DEVELOPMENT OF A FINITE ELEMENT MODEL AND ANALYSIS OF A REAR-IMPACT SCENARIO OF A LOW-FLOOR MASS TRANSIT BUS

A Thesis By

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

December 2006
I have examined the final copy of this thesis for the form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my father Shivaji, my mother Usha, my sister Sarika, my family and friends
ACKNOWLEDGMENTS

I express my sincere gratitude to my advisor Dr. Hamid Lankarani, Professor of Mechanical Engineering, for his support, encouragement, and timely guidance throughout my masters work at Wichita State University. I also thank Dr. Gerardo Olivares, Research Scientist from the National Institute of Aviation Research (NIAR) for giving me the opportunity to work on this research project, and for his invaluable advice, continuous guidance and support while working in the Computational Mechanics Laboratory at NIAR.

I also thank the National Institute for Aviation Research for providing facilities required for conducting this research, and also the Federal Transit Authority of the United States Department of Transportation for providing financial support for this research.

I express my gratitude to members of my committee, Dr. Bob Minaie and Dr. Bayram Yildirim for their insightful comments and suggestions on my thesis. Special thanks to the library staff and Kristie Bixby, Managing Editor at Wichita State University.

I am also thankful to my colleagues and friends in the Computational Mechanics Laboratory at NIAR who helped me throughout my research work. I thank my friends Amit, Santosh, Gaurav, Kedar, Nikhil, Ashutosh, Aditya, Anand, Pankaj and Sujeet. I would also like to thank my friends Salil, Bhalchandra, and Sachin from India for their motivation. Lastly, I thank my parents for their continuous and unconditional support throughout my studies, and my sister for her timely encouragement.
ABSTRACT

Transit buses provide transportation within cities and counties. They have been involved in approximately 284,000 traffic accidents over the past five years with an average of 57,000 buses involved in accidents per year. Traffic Safety Facts reports show that rear impact is the third most common type of transit bus accident, causing deaths and a large number of injuries. Government standards are very limited for crashworthiness of transit buses, and manufacturers have done few studies on crashworthiness of transit buses. Most studies thus have concentrated on frontal impact scenarios, but very little attempt has been made to study rear impacts of transit buses.

Physical testing of transit buses to study crashworthiness during rear impacts is costly, and data obtained from testing is limited, therefore, so finite element (FE) analysis technique is used. A detailed Computer-Aided Design (CAD) model was obtained from the manufacturer for a typical 30-foot-long low-floor mass transit bus. Meshing was done for structural parts of the bus. Proper joints and connection were provided at appropriate locations. Mesh quality was kept superior so that the model could be used for multiple load cases. Material testing was done to obtain strain rate dependent material properties. The model was validated for front and rear bumper slow-speed tests by comparing FE simulation results with physical tests done by the manufacturer according to Standard Bus Procurement Guidelines (SBPG). Also a high-speed side impact simulation was done and validated. The interior of the bus was modeled in detail and then used to carry out a series of FE simulations for different impact velocities. They were found stable.
Insurance Institute for Highway Safety (IIHS) rear-impact test was carried out, whereby a stationary bus was impacted from the rear at 20 mph by another bus of same weight. Acceleration, velocities, and displacements were measured at different locations in the transit bus. Finite element dummy occupants were placed in the model to observe occupant kinematics in a rear-impact scenario. A MADYMO occupant model was developed to determine injury levels under a rear-impact condition. Accelerations from FE simulations were used for the MADYMO model, and injuries were plotted. It was found that injuries experienced by occupants in the bus during the 20 mph rear impact were much lower than standards specified in the Federal Motor Vehicle Safety Standards (FMVSS).

Real-world rear-impact crash conditions were simulated using three bullet vehicles: Dodge Caravan a minivan, Dodge Neon a passenger car, and Chevrolet 2500 a pickup truck. Also FE simulations were done to study the effect of change in speed of the bullet vehicle and the transit bus. Full overlap and 60 percent overlap conditions of the bullet vehicle impacting the transit bus from rear were simulated. Results of this study show that the finite element model was stable for a range of impact speeds. Also, it was found that at 20 mph, rear-impact occupant injuries were lower than established standards.
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</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background

A bus is a large automobile designed to carry persons in addition to the driver from one place to other. Bus is a short form of the term "Omnibus," which means "for everyone." The organized public transit bus system in the United States was begun in New York in 1829. New York operates one of the largest and heavily used transit bus systems in U.S. Nowadays, buses are an intrinsic part of everyday life, and play an important part in the social fabric of many cities. Transit bus is a category that provides a transportation facility within the city or within counties. The number of transit buses has increased by 30 percent in United States from 1990 to 2002 which shows the importance and increasing usage of transit buses in public transportation (Traffic Safety Facts).

The first motor vehicle fatality occurred in 1889 in New York City. Averages of 11 bus occupants are killed per year in two-vehicle crashes while 162 occupants in other vehicles are killed per year (Fatality Analysis Reporting System FARS database). The number of fatalities in bus accidents is less compared to other types of automobile accidents but the number of injured bus occupants is cause for concern. Averages of 12,000 bus occupants per year are injured in two-vehicle crashes, while 8,800 occupants in other vehicles are required per year (Traffic Safety Facts). Although the total number of accidents involving transit buses is a relatively small number of national accident data statistics, accidents involving transit buses do result in significant social and economic consequences.
In the real world, occupants of motor vehicles are injured and killed in different types of motor vehicle crashes that vary in the direction of impact. Many motor vehicle crashes are generally classified into four categories: frontals, side, rear, and rollovers. There are also different sub categories for each of these types, such as offset frontals, barrier-type frontals, frontals with underride or override, and pole-type frontals.

In the United States, rear impact is the third most common type of vehicle impact, after front and side, respectively which results in fatalities and injuries to occupants (Traffic Safety Facts 1999-2003). Rear impacts account for approximately five percent of motor vehicle crash fatalities and, a quarter of motor vehicle crash injuries, and are associated with serious medical consequences and significant societal costs.

Although frontal impacts constitute the majority of bus collisions, the number of injuries and fatalities suggests that there is a need to examine rear impact bus crashworthiness. Rear collision is associated with different possibilities of crash events, a different distribution of crash severity, and different patterns and causes of injuries. Transit buses are particularly susceptible to rear impact collisions because of their frequent stops.

To deal with the full spectrum of rear end crash types, there is a need to design and develop a detailed finite element (FE) model of transit bus, validate this model, analyze the transit bus for rear-end crashes according to the standard of the Insurance Institute for Highway Safety (IIHS), and subject the FE model of transit bus to different types of rear end collisions. Also, there is a need to investigate different rear end collisions where a bus is hit from behind by different vehicles, such as a passenger car, truck, and minivan traveling at various speeds. These analyses will provide detailed
information about rear end crash events, which can be further used to develop a multi-body model to analyze occupant kinematics and injury levels in a rear end crash scenario.

1.2 Objectives

The objectives for finite element model development and analysis of the rear impact of transit buses are as follows:

► Literature Review and Statistical Study of Rear Impact of Transit Buses in the US

Review the database and literature for accident statistics in order to identify the number of fatalities, injuries, and typical rear impact crash conditions for mass transit buses. Review the typical crashworthiness standard for buses. Review research done on finite element modeling of a bus, material testing, a study of rear impact scenarios, and a study on injury pattern in rear impact.

► Development of Detailed Finite Element Model of Transit Bus

Process the CAD geometry of bus. Generate an FE mesh. Assemble different meshed components, spot welds, and connections. Assign properties and thickness. Model a detailed suspension system, the interior of a transit bus.

► Material Testing

Obtain strain rate dependent properties of various materials used for transit buses. Perform coupon level testing of some material to determine mechanical properties. Assign material properties to the FE model using material models in LS-DYNA, which takes strain rate effects into account for accurate representation of an actual transit bus.
► Validation of FE Model of Transit Bus

Carry out front and rear bumper tests similar to actual tests done by the bus manufacturer. Carry out side impact tests. Validate by comparing results from simulation with physical test results.

► IIHS Rear Impact Test

Test the FE model of the transit bus for IIHS rear impact test condition. Since there is no rear impact crashworthiness standard that evaluates performance of transit buses during rear impact, carry out the IIHS test for seat testing in a rear impact scenario.

► Simulations of Different Rear End Crash Scenarios of Transit Bus

Study the transit bus crashworthiness response in conditions involving different vehicles, such as a car (Dodge Neon), a minivan (Dodge Caravan), and a truck (Chevrolet 2500). To observe the variation in transit bus response by changing the impacting vehicle speed and overlap condition.

► Occupant Simulation Using MADYMO

Study occupant kinematics and the injury pattern during a rear impact crash scenario of a transit bus. The Mathematical Dynamic Model (MADYMO) model will be developed to determine injury criteria and will be compared with the standard.
CHAPTER 2
LITERATURE REVIEW AND BACKGROUND

The U.S. Department of Transportation (DOT) does not have a standard definition of bus or classification for various bus types. In the Traffic Safety Reports, buses are defined as large motor vehicles used to carry more than ten passengers, including school buses, intercity buses, and transit buses. The Federal Motor Vehicle Safety Standard (FMVSS) defines bus as a motor vehicle with motive power, except a trailer designed for carrying more than ten persons. FMVSS defines school bus according to its use; all other motor vehicles are defined by body type. The body types that are not further defined in the FMVSS includes what are commonly referred to in the industry as motor coach /intercity buses and transit/urban buses.

The Federal Motor Carrier Safety Regulations (FMCSR) defines a bus in two ways: as any motor vehicle, including taxicab, designed, constructed or used for the transportation of passengers and as a vehicle designed to carry more that 15 passengers, including driver. This shows that the National Highway Traffic Safety Administration (NHTSA) and Federal Highway Administration (FHWA) of the U.S. Department of Transportation have three different definitions of a bus, which also differ in the minimum number of passenger seats in each.

Generally, buses are categorized according to their service. A transit bus provides public transportation within city or within counties. Intercity or interstate buses provide transit specifically between cities, towns, and rural areas, as well as between states. Shuttle buses provide transit between two destinations. Tour buses provide
transit for tourists to see different sites in a city. *School bus* provides transit to and from school for students. Figure 2.1 shows typical transit buses in United States (U.S.)

![Figure 2.1. Typical transit buses.](image)

### 2.1 Statistical Review

A transit bus is typically equipped for city or frequent-stop suburban service, and features usually include fare box, multiple door, and efficient seating arrangement as opposed to comfortable seating arrangement in intercity buses. The National Transportation Statistics publishes data regarding utilization of a transit bus. The report shows that transit bus miles have increased 40 percent from 1975 to 1990, were constant from 1990 to 1998 and increased 11 percent from 1998 to 2002. The number of transit buses on the road in the U.S. increased by 30 percent from 1990 to 2002, and the delivery of new transit bus motor vehicles have been increased during the same period.

Transit motor bus data from the 2005 National Transportation Statistics [1] report that documents data from 1996 to 2003 shows that there has been a 30 percent increase in the number of transit buses in the U.S. from 1990 to 2002, as shown in figure 2.2. Also, Figure 2.3 shows that the delivery of new transit bus motor vehicles has increased during the same period.
Figure 2.2. Number of U.S. transit motor bus vehicles.

Figure 2.3. Sales or new deliveries of transit motor bus vehicles.

A study of bus accidents in the United States, by The University of Michigan Transportation Research Institute (UMTRI) states that, during 1995 to 1999, an annual average of 704,796 buses was registered to operate on U.S. roads. Buses are involved in approximately 284,000 traffic accidents over five years, with an average of 57,000
buses involved in accidents per year. Almost 300 buses per year are involved in fatal accident according to a report by UMTRI [2].

The *Traffic safety facts* report is an annual compilation of motor vehicle crash data presented by the NHTSA. This report shows an increase in the number of bus crashes resulting in many fatalities and injuries. A study by Volpe [3] that focuses on nationwide collision statistics has concluded that the highest crash-rate-and-severity-rating accident is intersection type crashes where a bus is struck by another vehicle. The second major type of accident is rear end collisions where a bus is struck by another vehicle. These two types of crashes account for almost one third of the top five crash scenarios.

Rear end impact has not been studied in detail because, in transit bus accidents, frontal crash has played the most dominating role. Frontal crashes constitute more than 50 percent of serious and fatal injury-producing passenger motor-vehicle accidents, and have been given the highest priority in establishing the FMVSS. But many statistical data studies have shown that rear end impacts are also major portion of transit bus accidents and should not be neglected while establishing standards. Rear impact accounts for considerable motor vehicle crash fatalities and motor vehicle crash injuries, and are associated with serious medical consequences and significant societal costs.

National Automotive Sampling Systems, General Estimates System (GES) data have indicated that the five most frequent crash types involving motor coaches are as follows: lane change, rear end, intersection, parked, and backing up scenarios. The total for the top five crash categories comprises approximately 87 percent of crashes involving motor coaches within the United States.
A study by Volpe [3] for the National Transportation System which focuses on nationwide collision statistics has concluded that the highest crash-rate-and-severity-rating accident is intersection type crashes where a bus is struck by another vehicle. The second major scenario is rear-ending type of collisions where a bus is struck by another vehicle. These two types of crashes account for almost one third of the top five scenarios. This study also showed that in 1994, transit buses were involved in 3,119 rear-end collisions. By 1996, that number increased 56 percent. For the same period, the number of injuries increased 161 percent, as shown in Table 2.1.

Table 2.1

<table>
<thead>
<tr>
<th>CRASHES AND INJURIES FOR TRANSIT BUS REAR END COLLISION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>Crashes</td>
</tr>
<tr>
<td>Injuries</td>
</tr>
</tbody>
</table>

The Transit IVI Committee, composed of the Federal Transit Administration (FTA), representative transit agencies, manufacturers, and academia, have identified four user services as high priority transit IVI services, using systems that enable drivers to process information, make better decisions, and operate vehicles more safely:

- Lane Change and Merge Collision Avoidance
- Forward Collision Avoidance
- Rear Impact Collision Mitigation
- Tight Maneuvering/Precision Docking
This study says that if more information about rear impact mechanism of transit buses is available, then more regulation and training can be given to drivers to prevent accidents. Also, it is indicated in this study that the majority of collisions occurs when the bus is decelerating or stopped.

Both NHTSA and GES accident statistics also included crash data involving buses. The statistics in NHTSA Traffic Safety Facts 2000 [4] offers some insights into types of crashes. Roughly, frontal collisions and rear collisions each account for one-fourth and side collisions half of all crashes. Table 2.2 and Figure 2.4 outline the distribution of bus crashes by the initial point of impact in the year 2000:

TABLE 2.2
BUSES INVOLVED IN ALL CRASHES BY THE INITIAL POINT OF IMPACT (2000)

<table>
<thead>
<tr>
<th>Initial Point of Impact</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>16,000</td>
<td>28.2</td>
</tr>
<tr>
<td>Left Side</td>
<td>14,000</td>
<td>24.3</td>
</tr>
<tr>
<td>Right Side</td>
<td>13,000</td>
<td>23.3</td>
</tr>
<tr>
<td>Rear</td>
<td>13,000</td>
<td>22.9</td>
</tr>
<tr>
<td>Non-Collision</td>
<td>&lt; 500</td>
<td>0.3</td>
</tr>
<tr>
<td>Other/Unknown</td>
<td>1000</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>56000</td>
<td>100</td>
</tr>
</tbody>
</table>

Total 56,000 buses was involved in accidents in that year, of which 13,000 buses where involved in rear impacts. Rear impacts constitute approximately 23 percent of the total bus accidents involved in the year 2000.
Traffic safety facts reports generally give accident data in crash severity form, differentiating between fatalities and injuries. FARS, established by NHTSA, gives information about all accidents in which death of occupant occurs. GES publishes data about accidents in which the occupant incurs injuries. These two distinctive crash scenarios can be explained as follows:

(1) Fatal Crash. A police-reported crash involving a motor vehicle in transport on a traffic way in which at least one person dies within 30 days of the crash.

(2) Injury Crash. A police-reported crash that involves a motor vehicle in transport on a traffic way in which no one died but at least one person was reported to have one of the following:

(a) Incapacitating injury

(b) Visible, but not incapacitating injury

(c) Possible, not visible injury

(d) Injury of unknown severity
The Traffic safety Report from 1999 to 2003 [4, 5, 6, 7, 8] shows that 16 percent of rear impacts accounts for bus crashes involving fatalities. Approximately 25 percent of bus crashes involving injuries occur when the initial point of impact is at the rear. Approximately 36 percent of buses involved in fatal crashes are transit bus. Also, this report gives interesting facts about two-vehicle crashes. Approximately 68 percent of bus occupant injuries occur during two vehicle crashes, and 30 percent of bus occupant injuries occur from rear crashes. Averages of 40 bus occupants were killed and 18,430 injured from 1999 to 2003. Approximately 38 percent of buses involved in fatal accidents are school buses, 36 percent are transit buses, 11 percent other, 9 percent intercity, and 6 percent unknown. Also, 40 percent of bus occupant injuries results from school bus crashes, 24 percent from intercity bus crashes, and 23 percent from transit bus crashes.

A trend in bus occupant fatalities during the years 1975 to 2003, obtained from Traffic Safety Facts is observed: Until 1990, the number of fatalities remained consistent, but after that period, it was reduced, and the number of fatalities again increased during the last couple of years. The number of bus occupant injuries is a point of concern after reviewing the statistics presented by the Traffic Safety Report. Though fatalities in bus crashes are minimal, compared to fatalities in other vehicle crashes, the number of injuries in bus crashes is causing large social and economical consequences.

The main objective of this statistical review was to focus on rear end bus crashes. Traffic Safety Facts reports show that there are considerable fatalities and injuries in rear end bus crashes. Many studies have been done on occupant kinematics
and the injury mechanism in frontal bus crashes, but statistics shows that there is also a need to examine rear end crash mechanism. Statistics shown in Figure 2.5 indicate that 16 percent buses are involved in rear end type crashes which rank second in total bus crashes.

![Figure 2.5. Buses involved in crashes with fatalities by initial point of impact.](image1)

Injuries have been a major part of bus accidents. Statistical reports show that when a bus crashes with the rear end as the initial point of impact, 24 percent occupants are injured, as shown in Figure 2.6.

![Figure 2.6. Buses involved in crashes with injuries by initial point of impact.](image2)
In conclusion rear impact collision is responsible for significant costs including damage to the bus, injuries to the occupants, and disruption of the operation of the transit agency. Various studies have shown that the rear impact scenario is the second most frequent crash incident. The rear end type of accident is common with transit companies all over the United States. The preponderance of crashes occurs with buses stopped during daylight, while traversing a straight path, and involving a striking vehicle attempting no avoidance or corrective action. A summary of rear end transit bus crashes [9] is given in Table 2.3, which shows that almost 67 percent of accidents occurs when the bus is stationary.

### TABLE 2.3
SUMMARY OF REAR END TRANSIT BUS CRASHES

<table>
<thead>
<tr>
<th>Feature</th>
<th>Most Common (%)</th>
<th>Second Most Common (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Lanes</td>
<td>Two (41.7%)</td>
<td>More than Two (39.1%)</td>
</tr>
<tr>
<td>Relation to Junction</td>
<td>Non-Junction (62.7%)</td>
<td>Approach to Intersection (22.2%)</td>
</tr>
<tr>
<td>Grade</td>
<td>Level (59.6%)</td>
<td>Grade (15.4%)</td>
</tr>
<tr>
<td>Alignment</td>
<td>Straight (89.1%)</td>
<td>Curve (7.6%)</td>
</tr>
<tr>
<td>Speed Limit</td>
<td>30-45 (55.3%)</td>
<td>50-75 (15.8%)</td>
</tr>
<tr>
<td>Following Vehicle Speed</td>
<td>&lt;= 25 mph (47.3%)</td>
<td>26-40 Mph (34.4%)</td>
</tr>
<tr>
<td>Bus Motion</td>
<td>Stopped (67.2%)</td>
<td>Slowing in Lane (13.5 %)</td>
</tr>
<tr>
<td>Corrective Action Attempted by Striking Vehicle</td>
<td>None (67.3%)</td>
<td>&gt;2 Vehicles Involved (15.4%)</td>
</tr>
<tr>
<td>Following Vehicle Movement Prior to Critical Event</td>
<td>Going Straight (67.3%)</td>
<td>Slowing or Starting (6.6%)</td>
</tr>
</tbody>
</table>
2.2 Previous Research

A statistical review shows the need to do more research on the rear end crash scenario of a transit bus to analyze the crash mechanism and occupant kinematics. Little research has been done on finite element modeling of whole a transit bus and analyzing the FE model for different crash conditions. A few researches have tried to model transit bus but, the model was limited to only the chassis and outer frame.

