Development and Validation of a Vehicle Front Profile Finite Element Model to Evaluate Pedestrian Impacts

James Wolf
Marquette University

Follow this and additional works at: https://epublications.marquette.edu/theses_open
Part of the Biomechanics Commons

Recommended Citation
Wolf, James, "Development and Validation of a Vehicle Front Profile Finite Element Model to Evaluate Pedestrian Impacts" (2024). Master's Theses (2009-). 783.
https://epublications.marquette.edu/theses_open/783
DEVELOPMENT AND VALIDATION OF A VEHICLE FRONT PROFILE FINITE ELEMENT MODEL TO EVALUATE PEDESTRIAN IMPACTS

by

James Wolf, B.S.

A Thesis submitted to the Faculty of the Graduate School, Marquette University, in Partial Fulfillment of the Requirements for the Degree of Master of Science

Milwaukee, Wisconsin

May 2024
ABSTRACT

DEVELOPMENT AND VALIDATION OF A VEHICLE FRONT PROFILE FINITE ELEMENT MODEL TO EVALUATE PEDESTRIAN IMPACTS

James Wolf, B.S.
Marquette University, 2024

In 2021, there were nearly 7500 pedestrians killed in traffic crashes in the U.S., the highest since 1981. Since the year 2000, Europe and Japan have adopted pedestrian crash protection programs for vehicles and have seen a decline in pedestrian fatalities; the U.S. has not yet adopted pedestrian crash protection and has seen an increase in pedestrian fatalities in that same time. European New Car Assessment Programme (Euro NCAP) outlines a detailed procedure for evaluations of new vehicles for pedestrian safety through headform, upper legform, and lower legform tests. Euro NCAP also uses generic finite element (FE) front-end vehicle models, representative of different vehicle classes, for safety ratings and analysis of pedestrian kinematics. While these models are useful, they are not always applicable to the U.S., because they represent the European fleet and do not account for variability in stiffness across the hood and bumper. There are no publicly available FE models representative of a U.S. pickup truck/large SUV that are validated from pedestrian injury data. This study aimed to develop a vehicle front profile FE model, representative of a large U.S. vehicle, and validate the model from pedestrian component test data.

Analysis of National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System (FARS) data showed that pickup trucks pose the highest risk factor to pedestrians in the U.S. As a result, an FE model was developed based on the scanned geometry of a 2023 Ford F-150. Material properties from the Euro SUV model were applied to the developed FE model as a baseline. Pedestrian headform, upper legform, and lower legform FE simulations were performed on the model. Model data was validated against experimental test corridors of a Ford F-150 and Chevrolet Tahoe from literature. Model parameters such as thickness, stiffness, and damping were tuned for increased correlation to the experimental test corridors. Correlation and Analysis (CORA) scores improved for all model outputs. A larger experiment sample size would improve model validation. Future studies will be performed using Pedestrian Human body models with the FE vehicle to analyze pedestrian kinematics.
ACKNOWLEDGEMENTS

James Wolf

I would like to thank my parents for their continuous support and encouragement throughout my life. Without them, I would not be where I am today.

I would like to thank my advisor, Dr. Frank Pintar for granting me the opportunity to research in his lab and pursue my interest of biomechanics, as well as his mentorship and guidance throughout this project. I would like to thank Dr. Karthik Somasundaram for his support on this project and for being a great mentor. I am thankful for my committee members, Dr. John Moore, and Dr. Jessica Fritz for their support on this project. I also would like to thank Dale Halloway, Vaibhav Porwal, Balaji Harinathan, and Karthik Devaraj for their willingness to answer questions and assist on this project.

I would like to thank Dr. Brian Stemper and Alok Shah for encouraging collaboration among the graduate students, and for providing me with helpful and constructive feedback on this work. I would like to thank my fellow graduate students Joe LeSueur, Jack Seifert, JJ Wilder, Rachel Cutlan, and Veruschca Labuschagne for their friendship and support, and for creating an enjoyable work environment.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................... i
TABLE OF CONTENTS ............................................................................................................. ii
LIST OF TABLES ....................................................................................................................... iv
LIST OF FIGURES ...................................................................................................................... v

1 BACKGROUND ...................................................................................................................... 1

1.1 Introduction ......................................................................................................................... 1
1.2 U.S. Pedestrian Epidemiology ............................................................................................... 1
1.3 Pedestrian Frequently Injured Body Regions ....................................................................... 6
1.4 Pedestrian Protection Regulations and Procedures ............................................................... 7
1.5 Full-Scale Pedestrian Testing ............................................................................................... 25
  1.5.1 PMHS Tests ................................................................................................................... 25
  1.5.2 Dummy Tests ............................................................................................................... 27
1.6 Pedestrian Component Tests ............................................................................................... 29
  1.6.1 European Vehicle Fleet ............................................................................................... 29
  1.6.2 U.S. Vehicle Fleet ....................................................................................................... 30
1.7 Pedestrian Protection Systems .............................................................................................. 33
  1.7.1 Passive Safety .............................................................................................................. 33
  1.7.2 Active Safety .............................................................................................................. 35
1.8 Finite Element Modeling ..................................................................................................... 36
  1.8.1 Hood and Bumper Modeling ......................................................................................... 36
  1.8.2 Full Vehicle Computational Models ........................................................................... 38
  1.8.3 Euro NCAP Generic Vehicle Models .......................................................................... 39

2 PROBLEM STATEMENT ......................................................................................................... 44

3 AIM 1: VEHICLE RISK EVALUATION ............................................................................... 45

3.1 Data Sorting Methods ......................................................................................................... 45
3.2 Results ................................................................................................................................. 46
3.3 Discussion ............................................................................................................................ 48

4 AIM 2: FINITE ELEMENT MODEL DEVELOPMENT ............................................................. 49

4.1 Vehicle Lidar Scan .............................................................................................................. 49
  4.1.1 Methods and Setup .................................................................................................... 50
4.1.2 Results of Scan

4.2 Modeling Technique

5 AIM 3: FINITE ELEMENT MODEL VALIDATION

5.1 Test Corridor Development

5.1.1 Headform Corridors

5.1.2 Upper Legform Corridors

5.1.3 Lower Legform Corridors

5.2 Finite Element Pedestrian Component Simulations

5.2.1 Methods

5.2.2 Results

5.2.3 Discussion

5.2.4 Limitations

6 APPLICATIONS AND FUTURE WORK

6.1 Human Body Model Simulations

6.1.1 Setup

6.1.2 Results

7 SUMMARY AND CONCLUSIONS

BIBLIOGRAPHY

APPENDICIES

Appendix A: Tuned Material Cards

Appendix B: Experimental Test Corridors

Appendix C: Simulation Setup

Headform Setup

Upper Legform Setup

Lower Legform Setup

Appendix D: Simulation Results

Headform Simulation Results

Upper Legform Simulation Results

Lower Legform Simulation Results
LIST OF TABLES

Table 1-1: AIS Injury Scale. .............................................................................................................. 6
Table 1-2: HIC ranges by color (Euro NCAP, 2018). ................................................................. 14
Table 1-3: Euro NCAP lower legform to bumper test limits (Euro NCAP, 2018) .......... 20
Table 1-4: Upper legform performance limits (Euro NCAP, 2018). ........................................ 25
Table 1-5: Subit et al PMHS details and HIC/WAD results from tests (Subit, 2008). .......... 26
Table 1-6: Schroeder et al PMHS height, weight, and test vehicle (Schroeder, 2008). ... 27
Table 1-7: Color rating for pedestrian tests (Martinez, 2007). .............................................. 30
Table 1-8: Vehicles tested in Suntay et al study. Vehicles with "*" by the name are global vehicles that have European variants (Suntay, 2019). .................................................. 31
Table 1-9: U.S. vehicles closest in comparison to Euro NCAP generic vehicle models. . 40
Table 4-1: Baseline properties of hood, grille, bumper, and spoiler................................. 57
Table 5-1: Lateral hood width and front-end width of Ford F-150 and Chevrolet Tahoe.62
Table 5-2: CORA Rating System (Gehre et al., n.d.). ................................................................. 79
Table 5-3: Material properties altered during model tuning. “X” indicates which properties were changed for the hood and bumper, respectively................................. 79
Table 5-4: Baseline CORA score and rating for headform to “front and rear” hood ...... 81
Table 5-5: Tuned iteration (V1) CORA score and rating for headform to “front and rear” hood.......................................................... 82
Table 5-6: Baseline and tuned hood model properties......................................................... 83
Table 5-7: “Middle” hood headform: Test and tuned model HIC values............................... 85
Table 5-8: “Front and rear” hood headform: Test and tuned model HIC values.............. 87
Table 5-9: Baseline and tuned CORA scores for the “middle” and “front and rear” hood model headform tests................................................... 88
Table 5-10: Baseline and tuned bumper model properties..................................................... 89
Table 5-11: Baseline and tuned CORA scores for the lower legform to bumper tests (Tahoe corridor)......................................................................................... 93
Table 5-12: Baseline and tuned bumper model properties..................................................... 94
Table 5-13: Baseline and tuned CORA scores for upper legform to bumper model tests.97
LIST OF FIGURES

Figure 1-1: Pedestrian fatalities in U.S., EU, and Japan from 2000-2018 (NHTSA, 2023).

Figure 1-2: U.S. Pedestrian Fatalities from 2010-2021 in which the first harmful event was a vehicle collision with a pedestrian (NHTSA 2023).

Figure 1-3: Pedestrian fatalities (A) and injuries (B) in U.S. by travel speed from 2011-2020 (NHTSA, 2023).

Figure 1-4: U.S. average registered vehicles (A) and average vehicle miles driven (B) by vehicle type 2015-2021.

Figure 1-5: Number of vehicles registered each year by vehicle type 2015-2021. Vehicle miles driven each year by vehicle type 2015-2021.

Figure 1-6: Adult headform impactor (A) and child headform impactor (B) (GTR, 2009).

Figure 1-7: Wrap around distance lines (Euro NCAP, 2018).

Figure 1-8: Headform test zones. The left vehicle (A) used the child headform test zone up to 1700 mm, while the right vehicle (B) used the child headform test zone up to the BRRL (Euro NCAP, 2018).

Figure 1-9: Marking the bonnet rear reference line (BRRL) (Euro NCAP, 2018).

Figure 1-10: Headform test grid points (Euro NCAP, 2018).

Figure 1-11: Marking bonnet leading edge (BLE) reference line (Euro NCAP, 2018). Windscreen glazing. The red box represents where head test points will be default green (Euro NCAP, 2018).

Figure 1-12: Aiming point of headform impactor (Euro NCAP, 2018).

Figure 1-13: Lower bumper reference line (Euro NCAP, 2018).

Figure 1-14: Schematic and instrumentation of Flex PLI lower legform impactor. The direction of travel is in the local Y-axis. (UN Regulations NO. 127, 2012).

Figure 1-16: Upper bumper reference line (Euro NCAP, 2018).

Figure 1-17: Bumper corner (Euro NCAP, 2018).

Figure 1-18: JNCAP lower legform test areas (JNCAP, 2019).

Figure 1-19: Advanced Pedestrian Legform Impactor (aPLI) (NHTSA, 2023).

Figure 1-20: Schematic and instrumentation of upper legform impactor (UN Regulations NO. 127, 2012).

Figure 1-21: Marking upper legform and lower legform grid points (Euro NCAP, 2018).

Figure 1-22: Upper legform to WAD 775 mm test (Euro NCAP, 2018).

Figure 1-23: Polar dummy setup with test vehicle (Matsui, 2002).

Figure 1-24: Comparison of dummy (A) and lower legform impactor (B) interaction with SUV. The dummy’s thigh and hip load the vehicle while the lower legform impactor rebounds from the vehicle (Matsui, 2002).

Figure 1-25: Example Euro NCAP vehicle test matrix (Martinez, 2007).

Figure 1-26: 2012 Ford Focus U.S. bumper absorber (A). 2012 Ford Focus EU bumper absorber (B) (Suntay, 2020).
Figure 1-27: Operation of pop-up hood (A). Headform acceleration with a conventional hood and pop-up hood (B) (Inomata, 2007). ................................................................. 34
Figure 1-28: Polar II dummy impact with deployed bonnet air bag (Hamacher, 2011) ................................................................. 34
Figure 1-29: Deployment of bumper air bag (Zhu et al., 2022) ................................................................................................................................. 35
Figure 1-30: Bumper shape influence on pedestrian knee injuries (Yang, 2020). ........................................ 37
Figure 1-31: Sedan front profile (A) and SUV front profile (B) FE models (Gupta, 2015). ................................................................. 39
Figure 1-32: Generic FE vehicle models (Klug, 2017) ................................................................................................................................. 40
Figure 1-33: Median geometry profiles of the Roadster (A), Family Car (B), SUV (C), and MPV (D) (Klug, 2017) ................................................................................................................................. 40
Figure 1-34: Components of Euro NCAP generic FE vehicle model (Klug, 2017) ................................................................................................................................. 41
Figure 1-35: Layers of the generic vehicle models (Klug, 2017) ................................................................................................................................. 42
Figure 1-36: Example of rigid cylindrical impactor tests (Klug, 2017). ................................................................................................................................. 42
Figure 3-1: Average pedestrian fatalities by vehicle body type from 2015-2021 (A). Total number of pedestrian fatalities by vehicle body type from 2015-2021 (B)................................................................................................................................. 47
Figure 3-2: Total fatalities by 4-door sedan models (A). Total fatalities by light truck models (B) ................................................................................................................................. 47
Figure 4-1: Flowchart of FE model development depicting the lidar scan, scan post processing, shell model development, solid model development, model part layers, and full FE model. ................................................................................................................................. 49
Figure 4-2: FARO Focus S lidar scanner ................................................................................................................................. 50
Figure 4-3: Target sphere used during scan ................................................................................................................................. 51
Figure 4-4: Lidar scan locations ................................................................................................................................................................. 52
Figure 4-5: Lidar scan of truck before meshing (A) and after meshing (B) ................................................................................................. 53
Figure 4-6: Shell model developed in Hypermesh ................................................................................................................................. 54
Figure 4-7: Solid shell model developed in Ansa ................................................................................................................................. 55
Figure 4-8: Material layers that make up FE vehicle model from bottom to top, i.e., rear foam is bottom most layer and interface is topmost layer ................................................................................................................................. 55
Figure 4-9: Fu Chang Foam material card to represent the hood foam ................................................................................................................................. 58
Figure 4-10: Fu Chang Foam material card to represent the grille foam ................................................................................................................................. 58
Figure 4-11: Fu Chang Foam material card to represent the bumper foam ................................................................................................................................. 59
Figure 4-12: Fu Chang Foam material card to represent the spoiler foam ................................................................................................................................. 59
Figure 4-13: Piecewise Linear Plasticity material card to represent the hood interface ................................................................................................................................. 60
Figure 4-14: Piecewise Linear Plasticity material card to represent the grille, bumper, and spoiler interfaces ................................................................................................................................. 60
Figure 4-15: Rigid material card to represent the compaction and rear layers of all model parts ................................................................................................................................. 60
Figure 4-16: Full FE vehicle model and its labeled parts ................................................................................................................................. 61
Figure 5-1: Schematic of headform to hood impact. The local z-axis is the direction of headform launch ................................................................................................................................. 64
Figure 5-2: All headform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B) (Suntay, 2019) ................................................................................................................................. 65
Figure 5-3: Headform impact (“A11,8”) to Ford F-150 hood. Note the peak acceleration magnitude occurs beyond 10ms. 66
Figure 5-4: Headform impact locations with an adult (“A”) and child (“C”) headform. The numbers represent the x- and y-coordinates (x,y) of the impact. Red dots represent “middle” hood impacts, and blue dots represent “front and rear” hood impacts. 67
Figure 5-5: Head impact acceleration (g) vs time (ms) test corridors. “Middle” hood corridor (A). "Front and rear" hood corridor (B). The black line is the average acceleration, and the dashed gray lines are the upper and lower bounds. 68
Figure 5-6: Schematic of upper legform test. The local x-axis of the upper legform is in line with the direction of impact. 69
Figure 5-7: Upper legform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B)(Suntay, 2019). 70
Figure 5-8: Upper legform force (kN) vs time (ms) test corridors for the lower load cell (left) and upper load cell (right). The black line is the average acceleration, and the dashed gray lines are the upper and lower bounds. 70
Figure 5-9: Schematic of lower legform test. The local y-axis of the lower legform is in line with the direction of impact. 71
Figure 5-10: Lower legform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B)[27]. 72
Figure 5-11: Lower legform acceleration (g) vs time (ms) corridors. Ford F-150 corridor (A) and Chevrolet Tahoe corridor (B). The black line is the average acceleration, and the dashed gray lines are the upper and lower bounds. 72
Figure 5-12: Example of headform positioning for adult headform impacts “A9,2” (A and C) and child headform impact “C5,0” (B and D). 74
Figure 5-13: LSTC child headform with head accelerometer node (Sommer, 2018). 75
Figure 5-14: Upper legform FE simulation setup for impacts “U,-1” (A) and “U,+7” (B). 76
Figure 5-15: Lower legform FE simulation setup for impacts “L,0” (A) and “L,-5” (B). 77
Figure 5-16: Lower legform node 19356 from which acceleration output was plotted. 78
Figure 5-17: Model parameter tuning flowchart. 80
Figure 5-18: Baseline headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor. 81
Figure 5-19: Tuned iteration (V1) headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor. 82
Figure 5-20: Baseline headform to “middle” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor. 84
Figure 5-21: Tuned headform to “middle” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor. 84
Figure 5-22: Tuned average headform to “middle” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor. ................................................................. 85
Figure 5-23: Baseline headform to “front and rear” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor. ................................................................. 86
Figure 5-24: Tuned headform to “front and rear” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor. ................................................................. 86
Figure 5-25: Tuned average headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor. ................................................................. 86
Figure 5-26: 2023 Ford F-150 (left) and 2016 Chevrolet Tahoe (right) test vehicle. ..................... 87
Figure 5-27: Baseline lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Ford F-150 test corridor. ................................................................. 90
Figure 5-28: Baseline lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor. ................................................................. 90
Figure 5-29: Tuned lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Ford F-150 test corridor. ................................................................. 91
Figure 5-30: Tuned average lower legform to bumper acceleration (g) vs time (ms) output. The red line is the average lower legform model acceleration. The black line and gray dashed lines represent the Ford F-150 test corridor. ................................................................. 91
Figure 5-31: Tuned lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor. ................................................................. 92
Figure 5-32: Tuned average lower legform to bumper acceleration (g) vs time (ms) output. The red line is the average lower legform model acceleration. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor. ................................................................. 92
Figure 5-33: Baseline upper legform to bumper lower load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the lower load cell test corridor. ................................................................. 94
Figure 5-34: Baseline upper legform to bumper upper load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the upper load cell test corridor. ................................................................. 95
Figure 5-35: Tuned upper legform to bumper lower load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the lower load cell test corridor. ................................................................. 95
Figure 5-36: Tuned average upper legform to bumper lower load cell force (kN) vs time (ms) output. The red line is the average upper legform model force. The black line and gray dashed lines are the lower load cell test corridor. ................................................................. 96
Figure 5-37: Tuned upper legform to bumper upper load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the upper load cell test corridor. ................................................................. 96

