A COMPUTATIONAL STUDY ON STATIC AND UNCONSTRAINED DYNAMIC ROLLOVER CRASH TESTS OF A MID-SIZE SUV FOR VARIOUS INITIAL ROLLOVER PARAMETERS

A Thesis by

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

________________________________________
Hamid M. Lankarani, Committee Chair

________________________________________
Krishna Krishnan, Committee Member

________________________________________
Rajeev Nair, Committee Member
DEDICATION

To my parents, friends

And

To my adviser Dr. Hamid M. Lankarani
ACKNOWLEDGEMENTS

I am thankful to my advisor, Dr. Hamid M. Lankarani, Professor of Mechanical Engineering Department at Wichita State University, for all his guidance and support throughout my studies. His encouragement and patience helped me to complete this thesis. I would like to thank my committee members Professor Krishna Krishnan and Professor Rajeev Nair for their valuable time in reviewing this thesis. I would also like to thank my friends Saketh, Pankaj, Bhargav, Sachin Patil, Prasanna, Ranjith Kumar, Vishal, Suresh, Kushal, Aasheesh, Sumanth PV and Vijay Sai for their constant support and making my stay in Wichita enjoyable.

Finally, I would take this opportunity to thank my parents Mrs. Sandhya Rani and Mr. Ramesh, my uncle Mohan, my sisters Reshma and Rajitha, my brother Ram Chander, for their love, support and constant encouragement throughout my master’s studies.
ABSTRACT

In terms of frequency of accidents, rollover crashes are uncommon among all other crash types or directions. However, they are associated with highest fatality rate than any other crashes, as 33% of fatalities in automobile crashes correspond to rollover crashes. Beside a static roof crush test procedure, there is yet no standard dynamic test procedure to certify a vehicle for occupant rollover protection, because of its complexity and various factors that affect the outcome of the rollover crashes. The unpredictability of the rollover makes it difficult to design standard test procedure. There are various factors and parameters that affect the rollover crashes such as vehicle speed, height of its fall, angle of contact with the ground, side of contact, reason for the rollover, etc. The countermeasure for these parameters are also difficult to be included in a standard test procedure.

The present study is focused on development and utilization of a computational finite element model of typical SUV vehicle in static and unconstrained dynamic rollover tests. The vehicle is subjected to various dynamic rollover parameters, including the height of its fall, longitudinal speed of the vehicle during the rollover and angle of contact with the ground. In the end, various parametric studies are examined on a Toyota RAV4 rollover crash, the energy inducing and the force imparting to the vehicle are analyzed, and their effects shall be identified for a recommended set of initial roll parameters.
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<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>HIC</td>
<td>Head Injury Criteria</td>
</tr>
<tr>
<td>IIHS</td>
<td>Insurance Institute for Highway Safety</td>
</tr>
<tr>
<td>MPP</td>
<td>Massively Parallel Processing</td>
</tr>
<tr>
<td>MATLAB</td>
<td>Matrix Laboratory</td>
</tr>
<tr>
<td>MADYMO</td>
<td>Mathematical Dynamic Model</td>
</tr>
<tr>
<td>NCAC</td>
<td>National Crash Analysis Center</td>
</tr>
<tr>
<td>NCAP</td>
<td>New Car Assessment Program</td>
</tr>
<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety</td>
</tr>
<tr>
<td></td>
<td>Administration</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 Background

Vehicle rollover accidents take place for only 8 percent of all the vehicle crashes types (directions) yet, they constitute nearly one-third of the fatalities of occupants in passenger vehicles during crash, as shown in Figure 1.1 [5]. Hence, rollover crashes are quite violent in nature as they expose occupants (especially unrestrained ones) to significant levels of impact forces, which could contribute to higher fatalities in these crashes, compared to non-rollover crash scenarios.

Figure 1.1 Overview of Vehicle Crashes, Occupant Injuries and Fatalities [5]
Within the vehicle category, light truck vehicles are extensively involved in rollover crash compared to the other passenger vehicles. This is due to the fact that the location of center of gravity of these vehicles is typically higher, compared to other category cars. Pickup trucks, SUV’s, and vans are all included in light trucks category. In 2000, SUV’s involved in rollover crash were around 6 percent, compared to 4 percent of pickup trucks and 2 percent of vans [8].

Figure 1.2 illustrates that the percentage of vehicle rollover occurrence in pick-up trucks, SUV’s, and vans in 2000 [5]. A comparison of crash occurrence, results in high fatality, occupant injuries and property damage in SUV’s, Pick-up trucks, and vans can be observed.

![Figure 1.2 Rollover Crash Severity](image)

One-fifth of all the vehicles involved in fatal crashes in year 2000 experienced rollovers, that portion has remained unchanged over past ten years[1]. Vehicle rollover incidents has remained constant. These portions remained the same through all these years suggest that the increasing incidence of fatal rollovers results in the number of vehicles exposed to the risk of crash rather than an increase in the instability of the vehicles themselves [13].

Rollovers are not very common crash among all the vehicles, it predominantly occurs in vehicles that has high Center of Gravity from the ground. Vehicles such as Buses, Trucks, Pick-up trucks and SUV’s etc. Vehicles such as sedan will also experience the rollover crashes but not as much as the above-mentioned vehicles. The data in the Table 1.1 represents the percentage of cars and light trucks involved in fatal crashes [1].
As observed from Table 1.1, fatal crashes in rollovers are more than two times higher for light trucks compared to passenger cars in the entire decade from 1991 to 2000. Moreover, the total fatal crash percentage was increased a bit, whereas there was a small decrease in no rollover fatal crashes. And, after enormous improvements in vehicle crashworthiness in this decade, there is still no change in the number of fatal crashes, particularly in the case of SUV’s as it was 36 % in 1991, increased to 37% in 1995 and then fall back to 36% in 2001 [17]. Figure 1.3 describes that SUV’s involved in fatal rollovers increased as the years passed by, the crashes increased from 22 percent to 37 percent between 1991 to 2000. Though the fatality rate of inside the vehicles

<table>
<thead>
<tr>
<th>Year</th>
<th>Crash Type</th>
<th>Passenger Cars (%)</th>
<th>Light Trucks (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>SUV’s</td>
<td>PU Trucks</td>
</tr>
<tr>
<td>1991</td>
<td>Rollovers</td>
<td>16</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>No Rollovers</td>
<td>84</td>
<td>64</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>All Crashes</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1995</td>
<td>Rollovers</td>
<td>15</td>
<td>37</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>No Rollovers</td>
<td>85</td>
<td>63</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>All Crashes</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2000</td>
<td>Rollovers</td>
<td>15</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>No Rollovers</td>
<td>85</td>
<td>64</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>All Crashes</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

As observed from Table 1.1, fatal crashes in rollovers are more than two times higher for light trucks compared to passenger cars in the entire decade from 1991 to 2000. Moreover, the total fatal crash percentage was increased a bit, whereas there was a small decrease in no rollover fatal crashes. And, after enormous improvements in vehicle crashworthiness in this decade, there is still no change in the number of fatal crashes, particularly in the case of SUV’s as it was 36 % in 1991, increased to 37% in 1995 and then fall back to 36% in 2001 [17]. Figure 1.3 describes that SUV’s involved in fatal rollovers increased as the years passed by, the crashes increased from 22 percent to 37 percent between 1991 to 2000. Though the fatality rate of inside the vehicles
dropped from high 80 percent from (1996-2000) to 67 percent (2015-2016) and relatively people killed outside the vehicle increased from low of 20 percent (1996-2000) to a high of 33 percent (2015-2016) [16]. However still the rollover crashes did not decrease as its corresponding fatalities in rollovers increased by 9.1 percent from 2015 to 2016, as shown in Figures 1.3, 1.4 and 1.5.

![Figure 1.3 Light Trucks Involved in Fatal Crashes in 1991 and 2000 [1]](image1)

![Figure 1.4 Fatalities in Vehicle Crashes from 1975-2016 [1]](image2)

![Figure 1.5 Percentage Change by Crash Category [1]](image3)

As observed rollover crashes are considered as quite dangerous, and the most serious crash type, and yet there is no standard to evaluate rollover safety in government safety standards [15].
But there is promising research being developed in countries like U.S and Australia as shown in Figure 1.6.

1.2 Standards and Regulations

Rollover categories are of two types tripped and un-tripped [4].

- Tripped rollovers:

  If a vehicle strikes the curb or guard rails due to external influence on the vehicle, as in Figure 1.6.

  ![Figure 1.6 Tripped rollovers](image)

- Un-Tripped rollovers:

  If the vehicle rollover due to its own weight it is an un-tripped rollover, as in Figure 1.7.