Vincze –Pap and Csiszar [10] carried out a full-impact laboratory test on a Hungarian Ikarus 411 bus and compared results with a finite element model (FEM) simulation. The main focus of their study was the frontal impact of the bus with a rigid wall. They performed dynamic impact tests on a full-scale bus, driver space, front wall, understructure, and bumper. They put two 50 percentile Hybrid II dummies inside the test bus and impacted it three times at three different speeds. At a speed of 3 and 6 km/hr there was only elastic deformation and no outer damage on the right leg. Crushig destruction occurred on the left side of the bus and bumper-connecting tubes during the second test of 6, 9 km/hr speed. The third test at a speed of 29, 76 km/hr showed significant deformation on the left beam of the bus. Vincze – Papp and Csiszar also created an FE model of a bus using PAMCRASH. Their model consisted a front crash impacting a rigid wall for three load cases, similar to the dynamic full scale tests. Their FEM simulation led to an analogous result as a frontal impact test. But a rear end impact test or any other test was not performed on their FE model. Although their FE model was not designed to carry out a variety of crash tests, they were able to correlate their results for a full scale frontal impact of a bus with a rigid wall.
Kwasniewski et al. [11] studied the crashworthiness of a Para transit bus, the Ford Eldorado Aerotech 240. An FE model was developed based on geometry obtained by disassembling and digitizing all major parts of the actual bus. The geometry required to develop the FE model of the Ford Eldorado transit bus was obtained by a reverse engineering technique. The bus was disassembled and all major structural parts of bus were digitized using FARO arm and software tools such as AnthroCAM, AutoCAD, and Msc-Patran. Disassembling the bus was useful to obtain accurate geometric data acquisition. Polyline scans were processed in AnthroCAM and imported in preprocessor Msc-Patran to generate finite element mesh. The FE model developed consisted of 73,600 elements, 174 property sets, and 23 material models. An Ls-DYNA non-linear, 3-D dynamic FE computer code was used to simulate the behavior of the transit bus under different impact scenarios such as front and side impacts of two buses at various speeds. This model was used to carry out only front and side crash conditions; the rear end impact of transit bus was totally neglected.

Mayrhofer et al. [12] evaluated the effectiveness of a bus and coach seat during rear end impact by means of sled tests. Specifications about strength of seats and their anchorages were specified in ECE regulation 80. But regulation 80 specifies seat testing for only frontal collisions but no rear end collisions. A segment of a real bus structure with two new double seat rows was mounted on a sled with standard spacing. Since the rear impact pulse is weak compared to the front impact pulse, the front impact pulse specified in ECE R80 was also used for sled testing. They concluded that there should be some regulation for testing of seats in rear impact crash conditions to improve the safety for bus and coach occupants.
The Enhanced Coach and Bus Occupant Safety (ECBOS) project [13] was undertaken by seven European research institutes and universities to investigate the field of current bus and coach accidents, and to propose new cost effective test methods and suggestions for improved regulations in order to reduce the risk of injuries to bus occupants. This project covered a wide area such as statistical collision data analysis, development of bus accident database, accident reconstruction, component and full scale testing, development of numerical simulation models for vehicle structure and occupant behavior, detection of injury mechanism, cost analysis and suggestions for improvement in current testing methods. Technical university (TU) Graz conducted a test to investigate the behavior of sitting occupants under a rear impact condition. The validated frontal impact seat model performed by TNO was used as the basis for creating a detailed model for rear impact. TU also performed a rear end impact sled test. The objective of the analysis was to investigate the injury risk in that rear end type of impact incidence and to detect and emphasize the weak points. The main objective of this study was to provide design guidelines for bus seats. The rear end impact study in the ECBOS project was only limited to testing seats and creating guidelines for seats.

Research related to the rear end impact of transit buses is insufficient. Most researchers have tried to simulate front end collision crash scenarios and occupant injury mechanisms. There have been many studies on injuries, such as whiplash, occurring due to rear end impact. Still this research has been limited to the crash of small sedans or cars. The following research review provides some information about the research done relative to rear end impact injuries.
Siegmunds et al. [14] studied the effect of collision pulse properties on seven proposed whiplash injury criteria. They explored this injury phenomenon which is related to a vehicle’s average acceleration rather than its speed change during rear end collisions. Variation within the proposed injury criteria between the different pulses was compared using analysis variance. They concluded that upper neck shear force, upper neck moment, peak retraction, the neck injury criteria (NIC) and two normalized neck injury criteria (Nij and Nkm) were most sensitive to the average acceleration of the collision pulse. In their study, they also suggested that risk of whiplash injury can be reduced by bumper and seat designs that will prolong the crash pulse, thereby reducing the average vehicle and occupant acceleration for a given speed change.

Zellmer et al. [15] studied the enhancement of seat performance in low-speed rear impact. They used a seat equipped with an anti-whiplash system (AWS), consisting of a yielding device fitted to the seat rail, which allowed the entire seat to rotate and move backward. There was a noticeable reduction in the NIC and head rebound speed compared to a standard seat using rear impact dummies. Also, the potential benefits of AWS were estimated on the basis of results obtained from MADYMO simulations done with a real crash pulse.

Kleinberger et al. [16] tried to study the effect of seatback and head restraint design parameters on an occupant in a rear impact. Using a Hybrid III 50 percentile male dummy and a modified production seat, rear impact sled tests were conducted. The seat could be adjusted for recliner stiffness, seatback cushion stiffness, and head restraint height. Neck forces and moments, head motion relative to torso, seatback rotation, and head contact were measured. Their study concluded that risk of whiplash
injury is not simply related to the head restraint position but is also dependent on a combination of factors related to both head restraint and seatback design.

Very few of attempts have been made on finite element modeling and simulation of rear end crashes. Some of them are as follows:

Liu [17] carried out a vehicle rear barrier impact simulation by using a nonlinear finite element approach. FMVSS 301 requires a vehicle to maintain its fuel system integrity in a 30 mph rear moving barrier crash test. The author used nonlinear dynamic, finite element code PAM-CRASH to simulate a rear barrier test which provided quick and inexpensive results. Body in white, full-scale tire, spare tire, engine, and suspension system were modeled of full size sedan. Deformation of the FE model of the sedan obtained for a 50 millisecond simulation of 30 mph rear barrier test matched reasonably with the physical barrier test. Therefore Liu concluded that this nonlinear finite element approach method can help engineers to evaluate rear impact crash characteristics.

Calso et al. [18] simulated an offset and inline car-to-car rear impact. A Detailed 50,000 element FE model was developed to simulate an inline and a 50 percent offset car-to-car rear impact when the bullet vehicle hit the target vehicle at a speed of 50 mph. Finite element analysis (FEA) and tests showed a good comparison of contact timing between the fuel tank and differential, and between the right tire and wheel house. The inline impact occurred 15 milliseconds sooner than that of the offset impact because during inline impact the impacting vehicle loads both rear rails of the target vehicle evenly. Also uniform loading during inline impact puts more energy into the car which results in higher acceleration and earlier separation time. This study helped in
understanding vehicle behavior under car-to-car rear impact, the energy absorption mechanism, and the collapse pattern of rear end components.

A statistical and research review strongly points out the necessity of obtaining knowledge about the rear end crash mechanism of transit buses. The review shows that little research has been done on finite element modeling and simulation of transit bus crashes. Previous researchers have tried to model only a partial transit bus. There is need for modeling and analyzing a full model of a transit bus in order to the study crushing mechanism, and injury patterns in a rear end crash.

2.3 Crashworthiness of Vehicle

In the early 1950's, the term “crashworthiness” meaning ability of structure or any of its component to protect occupant in survivable crashes was first coined in aerospace industry. A similar term was used in the automotive industry as the measure of a vehicle’s structure ability to plastically deform and yet maintain a sufficient survival space for its occupant in crashes involving reasonable deceleration loads. The main goal of a crashworthy of vehicle is one that can absorb energy during a crash by controlled vehicle deformation, while maintaining adequate space so that remaining crash energy can be managed by the restraint system to minimize load transfer to the occupant. Some general guidelines for vehicle crashworthiness are as follows:

- The front structure should be deformable but stiff with a crushable zone to absorb kinetic energy during a frontal crash, and it should prevent any intrusions to the occupant compartment.
• There should be a deformable rear structure to absorb crash energy during rear end impact so as to protect occupants in the rear end compartment.

• The side structure and doors should prevent intrusions to the occupant compartment during a side impact event.

• For rollover protection a strong roof structure should be designed.

2.4 Crashworthiness Tests

Crashworthiness of a vehicle is evaluated by a combination of tests and analytical methods. Every vehicle manufacturer in the United States must meet crash testing standards specified by NHTSA and IIHS for certification purposes. These certification tests require physical laboratory crash tests of the vehicle from the front, side, and rear at different speeds. Therefore the vehicle manufacturer must rely on full-scale laboratory crash test for vehicle certification. Also, the New Car Assessment Program (NCAP) test requires a physical crash test.

Tests for vehicle crashworthiness can be categorized as component tests, sled tests, and full-scale barrier tests. A component test is important to identify the crush mode and energy-absorbing capacity of individual parts. In sled testing, a structure is designed to represent the interior part of a passenger compartment such as seat, instrument panel, steering system, airbags, and seat belts. Anthropomorphic test dummies (ATD) or cadaver subject are seated in the sled to simulate the driver and passenger, and are subjected to similar dynamic loads and acceleration pulses so the occupant response can be evaluated in case of front, side, or rear impact. The evaluation of a restraint system is done by sled testing. Fully instrumented dummies
and sensors on a restraint system help to measure forces and moments, which allows to evaluation of impact severity and effectiveness of the restraint system in transferring loads.

2.4.1 Front Impact Test

Vehicle manufacturers must conduct various front barrier tests in order to ensure a vehicle’s structural stability and compliance to a number of government-mandated regulations. FMVSS specifies standard number 208 for occupant frontal crash protection. A fully instrumented vehicle with numerous load cells, accelerometer and instrumented dummy in the driver seat impacts on a rigid wall at 30 mph. Also, an offset frontal impact test is conducted in which the vehicle impacts on a rigid barrier with certain offset. The purpose of this FMVSS 208 is to reduce the number of fatalities and the severity of injuries to occupants involved in a Frontal crash. Injury assessment values of an ATD dummy should be less than those established for human injury thresholds for head, chest, and legs. In NCAP test dummy performance is evaluated in a frontal crash at speed of 35 mph.

Figure 2.7 shows the setup for a frontal impact test, in which two types of test are carried out. In the first test, the target vehicle impacts a rigid wall, with the front bumper as its full energy absorbing face. In some cases, offset frontal impact tests are also carried out, in which the vehicle impacts a rigid wall with some offset.
2.4.2 Side Impact Test

Standard 214 specified by the Federal Motor Vehicle Safety Standards, outlines performance requirements for protection of occupants in side impact crashes. In this test, side impact dummies (SID) are used in the driver and outboard rear seat locations. A stationary vehicle is impacted by a moving deformable barrier at 33.5 mph. Occupant injury levels experienced during side impact should be minimum in order for the vehicle comply to the FMVSS 214 standard.

Figure 2.8 shows the setup for a side impact test. Here the vehicle is stationary, and a moving deformable barrier (MBD) hits the side of vehicle. Weight, speed, and dimensions of the moving deformable barrier are governed by specifications given in FMVSS 214. A similar test was carried out by the manufacturer of a bus using a 4,000 pound vehicle rather than using a moving deformable barrier.
2.4.3 Rear Impact Test

Integrity of the fuel system of a vehicle is checked by standard 301 whereby a deformable moving barrier or bullet car is impacted on the rear structure of a vehicle. The purpose of this standard is to reduce deaths and injuries occurring from fires that result from fuel leakage in crash events. Standard 224 was established to provide requirements for installation of rear impact guards. The Insurance Institute for Highway Safety rear impact test simulates a collision in which a stationary vehicle is struck in the rear by a vehicle of the same weight traveling at 20 mph. Figure 2.9 shows the setup for a rear impact test.

FMVSS standards 222 and 223 are used to specify rear impact guards and rear impact protection respectively. The purpose of this standard is to reduce the number of deaths and serious injuries that occur when light-duty vehicles collide with the rear end of trailers.
2.4.4 Roof Crush / Rollover Test

Standard 216 specifies the requirements for roof crush resistance over the passenger compartment. The purpose of Standard 220 is to reduce the number of deaths and severity of injuries that results from failure of a school bus body structure to withstand forces encountered in rollover crashes.

2.5 Overview of Bus Regulations and Bus Procurement Guidelines

Government and private organizations in the United States have different guidelines and regulations about transit buses. Regulations created by different agencies mainly focus on their point of interest. Agencies involved in transit bus regulations and safety are as follows:

- Federal Transit Administration (FTA): This government agency comes under the Department of Transportation for primary purpose of providing capital and operating funding assistance to transit providers to improve safety standards.
Also, it provides resources for transit-related training, research, and technical assistance to transit providers for safety and security related issues.

- **Federal Motor Carrier Safety Administration (FMCSA):** This organization establishes safety standards, and regulates the safety of motor carriers and privately owned interstate bus operations.

- **National Highway Traffic Safety Administration (NHTSA):** Testing according to the FMVSS standard is the responsibility of the manufacturer. NHTSA has established motor vehicle safety standards that must be adhered to in the manufacturing process to ensure the safety of a vehicle at its initial sale.

- **National Transportation Safety Board (NTSB):** This independent federal agency is responsible for investigating transportation accidents in the United States, conducting special studies and research in transportation safety, and making recommendations to improve transportation safety based on the results of investigation and research.

### 2.5.1 Standard Bus Procurement Guidelines (SBPG)

The Standard Bus Procurement Guidelines (SBPGs) [19] is a model for solicitation of offers and contracts for the supply of transit buses. They are intended to replace the Baseline Advanced Design Transit Coach Specification or “White Book,” which was developed 20 years earlier for the Federal Transit Administration. The SBPG are organized in five parts:

1. Request for Proposals, Offer, and Award (to be used in competitive negotiation)
2. Solicitation, Offer, and Award (to be used for sealed bids)


5. Warranty Provisions

6. Technical Specifications

Part 6 provides details about technical specifications for transit buses, including many guidelines provided for bus crashworthiness and individual part specifications. According to SBPG, transit buses should have a minimum expected life of 12 years or 500,000 miles, which ever comes first and are intended for the widest possible spectrum of passengers, including children, adults, the elderly, and persons with disabilities.

SBPG requirement for bus crashworthiness states that the bus body and roof structure shall withstand a static load equal to 150 percent of the curb weight evenly distributed on the roof, with no more than a six inch reduction in any interior dimension. Windows shall remain in place and shall not open under such a load. These requirements must be met without components, such as a roof-mounted air conditioner installed. The bus shall withstand a 25-mph impact by a 4,000-pound automobile at any point, excluding doorways, along either side of the bus with no more than three inches of permanent structural deformation at seated passenger hip height. This impact shall not result in sharp edges or protrusions into the bus interior. Exterior panels below 35 inches from ground level shall withstand a static load of 2,000 pounds applied perpendicular to the bus by a pad no larger than five inches square.

SBPGs also provide crashworthiness requirements for bumpers. They should provide impact protection for the front and rear of the bus with the top of the bumper being 26 ± 2 inches above the ground. Requirements for the rear bumper as follows:
• No part of the bus, including the bumper, shall be damaged as a result of a two mph impact with a fixed, flat barrier perpendicular to the longitudinal centerline of the bus.

• The bumper shall return to its pre-impact shape within 10 minutes of the impact. When using a yard tug with a smooth, flat plate bumper 2 feet wide contacting the horizontal centerline of the rear bumper, the bumper shall provide protection at speeds up to five mph, over pavement discontinuities up to one inch high, and at accelerations up to 2 mph/sec.

• The rear bumper shall protect the bus, when impacted anywhere along its width by the Common Carriage with Contoured Impact Surface defined in Figure 2 of FMVSS 301 loaded to 4,000 pounds, at 4 mph parallel to, or up to a 30 degree angle to, the longitudinal centerline of the bus.

• The rear bumper shall be shaped to preclude unauthorized riders standing on the bumper. The bumper shall be independent of all power systems of the bus and shall not require service or maintenance in normal operation during the service life of the bus. The bumper may increase the overall bus length no more than 10 inches.

Bus manufacturers carry out testing of buses as specified by the Standard Bus Procurement Guidelines. This standard helps potential bus buyers to know all necessary information before purchase.

2.5.2 Testing of Buses

The Federal Transit Administration of the U.S. Department of transportation established bus testing program [20] for transit buses in 1987. This program states that testing is required on all new models of buses before they can be purchased with
federal funds. The FTA collaborated with the Bus Research and Testing facility at Pennsylvania State University to conduct some testing, but most was done at the Altoona Research and Testing Center. There is a significant difference in the FTA bus testing program and testing required by the Federal Motor Vehicle Safety Standard issued by NHTSA. Tests conducted under the bus testing program are done by federal government, and FMVSS testing is the responsibility of the vehicle manufacturer. The results of tests conducted under bus testing program are available to bus manufacturer and potential purchasers.

According to the bus testing program, transit buses are tested for maintainability, reliability, safety, performance, structural integrity and durability, fuel economy, noise, emissions, and brakes.

2.6 **Overview of Finite Element Models**

An analytical simulation of vehicle crashworthiness has evolved over the past 30 years. The history of structural crashworthiness analysis can be best characterized by two periods of historical development: an early period from 1970 to 1985, and a second period that began in the mid 1980s’ with the introduction of supercomputers and explicit finite element codes.

In 1992, a cooperative effort by the Federal Highway Administration, National Highway Traffic Safety Administration, Gorge Washington University, and several industry and academic experts formed the National Crash Analysis Center (NCAC) for automotive and highway safety research. This center has developed detailed finite
element models of various automobiles that are available in public domain for further research as shown in Figure 2.10.

Figure 2.10. Finite element models of different vehicles.
CHAPTER 3
COMPUTATIONAL TOOLS

Different types of software tools are necessary for developing a finite element model of a transit bus. These tools are divided into three categories: Pre-Processor, FEA solver, and Post-Processor, which are explained here.

3.1 Pre-Processors

As the name implies, Pre-Processor is a tool that does preliminary processes on its input data to produce output that is used as input to another program. These are widely used tools in any finite element model development. Pre-Processors used for transit bus FE model development are as follows.

HyperMesh

HyperMesh is a Pre-Processor developed and marketed by Altair Engineering Inc. HyperMesh version 7.0 is used as the Pre-Processor for generating a transit bus FE model. HyperMesh is a high-performance finite element processor that enables engineers to quickly and efficiently create finite element models for engineering simulation and analysis. HyperMesh allows users to efficiently mesh high fidelity models. This functionality includes user-defined quality criteria and controls, morphing technology to update existing meshes to new design proposals, and automatic mid-surface generation for complex designs with varying wall thicknesses. HyperMesh provides direct access to a variety of CAD data formats for generating finite element models. It also provides robust tools to clean imported geometry containing surfaces
with holes, gaps, overlaps, or misalignment, which prevent auto meshing and high-
quality mesh generation.