Figure 5-38: Tuned average upper legform to bumper upper load cell force (kN) vs time (ms) output. The red line is the average upper legform model force. The black line and gray dashed lines are the upper load cell test corridor. ................................................................. 97

Figure 5-39: “C5,0” baseline (A) and tuned (B) child headform to “front and rear” model impact. “A9,2” baseline (C) and tuned (D) adult headform to “middle” hood model impact................................................................. 100

Figure 5-40: Bumper intrusion from “L,0” baseline (A) and tuned (B) lower legform to bumper model. .................................................................................................................................................. 101

Figure 5-41: “L,0” baseline (A and C) and tuned (B and D) lower legform to bumper model.................................................................................................................................................. 101

Figure 5-42: Bumper intrusion from “U,+1” baseline (A) and tuned (B) upper legform to bumper model. .................................................................................................................................................. 102

Figure 5-43: “U,+1” baseline (A and C) and tuned (B and D) upper legform to bumper model.................................................................................................................................................. 103

Figure 6-1: THUMS 50th male model positioning against the FE vehicle model from this study (A and C), and the Euro NCAP generic FE SUV model (B and D). ....................... 106

Figure 6-2: THUMS head contact time on developed model (A) and Euro NCAP SUV model (B). .................................................................................................................................................. 107

Figure 6-3: THUMS interaction with developed model (A) and Euro NCAP SUV model (B) from 0 ms to 120 ms. .................................................................................................................................................. 108
1 BACKGROUND

1.1 Introduction

According to the World Health Organization (WHO) (WHO, 2023), there are approximately 1.19 million fatalities per year as a result of road traffic crashes. More than half of these fatalities are vulnerable road users (VRU’s), such as pedestrians (23%), motorcyclists (21%), cyclists (6%), and e-scooters (3%). Research has indicated that 80% of the world’s roads fail to meet pedestrian safety standards (WHO, 2023). Between 2010 and 2021 pedestrian deaths have risen 3% globally (WHO, 2023). In 2021 the U.S reported its highest number of pedestrian fatalities in 40 years (NHTSA, 2023). Factors such as vehicle speed, vehicle size, location, alcohol, and time of day are all risks that can influence pedestrian fatalities (CDC, 2023). Overall, pedestrian fatalities are a major issue globally, especially in the U.S. as the U.S. does not currently have vehicle regulations in place for pedestrian crashworthiness protection.

Sections 1.2-1.8 in this chapter encompass a literature review of U.S. pedestrian epidemiology, pedestrian injured body regions, pedestrian protection regulations, research on pedestrian kinematics and injuries through use of Postmortem Human Subjects (PMHS), dummies, and pedestrian component impactors, active and passive pedestrian protection systems, and finite element modeling of vehicles for pedestrian protection.

1.2 U.S. Pedestrian Epidemiology

In 2021, there were nearly 7500 pedestrians killed in traffic crashes in the U.S., the highest since 1981 (NHTSA, 2023). Since the year 2000, Europe and Japan have
adopted pedestrian crash protection programs for their vehicles and have seen approximately a 40% decline in pedestrian fatalities. Conversely, U.S. has not yet adopted pedestrian crash protection programs for vehicles and has seen an increase in pedestrian fatalities since the year 2000 (NHTSA, 2023) (Figure 1-1).

![Pedestrian Fatalities in E.U., U.S., and Japan 2000-2018](image)

*Figure 1-1: Pedestrian fatalities in U.S., EU, and Japan from 2000-2018 (NHTSA, 2023).*

Pedestrian fatalities in which the first harmful event was a pedestrian-to-vehicle collision have increased 43% in the U.S. from 2010 to 2021 (Figure 1-2) (NHTSA, 2023). In 85% of the fatality cases, the front of the vehicle was the first point of contact with the pedestrian (NHTSA, 2023). There has been an average of 66,007 pedestrian injuries per year in the U.S. from 2010-2020 where the first harmful event was a vehicle-to pedestrian collision (NHTSA, 2023). From 2011-2020, 67% (128,365) of pedestrian injuries and 12% (2467) of pedestrian fatalities occurred at speeds ranging from 1 - 25 mph (Figure 1-3). Speeds of 41-45 mph accounted for 17.4% (3,684) of pedestrian
fatalities during the same time period (NHTSA, 2023) (Figure 1-3). The Centers for Disease Control and Prevention (CDC) (CDC, 2023) reported that 60% of U.S. pedestrian fatalities in 2020 occurred on crowded urban roads with posted speed limits of 45-55 mph.

![Pedestrian Fatalities in which First Harmful Event was a Vehicle-to-Pedestrian Collision (2010-2021)](image)

*Figure 1-2: U.S. Pedestrian Fatalities from 2010-2021 in which the first harmful event was a vehicle collision with a pedestrian (NHTSA 2023).*
Figure 1-3: Pedestrian fatalities (A) and injuries (B) in U.S. by travel speed from 2011-2020 (NHTSA, 2023).

The National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System (FARS) reported that passenger cars and light trucks were involved in
88% (36,076) of cases where a pedestrian was killed by a single front vehicle crash from the years 2011-2020 (NHTSA, 2023). In the same years, large trucks and buses accounted for 2058 and 361 cases, respectively, followed by “other/unknown” vehicle types with 2547 cases (NHTSA, 2023). The vehicles involved in pedestrian crashes relate with the types of vehicles registered in the U.S. From 2015-2021, passenger cars (sedans) and light trucks (SUV’s and pickups trucks) accounted for 43% and 49.6%, respectively, of the number of vehicles registered in the U.S. In that same time period, passenger cars and light trucks accounted for 41.8% and 47.9%, respectively, of vehicle miles traveled in the U.S (Figure 1-4). The number of light trucks registered, and their miles driven steadily increased from 2015-2021, while the same criteria for passenger cars have decreased (NHTSA, 2017)( NHTSA, 2021) (Figure 1-5). It is known that SUV’s can cause more harm to a pedestrian due their larger profile (CDC, 2023). More specifically, the Insurance Institute for Highway Safety (IIHS) reported that vehicles with tall front ends (>40 inches) are 45% more likely to cause pedestrian fatalities than vehicles with a hood height of less than 30 inches (IIHS, 2023). Thus, the increased number of trucks on the road in the U.S. may relate to the increase of pedestrian fatalities.

![Figure 1-4: U.S. average registered vehicles (A) and average vehicle miles driven (B) by vehicle type 2015-2021.](image-url)
1.3 Pedestrian Frequently Injured Body Regions

The Abbreviated Injury Scale (AIS) is an ordinal scale (Table 1-1) used to evaluate the severity of injuries in vehicle-to-pedestrian crashes (Chidester, 2004).

<table>
<thead>
<tr>
<th>AIS Score</th>
<th>Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minor</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
</tr>
<tr>
<td>6</td>
<td>Fatal</td>
</tr>
</tbody>
</table>

From 1994 to 1998, the Pedestrian Crash Data Study (PCDS) was conducted in the U.S., in which a total of 4184 injuries by 511 pedestrians were analyzed (Chidester, 2004). Most of the injuries from this study were AIS 1 (64%), while 18 of the pedestrians in the study suffered AIS 6 injuries. Lower extremity and upper extremity injuries accounted for 33% and 20% of the total injuries, respectively. The head and face were the next most injured body regions accounting for 17% and 16% of total injuries,
respectively. When excluding AIS 1 injuries and focusing on the more severe injuries (AIS 2-6), lower extremity injuries accounted for 32% of the total injuries, followed by the head with 30% of the total injuries. The bumper was the primary cause of lower extremity injuries, specifically tibia and fibula fractures, and the windshield was the primary cause of head injuries (Chidester, 2004).

A similar study done by Mueller et al (Mueller, 2012) examined 67 vehicle-to-pedestrian collisions gathered from the Crash Injury Research and Engineering Network (CIREN) from 2002-2006. AIS 2+ head injuries were found in 45 (67%) of the cases, and AIS 2+ leg injuries were found in 42 (63%) of the cases. Injuries greater than maximum AIS (MAIS) 3 were majority head, thorax, and abdomen. Impact locations were available for 19 cases. Only two of the cases resulted in hood contact, the remaining were on the windshield or A-pillar (material surrounding perimeter of windshield; Mueller, 2012).

1.4 Pedestrian Protection Regulations and Procedures

Pedestrian safety regulations have been implemented to reduce the risk of pedestrian injuries and fatalities when being struck by a vehicle. Global Technical Regulation (GTR) No. 9 (GTR, 2009) was first published in 2004 to implement test regulations for pedestrian safety. The regulations were based on data collected by International Harmonized research activities (IHRA) and Pedestrian Safety Working Group (IHRA/PS). The data indicated the highest frequency of accidents is for children aged 5 - 9 years old, and adults over 60 years old. Crash speeds of up to 40 kph accounted for more than 75 % of total pedestrian injuries. The frequency of AIS 2-6 injuries is highest for a child and adult head, and an adult leg. These body regions account for more than 30% of total fatal and severe injuries. The bonnet (hood) was the
major source of injury for the child head, and the bonnet/windshield and bumper are the major sources of injury for the adult head and leg, respectively (GTR, 2009). The European term ‘bonnet’ will often be used for ‘hood’ throughout this paper as most of the pedestrian regulations reviewed were from Europe.

Euro NCAP (Euro NCAP, 2018) implemented a scoring system that applies a mathematical scale to rate vehicles based on the performance of headform, upper legform, and lower legform tests. There are a total of 36 points available across these three tests. Headform tests account for 24 of 36 points (66.7%), and the upper legform and lower legform account for 6 points (16.7%) each. Scores for head performance are based on head injury criterion (HIC), while scores for the upper and lower legform are based on bending moment, force, and ligament elongation.

The most representative vehicle-to-pedestrian impact was with the pedestrian standing sideways to the vehicle (GTR, 2009). The tests and regulations implemented were to simulate injuries sustained by pedestrians during a vehicle-to-pedestrian collision. When an adult pedestrian is struck by a vehicle, the fist point of contact is usually between the pedestrian’s knee and the bumper, followed by the pedestrian’s pelvis onto the grille or bonnet leading edge, and then the pedestrian’s thorax and head onto the bonnet or windshield area. GTR 09 states that the above-mentioned areas cover more than 65% of fatal and serious injuries. The average height and weight of the adult pedestrians from IHRA was about equivalent to the 50th percentile male. Thus, the adult headform (used to assess potential for head injury) was constructed with a 4.5 kg mass and 165 mm diameter to represent a 50th male head (Figure 1-6). The child headform is based on the average head of a 6-year-old child. The child headform diameter is 165 mm
and its mass is 3.5 kg (Figure 1-6; GTR, 2009). The headform impactors are made of aluminum and are covered with 14 ± 0.5 mm thick synthetic skin. A triaxial or three uniaxial accelerometers are mounted at the center of gravity to measure headform acceleration (Figure 1-6).

![Figure 1-6: Adult headform impactor (A) and child headform impactor (B) (GTR, 2009).](image)

GTR’s head impact test is representative of a 40kph vehicle-to-pedestrian impact. The bonnet top is impacted with adult and child headforms at 35kph, as head impact speed is known to be less than initial impact speed (GTR, 2009). The impact angles for the child and adult headform are 50° and 65° relative to the ground, respectively. These impact angles were based on PMHS tests and computer simulations. PMHS tests showed a peak distribution of adult head impact angles at 60°, and the simulations of a 50th male model showed a 67° impact angle. Simulations also indicated that vehicle shape had little influence on head impact angle. A value of 65° for adult head impact angle was chosen because it was close to the 67° of simulations and close to the average head angle of PMHS tests (GTR, 2009). For the child head, simulations of a 6-year-old child model
were considered. Results showed a head impact angle around 50°, thus this impact angle was chosen (GTR, 2009).

Per GTR standards, the bonnet area for the headform tests is divided into sections based on wrap around distance (WAD). WAD is the distance from a point on the ground directly under the bumper’s leading edge to a point on the bonnet, measured with a flexible tape measure (Euro NCAP, 2018; GTR, 2009; Figure 1-7). The test area for the child headform is from 1000 to 1700 mm, and the adult headform test area is from 1700-2100 mm. These were selected based on accident data that showed pedestrian child head impact above a WAD of 1000 mm, and adult head impact above a WAD of 1700 mm (Euro NCAP, 2018; GTR, 2009). At the time, the child and adult headform test zones covered approximately 62% of the PCDS U.S. cases. GTR also states that 35% of the U.S. cases occurred at WADs exceeding 2100 mm, and many of these cases were greater than 40 kph (GTR, 2009).

![Figure 1-7: Wrap around distance lines (Euro NCAP, 2018).](image)

The same headform impactors and impact angles are used by Euro (Europe) New Car assessment program (NCAP), ANCAP (Australia), JNCAP (Japan), KNCAP (Korea)
and C-NCAP (China); however, the test impact speed is 40 kph (Safety Wissen, 2023).

Per Euro NCAP (Euro NCAP, 2018) standards, when the Bonnet Rear Reference Line (BRRL) is between 1500 mm and 1700 mm, the child headform is used for everything forward of the BRRL, and the adult headform is used for everything rear of the BRRL up to 2100 mm WAD (Figure 1-8). This procedure is followed by all the above listed NCAP programs besides KNCAP, which test the child headform from 1000-1700 like GTR (Safety Wissen, 2023). JNCAP (JNCAP, 2019) utilized wrap around distances up to 2300 mm if the vehicle front end is V-shaped. The BRRL is the geometric trace of the most rearward point of contact between a 165 mm sphere and the frontal upper surface, while the sphere is moved across the frontal surface and in contact with the windshield (Euro NCAP, 2018; Figure 1-9).

![Figure 1-8: Headform test zones. The left vehicle (A) used the child headform test zone up to 1700 mm, while the right vehicle (B) used the child headform test zone up to the BRRL (Euro NCAP, 2018).](image-url)
Per Euro NCAP, grid points are overlayed on the vehicle for headform testing. The child head origin starts at the intersection of the vehicle centerline and the WAD 1000 mm line. This point is called C (0,0). The column of grid points on the center line is column 0 and the columns to the left of the center line will be +1, +2, etc. The columns to the right of the centerline are -1, -2, etc. Grid points in the adult headform test zone are labeled with the letter “A”. Figure 1-10 is an example of how headform grid points are labeled (Euro NCAP, 2018). Euro NCAP and JNCAP state that for any headform grid points on or forward of the bonnet leading edge (BLE) reference line, the child head impactor is tested at an angle of 20° relative to the ground (Euro NCAP, 2018; JNCAP, 2019). The BLE reference line is the geometric trace of points of contact between a 1000 mm straight edge and the surface of the bonnet. The straight edge is held parallel to the vertical longitudinal plane and inclined rearwards by 50° while the lower end of the straight edge is 600 mm above the ground (Figure 1-11; Euro NCAP, 2018).
Head protection performance is based on HIC because most pedestrian fatalities are due to head injuries. The HIC is calculated over a 15 ms interval (HIC\textsubscript{15}) because head impacts to vehicles occur within a few milliseconds of contact (UN Regulations NO. 127, 2012). HIC can be seen in Equation 1-1 below, where a(t) is the resultant acceleration and t\textsubscript{2} – t\textsubscript{1} is the duration of the acceleration pulse, which could be any two times during the event (Untaroiu, 2007). A HIC of 1000 generally represents the “safe” limit for human tolerance (Science Direct, 2024).
$HIC = \max \left\{ (t_2 - t_1) \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \, dt \right]^{2.5} \right\}$

_Equation 1-1: HIC formula_ (Untaroiu, 2007).