  ![Figure 1.7 Un-Tripped rollovers](image)
Tripped rollovers constitute over 95% of single vehicle rollovers according NHTSA (National Highway Traffic Safety Administration). These rollovers are occurred when vehicle roll is caused due to sliding tires of the vehicle, vehicle strikes curb or guard rail and so on. While Un-tripped rollovers are rare compared to tripped, usually happens to top heavy vehicles while maneuvering to avoid high speed crashes [12].

Tests to predict the rollover crashes

- Static test,
- Dynamic test.

The effectiveness of predicting rollover crashes can be assessed using static and dynamic tests. Since there are many different causes for rollover, it is difficult to create a dynamic test for any types of rollover.

Manufacturing companies needs to comply with Federal Motor Vehicle Safety Standards (FMVSS) for safety of passengers. National Highway Traffic Safety Administration (NHTSA) issues Federal Motor Vehicle Safety Standard its data to set a standard for the manufacturers. At present requirement for all vehicles in United States. This standard specifies requirements for roof crush resistance over passenger compartment for passenger cars (except convertibles), multi-purpose vehicle(MPV), trucks and buses (except school buses) with a gross vehicle weight rating of 6000 pounds or less. In year 1990 Federal Motor Vehicle Safety Standard No.216 requires that a with either side of the forward edge of a passenger car roof should not displace over 125mm when subjected to 1.5 times of vehicles unloaded weight in kilograms. These same standards also apply to light trucks and vans (LTV’s) with Gross Vehicle Weight Rating of 2,722 kilograms or less, as shown in Figure 1.6. This standard has been criticized for being static test which does not

Figure 1.8 FMVSS 216 Static Roof Crush Test Configuration [2]

It is a static test for vehicle rollover that tests the strength of vehicle roof. It is a primary test for vehicles roof strength to withstand rollover. It came to effective in year 1973 and is a mandatory.

a. Force application is applied in such a way that makes windscreens play significant role in curbing the deformation which is unrealistic.

b. The angles that are used in the test are unrealistic to actual crash.

c. The force experienced in rollover is significantly higher compared to the force applied in the test.

Though fatalities in rollover crashes are occurred by passenger ejecting from the car or passenger knocked in the car. In effort to reduce that fatalities in the car NHTSA is investigating possible upgrade for FMVSS 216.

On August 19, 2005, the NHTSA proposed the following improvements to FMVSS 216 [2]
a. It increased its Gross Vehicle Weight Rating from 2,722 kg to 4,536 kg or less.

b. The applied force by platen is increased from 1.5 to 2.5 times of the unloaded vehicle weight.

c. Replace the current limit on the amount of roof intrusion with a new requirement to maintain enough headroom to accommodate a mid-size adult male occupant.

A full-scale rollover test does not have any standard safety regulation to conduct crashworthiness tests. Hence, these tests are repeatable. A static test has an advantage by its repeatability [11]. Roof structure failure modes are also like rollover tests and real-world collisions.

The FMVSS No. 216 is used to measure the roof strength, A dynamic test is conducted by utilizing an inverted drop test followed by SAE J996 safety regulations, which was proposed by Society of Automotive Engineers (SAE). This test is to measure injury severities to the occupants occurred due to induced dynamic forces on the roof in a rollover crash. This inverted rollover test is considered by NHTSA as an alternative test procedure to study strength of a roof structure to improve its crashworthiness for occupant safety.

The following set of instructions should be considered in Inverted Drop Test:

- Inverted Drop Test is incorporated with a Lateral or sliding velocity of the ground as it moves underneath the vehicle.
- It is a must to test both sides of the roof, current study tests only one side. The study shows that the passenger at trailing edge is severely injured, this is due to, the roof is already weakened for first impact, it crushes downwards towards occupant’s head for the second impact.
• It was observed that the severity of the injuries is higher after the windshield shatters in first impact. Generally, windshield provides up to one third of the roof strength in static tests.

• This test is an exact replica of the real dynamic crush and depends on geometry of the roof like roundness, curvature, etc. In general, static tests does not include roof geometry, which excludes the most important factor for survivability.

In Inverted Drop Test, to test roof crush resistance, the vehicle is inverted upside down at 25° roll angle and 5° pitch angle, as shown in Figure 1.9. This configuration is the same as the static roof crush test. After that, the vehicle is released and dropped onto a concrete floor against gravity and drop heights are suggested to be around 12 and 18 inches.

The inverted Dynamic test has few drawbacks as it lacks the representation of lateral speed of the vehicle and reproducibility of test procedure.

In Figure 1.10, the JRS rollover is shown as repeatable test procedure where the vehicle is held using a cross beam and dropped on to the lateral moving floor from desired height. This test procedure is referred to as “constrained” rollover test.
1.3 Literature Review

Extensive research has already been conducted on static and dynamic rollover crash tests to standardize a perfect procedure for rollover crash scenarios.

Tahan, et al. [7] investigated rollover crashes to evaluate performance of a mid-sized SUV using Unconstrained rollover, under same initial conditions. In addition to that, the study used different Test Bed Mass for the rollover tests and analyzed its effects. And observed the changes with different roll angle of the contacts at time of crash and studied its responses.

Deshmukh, et al. [11] studied rollover and roof crush analysis of low-floor mass transit bus. In this study developed finite element (FE) model of a bus was used, analyzed the roof crush and rollover crash tests in LS-DYNA. In addition to that, conducted rollover crash tests on
developed MADYMO bus model and analyzed dummy kinematics, Injury criteria for various seated and standing positions of occupants in rollover.

Tahan et al. [9] researched on influence of quasi-static and dynamic loading directions on roof deformation. Studied normal Force for FMVSS 216 One sided Loading with Variable Roll and Pitch Angles. In addition to this study roof crush shapes and lateral roof displacements, unconstrained rollover tests with different roll angle normal forces, unconstrained roof crush shapes for different roll and pitch angles were evaluated.

Shenoy, et al. [20] researched on energy absorption of a car roof reinforced with a stiffened composite panel in the event of rollover, In this the car roof is reinforced with the composites and tested its resistance during the roof crush test and its ability to withstand in the event of rollover. A simulation of the quasi-static test is carried out in accordance with FMVSS No. 216. Also, an inverted dynamic drop test is carried out as per SAE J996 standards.

Pai, et al. [21] studied modelling of rollover protective structure and falling object protective structure tests on a composite cab for skid steer loaders. Steel parts of the skid steer loader are replaced with composites and tested using the ISO standards to evaluate its loading capabilities. Also, the skid steer model is designed using PROE. These composites are used in roof strengthening procedure.

Donga, et al. [26] studied applications of sandwich beam in automobile front bumper for frontal crash analysis. In this study behaviour of sandwich beams under static loading is observed and how it can with stand during various crashes such as Frontal, Rear, Side and Rollover crashes.

Marudhamuthu, et al. [25] study was based on 3+2 point seat belt responses of the passengers while undergone a rollover. These rollovers are on pick-up trucks. Further the injury
responses are studied in MADYMO code with the use of Easi-Crash. Dolly Rollover standard is used to replicate rollover scenario. The MADYMO results for the Dolly Rollover test is analysed by comparing the injury parameter standards and specifications of NHTSA.

Malli et al. [24] conducted study on performance evaluation of thin walled tube filled with nano based polyurethane rigid foam for increased roof strength of a vehicle. Due to high fatality rate in rollover crashes, nano polyurethane was used in the FEA model to strengthen the roof. And doors have padding materials at different parts of vehicle. The materials are also used in bumper for more energy absorption during the frontal crash.

Examination of the literature review on this topic indicates that rollover crash tests conducted in developed LS-Dyna models showed some excellent results in simulation tests. Still it is important and necessary to understand the dynamic behavior of finite element vehicle model for various initial conditions in rollover crashes. The study is conducted to for better understanding analyzing the parameters and their effects in rollover tests.

1.4 Motivation

The motivation of the study is to arrive at and to, propose the optimized parameters required for the constrained or unconstrained rollover tests that validate the scope and severity of crash in real world. It is also intended to make amendments to the standards in order to improve the vehicle’s rollover crashworthiness and the design of proper safety measures for vehicle occupants.
CHAPTER 2
OBJECTIVES AND METHODOLOGY

2.1 Objectives

There exist different crashworthiness tests to measure structural integrity of a vehicle to withstand deceleration loads at an event of crash. In general, the roof strength of the vehicle is determined first, to ensure its ability to withstand for rollover crash according to FMVSS 216. But roof strength test does not replicate the actual crash scenario, A standard test replicating the actual crash scenario is yet to be produced. Despite of extensive research performed on dynamic rollover crashes. The reason for this is, involving several parameters. Using finite element methods, this study is initially focused on examining roof strength of the vehicle by conducting static roof crush tests and then study continued to analyze the parameters of dynamic rollover crash and to suggest a better approach in testing procedure to improve crashworthiness and occupant protection.