HyperMesh presents users with a sophisticated suite of easy-to-use tools to build
and edit models. For 2D and 3D model creation, users have access to a variety of mesh
generation panels in addition to HyperMesh’s powerful auto-meshing module. The
surface auto meshing module in HyperMesh is a robust tool for mesh generation that
provides users the ability to interactively adjust a variety of mesh parameters for each
surface or surface edge. These parameters include element density, element biasing,
mesh algorithm, and more. Element generation can be automatically optimized for a set
of quality criteria.

Model setup and assembly is easy with HyperMesh. Weld models using
connectors, create contacts, apply boundary conditions, and quickly set up solver runs
within the HyperMesh interface. HyperMesh supports a host of different solver formats
such as OptiStruct, Ls-DYNA, Nastran, Ansys, Radioss, Pamcrash, MADYMO, Marc,
etc. for both import and export. Advantages of HyperMesh are as follows:

- Reduction in time and engineering analysis costs through high-performance finite
element modeling.
- Open-architecture design and customization functionality allowing it to fit
  seamlessly in any environment.
- Reduction in redundancy and model development costs through the direct use of
  CAD geometry and legacy finite element models.
- Simplification of the modeling process for complex geometry through high-speed,
  high-quality automeshing, hexa-meshing, and tetrameshing.
- Advanced functionality allowing users to efficiently mesh highly complicated models.

![Typical screen shot of HyperMesh.](image)

**Oasys PRIMER**

The Oasys PRIMER Pre-Processor developed by Oasys (Ove Arup SYStems) is designed to make preparation and modification of LS-DYNA models as fast and simple as possible, improving user productivity and efficiency, and reducing the time spent manipulating and developing models suitable for LS-DYNA. PRIMER is designed specifically for Pre-Processing with LS-DYNA. Therefore, the user interface is clear, simple, and tailored toward LS-DYNA, without any compromises. All of the common keywords can be created, modified, and graphically visualized to help users understand exactly what a model contains and how the various entities are inter-related. Features of PRIMER are as follows:
• Full LS-DYNA keyword comprehension.
• Visualization of all LS-DYNA entities.
• Ability to read in LS-DYNA keyword, NASTRAN, RADIOSS, and IDEAS input files.
• Ability to create, edit, copy, and delete all common keywords.
• Control card and database editing facility.
• Mesh-independent spot weld creation, fixing, reprocessing and checking.
• Creation of spot welds from a weld data file either interactively or in batch mode.
• Automatic creation of spot welds without an input file.
• Contact visualization, penetration checking with automatic or manual fixing.
• Advanced model deletion, renumbering and merging.
• Part replace function.
• Quick-pick modification and editing of keywords.

This Pre-Processor is widely used in the last stages of transit bus model development because of its effectiveness and efficiency in locating errors in keyword, mesh quality, joints, etc. PRIMER has 2,000 individual model checks and various autofix options. It also provides advanced features related to the merging of two FE models, creating contacts and rigid walls, checking element formulations, and shell normals. PRIMER has a cross reference viewer, which enables it to quickly determine how entities are related.
EASi CRASH DYNA

EASi-CRASH DYNA is the first fully integrated package for crash simulation, which covers the CAE process from start to finish. It achieves this by integrating all aspects of model building, dataset preparation, result evaluation, and design comparisons. EASi-CRASH DYNA can be used for concept crash, FE crash and coupled rigid body/FE crash simulations in conjunction with solvers like LS-DYNA. It directly reads in IGES, NASTRAN, PAM-CRASH, MADYMO, and LS-DYNA data. It has features like rapid graphical assembly of system models, minimum time-step calculation and visualization, and organization and export of models including file format. This Pre-Processor is primarily used for merging two models, contact definition, center of gravity checks, etc. in the FE model development of a transit bus.
3.2 FEA Solver: LS-DYNA

LS-DYNA is an explicit three-dimensional, finite element code for analyzing the large deformation dynamic response of inelastic solids and structures. LS-DYNA is a multifunctional applicable explicit and implicit finite element program used to simulate and analyze highly nonlinear physical phenomenon obtained in real-world problems. Usually those phenomenons are subjected to large deformations within short time duration, e.g., crashworthiness simulations. Moreover, LS-DYNA provides many features that make it a very powerful tool to solve a broad spectrum of applications, i.e., from easy to very complex problems. LS-DYNA was developed by Livermore Software Technology Cooperation (LSTC) in California. LSTC was founded in 1986; however, the
beginning of LS-DYNA can be traced back to the early 70. The features of LS-DYNA are as follows:

- fully automatic definition of contact areas
- large library of constitutive models (over 130 material laws)
- large library of element types
- special application for the automotive industry (seatbelt, airbag, dummy)
- special features for metal-forming applications (adaptive mesh)
- different implicit solvers
- Arbitrary Lagrangian Eulerian (ALE)
- coupled fluid dynamics (CFD)

These features allow the user to apply LS-DYNA to a wide range of different application areas. Primarily crashworthiness (automotive, truck, bus, ship building, train, and airplanes), metal forming, and drop testing (consumer goods). Other applications could be limit-load analysis or safety of buildings after an earthquake or after an impact (airplane). LS-DYNA runs on almost all hardware platforms on both UNIX (SGI, HP, Compay, Sun, CRAY, etc.) and Intel based (Windows, Linux) systems. LS-DYNA is fully vectorized and can be run in shared memory parallelization (SMP) or distributed memory (MPP) mode.

LS-DYNA uses a keyword input format which provides a flexible and logically organized database that is simple to organize. Similar functions are grouped together under the same keyword. For example, under the keyword *ELEMENT are included solid, shell, beam, and damper elements. Each keyword has a certain card defined in
LS-DYNA in its rigid format form and shown as a number of fields in an 80-character string. Nearly all model data can be input in block form. A data block begins with a keyword followed by the data pertaining to that keyword. The next keyword encountered during reading of the block data defines the end of the block and beginning of a new block. A keyword must be left justified with an asterisk (*) contained in the first column. A dollar sign “$” in column one shows that it is a comment and causes the input line to ignore it.

Data blocks are not a requirement for LS-DYNA, but they can be used to group nodes and elements for user convenience. When a keyword input deck is submitted to LS-DYNA, it first checks all data and writes a D3HSP file. If there is an error in the input deck, then analysis is terminated and an error is written in the message or D3HSP file. LS-DYNA writes many Ascii database files containing information regarding cross sectional forces, rigidwall forces, nodal data, etc.

LS-DYNA is widely used by the automotive industry to analyze vehicle designs. It accurately predicts a car's behavior in a collision and the effects of the collision upon the car's occupants. With LS-DYNA, automotive companies and their suppliers can test car designs without having to tool or experimentally test a prototype, thus saving time and expense. LS-DYNA is used to study several crash cases such as frontal impact with different offset values, side impact of barriers with varying velocities, low-speed collisions, or the flashover of a car. LS-DYNA is also widely used in the metal-forming process, military and defense applications, and aerospace applications.
3.3 Post-Processor

Post-processing as the name implies, involves tools that are used to processes that written by solver. The post-processing of data is very important in FE analysis to visualize the results. Two types of post-processors are used in the FE model development of a transit bus – MotionView and LS-Pre/Post.

MotionView

Altair MotionView is a general purpose pre- and post-processor and visualization tool for mechanical system simulation including industry-leading capabilities for flex bodies. MotionView pre-processing provides analysts with an intuitive interface for PC and UNIX and an efficient, neutral multi-body dynamics language that can export to several solvers including MotionSolve, ADAMS, DADS, SIMPACK, ABAQUS, and NASTRAN. MotionView post-processing contains the power of HyperView, combining data plotting and high-performance interactive 3D animation for models containing rigid as well as flexible components. Optimized for speed, MotionView post-processing is capable of synchronized multi-graphic animation and plotting for CAE results.

MotionView's post-processing tools automate analysis procedures for consistent, standardized results analysis. The animation window allows loading and overlay of two or more similar animation files in a single replay window, allowing comparison between animation results from separate analyses. MotionView's sophisticated math engine processes complex mathematical expressions, allowing users to easily graph and interpret engineering data. Users can label and manipulate plots with point-and-click access to axis labels, legends, plot headers, and footers. They can also annotate plots with advanced notes using Templex, a built-in text and numeric processor. The
MotionView process enables users to discover the combination of design variables that leads to an ideal product design. In transit bus model FE development, MotionView is used to visualize the results and plot the graphs. Figure 3.4 shows typical screen shot of MotionView.

![Typical screen shot of MotionView.](image)

**Figure 3.4.** Typical screen shot of MotionView.

**LS-Pre/Post**

LS-Pre/Post is a pre and post-processor developed and maintained by LSTC. LS-Pre/Post emerged from the post-processor LS-Post. The post processing part of LS-Pre/Post is very mature. It supports all features of LS-DYNA. The handling is absolutely intuitive. The advantage is that LS-Pre/Post always provides the latest LS-DYNA features, since it is directly developed from LSTC. In transit bus model FE development, LS-Post is used to visualize the results and plot the graphs.
3.4 MADYMO Occupant Simulation

A MAthemtical DYnamical Models (MADYMO) is a general-purpose software package, which can be used to simulate the dynamic behavior of mechanical systems. Although originally developed for studying passive safety, MADYMO is now increasingly used for active safety and general biomechanics studies. MADYMO is a software package that allows users to design and optimize occupant safety systems efficiently, quickly, and cost-effectively. MADYMO is the worldwide standard for occupant safety analysis and simulation, and it is used extensively in engineering departments, design studios, research laboratories, and technical universities.
With MADYMO, an occupant safety system can be thoroughly assessed and optimized early in its development cycle. Users, therefore, avoid the delays and costs involved in having to change a product late in its development. MADYMO also reduces the requirement for costly and time-consuming prototyping. MADYMO combines in one simulation program the capabilities offered by multibody, for the simulation of the gross motion of systems of bodies connected by complicated kinematical joints and finite element techniques for the simulation of structural behavior. It is not necessary to include both in a model, i.e., a model with either finite elements or multibodies can be used.

To create a MADYMO input data file the user first selects the number of multibody systems and finite element structures to be included in the simulation model. For instance, a simulation model can consist of one multibody system for a dummy, one for a deformable steering column, and one for a child restraint system, and finite element structures for the driver-passenger side airbag and the knee-bolster. For crash dummies, standard databases are available. Next, for each multi-body system, the number of bodies and their configuration for each structure, the finite element mesh, element types and material properties must be specified. An input data file is then set up. This file specifies the configuration, mass distribution, general properties of the multi-body systems (joint characteristics), finite element structures, and acceleration fields. Once a given crash situation has been modeled with the MADYMO package, it is relatively straightforward for users to determine how the scale of potential injuries can be reduced by introducing special safety features or by changing certain design
parameters. This makes the MADYMO package an extremely useful tool for enhancing vehicle safety.

MADYMO is used in automotive and industrial engineering, research laboratories, and human body and mechanical systems. Applications include crash victim safety; crashworthiness for cars, trucks, buses, aircraft, and trains; accident reconstruction, and seating comfort. Highlights include a comprehensive set of validated crash dummy models, biomechanical human body models, advanced restraint systems, (belts, multi-chambered airbags, gas flow dynamics) and airbag folding.

3.4.1 Dummy Database

MADYMO provides the user with different types of validated anthropomorphic test dummies which can be used for occupant simulations. The dummy database of MADYMO provides dummies of different sizes ranging from a child dummy to adult male and female dummies. These dummy models are generally divided into three categories:

1. Ellipsoid
2. Facet
3. Finite Element

The main difference between the model types lies in the modeling techniques applied to represent the geometry and mechanical properties of the modeled components. Ellipsoid models are models that are based fully on MADYMO’s rigid body modeling features; therefore, they are very cost efficient compared to other models. Facet models are, in principle, also multibody models, but compared to ellipsoid models
they benefit from more advanced multibody and also rigid surface FE technology. The FE models are able to reproduce accurately not only kinematics and global deformations, but also local deformations of components and flesh/skin/honeycomb materials as compared to other models. Also FE models are less cost efficient compared to ellipsoid and facet models. Dummies are instrumented with load cells, accelerometers, and displacement transducers at various locations.

A wide range of MADYMO ATD models are available. The standard models of the adult and child Hybrid III dummies are the 5th percentile female, 50th percentile male, 95th percentile male, six-year-old child, and three-year-old child Hybrid III dummy models. The size and weight of the American adult male is represented by Hybrid III 50th percentile male ATD. In order to cover the extremes of the American adult population, two other versions of the Hybrid III have been developed—the 5th percentile small female and the 95th percentile large male.
CHAPTER 4

DEVELOPMENT OF FINITE ELEMENT MODEL OF TRANSIT BUS

Finite element analysis is an extremely efficient and cost-effective tool to test crashworthiness of a vehicle. FEA can be used to predict dynamic behavior of vehicles in crash event. The traditional method of crashing vehicles is extremely costly, and they do not provide definitive information; on the other hand, finite element analysis coupled with high-speed computers is useful for testing crashworthiness of automobiles.

In recent years, the auto industry has experienced the greatest demand from customers, regulators, and the media to provide safer vehicle. To ensure vehicle crashworthiness, a manufacturer must comply with Federal Motor Vehicle Safety Standards, New Car Assessment Program tests, Insurance Institute for Highway Safety regulations, compatibility testing, and child safety testing. Conducting these tests requires a considerable amount of money and time. Many vehicle manufacturers are using finite element techniques to create FE models of their vehicles in order to conduct government compliance tests.

4.1 Procedure Followed to Develop FE Model of Transit Bus

An extensive literature study was done before deciding on the methodology and procedure to create a finite element model of a transit bus. NHTSA and many other university communities have a program to develop a set of finite element models for various vehicles that represents the full range of vehicle types currently on the road, ranging from a subcompact car to a sport utility vehicle to a full size truck. Many
organizations face major problems before developing a model with correct geometrical data of the vehicle. National Crash Analysis Center (NCAC) and other university researchers have followed vehicle tear down and digitization method for acquiring geometrical data. To develop a transit bus model, CAD data regarding geometry of a typical 35-foot, long transit bus was obtained from the Optima Bus Corporation. Availability of 3D CAD data changed the first phase – vehicle tear down for geometry – of model development considerably from the procedure followed by NCAC.

Development of the FE model is categorized in four major steps:

- Cleaning CAD data.
- Development of FE mesh.
- Assigning properties, connection, and defining suspension.
- Validating FE model for front and rear bumpers and side impact test.

The general procedure followed for developing the finite element model of a transit bus is explained in detail in the following steps:

- Detailed CAD data of a 35-foot long transit bus was obtained from the bus manufacturer, Optima Bus Corporation. Three dimensional geometry obtained was created using Pro/Engineer Wildfire 2.0 modeling software.
- The bus assembly was divided into six different sub-assemblies, keeping the original coordinate system.
- The whole bus assembly was opened with Pro/E, and subassemblies were created by deleting unnecessary parts, e.g., for creating the top roof assembly, the entire bus was
opened, all parts were deleted, except the top roof parts, and individual assemblies were saved. This procedure was followed for creating six sub-assemblies.

- Sub-assemblies were exported to IGES format from Pro/E.
- Engine assembly is very complex and contains many small parts. Therefore remodeling of the engine was done using CATIA V5, which concluded the geometry data manipulations.
- The Second phase involved actual modeling of the FE mesh. The Altair HyperMesh preprocessor was used in this stage of model development to create 2D, and 3D mesh and all necessary preprocessing operations to create the finite element model.
- The chassis IGES file was imported in Hypermesh. It consists of almost 300 components. For each component, an individual collector is created in HyperMesh so that the display of individual parts display can be toggled on and off. Since shell elements are cheaper than solid elements for finite element analysis, it was decided to do shell meshing of all the bus components, which requires the middle surface of all components. Since CAD data is available in a 3D solid, the middle surfaces were extracted from every component using HyperMesh.
- The middle surface from each component of the chassis assembly was extracted and transferred to respective collectors.
- Pro/E geometry obtained from the bus manufacturer contains all small features on the parts, such as fillets and small holes these features are harmful while creating mesh. This feature creates unnecessary complications when creating the FE model; therefore these features were cleaned using the geometry cleanup features in HyperMesh.
• Using the auto mesh option in HyperMesh, the middle surface of the component was meshed.
• This meshing procedure of extracting the middle surface and cleaning the surface by removing holes and fillets was followed for all components in chassis subassembly.
• A proper mesh quality criterion was used while creating mesh, and parts were remeshed to meet quality criteria. Parts were connected to each other by spot welds.
• Implicit analysis of subassemblies for Eigen values was done using LS-DYNA to ensure connectivity of different parts in subassembly.
• The above procedure was followed for meshing all six subassemblies. Individual subassembly files are then merged to create one model of a bus. Proper connections were used to join different subassemblies.
• A simplified solid geometry of an engine created in CATIA was used to mesh with the solid elements.
• In this way meshing part of the transit bus was completed.
• The third phase mainly dealt with creating suspension joints and property sets, deciding and assigning material models, and creating initial boundary conditions.
• Strain rate dependent material properties were obtained from material testing, and the data is used to define material models in LS-DYNA.
• Tires are properly meshed and using airbag keyword air pressure is created in tires.
• The final stage of the finite element model development was validation.
• The FE model was set for front and rear bumper tests as well as for a side impact test according to the actual test conducted by the manufacturer. Simulation was run for 150 ms and the results compared with actual test data.
• Simulation results for bumper tests and the side impact test correlated quite well with actual test results.

• Thus, validation of the FE model was complete.

The process of development of finite element model is summarized in the flow chart shown in Figure 4.1.

![Flow chart of FE model development of transit bus.](image)

**Figure 4.1. Flow chart of FE model development of transit bus.**

### 4.2 CAD Data of Bus

Geometry detail and drawing are very important information required for development of finite element model of any vehicle. Since this data is usually the property of the manufacturer of the vehicle, NCAC would have to do a tear down and digitization of the actual vehicle to obtain geometry which is very costly and time
consuming. For the transit bus CAD data, the bus manufacture, Optima Bus Corporation was contacted. A 3D geometry of the transit bus generated with the help of Pro/Engineer wildfire 2.0 obtained from the manufacturer. The Optima bus provided CAD data for their OPUS LFB -29 model of the transit bus. CAD data obtained from the bus manufacturer is shown in Figure 4.2. Dimensions of the transit bus are given in the Table 4.1.

**TABLE 4.1**

**BUS DIMENSIONS**

<table>
<thead>
<tr>
<th>Type</th>
<th>Length (mm)</th>
<th>Width(mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>9,248</td>
<td>2,519</td>
<td>3,192.4</td>
</tr>
<tr>
<td>Front Bumper</td>
<td>2,534</td>
<td>299</td>
<td>198</td>
</tr>
<tr>
<td>Rear Bumper</td>
<td>2,468</td>
<td>246</td>
<td>241</td>
</tr>
</tbody>
</table>

Specifications of Transit bus obtained of FE modeling are as follows,

Number of Seats: 23 + 1 (Driver Seat)
Number of Forward Facing Seats: 17
Number of Side Facing Seats: 6
Number of Doors: 2
Engine Location: Rear End
Number of Tires: 6
Weight of Vehicle: 21290 lbs
Gross Vehicle Weight: 29900 lbs
Engine: ISB Cummins Diesel 6 cylinder engine
Seating arrangements for the transit bus differ for different models. In this particular model, six side-facing seats and 17 forward facing-seats were used. Side-facing seats can be folded to accommodate wheelchair occupants. Figure 4.2 shows CAD data obtained from the manufacturer.