Per GTR, the HIC cannot exceed 1000 for over one half of the child headform test area and must not exceed 1000 for over two thirds of a combined child and adult headform test areas. The HIC for the remaining areas must not exceed 1700 for both headforms. There can be a relaxation zone up to 50% in the child headform test area where the HIC threshold is 1700 instead of 1000. This is due to under bonnet components such as locks and suspension towers. The vehicle manufacturer shall identify zones of the bonnet where the HIC shall not exceed 1000 or 1700 (GTR, 2009). Euro NCAP (Euro NCAP, 2018) assigns ranges of HIC values by color (Table 1-2). The vehicle manufacturer provides the Euro NCAP secretariat with HIC_{15} data detailing the protection offered at each headform grid location. A-pillars have a default red rating, unless the vehicle manufacturer can show data otherwise. The windscreen glazing is default green, except for test points within 165 mm of the solid strip around the edge of the windscreen (Figure 1-12). Grid points within 165 mm of the solid strip around the windscreen mounting frame cannot be defaulted green (Euro NCAP, 2018).

<table>
<thead>
<tr>
<th>HIC_{15} values</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC_{15} &lt; 650</td>
<td>Green</td>
</tr>
<tr>
<td>650 ≤ HIC_{15} &lt; 1000</td>
<td>Yellow</td>
</tr>
<tr>
<td>1000 ≤ HIC_{15} &lt; 1350</td>
<td>Orange</td>
</tr>
<tr>
<td>1350 ≤ HIC_{15} &lt; 1700</td>
<td>Brown</td>
</tr>
<tr>
<td>HIC_{15} ≥ 1700</td>
<td>Red</td>
</tr>
</tbody>
</table>

_Table 1-2: HIC ranges by color (Euro NCAP, 2018)._
For the Euro NCAP scoring, the vehicle sponsor funds 10 headform verification tests. The location of all tests is selected at the same time and at random by the Euro NCAP secretariat. Grid points on the defaulted grid positions are excluded from the randomly selected points. There is no restriction of the location of the randomly selected test points, and tests to adjacent impact locations are acceptable if there is no vehicle damage that influences test results. When damage from already tested grid points affects other tests, the Euro NCAP secretariat decides how to proceed. Selected headform grid points are treated as aiming points for the impactor. The centerline of the headform impactor is directly in line toward the aiming point. The head is launched from a propulsion system and gravity is accounted for to establish the correct trajectory for the headform. The headform is in “free flight” at impact (Euro NCAP, 2018; Figure 1-13). The same procedure is used by ANCAP, KNCAP, JNCA, and C-NCAP (Safety Wissen, 2023).
The most common pedestrian knee injury mechanism is lateral bending between the thigh and leg (GTR, 2009). The lower legform impact test is representative of a 40 kph impact to the bumper on a mid-sized male adult leg. The test is designed for vehicles with low bumper heights of around 200 - 250 mm (GTR, 2009). If the lower bumper reference line (LBR) is less than 425 mm, the lower legform to bumper test is performed. If the LBR is more than 500 mm, the bumper is impacted with the upper legform. If the LBR is between 425 mm and 500 mm, the vehicle manufacturer can perform either a lower legform test or an upper legform test (Euro NCAP, 2018). The LBR is the lower most point of contact between a 700 mm straight edge, inclined forward by 25°, and the bumper (Figure 1-14; Euro NCAP, 2018). The reasoning for limiting the bumper heights is so the lower legform impacts the bumper at the knee. High bumpers would impact the femur part of the lower legform impactor where no acceleration is measured to assess the risk of fractures (Euro NCAP, 2018; GTR, 2009).
17

Figure 1-14: Lower bumper reference line (Euro NCAP, 2018).

Until 2014, the Transportation Research Laboratory (TRL) legform impactor was used in lower legform to bumper tests (Zeitouni, 2023). The flexible pedestrian legform impactor (Flex-PLI) is called for in the current GTR and was used by Euro NCAP from 2014 until 2022, when they switched to the advanced Pedestrian Legform Impactor (aPLI) (NHTSA, 2023). The Flex PLI has been proven to be more flexible and biofidelic than the TRL impactor (Zeitouni, 2023). The Flex-PLI impactor consists of flesh and skin composed of synthetic rubber and neoprene sheets, as well as the femur (upper portion), tibia (lower portion), and a knee joint in the middle. The total mass is 13.2 kg ± 0.4 kg. The mass of the knee joint is 4.28 kg. There are four transducers in the tibia and three in the femur to measure bending moments. There are three transducers at the knee joint to measure elongation of the Anterior Cruciate Ligament (ACL), medial cruciate ligament (MCL), and posterior cruciate ligament (PCL). There is also an accelerometer mounted at the knee joint to measure acceleration. The direction of travel for the Flex-PLI is in the local Y-axis (Figure 1-15; UN Regulations NO. 127, 2012). The impactor is 25 ± 10 mm above the ground and in free flight during the test (Euro NCAP 2018).
Per Euro NCAP, the lower legform grid points are marked starting at the intersection of the vehicle centerline and upper bumper reference line (UBR). The UBR is the upper most points of contact between a 700 mm straight edge, declined rearward by 20°, and the bumper (Euro NCAP, 2018; Figure 1-16).

![Diagram](image)

**Figure 1-15**: Schematic and instrumentation of Flex PLI lower legform impactor. The direction of travel is in the local Y-axis. (UN Regulations NO. 127, 2012).

![Diagram](image)

**Figure 1-16**: Upper bumper reference line (Euro NCAP, 2018).

Grid points are marked every 100 mm laterally in both directions up to the edge of the bumper test zone. The bumper test zone is either the area limited by the bumper corners or the outermost ends of the underlying bumper beam, whichever is larger. The bumper corners are defined as the point of contact of the vehicle that makes a 60° angle
with the vertical longitudinal plane of the car and is tangent to the outer surface of the bumper (Euro NCAP 2018; Figure 1-17).

![Diagram of bumper corner](image)

*Figure 1-17: Bumper corner (Euro NCAP, 2018).*

The intersection of the vehicle centerline and UBR is known as (L,0). The grid points to the left of the center line are +1, +2, etc., and the grid points to the right of the centerline are -1, -2, etc. (Euro NCAP, 2018; Figure 1-21). A minimum of three lower legform to bumper tests are performed, one each to the middle and outer thirds of the bumper test area (Euro NCAP, 2018). The Euro NCAP secretariat selects either L0 or L1 for testing. Additional tests are performed to every second grid point outboard of this point. Symmetry is applied across the vehicle and both sides of the vehicle can be tested. If a pair of symmetrical points are selected, the laboratory decides which point to test. Grid points that are not tested receive the worst result from one of the adjacent tested points. The direction of impact is in the horizontal plane and is parallel to the longitudinal vertical plane of the vehicle (Euro NCAP 2018; GTR, 2009; UN Regulations NO. 127, 2012). JNCAP (JNCAP, 2019) requires that the lower legform test area be divided into
three sections using the UBRL length. The three sections are called “L1”, “L2”, and “L3.” Those are then each divided into sub test areas labeled “A” and “B” (Figure 1-18). An impact point is selected from each sub test area. (JNCAP, 2019). The performance limits of the lower legform impactor, as defined by Euro NCAP, can be seen in Table 1-3 below (Euro NCAP, 2018).

![Figure 1-18: JNCAP lower legform test areas (JNCAP, 2019).](image)

**Table 1-3: Euro NCAP lower legform to bumper test limits** (Euro NCAP, 2018)

<table>
<thead>
<tr>
<th></th>
<th>Tibia Bending (Nm)</th>
<th>MCL Elongation (mm)</th>
<th>ACL/PCL Elongation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
</tr>
<tr>
<td>Flex-PLI Metric</td>
<td>282</td>
<td>340</td>
<td>19</td>
</tr>
</tbody>
</table>

It should be noted that Euro NCAP has transitioned to using the advanced Pedestrian Legform Impactor (aPLI) for lower legform impacts. This is also used by ANCAP, KNCAP, C-NCAP, and JNCAP will be using it starting April 2024 (Safety Wissen, 2023). The aPLI (Figure 1-19) contains an upper mass to represent the torso contribution during impact and has been found to produce a more biofidelic response. It
contains a knee accelerometer, potentiometers to measure ACL, MCL, and PCL elongation, three femoral strain gauges to measure femur bending moment, and four tibia strain gauges to measure tibia bending moment. Its total mass is 25 kg (NHTSA, 2023).

Figure 1-19: Advanced Pedestrian Legform Impactor (aPLI) (NHTSA, 2023).

Upper legform to bumper tests are designated for vehicles with high bumpers, in which the bumper would strike the pedestrian above the knee (Euro NCAP, 2018; GTR, 2009). The upper legform impactor is foam covered at the impact site and 350 ± 5 mm long. The total mass of the impactor including the propulsion and guidance components which are a part of the impactor during the impact are 9.5 ± 0.1 kg. The mass of the front member, load transducer assemblies, and components in front of the load transducer assemblies, but excluding the foam and skin shall be 1.95 ± 0.05 kg. The front member has three strain gauges (upper, middle, and lower) to measure bending moments. Two load transducers are located at both ends of the impactor to individually measure the forces at impact (UN Regulations NO. 127, 2012; Figure 1-20).
The upper legform to bumper test is representative of a 40kph impact to the bumper on a mid-sized male adult upper leg (GTR, 2009). As stated earlier, this test is performed when the LBR is higher than 500 mm. A minimum of three upper legform to bumper tests are performed, one each to the middle and outer thirds of the bumper (Euro NCAP, 2018). The direction of impact is in the horizontal plane and is parallel to the longitudinal vertical plane of the vehicle. This test is used by GTR and Euro NCAP; however, the upper legform impactor used by Euro NCAP has a mass of 10.5 kg. Per GTR, the upper legform performance limits are 7.5 kN and 510 Nm for the sum of forces and bending moment, respectively (Euro NCAP, 2018). The same grid points outlined in the lower legform test are used (Euro NCAP, 2018).
Euro NCAP (Euro NCAP, 2018) regulations require an upper legform to WAD 775 mm (bonnet leading edge) test. This test is conducted if the LBR is less than 425 mm. Upper legform to WAD 775 mm grid points are marked starting at the intersection of the vehicle centerline and WAD 775 mm. This point is known as (U,0). Grid points are marked every 100 mm in both lateral directions along WAD 775 up to the corner reference points. The grid points to the right of the center line are +1, +2, etc., and the grid points to the left of the centerline are -1, -2, etc. (Figure 1-21). The Euro NCAP secretariat selects either U0 or U1 for testing; additional tests are then performed to every second grid point outboard of this point. The impact angle in relation to the ground is perpendicular to straight line passing through the internal bumper reference line and WAD 930 mm (Euro NCAP, 2018; Figure 1-22).

*Figure 1-21: Marking upper legform and lower legform grid points (Euro NCAP, 2018).*
The angle of impact is measured and recorded at each grid point. A test is not required if the calculated impact energy is less than 160J. The impactor energy is calculated using Equation 1-2 below.

\[ E = 0.5 \times m_n \times v_c^2 \]
\[ m_n = 7.4 \text{ kg} \]
\[ v_c = v_0 \cos(1.2\alpha) \]
\[ v_0 = 11.1 \text{ m/s} \]

*Equation 1-2: Impact energy for upper legform test (Euro NCAP, 2018)*

The test velocity is then adjusted to meet the energy using Equation 1-3 below.

\[ v_t = \sqrt{\frac{2E}{m_n}} \]

*Equation 1-3: Upper legform test velocity (Euro NCAP, 2018)*

The performance limits of the upper legform impactor, as specified by Euro NCAP are seen in Table 1-4 below (Euro NCAP, 2018).
Table 1-4: Upper legform performance limits (Euro NCAP, 2018).

<table>
<thead>
<tr>
<th></th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Moment</td>
<td>285 Nm</td>
<td>350 Nm</td>
</tr>
<tr>
<td>Sum of Forces</td>
<td>5.0 kN</td>
<td>6.0 kN</td>
</tr>
</tbody>
</table>

In general, the pedestrian component tests and regulations are a good way to improve pedestrian safety and decrease pedestrian fatalities. However, these component tests are primarily based on dimensions for the 50th percentile male and are only performed at 40 kph. In addition, there are not designated tests for the a-pillar and cowl (space between the rear edge of the hood and windshield). If the U.S. were to adopt pedestrian regulations, it may be best to consider higher impact speeds as well as tests that represent a wider range of body sizes and impact locations.

1.5 Full-Scale Pedestrian Testing

Postmortem Human Subjects (PMHS) and pedestrian dummies have been used in research to better understand pedestrian-to-vehicle interactions and kinematics.

1.5.1 PMHS Tests

Vehicle-to-PMHS studies have been performed to reconstruct kinematics and injuries. Kerrigan et al (Kerrigan, 2004; Kerrigan, 2005; Kerrigan, 2007; Kerrigan 2009) demonstrated tests that included the front end of a vehicle, or a custom buck, representative of a sedan or SUV. The test subject was in a mid-gait stance, positioned laterally along the vehicle centerline, and was struck at 40 kph to the right posterior leg. One study in particular provided results of WAD and HIC relative to the vehicle type. Results showed that the WAD decreased for the SUV’s. In other words, the test subjects wrapped further onto the sedans causing a head strike on the windshield, while all head
strikes on the sedans occurred on the hood. The kinematic corridors from these studies have been used to validate human body models (HBM’s). However, these studies did not provide vehicle deformation that could be used in finite element vehicle model validation.

Two reviewed studies (Subit, 2008; Schroeder, 2008) involving PMHS’s provided injury data and vehicle deformation. A study performed by Subit et al (Subit, 2008) demonstrated four tests on four PMHS subjects. A mid-sized sedan (MSS) and a small city car (SCC) were used for two impacts each. The test setup was the same as Kerrigan et al described above. HIC and WAD for all impacts were also recorded. Subject details and HIC and WAD results can be seen in Table 1-5. Vehicle deformation was measured with a CMM and plotted for the x, y, and z directions.

*Table 1-5: Subit et al PMHS details and HIC/WAD results from tests* (Subit, 2008).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>HIC</th>
<th>WAD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSS-1</td>
<td>154</td>
<td>72.6</td>
<td>1730</td>
<td>1600</td>
</tr>
<tr>
<td>MSS-2</td>
<td>183</td>
<td>114</td>
<td>924</td>
<td>2125</td>
</tr>
<tr>
<td>SCC-1</td>
<td>161</td>
<td>86.2</td>
<td>716</td>
<td>1630</td>
</tr>
<tr>
<td>SCC-2</td>
<td>182</td>
<td>46.3</td>
<td>280</td>
<td>1900</td>
</tr>
</tbody>
</table>

Vehicle deformation was larger from the pelvis contact in the y and z directions at the bonnet leading edge of MSS-1 than MSS-2. The largest deformation for MSS-2 occurred on the hood from contact with the subject’s right greater trochanter (RGT). Overall, more vehicle deformation occurred in the SCC than the MSS. The SCC had deformation at the top edge of the hood and the windshield from the torso and rib cage, respectively (Subit, 2008).
Schroder et al (Schroeder, 2008) performed a similar study where two PMHS subjects were impacted by an SUV and two were impacted by a van. The two subjects struck by the SUV had heights 165 cm and 185 cm, respectively. The subjects struck by the minivan both had a height of 171 cm. Details of the test subjects can be seen in Table 1-6. All impacts were at 40 kph, and the struck leg of the test subjects was forward. Whole body kinematics were analyzed and the maximum permanent deformation at each deformed part of the vehicle was measured.

*Table 1-6: Schroeder et al PMHS height, weight, and test vehicle (Schroeder, 2008).*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMHS-1</td>
<td>165</td>
<td>60</td>
<td>SUV</td>
</tr>
<tr>
<td>PMHS-2</td>
<td>185</td>
<td>85</td>
<td>SUV</td>
</tr>
<tr>
<td>PMHS-3</td>
<td>171</td>
<td>80</td>
<td>Mini-Van</td>
</tr>
<tr>
<td>PMHS-4</td>
<td>171</td>
<td>61</td>
<td>Mini-Van</td>
</tr>
</tbody>
</table>

The head of PMHS-1 impacted the center-rear hood, and the hips impacted the bonnet leading edge. The deformation for the hood and bonnet leading edge was 18 mm and 27 mm, respectively. The head of PMHS-2 impacted the lowest edge of the windshield, and the deformation was 51 mm. The heads of PMHS-3 and PMHS-4 impacted the right-center of the windshield and the lowest edge of the right-windshield, respectively. The deformations were both 68 mm. The HIC values for subjects 1-3 were 443, 2228, and 1591, respectively. The HIC for subject 4 was not reported (Schroeder, 2008).