The specific objectives of this research are:

- To develop computational models and simulations of mid-size SUV vehicles, undergoing static roof crush and dynamic rollover test conditions,
- To validate and analyze roof crush analysis of mid-size SUV (Toyota RAV4),
- To evaluate roof strength of the vehicle under initial conditions of vehicle with ground during impact to its ground,
- To validate force vs displacement graph of roof crush of different vehicle,
- To evaluate the vehicle intrusion near the drivers and passengers head space for different speeds, heights dropped and angle of contact of vehicle,
- To compare the significant parameters and propose a better dynamic approach for standardizing the dynamic rollover.
2.2 Methodology

This research starts with the modeling, simulation, and examination of finite element static roof crush tests in accordance with the FMVSS 216 safety regulatory standard. Upon validation of static test results with standard laboratory tests, the finite element model can be used for unconstrained dynamic rollover tests. The finite element model of mid-size SUV is tested under various parameters such as Roll angle of vehicle with ground at time of impact, speed of the vehicle during rollover, and drop height of the vehicle. The energy induced, and the force imparted to the vehicle are compared and analyzed its effects on vehicle occupants. The methodology is illustrated in Figure 2.1.

![Figure 2.1 Methodology](image-url)
CHAPTER 3

STATIC ROOF STRENGTH ANALYSIS

3.1 Static Finite Element Analysis Tests for Roof Strength

In Rollover crashes, mostly vehicle damage is due to deformation of the roof and its supporting structures. Generally, this roof deformation leads to severe head and neck injuries in rollover crash. Therefore, occupant protection is necessary even if it is not a frequent type of crash. Strengthening of the roof and its supporting structures is suggested as an alternative countermeasure for such serious injuries.

The National Highway Traffic Safety Administration (NHTSA) mandated the static roof crush tests. In this test the force-deflection behavior of the roof structure is measured by quasi-statically applying load by pressing a precisely positioned rigid plate against the automobile. The requirements for roof crush resistance of an automobile are mentioned in Federal Motor Vehicle Safety Standard (FMVSS) 216 [2]. In this roof crush resistance test, a force is applied quasi-statically to the side of the forward edge of a vehicle roof structure through a large rigid block by constraining chassis frame and car sills to a horizontal surface, as shown in Figure 3.1.

Figure 3.1 Finite Element Model Representation of Static Roof Crush Resistance Test [4].
The applied force and displacement of the block are recorded throughout the test to calculate the roof crush resistance. Automotive companies generally use finite element modelling of the roof crush resistance tests to get an accurate and efficient designs of automobiles and to reduce development and testing costs.

### 3.2 Finite Element Models of Toyota Rav4 and Ford Explorer

Finite element model of Toyota Rav4 and Ford Explorer, in Figures 3.2 and 3.3, were developed by National Crash Analysis Center (NCAC) in the time period of 2003 - 2005 by utilizing FARO arm to get an accurate finite element model and subsequent model response. This detailed finite element model was constructed to include full functional capabilities of the suspension and steering systems. 2000 model Toyota Rav4 and 2002 model Ford Explorer cars were disassembled, and all of the parts was cataloged, scanned to identify its geometry, measured for thickness, and classified by material type. All data is digitized and by using finite element modelling software created a finite element model that reflected all structural and mechanical features.

Material data for the important structural components was updated using coupon testing of samples taken from vehicle parts. Material tests were conducted to use an appropriate stress-strain values in material models for the analysis of crush behavior in crash simulation.

![Figure 3.2 Finite Element Model of Ford Explorer][5]
Figure 3.3 Finite Element Model of Toyota Rav4 [6].

A Summary of the details of the finite element models is listed in Tables 3.1 and 3.2. The finite element models have been verified and validated by the government in different tests to ensure that they produce exact representations of the actual vehicles [5].

The finite element models are again validated here by comparing simulations of NCAP frontal wall impact with actual test data from NHTSA tests. Simulation results reflected the expected responses and consistency. This model development process proved the developed finite element model is robust and applicable for the study of various crash scenarios.

Table 3.1 Ford Explorer Finite Element Model Summary [5].

<table>
<thead>
<tr>
<th>Number of parts</th>
<th>923</th>
<th>Beam Element Connections</th>
<th>4,425</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>724,628</td>
<td>Nodal Rigid Body Connections</td>
<td>2,102</td>
</tr>
<tr>
<td>Number of shells</td>
<td>680,288</td>
<td>Extra Node Set Connections</td>
<td>132</td>
</tr>
<tr>
<td>Number of Beams</td>
<td>185</td>
<td>Rigid Body Connections</td>
<td>7</td>
</tr>
<tr>
<td>Number of Solids</td>
<td>33,690</td>
<td>Spot Weld Connections</td>
<td>6,842</td>
</tr>
<tr>
<td>Total Number of Elements</td>
<td>714,205</td>
<td>Joint Connections</td>
<td>54</td>
</tr>
</tbody>
</table>
Table 3.2 Toyota Rav4 Finite Element Model Summary [6].

<table>
<thead>
<tr>
<th>Number of parts</th>
<th>577</th>
<th>Weight (Kg)</th>
<th>1266</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>478,624</td>
<td>Wheel Base (mm)</td>
<td>2415</td>
</tr>
<tr>
<td>Number of shells</td>
<td>472,423</td>
<td>Extra Node Set Connections</td>
<td>132</td>
</tr>
<tr>
<td>Number of Beams</td>
<td>2</td>
<td>C.G. (mm) Rearward of Front Wheel C/L</td>
<td>1135</td>
</tr>
<tr>
<td>Number of Solids</td>
<td>21,539</td>
<td>Engine Type 2.0 L4SFI DOHC 16V</td>
<td></td>
</tr>
<tr>
<td>Total Number of Elements</td>
<td>494,117</td>
<td>Model Year 2000</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Finite Element Model Setup for Roof Crush Resistance Test

The necessities for Roof crush resistance test are followed according to improved FMVSS 216 safety standards. The overall process is to study current characteristics of the roof structure’s strength, stiffness, energy and to determine roof failure characteristics when quasi-static load is applied.

In this study, the full finite element vehicle model is loaded for simulating roof crush test in LS-DYNA. Due to the negligible effect on overall roof crush resistance response, neglected interior and exterior components and only body in white of a car has been used for the study. It has been observed that roof and A, B, and C pillars have a significant effect in crush resistance response. Although, front and rear mirrors have negligible effect over the study still these components are including for the practical results approach.

A force is applied quasistatically at the top of the side rail at the angle on the vehicle top structure. Generally, the quasi-static load is applied through rigid rectangular flat plate with the dimension of 762 mm x 1829 mm. The Rigid plate is oriented longitudinally at an edge of 5° to
the level towards vehicle pivot and a lateral angle of 25° degrees beneath the horizontal and it was placed above the vehicle, as shown in Figure 3.4.

Figure 3.4 Finite Element Model Set-up for Static Roof Crush Test

The first contact point of plate on to the roof is on the longitudinal centerline of the plate at a point 254 mm first most edge of the plate. This procedure was replicated to simulate the roof contact with the ground in an actual rollover event. A quasi-static load was employed over the roof and the force is 3 times of unloaded vehicle weight which is calculated and applied as the roof displacement at a rate of 13 mm per second and in a direction normal to the load plate surface [9].

In LS-DYNA, a rigid plate is modelled with the dimension of 762 mm x 1829 mm and 2D shell elements are assigned using *SECTION_SHELL properties card including Belytschko-Tsay element formulation with 1 mm thickness. Linear steel properties are assigned as stated in Table 3.3 by using a material cad * MAT_RIGID ( MAT_20).

Table 3.3 Material Properties of Rigid Plate

<table>
<thead>
<tr>
<th>Component</th>
<th>Density (Ton/mm³)</th>
<th>Young’s Modulus (Mpa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Plate</td>
<td>7.890e-009</td>
<td>2.1e+005</td>
<td>0.30</td>
</tr>
</tbody>
</table>
To conduct roof crush resistance test, implicit solver is preferred in this study because
explicit solver leads to the higher speeds of the rigid plate, which in turn results in inertial effects
that smooth out the nonlinearities and reduce the efficiency of solution algorithms whereas implicit
solvers enforce equilibrium on the vehicle structure while loads are applied externally. In LS-
DYNA, to specify switch element formulation into fully integrated implicit spring back
formulation and retain back to original element formulation, and to define initial step size
*CONTROL_IMPLICIT_GENERAL card is used. *CONTROL_IMPLICIT_AUTO card is
utilized to define number of iterations per time step and to adjust time step automatically and to
introduce numerical damping to the model. Newmark time integration constants GAMMA and
BETA values are defined as 0.6 and 0.38 respectively in *IMPLICIT_DYNAMICS. Parameters
required for non-linear solver, control iterative equilibrium search and convergence are stated in
*CONTROL_IMPLICIT_SOLUTION. Finally, *CONTROL_IMPLICIT_EIGENVALUE card is
used to perform eigenvalue problem and to intermittent eigenvalue analysis for a better debugging
eigenvalues/vectors are defined.