![Figure 4.2. CAD geometry of transit bus.](image)

Data received in Pro/E files was rearranged, and subassemblies were created for convenience of the FE model development. Six major subassemblies were created from original Pro/E data. A file containing sidewalls and chassis was opened, all side wall parts were deleted, and then the Pro/E file was saved. Then this file contained only parts related to the bus chassis. In this way six assemblies were created. The geometry used by the bus manufacturer employs inches as the unit for distance. Since the preprocessor HyperMesh uses millimeters as the default unit for distance, before creating subassemblies, the entire bus geometry was converted into millimeters.

Before transferring CAD data into the preprocessor HyperMesh, it was converted into the Initial Graphics Exchange Specification (IGES) file format standard, which was developed to address the incompatibility issue with various CAD/CAM systems. All Pro/E files of the bus geometry were converted into IGES format to facilitate easy transfer of solid bus geometry data to HyperMesh. GES format files can be imported into Hypermesh, which shows detailed component with its name similar to that given in
Pro/E. Further processing on geometry cleanup and middle surface extraction can be done using Hypermesh.

4.3 Geometry Cleanup

The bus geometry received was very detailed and complex. The Pro/E files of bus geometry included parts which were drawn according to manufacturing specifications. These parts contained every detail like small fillets, curves, and holes. Finite element mesh generation of parts that have small holes, curvatures, and rivet holes can be done, but this will cause an increase in the number of elements, thereby increasing the computational time required for the FE model simulation. Therefore all small features from the bus components were removed as shown in Figure 4.3.

![Geometry cleanup.

Figure 4.3.](image)
Geometry cleanup is necessary because a fillet, pinholes does not affect the crashworthiness evaluation process of a vehicle. To remove these small features from the geometry, an IGES file was imported into Hypermesh. This preprocessor has options like geometry cleanup, defeature, and surface edit, which aid in removing fillets and pinholes.

The effect of geometry clean-up on mesh quality can be viewed in Figure 4.4. Unclean geometry with pinholes and fillets increases the number of elements and affects the quality of the mesh. In contrast, mesh quality is good in a cleaned geometry. Using HyperMesh, the geometry cleaning maintains a good quality mesh for all models. Features affecting load transfer characteristics of the part or the overall crashworthiness are left untouched.

![Figure 4.4. Effect of geometry on mesh.](image)

### 4.4 Mesh Development

Meshing can be defined as the process of breaking up one large component into smaller elements in order to facilitate numerical solutions. Normally, surface domains are subdivided into triangular or quadrilateral shapes, and volume may be divided into
tetrahedral or hexahedral shapes. A major and time-consuming part of finite element analysis is subdividing domains into usable elements. Transit bus meshing was decided to be done involving the majority of shell elements because of this advantage over solid elements.

HyperMesh is a high performance FE preprocessor selected because of its wide range of features and tools. Shell meshing is the process of generating a 2D triangle or quadrilateral element by dividing a large surface. Approximately 95 percent of transit bus meshing is done using shell meshing, which reduces the number of elements, thus resulting in less analysis time. Most shell elements in a transit bus mesh are quadrilateral in shape because of their superior performance over triangular and tetrahedral-shaped elements when comparing the equivalent number of degrees of freedom.

The procedure used to do meshing of a transit bus is as follows

- The IGES format geometry data is imported in HyperMesh.
- The subassembly imported in HyperMesh consists of several individual components having the original name given in Pro/E file.
- The chassis IGES geometry is imported in HyperMesh, as shown in Figure 4.5

![Imported IGES geometry in HyperMesh.](image)
• The display of one collector is kept on which contain one part and the remaining collectors displays are toggled off. Figure 4.6 shows the solid geometry of a part in one collector.

![Figure 4.6. Solid geometry of part in HyperMesh.](image)

• The middle surface extraction is an important phase in creating shell mesh. A new collector is created with the same name as that of displayed part. Midsurface option in HyperMesh is used to extract middle surface from solid geometry. Solid geometry with a middle surface as shown in Figure 4.7.

![Figure 4.7. Middle surface extraction.](image)

• The middle surface of a solid part is then transferred to a newly formed collector.
• Geometry cleanup is done on the extracted middle surface.
• If the middle surface is not extracted properly, the new surface is created using geometry options in HyperMesh. The middle surface is now ready to create a mesh.

• Using the Automesh option, the mesh seed is created with an element size of 50 mm, as shown Figure 4.8. Element density is varied until a satisfactory mesh obtained.

Figure 4.8. Mesh seed.

• Mesh is created from a mesh seed, and care is taken to retain the shape of all elements to quadrilateral. In case of complex surfaces, including curves and holes, all quadrilateral-shaped elements were not possible; therefore meshing was done with both quadrilateral-shaped and triangular-shaped elements. The finite element mesh generated is shown in Figure 4.9.

Figure 4.9. Meshed component.
• A quality index is an option that shows which elements pass or fail the criteria. The meshed component is checked for quality by using the quality index option.
• An element which does not satisfy the quality criteria were edited using options like edit element, optimize, delete element or recreate specific element in order to meet quality criteria.
• Remeshing is done where mesh quality is able to be controlled by using the above-mentioned options.
• Then equivalence of nodes, deleting duplicate elements, and checking shell normal direction is done.
• The above procedure is repeated to create a mesh of all components in one subassembly.
• In the transit bus model, some parts like the chassis beams, side-wall beams, and seat chair are used many times. Repeated components are meshed using mirror and copy elements option.
• This method was used to create 2D shell element mesh of transit bus parts.

4.5 Mesh Quality

Mesh quality has considerable impact on the computational analysis in terms of quality of the solution and time needed to obtain it. Quality of the mesh is the main cause for problems like non-convergence of the solution, aborted computation, warning or error message during simulation, and unexpected analysis results. Poor quality elements can influence analysis results, and lead to misleading and inaccurate results. Minimum and maximum side length, quadrilateral and triangular internal angles, aspect
ratio, warpage angle, and percentage of triangular shaped elements are the main parameters affecting mesh quality.

In HyperMesh, the mesh quality criteria are defined and every component is checked for mesh quality. Elements that don’t satisfy quality criteria were corrected using options like edit element, optimize, or delete element. In some components, the mesh quality was so poor that they were remeshed in order to meet quality criteria. Green-colored elements indicate that they have met the quality criteria; yellow indicates that those elements are acceptable and red indicates that fail to meet quality criteria. Figure 4.10 shows a mesh quality check with three distinct colors.

The above meshed component shows some elements in red and yellow color, which means they are not satisfying quality criteria set by the user. These elements were edited using many options in HyperMesh to meet quality criteria. Care was taken so that every component in the transit bus meets the quality criteria. Table 4.2 provides a summary of the transit bus FE model mesh quality which shows that all meshed parts in the FE model of transit bus met the quality criteria. A minimum side length was kept
at 5 millimeters in order to obtain a good time step. All components were checked for every criteria mentioned in the quality table, which ensured the removal of problems such as model instability and non-convergence of solutions.

**TABLE 4.2**

**SUMMARY OF MESH QUALITY**

<table>
<thead>
<tr>
<th>No</th>
<th>Quality Parameter</th>
<th>Min./Max. Value</th>
<th>Allowable</th>
<th>No. of Violations</th>
<th>Percentage of Violations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Min Side Length</td>
<td>5.0</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Max Side Length</td>
<td>97.5</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Max Aspect Ratio</td>
<td>5.5</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Min Quad Internal Angle</td>
<td>45</td>
<td>45.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Max Quad Internal Angle</td>
<td>138.7</td>
<td>135.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Min Tria Internal Angle</td>
<td>10.5</td>
<td>15.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Max Tria Internal Angle</td>
<td>119.9</td>
<td>120.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Max Warp Angle</td>
<td>15</td>
<td>15.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>% of Triangular Elements</td>
<td>3.9</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The shell normal direction also plays an important role in simulation time and the results. Using an Oasys Primer preprocessor, the shell normal direction was checked. Figure 4.11 shows the shell normal direction for a transit bus FE model.

![Shell normal](image_url)
HyperMesh provides a tool called model check, which checks the individual parts for shell normal direction, quality criteria, properties, etc. If the shell normal directions of some parts are different, then the direction is changed accordingly.

4.6 Engine Meshing

The engine is one of the bulky and solid components in a transit bus, usually mounted on the rear end. The OPUS model LFB 29 transit bus is equipped with a six-cylinder ISB Cummins diesel engine. Meshing of the engine was different than meshing other parts of the bus. Other parts are normally made up of sheet metal or something similar and the 2D shell meshing of such components resembles the characteristics of the original part. But in the case of the engine, composed primarily of solid parts manufactured from a casting process, the shell elements do not predict the behavior of the engine.

The engine’s geometric data obtained from the manufacturer is very detailed, consisting of approximately 600 to 700 components including small rings, nuts, and bolts. It was decided to draw a simplified geometry of the engine using CATIA V5, which represented the original engine. Overall dimensions were taken from a Pro/E file, and the engine was divided into 12 components. Simplification of the engine geometry is shown in Figure 4.12.

Figure 4.12. Geometry cleanup of transit bus engine.
The cleaned geometry still had many pinholes and fillets which were difficult to mesh; therefore it was decided to measure the dimensions of engine from the cleaned geometry and draw a simple engine using CATIA V5. Figure 4.13 shows the modified engine geometry.

![Modified engine geometry using CATIA.](image)

Figure 4.13. Modified engine geometry using CATIA.

The simplified geometry of the engine was imported into HyperMesh through an IGES format. An individual collector was created for each part, and components were meshed with 3D solid elements. Figure 4.14 shows the meshed engine.

![Meshed engine.](image)

Figure 4.14. Meshed engine.
4.7 Assembly of FE Model

Meshing of all components of the transit bus was done according to the procedure explained previously. The geometry modification was done where necessary, e.g., front bumper and rear bumper. The mesh quality of all components was kept under specified limits to ensure overall good quality. After meshing the individual components all geometry was deleted from the respective collectors so they only contain the mesh of the part. Thus all six subassemblies were meshed, and any geometry contents in the HyperMesh file were deleted.

HyperMesh files of subassemblies share the same coordinate system as Pro/E geometry, so to assemble all components, it is not necessary to translate or rotate individual parts or subassemblies. In the chassis assembly, all parts were meshed first, and surfaces of the components were deleted from their respective collectors. For each meshed component, an equivalence of nodes was done. Using the display option, the mesh of the components was displayed. Components were aligned together with their respective positions since all parts share a common coordinate system.

HyperMesh files of the chassis containing only mesh was saved, and the HyperMesh file of the side panels was imported to the chassis file. Thus, the side panels mesh file was merged into the chassis file. Since both chassis and side panel share the same coordinate system, both subassemblies assumed their original places as they are in a transit bus. It was not necessary to translate or rotate any subassembly to place it in the correct position.

In this way, all subassemblies were merged together to create an assembly of transit bus mesh. The only problem arose with the engine, since its coordinate system is
different than those of other subassemblies. Engine elements were selected and positioned correctly using options like translate and rotate in HyperMesh. Figure 4.15, 4.16, and 4.17 shows meshed subassemblies.

Figure 4.15. Meshed sub assemblies I.
Figure 4.16. Meshed sub assemblies II.
4.7.1 Connection for Assembly of FE model

In a transit bus, parts are joined using welding, bolting, or riveting. Generally, welding is commonly used to join two metal parts in the automotive industry. For a transit bus, most of the structural parts are joined by a continuous weld or spot welds, rather than bolting and riveting.

The information regarding coordinates of spot welds used in the bus can be used to define a weld at the exact location between two parts. The manufacturer of a transit bus does not have such information. The spot weld location of each part was obtained from pictures of manufactured individual subassemblies.

LS-DYNA was used as the simulation software because it has a spot weld card for defining a weld that joins two metal parts. LS-DYNA requires two nodes, one node on each part, to define the spot weld between the two parts. Normally, to join two different parts, multiple spots are required. For the transit bus parts joining this card was used. The *CONSTRAINED SPOTWELD card was used to give mass less spot welds between noncontiguous nodal pairs. The spot weld is a rigid beam that connects the
nodal points of the nodal pairs. In this way, nodal rotations and displacements are coupled. The spot welds must be connected to nodes having rotary inertias, e.g., beam or shell.

*CONSTRAINED_SPOTWELD

<table>
<thead>
<tr>
<th>Variable</th>
<th>WID</th>
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<th>N2</th>
<th>SN</th>
<th>SS</th>
<th>N</th>
<th>M</th>
<th>TF</th>
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<td>0</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example, in a chassis, all spot weld locations between two joining parts are decided. Hypermesh preprocessor has the option to create a spot weld by selecting nodes graphically from each component. When two nodes are selected, HyperMesh creates a spot weld between those two nodes. Figure 4.18 shows an example of a spot weld.

Figure 4.18. Spot weld between two parts.

Figure 4.18 explains the procedure used to join two components in a FE model of a transit bus. One precaution is taken during spot welding two parts in HyperMesh. If a particular node is attached to two spot welds, then that node can become over
constrained, and LS-DYNA gives an error message during analysis. Care is taken to avoid attaching the same node to two spot welds.

### 4.7.2 Steps of FE Model Assembly

Individual meshed parts and subassemblies were merged together to create an entire transit bus FE mesh. Spot welds were used to join necessary parts and assemblies. During joining first the chassis was opened, the side panel's were merged, and spot welds were given between adjoining parts to constrain two assemblies. Then the engine and rear floor mesh were merged and joined. After that the front and rear windshields were connected to the chassis frame. Followed by the front and rear bumpers. The roof structure mesh was merged and joined using spot welds. Then the windows, doors, floor, and AC vent were combined with the bus, and the drive train system, front and rear suspension, and tires were joined to the bus. After joining all the major structural parts, the interior parts, such as chairs, wheel cover, steering wheel system, bars, and modesty panels, were attached using spot welds. figure 4.19 and 4.20 shows this step-by-step FE model assembly.

The assembly of each part was done by modeling different spot welds and joints in HyperMesh. Spot welding was done using two nodes each on different parts. HyperMesh provided the tool to easily create spot welds between two parts by selecting nodes. Care was taken to avoid using the same node for two spot welds. If the same nodes, an error was created in analysis deck. The steps shown in Figure 4.19 show how the first structural part of the transit bus is assembled. The interior parts were meshed and assembled separately.
Figure 4.19. Steps in FE model assembly.
Figure 4.20. Final assembly of FE model of transit bus.
### 4.7.3 FE Model Size

Table 4.3 provides information about the FE model size of the transit bus.

**TABLE 4.3**

<table>
<thead>
<tr>
<th>FE MODEL SIZE</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>298,833</td>
</tr>
<tr>
<td>Number of Elements</td>
<td>282,025</td>
</tr>
<tr>
<td>Number of Parts</td>
<td>1,338</td>
</tr>
<tr>
<td>Number of Mass Element</td>
<td>1,315</td>
</tr>
<tr>
<td>Number of Airbags</td>
<td>6</td>
</tr>
<tr>
<td>Number of Properties</td>
<td>1,348</td>
</tr>
<tr>
<td>Number of Sets</td>
<td>166</td>
</tr>
<tr>
<td>Number of Material Models Used</td>
<td>26</td>
</tr>
<tr>
<td>Number of Section Force Planes</td>
<td>49</td>
</tr>
<tr>
<td>Number of Subassemblies</td>
<td>43</td>
</tr>
<tr>
<td>Number of Kinematics Joints</td>
<td>32</td>
</tr>
<tr>
<td>Number of Spot Welds</td>
<td>20,306</td>
</tr>
</tbody>
</table>

Table 4.4 provides information about the type of elements in the FE model of a bus.

**TABLE 4.4**

<table>
<thead>
<tr>
<th>TYPES OF ELEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Element</td>
</tr>
<tr>
<td>Beam</td>
</tr>
<tr>
<td>Triangular</td>
</tr>
<tr>
<td>Quadrilateral</td>
</tr>
<tr>
<td>Solid</td>
</tr>
<tr>
<td>Spring / Discrete</td>
</tr>
<tr>
<td>Accelerometer</td>
</tr>
</tbody>
</table>
4.8 Element Formulation and Section Properties

The transit bus FE model consists primarily of shell elements and fewer solid elements. Simulation results of the FE model vary due to a change in element formulation. Only a few element formulations give an accurate and stable finite element model of vehicles. LS-DYNA has different element formulations for shell, solid and beam elements. Element formulations used in the transit bus FE model are as follows:

**Belytschko-Lin-Tsay Shell (2):** The Belytschko-Lin-Tsay element formulation was used for all shell elements. Since integration points through the thickness increase, the mathematical operations required are more for the Hughes-Liu formulation as compared to the Belytschko-Lin-Tsay element. For example, for five integration points through the thickness of the shell element, the Hughes-Liu shell requires 4,066 mathematical operations, whereas Belytschko-Lin-Tsay requires only 725. Thus, the Belytschko-Lin-Tsay element formulation is more cost effective and efficient compared to the Hughes-Liu formulation.

**Hughes-Liu Shell (1):** This element formulation is used for shell elements that are created on outer extracted surface of components such as interior parts like seats and handle bars. This element formulation is costly since it takes more computational time. But for interior parts, extracting the middle surface was not possible, so by using this element, the outer surface could be meshed. This element formulation is the first shell element implemented in LS-DYNA.

**Constant Stress Solid Element (1):** This element formulation is used for all solid elements but primarily engine parts. It is used for a three dimensional structural
calculation of an eight-node element. Since all solid elements have given rigid material properties, skips these calculations, thus reducing analysis time.

Spotweld Beam (9): This element formulation is used for a beam element, such as a propeller shaft, which gives output from the engine to the differential. The element formulation can be specified in the * SECTION card, as

*SECTION_SHELL

This card is used to specify thickness, element formulation, and the number of integration points for shell elements. Since the majority of shell elements are created on the middle plane of each part, the thickness of each part is measured from Pro/E geometry and specified in this card.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SECID</th>
<th>ELFORM</th>
<th>SHRF</th>
<th>NIP</th>
<th>PROPT</th>
<th>QR/IRID</th>
<th>ICOMP</th>
<th>SETYP</th>
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<td>2</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Default</td>
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<td>1.0</td>
<td>2</td>
<td>0.0</td>
<td>0.01</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Variable</td>
<td>T1</td>
<td>T2</td>
<td>T3</td>
<td>T4</td>
<td>NLOC</td>
<td>MAREA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value</td>
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<td>3.175</td>
<td>3.175</td>
<td>3.175</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This card is used to define the section property of each component. Thickness is specified in the second card at T1, T2, T3, and T4 locations. NLOC is used to specify the location of reference surface as to whether it is a middle surface, outer surface or component. Similarly, *SECTION_SOLID and *SECTION_BEAM cards are defined for solid and beam elements. Figure 4.21 shows the pattern of element formulation in a bus.
The number of through-thickness integration points of shell elements is another important factor, after element formulation, which widely affects analysis results. Integration points can be specified in the section card of the component. Three or more integration points are required to capture deformation of parts like the chassis beams and bumpers. If the number of integration points is less in those areas, then simulation may not give the correct deformation pattern. For a transit bus, all parts that come in the direct path of load transfer during a crash event such as chassis beams, lower side panels, and bumpers, are specified with three integration points. The remaining parts of the transit bus, such as top roof and windows are provided with two integration points.

Figure 4.22 shows the variation of the number of integration points in the transit bus FE model. The red color indicates those parts that are assigned three integration points, and components in green color show that they have two integration points. As the number of integration points increases, the calculation time of analysis increases.
Therefore only parts, that come in direct contact during impact are given a greater number of integration points.

![Figure 4.22. Number of through-thickness integration points.](image)

### 4.9 Material Models and Testing

#### 4.9.1 Material Testing

To predict the actual behavior of a crash scenario using finite element analysis largely depends on accurate material properties definitions. Transit bus parts are composed of several types of material which behave differently in crash scenarios. Yield strength of the material is the stress point at which the material begins to plastically deform. Prior to the yield point, material will deform elastically and then return to its original state when the applied force is removed. Since a single model was used to study various crash configurations (impact velocities from 0 km/hr to 60 km/hr), it is important to define the strain rate effect on the mechanical properties of the main structural materials.
The tensile properties of material are sensitive to strain rate. Strain rate means the rate of change of strain with time. Normally, it is given by

$$
\varepsilon^* = \frac{1}{l} \frac{dl}{dt} = \frac{v}{l}
$$

...(4.1)

where \( l \) is the initial length, and \( v \) is the speed of deformation.