1.5.2 Dummy Tests

Vehicle-to-dummy tests have also been performed to compare dummy kinematics with that of PMHS’s and pedestrian component impactors. The Polar dummy was
developed by Honda R&D to reproduce kinematics of a 50th percentile male. Matsui et al (Matsui, 2002; Matsui, 2005) performed studies analyzing the Polar dummy interactions with a compact car, mid-size car, and SUV. Tests were performed with the dummy in a mid-gait stance facing lateral to the vehicles (Figure 1-23). Results showed that head trajectories were greater for the compact car and mid-size sedan than SUV due to the SUV having a higher bonnet leading edge. The head impact angle increased with bonnet leading edge height and was greatest for the SUV. Pedestrian lower legform and upper legform impact tests were performed on the same vehicles. The main difference was that the upper part (pelvis) of the lower legform began to rebound from the SUV while the dummy’s pelvis remained in contact with the bonnet leading edge (Figure 1-24). Also, the residual deformation on the SUV from the upper legform was greater than that produced by the whole dummy. This suggests that an added upper body mass to the lower legform impactor may be needed (Matsui, 2002; Matsui, 2005) (Hamacher, 2011).

*Figure 1-23: Polar dummy setup with test vehicle (Matsui, 2002).*
Figure 1-24: Comparison of dummy (A) and lower legform impactor (B) interaction with SUV. The dummy’s thigh and hip load the vehicle while the lower legform impactor rebounds from the vehicle (Matsui, 2002).

1.6 Pedestrian Component Tests

1.6.1 European Vehicle Fleet

Martinez et al (Martinez, 2007) performed a study deriving stiffness (force vs displacement) corridors from 425 Euro NCAP child and adult headform, upper legform, and lower legform tests. Each test was rated as “red”, “yellow”, or “green” based on Euro NCAP 2004 regulations (Martinez, 2007). Euro NCAP requires a result matrix for each vehicle tested (Figure 1-25). The criteria are outlined in Table 1-7. Results showed that 50% of all tests resulted in red scores. Based on test configuration, 70% of the adult head to windshield tests and 45% of adult headform tests were red. Based on force vs displacement curves, displacements of over 0.08 m in the bumper and over 0.02 m in the hood are valuable targets to achieve a green score (Martinez, 2007). The vehicle test matrix could be applied to vehicle finite element (FE) models for modeling stiffness zones across the hood and bumper.
Figure 1-25: Example Euro NCAP vehicle test matrix (Martinez, 2007).

Table 1-7: Color rating for pedestrian tests (Martinez, 2007).

<table>
<thead>
<tr>
<th>Test</th>
<th>“Red”</th>
<th>“Green”</th>
<th>“Yellow”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headform</td>
<td>HIC &gt; 1350</td>
<td>HIC &lt; 1000</td>
<td>Between red and green values</td>
</tr>
<tr>
<td>Upper legform</td>
<td>Total forces &gt; 6.0 kN</td>
<td>Total forces &lt; 5.0 kN</td>
<td>Between red and green values</td>
</tr>
<tr>
<td>Lower legform</td>
<td>Max tibia acceleration &gt; 200 g</td>
<td>Max tibia acceleration &gt; 150 g</td>
<td>Between red and green values</td>
</tr>
</tbody>
</table>

1.6.2 U.S. Vehicle Fleet

A study was performed in 2019 by Suntay et al (Suntay, 2019) to evaluate pedestrian safety on vehicles from the U.S. fleet. Pedestrian headform, upper legform, and lower legform tests were performed according to Euro NCAP standards on nine U.S. vehicles seen in Table 1-8 below. The Honda Fit, Toyota Prius, Nissan Rogue, and Ford Edge were considered “global” as they have variants sold in Europe, and their test results were compared to those from Euro NCAP.
Table 1-8: Vehicles tested in Suntay et al study. Vehicles with "*" by the name are global vehicles that have European variants (Suntay, 2019).

<table>
<thead>
<tr>
<th>Vehicle Make and Model</th>
<th>Vehicle Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 Honda Fit*</td>
<td>Small Passenger Car</td>
</tr>
<tr>
<td>2016 Toyota Prius*</td>
<td>Small Passenger Car</td>
</tr>
<tr>
<td>2017 Audi A4*</td>
<td>Midsize Passenger Car</td>
</tr>
<tr>
<td>2016 Chevrolet Malibu</td>
<td>Midsize Passenger Car</td>
</tr>
<tr>
<td>2016 Nissan Rogue*</td>
<td>Small SUV</td>
</tr>
<tr>
<td>2016 Ford Edge*</td>
<td>Midsize SUV</td>
</tr>
<tr>
<td>2016 Chevrolet Tahoe</td>
<td>Large SUV</td>
</tr>
<tr>
<td>2015 Toyota Sienna</td>
<td>Minivan</td>
</tr>
<tr>
<td>2015 Ford F-150</td>
<td>Standard Pickup Truck</td>
</tr>
</tbody>
</table>

The Chevrolet Tahoe and Ford F-150 had higher front ends and ride heights than the other vehicles. Thus, they performed poorly in lower legform tests, resulting in an increased bending moment from the legform bending around the bumper. The higher ride height also led to the upper legform impacting the stiffer parts of the vehicle such as the grille, resulting in increased bending moments and impact forces. These two vehicles also performed the worst for the headform tests. The higher ride height and larger hoods of the vehicles led to all headform grid points being overlayed on the hood. No headform points were on the windshield. The forward most headform points were on the leading edge of the hoods. This is known to be a stiff surface, resulting in high HIC (Suntay, 2019).

The global vehicles all performed better than the other U.S. market vehicles for the lower legform and upper legform tests. However, the lower legform tests performed worse on the U.S. version of the global vehicles compared to their European variants. This was likely due to the difference in bumper regulations between the U.S. and Europe. Part 581 U.S. bumper regulation in the U.S. is designed to reduce physical damage to front and rear ends of passenger motor vehicles in low-speed collisions. In Europe, UNECE Reg No. 127
requires vehicles to have softer, energy absorbing bumpers to comply with pedestrian safety standards. The only exception was the Nissan Rogue that performed just as well as its European variant (Suntay, 2019, 2020).

The difference between U.S. and European (EU) bumpers was further studied by Suntay et al (Suntay, 2020) in 2020. Due to the difference in regulations, the bumper absorbers differ between U.S. and EU vehicles. Lower legform responses to both U.S. and EU bumpers were tested. Results showed that the lower legform experienced much greater tibia bending moment and ligament elongation on the U.S. bumper for all impacts except the corners. The corner bumper impacts between the U.S. and EU bumper were similar. This is because the U.S. bumper absorber spans the entire bumper beam, while the EU bumper absorbers are at the corner of the bumper, thus leaving an empty space in the middle (Figure 1-26). The empty space results in a more compliant bumper because it allows for more intrusion (Suntay, 2020).

![Figure 1-26: 2012 Ford Focus U.S. bumper absorber (A). 2012 Ford Focus EU bumper absorber (B) (Suntay, 2020).](image)

Overall, there is a much larger sample size of European vehicles tested for pedestrian safety than U.S. vehicles. U.S. vehicles generally perform worse in pedestrian
protection tests due to differences in vehicle regulations such as bumper Part 581. There is also a lack of testing larger U.S. vehicles such as trucks, and large SUV’s which have been shown to perform poorly in terms of pedestrian protection. Therefore, more pedestrian protection testing on U.S. vehicles, especially trucks and large SUV’s, should be considered.

1.7 Pedestrian Protection Systems

1.7.1 Passive Safety

Several different research studies have been performed on passive safety systems, such as deployable hoods and bumper airbags, for pedestrian safety (Hamacher, 2011; Inomata, 2007; Zhu, 2022). A deployable (pop-up) hood raises the rear of the hood through use of sensors and actuators. The sensors are placed behind the front bumper to detect vehicle contact with a pedestrian. After detection, actuators raise the rear of the hood by 100 mm to create space between the hood and stiff under-hood parts (Figure 1-27). This can prevent the head from having a secondary impact with the engine block or other stiff under-hood parts if the sheet metal bottoms-out. Headform test results on a deployable hood showed a significantly reduced secondary acceleration peak from head contact with under-hood parts (Inomata, 2007; Figure 1-27).
The implementation of air bags for pedestrian head and leg protection has also been studied. Hamacher et al (Hamacher, 2011) analyzed the effect of a deployable bonnet airbag on the Polar II dummy in a 40 kph collision (Figure 1-28). The bonnet airbag absorbed the head impact and reduced head acceleration from 203 g to 72 g and reduced HIC from 1736 to 566.

Wang et al installed an air bag on a car bumper (Figure 1-29) and analyzed the injury response from upper legform and lower legform tests (Wang, 2022). Tests
performed with the air bag were shown to significantly reduce ACL, MCL, and PCL as well as tibia bending moment, femur bending moment, and femur force. Unlike deployable hoods, the air bag needs to deploy before hitting a pedestrian. To be implemented, the bumper airbag would need to trigger from the automatic emergency braking pedestrian (AEB-P) system (Wang, 2022).

![Figure 1-29: Deployment of bumper air bag (Zhu et al., 2022).](image)

Overall, active safety systems such as deployable hoods and hood/bumper air bags are useful ways to improve pedestrian protection. More research should be pursued in this field to help reduce pedestrian injury and fatality risk.

### 1.7.2 Active Safety

Autonomous emergency braking (AEB) is designed to brake autonomously for pedestrians crossing the path of the vehicle (Euro NCAP, 2017), thus reducing the speed of a vehicle-to-pedestrian collisions. Many studies have shown that reducing impact speed reduces head impact speed, HIC, and lower extremity injuries (Hamacher, 2011). Other active safety sensors such as ultrasonic, radar, video cameras, and lidar help detect
pedestrians and vulnerable road users (Tous, 2022). The AEB system must be able to
detect pedestrians walking as slow as 3 kph at both day and night. When testing the AEB
system up to 40 kph, Euro NCAP scores the test based on relative speed reduction
achieved. For test speeds greater than 40 kph, a score is awarded when the speed is
reduced by at least 20 kph (Euro NCAP, 2017).

1.8 Finite Element Modeling

Finite element (FE) modeling is a useful tool for assessing pedestrian safety and is
less expensive and generally faster than physical testing. Many studies have been
performed to model components of the vehicle, such as hood and bumpers, for pedestrian
safety as well as for full vehicle and generic front end vehicle models to analyze
pedestrian kinematics and injuries.

1.8.1 Hood and Bumper Modeling

Vehicle hoods usually consist of an upper and inner body. The inner body is used
for structural strength and upper body is used for aerodynamics and style (Masoumi,
2011). When global pedestrian protection regulations were announced, numerous FE
studies were performed to optimize the design of hoods for pedestrian safety. Common
findings were that HIC increased with the increase in hood thickness and HIC was higher
towards the edges of the hood near the fenders (Shojaeefard, 2014; Wang., 2012; Zeng,
2018). Aluminum was also shown to be better than steel and composite materials to
reduce HIC (Masoumi, 2011).

Factors such as bumper material, geometry, and height have an influence on
pedestrian injuries and kinematics (Teng, 2016; Otte, 2012; Yang, 2020). FE studies have
been performed to optimize bumper design to meet requirements for pedestrian safety
and protection against low-speed impacts. Teng et al (Teng, 2016) showed that reducing bumper thickness and having a wider, smoother-shaped bumper can reduce tibia acceleration, and knee bending angle. This is further supported by Otte et al (Otte, 2012) in which they found the number of leg injuries in real-world cases was significantly less for vehicles with smoother bumpers than vehicles with protruding bumpers (Figure 1-30).

Yang et al (Yang, 2020) compared the effect of aluminum and steel bumpers on the TRL lower legform impactor. Results showed the steel bumper resulted in greater acceleration, bending angle, and deformation of the lower legform.

![Figure 1-30: Bumper shape influence on pedestrian knee injuries (Yang, 2020).](image)

Bumper height also has a great effect on pedestrian injury and kinematics. Sáez et al (Sáez, 2012) performed FE simulations with the human Toyota Human Model for Safety (THUMS) model on five simplified front end models of varying bumper heights. The two models with the highest bumper heights resulted in contact forces of greater than
15 kN to the femur and fractures to the lower ribs as well as femur and tibia. The models with reduced lower bumper heights produced lesser contact forces and did not cause rib fractures (Sáez, 2012). Martinez et al performed a similar study examining leg injury and kinematics through use of THUMS and legform FE model on FE vehicles. Results showed that the femur part of the legform impactor loses contact with high bumper vehicles much earlier than the THUMS model. This suggests that the addition of an upper body mass to the legform may be needed to predict leg injuries more accurately in high bumper vehicles (Martínez, 2008).

1.8.2 Full Vehicle Computational Models

The National Crash Analysis Center (NCAC) (George Mason University, 2024) developed full FE vehicle models representative of common U.S vehicles. The front end of one of the mid-size sedan and SUV models were used in a study to investigate the effect of vehicle front profile on pedestrian kinematics (Gupta, 2015). The study generated four vehicle front profiles for the sedan and SUV by increasing the slope of the hood and lowering the front end (Figure 1-31). Simulations were run with the MADYMO 6-year-old child, 5th percentile female, and 50th percentile male human models at impact speeds of 30 and 40 kph. Results showed that both speed and hood slope affected head impact angle. The steeper hood slope caused the human model to slide up on the hood resulting in a head strike on the windshield. Head impact angles, with respect to the ground, were greater at 40 km/h. The largest head impact angle for the child head was 45° while the adult head was approximately 35°. While these results give good insight, the front-end models used were from vehicle models that were validated from NHTSA frontal NCAP tests to support research related to occupant risk. This does not necessarily
make the models suitable for vehicle-to-pedestrian crash analysis (Gupta, 2015). Further studies and validation are needed to ensure FE vehicle models are best suited for analyzing pedestrian crashes.

![Figure 1-31: Sedan front profile (A) and SUV front profile (B) FE models (Gupta, 2015).](image)

### 1.8.3 Euro NCAP Generic Vehicle Models

FE vehicle models are used as a tool to simulate and analyze pedestrian crashes. Euro NCAP requires both physical testing and numerical Human Body Model (HBM) simulations from vehicle manufactures to demonstrate pedestrian crashworthiness safety (Klug, 2019). Euro NCAP technical bulletin (TB) 024 (Klug, 2019) outlines the development of generic front profile FE models representative of four vehicle categories (Figure 1-32): Roadster, Family Car/Sedan, SUV, and Multipurpose Vehicle/Supermini. Median geometries (Figure 1-33) for each generic model were derived based on vehicle measurements from the European fleet (Klug, 2017; Klug, 2019). Table 1-9 outlines the U.S. vehicle classes that are closest in comparison to the Euro NCAP vehicle models. Note that these comparisons were made from the writer’s perspective.
Figure 1-32: Generic FE vehicle models (Klug, 2017).

Figure 1-33: Median geometry profiles of the Roadster (A), Family Car (B), SUV (C), and MPV (D) (Klug, 2017).

Table 1-9: U.S. vehicles closest in comparison to Euro NCAP generic vehicle models.

<table>
<thead>
<tr>
<th>Euro NCAP Generic Vehicle Model</th>
<th>U.S. Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roadster</td>
<td>Small Sedan/2-Door Sedan</td>
</tr>
<tr>
<td>Family Car</td>
<td>Mid-Size Sedan/4-Door Sedan</td>
</tr>
<tr>
<td>SUV</td>
<td>SUV/Pickup Truck</td>
</tr>
<tr>
<td>Multipurpose Vehicle (MPV)</td>
<td>Minivan</td>
</tr>
</tbody>
</table>
The generic vehicle models were separated into six component regions: Spoiler, Bumper, Grille, Bonnet (hood) Lead, Bonnet (hood), and Windshield/Rigid Structure (Klug, 2019; Figure 1-34). The structural response for the spoiler, bumper, grille, bonnet lead, and bonnet were modeled with a rigid foam bottom layer, compaction layer, generic foam layer, and an outer shell interface layer (Figure 1-35). The compaction layer replicates hard structures and the foam replicates energy absorbing structures and was 100 mm in thickness. The windshield was modeled as a single shell layer rigid structure. The interface layer covering the foam provides realistic structural mechanical characteristics such as Young’ modulus, tangential modulus, and yield stress of steel for the bonnet and plastic for the other parts of the model (Klug, 2017).

![Figure 1-34: Components of Euro NCAP generic FE vehicle model (Klug, 2017).](image)
The material parameters of the generic vehicle models from TB024 were optimized to represent structural behavior that aimed to lie within predefined corridors. The predefined corridors were established by launching a close-to-rigid 5.95 kg FE cylindrical impactor against full FE numerical models (Klug, 2017; Figure 1-36). A total of 11 vehicle models from five different car manufacturers were used. The FE impactor was launched against eight total locations on the spoiler, bumper, bonnet lead, and bonnet, once at the vehicle centerline, and once at the bumper corner location. The same procedure was repeated with the four generic FE vehicle models. Acceleration and displacement (deflection) are obtained from node history of the impactor. Force was calculated by multiplying the impactor mass by its acceleration (Klug, 2017).