According to the roof crush test requirements, a fixed contact is must between car chassis
and base plate. To conformance the above requirement, the degree of freedom of the chassis is
constrained by restricting translation and rotation of nodal set of chassis with respect to global
coordinate system by utilizing *BOUNDARY_SPC card. The contact between rigid plate and the
roof structure is described by using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE
card along with both static and dynamic friction co-efficient values as 0.2.
*CONTACT_SINGLE_SURFACE contact card is also defined for a global contact between all
the components in the set-up model. According to safety standard’s requirements, the rigid plate
displacement rate is 13 mm per second in a direction normal to the plate surface. This is applied
to the rigid plate by using *BOUNDARY_PRESCRIBED_MOTION_RIGID card. In this card translational degree of freedom for the rigid plate is applied in normal direction to the plate (i.e. Z-direction) and displacement curve is defined to apply desired displacement rate. The displacement with respect to time curve is shown in Figure 3.5.

![Figure 3.5 Displacement vs Time Curve for Static Roof Crush](image)

In LS_DYNA *DATABASE cards such as ASCII_Option, BINARY_D3PLOT, EXTENT_BINARY and HISTORY_NODE_ID are defined to get the required results for quasi-static roof crash resistance test. Control cards such as ACCURACY, CONTACT, ENERGY, HOURGLASS, OUTPUT, SHELL, and SOLID are used for smooth run of the model and to improve the results accuracy. *CONTROL_TERMINATION card is used to terminate the analysis after 0.1 seconds. At the end, control cards *CONTROL_MPP_IO_NODE3DUMP and *CONTROL_MPP_IO_NODUMP are defined to run the set-up model using multi parallel processing in LS_DYNA solver.
3.4 Analyzing Static Roof Crush Results of Ford Explorer and Toyota Rav4

Figure 3.6 illustrates the reaction force induced due to crushing of platen on Ford Explorer’s roof. In accordance with FMVSS 216 regulations, the Explorer was subjected to 3 times of its body weight load through platen. The readings show the resultant force of Explorer against time. The maximum force subjected on to RAV4 is 21 kN.

![Figure 3.6 Reaction Force vs Time for Static Roof Crush test of Ford Explorer](image1)

Figure 3.7 Comparison of Force vs Time for Finite Element and Standard Test of Ford Explorer

![Figure 3.7 Comparison of Force vs Time for Finite Element and Standard Test of Ford Explorer](image2)
Figure 3.7 illustrates the comparison of induced reaction force of Finite Element model with Standard Laboratory roof crush test for Ford Explorer. The FE model results correlated well compared with standard laboratory roof crush tests in accordance with FMVSS 216 safety regulations.

![Figure 3.7 Reaction Force vs Time for Static Roof Crush test of Ford Explorer](image)

Figure 3.8 Reaction Force vs Time for Static Roof Crush test of Toyota Rav4

Figure 3.8 illustrates that the reaction force induced to Toyota RAV4 through platen by gradual increase of load to 3 times of its weight. The maximum resultant force induced at roof was 24 kN. Toyota Rav4 finite element model’s roof can withstand the static roof crush load. So, it can be used for further Dynamic roll rollover crash scenarios. There is no standard test conducted on RAV4 for further validation with its FE model. The maximum force induced in static roof crush test of Ford Explorer and Toyota Rav4 are shown in Table 3.4.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Explorer</td>
<td>22</td>
</tr>
<tr>
<td>Toyota Rav4</td>
<td>24</td>
</tr>
</tbody>
</table>
CHAPTER 4
UNCONSTRAINED DYNAMIC ROLLOVER TESTS

4.1 Dynamic Rollover Model Setup for Finite Element Analysis

From the static rollover test, roof strength of Ford explorer and Toyota Rav4 finite element models was within FMVSS 216 standard. Extensive research was already conducted on Ford Explorer, in this study Toyota Rav4 model was used to conduct unconstrained dynamic rollover test. The dynamic rollover crash response of Toyota Rav4 finite element model is studied for different speeds, different drop heights, and different roll angles.

Parametric study is conducted based on Santos test protocols for the Jordon Rollover System tests [7]. The dynamic rollover tests were conducted with multiple initial parameter variations on Toyota Rav4 finite element model. The design parameters considered for the dynamic tests are floor speeds of 0, 24, and 36kmph, roll angle of 135°, 145°, and 155°, and drop heights of 10, 20, and 30 cm. The set of finite element models described in Table 4.1 were used to conduct dynamic rollover tests. Fixed initial variables, such as Yaw angle 10°, pitch angle 5° were used for model setup [10].

Table 4.1 Design Parameters Considered for Parametric Study

<table>
<thead>
<tr>
<th>Drop Height</th>
<th>Floor Speed</th>
<th>Roll Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>0kmph</td>
<td>135°</td>
</tr>
<tr>
<td>20 cm</td>
<td>24kmph</td>
<td>145°</td>
</tr>
<tr>
<td>30 cm</td>
<td>36kmph</td>
<td>155°</td>
</tr>
</tbody>
</table>
In LS-DYNA, a rigid floor is modelled with the dimension of 4800mm x 4800 mm and 2D shell elements are assigned using *SECTION_SHELL properties card including Belytschko-Tsay element formulation with 1 mm thickness. Linear steel properties are assigned as mentioned in Table 4.1 by using a material card * MAT_RIGID (MAT_20).

Table 4.2 Material Properties of Floor

<table>
<thead>
<tr>
<th>Component</th>
<th>Density (Ton/mm$^3$)</th>
<th>Young’s Modulus (Mpa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Plate</td>
<td>7.890e-009</td>
<td>2.1e+005</td>
<td>0.30</td>
</tr>
</tbody>
</table>

To conduct dynamic rollover crash test, explicit solver is preferred for this study because explicit solver has the good correlation for higher speeds and to reduce time required for solving numerical simulations. The contact between floor and the entire Rav4 finite element model is described by using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE card along with both static and dynamic friction co-efficient values as 0.2. For a global contact between all the components in the set-up model *CONTACT_AUTOMATIC_SINGLE_SURFACE contact card was defined.

According to parametric study requirements, the floor velocity is given by using *BOUNDARY_PRESCRIBED_MOTION_RIGID card. In this card translational degree of freedom for the floor is applied in Y-direction and velocity curve is defined to apply desired velocity for the floor. *DEFINE_CURVE keyword was used to create velocity curves for 24kmph and 36kmph speeds for this study. Velocity with respect to time curves used in this study are shown in Figures 4.1, and 4.2.
Figure 4.1 Lateral (Roll) Velocity Input Curve for 24 kmph

Figure 4.2 Lateral (Roll) Velocity Input Curve for 36 kmph
In LS_DYNA *DATABASE cards such as ASCII_OPTION, BINARY_D3PLOT, EXTENT_BINARY and HISTORY_NODE_ID are defined to get the required plots for dynamic rollover test. Control cards such as ACCURACY, CONTACT, ENERGY, HOURGLASS, OUTPUT, SHELL, and SOLID are used for smooth run of the model and to improve the results accuracy. *CONTROL_TIMESTEP was used to define time step value -1.112e-006. Negative value is mentioned for mass scaling purpose and to obtain this timestep value several models was initially conducted to compensate calculation time and also to eradicate run time errors like negative volume and node shootout. *CONTROL_TERMINATION card is used to terminate the analysis after 0.35 seconds. At the end, control cards *CONTROL_MPP_IO_NODE3DUMP and *CONTROL_MPP_IO_NODUMP are defined to run the set-up model using multi parallel processing in LS_DYNA solver by using High performance computer. The finite element model set up for dynamic rollover crash sets are shown in Figures 4.3, 4.4, and 4.5.

Figure 4.3 Finite Element Model Setup for 10 cm Drop Height, 135° Roll Angle, 0kmph.
Figure 4.4 Finite Element Model Setup for 20 cm Drop Height, 145° Roll Angle, 24kmph.

Figure 4.5 Finite Element Model Setup for 30 cm Drop Height, 155° Roll Angle, 36kmph.
4.2 Rollover Crash Simulation Results

Considering three design parameters rollover angle, speed and height drops in LS-DYNA, a total 27 models are preprocessed and simulated. Figure 4.6 shows a sample model set up and dynamic rollover response of Toyota Rav4 for 20cm height, 145 rollover angle, and 24 kmph speed.