The properties of material are dependent on the rate at which strain occurs. Yield strength and ultimate tensile strength of steel increases with strain rate. The increase of yield strength and ultimate tensile strength with an increase in strain rate is smaller in the strain rate region below 10/s and much higher above 10/s. This shows that material behavior in real life largely depends on strain rate.

Strain rate dependent properties of material are not available in the material handbook. To obtain material data for a transit bus, tensile testing of the material was done. The material required for testing was obtained from the bus manufacturer. To find the material properties for crashworthiness applications, three types of testing are required:

- Mechanical / Servo-Hydraulic: quasi-static condition, i.e., strain rate below 0.1/s.
- Servo-Hydraulic: strain rate range from 0.1 to 500/s.
- Bar System: strain rate range from 100 to 1,000/s and higher.

Strain rate increments of 1, 10, 100, 250, and 500/s are sufficient for describing material strain rate sensitivity. An MTS servo machine and dog bone-shaped material coupons were used for testing. The gauge length and width of the coupon was kept at the load capacity of testing machine. Figure 4.23 shows the specimen geometry and actual specimen used for testing. The results of the material testing show that the steel materials used are more strain rate sensitive than the aluminum materials. In order to
define the input properties for the FE model, the following procedure to convert the
tension test data was adopted:

a. Obtain the engineering stress and strain from the tension test as

\[ \sigma = \frac{f}{A_o} \quad \varepsilon = \frac{\Delta l}{l} \]  \hspace{1cm} (4.2)

b. Calculate the true stress and true strain as

\[ \sigma_{true} = \frac{f l}{A_0 A_o} = \sigma (1 + \varepsilon) \quad \varepsilon_{true} = \ln \left( \frac{l}{l_0} \right) = \ln (1 + \varepsilon) \]  \hspace{1cm} (4.3)

c. Calculate the effective stress and strain curves that will be used as input for the
   FE model as

\[ \sigma_{eff} = \sigma_{true} \quad \varepsilon_{eff} = \varepsilon_{true} - \frac{\sigma_{true}}{E} \]  \hspace{1cm} (4.4)

Figure 4.23. Coupons for material testing.
The test machine is shown in Figure 4.24.

![MTS testing machine](image1)

**Figure 4.24.** MTS testing machine.

The strain gauge was attached to test coupon to measure strain. Test set up is shown in Figure 4.25.

![Material test set up](image2)

**Figure 4.25.** Material test set up.

Material testing provided strain rate dependent material properties, which were used in FE model.
4.9.2 Material Models in LS-DYNA

The LS-DYNA finite element solver used for simulation of an FE model transit bus offers approximately 100 material models. Using these material models, the user can define any material properties for materials ranging from metals to non-metals. In the transit bus FE model, almost 26 material models are used to define properties for material like aluminum, steel, glass, and rubber etc. LS-DYNA provides the ability to define material with properties such as yield strength, Poisson’s ratio, modulus of elasticity, density, etc.

In this section, all the material models used in the bus are discussed. It is necessary to maintain a consistent unit system while defining material properties in order to obtain the correct results from the FE simulation. Table 4.5 shows the units of measure used for defining material properties. Material properties obtained from testing were submitted to LS-DYNA using the material model in card format.

TABLE 4.5

UNITS

<table>
<thead>
<tr>
<th>Variable</th>
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</thead>
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<tr>
<td>Length</td>
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<tr>
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<td>Ton</td>
</tr>
<tr>
<td>Time</td>
<td>Second</td>
</tr>
<tr>
<td>Force</td>
<td>Newton</td>
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<tr>
<td>Young’s Modulus of Steel</td>
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<tr>
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<tr>
<td>Velocity Equivalent to 30 mph</td>
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</table>
Steel Component

Two types of steel, which have different properties, are used in transit bus. Parts of the chassis and below the chassis are made of one type of steel, and the remaining parts such as seat and handle bars are made of a different type. Two types of material models were used to define the properties of the steel. *MAT_PIECEWISE_LINEAR_PLASTICITY* is the keyword used for one steel. This is material type 24 in LS-DYNA. An elasto-plastic material with an arbitrary stress versus strain curve and arbitrary strain dependency can be defined using this model. Failure based on plastic strain or minimum time step can be defined using this card. This card is defined as follows:

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<th>PR</th>
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<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Other steel used for parts like the chassis is defined as strain rate sensitive material using the keyword *MAT.Modified_Piecewise_Linear_Plasticity*. This is material type 123 in LS-DYNA. An elasto-plastic material with an arbitrary stress versus strain curve and arbitrary strain dependency can be defined using this model. This material model is similar to MAT_PIECEWISE_LINEAR_PLASTICITY but is able to define enhanced failure criteria. This material model is used to define properties for shell elements only. This card is defined as follows:
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<th>Variable</th>
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<th>PR</th>
<th>SIGY</th>
<th>ETAN</th>
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</thead>
<tbody>
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<td>None</td>
<td>0</td>
<td>10e+20</td>
<td>0</td>
</tr>
</tbody>
</table>

In the above card, LCSS is used to define the Table ID, which defines for each strain rate value a load curve ID giving the stress versus effective plastic strain for that rate. Three load curve IDs are specified in the Table ID. The stress versus effective plastic strain curve for the lowest value of strain rate is used if the strain rate falls below the minimum value. Similarly, the stress versus effective plastic strain curve for the highest value of strain rate is used if the strain rate exceeds the maximum value.

Three curves of stress versus effective plastic strain were defined for strain rate values of 0.00001/s, 0.1/s, and 1,000/s, and their load curve ID is specified in the Table ID of the above card. According to the strain rate value, one of the curves shown in Figure 4.26 is used by LS-DYNA to define strain rate of the steel material.

![Figure 4.26. Stress versus effective plastic strain curves for steel.](image)

In the above card, LCSS is used to define the Table ID, which defines for each strain rate value a load curve ID giving the stress versus effective plastic strain for that rate. Three load curve IDs are specified in the Table ID. The stress versus effective plastic strain curve for the lowest value of strain rate is used if the strain rate falls below the minimum value. Similarly, the stress versus effective plastic strain curve for the highest value of strain rate is used if the strain rate exceeds the maximum value.

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Three curves of stress versus effective plastic strain were defined for strain rate values of 0.00001/s, 0.1/s, and 1,000/s, and their load curve ID is specified in the Table ID of the above card. According to the strain rate value, one of the curves shown in Figure 4.26 is used by LS-DYNA to define strain rate of the steel material.

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Three curves of stress versus effective plastic strain were defined for strain rate values of 0.00001/s, 0.1/s, and 1,000/s, and their load curve ID is specified in the Table ID of the above card. According to the strain rate value, one of the curves shown in Figure 4.26 is used by LS-DYNA to define strain rate of the steel material.
Aluminum Components

Aluminum material is a widely used material in transit buses for components such as side panels, top roof, windows, connectors, etc. For defining aluminum properties, *MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY* was used, and this card is defined as follows:

<table>
<thead>
<tr>
<th>Variable</th>
<th>MID</th>
<th>RO</th>
<th>E</th>
<th>PR</th>
<th>SIGY</th>
<th>ETAN</th>
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<th>TDEL</th>
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</thead>
<tbody>
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<td>10e+20</td>
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<table>
<thead>
<tr>
<th>Variable</th>
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<th>LCSR</th>
<th>VP</th>
<th>EPSTHIN</th>
<th>EPSMAJ</th>
<th>NUMINT</th>
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<td>0</td>
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</tr>
</tbody>
</table>

Figure 4.27 shows stress versus effective plastic strain curves used to define strain rate dependency of aluminum material. This figure shows strain rate dependent values for aluminum for three different strain rates.

![Tr. Strain Vs Tr. Stress](image)

Figure 4.27. Stress versus effective plastic strain curves for aluminum.
Bumper Material

Both front and rear bumpers are made of plastic material. Material properties for bumpers are not available from the bus manufacturer, so they were obtained from the material data handbook. *MAT_PIECEWISE_LINEAR_PLASTICITY was used to define material for bumpers and is defined as follows.

<table>
<thead>
<tr>
<th>Variable</th>
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<th>PR</th>
<th>SIGY</th>
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<tr>
<td>Variable</td>
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<td>P</td>
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</tbody>
</table>

Tire Material

Rubber is the material used for all six tires. *MAT_ELASTIC material model was used to define elastic properties of rubber. This is material type 1, an isotropic elastic material available for beam, shell, and solid elements in LS-DYNA.

<table>
<thead>
<tr>
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<td>None</td>
<td>None</td>
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<td>0</td>
</tr>
</tbody>
</table>

Glass Material

Glass material is widely used in transit buses for front and rear windshield, and glass doors. Glass properties were obtained from the material data handbook and defined using *MAT_PIECEWISE_LINEAR_PLASTICITY keyword, as follows:
The failure criteria for glass are defined in the above card to simulate real-life behavior, since all windows and glass of the front and rear windshields break during a crash. The failure criteria defined in the above card is responsible for breaking glass during simulation when the stress value reaches a specified value.

**Engine Material**

The engine of a transit bus normally acts as rigid during a crash event because the deformation of an engine is very little compared to other parts, the engine is defined as rigid. Thus the computational time required to process the engine element will be much less compared to deformable parts. *MAT_ RIGID* keyword was used to define engine material, which is material type 20. Parts made from this material are considered to belong to a rigid body. This material type provides a useful way of turning one or more parts comprised of the beam, shells, and solid elements into a rigid body. Elements that are rigid are bypassed in the element processing, and no storage is allocated for storing history variables. Thus, rigid material is very cost efficient.
Accelerometer

The material for an accelerometer is defined as rigid. *MAT_ RIGID keyword was used for defining rigid material is as follows:

<table>
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<th>Variable</th>
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<td>0</td>
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</table>

Spot Weld Material

*MAT_SPOTWELD keyword was used to define material for spot welds in LS-DYNA. This is material type 100. This material model applies to beam element type 9 and to solid element type 1.

<table>
<thead>
<tr>
<th>Variable</th>
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4.10 Suspension System

Suspension in a transit bus is a system of springs, shock absorbers, and linkages that connect a vehicle to its wheels. The suspension system in a transit bus serves two purposes: to contribute to bus handling and braking and to keep vehicle occupants comfortable and isolated from road noise, bumps, and vibrations. In a transit bus, springs are used to absorb impact, and dampers are used to control spring motions. The bus uses an air-ride suspension. A height control valve is used to maintain the proper ride height by controlling the volume of air in the springs.

The front and rear axles have different configurations in a suspension system. In the FE model of the bus all suspension parts were modeled and properties were assigned to them. Figure 4.29 and 4.30 show the meshed components of a suspension system.
Detailed modeling of a suspension system was done with shell elements. The front axle has four air springs that were modeled with four translational kinematic joints with nonlinear spring functions, and two hydraulic shock absorbers that were modeled with two translational joints with nonlinear damper functions. Figure 4.31 shows the translation joints modeled to replicate springs and damper with two additional spherical joints in the control arms and two revolute joints in the wheels defined.

Spring and damper cards provided by LS-DYNA were used to define material properties for front axle springs and dampers. Also, joints were defined using HyperMesh.
Total Joints used in front axle suspension system are as follows:

- Translation : 6
- Revolute : 6
- Spherical : 2

LS-DYNA provided the *CONSTRAINED_JOINT_OPTION card to define various types of joint between two bodies. Two cards were needed to define a single joint. For all joints the card is similar: for every joint, there is one node on one body and two or more nodes on the other body depending on the joint.

<table>
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<tr>
<th>*CONSTRAINED_JOINT_SPHERICAL_ID</th>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The spring and damper functions are obtained from the bus manufacturer, have typical units of N/mm. In a transit bus, both the spring and damper have nonlinear functions, meaning the force exerted increases exponentially.
*MAT_SPRING_NONLINEAR_ELASTIC* keyword was used to define springs with nonlinear spring rates. This material type 4 for discrete spring and dampers, provides nonlinear elastic translational and rotational spring with arbitrary force versus displacement.

<table>
<thead>
<tr>
<th>Variable</th>
<th>MID</th>
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<th>LCR</th>
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<tbody>
<tr>
<td>Type</td>
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</tbody>
</table>

*MAT_DAMPER_NONLINEAR_VISCOUS* keyword was used to define the nonlinear function of the front axle damper. This is material type 5 used for discrete spring and dampers. This material provides a viscous translational damper with an arbitrary force versus velocity dependency. In this card, the user can define the force versus rate of displacement curve, but the curve must define a response in the negative and positive quadrants and must pass through points (0, 0).

<table>
<thead>
<tr>
<th>Variable</th>
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</thead>
<tbody>
<tr>
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</tbody>
</table>

Nonlinear functions used to define spring and damper characteristics in the above keyword are shown in Figure 4.32.

![Front Axle Spring Function](image_url)

![Front Axle Damper Function](image_url)

Figure 4.32. Front axle suspension functions.
The rear axle has four air springs that have been modeled with four translational kinematic joints with nonlinear spring functions, and two hydraulic shock absorbers that have been modeled with two translational joints using nonlinear damper functions. Springs and dampers modeled in rear axle with eight additional revolute joints in the four control arms and two revolute joints in the wheels are defined shown in Figure 4.33.

![Kinematic joints in rear axle suspension system.](image)

The numbers of joints used in the front axle suspension system are as follows:

Translation : 6    Revolute : 12

Rear axle spring and damper functions are also defined using similar cards as those used to define front axle. Data obtained from the manufacturer provides load versus deflection characteristics of springs and damping force versus piston velocity of dampers. Both curves were digitized and then applied to the FE model using nonlinear spring and damper cards provided by LS-DYNA.

The nonlinear function used for the rear axle is shown in Figure 4.34.
4.11 Tire / Wheel Modeling

In vehicle crashes the tire/wheel system plays a role in load path. To obtain accurate results from vehicle crash simulations, it is important to have good a tire/wheel model. A transit bus consists of six wheels, four on the rear axle and two on the front axle. The wheel system consists of two major parts one rubber part, i.e., the tire and the rim as the other metal part. Both the tire and rim were meshed using shell elements, taking care to avoid any holes or openings in the tire and rim mesh. Equivalency was done between the tire and rim elements at edges to ensure that total volume was enclosed.

In order to realistically simulate the interaction between a pneumatic tire and the road surface, an internal pressure was generated inside tire using the AIRBAG option. In LS-DYNA air pressure can be introduced inside a closed volume by using the AIRBAG card. For a transit bus model, *AIRBAG_SIMPLE_AIRBAG_MODEL_ID card was used to create 110 psi of pressure. Six airbags were defined for the six tires of the transit bus. Figure 4.35 shows the meshed tire and rim. Tire pressure and other relevant data verified by checking the glstat file written by LS-DYNa during analysis.
Figure 4.35. Meshed tire.

Figure 4.36 shows that pressure in tire was introduced at time zero and was 0.8 MPa, i.e., 110 psi. Also, the volume of air remained steady during analysis showing that there was no air leakage through the tire.

Figure 4.36. Tire statistics.
4.12 Mass, Center of Gravity, and Time Step

Accurate mass distribution and center of gravity are very important factors for validating the FE model of transit bus. The transit bus model used for developing this FE model had a gross vehicle weight rating (GVWR) equal to 29,000 pounds. The GVWR included the net vehicle weight of the vehicle, plus the weight of passengers, fuel, luggage, etc. A side impact test on the transit bus was done at a vehicle weight of 21,290 pounds. Bumper tests on bus were carried out at a weight of 21,800 pounds. An accurate mass definition in the FE model was necessary to get correct results.

The transit bus center of gravity is approximately 1.4 meters forward of the rear axle. An exact mass distribution can be obtained by assigning correct material properties such as density and young’s modulus to each part. Preprocessors Primer and HyperMesh were used to measure the mass of each component. A large deviation of mass observed between the actual and the FE model component was corrected by changing properties.

A different mass of the transit bus FE model was obtained by adding some point mass. LS-DYNA has an option that allows this. By adding this nodal mass, the bus’s center of gravity was kept at approximately the same position as on the actual bus. The *ELEMENT_MASS keyword was used to define nodal mass. While adding mass care was taken to distribute mass over a number of nodes rather than assigning it all to a single node. Figure 4.37 shows the center of gravity of the FE model of the transit bus. The center of gravity of the FE model was kept at same location as in the actual bus. Masses of different components, such as interior seat parts, handle bars, etc were adjusted using the nodal mass card.
Time step calculations are very important during FE analysis. LS-DYNA uses different methods to calculate time steps for shell, solid, and beam elements. For solid elements, the time step $\Delta t_e$ is calculated as

$$\Delta t_e = \frac{L_e}{Q + \left(1 + \frac{C^2}{L_e^2}\right)^{1/2}}$$  \hspace{1cm} (4.5)$$

Where $Q$ is a function of the bulk viscosity coefficient.

For shell elements, the time step is given as

$$\Delta t_e = \frac{L_s}{C}$$  \hspace{1cm} (4.6)$$

where

$$C = \sqrt{\frac{E}{\rho(1 - \nu^2)}}$$  \hspace{1cm} (4.7)$$

where $L_s$ is the characteristic length, and $C$ is the speed of sound.

Time step calculations for beam elements are given as
\[ \Delta t_e = \frac{L}{C} \quad \text{(4.8)} \]

where \( L \) is the length of an element, and \( C \) is the wave speed

\[ C = \sqrt{\frac{E}{\rho}} \quad \text{(4.9)} \]

The time step for a transit bus FE model is shown in Figure 4.38.

Figure 4.38. Time step for a transit bus FE model.

### 4.13 Contacts

Contact modeling is a very important step in the FE model development process. The transit bus consists of many parts which adjoin each other. During a crash event, large deformations occur, creating interaction of the adjoining parts. The load transfer from one component to another during crushing will not be proper in an FE model if the contacts are not defined properly. Slave and master are two concepts that must be explored in order to understand the contact definition in LS-DYNA. Slave is the
component that could impact or slide against another surface, and master is the component that controls whether the slave impacts or slides against its surface.

Five types of contacts can be defined in LS-DYNA: one-way, two-way, single-surface, geometric entities, and tied. A one-way contact is cheaper computationally and defines only slave nodes to be checked for any penetration with the master segment. A two-way contact is the same as a one-way, with the only difference that it is fully symmetric in that both slave and master nodes can be defined for penetration check.

Single-surface contact is widely used in automotive crash analysis. Only the slave component is required to define this contact in LS-DYNA. This component creates contact between all slave parts and as well as self contact. This contact uses a thickness offset algorithm to evaluate contact so a good model quality is required. For the transit bus FE model, a single-surface contact was used to create self contact and contact between adjoining parts. The *CONTACT_AUTOMATIC_SINGLE_SURFACE card was used to define the single-surface contact.

Single-surface contact is not sufficient when the transit bus hits a rigid wall or another vehicle. In this case, LS-DYNA provides a card named *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID. Using this card helps to define contact between interacting parts of the transit bus and another vehicle.

4.14 Implicit: Eigen Value Analysis of Subassemblies

LS-DYNA offers an extensive set of implicit analysis capabilities. Implicit refers to the numerical method used to represent and solve the time derivatives in the momentum and energy equations. The advantage of this approach is that it is
unconditionally stable. Implicit simulations typically involve a relatively small number of computationally expensive time steps. There are three major types of implicit analysis.