The Euro NCAP generic FE models are useful because they represent classes of vehicles and reduce computation time by only modeling the front end of the vehicle.
However, they do not account for modeling changes in stiffness across the hood and bumper. Hood stiffness depends on the material as well as under-hood clearance and components such as hinges. Interactions with these components result in secondary acceleration peaks and variable peak morphology. Impacts that are in the center of the hood usually result in a short single peak acceleration if there is no contact with an under-hood component (Masoumi, 2011; Shojaeefard, 2014; Wang, 2012). Similar findings were presented in Martinez et al (Martinez, 2007) in which they found variable responses in force-deflection from pedestrian tests across the hood and bumper. These models are also more applicable to the European fleet which is known to sell a greater number of smaller vehicles than the U.S. (New York Times, 2024). The largest Euro NCAP vehicle model is represented by the SUV, which has a vertical distance of approximately 920 mm (36 inches) from the ground to the hood edge. This is not an accurate representation of U.S. trucks. For example, a 2023 Ford F-150 has a ground to hood opening distance of approximately 1170 mm (46 inches). The Insurance Institute for Highway Safety (IIHS) (IIHS, 2023) reported that vehicles with tall front ends (>40 inches) are 45% more likely to cause pedestrian fatalities than vehicles with a hood height of less than 30 inches. Thus, the variation in height will influence pedestrian kinematics and injuries.
2 PROBLEM STATEMENT

Pedestrian fatalities in the U.S. due to vehicle-to-pedestrian crashes have steadily increased since 2010. Studies have been performed to evaluate pedestrian injuries and kinematics through use of PMHS and dummy tests, physical pedestrian component tests, and finite element models. However, there is a lack of testing performed on larger SUV’s and trucks that are representative of the current U.S. vehicle fleet. While the Euro NCAP generic vehicle models are useful, they are not always applicable to the U.S., because they better represent the European vehicle fleet and do not account for variability in stiffness across the hood and bumper. The publicly available FE models that are representative of common U.S. vehicles are validated for frontal crash and occupant protection. These models are not necessarily suitable for evaluating pedestrian protection. Thus, a validated finite element model representative of the U.S. fleet that is validated from pedestrian injury data was needed. This was done through three aims.

- Aim 1: Vehicle Risk Evaluation.
- Aim 2: Finite Element Model Development.
- Aim 3: Finite Element Model Validation.

The purpose of Aim 1 was to sort through NHTSA FARS data to determine the vehicle make and model from the U.S. that is the highest risk to pedestrians. The purpose of Aim 2 was to develop a FE model based on the vehicle make and model determined in Aim 1. The purpose of Aim 3 was to validate the FE model using pedestrian test data from the test vehicle most similar to the modeled vehicle.
3 AIM 1: VEHICLE RISK EVALUATION

NHTSA FARS (NHTSA 2024) data is made publicly available each year. The most recent year of available data at the time of this study was 2021. This section outlines the methods used to analyze FARS data from 2015-2021 to find the vehicle(s) that poses the highest risk to pedestrians.

3.1 Data Sorting Methods

Fatality Analysis Reporting System (FARS) (NHTSA 2024) data from 2015-2021 in the U.S. was acquired from the NHTSA’s website. The excel file labeled “vehicle” for each case year was opened. The variable for the “first harmful event name” was filtered to only include “pedestrians.” “Vehicle body types” were filtered to include convertibles, 2-door sedans, 3-door/2-door hatchbacks, 4-door sedans, 5-door/4-door hatchbacks, compact utility vehicles, large utility vehicles, light pickups, minivans, and station wagons. Cases with an unknown or non-reported travel speed were excluded. Cases without a driver present or unknown if a driver was present were also excluded. Cases in which the crash was coded as “backing up” or “unknown” were excluded to narrow the cases down to primarily front pedestrian crashes. The vehicle model year was filtered to include only models up to 10 years prior to the case year. For example, 2015 data included vehicle model years from 2005 and on. This was done to obtain a large sample size while also excluding model year cars that are becoming obsolete. The cases for each “vehicle body type” listed above were totaled for each year from 2015-2021 and averaged over the same years. The data was then sorted by “vehicle make/model” to determine the most frequent vehicle make/models involved in pedestrian crashes. Specific vehicle model risk factors ($RF_{vehicle}$) were calculated using Equation 3-2.
\[ RF_{\text{vehicle}} = \frac{\text{Fatalities}_{\text{model}}}{\text{Fatalities}_{\text{vehicle body}}} \]

Where:

\( \text{Fatalities}_{\text{model}} \): Number of fatalities by specific vehicle make/model.

\( \text{Fatalities}_{\text{vehicle body}} \): Total number of fatalities by vehicle body from which the vehicle make/model belongs to.

\textit{Equation 3-1: Vehicle risk factor}

### 3.2 Results

Results from the FARS data shows that 4-door sedans were the most common vehicle body type involved in pedestrian fatalities with 3739 cases (43%), followed by compact utility vehicles and light pickups with 1431 (17%) and 1222 (14%) cases, respectively, from 2015-2021 (Figure 3-1). Figure 3-2 shows the most frequent make/model vehicles involved in pedestrian crashes. Only vehicles with 150 or more cases are shown. All vehicles were from 4-door sedan and light pickup vehicle body types. The Ford F-series had the most pedestrian fatality cases overall and from the light truck category with 265 cases, followed by the Chevrolet Silverado with 249 cases, and the Dodge Ram with 181 cases. The Toyota Camry had the second most pedestrian fatalities overall and the most from the four-door sedan category with 244 cases, followed by the Nissan Altima and Toyota Corolla with 211 and 190 cases, respectively.

Vehicle risk factors were calculated for the Ford F-series, Chevrolet Silverado, Dodge Ram, and Toyota Camry using Equation 3-2. The risk factors were 0.22, 0.20, 0.15, 0.07 for the Ford F-series, Chevrolet Silverado, Dodge Ram, and Toyota Camry, respectively.
Figure 3-1: Average pedestrian fatalities by vehicle body type from 2015-2021 (A). Total number of pedestrian fatalities by vehicle body type from 2015-2021 (B).

Figure 3-2: Total fatalities by 4-door sedan models (A). Total fatalities by light truck models (B).

\[
RF_{\text{vehicle}} = \frac{\text{Fatalities}_{\text{model}}}{\text{Fatalities}_{\text{vehicle body}}}
\]

Equation 3-2: Vehicle risk factor

\[
RF_{\text{Ford F-series}} = \frac{\text{Fatalities}_{\text{Ford F-series}}}{\text{Fatalities}_{\text{Light pickups}}} = \frac{265}{1222} = 0.22
\]

\[
RF_{\text{Chevrolet Silverado}} = \frac{\text{Fatalities}_{\text{Chevrolet Silverado}}}{\text{Fatalities}_{\text{Light pickups}}} = \frac{249}{1222} = 0.20
\]
\[RF_{\text{Dodge Ram}} = \frac{\text{Fatalities}_{\text{Dodge Ram}}}{\text{Fatalities}_{\text{Light pickups}}} = \frac{181}{1222} = 0.15\]

\[RF_{\text{Toyota Camry}} = \frac{\text{Fatalities}_{\text{Toyota Camry}}}{\text{Fatalities}_{4\text{-door sedans}}} = \frac{244}{3739} = 0.07\]

3.3 Discussion

The above vehicle make and models with the greatest pedestrian risk factor are highly sold in the U.S (Wall Street, 2023). The Ford F-series, Chevrolet Silverado, Dodge Ram, and Toyota Camry have been the highest selling vehicles, respectively, in the U.S. from 2012-2021. Since these vehicles are highly sold, they are more often on the road, and thus more involved in pedestrian fatalities. While the four-door sedan body category had a higher number of pedestrian fatality cases than the light pickup, the specific model of the Ford F-Series had more pedestrian fatality cases than any other four-door sedan model.

Calculations from Equation 3-2 show that the Ford F-series, Chevrolet Silverado, and Dodge Ram pose a higher risk factor to pedestrians than the Toyota Camry. This is further supported in a report by the IIHS (IIHS, 2023), which state that vehicles with tall front ends (>40 inches) are 45% more likely to cause pedestrian fatalities than vehicles with a hood height of less than 30 inches. Based on the above calculations and the supporting statistics that the number of trucks registered and driven in the U.S. has increased since 2015 (NHTSA, 2021), the front end of a Ford F-150 truck was chosen as the basis for the FE model.
4 AIM 2: FINITE ELEMENT MODEL DEVELOPMENT

An FE front-end vehicle model based on a 2023 Ford F-150 was developed through use of a lidar scan and Hypermesh V2021.2 (Altair, Troy, MI), Ansa V22.1.0 (Beta CAE Systems, Farmington Hills, MI), and LS Pre-Post V4.5 (Ansys, Livermore, CA) modeling software. A flow chart of the model development methodology can be seen in Figure 4-1. These steps will be explained in more detail in sections 4.1 and 4.2 of this chapter.

![Flowchart of FE model development](image)

*Figure 4-1: Flowchart of FE model development depicting the lidar scan, scan post processing, shell model development, solid model development, model part layers, and full FE model.*

4.1 Vehicle Lidar Scan

A 2023 Ford F-150 was available at the VA Labs and was 3D scanned using a Faro Focus S Lidar Scanner. The Faro Focus S Lidar scanner (Figure 4-2) emits infrared beams into a rotating mirror that paints the surrounding environment with light (FARO, 2023). The scanner head rotates, moving the laser across the object or area of interest
resulting in 3D images. These scanners are commonly used in construction, civil engineering, and law enforcement (FARO, 2023). The scan was used to develop the geometry of the finite element model.

![FARO Focus S lidar scanner.](image)

**Figure 4-2: FARO Focus S lidar scanner.**

4.1.1 Methods and Setup

Six target spheres (140 mm diameter) were arranged around the vehicle at varying heights (Figure 4-3). The scanner uses the spheres as markers to align itself in space and align the scans. The spheres were arranged so the scanner could see all the spheres from each scan position. The scanner was set on a tripod, and its built-in inclinometer sensor was used to level the scanner. The scanner parameters were opened and the “Indoor HDR” default setting was chosen. The advanced settings were opened, and the distance range was changed from “normal” to “near.” The settings chosen were best for achieving a high-quality scan in an indoor space when the object of interest is highly reflective and is 10 m or less away from the scanner (FARO, 2023). The output is an 8192 x 3413-point scan with a file size of 273 megabytes.
A total of four scans were taken around the front end of the vehicle: Two at the outboard ends of the vehicle front end, and two at each half of the bumper (Figure 4-4). The two scans on the outboard ends of the vehicle were with the tripod fully extended and standing on an 18-inch platform. The scanner was approximately 6.5 feet high at these positions. Added height was used so the scanner could more easily capture the hood of the vehicle. The two scans across the bumper were performed with the scanner about 4 feet high to accurately capture the geometry of the bumper. The scans were performed from left to right while facing the vehicle (left outboard, left half of bumper, right half of bumper, right outboard). The scanner was approximately 8 feet from the vehicle at each position. Each scan took approximately 10 minutes. The scanner produces poor results on transparent surfaces, so the windshield of the vehicle was covered with brown parchment paper to capture the windshield surface.
4.1.2 Results of Scan

After the four scans were finished, they were uploaded into Faro’s SCENE software. The software compiled and registered the scans together into one large 3D scan. After registration was complete, the scan was cropped to only include the vehicle, and the coordinate system was adjusted to be orthogonal to the vehicle. The scan was then meshed, and the “watertight” option was selected in post-processing which filled in small gaps in the scan geometry. The scan was saved and exported as an STL file. Figures of the scan before and after meshing can be seen in Figure 4-5 below.
Figure 4-5: Lidar scan of truck before meshing (A) and after meshing (B).

4.2 Modeling Technique

The STL file of the scanned truck was imported into Hypermesh software to create a shell model (Figure 4-6). Temporary nodes were created along the surfaces of the roof, windshield, a-pillar, hood, grille, bumper, and spoiler of the vehicle model. Due to the “box-like” shape of the vehicle, a hood (bonnet) leading edge area was not created as seen in the Euro NCAP vehicle models. The nodes for each part were connected using smooth lines and the “spline” function was used to create a mesh of 10 mm quadrilateral shell 4-node elements. The vehicle model parts were connected via their nodes. This procedure was performed for one half of the shell vehicle model and the “reflect” tool in Hypermesh was used to create the other half.
The shell model was uploaded into Ansa software to extrude and mesh the model as a solid (Figure 4-7). The “hexablock” extruded and meshed the shell parts of the hood, bumper, grille, and spoiler into 3D solid parts of 100 mm thickness. Hexahedral 8-node elements of 10 mm were used. Ansa was also used to model part layers. The hood, grille, bumper, and spoiler were each modeled with three shell layers (Figure 4-8); rear foam, compaction, and interface; and one solid foam layer (Figure 4-8), according to Klug et al (Klug, 2017; Klug, 2019). The 3D extruded model was treated as the solid foam layer. The “volume shell mesh function” was used to create the shell layers. The interface, foam, and rear layers were all connected via their nodes. The compaction layers were modeled to be 1 mm in front of the rear foam layers (Klug, 2017; Klug, 2019). A surface-to-surface contact was assigned between the interface and rear foam layers to imitate an end-stop (Klug, 2017; Klug, 2019).
Figure 4-7: Solid shell model developed in Ansa.

Figure 4-8: Material layers that make up FE vehicle model from bottom to top, i.e., rear foam is bottom most layer and interface is topmost layer.

LS Pre-Post was used to assign material properties to the respective part layers according to Klug et al (Klug, 2017; Klug, 2019). The Fu-Chang Foam (Chang, 1998) material card was used for the foam layer. This foam represents a viscoelastic model (Hallquist, 2006) and was validated against polyurethane and polypropylene foams (Chang, 1998). These foams are commonly used as energy absorbing foams in the automotive industry (Chang, 1998). The foam was assigned a Young’s modulus of 1.2E-9 GPa, 3.3E-6 GPa, 6.4E-5 GPa and 2.9E-5 GPa for the hood, grille, bumper, and spoiler, respectively, according to Klug et al (Klug, 2017;
The foam was assigned a mass density of 7.0E-8 kg/mm³ for the hood, grille, bumper, and spoiler, respectively (Table 4-1; Figure 4-12; Figure 4-10; Figure 4-11; Figure 4-12). The piecewise linear plasticity material card was used for all interface layers. This material card is commonly used for metals and defines a yield stress at the point where plastic deformation occurs (Hallquist, 2006). The hood interface layer was 1.3mm thick and assigned a Young’s modulus, yield stress, and mass density of 60 GPa, 0.185 GPa, and 2.65E-6 kg/mm³, respectively, to represent aluminum (Klug, 2017; Table 4-1; Figure 4-13). The grille, bumper, and spoiler interface layers were 1.99 mm, 1.86 mm, and 1.68 mm thick, respectively. They were assigned a Young’s modulus, yield stress, and mass density of 2.5 GPa, 0.024 GPa and 1.1E-6 kg/mm³ to represent plastic (Klug, 2017; Table 4-1; Figure 4-14). The rear foam layer, compaction layer, cowl, a-pillars, and roof were all modeled as shell layers. They were assigned a thickness of 1 mm and the rigid material card with a Young’s modulus and mass density of 210 GPa and 7.89E-6 kg/mm³, respectively to represent steel (Table 4-1; Figure 4-15; Klug, 2019). The windshield was modeled according to the Ford F-250 windshield model from the NCAC (George Mason University, 2024). The windshield was assigned a thickness of 4 mm, and a material card of piecewise linear plasticity with a Young’s modulus of 73.9 GPa. The material properties described in this section will be referred to as the ‘baseline’ properties throughout this document. The baseline material cards from LS-Dyna can be seen in
A ground plane was created at the origin, and the distance from the bottom of the bumper to the ground was set to 380 mm, as measured on the scanned Ford F-150. The model was assigned a mass of 2134 kg, which is the curb weight of a 2023 Ford F-150 (Edmunds, 2023). The full FE model can be seen in Figure 4-16.

*Table 4-1: Baseline properties of hood, grille, bumper, and spoiler.*

<table>
<thead>
<tr>
<th>Property</th>
<th>Hood</th>
<th>Grille</th>
<th>Bumper</th>
<th>Spoiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Thickness (mm)</td>
<td>1.3</td>
<td>1.99</td>
<td>1.86</td>
<td>1.68</td>
</tr>
<tr>
<td>Interface Stiffness (GPa)</td>
<td>60</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Interface Density (kg/mm³)</td>
<td>2.65E-6</td>
<td>1.1E-6</td>
<td>1.1E-6</td>
<td>1.1E-6</td>
</tr>
<tr>
<td>Interface Yield Stress (GPa)</td>
<td>0.185</td>
<td>0.024</td>
<td>0.024</td>
<td>0.024</td>
</tr>
<tr>
<td>Foam Thickness (mm)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Foam Stiffness (GPa)</td>
<td>1.2E-9</td>
<td>3.3E-6</td>
<td>6.4E-5</td>
<td>2.9E-5</td>
</tr>
<tr>
<td>Foam Density (kg/mm³)</td>
<td>7.0E-8</td>
<td>7.0E-8</td>
<td>7.0E-8</td>
<td>7.0E-8</td>
</tr>
<tr>
<td>Compaction and Rear Foam Thickness (mm)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Compaction and Rear Foam Stiffness (GPa)</td>
<td>210</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Compaction and Rear Foam Density (kg/mm³)</td>
<td>7.89E-6</td>
<td>7.89E-6</td>
<td>7.89E-6</td>
<td>7.89E-6</td>
</tr>
</tbody>
</table>
Figure 4-9: Fu Chang Foam material card to represent the baseline hood foam. Baseline values for material cards were adopted from Klug et al.