![Figure 4.6 Simulation Result of Toyota Rav4 Dynamic Rollover Test](image)

Time 0 msec

Time 0.1 msec

Time 0.2 msec

Time 0.3 msec

Time 0.4 msec

Figure 4.6 Simulation Result of Toyota Rav4 Dynamic Rollover Test
4.3 Comparison of Force vs Time for Different Speeds

Figure 4.7 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 142 kN induced at floor speed 36 kmph. For 10 cm height drop with 135° roll angle, it can be seen that with increasing in speeds, the increment in reaction force induced at driver’s end is less while compared to the passenger’s end.

![Figure 4.7 Reaction Force Response for 10 cm Height, 135° Roll Angle and Different Speeds](image)

Figure 4.7 Reaction Force Response for 10 cm Height, 135° Roll Angle and Different Speeds

![Figure 4.8 Reaction Force Response for 10 cm Height, 145° Roll Angle and Different Speeds](image)

Figure 4.8 Reaction Force Response for 10 cm Height, 145° Roll Angle and Different Speeds
Figure 4.8 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 123 kN induced at driver’s end with rolling speed 36 kmph. For 10 cm height drop with 145° yaw angle, it is observed that the increment in reaction force induced at both driver’s end and passenger end is very high with increasing in speeds. For 145° roll angle it can be seen that the reaction force is almost same for the 0 kmph and 24 kmph.

Figure 4.9 Reaction Force Response for 10 cm Height, 155° Roll Angle and Different Speeds

Figure 4.9 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 141 kN induced at floor speed 36 kmph. For 10 cm height drop with 155° Roll angle, it can be seen that the increment in reaction force induced at driver’s end is higher than passenger end with increasing in speeds. The reaction force decreases with increase in Raw angle decreases the passenger’s fatality rate even with the increase in the speeds.
Figure 4.10 Reaction Force Response for 20 cm Height, 135° Roll Angle and Different Speeds

Figure 4.10 illustrates the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 162 kN induced at floor speed 36 kmph. For 20 cm height drop with 135° Roll angle, it can be seen that the increment in reaction force induced at passenger’s end is higher than driver’s end with increasing in speeds. The reaction force increases with increase in height decreases the driver’s fatality rate even with the increase in the speeds.

Figure 4.11 Reaction Force Response for 20 cm Height, 145° Roll Angle and Different Speeds
Figure 4.11 demonstrates the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 136 kN induced at floor speed 36 kmph. For 20 cm height drop with 145° Roll angle, it can be seen that the increment in reaction force induced at both driver’s end and passenger’s end is higher with increasing in speeds. The reaction force is almost same for the 0 kmph and 24 kmph.

Figure 4.12 Reaction Force Response for 20 cm Height, 155° Roll Angle and Different Speeds

Figure 4.12 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 138 kN induced at floor speed 36 kmph. For 20 cm height drop with 155° Roll angle, it can be seen that the increment in reaction force induced at both driver’s end and passenger’s end is higher and nearly same with increasing in speeds. The reaction force is further increased at passenger’s end for the 36 kmph.
Figure 4.13 Reaction Force Response for 30 cm Height, 135° Roll Angle and Different Speeds

Figure 4.13 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 162 kN induced at floor speed 36 kmph. For 30 cm height drop with 135° roll angle, it can be seen that with increasing in speeds, the increment in reaction force induced at driver’s end is less while compared to the passenger’s end. At driver’s side observed a small increase in reaction force while it is significantly improved at passenger’s end.

Figure 4.14 Reaction Force Response for 30 cm Height, 145° Roll Angle and Different Speeds
Figure 4.14 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 138 kN induced at floor speed 36 kmph. For 30 cm height drop with 145° Roll angle, it can be seen that the increment in reaction force induced at both driver’s end and passenger’s end is higher with increasing in speeds. The reaction force is further increased at driver’s end and passenger’s end for the 36 kmph.

![Reaction Force Response for 30 cm Height, 145° Roll Angle and Different Speeds](image)

Figure 4.15 Reaction Force Response for 30 cm Height, 145° Roll Angle and Different Speeds

Figure 4.15 represents the comparison of resultant force against time for different speeds 0, 24, and 36 kmph in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 162 kN induced at floor speed 36 kmph. For 30 cm height drop with 155° roll angle, it can be seen that with increasing in speeds, the increment in reaction force induced at driver’s end is nearly same and it is increased at the passenger’s end. At driver’s side observed almost same reaction force in both 24 kmph and 36 kmph speeds while it is significantly improved at passenger’s end for 36 kmph speed.
4.4 Comparison of Force vs Time for Different Heights

Figure 4.16 illustrates the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 73 kN induced at both drop heights 20 and 30 cm. For 0kmph Speed, 135° roll angle, it can be seen that with increasing in heights, the increment in reaction force induced is nearly same and it is further increased at the passenger’s end.

Figure 4.16 Reaction Force Response for 0kmph Speed, 135° Roll Angle and Different Heights

Figure 4.17 Reaction Force Response for 24kmph Speed, 135° Roll Angle and Different Heights
Figure 4.17 represents the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 125 kN induced at both drop heights 20 and 30 cm. For 24kmph Speed, 135° roll angle, it can be seen that with increasing in heights, the increment in reaction force induced at driver’s end is very less comparing with passenger’s end.

Figure 4.18 Reaction Force Response for 36kmph Speed, 135° Roll Angle and Different Heights

Figure 4.18 describes the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 162 kN induced at both drop heights 20 and 30 cm. For 36kmph Speed, 135° roll angle, it can be seen that with increasing in heights, the increment in reaction force induced is nearly same and it is further increased at the passenger’s end.
Figure 4.19 Reaction Force Response for 0kmph Speed, $145^0$ Roll Angle and Different Heights

Figure 4.19 shows the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 81 kN induced at drop height 30 cm. For 0kmph Speed, $145^0$ roll angle, it can be seen that with increasing in heights, the increment in reaction force induced at driver’s end is almost same all height drops and at passenger’s end it is increased with increase in height.

Figure 4.20 Reaction Force Response for 24kmph Speed, $145^0$ Roll Angle and Different Heights
Figure 4.20 shows the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 82 kN induced at drop height 30 cm. For 24 kmph Speed, 145° roll angle, it can be seen that with increasing in heights, the increment in reaction force induced at driver’s end is almost same all height drops and at passenger’s end it is increased with increase in height and maximum at 30 cm drop.

Figure 4.21 Reaction Force Response for 36kmph Speed, 145° Roll Angle and Different Heights

Figure 4.21 shows the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 138 kN induced at drop height 30 cm. For 36 kmph Speed, 145° roll angle, it can be seen that with increasing in heights, the reaction force induced at driver’s end is slightly increased and at passenger’s end it is increased gradually with increase in height and maximum at 30 cm drop.
Figure 4.22 Reaction Force Response for 0kmph Speed, 155° Roll Angle and Different Heights

Figure 4.22 illustrates the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 86 kN induced at drop height 30 cm. For 0kmph Speed, 155° roll angle, it can be seen that with increasing in heights, the reaction force induced at driver’s end is slightly increased and at passenger’s end it is increased gradually with increase in height and maximum at 30 cm drop.

Figure 4.23 Reaction Force Response for 24kmph Speed, 155° Roll Angle and Different Heights
Figure 4.23 describes the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 144 kN induced at drop height 30 cm. For 24 kmph Speed, 155° roll angle, it can be seen that with increasing in heights, the reaction force induced at driver’s end is slightly increased and at passenger’s end it is a little increased with increase in height and maximum at 30 cm drop.

Figure 4.24 Reaction Force Response for 36 kmph Speed, 155° Roll Angle and Different Heights

Figure 4.24 describes the comparison of resultant force against time for different heights 10, 20, and 30 cm in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 141 kN induced at drop height 30 cm. For 36 kmph Speed, 155° roll angle, it can be seen that with increasing in heights, the reaction force induced at driver’s end is almost same and at passenger’s end it is slightly increased with increase in height and maximum at 30 cm drop.
4.5 Comparison of Force vs Time for Different Roll Angles

Figure 4.25 shows the comparison of resultant force against time for different Roll angles $135^0, 145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 68 kN induced at roll angle $155^0$. For 0kmph Speed, 10 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced at driver’s end is slightly increased with increase in roll angles and is maximum at $155^0$.

![Figure 4.25 Reaction Force Response for 10 cm Height, 0kmph and Different Roll Angles](image1)

![Figure 4.26 Reaction Force Response for 10 cm Height, 24kmph and Different Roll Angles](image2)
Figure 4.26 illustrates the comparison of resultant force against time for different Roll angles 135°, 145°, and 155° in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 126 kN induced at roll angle 155°. For 24kmph Speed, 10 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced at driver’s end is drastically increased at driver’s end for roll angle 155° and slight increment in reaction force is observed for 145°.