- Eigenvalues
- Static-linear and nonlinear
- Dynamic-Newmark $\beta$ method

For eigenvalue implicit analysis two keywords are used in LS-DYNA. The keyword *CONTROL_IMPLICIT_GENERAL is used to activate the implicit method, and *CONTROL_IMPLICIT_EIGENVALUE is used for eigenvalue analysis. Eigen value implicit analysis is done for linear shell and solid elements. This analysis gives d3eign as the output file, which contains different modes of vibrations. The advantages of using implicit eigenvalue analysis in the FE model development of a transit bus are given below:

- Convenient tool to debug a missed connection, to find parts that are not properly attached to the assembly.
- Easy to determine unconstrained degrees of freedom.
- Requires very little CPU time to carry out implicit analysis.

In a transit bus, eigenvalue implicit analysis is done on small subassemblies like the suspension assembly, top roof and windshield assembly, and side wall assembly. Since these assemblies consist of a very large number of small components, it is very difficult to determine unattached components in the entire transit bus FE model. This method is used to debug all errors in small assemblies and then finally assemble the transit bus without any unattached or unconstrained components. Figure 4.39 shows implicit eigenvalue analysis of a top roof and windshield assembly.
Figure 4.39. Implicit eigen value analysis.
4.15 Accelerometer and Section Force

An accelerometer is a device used to measure accelerations. In the FE model of transit bus, accelerometers are modeled for accurate measurement of acceleration at various locations. The accelerometer is defined by three nodes in a rigid body, which defines a triad to measure accelerations in the local system. The presence of an accelerometer means that the accelerations and velocities of node 1 will be output to all output files in a local coordinate instead of global coordinates. The three nodes should be part of the same rigid body. There are almost 119 accelerometers modeled in the FE model of a transit bus. The location of all accelerometers is shown in Figure 4.40.

![Accelerometer location](image)

**Figure 4.40.** Accelerometer locations.
Measuring the cross sectional force on all beams in a transit bus is very important in order to study the load transfer mechanism during a crash event. A deformable part in a transit bus is cut by a cross section to monitor transmission of forces and moments through that part. Output intervals for cross sectional data were specified by the *DATABASE_SECFORC keyword. To define the cutting plane two sets of cards were required for each cross section. Forty nine cross section planes were defined in the FE model of the bus at various locations to obtain cross sectional data as shown in Figure 4.41.

![Cross section planes](image)

Figure 4.41. Cross section planes.

**4.16 Initial State and Boundary Conditions**

Initial state and boundary conditions are necessary to define before crashworthiness simulation of a transit bus FE model. Defining parameters like gravity on FE model, initial velocity, road surface definition, contacts, etc. comes under initial state. After assigning properties to the model, the gravitational force effect must be
considered before simulation. Gravitational acceleration produced by gravitational force is typically denoted by “g.” Gravity on the entire FE model was applied using the *LOAD_BODY keyword. Here gravitational acceleration is defined using a load curve, which acts at the beginning of simulation. The gravitational acceleration value used for transit bus FE model is 9.81 m/s².

Road surface was defined by using *RIGIDWALL_PLANER keyword in LS-DYNA. Using this keyword, an infinite rigidwall was created to act as a surface. The contact between the rigid surface and nodal points of the deformable body were also specified using this card. Care was taken while defining road surface to not penetrate into the bus tires. In the contact between the road and bus, tires are treated as a slave surface. Friction between the tires and road surface was kept at 0.8; a value taken from the literature review. The same keyword was used to define rigidwall during frontal and rear impact of the transit bus. But while defining contacts, all frontal portions of the bus were added as slaves and in case of a frontal impact and vice versa. During a bus-to-other vehicle impact, same keyword was used to define road surface but in slave contact with bus tires, other vehicle tires were also added.

Contact definition varies according to crash simulation conditions. Bus to other vehicle needs additional contacts than a single vehicle crash. To consider the encounter of two vehicle addition to single surface contact for both vehicles, a surface-to-surface contact was added. The *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword was used to define contact between bus and another vehicle. TO define the contact the impacting vehicle parts were selected as slave surfaces, and parts of the vehicle on which other vehicle impact were taken as master surface.
The initial velocity of a vehicle is a very important factor in crashworthiness since it defines kinetic energy and intensity of impact. The initial velocity in a transit bus FE model was defined using the keyword "INITIAL VELOCITY." This card was used to define nodal point translational velocities using nodal set ID's. For each vehicle velocity was changed according to crash condition. In the case of two-vehicle crash, different initial velocity conditions were specified.

### 4.17 FE Dummy

Some finite element dummies developed by Livermore Software Technology Corporation (LSTC) were placed in the FE model of a transit bus. Though FE dummies were not validated, they were used to observe the occupant kinematics. An LSTC Hybrid III 50th percentile rigidized finite element dummy was used. The advantage of using this dummy is the smaller computational time since they are rigidized. LSTC dummy models are available as HYBRID III 5th, 50th and 95th percentile dummies, both rigid as well as deformable. They are positioned by a positioning file. The 95th and 5th percentile dummies are scaled versions of the 50th percentile dummy model. Their internal contacts are already defined. A total of five dummies were placed in the transit bus FE model, which add a small amount of computational time. Since these dummies are not validated, injury values obtained from them are not reliable, but occupant kinematics can be obtained which will give an idea of occupant behavior in different crash scenarios.
CHAPTER 5
VALIDATION OF FINITE ELEMENT MODEL

An important step in the overall finite element model development of a transit bus is the validation of the model, which is very difficult. In general, validation is a process to check if certain criterions are satisfied. Validation also implies being able to testify that a solution or process is correct and is compliant with a set a standards or rules. The overall crash response is composed of contributions from the vehicle frame and body components, as well as load transmitted through the components, such as the engine, suspension, and drive train. Data from full vehicle crash is required for validating the FE model of vehicles. Due to a limited number of measurements from a full vehicle crash test and the complexity of complete vehicle crash behavior, it is difficult to validate detailed FE model.

The bus manufacturer has conducted three actual crash tests on transit buses to meet requirements of the Bus Procurement Guidelines. Side impact and front and rear bumper tests were conducted by the manufacturer to meet requirements of various government agencies. The data of an actual full vehicle crash test was obtained from the manufacturer for validation purposes. Limited test data was available because in an actual full vehicle test, the data acquisition system is limited. The FE model validation parameters are limited due to very limited test data. Data obtained included bus CG displacements, velocities, accelerations, rigid wall reaction forces, and pictures of permanent structural deformation. An FE simulation of transit bus was done similar to a full-scale test, and the results were compared for validation purposes.
5.1 Frontal Impact Validation

The manufacturer of a transit bus conducted a front bumper impact test to certify the vehicle to Romeo Rim, White Book Specifications and Bus Procurement Guidelines. The Standard bus procurement guidelines — a book of procurement standards for purchasing buses, created by the American Public Transit Association (APTA) — ensures the quality of buses purchased by transit authorities (section 5.4.3.9.2) [11]; no part of the bus, including the bumper, shall be damaged as a result of a 5-mph (8 km/hr) impact of the bus at curb weight with a fixed, flat barrier perpendicular to the bus' longitudinal centerline. Also, it states that the bumper shall return to its pre-impact shape within 10 minutes of impact without permanent damage or degradation in strength. The setup of the FE model of the transit bus was done according to the front bumper test procedure. A transit bus of 21,800 pounds weight was impacted on a fixed flat barrier, i.e., rigid wall, from the front side. The full energy-absorbing face of the front bumper contacted the rigid wall. The front bumper test condition is explained in Table 5.1.

### TABLE 5.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical Test</th>
<th>Finite Element Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Type</td>
<td>Frontal Bumper Barrier Test</td>
<td>Frontal Bumper Barrier Test</td>
</tr>
<tr>
<td>Bus Weight</td>
<td>21,800 lbs (9,888 kg)</td>
<td>21,800 lbs (9,888 kg)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>5 mph (8.0 km/hr)</td>
<td>5 mph (8.0 km/hr)</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>0 degrees</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Fixed Target</td>
<td>Fixed Flat Barrier</td>
<td>Fixed Flat Barrier</td>
</tr>
<tr>
<td>Test Setup</td>
<td>Bumper Contacts Flat Barrier</td>
<td>Bumper Contacts Flat Barrier</td>
</tr>
<tr>
<td>Occupants</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Tire Pressure</td>
<td>110 Psi (7.6 bar)</td>
<td>110 Psi (7.6 bar)</td>
</tr>
</tbody>
</table>
An FE simulation was conducted for 200 ms, and data regarding CG displacement, velocity, and total force on rigid wall were obtained. Data from the manufacturer was digitized, and the unit system was converted to match unit system followed in FE analysis.

Figure 5.1 shows that simulation results (shown in blue) show resemblance to the actual test results (shown in red) obtained from the manufacturer. The bus CG displacement and velocity data from the simulation match well with the actual test. Also, the force exerted on the rigid wall that was measured in the FE simulation also matched the actual test wall force.

Figure 5.1. Front bumper test validation.
The second part of the standard states that the bumper should not be permanently damaged and should regain its original shape. To check this condition, stress levels in the front bumper and front structure were measured. It was found that stress levels did not exceed the yield strength of bumper; therefore, it can be assumed that the bumper was not permanently damaged and regained its original shape. Figure 5.2 shows a cross section of the front bumper and Von Mises stress levels in the front structure.

Figure 5.2. Cross section of front bumper and Von Mises stresses (MPa).

Thus, two criteria of the standard bus procurement guidelines were simulated on the transit bus FE model. To validate the first criteria, simulation results were compared to the actual front bumper test conducted by the manufacturer. Permanent damage to the bumper is checked by measuring stress levels in the bumper. Since stress levels were lower than the yield strength of the bumper material, the bumper should return to its original position without permanent damage.
Vehicle kinematics in a front bumper test is shown in Figure 5.3.

Figure 5.3. Vehicle kinematics in front bumper validation test.
5.2 Rear Impact Validation

The manufacturer of the transit bus conducted a rear bumper test to certify the vehicle meeting specifications provided by the Standard Bus Procurement Guidelines. The guidelines section 5.4.3.9.2 [11] states the specifications for a rear bumper of a transit bus. It says that no part of the bus, including the bumper, shall be damaged as a result of a 2-mph (3.2 km/hr) impact of the bus at curb weight with a fixed, flat barrier perpendicular to the longitudinal centerline of the bus. Also, it states that the bumper shall return to its pre-impact shape within 10 minutes of impact without permanent damage or degradation in strength.

A setup of an FE model of the transit bus was done according to the rear bumper test procedure. A transit bus weighing 21,800 pounds was impacted on a fixed flat barrier, i.e., rigid wall, from the rear side. The full energy-absorbing face of the rear bumper contacted the rigid wall. The rear bumper test conditions are shown in Table 5.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical Test</th>
<th>Finite Element Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Type</td>
<td>Rear Bumper Barrier Test</td>
<td>Rear Bumper Barrier Test</td>
</tr>
<tr>
<td>Bus Weight</td>
<td>21,800 lbs (9,888 kg)</td>
<td>21,800 lbs (9,888 kg)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>2 mph (3.2 km/hr)</td>
<td>2 mph (3.2 km/hr)</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>Fixed Target</td>
<td>Fixed Flat Barrier</td>
<td>Fixed Flat Barrier</td>
</tr>
<tr>
<td>Test Setup</td>
<td>Bumper Contacts Flat Barrier</td>
<td>Bumper Contacts Flat Barrier</td>
</tr>
<tr>
<td>Occupants</td>
<td>Rear Bumper Barrier Test</td>
<td>Rear Bumper Barrier Test</td>
</tr>
<tr>
<td>Tire Pressure</td>
<td>110 Psi (7.6 bar)</td>
<td>110 Psi (7.6 bar)</td>
</tr>
</tbody>
</table>
An FE simulation was conducted for 200 ms, and data regarding CG displacement, velocity, and total force on the rigid wall was obtained. Data from the manufacturer is digitized and the unit system converted to match the unit system followed in FE analysis. Figure 5.4 shows that the simulation results (shown in blue) were similar to the actual test results (shown in red) obtained from the manufacturer.

Figure 5.4. Rear bumper test validation.
Bus CG displacement and velocity data was obtained from the FE simulation and compared with actual test data. The values and nature of curves matched for the rear bumper simulation and actual test results. Wall force from the FE simulation also matched the actual test wall force.

Rear bumper damage was checked by measuring stress levels in the rear bumper and rear structure member. Stress levels did not exceed the yield strength of the bumper or any of the rear structure components; therefore, it can be assumed that the bumper cover should return to its pre-impact shape. Figure 5.5 shows a cross section of the rear bumper and Von Mises stress levels in the rear structure.

![Figure 5.5. Cross section of rear bumper and Von Mises stresses (MPa).](image)

Validation of the transit bus model was done by using the rear bumper test as specified in the Standard Bus Procurement Guidelines. Data from the manufacturer was available, and the rear bumper simulation was carried out as specified in the standard. Simulation results were compared with actual test results, and they matched well. This shows that the FE model predicted similar results as the actual test.
Vehicle kinematics for the front bumper test is shown in Figure 5.6

5.3 Side Impact Validation

The side impact test-25 mph bullet vehicle impacting transit bus from the side-was conducted by the manufacturer of the bus to evaluate performance of the transit bus. Standard bus procurement guidelines have specification about side impact protection of transit bus mentioned in the guidelines section 5.4.1.2 [11]. According to
this, the bus shall withstand a 25-mph (40.4 km/hr) impact by a 4,000-pound (1814 kg) automobile at any point, excluding doorways, along either side of the bus with no more than 3 inches (76 mm) of permanent structural deformation at seated passenger hip height. Also, there should not be any sharp edges or protrusions into the bus interior.

In an actual full-scale side impact crash test, a 1983 Chevrolet Caprice model was used as the bullet vehicle. The test vehicle was positioned so that the longitudinal centerline of the bullet vehicle was at the midway point, between the front and rear axle, of the test vehicle. The side impact test condition is summarized in Table 5.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical Test</th>
<th>Finite Element Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Type</td>
<td>Side Impact</td>
<td>Side Impact</td>
</tr>
<tr>
<td>Target Vehicle</td>
<td>Transit Bus</td>
<td>Transit Bus</td>
</tr>
<tr>
<td>Target Vehicle Weight</td>
<td>21,290 Lbs (9,656 kg)</td>
<td>21,290 Lbs (9,656 kg)</td>
</tr>
<tr>
<td>Impact Speed</td>
<td>25.1 mph (40.4 Km/hr)</td>
<td>25.1 mph (40.4 Km/hr)</td>
</tr>
<tr>
<td>Impact Angle</td>
<td>270°</td>
<td>270°</td>
</tr>
<tr>
<td>Bullet Vehicle Weight</td>
<td>4,018 Lbs (1822 kg)</td>
<td>4,018 Lbs (1822 kg)</td>
</tr>
<tr>
<td>Bullet Vehicle</td>
<td>1983 Chevrolet Caprice</td>
<td>Modified FMVSS 214 Barrier</td>
</tr>
<tr>
<td>Occupants</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Bus Tire Pressure</td>
<td>110 Psi (7.6 bar)</td>
<td>110 Psi (7.6 bar)</td>
</tr>
</tbody>
</table>

The FE model of a 1983 Chevrolet Caprice was not available, in the FE simulation setup to replicate a physical side impact test. To overcome this problem a modified FMVSS 214 type deformable barrier model was created to resemblance the properties of the 1983 Chevrolet Caprice. Modifications of the FMVSS 214 barrier were done on all parameters, such as the vehicle’s wheelbase, track width, bumper height, and vehicle weight. The parameters for the 1983 Caprice were obtained from the
NHTSA Light Vehicle Inertial Parameter Database. The 1983 Caprice maximum dynamic crush displacements (0.838 m), vehicle weight (1,869 kg), weight distribution (54.2% front and 48.8% rear), and front structure linear stiffness values (662.5 kN/m) were derived from NHTSA’s 56.8 km/hr front crash test number 515 [12,13].

The modified FMVSS 214 barrier mass, stiffness, and crush region were modified accordingly, as shown in Figure 5.7. The modified barrier model performance for a 56.8 km/hr frontal test was compared with the results of a 1983 Chevrolet Caprice crash test [13]. Figure 5.7, shows that the modified deformable barrier (MDB) model captures the overall phasing and amplitude of the vehicle’s CG velocity and displacement test profiles.

Figure 5.7. Modified FMVSS 214 barrier 35 mph (56 km/hr) frontal impact validation.
A modified FMVSS 214 barrier was used as the bullet vehicle in the FE side impact simulation. A 150-millisecond simulation was done and the bus CG displacement and velocity data were measured. A comparison with the test of the bus center of gravity velocity and displacement time histories compared with the simulation results. There was a difference in bus CG y-velocity after 60 ms; this discrepancy is attributed to the differences in linear stiffness characteristics and structural load path of the MDB with respect to the actual 1983 Caprice frontal structure. Figure 5.8 shows a comparison of side impact validation plots with blue representing simulation data and red representing physical test data.

![Figure 5.8. Side-impact test validation.](image-url)
The FE simulation bus kinematics compared to the physical test is shown in Figure 5.9.

![Figure 5.9. Comparison of bus kinematics.](image)

After the physical side impact test, protrusions inside the passenger compartment were measured. Intrusions in the bus compartment were measured at seated passenger hip height. There was 8 mm deformation found inside the compartment during the full-scale physical test. To measure deformation in the FE simulation the displacement of the node located at passenger hip height was measured.
In the simulation, a 12 mm deformation was found. Figure 5.10 shows displacement and Von Mises stress during side impact crash event. Also, the Standard Bus Procurement Guidelines allow for a deformation of three inches, which is very high compared to the simulation results.

Figure 5.10. Displacement (mm) and Von Mises stress (MPa) contour plots.
CHAPTER 6
IIHS REAR IMPACT TEST

The Insurance Institute for Highway Safety is an independent, nonprofit, scientific and educational organization dedicated to reducing the losses—deaths, injuries, and property damage—from crashes on the nation's highways. IIHS also carries research to support the goal of the Safe, Accountable, Flexible, Efficient transportation Equity Act: A Legacy for Users (SAFETEA-LU), that aims to increase consumer awareness by providing the comparative levels of crash protections afforded by vehicle. IIHS has introduced several vehicle crashworthiness tests using procedures and ratings that differ from NCAP tests.

NHTSA has many rules and regulation about the frontal and side crashworthiness performance of vehicle. But FMVSS standards and regulations created by NHTSA fail to highlight the issue of rear impact crashworthiness. FMVSS standard 223,224 addresses installation of rear impact guards on trailers and semi-trailers. Transit buses are more susceptible to rear impact collisions because of their frequent stops, which often occur in traffic lanes. FMVSS standards 208 and 214 specify performance requirements for an occupant’s protection in frontal and rear vehicle crashes. Although the statistical review in Chapter 2 suggests that transit bus rear impact accidents causes a large number of deaths and injuries, no FMVSS standard addresses issue of performance requirements in rear end impacts.

The New Car Assessment Program of NHTSA carries out full vehicle crash tests to study vehicle performance in front and rear crash events. Vehicles are not tested for full vehicle rear impact conditions to evaluate their crashworthiness performance. IIHS
conducts rear impact tests, but they are related to reviewing the effectiveness of the seat and head restraint systems during a rear end crash. In the rear impact test conducted by IIHS, dynamic sled testing is done rather than full scale vehicle crash testing.

There are no regulations such as FMVSS 208,214 to study the rear impact crashworthiness of a transit bus. The IIHS rear impact test is conducted, although it is only for seat and head restraint system evaluation. The IIHS rear impact test conducts a dynamic sled test to the test seat and head restraint system. This test simulates a collision in which a stationary vehicle is struck in the rear by a vehicle of the same weight going 20 miles per hour. Each seat and head restraint’s dynamic performance is based on two sets of criteria measured on a BIORID dummy. The first set includes the two seat design parameters, time to head restraint contact, and peak torso acceleration. The second set includes maximum neck shear and tension forces. A seat that passes at least one of the seat design parameters and has low neck forces earns a dynamic rating of good. For the transit bus, since there is no standard or regulation for rear impact crashworthiness, the IIHS rear impact condition is used to study the overall vehicle behavior in a rear impact condition. Rather than using the seat and head restraint parameter for the study, overall crashworthiness of the transit bus was studied in an IIHS rear-impact test.