Figure 4-10: Fu Chang Foam material card to represent the baseline grille foam. Baseline values for material cards were adopted from Klug et al.
Figure 4-11: Fu Chang Foam material card to represent the baseline bumper foam. Baseline values for material cards were adopted from Klug et al.

<table>
<thead>
<tr>
<th>TITLE</th>
<th>Foam_Mat_Bumper</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID</td>
<td>RO</td>
</tr>
<tr>
<td></td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>ECON</td>
</tr>
<tr>
<td></td>
<td>TC</td>
</tr>
<tr>
<td></td>
<td>FAIL</td>
</tr>
<tr>
<td></td>
<td>DAMP</td>
</tr>
<tr>
<td></td>
<td>TBRD</td>
</tr>
<tr>
<td>1</td>
<td>997546430</td>
</tr>
<tr>
<td>2</td>
<td>0.000-00</td>
</tr>
<tr>
<td>3</td>
<td>0.000-00</td>
</tr>
<tr>
<td>4</td>
<td>0.000-00</td>
</tr>
<tr>
<td>5</td>
<td>0.000-00</td>
</tr>
</tbody>
</table>

Figure 4-12: Fu Chang Foam material card to represent the baseline spoiler foam. Baseline values for material cards were adopted from Klug et al.

<table>
<thead>
<tr>
<th>TITLE</th>
<th>Foam_Mat_Spoiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID</td>
<td>RO</td>
</tr>
<tr>
<td></td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>ECON</td>
</tr>
<tr>
<td></td>
<td>TC</td>
</tr>
<tr>
<td></td>
<td>FAIL</td>
</tr>
<tr>
<td></td>
<td>DAMP</td>
</tr>
<tr>
<td></td>
<td>TBRD</td>
</tr>
<tr>
<td>1</td>
<td>687546430</td>
</tr>
<tr>
<td>2</td>
<td>7.000-08</td>
</tr>
<tr>
<td>3</td>
<td>2.800-05</td>
</tr>
<tr>
<td>4</td>
<td>0.000-00</td>
</tr>
<tr>
<td>5</td>
<td>0.000-00</td>
</tr>
</tbody>
</table>
Figure 4-13: Piecewise Linear Plasticity material card to represent the baseline hood interface. Baseline values for material cards were adopted from Klug et al.

Figure 4-14: Piecewise Linear Plasticity material card to represent the baseline grille, bumper, and spoiler interfaces. Baseline values for material cards were adopted from Klug et al.
Figure 4-15: Rigid material card to represent the baseline compaction and rear layers of all model parts. Baseline values for material cards were adopted from Klug et al.

Figure 4-16: Full FE vehicle model and its labeled parts.
5 AIM 3: FINITE ELEMENT MODEL VALIDATION

5.1 Test Corridor Development

NHTSA’s research test database (NHTSA, 2023) is publicly available and allows for America Standard Code for Information Interchange (ASCII) data to be downloaded. ASCII data from pedestrian headform, upper legform, and lower legform tests on a 2015 Ford F-150 and 2016 Chevrolet Tahoe were acquired from the database. Results of these data are also outlined by Suntay et al (Suntay, 2019). The Chevrolet Tahoe is made on the vehicle platform GMT K2XX which is the platform used for large SUV’s and pickup trucks (GM Authority, 2024; The Car Guide, 2024). Therefore, the Chevrolet Silverado and Chevrolet Tahoe are made from the same vehicle platform. As outlined in section 4.2, the Ford F-150 and Chevrolet Silverado were calculated to have the highest risk factors to pedestrians. Having data from both the F-150 and Tahoe provided a larger sample size for model validation. The two vehicles are similar in size and front-end geometry. The lateral hood width and front-end width of the F-150 and Tahoe can be seen in Table 5-1 (Suntay, 2019).

Table 5-1: Lateral hood width and front-end width of Ford F-150 and Chevrolet Tahoe (Suntay, 2019).

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Lateral Hood Width (mm)</th>
<th>Front End Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 Ford F-150</td>
<td>1646</td>
<td>1970</td>
</tr>
<tr>
<td>2016 Chevrolet Tahoe</td>
<td>1760</td>
<td>2020</td>
</tr>
</tbody>
</table>

The ASCII data were plotted and exported as Excel files. Acceleration vs time corridors were developed for the headform and lower legform tests, and force vs time corridors were developed for the upper legform tests. All corridors consisted of an
average and upper and lower bound of \( \pm 1 \) standard deviation. The average and \( \pm 1 \)
standard deviation methodology was previously used by Martinez et al for deriving force
vs displacement corridors (Martinez, 2007).

Averages were calculated by averaging the acceleration (headform and lower
legform) and force (upper legform) across each time point for each respective corridor
impact test. The standard deviation was calculated across each time point for each
respective corridor impact test. The standard deviation was added to the average at each
time point to obtain the upper bound and subtracted from the average at each time point
to obtain the lower bound.

5.1.1 Headform Corridors

The headform tests by Suntay et al (Suntay, 2019) were performed with child and
adult headform impactors and procedures were followed according to Euro NCAP. These
test procedures and impactors were previously described in section 1.4 of this document.
The local headform z-acceleration from the ASCII data of the headforms was used in
corridor development. The local z-axis was in line with the direction of headform launch
and impact (Figure 5-1).
A total of 22 headform impact tests, 11 each for the Ford F-150 and Chevrolet Tahoe, were performed by Suntay et al (Suntay, 2019) (Figure 5-2). A total of 16 headform impacts, five from the Ford F-150 and 11 from the Chevrolet Tahoe, were analyzed for headform corridor development. The only headform impacts analyzed from the Ford F-150 were (“A 10,4”), (“C 5,0”). (“C4,7”), (“C3,-5”), and (“C3,-3”). The remaining headform impacts from the Ford, such as (“A11,8”) had acceleration peaks that had a slow rise time resulting in a peak acceleration around beyond 10 ms (Figure 5-3). This was difficult to replicate in the model validation. The slower rise time likely results from the contoured hood geometry of the F-150. The raised surfaces and curvature of the hood likely absorb the impact resulting in a slower rise time. The slower rise time may also be influenced by properties and/or locations of components under the hood.

Head impacts on the flatter portion of the F-150 hood, such as, (“C5,0”) and (“A10,4”) had a quicker rise time resulting in a peak acceleration at 2ms. Head impact near the front of the F-150 hood such as, (“C4,7”), (“C3,-5”), and (“C3,-3”), had a time to peak acceleration around 8 ms so they were still considered for corridor development. The Chevrolet Tahoe has a much flatter hood geometry than the F-150, as a result the head
impacts on the Tahoe all had peak accelerations around 2 to 5 ms. The flatter hood geometry of the Tahoe is more representative of the hood from the generic vehicle FE model.

Figure 5-2: All headform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B) (Suntay, 2019).
Time T-Zero ($t_0$) was defined as the time at which the headform contacted the vehicle (0 ms in the ASCII data). The considered headform test impacts were grouped into headform corridors of “middle”, and “front and rear” based on similarity of acceleration data and HIC as well as impact locations on the hood (Figure 5-4). The “front and rear” impacts had peak accelerations ranging from 125 g to 194 g compared to a peak acceleration range of 90 g to 119 g for the “middle” impacts. The average HIC value for the “front and rear” impacts was 1451, compared to 635 for the “middle” impacts. Average HIC was determined by taking the average of the individual HIC values for the respective head impacts reported in Suntay et al (Suntay, 2019). The “front and rear” corridors included any impact up to and including 500 mm in the x-direction, as well as impacts that were both 800 mm or more in the x-direction and 700mm or more from centerline in the y-direction. The “middle” corridors included impacts beyond 500 in the x-direction of the vehicle coordinate system, and up to 700 mm from either side of

![Acceleration vs Time Ford F-150 Hood](image)

*Figure 5-3: Headform impact ("A11,8") to Ford F-150 hood. Note the peak acceleration magnitude occurs beyond 10ms.*
the centerline in the y-direction of the vehicle coordinate system. The hood model was separated into two corresponding parts representing the “middle” (red) and “front and rear” (blue) hood as seen in Figure 5-4. The “front and rear” and “middle” groups consisted of nine and seven impacts, respectively. The corridors were created by calculating and plotting the average acceleration and upper and lower acceleration bounds across the respective impacts for both the “front and rear” and “middle” groups.

![Figure 5-4: Headform impact locations with an adult (‘A’) and child (‘C’) headform. The numbers represent the x- and y-coordinates (x,y) of the impact. Red dots represent “middle” hood impacts, and blue dots represent “front and rear” hood impacts.](image)

The “middle” corridor had an average peak acceleration of 94.3 g compared to the “front and rear” corridor average peak acceleration of 127.2 g. The higher acceleration for the “front and rear” corridor is likely due to the headform contacting stiffer parts of the hood. The front and rear impact locations have rigid under hood parts, such as hinges, that result in a stiffer response and greater headform acceleration (Wang, 2012; Shojaeefard, 2014). The corridors can be seen in Figure 5-5 below. The corridors with the individual head impact accelerations can be seen in Appendix B: Experimental Test Corridors.
5.1.2 Upper Legform Corridors

The upper legform to WAD 775 mm tests by Suntay et al (Suntay, 2019) were performed with the Transport Research Laboratory (TRL) upper legform impactor. Test procedures were followed according to Euro NCAP. The test procedures and impactor were previously described in section 1.4 of this document. The local x-axis force of upper and lower load transducers from the ASCII data of the upper legform were used in corridor development. The local x-axis was in line with the direction of impact to the vehicles (Figure 5-6).
Figure 5-6: Schematic of upper legform test. The local x-axis of the upper legform is in line with the direction of impact.

A total of eight upper legform impacts were analyzed, four from the Ford F-150 and four from the Chevrolet Tahoe (Figure 5-7). Time $t_0$ was defined as the time at which the upper legform contacted the vehicle (0 ms in ASCII data). The upper and lower load cell data was plotted for each impact. Load cell force was chosen for the corridors because it is a required metric for pedestrian safety and was an available output from the upper legform FE model. One corridor each for the upper load cell force and lower load cell force was created for all eight impacts. Corridors were created by calculating the average upper load cell force and lower load cell force as well as the upper and lower force bounds for the respective impacts.

The average corridors show that the lower load cells exhibited higher average force (4 kN) compared to the upper load cells (1 kN) (Figure 5-8). This was a result of the lower portion of the impactor contacting the protruding stiff bumpers of the vehicles first, followed by the top part of the impactor contacting the grille. The corridors and forces from the individual impacts can be seen in Appendix B: Experimental Test Corridors.
Figure 5-7: Upper legform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B) (Suntay, 2019).

Figure 5-8: Upper legform force (kN) vs time (ms) test corridors for the lower load cell (left) and upper load cell (right). The black line is the average acceleration, and the dashed gray lines are the upper and lower bounds.

5.1.3 Lower Legform Corridors

The lower legform to bumper tests by Suntay et al (Suntay, 2019) were performed with the Flex-PLI legform impactor. Test procedures were followed according to Euro NCAP. The test procedures and impactor were previously described in section 1.4 of this document. The local y-axis acceleration of the knee joint accelerometer from the ASCII data of the legform was used in corridor development. The local y-axis was in line with the direction of impact to the vehicles (Figure 5-9).
A total of six lower legform impacts were analyzed, three from the Ford F-150 and three from the Chevrolet Tahoe (Figure 5-10). Time $t_0$ from the raw data was not at the time of impact between the lower legform and bumper. As a result, time $t_0$ of the test was defined as the time when the lower legform acceleration exceeded 2 g. This was to ensure there was contact between the legform and bumper. Acceleration vs time was plotted for each impact. Acceleration was chosen for the corridors because it could be easily obtained from the lower legform FE model. While, bending moment and ligament elongation are standards for pedestrian safety, these metrics could not be obtained from the model output.

The average lower legform acceleration, and upper and lower acceleration bounds, were calculated and plotted for both vehicles, respectively. Corridors were separated by vehicle model. The corridors showed an average peak acceleration of 270 g for the F-150 compared to 367 g for the Tahoe. The lower legform exhibited a much stiffer response on the F-150, as it reached its peak acceleration in less than 2ms.
compared to the peak acceleration of 4ms on the Tahoe. The stiffer response on the F-150 is likely due to the protruding bumper and pronounced curvature at the top and bottom of the bumper (Figure 5-10). While the Tahoe has a protruding bumper, it seems to have a smoother and flatter surface than the F-150. The Ford F-150 and Chevrolet Tahoe lower legform corridors can be seen in Figure 5-11. The corridors along with the individual impacts can be seen in Appendix B: Experimental Test Corridors.

Figure 5-10: Lower legform test impacts. Ford F-150 (A) and Chevrolet Tahoe (B)[27].

Figure 5-11: Lower legform acceleration (g) vs time (ms) corridors. Ford F-150 corridor (A) and Chevrolet Tahoe corridor (B). The black line is the average acceleration, and the dashed gray lines are the upper and lower bounds.
5.2 Finite Element Pedestrian Component Simulations

5.2.1 Methods

Headform, upper legform, and lower legform FE simulations were performed on the vehicle model according to Euro NCAP procedures. Livermore Software Technology Corporation (LSTC) pedestrian child headform, adult headform, upper legform, and lower legform models were available for use (LSTC, 2014, 2018; Sommer, 2018). All simulations were completed on Medical College of Wisconsin’s (MCW) Research Computing Center (RCC) with LS-Dyna single precision MPP version R8.0.0 and 64 cores on a cluster. Simulations took approximately 40 minutes to complete. Impact locations were the same as those in Figure 5-4, Figure 5-7, and Figure 5-10. All baseline simulations were run with the FE model having the same material properties as the Euro NCAP generic SUV model. The individual model parts can be referred to in Figure 4-16.

5.2.1.1 Headform methods

LSTC child headform V1.03 and LSTC adult headform V1.06 were used (LSTC, 2018; Sommer, 2018). The child and adult headform masses were 3.5 kg and 4.5 kg, respectively. Both headforms include skull, skin, accelerometer block, and back plate. The outer skin is modeled as rubber and all other parts are rigid. Head impact points were measured by selecting a node from the ground and using the “curves” measurement tool in LS Pre-Post to measure the wrap around distance from the ground to the impact positions. The child and adult headforms were imported into LS Pre-Post and rotated to be 50° and 65° relative to the ground, respectively, per Euro NCAP standards (Euro NCAP, 2018). The headforms were aligned with their respective impact positions on the hood and assigned an initial velocity of 11.1 m/s (40 kph). A surface-to-surface contact
was defined between the vehicle and the headforms. Figure 5-12 shows the setup of a child and adult headform simulation. The rest of the test setups can be seen in Appendix C: Simulation Setup.

Figure 5-12: Example of headform positioning for adult headform impacts “A9,2” (A and C) and child headform impact “C5,0” (B and D).

After simulations were complete, the data was downloaded and the “d3plot” and “binout” files were imported into LS Pre-Post. The “nodout” file was selected to obtain output acceleration from the headform accelerometer. The head accelerometer was defined as a single node (Figure 5-13) according to the LSTC pedestrian headform manuals (LSTC, 2018; Sommer, 2018). After simulations were complete, the data was downloaded and the “d3plot” and “binout” files were uploaded into LS Pre-Post. The local head x-acceleration and resultant acceleration were plotted and saved to Excel. The local head x-acceleration was aligned with the center of the headform and the direction of
impact. This acceleration was plotted against the calculated headform experimental test corridors. The resultant acceleration was used in Equation 5-1 to calculate HIC\(_{15}\) for each simulation impact. Note the HIC equation maximized the HIC value over a time window (\(t_2 - t_1\)) not to exceed 15 ms. The individual HIC\(_{15}\) simulation values were averaged for their respective “front and rear” and “middle” hood locations and compared to the average test HIC\(_{15}\) values of the Ford F-150 and Chevrolet Tahoe at the same impact locations.

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

*Equation 5-1: HIC-15 formula.*

![Figure 5-13: LSTC child headform with head accelerometer node (Sommer, 2018).](image)

5.2.1.2 Upper Legform Methods

LSTC Upper Legform Impactor V2.3.2 (LSTC, 2014) was used. The impactor consists of 16 parts modeled with rigid material and foam and includes post processing nodes for upper and lower load cell contact forces. The 775 mm wrap around distance was measured to determine the upper legform impact locations, per Euro NCAP (Euro NCAP, 2018). A ground node was selected, and the “curves” tool was used to determine
the 775 mm mark. The LSTC upper legform impactor was imported into LS Pre-Post and positioned at the vehicle centerline. The impactor was moved laterally to align with the other test points (Figure 5-14). All test setups can be seen in Appendix C: Simulation Setup. A surface-to-surface contact was defined between the impactor and the bumper and grille. Upper legform was assigned an initial velocity of 9.7 m/s (35 kph). The test velocity was calculated according to Equation 5-2, per Euro NCAP. The angle of impact for the upper legform tests was 0°.