Figure 4.27 Reaction Force Response for 10 cm Height, 36kmph and Different Roll Angles

Figure 4.27 illustrates the comparison of resultant force against time for different Roll angles 135°, 145°, and 155° in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 142 kN induced at roll angle 155°. For 36kmph Speed, 10 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced at driver’s end is considerably increased at driver’s end and decrement in reaction force is observed for 145° and 155° at passenger’s end.
Figure 4.28 Reaction Force Response for 20 cm Height, 0kmph and Different Roll Angles

Figure 4.28 illustrates the comparison of resultant force against time for different Roll angles 135°, 145°, and 155° in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 78 kN induced at roll angle 155°. For 0kmph Speed, 20 cm drop height, it can be seen that with increasing in roll angle, initially the reaction force induced at driver’s end is almost same and decrement in reaction force is observed for 135° and 155° at passenger’s end.

Figure 4.29 Reaction Force Response for 20 cm Height, 0kmph and Different Roll Angles
Figure 4.29 illustrates the comparison of resultant force against time for different Roll angles $135^0, 145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of $138$ kN induced at roll angle $155^0$. For $24$ kmph Speed, $20$ cm drop height, it can be seen that with increasing in roll angle, the reaction force induced at driver’s end is maximum for $155^0$ roll angle and reaction force at passenger’s end is maximum for roll angle $135^0$.

Figure 4.30 Reaction Force Response for $20$ cm Height, $36$ kmph and Different Roll Angles

Figure 4.30 describes the comparison of resultant force against time for different Roll angles $135^0, 145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of $162$ kN induced at roll angle $135^0$. For $36$ kmph Speed, $20$ cm drop height, it can be seen that with increasing in roll angle, the reaction force induced at driver’s end is maximum for $155^0$ roll angle and reaction force at passenger’s end is maximum for roll angle $135^0$ whereas for roll angle $145$ reaction force induced at driver’s end and passenger’s end is very low.
Figure 4.31 Reaction Force Response for 30 cm Height, 0kmph and Different Roll Angles

Figure 4.31 describes the comparison of resultant force against time for different Roll angles $135^0, 145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 86 kN induced at roll angle $155^0$. For 0kmph Speed, 30 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced is increased.

Figure 4.32 Reaction Force Response for 30 cm Height, 24kmph and Different Roll Angles
Figure 4.32 describes the comparison of resultant force against time for different Roll angles $135^0,145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 144 kN induced at roll angle $155^0$. For 24kmph Speed, 30 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced is increased at driver’s end and at passenger’s end it is decreased drastically.

![Figure 4.32 Reaction Force Response for 24 kmph, 30 cm Drop Height and Different Roll Angles](image)

Figure 4.33 Reaction Force Response for 30 cm Height, 36kmph and Different Roll Angles

Figure 4.33 describes the comparison of resultant force against time for different Roll angles $135^0,145^0,$ and $155^0$ in rollover crash response of Toyota - Rav4. It is observed that the maximum resultant force of 162 kN induced at roll angle $155^0$. For 36kmph Speed, 30 cm drop height, it can be seen that with increasing in roll angle, the reaction force induced is increased at driver’s end and at passenger’s end it is decreased gradually.
4.6 Comparison of Internal Energy vs Time for Different Speeds

Figure 4.34 describes the comparison of Internal Energy with respect to time at varying speeds respectively 0kmph, 24kmph and 36kmph of Toyota RAV4. It is observed from the responses that the speeds from the rest to 24kmph does not vary much of its energy either at Drivers nor at Passengers end. While at increase in speed over 24kmph with drop height of 10 cm and 135° angle the passenger gets affected compared to the driver’s end. The maximum Energy induced due to crash is 32 kJ.

Figure 4.34 Internal Energy Response for 10 cm Height, 135° Roll Angle and Different Speeds

Figure 4.35 Internal Energy Response for 10 cm Height, 145° Roll Angle and Different Speeds
Figure 4.35 describes the comparison of Internal Energy with respect to time at varying speeds respectively 0kmph, 24kmph and 36kmph of Toyota RAV4. The responses with increase in angle to 145° with same drop height and varying speeds of 0kmph, 24kmph and 36kmph is not much different. It affects the passenger side with increase in speed beyond 24kmph. The maximum energy induced at passenger end is 33 kJ.

Figure 4.36 Internal Energy Response for 10 cm Height, 155° Roll Angle and Different Speeds

Figure 4.36 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. With increase in the Roll Angle to 155°, there is increase in energy induced between the speeds 0kmph and 24kmph which is not observed in previous of the two angles 135° and 145° respectively this suggests that with increase in roll angle during the contact with 10 cm drop it can be seen that the increase in dissipation on energy at both ends of the vehicle causing higher fatality rate for the humans in the vehicle. The highest energy induced is 32 kJ.
Figure 4.37 Internal Energy Response for 20 cm Height, 135° Roll Angle and Different Speeds

Figure 4.37 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. It can be seen that the increase in speed directly affects the energy induced at time of crash leads to higher fatalities of passengers compared to driver. The highest energy induced is 40 kJ at speed of 36kmph.

Figure 4.38 Internal Energy Response for 20 cm Height, 145° Roll Angle and Different Speeds
Figure 4.38 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. The height of the vehicle drop is 20 cm and the angle of contact is 145° are constant in the study. It was observed that 0kmph and 24kmph studies are the same but with increase of speed above 24kmph increase the fatality rate of both driver and passenger and it is severe for the passenger. The highest energy induced is 37 kJ at 36kmph. It can be observed from previous study that the energy induced at 10 cm drop height is greater when compared to energy induced at 20 cm height and this is due to large amount of contact area with floor at the time of crash.

![Figure 4.39 Internal Energy Response for 20 cm Height, 155° Roll Angle and Different Speeds](image)

Figure 4.39 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. It can be observed that with increase in speed energy induced increases. The passenger gets more affected and the highest energy induced is 38 kJ at 36kmph.
Figure 4.40 Internal Energy Response for 30 cm Height, 135° Roll Angle and Different Speeds

Figure 4.40 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. At constant drop height of 30 cm and roll angle of 135°, it can be seen that with increase in speed of the vehicle the energy induced in the vehicle increases and leads to maximum which causes more injuries to the passenger compared to driver. The highest energy induced is 40 kJ at 36 kmph.

Figure 4.41 Internal Energy Response for 30 cm Height, 145° Roll Angle and Different Speeds
Figure 4.41 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. At constant drop height of 30 cm and roll angle of 145°, the Energy induced in vehicle at 0kmph and 24kmph do not vary much when compared to the 36kmph. Maximum Energy is induced at 36kmph and it is 41 kJ. At 0kmph and 24kmph the energy induced for 30 cm 145° roll angle are in the close range when compared to 30 cm 135°. The maximum energy induced in the vehicle increases with increase in the angle of contact.

![Graph showing Internal Energy response](image)

Figure 4.42 Internal Energy Response for 30 cm Height, 155° Roll Angle and Different Speeds

Figure 4.42 describes the comparison of Internal Energy with respect to time at varying speeds 0kmph, 24kmph and 36kmph respectively for Toyota RAV4. At constant drop height of 30 cm and roll angle of 155°, it is observed that with increase in speeds energy induced in the vehicle increases and affects both driver and passenger. Highest energy induced is 41 kJ at 36kmph speed.
4.7 Comparison of Internal Energy vs Time for Different Drop Heights

Figure 4.42 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 0kmph and roll angle of 135°, it was observed that 20cm and 30cm heights are lapped on each other and indicating that there is no change in energy when dropped at freely. There is increase in energy induced in the vehicle with increase of height from 10 cm to 30 cm and passenger end of the vehicle is induced with more energy compared to driver end. Highest energy induced is 10 kJ.

![Internal Energy Response](image)

Figure 4.43 Internal Energy Response for 0kmph Speed, 135° Roll Angle and Different Heights

Figure 4.44 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24kmph and roll angle of 135°, it was observed that 20cm and 30cm heights are overlapped and indicating
that there is no change in energy when dropped at 135° angle. There is increase in energy induced in the vehicle with increase of height from 10 cm to 30 cm and passenger end of the vehicle is induced with more energy compared to driver end. Then highest energy induced is 26 kJ. The same response is observed in the previous study of 135° angle and 0kmph. When the angle is constant the energy isn’t changed.

Figure 4.44 Internal Energy Response for 24kmph Speed, 135° Roll Angle and Different Heights

Figure 4.45 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36kmph and roll angle of 135°, it was observed that 20cm and 30cm heights are overlapped and indicating that there is no change in energy when dropped at 135° angle. The energy induced in the vehicle increased with increase in height from 10 cm to 30 cm. And, passenger end of the vehicle is induced with more energy compared to driver end. Then highest energy induced is 40 kJ.
Figure 4.45 Internal Energy Response for 36kmph Speed, 135° Roll Angle and Different Heights

Figure 4.46 Internal Energy Response for 24kmph Speed, 145° Roll Angle and Different Heights
Figure 4.46 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24kmph and roll angle of 145°, it was observed that increase in heights increases the energy induced in the vehicle. As drop height drop increases the driver’s injury severity decreases and passenger’s injury severity increases. The highest induced energy was 6 kJ at 30cm of drop height.

