>106</td>
<td>0.2</td>
</tr>
<tr>
<td>11</td>
<td>Taurus FMVSS 214 Rigid Pole Test PSM-HBM without belt</td>
<td>195</td>
<td>31</td>
<td>346</td>
<td>162</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Table 7.5 summarizes the IIHS MDB test overall results comparison of a mid-size sedan (Ford Taurus) and a small-size compact car (Toyota Yaris).

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Test</th>
<th>HIC36</th>
<th>Rib Defl (mm)</th>
<th>Pelvis Acc(g)</th>
<th>TTI (g)</th>
<th>VC (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Taurus IIHS MDB Test ES-2re dummy without belt</td>
<td></td>
<td>177</td>
<td>39</td>
<td>71</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>Yaris IIHS MDB Test ES-2re dummy without belt</td>
<td></td>
<td>191</td>
<td>44</td>
<td>90</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>Taurus IIHS MDB Test ES-2re dummy with belt</td>
<td></td>
<td>183</td>
<td>38</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Yaris IIHS MDB Test ES-2re dummy with belt</td>
<td></td>
<td>194</td>
<td>46</td>
<td>64</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Taurus IIHS MDB Test HBM without belt</td>
<td></td>
<td>170</td>
<td>49</td>
<td>109</td>
<td>49</td>
</tr>
<tr>
<td>6</td>
<td>Yaris IIHS MDB Test HBM without belt</td>
<td></td>
<td>177</td>
<td>55</td>
<td>230</td>
<td>54</td>
</tr>
<tr>
<td>7</td>
<td>Taurus IIHS MDB Test HBM with belt</td>
<td></td>
<td>169</td>
<td>57</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>8</td>
<td>Yaris IIHS MDB Test HBM with belt</td>
<td></td>
<td>175</td>
<td>64</td>
<td>86</td>
<td>49</td>
</tr>
<tr>
<td>9</td>
<td>Taurus IIHS MDB Test PSM-ES-2re dummy without belt</td>
<td></td>
<td>171</td>
<td>48</td>
<td>118</td>
<td>123</td>
</tr>
<tr>
<td>10</td>
<td>Yaris IIHS MDB Test PSM-ES-2re dummy without belt</td>
<td></td>
<td>169</td>
<td>38</td>
<td>128</td>
<td>133</td>
</tr>
<tr>
<td>11</td>
<td>Taurus IIHS MDB Test PSM-HBM without belt</td>
<td></td>
<td>167</td>
<td>28</td>
<td>210</td>
<td>67</td>
</tr>
<tr>
<td>12</td>
<td>Yaris IIHS MDB Test PSM-HBM without belt</td>
<td></td>
<td>179</td>
<td>83</td>
<td>240</td>
<td>151</td>
</tr>
</tbody>
</table>
CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In this study, a computational methodology was utilized and implemented to examine the dynamic behavior of an ES-2re dummy and a human body model in different side-impact crash test regulations. The FMVSS 214 moving deformable barrier test, FMVSS 214 rigid pole test, and the IIHS side-impact protocol, test conditions were modeled and applied to finite element car models using the nonlinear FE software LS-DYNA. The acceleration pulses were acquired from the driver seat, which were further utilized to study the occupant kinematics and injury potential using MADYMO software. A vehicle interior model from the MADYMO database was used and a rigid side wall was added to the interior model as a side-door panel. Using the vehicle interior model, regulatory sled test simulations were conducted using the ES-2re dummy and HBM. A prescribed structural motion technique was successfully implemented to the side-door panel to study the dynamic behavior of both models in an actual crash scenario. The near side-door panels were modeled in MADYMO using the same FE car models that were used in LS-DYNA.

This study was performed to understand the dynamic responses and injury mechanisms of the ES-2re dummy and the human body model in side-impact crash scenarios. To understand the injury mechanisms, a list of injury or performance criteria including the head injury criterion, rib deflection, pelvis acceleration, thorax trauma index, and viscous criteria were used for all simulations based on various test criteria. A typical mid-size sedan (Ford Taurus) and a small-size compact car (Toyota Yaris) were used to understand and quantify the injuries for occupants in different-sized cars.
From the sled tests and PSM test simulations, it was found that typically no head injuries occurred because the HIC36 values all fell below the injury limit of 1000 for both the ES-2re dummy and the HBM. From the simulations, it was observed that before the head struck the sled side-door panel, the thorax impacted it first, taking all the impact forces from the sled. In the PSM simulations, no contact between the head and door panel was observed.