![Figure 5-14: Upper legform FE simulation setup for impacts “U,-1” (A) and “U,+7” (B).](image)

\[ E = 0.5 \times m_n \times v_c^2 \]
\[ m_n = 7.4 \text{kg} \]
\[ v_c = v_0 \cos(1.2\alpha) \]
\[ v_0 = 11.1 \frac{m}{s} ; \alpha = 0^\circ \]
\[ v_c = 11.1 \cos(0) = 11.1 \frac{m}{s} \]
\[ E = 0.5 \times 7.4 \text{kg} \times (11.1 \frac{m}{s})^2 = 455.9 \text{J} \]

\[ v_t = \sqrt{\frac{2E}{10.5kg}} = \sqrt{\frac{2 \times 455.9 \text{J}}{10.5kg}} = 9.3 \frac{m}{s} \]

*Equation 5-2: Upper legform test velocity.*

After simulations were complete, the data was downloaded and the “d3plot” and “binout” files were imported into LS Pre-Post. The “RCFORC” output was selected, according to the LSTC manual (LSTC, 2014), and contact force from the load cells were
plotted and saved to Excel. The contact force outputs from the load cells were plotted against the calculated upper legform test corridors.

5.2.1.3 Lower Legform Methods

LSTC Legform V2.3 (LSTC, 2014) was used. This model is representative of the TRL Legform impactor, which is not the same as the Flex-PLI impactor used in the experimental tests by Suntay et al (Suntay, 2019). The Flex-PLI is known to be more biofidelic, as stated in section 1.4. The lab did not have access to the Flex-PLI FE impactor. The LSTC legform model includes 29 parts divided into an upper leg (femur) and lower leg (tibia) connected by a ligament part. The femur and tibia are represented by rigid tubes and surrounded by a foam layer, which is covered by a neoprene skin (Lstc et al., 2014). The legform was imported into LS Pre-Post and was positioned 25 mm above the ground, per Euro NCAP standards. The lower legform was assigned an initial velocity of 11.1 m/s (40 kph), and a surface-to-surface contact was defined between the lower legform and bumper. The legform was positioned at the centerline of the bumper to align with impact point (L,0), and was moved laterally to align with the other test points (Figure 5-15). All test setup points can be seen in Appendix C: Simulation Setup.

Figure 5-15: Lower legform FE simulation setup for impacts “L,0” (A) and “L,-5” (B).
After the simulations were complete, the “d3plot” was imported into LS Pre-Post. The x-acceleration history of node 19356 at the center of the legform model (Figure 5-16) was recorded and plotted. The acceleration was output was plotted against the calculated lower legform test acceleration corridors.

![Figure 5-16: Lower legform node 19356 from which acceleration output was plotted.](image)

5.2.1.4 Model Validation - CORA

The Correlation and Analysis (CORA) V3.6.1 method (Table 5-2; Gehre, 2009) was used as a metric for evaluation of model time history outputs. The total rating averages the corridor rating and correlation rating resulting in a value from 0 (“unacceptable”) to 1 (“excellent”). CORA is generally used as a biofidelity rating but was used in this study as a metric to compare the model outputs to their respective calculated corridors. CORA combines methods of a corridor rating and correlation rating. The corridor rating evaluates the deviation of a response curve to user defined inner and outer corridors. The corridors used in this study were ± 1 and ± 2 standard deviations from the average curves of the headform, upper legform, and lower legform tests. The correlation rating evaluates phase shift, area under the curve (size), and progression of the
signals by means of cross-correlation. The correlation rating is obtained by assigning weights of 0.5 to the cross correlation, and 0.25 to the size and phase shift, respectively.

Table 5-2: CORA Rating System (Gehre, 2009).

<table>
<thead>
<tr>
<th>Rating</th>
<th>Average Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>0.86 ≤ score ≤ 1.0</td>
</tr>
<tr>
<td>Good</td>
<td>0.65 ≤ score &lt; 0.86</td>
</tr>
<tr>
<td>Fair</td>
<td>0.44 ≤ score &lt; 0.65</td>
</tr>
<tr>
<td>Marginal</td>
<td>0.26 ≤ score &lt; 0.44</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>0.0 ≤ score &lt; 0.26</td>
</tr>
</tbody>
</table>

5.2.1.5 Model Parameters Tuning

Parameters of the FE model were tuned to output results that better correlated to the experimental test corridors. A trial-and-error method was used to alter parameters of interface thickness, interface stiffness, foam stiffness, and foam damping coefficient of the hood and bumper (Table 5-3).

Table 5-3: Material properties altered during model tuning. “X” indicates which properties were changed for the hood and bumper, respectively.

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Hood</th>
<th>Bumper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Thickness</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Interface Stiffness</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Foam Stiffness</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Foam Damping Coefficient</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

First, baseline simulations were run with the Euro NCAP SUV parameters, and CORA was run to obtain baseline scores. Next a hood/bumper parameter was altered (Table 5-3), and model simulations were run. The respective average model output was plotted against the respective experimental test corridor. A visual check was performed to see if the average model output amplitude was within the experimental test corridor and/or was close in amplitude to the average experimental output. If this check was not
passed, the parameter was altered again, and the process was repeated. If the visual check passed, a CORA analysis was run to compare the average model output to the experimental corridors. If there was no improvement in the CORA score from the baseline model output, the process was repeated. If there was significant improvement in the CORA score from the baseline the process was ended. A flowchart of this method can be seen in Figure 5-17.

![Model parameter tuning flowchart.](image)

The following figures and tables outline an example of this methodology. Simulations for the headform to “front and rear” hood were run with the baseline model parameters. The average headform model acceleration from the “front and rear” impacts was plotted against the “front and rear” experimental test corridor (Figure 5-18). A CORA analysis compared the model result (red trace) to the experimental corridors (black and gray). The CORA score was 0.485 with a rating of ‘Fair’ (Table 5-4).

The “front and rear” hood interface thickness was decreased from 1.3 mm to 0.8 mm, and the hood foam damping coefficient was increased from 0 to 1. Simulations for the headform to “front and rear” hood were run with the altered model parameters. This
iteration was labeled “Tuned V1.” The average headform model acceleration from the “Tuned V1” “front and rear” impacts was plotted against the “front and rear” experimental test corridor (Figure 5-19). It is obvious from Figure 5-19 that the model output is outside the experimental test corridor. In this case, a CORA analysis would not have been run. Instead, the damping coefficient or interface thickness would have been altered again and the process repeated. For the purpose of explaining this methodology, a CORA analysis was run to support the visual check of the model output falling outside the experimental corridor. The CORA score for “Tuned V1” was 0.493 with a rating of “Fair” (Table 5-5). The CORA score did not significantly improve so hood model parameters needed to be altered and the process was repeated. The final tuned results will be explained further in the results and discussion sections of this document.

![Figure 5-18: Baseline headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor.](image)

![Table 5-4: Baseline CORA score and rating for headform to “front and rear” hood](table)

<table>
<thead>
<tr>
<th>Baseline Headform to “Front and Rear” Hood</th>
<th>CORA Score</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.485</td>
<td>Fair</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-19: Tuned iteration (V1) headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor.

Table 5-5: Tuned iteration (V1) CORA score and rating for headform to “front and rear” hood.

<table>
<thead>
<tr>
<th>Tuned V1 to “Front and Rear” Hood</th>
<th>CORA Score</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.493</td>
<td>Fair</td>
</tr>
</tbody>
</table>

5.2.2 Results

This section outlines the baseline and tuned model results for the headform, upper legform, and lower legform simulations.

5.2.2.1 Headform Results

Baseline parameters of interface thickness and foam damping coefficient were tuned for increased correlation to the experimental corridors for the “middle” hood and “front and rear” hood (Table 5-6). Tuned material cards can be seen in Appendix A: Tuned Material Cards. Baseline model results for the “middle” hood (Figure 5-20) showed high peak accelerations (120 g) outside the test corridor at about 15ms. The tuned model results for both the “middle” and “front and rear” hood eliminated the second large acceleration peak seen in the baseline models. Tuned model results for the “middle” hood
(Figure 5-21 and Figure 5-22) had an average peak acceleration of 103.2 g and compared to the average corridor peak acceleration of 94.3 g. The average HIC\textsubscript{15} value for the tuned “middle” hood was 705, which was within one standard deviation of the average tests HIC\textsubscript{15} value of 635 (Table 5-7).

Baseline results for the “front and rear hood” (Figure 5-23) showed high peak accelerations (> 200 g) outside the test corridor at about 15ms. Tuned model results for the “front and rear” hood (Figure 5-24) had an average peak acceleration of 138.2 g compared to the average corridor peak acceleration of 127.2 g. The average HIC\textsubscript{15} value for the tuned “front and rear” hood was 1253, which was within one standard deviation of the average tests HIC\textsubscript{15} value of 1451 (Table 5-8).

CORA scores for the “middle” hood improved from 0.643 (baseline) to 0.696 (tuned; Table 5-9). CORA scores for the “front and rear” hood improved from 0.485 (baseline) to 0.897 (tuned; Table 5-9). Baseline and tuned results with the individual model impacts can be seen in Appendix D: Simulation Results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Middle Hood</th>
<th></th>
<th>Front and Rear Hood</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Tuned</td>
<td>Baseline</td>
<td>Tuned</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.3</td>
<td>0.8</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Foam damping coefficient</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Figure 5-20: Baseline headform to “middle” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor.

Figure 5-21: Tuned headform to “middle” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor.
Figure 5-22: Tuned average headform to “middle” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor.

Table 5-7: “Middle” hood headform: Test and tuned model HIC values.

<table>
<thead>
<tr>
<th>Head Impact Location</th>
<th>Test HIC</th>
<th>Tuned Model HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 7,0</td>
<td>506</td>
<td>907</td>
</tr>
<tr>
<td>C 7,-7</td>
<td>764</td>
<td>749</td>
</tr>
<tr>
<td>C 6,-3</td>
<td>611</td>
<td>812</td>
</tr>
<tr>
<td>A 10,5</td>
<td>979</td>
<td>484</td>
</tr>
<tr>
<td>A 11,0</td>
<td>615</td>
<td>853</td>
</tr>
<tr>
<td>A 9,2</td>
<td>398</td>
<td>623</td>
</tr>
<tr>
<td>A 10,4</td>
<td>575</td>
<td>509</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>635</td>
<td>705</td>
</tr>
<tr>
<td>Plus 1 Stdev</td>
<td>810</td>
<td></td>
</tr>
<tr>
<td>Minus 1 Stdev</td>
<td>461</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-23: Baseline headform to “front and rear” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor.

Figure 5-24: Tuned headform to “front and rear” hood model acceleration (g) vs time (ms) output. The colored lines are the headform model impacts. The black line and gray dashed lines represent the test corridor.
Figure 5-25: Tuned average headform to “front and rear” hood model acceleration (g) vs time (ms) output. The red line is the average headform model acceleration. The black line and gray dashed lines represent the test corridor.

Table 5-8: “Front and rear” hood headform: Test and tuned model HIC values.

<table>
<thead>
<tr>
<th>Head Impact Location</th>
<th>Test HIC</th>
<th>Tuned Model HIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 2,0</td>
<td>1862</td>
<td>1688</td>
</tr>
<tr>
<td>C 3,3</td>
<td>1622</td>
<td>1530</td>
</tr>
<tr>
<td>C 5,8</td>
<td>2122</td>
<td>1194</td>
</tr>
<tr>
<td>A 12,-7</td>
<td>1502</td>
<td>759</td>
</tr>
<tr>
<td>A 9,-7</td>
<td>1050</td>
<td>673</td>
</tr>
<tr>
<td>C 5,0</td>
<td>1070</td>
<td>1054</td>
</tr>
<tr>
<td>C 4,7</td>
<td>1466</td>
<td>1396</td>
</tr>
<tr>
<td>C 3,-5</td>
<td>1244</td>
<td>1382</td>
</tr>
<tr>
<td>C 3,-3</td>
<td>1121</td>
<td>1604</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>1451</strong></td>
<td><strong>1253</strong></td>
</tr>
<tr>
<td>Plus 1 Stdev</td>
<td>1802</td>
<td></td>
</tr>
<tr>
<td>Minus 1 Stdev</td>
<td>1100</td>
<td></td>
</tr>
</tbody>
</table>
Table 5-9: Baseline and tuned CORA scores for the “middle” and “front and rear” hood model headform tests.

<table>
<thead>
<tr>
<th>Hood Region</th>
<th>Cross Correlation</th>
<th>Size</th>
<th>Phase Shift</th>
<th>Total</th>
<th>Corridor</th>
<th>Overall Score</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle</td>
<td>0.936</td>
<td>0.762</td>
<td>1.0</td>
<td>0.922</td>
<td>0.363</td>
<td><strong>0.643</strong></td>
<td>Fair</td>
</tr>
<tr>
<td>Front and Rear</td>
<td>0.983</td>
<td>0.219</td>
<td>0.333</td>
<td>0.630</td>
<td>0.339</td>
<td><strong>0.485</strong></td>
<td>Fair</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tuned</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle</td>
<td>0.985</td>
<td>0.808</td>
<td>1.0</td>
<td>0.944</td>
<td>0.672</td>
<td><strong>0.696</strong></td>
<td>Good</td>
</tr>
<tr>
<td>Front and Rear</td>
<td>0.974</td>
<td>0.918</td>
<td>0.442</td>
<td>0.827</td>
<td>0.557</td>
<td><strong>0.897</strong></td>
<td>Excellent</td>
</tr>
</tbody>
</table>

5.2.2.2 Lower Legform Results

The F-150 and Tahoe test corridors are different due to the varying front-end geometries. The FE model geometry was based off a 2023 Ford F-150, which is better represented by the Tahoe front end (Figure 5-26). Thus, results were tuned to match the Tahoe lower legform corridor. Baseline parameters of interface thickness, interface stiffness, and foam stiffness were tuned for increased correlation to the experimental corridors for the bumper (Table 5-10). Tuned material cards can be seen in Appendix A: Tuned Material Cards. Baseline model results for the lower legform to bumper tests has very low (< 100 g) and compliant accelerations outside the test corridors (Figure 5-27 and Figure 5-28).

The average tuned acceleration peaks were 307 g and 312 g for the F-150 (Figure 5-29 and Figure 5-30) and Tahoe (Figure 5-31 and Figure 5-32) impacts, respectively. The similar acceleration values show the consistency of the model output across the six lower legform impacts. This was expected as properties were changed for the entire bumper and not separated into sections like the hood model. Therefore, the model was
tuned to fit the Tahoe test corridor. CORA scores for the lower legform model improved from 0.445 (baseline) to 0.672 (tuned; Table 5-11). Baseline and tuned results with the individua model impacts can be seen in Appendix D: Simulation Results.

![Figure 5-26: 2023 Ford F-150 (left) and 2016 Chevrolet Tahoe (right) test vehicle.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bumper interface thickness (mm)</td>
<td>1.86</td>
<td>6.0</td>
</tr>
<tr>
<td>Bumper interface stiffness (GPa)</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>Bumper foam stiffness (GPa)</td>
<td>6.4E-5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 5-10: Baseline and tuned bumper model properties.
Figure 5-27: Baseline lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Ford F-150 test corridor.

Figure 5-28: Baseline lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor.
Figure 5-29: Tuned lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Ford F-150 test corridor.

Figure 5-30: Tuned average lower legform to bumper acceleration (g) vs time (ms) output. The red line is the average lower legform model acceleration. The black line and gray dashed lines represent the Ford F-150 test corridor.
Figure 5-31: Tuned lower legform to bumper acceleration (g) vs time (ms) output. The colored lines are the lower legform model impacts. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor.

Figure 5-32: Tuned average lower legform to bumper acceleration (g) vs time (ms) output. The red line is the average lower legform model acceleration. The black line and gray dashed lines represent the Chevrolet Tahoe test corridor.
Table 5-11: Baseline and tuned CORA scores for the lower legform to bumper tests (Tahoe corridor).

<table>
<thead>
<tr>
<th>Lower Legform Tahoe</th>
<th>Baseline</th>
<th>Tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross Correlation</td>
<td>0.916</td>
<td>0.975</td>
</tr>
<tr>
<td>Size</td>
<td>0.016</td>
<td>0.976</td>
</tr>
<tr>
<td>Phase Shift</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>0.712</td>
<td>0.981</td>
</tr>
<tr>
<td>Corridor Overall Score</td>
<td>0.179</td>
<td>0.362</td>
</tr>
<tr>
<td>Rating</td>
<td>Fair</td>
<td>Good</td>
</tr>
</tbody>
</table>

5.2.2.3 Upper Legform Results

Baseline parameters of interface thickness, interface stiffness, and foam stiffness were tuned for increased correlation to the experimental corridors for the bumper (Table 5-12). Tuned material cards can be seen in Appendix A: Tuned Material Cards. These were the same bumper properties used in lower legform tuning.