Figure 4.47 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36kmph and roll angle of 145°, it was observed that increase in heights increases the energy induced in the vehicle. As drop height drop increases the driver’s injury severity decreases and passenger’s injury severity increases. The highest energy was induced at highest height of 30cm and it was is 42 kJ. This study shows increase in heights leads to increase in energy and affecting more to the passenger end compared to driver end.
Figure 4.48 Internal Energy Response for 0kmph Speed, 155° Roll Angle and Different Heights

Figure 4.48 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 0kmph and roll angle of 155°, it was observed that increase in heights increases the energy induced in the vehicle. As drop height drop increases the driver’s injury severity decreases and passenger’s injury severity increases. The highest energy was induced at highest height of 30cm and it was 9 kJ.

Figure 4.49 Internal Energy Response for 24kmph Speed, 155° Roll Angle and Different Heights
Figure 4.49 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24kmph and roll angle of 155°, it was observed that increase in heights increases the energy induced in the vehicle. As drop height drop increases the driver’s injury severity decreases and passenger’s injury severity increases. The highest energy was induced at highest height of 30cm and it was 23 kJ.

Figure 4.50 Internal Energy Response for 36kmph Speed, 155° Roll Angle and Different Heights

Figure 4.50 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36kmph and roll angle of 155°, it was observed that increase in heights increases the energy induced in the vehicle. As drop height drop increases the driver’s injury severity decreases and passenger’s injury severity increases. The highest energy was induced at highest height of 30cm and it was 41 kJ.
4.8 Comparison of Internal Energy vs Time for Different Angles

Figure 4.51 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 0kmph and drop height of 10 cm, the Internal Energy was decreased with increasing in the roll angle. The highest Internal Energy induced in the vehicle is 6 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.

Figure 4.51 Internal Energy Response for 0kmph, 10 cm Height and Different Roll Angles

Figure 4.52 Internal Energy Response for 24kmph, 10 cm Height and Different Roll Angles
Figure 4.52 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24kmph and drop height of 10 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 21 kJ at roll angle 155°, and it was close to passenger’s end of the vehicle.

Figure 4.53 Internal Energy Response for 36kmph, 10 cm Height and Different Roll Angles

Figure 4.53 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36kmph and drop height of 10 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 33 kJ at roll angle 155°, and it was close to passenger’s end of the vehicle.
Figure 4.54 Internal Energy Response for 0kmph, 20 cm Height and Different Roll Angles

Figure 4.54 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 0kmph and drop height of 20 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 10 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.

Figure 4.55 Internal Energy Response for 24kmph, 20 cm Height and Different Roll Angles
Figure 4.55 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24 kmph and drop height of 20 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 25 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.

![Image of Internal Energy graph for Toyota RAV4]

Figure 4.56 Internal Energy Response for 36 kmph, 20 cm Height and Different Roll Angles

Figure 4.56 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36 kmph and drop height of 20 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 40 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.
Figure 4.57 Internal Energy Response for 0kmph, 30 cm Height and Different Roll Angles

Figure 4.57 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 0kmph and drop height of 30 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 10 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.

Figure 4.58 Internal Energy Response for 24kmph, 30 cm Height and Different Roll Angles
Figure 4.58 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 24 kmph and drop height of 30 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 25 kJ at roll angle 135°, and it was close to passenger’s end of the vehicle.

Figure 4.59 Internal Energy Response for 36 kmph, 30 cm Height and Different Roll Angles

Figure 4.59 describes the comparison of Internal Energy with respect to time at varying heights 10 cm, 20 cm, 30 cm respectively for Toyota RAV4. At constant floor speed of 36 kmph and drop height of 30 cm, the Internal Energy is increased with increase in the roll angle. The highest Internal Energy induced in the vehicle is 42 kJ at roll angle 155°, and it was close to passenger’s end of the vehicle.
CHAPTER 5
RESPONSE SURFACES AND DESIGN OF EXPERIMENTS/KRIGING MODEL

5.1 Design of Experiments

A computational experiment is used in this research to study and analyze the various factors affecting the energy and force induced by developing a response surface data obtained from the results. Initially, the design points are selected to obtain the performance data from the LS-DYNA simulations. A set of design parameters are selected from each finite element simulation to get a set of results. These design parameters are used to build a Kriging model and the main objective of this model is to optimize the results and to generate a prediction model for the given design points. Kriging models help in reducing number of simulations, this method is show in Figure 5.1, which describes the methodology of DOE/kriging process.

![Methodology of DOE/Kriging Model](image)

Figure 5.1 Methodology of DOE/ Kriging Model

5.2 Kriging Model

Kriging model is developed using the multi-objective optimization method to interpolate the given set of sample points to generate an approximate model [27,28].
A Kriging model to estimate the unknown function $y(x)$ can be expressed as

$$ Y(x) = \mu + Z(x) \quad (5.1) $$

where $x$ is $m$-dimensional vector, $Y(x)$ is the unknown function, $\mu$ is the constant global model and $Z(x)$ is the realization of a Gaussian stochastic process which represents the local deviation from the global model. The correlation for the $Z(x)$ matrix can be given by

$$ \text{Corr}[Z(x_i, x_j)] = \sigma^2 \ d(x_i, x_j) \quad (5.2) $$

where the distance between the two-sample point’s $x_i$ and $x_j$ can be expressed as follows

$$ d(x_i, x_j) = \left( \exp \left( \sum_{k=1}^{m} \Theta_k \left| \frac{x^i_k}{\Theta_k} - \frac{x^j_k}{\Theta_k} \right|^2 \right) \right) \quad (5.3) $$

where $\Theta_k$ is the $k$th element of the correlation vector and term inside the exponential is the distance between the two-sample point $x_i$, $x_j$. With $n$ sample point the like hood function of model parameters can be given by:

$$ \text{Likelihood} = -\frac{n}{2} \ln(2\pi) - \frac{n}{2} \ln \sigma^2 - \frac{1}{2} \ln \left| R \right| - \frac{1}{2\sigma^2} (y-A\mu)^T R^{-1} (y-A\mu) \quad (5.4) $$

where $y$ is the column vector response, $A$ denotes the $m$ dimensional unit vector, $R$ denotes the $n \times m$ matrix whose $(i,j)$ entry is $\text{Corr}[Z(x_i, x_j)]$. The parameters $\mu$ and $\sigma^2$ can be defined as

$$ \mu = \left[ A^T R^{-1} Y \right]^{-1} A^T R^{-1} y \quad (5.5) $$

The $\sigma^2$ can be estimated as:

$$ \sigma^2 = \{ (y-A\mu)^T R^{-1} (y-A\mu) \} / n \quad (5.6) $$

Using the two Equations (5.5) and (5.6), the like hood function can be transformed and maximized. Therefore, correlation matrix $R$ can be calculated. The Kriging predictive model is given by

$$ y(x^*) = \mu + r^T(x^*) R^{-1} (y-A\mu) \quad (5.7) $$

which can be used to predict the model response at a different set of output values.
As there are three input parameters namely height, speed, and roll, there are 27 different simulations, and their results are tabulated in Table 5.1. The output parameters are forces (on driver and passenger), and the Energy.

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5.3 Surface Plots for Rollover Parameters

5.3.1 Surface Plots for Force Induced on Driver for Constant Height with Varying Roll Angles and Speeds

From the Figures 5.3, 5.4 and 5.5, it can be observed that for 10 cm drop, as the speed and roll angle increase, the force on the driver increases as well. This was the same with 20 cm height and 30 cm height as the roll angle and speed increase, force on the driver side increase. Overall the maximum force is acting on driver at at 36 kmph, 30 cm height and 155 angle.

![Figure 5.2 Surface Plot for Force on Driver for Varying Speeds and Roll Angle at 10 cm Height](image1)

![Figure 5.3 Surface Plot for Force on Driver for Varying Speeds and Roll Angle at 20 cm Height](image2)
5.4 Surface Plot for Force on Driver for Varying Speeds and Roll Angle at 30 cm Height

5.3.2 Surface Plots for Force Induced Driver for Constant Roll Angle with Varying Speeds and Heights

From the Figures 5.6, 5.7 and 5.8, it can be observed that at roll angle 135°, as the speed and height increase, the force on the driver increases. This was the same with 145 degree roll angle and 145 degree roll angle as the roll angle and speed increase force on the driver side increase. Overall, the maximum force is acting on driver at at 36 kmph, 30 cm height and 155 angle.