The chest injury criteria were evaluated by measuring the maximum rib deflection in the occupant model. Most of the time, the rib deflection measured exceeded the injury limit of 44 mm for both cars and both occupant models. The rib extension mechanism in the ES-2re dummy helped to accurately measure the rib deflection, while the rib complex in the HBM was somewhat simpler. The maximum rib deflection of all the ribs was considered for the human body model.

The pelvic injury was assessed and calculated using pelvis acceleration with an injury limit of 130 g. From the simulations and pelvic acceleration results, it was found that the pelvis of the occupant model contacted the side-door panel at a high magnitude of compression loads. Pelvic accelerations from the PSM simulations were found to be higher in magnitude because there was no restraint system to keep the occupant model in the driver seat. It was observed that when the HBM impacted the sled, it exhibited more flexibility and behaved in a manner that was more human-like. The pelvis of the human body model was connected through the spine elements and had several degrees of freedom as in human. When a seatbelt was added to the system, the pelvic acceleration was further reduced.

The thorax trauma is the leading cause of fatalities in side-impact crashes. In the simulations, the major portion of the body that made contact with the intruding structure was the thorax. The thorax trauma index was used to evaluate injuries in this region. It was found that both the ES-2re dummy and the HBM exhibited larger TTI values when there was no restraint system.
In both the regular sled tests and the PSM simulations, the ES-2re dummy showed higher TTI values than the HBM.

To examine additional chest injuries, the viscous criterion with an injury limit of 1.0 m/s was also considered. In this study, the viscous criterion was found to be uniform and less than 1.0 m/s in almost all simulations. The VC exceeded the injury limit when the occupant was in a mid-size sedan vehicle. When the occupant models were compared, the ES-2re dummy exceeded the injury limit most often.

Overall, the following conclusions can be made from this study:

- The TTI and VC calculations were not uniform throughout the study. The impact of the head on side door was not as severe since the shoulder and rib cage took most of the crash energy before the head impacted the door. It was observed that the ES-2re multi-body dummy exhibited larger acceleration values than the FE human body model.

- Since the human body model has a very limited number of parts compared to the ES-2re dummy model, the results were quite sensitive but followed a trend. Overall this study shows that the human body model can be applied to all other crash scenarios.

- For the FMVSS 214 MDB size-impact test, the human body model showed 20–30% higher values in rib deflection, 10–20% higher values in pelvic acceleration, 10–15% higher values in viscous criterion, and 20–30% higher values in TTI, in comparison to those of the ES-2re dummy.

- For the FMVSS 214 rigid pole side-impact test, the human body model showed 20–40% higher values in rib deflection, 30–50% higher values in pelvic acceleration, and 5–10% higher values in viscous criterion, 20–30% in TTI, in comparison to those of the ES-2re dummy.
• For the IIHS test, the human body model showed 20–40% higher values in rib deflection, 30–50% higher values in pelvic acceleration, 5–10% higher values in viscous criterion, and 20–30% higher values in TTI, in comparison to those of the ES-2re dummy.

• When a seatbelt was used, the difference between the the ES-2re dummy and the human body model injury criteria increased by up to 5–10%.

Overall the HBM behaved similarly to the ES-2re dummy in terms of the kinematic responses. However, the injury performance values for the ES-2re dummy and the HBM indicated that the human body model could exhibit up to 20–30% higher values than those of the ES-2re dummy. This means that the regulatory side-impact test results with ES-2re dummies must be observed with care, because an actual human might experience higher injury-producing loads. This study also demonstrates that the human body model can be applied to other crash scenarios as well.

8.2 **Recommendations**

This study could be extended to future research areas in the following ways:

• More research must be done and more simulations must be conducted using human body models in order to make the HBM compatible in all types of crash applications.

• Injury parameters such as the TTI, chest deflection, and HIC could be studied more because the anatomy of the human body model is different from the existing ES-2re dummy model.

• This study could be further extended using the human body model to analyze the response characteristics on the far-side passenger and rear passenger.

• Human body models could be applied to other finite element packages through coupling, and performance characteristics could be checked.

• Using the PSM method, one could experiment with a real-time crash construction in a computer numerical environment.
REFERENCES
REFERENCES


REFERENCES (continued)


REFERENCES (continued)


REFERENCES (continued)