Baseline model results (Figure 5-33 and Figure 5-34) for the upper legform to bumper tests had average lower and upper load cell forces of 2.6 kN and 3.6 kN, respectively. The tuned model results (Figure 5-35, Figure 5-36, Figure 5-37, and Figure 5-38) had average lower and upper load cell forces of 4.7 kN and 2.1 kN, respectively, compared to the test corridor lower and upper load cell forces of 4.2 kN and 1.0 kN, respectively. CORA scores (Table 5-13) for the lower load cell improved from 0.642 (baseline) to 0.927 (tuned). CORA scores (Table 5-13) for the upper load cell improved from 0.498 (baseline) to 0.547 (tuned). Baseline and tuned results with the individual model impacts can be seen in Appendix D: Simulation Results.
Table 5-12: Baseline and tuned bumper model properties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Tuned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bumper interface thickness (mm)</td>
<td>1.86</td>
<td>6.0</td>
</tr>
<tr>
<td>Bumper interface stiffness (GPa)</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>Bumper foam stiffness (GPa)</td>
<td>6.4E-5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Figure 5-33: Baseline upper legform to bumper lower load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the lower load cell test corridor.
Figure 5-34: Baseline upper legform to bumper upper load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the upper load cell test corridor.

Figure 5-35: Tuned upper legform to bumper lower load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the lower load cell test corridor.
Figure 5-36: Tuned average upper legform to bumper lower load cell force (kN) vs time (ms) output. The red line is the average upper legform model force. The black line and gray dashed lines are the lower load cell test corridor.

Figure 5-37: Tuned upper legform to bumper upper load cell force (kN) vs time (ms) output. The colored lines are the upper legform model impacts. The black line and gray dashed lines are the upper load cell test corridor.
Figure 5-38: Tuned average upper legform to bumper upper load cell force (kN) vs time (ms) output. The red line is the average upper legform model force. The black line and gray dashed lines are the upper load cell test corridor.

Table 5-13: Baseline and tuned CORA scores for upper legform to bumper model tests.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Correlation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper Legform Load Cell</strong></td>
<td><strong>Cross Correlation</strong></td>
</tr>
<tr>
<td>Lower Load Cell</td>
<td>0.864</td>
</tr>
<tr>
<td>Upper Load Cell</td>
<td>0.794</td>
</tr>
<tr>
<td><strong>Tuned</strong></td>
<td></td>
</tr>
<tr>
<td>Lower Load Cell</td>
<td>0.985</td>
</tr>
<tr>
<td>Upper Load Cell</td>
<td>0.857</td>
</tr>
</tbody>
</table>
5.2.3 Discussion

5.2.3.1 Hood Material Model Tuning

Both sets of baseline simulations showed initial acceleration peaks around 2 ms from when the headform first contacts the hood. However, they also showed high acceleration peaks of almost 120g for the “middle” hood and greater than 200g for the “front and rear” hood around 15-20 ms. This was due to the headform impact causing the foam layer to compress and contact the rear rigid compaction layer (Figure 5-39).

Increasing hood thickness in FE modeling has been known to increase acceleration and induce a stiffer response (Wang, 2012; Zeng, 2018). The hood interface thickness was increased from 1.3 mm to as high as 2.5 mm and 2.8 mm for the “middle” hood and “front and rear” hood, respectively. This led to an increase in initial peak acceleration and prevented contact with the rigid compaction layer, thus eliminating the late peak accelerations. However, there was high variability in headform acceleration between individual model impacts, the time to peak accelerations were too quick. The time to peak acceleration for the model output was approximately 2 ms and needed to be around 3ms and 8 ms for the “middle” and “front and rear” hood, respectively. Results of these simulations can be seen in Appendix D: Simulation Results.

The hood interface thickness was set to 0.8 mm and held constant. The 0.8 mm hood thickness was a parameter used by Wang et al for the outer thickness of an FE modeled aluminum hood (Wang, 2012). The constant thickness made the most sense from a design perspective, as it would not be realistic if the hood thickness changed between the “front and rear” and “middle” zones. The foam viscous damping coefficient was altered as it is known to help absorb energy and limit crush (Hallquist, 2006).
Simulations were run with the damping coefficient as low as 0.05 and as high as 1.0. Simulations with the damping coefficient at 0.05 resulted in the hood bottoming out as in the baseline results. Simulations with the damping coefficient at 1.0 resulted in too large of an acceleration amplitude. Tuned results for the “front and rear” hood and “middle” hood were achieved with a viscous damping coefficient of 0.4 and 0.1, respectively.

The tuned hood model prevented deformation down to the rigid compaction layer as well as a quick rebound from the headform (Figure 5-39). The greater damping coefficient for the “front and rear” hood resulted in a time to peak acceleration of 7 ms as well as greater head acceleration and less deformation than the “middle” hood. (Figure 5-39) This was expected as the “front and rear” test corridors had greater acceleration and HIC than the “middle” test corridors. The CORA score for the “front and rear” hood improved from ‘Fair’ to ‘Excellent’. While the model time to peak acceleration was 6 ms on the “middle” hood compared to 2 ms from the experimental corridor, the CORA score still improved from ‘Fair’ to ‘Good’. The slower time to peak acceleration for the “middle” hood may have been due to the material property boundary interactions and edge effects with the “front and rear” hood.
5.2.3.2 Bumper Material Model Tuning

Baseline results from the lower legform model showed a compliant response resulting in low accelerations and a time to peak beyond the 10ms corridor. This was expected because baseline properties from Euro NCAP are modeled with low stiffness to resemble European bumpers. European vehicles must comply with UNECE Reg No. 127 which requires compliant, energy absorbing, bumpers to reduce leg injury risk to pedestrians.

FE studies have shown that reducing bumper thickness as well as modeling a more energy absorbent bumper reduces lower legform acceleration (Mo, 2018; Teng, 2016). In this case, increasing the thickness and stiffness of the bumper interface layer, and the foam stiffness, allowed for a more rigid response and increased acceleration, thus better resembling a U.S. bumper. The tuned bumper interface stiffness value of 10 GPa more closely resembles the stiffness of compliant aluminum alloy than plastic. The tuned bumper resulted in significantly less intrusion (Figure 5-40), and more deformation and

Figure 5-39: “C5,0” baseline (A) and tuned (B) child headform to “front and rear” model impact. “A9,2” baseline (C) and tuned (D) adult headform to “middle” hood model impact.
bending to the lower legform impactor (Figure 5-41) than the baseline. CORA scores improved from “fair” to “good” for the lower legform simulations.

Figure 5-40: Bumper intrusion from “L,0” baseline (A) and tuned (B) lower legform to bumper model.

For upper legform baseline simulations, the model showed a compliant response as forces did not peak until 15 ms. As stated earlier, this was expected with the baseline model properties representing European bumpers. The upper load cell force was greater
than the lower load cell force due to most of the impactor contacting the grille. For the tuned simulations, the upper legform impactor was lowered by 80 mm in the z-direction. This allowed for more contact with the bumper and less with the grille resulting in a reduced upper load cell force. Grille properties were the same as those in the Euro NCAP SUV model (Klug, 2019). The same tuned bumper properties for the lower legform simulations were used to achieve optimal upper legform results. Increasing the bumper interface layer thickness and stiffness and foam stiffness resulted in greater lower load cell forces and reduced upper load cell forces. The tuned model resulted in significantly less bumper intrusion (Figure 5-42) and more deformation and bending in the upper legform (Figure 5-43) than the baseline. The upper load cell output remained greater than the experimental test corridor, and CORA scores remained “fair.” However, the tuned model score still improved from the baseline. CORA scores improved from “fair” to “excellent” for the lower load cell output.

![Figure 5-42: Bumper intrusion from “U,+1” baseline (A) and tuned (B) upper legform to bumper model.](image-url)
5.2.4 Limitations

The FE model was based off one lidar scan from a 2023 Ford F-150. Scanning multiple vehicles from the “pickup truck” vehicle class and designing the model based on the average geometry could provide a more generic model representative of a U.S. pickup truck. In addition, this study utilized a total sample size of 16 headform tests, eight upper legform tests, and six lower legform tests across two vehicles. A larger sample size of pedestrian component tests on large SUV’s and trucks would further improve the validation of the model. Additional data could lead to modeling more sections on the hood and bumper that have different material properties to more accurately replicate head and leg injury. The additional data could also reduce the standard deviations in the test corridors, thus leading to a more accurate validation. Using a numerical optimization
method or optimization software to alter the model parameters would also improve validation.

This study altered the parameters of the baseline material cards from the Euro NCAP FE models but did not analyze implementing different material cards. For example, there may be other material cards in LS-Dyna that would better represent the bumper interface or foam. The bumper foam stiffness was increased from 6.4E-5 GPa to 6.5 GPa. At that stiffness value, the foam is almost acting as a rigid plastic or metal. Modeling the bumper like the hood, with an aluminum interface layer and foam layer underneath might be more realistic of a U.S. bumper and produce more accurate upper legform and lower legform results. In addition, the lab did not have access to the FE Flex-PLI lower legform impactor. The Flex-PLI was used in the experimental tests by Suntay et al (Suntay, 2019) Instead, the TRL lower legform impactor was used for lower legform simulations. The TRL is less flexible and less biofidelic than the Flex-PLI. Using the FE Flex-PLI may alter acceleration results from the lower legform simulations.

A full study in which physical pedestrian component tests were performed on many vehicles of the U.S. large SUV/truck class, followed by the development of a validated FE model from the test data would be beneficial to the field. Measuring other outputs from the physical tests such as impact force and vehicle deformation could provide a better insight to material characterization in model development. Physical tests could also be performed on the cowl and a-pillars to obtain injury metrics and validate those parts of the FE model.
6 APPLICATIONS AND FUTURE WORK

Future studies could expand the scope of this project to analyze pedestrian kinematics through use of human body model (HBM) simulations. Studies could examine the effect of pedestrian size, gait, and position relative to the vehicle on kinematics and injuries. These simulations could even be used to recreate real world vehicle-to-pedestrian crashes to deduce kinematics and injuries. HBM simulations were run at the end of this study to show an example of future work.

6.1 Human Body Model Simulations

6.1.1 Setup

Simulations were run with the Toyota Human Model for Safety (THUMS) V4.02 50th male model (Toyota Motor Corporation, 2010) against the FE vehicle model developed in this study, and the Euro NCAP generic FE SUV model. The THUMS 50th male model is representative of an average adult size male and has a height of 175 cm and weight of 77 kg. The THUMS model was positioned laterally at the centerline of the vehicle models to setup a strike to the right posterior leg (Figure 6-1). The vehicle models were assigned an initial velocity of 11.1 m/s (40 kph). Surface to surface contacts were applied between the HBM and vehicle models. The head acceleration from the THUMS model was obtained from the head accelerometer “nodout” file.
6.1.2 Results

Head contact time (HCT) was evaluated for both simulations. HCT was defined as the time of first contact between the THUMS head and vehicle model. The HCT was 89 ms for the developed truck model and 116 ms for the Euro NCAP SUV model (Figure 6-2). The HCT for the developed truck model was similar to the average HCT time of approximately 95 ms from seven full-scale PMHS/ATD tests on a large SUV (Kerrigan, 2009). The HCT would be significant if a future study were to model a deployable hood, as the hood would have to deploy significantly sooner than the Euro SUV model. The quicker HCT for the developed truck model was due to the greater ride height than the
Euro SUV model. The greater ride height resulted in a faster wrap onto the hood by the THUMS model, and a lesser distance for the head to contact the hood (Figure 6-3). The HIC from the THUMS model was 818 and 612 against the developed FE model and Euro SUV model, respectively. The greater HIC for the developed model was expected as the hood model properties were tuned to represent the head acceleration from the Ford F-150 and Chevrolet Tahoe.

Figure 6-2: THUMS head contact time on developed model (A) and Euro NCAP SUV model (B).
Figure 6-3: THUMS interaction with developed model (A) and Euro NCAP SUV model (B) from 0 ms to 120 ms.
7 SUMMARY AND CONCLUSIONS

Pedestrian fatalities have steadily increased in the U.S. since 2010, and the U.S. currently does not have vehicle regulations for pedestrian safety. Much research has been done utilizing PMHS, pedestrian dummies, and FE vehicle models to better understand vehicle-to-pedestrian interaction. Overall, there is a lack of testing on trucks and large SUV’s representative of the U.S. vehicle fleet. The Euro NCAP FE models are useful, but are more applicable to the European fleet which is known to sell smaller vehicles than the U.S. This study aimed to develop an FE front profile vehicle model representative of a truck from the U.S. fleet.

NHTSA FARS data analysis showed that the Ford F-150 was estimated as the highest risk to pedestrians. Therefore, a model based on an available 2023 Ford F-150 was developed through use of lidar scan and Hypermesh, Ansa, and LS Pre-Post modeling software. Material properties from the Euro NCAP SUV model were applied to the developed model as a baseline.

ASCII test data from pedestrian component tests on a 2015 Ford F-150 and 2016 Chevrolet Tahoe was acquired from NHTSA’s research test database. Headform, upper legform, and lower legform tests were separated into experimental test corridors.

Simulations were run using LSTC child and adult headform, upper legform, and lower legform FE impactors on the developed FE vehicle model. Impact locations were the same as those performed on the F-150 and Tahoe. Acceleration output was obtained for the headform and lower legform simulations, and force output was obtained for the upper legform simulations. Model outputs were plotted against their respective experimental test corridors. Hood model parameters of interface thickness and foam
damping coefficient were tuned for increased correlation to the headform experimental test corridors. Bumper model parameters of interface thickness, interface stiffness, and foam stiffness were tuned for increased correlation to the upper legform and lower legform experimental test corridors. CORA scores improved for all simulations. In conclusion, a front-end FE vehicle model representative of a U.S. truck was able to be developed and validated from available pedestrian component test data.

Future studies could use a larger sample size across more vehicles to improve validation. Future studies could also use a numerical optimization method to find the most optimal material parameters and material cards to include in the model. Applications of this work could include HBM simulation to analyze pedestrian kinematics and model real-world vehicle-to-pedestrian crashes.
BIBLIOGRAPHY

American Cars vs European Cars: Whats the Difference? (2024).
https://www.carsiceland.com/post/american-cars-vs-european-cars


Buying Guide: European vs American Cars. (2024).


EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) PEDESTRIAN TESTING PROTOCOL. (2018).


George Mason University. (2024). Center for Collision Safety and Analysis .


GM Authority. (2024).

http://www.asme.org/about-asme/terms-of-use


ASSESSMENT OF ACTIVE AND PASSIVE TECHNICAL MEASURES FOR PEDESTRIAN PROTECTION AT THE VEHICLE FRONT.


IIHS. (2023). Vehicles with higher, more vertical front ends pose greater risk to pedestrians.


Proceedings, September, 243–257.


National Statistics - NHTSA. (n.d.).


NHTSA Research Testing Database. (n.d.).


https://doi.org/10.1080/13588265.2011.616117

Safety Wissen. (n.d.).
https://www.safetywissen.com/object/B04/B04.iab738708vn34xt8xtg5822104wklw63824343021/safetywissen?prev=%2FRequirement%2FW02.c0h7345768cInqmo8ty26378o0hsmk.63467306378%2F


Science Direct. (2024). *Head Injury Criterion.*
https://www.sciencedirect.com/topics/engineering/head-injury-criterion

https://doi.org/10.1016/j.tws.2013.11.003


https://doi.org/10.1007/s12206-016-0632-5

The Car Guide. (2024).


UN Regulations NO. 127: Uniform provisions concerning the approval of motor vehicles with regard to their pedestrian safety performance. (n.d.).


APPENDICIES

Appendix A: Tuned Material Cards

Figure A-1: Tuned Piecewise Linear Plasticity material card to represent the tuned bumper interface.

Figure A-2: Tuned Fu Chang Foam material card to represent the tuned bumper foam.
Figure A-3: Tuned Fu Chang Foam material card to represent the tuned “middle” hood foam.

Figure A-4: Tuned Fu Chang Foam material card to represent the tuned “front and rear” hood foam.
Appendix B: Experimental Test Corridors

Figure B-1: Experimental test corridors plotted with individual experimental impacts. Headform corridors (A,B), lower legform corridors (C,D), and upper legform corridors (E,F).
Appendix C: Simulation Setup

Headform Setup

![Headform Setup Diagram](image)

*Figure C-1: FE headform simulation setups.*

Upper Legform Setup

![Upper Legform Setup Diagram](image)

*Figure C-2: FE upper legform simulation setups.*
Lower Legform Setup

<table>
<thead>
<tr>
<th>Setup</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>“L,0”</td>
<td></td>
</tr>
<tr>
<td>“L,+1”</td>
<td></td>
</tr>
<tr>
<td>“L,+2”</td>
<td></td>
</tr>
<tr>
<td>“L,-3”</td>
<td></td>
</tr>
<tr>
<td>“L,-4”</td>
<td></td>
</tr>
<tr>
<td>“L,-5”</td>
<td></td>
</tr>
</tbody>
</table>

*Figure C-3: FE lower legform simulation setups.*
Appendix D: Simulation Results

Headform Simulation Results

Figure D-1: FE headform simulation results. Baseline and tuned “middle” hood (A,B) and baseline and tuned “front and rear” hood (C,D).
Figure D-2: FE headform simulation results. Interface thickness of 2.5 mm for “middle” hood (A) and interface thickness of 2.8 mm for “front and rear” hood (B).

Upper Legform Simulation Results

Figure D-3: FE upper legform simulation results. Baseline and tuned upper load cell force (A,B), and baseline and tuned lower load cell force (C,D).
Lower Legform Simulation Results

Figure D-4: FE lower legform simulation results. Baseline and tuned F-150 bumper (A,B), and baseline and tuned Tahoe bumper (C,D).