6.1 Test Setup

In an IIHS rear-impact test, a stationary vehicle is struck in the rear by a vehicle of the same weight going 20 miles per hour. According to test procedure, one transit
The bus is stationary and the other is moving at 20 miles per hour hitting it from the rear. The following procedure explains the setup of an FE model of a transit bus for an IIHS rear impact test.

- The FE model of a transit bus was imported in the preprocessor Primer.
- Five FE dummies were placed inside the transit bus to simulate occupant kinematics during a crash.
- The second FE model of the transit bus was imported in preprocessor Primer.
- Using functions like translate rotate in the preprocessor; the second transit bus was positioned at the rear end of the first bus.
- The second bus fully overlapped the first bus. A distance of 50 mm was kept between the rear bumper of the first bus and front bumper of the second bus.
- An infinite road structure was created using functions like *RIGIDWALL in LS-DYNA. The contact between the road surface and tires of both buses was defined. A friction coefficient of 0.8 was used between the tire and road surface.
- During a rear crash, a large number of parts of both buses come into contact with each other. To consider the effect of part interaction, parts were identified in both the buses and contact was defined between them.
- Initial velocity was assigned to the second bus, which was moving at a speed of 20 miles per hour. The first bus was kept stationary.
- Control cards were defined in the LS-DYNA input deck to mention termination of simulation, contacts, etc.
- Termination time of the analysis was kept at 300 milliseconds.
• The time interval was specified to write the database output file containing information about nodal, rigid body displacement, velocity and acceleration, section force data, energy data etc.
• The input deck for LS-DYNA was written from preprocessor.
• The file was submitted to LS-DYNA for analysis.

Figure 6.1 shows the IIHS rear-impact test setup.

![IIHS rear-impact test setup](image)

Figure 6.1. IIHS rear-impact test setup.

The transit bus FE model for the IIHS rear-impact test condition was simulated. Figure 6.2 and 6.3 show vehicle deformation pattern and stress contours at different time intervals.
Figure 6.2. Vehicle deformation pattern.

Figure 6.3. Stress contours.
Displacement, velocity, and acceleration were measured at the center of gravity of the bus and plotted as shown in Figure 6.4, 6.5, 6.6 and 6.7. The maximum acceleration of 35.7175 Gs was reached at the CG at 153 milliseconds. The resultant displacement of the CG was 1237.35 mm.

Figure 6.4. CG displacement.

Figure 6.5. CG X and Y velocity.
Since a bus is very long compared to a passenger car, there was a significant change in acceleration levels at different locations. Figure 6.8 shows a comparison of accelerations at CG, driver seat, and occupant compartments on the left and right sides. Displacement and velocity were almost similar at these four locations but the
acceleration levels varied considerably at these different locations. The different energy plots are shown in Figure 6.8.

![Comparison of displacement, velocity, and acceleration at different locations.](image)

Figure 6.8. Comparison of displacement, velocity, and acceleration at different locations.

The cross section forces coming on the rear chassis beams are shown in Figure 6.9.

![Cross section forces on the rear chassis beams.](image)

Figure 6.9. Cross section forces on the rear chassis beams.
The occupant kinematics at different time intervals is shown in Figure 6.10.

![Figure 6.10. Occupant kinematics at different time intervals.](image)

### 6.2 Offset Impact of Transit Bus

A simulation of one transit bus impacting another transit bus from an offset rear impact was done. One bus was stationary, and the other bus was moving at 20 mph, impacting at 60% offset from the rear. The test set up was done as shown in Figure 6.8.

This test was carried out to simulate a frequently occurring offset impact scenario for transit buses. Since transit buses stops frequently in traffic lanes, vehicles coming from the rear try to avoid impact and hits the bus at an offset. This FE simulation replicates a 60% overlap rear impact of a transit bus.
The stress contours of an offset rear impact of a transit bus are shown in Figure 6.12. Displacement, velocity, and acceleration at the CG are shown in Figure 6.13. Maximum acceleration at the CG is 23.82 Gs at 217ms.
Figure 6.13. Displacement, velocity and acceleration of an offset rear impact of a transit bus.

Figure 6.14. Vehicle deformation pattern.
6.3 Comparison of Bus-to-Bus Offset and Full-overlap Impact

The offset rear-impact test varies significantly in the crashworthiness response of a transit bus compared to full overlap rear impact. The main difference can be observed by comparing the acceleration pulse at the CG. Also, the load transfer through the chassis beams during an offset impact scenario can be monitored by plotting the cross sectional force.

Figure 6.15 shows comparison of acceleration during offset and full overlap event. The cross section force at chassis beams is plotted in Figure 6.16.

![Comparison of CG Accelerations](image)

**Figure 6.15.** Comparison of CG acceleration pulses.

![100% Overlap Section Force](image)  ![60% Overlap Section Force](image)

**Figure 6.16.** Comparison of cross section force.
Numerous occupants are injured or suffer fatal injuries due to rear-impact accidents involving transit buses. The accidental pattern reveals that many types of vehicles strike a transit bus from the rear. Since each vehicle is of a different size, weight, and type, the transit bus crashworthiness response is different and the bus deformation pattern changes as the vehicle impacting from the rear changes. This chapter deals with the simulation of transit bus rear-impact scenarios with different types of vehicles.

Vehicles impacting transit buses are divided roughly into three types: cars, minivans, and pickup trucks. The greatest number of rear-impact accidents occurs because of frequent bus stops in traffic lanes. Normally, a vehicle impacts the rear of the bus with its full energy absorbing face. Sometimes the vehicle hitting from behind is struck at a 60% or 50% overlap. This type of accident occurs when the bus suddenly stops and the vehicle coming from behind tries to change lane.

A statistical review also suggests that vehicle crashworthiness response changes according to vehicle speed. Accidents occur where the bus is stationary or moving and the vehicle coming from the rear impact it at a different speed. Studying bus’s rear impact crashworthiness performance at different impacting speeds is necessary to evaluate the occupant injury pattern. Various finite element models of cars, vans, and trucks, developed by NCAC are available to conduct different rear impact accident scenarios with a transit bus. The Dodge Neon FE model was selected to represent
various midsize car segments. The Dodge Caravan FE model was selected to represent the minivan section, and the Chevy 2500 pick up FE model was selected for truck segment. Rear-impact simulation of a transit bus was conducted with different types of vehicles impacting at different speeds. Simulations of the rear impact of a transit bus with different categories of vehicles shown in Table 7.1 which represents almost all real-world crash conditions. All configurations were simulated using LS-DYNA.

### TABLE 7.1

**REAR IMPACT TEST MATRIX**

<table>
<thead>
<tr>
<th>No</th>
<th>Condition</th>
<th>Test Procedure</th>
<th>Simulation Time</th>
<th>CPU Time</th>
<th>Memory Size (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Bus - 26 mph</td>
<td>300 ms</td>
<td>111 hrs 15 min 46 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>2</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Bus - 40 mph</td>
<td>300 ms</td>
<td>134 hrs 30 min 6 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>3</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 20 mph</td>
<td>281 ms</td>
<td>269 hrs 35 min 43 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>4</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 40 mph</td>
<td>281 ms</td>
<td>294 hrs 33 min 42 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>5</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 30 mph</td>
<td>300 ms</td>
<td>140 hrs 26 min 2 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>6</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 20 mph</td>
<td>300 ms</td>
<td>161 hrs 5 min 70 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>7</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 40 mph</td>
<td>281 ms</td>
<td>159 hrs 44 min 46 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>8</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 30 mph</td>
<td>300 ms</td>
<td>141 hrs 3 min 33 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>9</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 30 mph</td>
<td>281 ms</td>
<td>268 hrs 32 min 36 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>10</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Chevy C2500 - 20 mph</td>
<td>281 ms</td>
<td>263 hrs 26 min 16 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>11</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Chevy C2500 - 20 mph</td>
<td>300 ms</td>
<td>264 hrs 45 min 59 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>12</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Chevy C2500 - 30 mph</td>
<td>300 ms</td>
<td>264 hrs 33 min 47 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>13</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Bus - Smth - Chevy C2500 - 30 mph</td>
<td>300 ms</td>
<td>264 hrs 45 min 37 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>14</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 20 mph</td>
<td>282 ms</td>
<td>224 hrs 34 min 30 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>15</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 20 mph</td>
<td>282 ms</td>
<td>244 hrs 21 min 52 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>16</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Caravan - 30 mph</td>
<td>300 ms</td>
<td>126 hrs 31 min / sec</td>
<td>33.7</td>
</tr>
<tr>
<td>17</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 20 mph</td>
<td>300 ms</td>
<td>223 hrs 1 min 12 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>18</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 20 mph</td>
<td>300 ms</td>
<td>130 hrs 30 min 23 sec</td>
<td>33.7</td>
</tr>
<tr>
<td>19</td>
<td>Rear 60% Overlap Bus to Bus</td>
<td>Bus - Smth - Dodge Neon - 30 mph</td>
<td>300 ms</td>
<td>130 hrs 16 min 40 sec</td>
<td>33.7</td>
</tr>
</tbody>
</table>

Simulations of the FE model of a transit bus were carried out according to these conditions. Table 7.1 also shows the processing time and storage space in gigabytes to complete analysis. All simulations were carried out for 300 milliseconds. The problem of models being unstable to run for 300 milliseconds was solved by mass scaling. Important major factors taken into consideration for the to statistical study are as follows:

- Overlap of Bullet Vehicle
- 100 % Overlap
- 60 % Overlap

- Speed of Target Vehicle i.e. Transit Bus
  - 0 mph Stationary
  - 5 mph
  - 15 mph

- Speed of Bullet Vehicle
  - 20 mph
  - 30 mph

- Type of Bullet Vehicle
  - Midsize Car : Dodge Neon
  - Minivan : Dodge Caravan
  - Pick Up Truck : Chevrolet 2500 Pickup

Figure 7.1 shows various test setups for different types of vehicles. The transit bus or target is shown in blue, and the bullet vehicle is shown in red.
Figure 7.2 shows the transit bus crash condition setup based on overlap. Bullet vehicle is shown in red and target vehicle i.e. transit bus in blue. An overlap of 100% means that the longitudinal axes of the target vehicle and bullet vehicle are aligned; meaning full-energy absorbing face of the bullet vehicle’s front bumper touches the rear of the target vehicle. A 60% overlap means that 60% of the bullet vehicle’s area touches the target vehicle.

Various graphs and figures related to crashworthiness performance of transit bus are plotted and shown in the Appendix. Results are plotted for all test configurations shown in Table 7.1. The main focus of the results plotted in these sections was crashworthiness performance of the transit bus. Crashworthiness performance of the bullet vehicle was not taken into consideration, since many of these studies have been done previously. A detailed discussion of these graphs takes place in chapter 9, Results and Discussion.
Mathematical Dynamic Model (MADYMO) is used to model occupants in the environment of the vehicle's interior and is primarily used in assessing occupant injuries. The objective of crashworthiness analysis is to design a vehicle's critical structural members so that their behavior is predictable with adequate occupant protection in crash event. Evaluating crashworthiness performance of any vehicle is done in two steps. Structural analysis is usually performed using finite element analysis and occupant simulation is done using multi-body analysis software, MADYMO. Multi-body dummy models using rigid bodies and ellipsoids as well as flexible bodies and facets are used in MADYMO.

A major advantage of MADYMO is the significantly shorter time for analysis compared to a full-vehicle FE simulation. A typical finite element analysis of a car containing 100,000 elements requires 48 hours of CPU time, irrespective of preprocessing and debugging time. In contrast, MADYMO computational time is much less, taking only minutes to complete simulation. Occupant simulation involves representing the occupants as a system of rigid bodies connected by mechanical joints that interact with the interior of the vehicle represented by simple shapes (e.g., planes, cylinders, ellipsoids, etc.) The analysis involves studying the behavior of the occupant system to an applied input, which is usually an acceleration pulse obtained from an actual crash test or FE analysis.
MADYMO is used to calculate injury parameters like femur and tibia loads, Head Injury Criterion (HIC), Gadd Severity Index (GSI), Thoracic Trauma Index (TTI), and Viscous Injury Response (VC), in addition to standard dummy output. Once a given crash situation has been modeled with MADYMO, it is relatively straightforward for users to determine how the scale of potential injuries can be reduced by introducing special safety features or by changing certain design parameters. This makes the MADYMO package an extremely useful tool for enhancing vehicle safety.

8.1 General Injury Mechanism and Injury Criteria

Many types of injuries occur to vehicle occupants in crash events. Generally, injuries are related to head, neck, thorax, etc. Since a vehicle crash is a very complex event, occupant injuries are related to different types of collision forces. The collision force created from the direct impact of one vehicle with another vehicle or stationary object is the major force causing injury. Forces from intruded parts of the vehicle and passenger body, and collision of body organs with the body frame cause far fewer injuries than direct impact.

Head injuries are categorized into skull injuries, brain injuries, and scalp injuries. Scalp injuries are quite common in accidents, but they are considered to be of minor importance. Skull fractures can occur with or without damage to the brain but, itself, is not an important cause of neurological death or disability. Focal brain Injuries are those in which a lesion large enough to be visualized with the naked eye has occurred, and comprises contusion, subdural hematoma, epidural hematoma, and intracerebral hematoma. Diffuse brain injuries, on the other hand, are associated with more
widespread or global disruption of neurological function and are not usually associated with a macroscopically visible brain lesion.

An injury criterion is a physical parameter or a function of several physical parameters, which correlates with the injury severity of the body region under consideration. Anatomical scales describe the injury in terms of its anatomical location, the type of injury and its relative severity. The mostly accepted anatomical scale worldwide is the Abbreviated Injury Scale (AIS), which distinguishes the following levels of injury:

- 0 – No Injury
- 1 – Minor
- 2 – Moderate
- 3 – Serious
- 4 – Severe
- 5 – Critical
- 6 – Maximum Injury (cannot be survived)
- 9 – Unknown

Injury criteria have been developed in terms that address the mechanical responses of crash test dummies in terms of risk to life or injury to a living human. Internal responses of a mechanical structure are uniquely governed by the structure’s geometric and material properties, and the forces and motions applied to its surface. The criteria have been derived from experimental efforts using human surrogates, where both measurable engineering parameters and injury consequences are observed, and the most meaningful relationships between forces/motions and resulting injuries are determined using statistical techniques.
**Head Injury Criteria (HIC)** A head injury criterion is derived to evaluate head injuries. HIC is calculated when the head of the occupant comes in hard contact with another rigid object during a frontal impact. HIC is calculated using the following formula:

\[
HIC = \max \left[ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} R(t) dt \right]^{2.5} \left( t_2 - t_1 \right) \quad (8.1)
\]

where \( R(t) \) is the resultant head acceleration in g’s, and \( t_1 \) and \( t_2 \) are the initial and final times of the interval during which HIC attains maximum value. A value of 1,000 specified for HIC by government agencies as the maximum allowable limit for the 50th percentile adult male.

**Neck Injury Criteria (Nij)**

Neck injury is often assessed by peak forces and moments in the upper and lower neck. Neck injury occurs due to excessive compressive or tensile forces along the neck axis or excessive shear forces acting perpendicular to the neck axis. Nij propose critical limits for all four possible modes of neck loading: tension or compression combined with either flexion (forward) or extension (rearward) bending moment.

**Thoracic Trauma Index (TTI)**

Lateral impact causes serious injuries to the thorax. The thoracic trauma index is the criteria used for assessing thorax injuries. The TTI is an acceleration criterion based on the accelerations of the lower thoracic spine and the ribs. It also incorporates the weight and the age of the human model. Injuries to the hard thorax are strongly related to the average of the peak lateral acceleration experienced by the impacted side of the rib cage and the lower thoracic spine.
Viscous Injury Response (VC)

Chest deflection and thoracic trauma index are not sufficient to evaluate injury mechanism at high-velocity rates of soft tissues. Therefore, another criterion is needed to address the injury mechanism related to soft tissues, since vital organs of the chest, heart, large blood vessels and lung are made of soft tissues. Viscous injury response is the maximum value of a time function formed by the product of the velocity of deformation (V) and the instantaneous compression function (C). The formula used to calculate is given as

\[
VC = \max \left[ \frac{dD(t)}{dt} \frac{D(t)}{SZ} \right] \quad \text{............... (8.2)}
\]

where D (t) is a deflection, and SZ is the prescribed size, or initial torso thickness for frontal impact.

8.2 FMVSS 208 Injury Criteria

The FMVSS 208 standard was developed to reduce the number of fatalities and number of severe of injuries to occupants involved in frontal crashes. This standard also specifies injury criteria for various ATDs. Since there is no standard available for rear-impact injury criteria, parameters from FMVSS 208 were used to compare the results obtained from the MADYMO model of a rear-impact involving a transit bus.

The injury criteria for various ATDs at 50 percentile and 5 percentile are shown in table 8.1. Injury values are listed for six-year-old, three-year-old and 12-month-old child dummy. Limits are specified for HIC, chest deflection, chest acceleration, femur load, and Nij.
8.3 Development of Model

8.3.1 Generation of Facet Model

MADYMO provides a unique tool of facet modeling, which enables the use of a finite element mesh. As in the transit bus, the entire FE mesh was available, so there was no need to model ellipsoids for structural representation of bus parts. A finite element mesh of required components was selected from the FE model of a transit bus in order to reduce simulation time. Only shell elements meshed parts can be used to define facets. The FE shell mesh was divided into two collectors according to element shape, i.e., triangular-shaped elements or quadrilateral-shaped elements. Although the facet surfaces are defined in FE_MODEL elements, facet models are still multibody models, since no FE solver is used in the simulations. Facet modeling was used here because it allowed a more accurate geometric representation in comparison to an ellipsoid.
8.3.2 Dummy Selection

MADYMO provides different types of dummies as discussed in Chapter 3, ranging from child to adult male and female. For the transit bus analysis, three types of multi-body dummies were selected. The Hybrid III 50th percentile male dummy was selected to represent the size and weight of an average adult male in the United States. The second type of dummy, a Hybrid III 95th percentile male dummy, was chosen to represent the largest size in the adult population. The third type of dummy type, a Hybrid III 5th percentile small female dummy, represented the smallest size in the adult population.

8.3.3 Property Selection

Interaction of the dummy with the facet part and interaction of the dummy part with itself was very influential during MADYMO simulation. Force deflection characteristics input by user for each part was responsible of contact definition. Contact characteristics and friction coefficients are two important factors affecting MADYMO simulations. Selection of appropriate contact parameters such as stiffness, coefficient of friction, hysteresis, and damping is extremely important. Lacking such data generally leads to "trial and error" methods to establish appropriate values for these parameters. Friction coefficients also play an important role in calculating responses. Injury criteria are very sensitive to change in a friction coefficient. Different contact characteristics were used for the ellipsoid parts and the facet parts.
8.3.4. Acceleration Pulse and Simulation Setup

The acceleration pulse for the MADYMO simulation was obtained from finite element simulation of the IIHS rear-impact test. The acceleration level in the passenger compartment was measured from the FE simulation of bus-to-bus rear impact, with the bullet vehicle traveling at 20 mph and provided to the dummies in the MADYMO model. Figure 8.1 shows the acceleration pulse used for MADYMO simulation.

![Acceleration Pulse](image)

Figure 8.1. Acceleration pulse used for MADYMO simulation.

The test setup is shown in Figure 8.2. The dummy positions are shown Figure 8.3, and the dummy kinematics are shown in Figure 8.4.

![Occupant model test setup](image)

Figure 8.2. Occupant model test setup.
The injury parameters mentioned in Chapter 8 (section 2) were measured from MADYMO simulations. HIC, chest deflections, and neck forces were measured for all the dummies.
CHAPTER 9
RESULTS AND DISCUSSIONS

9.1 Introduction

A validated finite element model of a transit bus was simulated for real-life rear-impact scenarios, as discussed in the preceding chapters. Rear-impact conditions were simulated varying the bullet vehicle type and speed.

9.2 Comparison of Acceleration Pulses

Maximum acceleration in the bus was measured at four locations: CG, driver seat, and the left and right occupant compartments. The variation of maximum acceleration is shown in Table 9.1. It is observed that four important factors affect the maximum acceleration: type of bullet vehicle, speed of bullet vehicle, speed of target vehicle, and full or 60% overlap impact. Varying these four conditions produces different acceleration levels in the bus.

TABLE 9.1
MAXIMUM ACCELERATION AT DIFFERENT LOCATIONS

<table>
<thead>
<tr>
<th>No</th>
<th>Condition</th>
<th>Test Procedure</th>
<th>C.G.</th>
<th>Driver Seat</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge 20mph</td>
<td>36</td>
<td>10</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge 20mph</td>
<td>22</td>
<td>10</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>36</td>
<td>10</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>22</td>
<td>7</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>16</td>
<td>8</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Nac - 20 mph</td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Nac - 20 mph</td>
<td>18</td>
<td>7</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Nac - 20 mph</td>
<td>16</td>
<td>8</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Nac - 20 mph</td>
<td>16</td>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Nac - 20 mph</td>
<td>14</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 15mph : Dodge Nac - 30 mph</td>
<td>11</td>
<td>9</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 15mph : Dodge Nac - 30 mph</td>
<td>11</td>
<td>9</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Rear 100% Overlap Bus to Bus</td>
<td>Dodge 15mph : Dodge Nac - 30 mph</td>
<td>13</td>
<td>9</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>Rear 80% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>18</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>Rear 80% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>16</td>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>Rear 80% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>16</td>
<td>7</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>Rear 80% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>16</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>Rear 80% Overlap Bus to Bus</td>
<td>Dodge 5mph : Dodge Caravan 20mph</td>
<td>13</td>
<td>8</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

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Type of Bullet Vehicle

It is observed from simulations that the type of bullet vehicle affects the acceleration pulse. In all the condition simulated one condition created maximum acceleration at CG of transit bus. The condition in which stationary transit bus was impacted by another transit bus at a speed of 20mph. Maximum acceleration depends on the size of the vehicle impacting from the rear. If a bus is the bullet vehicle impacting another bus, then maximum acceleration results. The value of accelerations is reduced as the impacting bullet vehicle reduces in size as shown in Table 9.2. For example, comparing minivans, pick-up trucks, and cars, maximum acceleration is produced by the minivan, then the pick-up truck, and finally the passenger car.

**TABLE 9.2**

**EFFECT OF BULLET VEHICLE ON ACCELERATION**

<table>
<thead>
<tr>
<th>Bullet Vehicle</th>
<th>Acceleration</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit Bus</td>
<td>35</td>
<td>100%</td>
</tr>
<tr>
<td>Dodge Caravan</td>
<td>26</td>
<td>72%</td>
</tr>
<tr>
<td>Chevrolet 2500 Pick Up</td>
<td>18</td>
<td>51%</td>
</tr>
<tr>
<td>Dodge Neon</td>
<td>15</td>
<td>42%</td>
</tr>
</tbody>
</table>

Table 9.2 shows that the maximum acceleration at the CG is affected by the type of bullet. The Dodge Caravan produced 27% less acceleration compared to when the transit bus is bullet vehicle and the Chevrolet 2500 pick up and Dodge Neon produced 48% and 57% less accelerations respectively.

Speed of Bullet Vehicle

Simulations show that the speed of the bullet vehicle also had an impact on the maximum acceleration at the CG in a transit bus. As the bullet vehicle’s speed
increased maximum acceleration increased at the CG. Also, acceleration levels increased at all other locations in the transit bus.

**Speed of Target Vehicle**

The target vehicle, i.e., transit bus, speed during a rear-impact scenario affected the maximum acceleration observed at the CG. If the transit bus was stationary during rear impact, then the acceleration produced was greater than when the bus was moving. It was also observed from simulations that, as the target vehicle speed increased acceleration levels decreased.

**Vehicle Overlap**

It was observed that during a rear-impact condition, position of bullet vehicle affects acceleration levels induced in transit bus. If bullet vehicle position is 100% overlap then acceleration is higher as compared to 60% overlap position.

**9.3 Comparison of Offset and Full-Overlap Rear-Impact Condition**

Full and offset overlap of impacting vehicle had various effects on accelerations in the occupant compartment. Simulations showed that there was a difference in acceleration between the door-side occupant compartment and the driver-side occupant compartment. It was observed in all rear-impact simulations that acceleration on the right side, i.e., door side had greater acceleration compared to that on the driver side, i.e., left side of transit bus. This occurred because of the two doors on the right side. Table 9.1 shows the values of acceleration on the right and left occupant compartments; nearly all simulations showed that the right side had greater acceleration than the left side.
Figure 9.1. Effect of accelerations on right and left side of bus.

Figure 9.1 shows the effects of different accelerations produced in the right and left occupant compartments. At a time interval of 150 milliseconds, three dummies were leaning backward, but at 300 milliseconds due to the greater acceleration on the right side, the right side dummies were still leaning backward on the modesty panel, and the right-side dummies were moving forward. This figure shows that the larger movement of dummies in the right-side occupant compartment than in the left side occupant compartment.

9.4 Under Ride of Dodge Neon

When a Dodge Neon passenger car impacts a transit bus from the rear, it underrides the transit bus. Although this model is a low-floor of transit bus, the passenger car still underrides because of the higher height of the rear bumper from the road surface. Therefore, the transit bus chassis is not directly loaded during impact with a Dodge Neon. Figure 9.2 shows the underride of the Dodge Neon into a transit bus.
9.5 MADYMO Simulation

MADYMO simulations were done for 20 mph bus-to-bus rear-impact, and the results are shown in Table 9.3. From the injury values, it is observed that all values of HIC, chest deflections, etc, are within the specified limits of the FMVSS standard.

### Table 9.3
INJURY VALUES FROM MADYMO SIMULATIONS

<table>
<thead>
<tr>
<th>ATD Position</th>
<th>50th</th>
<th>5th</th>
<th>50th</th>
<th>5th</th>
<th>50th</th>
<th>5th</th>
<th>50th</th>
<th>5th</th>
<th>50th</th>
<th>5th</th>
<th>50th</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC 15</td>
<td>86</td>
<td>449</td>
<td>7</td>
<td>239</td>
<td>42</td>
<td>11</td>
<td>20</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>Chest 3ms (cm)</td>
<td>16</td>
<td>14</td>
<td>36</td>
<td>14</td>
<td>32</td>
<td>31</td>
<td>19</td>
<td>19</td>
<td>20</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>Chest Def (mm)</td>
<td>2.3</td>
<td>2.9</td>
<td>3.9</td>
<td>2.9</td>
<td>6.4</td>
<td>6.9</td>
<td>8.5</td>
<td>8.5</td>
<td>7.2</td>
<td>4.2</td>
<td>4.6</td>
</tr>
<tr>
<td>Femur Lead Left (N)</td>
<td>6412</td>
<td>479</td>
<td>192</td>
<td>0.96</td>
<td>4713</td>
<td>1052</td>
<td>952</td>
<td>1241</td>
<td>2961</td>
<td>697</td>
<td>907</td>
</tr>
<tr>
<td>Femur Lead Right (N)</td>
<td>5336</td>
<td>472</td>
<td>3365</td>
<td>919</td>
<td>5050</td>
<td>7268</td>
<td>486</td>
<td>504</td>
<td>745</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Neck Tension (N)</td>
<td>668</td>
<td>361</td>
<td>663</td>
<td>260</td>
<td>698</td>
<td>636</td>
<td>695</td>
<td>802</td>
<td>1006</td>
<td>1044</td>
<td>1044</td>
</tr>
<tr>
<td>Neck Flexion (Nm)</td>
<td>-14</td>
<td>-12.5</td>
<td>-16.5</td>
<td>-47.3</td>
<td>-33</td>
<td>-13.9</td>
<td>-16.5</td>
<td>-16.1</td>
<td>-19.5</td>
<td>-19.5</td>
<td>-19.5</td>
</tr>
<tr>
<td>Neck Extension (Nm)</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td>8.9</td>
<td>24</td>
<td>17.7</td>
<td>10.7</td>
<td>13.9</td>
<td>17.5</td>
<td>24.6</td>
<td>24.6</td>
</tr>
<tr>
<td>Neck Shear (N)</td>
<td>-249</td>
<td>-175</td>
<td>-384</td>
<td>-223</td>
<td>-366</td>
<td>-116.8</td>
<td>-89.6</td>
<td>-7.7</td>
<td>-119</td>
<td>-266</td>
<td>-266</td>
</tr>
<tr>
<td>MTE</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>NFC</td>
<td>0.05</td>
<td>0.4</td>
<td>0.1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.09</td>
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<td>0.06</td>
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</tr>
</tbody>
</table>

Figure 9.2. Underride of Dodge Neon into transit bus.
IIHS condition states that a seat will earn a good rating if neck shear and tension forces are within limits. Also, Nij values are below 1, which suggests that there are no neck injuries during a 20 mph bus-to-bus rear impact. HIC values for all dummies were less than 1,000 so there was no serious head injury to bus occupants. Only the dummy at position 4 had a maximum HIC value because its head directly hit the shoulder of another dummy.

9.6 Comparison of Occupant Kinematics of FE and MADYMO Dummy

FE dummy and MADYMO dummy occupant kinematics are compared in Figure 9.3, and shown to be similar. Finite element dummies were placed in the FE model of a transit bus since they added very little in computational time. Although the FE dummies were not validated, they were used to visualize dummy kinematics during a crash scenario. Both FE and MADYMO dummies showed quite similar kinematics for rear impact, as shown in Figure 9.3
Figure 9.3.  Comparison of occupant kinematics.
CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The literature and statistical review show that the rear-impact scenario is the third most common type of transit bus accidents causing injuries and death to occupants. A detailed finite element model was successfully developed to study crashworthiness of the low-floor mass transit bus. An FE model composed of detailed component meshing of interior parts and exterior parts was developed. Material testing was done to extract strain rate-dependent material properties.

The FE model was validated for front and rear bumper low-speed tests and higher-speed side-impact tests. Results of the FE model simulations matched well with actual test done by the manufacturer. The FE model of transit bus was simulated for different impact speeds and found stable in the range of speed. An IIHS rear-impact test was simulated with an FE model of a transit bus. Accelerations levels were measured in a target vehicle at different locations. Accelerations levels in the occupant compartment were smaller compared to the car-to-car impact.

Real-life scenarios of transit bus rear impact were simulated with different bullet vehicles, varying the speed and overlap condition. The Dodge Caravan generated more acceleration in the transit bus compared to the Dodge Neon and Chevrolet 2500 pick up truck. The Dodge Caravan produced 27% less acceleration compared to when the transit bus was the bullet vehicle and the Chevrolet 2500 pick up and Dodge Neon produced 48% and 57% less acceleration respectively. Underride of the Dodge Neon
A passenger car occurred during rear impact with the transit bus. The door-side passenger compartment had 30% to 35% more acceleration than the driver-side compartment when the impacting vehicles were the Dodge Caravan, Dodge Neon, and Chevrolet 2500 pick up truck. This shows that the driver side, i.e., left side of the transit bus is stiffer than the door side, i.e., right side. During bus-to-bus rear impact, maximum acceleration at the driver seat was 48% less than acceleration at the CG, which is located at the rear end of the bus. The acceleration pulse lessens as it travels from the rear to front part of a bus due to deformation of the rear components. In the impact involving the Dodge Caravan, maximum acceleration at the driver of transit bus was 65% less than CG acceleration. Similarly, it was 64% and 56% less in the case of the Chevrolet 2500 pick up and Dodge Neon, respectively.

The occupant model was simulated in MADYMO using the acceleration pulse from a bus-to-bus 20 mph rear-impact condition. The injury values found were less than the specified limit by FMVSS standards. No ejection of the occupant occurred during the 20 mph rear impact. Neck tension and shear forces were lower than specified limits, so neck injuries occurring during IIHS impact condition were minimal. HIC values for the occupant were much lower than the specified limit of 1,000.

This study has shown that the finite element model of a transit bus can be used to carry out different crash scenarios. Additionally the MADYMO model shows that injury levels on bus occupants during rear-impact of a transit bus are very low compared to the criteria specified in FMVSS standards.
10.2 Recommendations

The transit bus FE model was simulated for different rear-impact conditions by changing the bullet vehicle and speed, need to be carried out simulations at higher speeds. NCAC models are not stable in high speeds during rear impact of a bus, by improving those models, transit bus rear-impact simulations can be carried out. A study could also be done by adding more safety features in the rear of the transit bus to prevent underride of passenger cars, i.e., compatibility of transit bus with other vehicles. The MADYMO model was not validated, so injury values obtained from the model may not occur in real life. By using sled testing, injury data could be obtained for rear-impact conditions and used to validate the MADYMO model. The Effect of change in seat pitch and head rest, and changing materials for modesty panels and handle bars on occupant injuries could be studied.
LIST OF REFERENCES
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APPENDIXES
APPENDIX A

SIMULATION CONDITION: 2

Target Vehicle: Transit Bus  Target Vehicle Speed: 5 mph
Bullet Vehicle: Transit Bus  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure A1. Simulation set up.

Figure A2. Displacement and velocity.
Figure A3. Acceleration.

Figure A4. Vehicle deformation pattern.
APPENDIX B

SIMULATION CONDITION: 3

Target Vehicle: Transit Bus  Target Vehicle Speed: 0mph Stationary
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure B1. Test set up.

Figure B2. Displacement and velocity.
APPENDIX B (continued)

Figure B3. Acceleration.

Figure B4. Vehicle deformation pattern.
APPENDIX C

SIMULATION CONDITION: 4

Target Vehicle: Transit Bus  Target Vehicle Speed: 5 mph
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure C1. Test set up.

Figure C2. Displacement and velocity.
APPENDIX C (continued)

Figure C3. Acceleration.

Figure C4. Vehicle deformation pattern.
APPENDIX D

SIMULATION CONDITION: 5

Target Vehicle: Transit Bus  Target Vehicle Speed: 15 mph
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 30 mph
Overlap: 100%

Figure D1. Test set up.

Figure D2. Displacement and velocity.
APPENDIX D (continued)

Figure D3. Acceleration

Figure D4. Vehicle deformation pattern.
APPENDIX E

SIMULATION CONDITION: 6

Target Vehicle: Transit Bus  Target Vehicle Speed: 0 mph Stationary
Bullet Vehicle: Dodge Neon  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure E1. Test set up.

Figure E2. Displacement and velocity.
APPENDIX E (continued)

Figure E3. Acceleration.

Figure E4. Vehicle deformation pattern.
APPENDIX F

SIMULATION CONDITION: 7

Target Vehicle: Transit Bus  Target Vehicle Speed: 5 mph
Bullet Vehicle: Dodge Neon  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure F1. Test set up.

Figure F2. Displacement and velocity.
Figure F3. Acceleration.

Figure F4. Vehicle deformation pattern.
APPENDIX G

SIMULATION CONDITION: 8

Target Vehicle: Transit Bus  Target Vehicle Speed: 15 mph
Bullet Vehicle: Dodge Neon  Bullet Vehicle Speed: 30 mph
Overlap: 100%

Figure G1. Test set up.

Figure G2. Displacement and velocity.
Figure G3.  Acceleration.

Figure G4.  Vehicle deformation pattern.
APPENDIX H

SIMULATION CONDITION: 9

Target Vehicle: Transit Bus    Target Vehicle Speed: 5 mph
Bullet Vehicle: Dodge Neon    Bullet Vehicle Speed: 25 mph
Overlap: 100%

Figure H1. Simulation set up.

Figure H2. Displacement and velocity.
APPENDIX H (continued)

Figure H3. Acceleration.

Figure H4. Vehicle deformation pattern.
APPENDIX I

SIMULATION CONDITION: 10

Target Vehicle: Transit Bus  Target Vehicle Speed: 0 mph Stationary
Bullet Vehicle: Chevrolet 2500 Pick up  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure I1. Simulation set up.

Figure I2. Displacement and velocity.
APPENDIX I (continued)

Figure I3.  Acceleration.

Figure I4.  Vehicle deformation pattern.
APPENDIX J

SIMULATION CONDITION: 11

Target Vehicle: Transit Bus  Target Vehicle Speed: 5 mph
Bullet Vehicle: Chevrolet 2500 Pick up  Bullet Vehicle Speed: 20 mph
Overlap: 100%

Figure J1. Simulation set up.

Figure J2. Displacement and velocity.
Figure J3.  Acceleration.

Figure J4.  Vehicle deformation pattern.
APPENDIX K

SIMULATION CONDITION: 12

Target Vehicle: Transit Bus  
Target Vehicle Speed: 15 mph

Bullet Vehicle: Chevrolet 2500 Pick up  
Bullet Vehicle Speed: 30 mph

Overlap: 100%

Figure K1. Simulation set up.

Figure K2. Displacement and velocity.
APPENDIX K (continued)

Figure K3. Acceleration.

Figure K4. Vehicle deformation pattern.
APPENDIX L

SIMULATION CONDITION: 14

Target Vehicle: Transit Bus  Target Vehicle Speed: 0 mph Stationary
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 20 mph
Overlap: 60%

Figure L1. Simulation set up.

Figure L2. Displacement and velocity.
APPENDIX L (continued)

Figure L3. Acceleration.

Figure L4. Vehicle deformation pattern.
APPENDIX M

SIMULATION CONDITION: 15

Target Vehicle: Transit Bus  Target Vehicle Speed: 5 mph
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 20 mph
Overlap: 60%

Figure M1. Simulation set up.

Figure M2. Displacement and velocity.
APPENDIX M (continued)

Figure M3. Acceleration.

Figure M4. Vehicle deformation pattern.
APPENDIX N

SIMULATION CONDITION: 16

Target Vehicle: Transit Bus  Target Vehicle Speed: 15 mph
Bullet Vehicle: Dodge Caravan  Bullet Vehicle Speed: 30 mph
Overlap: 60%

Figure N1. Simulation set up.

Figure N2. Displacement and velocity.
APPENDIX N (continued)

Figure N3. Acceleration.

Figure N4. Vehicle deformation pattern.
APPENDIX O

SIMULATION CONDITION: 17

Target Vehicle: Transit Bus    Target Vehicle Speed: 0 mph
Bullet Vehicle: Dodge Neon    Bullet Vehicle Speed: 20 mph
Overlap: 60%

Figure O1. Simulation set up.

Figure O2. Displacement and velocity.
APPENDIX O (continued)

Figure O3. Acceleration.

Figure O4. Vehicle deformation pattern.
APPENDIX P

SIMULATION CONDITION: 18

Target Vehicle: Transit Bus   Target Vehicle Speed: 5 mph
Bullet Vehicle: Dodge Neon   Bullet Vehicle Speed: 20 mph
Overlap: 60%

Figure P1. Simulation set up.

Figure P2. Displacement and velocity.
APPENDIX P (continued)

Figure P3. Acceleration.

Figure P4. Vehicle deformation pattern.
APPENDIX Q

SIMULATION CONDITION: 19

Target Vehicle: Transit Bus  
Target Vehicle Speed: 15 mph

Bullet Vehicle: Dodge Neon  
Bullet Vehicle Speed: 30 mph

Overlap: 60%

Figure Q1. Simulation set up.

Figure Q2. Displacement and velocity.
APPENDIX Q (continued)

Figure Q3. Acceleration.

Figure Q4. Vehicle deformation pattern.