Figure 5.5 Surface Plot for Force on Driver for Varying Speeds and Heights at 135° Roll Angle
Figure 5.6 Surface Plot for Force on Driver for Varying Speeds and Heights at 145° Roll Angle

Figure 5.7 Surface Plot for Force on Driver for Varying Speeds and Heights at 155° Roll Angle
5.3.3 Surface Plots for Force Induced Driver for Constant Speeds with Varying Roll Angle and Heights

From the Figures 5.9, 5.10 and 5.11, it can be observe that at 0 speed, as the height and roll angle increase, the force on the driver increases. A 24 kmph speed, the force on driver is maximum at minimum height of 10cm and highest angle of 155. At 36 kmph, the force on the driver increases with increase in roll angle and height. Overall, the maximum force is acting on driver at at 36 kmph, 30 cm height and 155° angle.

![Figure 5.8 Surface Plot for Force on Driver for Varying Roll Angles and Heights at 0 kmph](image)

Figure 5.8 Surface Plot for Force on Driver for Varying Roll Angles and Heights at 0 kmph

![Figure 5.9 Surface Plot for Force on Driver for Varying Roll Angles and Heights at 24 kmph](image)

Figure 5.9 Surface Plot for Force on Driver for Varying Roll Angles and Heights at 24 kmph
Figure 5.10 Surface Plot for Force on Driver for Varying Roll Angles and Heights at 36 kmph

### 5.3.4 Surface Plots for Force Induced Passenger for Constant Height with Varying Roll Angles and Speeds

From the Figures 5.12, 5.13 and 5.14, it can be observed that at 10 cm as the speed and roll angle increase, the force on the passenger decreases. This was the same with 20 cm height and 30 cm height, as the roll angle and speed increase, the force on the driver side increases. Overall, the maximum force is acting on passenger at 36 kmph, 30 cm height and 135 angle.

Figure 5.11 Surface Plot for Force on Passenger for Varying Speeds and Roll Angle at 10 cm Height
Figure 5.12 Surface Plot for Force on Passenger for Varying Speeds and Roll Angle at 20 cm Height

Figure 5.13 Surface Plot for Force on Passenger for Varying Speeds and Roll Angle at 30 cm Height
5.3.5 Surface Plots for Force Induced Passenger for Constant Roll Angle with Varying Speeds and Heights

From the Figures 5.15, 5.16 and 5.17, it can be observed that at roll angle 135 degree as the speed and height increase the force on the passenger increases. This was the same with roll angle 145 degree and roll angle 155 degree as the roll angle, and speed increase force on the driver side increase. Overall, the maximum force is acting on passenger at 36 kmph, 30 cm height and 155 angle.

Figure 5.14 Surface Plot for Force on passenger for Varying Speeds and Heights at 135° Roll Angle

Figure 5.15 Surface Plot for Force on passenger for Varying Speeds and Heights at 145° Roll Angle
5.3.6 Surface Plots for Force Induced Passenger for Constant Speeds with Varying Roll Angle and Heights

From the Figures 5.18, 5.19 and 5.20, it can be observed that at zero kmph, as the roll angle increases, the force on passenger decreases, and also height increase amplifies the force on the passenger. This was the same with 24 kmph and 36 kmph, as the roll angle and speed increase force on the driver side increase. Overall, the maximum force is acting on passenger at 36 kmph, 30 cm height and 135 angle.
5.3.7 Surface Plots for Energy for Constant Height with Varying Roll Angles and Speeds

From the Figures 5.21, 5.22, and 5.23, it can be observed that at 10 cm height, as the speed and roll angle increase, the internal energy of the vehicle increases. This was the same with 20 cm height and 30 cm height as the roll angle and speed increase energy absorbed by the vehicle.
increases. Overall, the maximum energy absorbed by vehicle at 36 kmph, 30 cm height and 155 angle.

Figure 5.20 Surface Plot for Energy for Varying Speeds and Roll Angle at 10 cm Height

Figure 5.21 Surface Plot for Energy for Varying Speeds and Roll Angle at 20 cm Height
From the Figures 5.23, 5.24, and 5.25, it can be observed that at 135 degree roll angle, as height and speed increases, the internal energy of the vehicle increase. This was the same with 145° degree roll angle and 155° roll angle, as the height and speed increase energy absorbed by the vehicle increases. Overall, the maximum energy absorbed by vehicle at 36 kmph, 30 cm height and 155° angle.
Figure 5.24 Surface Plot for Energy for Varying Speeds and Heights at 145° Roll Angle

Figure 5.25 Surface Plot for Energy for Varying Speeds and Heights at 155° Roll Angle
5.3.9 Surface Plots for Energy for Constant Speeds with Varying Roll Angle and Heights

From the Figures 5.26, 5.27 and 5.28, it can be observed that at 0 kmph speed, as the height increases, energy absorbed increases. Energy absorbed is highest at roll angle of 135°. This was the same case with speeds 24 kmph and 36 kmph. Overall, the maximum energy is absorbed by vehicle at at 36 kmph, 30 cm height and 135° angle.

Figure 5.26 Surface Plot for Energy for Varying Roll Angles and Heights at 0 kmph

Figure 5.27 Surface Plot for Energy for Varying Roll Angles and Heights at 24 kmph
Figure 5.28 Surface Plot for Energy for Varying Roll Angles and Heights at 36 kmph
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of this study was to analyze the rollover crash of mid-size SUV vehicles under static and dynamic conditions. Initially, the static roof crush tests on mid-size SUV vehicles, namely a Ford Explorer and Toyota RAV4, were analyzed using computational finite element modelling and simulations. The unconstrained dynamic rollover crash test at different speeds, drop heights, and roll angles were then carried out. Finally, the internal energy response and induced reaction forces were evaluated and compared for better understanding of the vehicle’s response in dynamic rollover crash tests.

The following specific and general conclusions can be made from this study.

- The FE roof crush test was performed on the Ford Explorer, and the results were compared to the FMVSS 216 physical test. The maximum force imparted to vehicle roof in experiment test was 22 kN compared to 21 kN for the FE model. The variation was less than 5%, and hence the model was correlated with experiment and was acceptable.

- The FE model of the Toyota RAV4 was compared to physical test of Ford Explorer, due to lack of physical test data on RAV4. As the weights of the RAV4 and the Ford Explorer are nearly the same, the force induced on the RAV4 was 23 kN to 22 kN on the Ford Explorer. The variation between these models was less than 6%, and hence RAV4 would be utilized for future examination.

- In the unconstrained dynamic rollover crash test of the Toyota RAV4, for 10 cm drop height and varying speeds, with the increase in the rollover angle, it was observed that the
induced reaction force was increased up to 44% and internal energy was 32 kJ at 135 roll angle, and it increased up to 3% at 155° roll angle.

- In the unconstrained dynamic rollover crash test of the Toyota RAV4, for 20 cm drop height and varying speeds, with the increase in the rollover angle, it was observed that the induced reaction force at passenger’s end was up to 160 kN at 135° rollover angle, it also noticed the force increased up to 28% at the driver’s end. In addition to that, the internal energy was 40 kJ at 135 roll angle and it decreased up to 8% at 155° roll angle.

- In the dynamic rollover crash test of the Toyota RAV4, for 30 cm drop height and varying speeds, with the increase in the rollover angle, it was observed that the induced reaction force at passenger’s end was up to 162 kN at 135° rollover angle. It was also noticed there was increased up to 30% at the driver’s end. In addition to that, internal energy was 40 kJ at 135 roll angle, and it increased up to 2.5% at 155° roll angle.

- In the dynamic rollover crash test of the Toyota RAV4, for 135° rollover angle and varying drop heights, with the increase in the speeds, it was observed that the induced reaction force at passenger’s end was 73 kN at 0kmph and it was increased up to 55% at 36kmph. In addition, the internal energy was 10 kJ at 0kmph, and it increased up to 75% at 36kmph.

- In the dynamic rollover crash test of the Toyota RAV4, for 145° rollover angle and varying drop heights, with the increase in the speeds, it was observed that the induced reaction force at passenger’s end was 81 kN at 0kmph and it was increased up to 41% at 36kmph. In addition, the internal energy was 9 kJ at 0kmph, and it increased up to 78% at 36kmph.

- In the dynamic rollover crash test of the Toyota RAV4, for 155° rollover angle and varying drop heights, with the increase in the speeds, it was observed that the induced reaction force
at passenger’s end was 86 kN at 0kmph and it was increased up to 39% at 36kmph. In addition to that, internal energy was 9 kJ at 0kmph and it increased up to 78% at 36kmph.

- In the dynamic rollover crash test of the Toyota RAV4, for 10 cm drop height and varying rollover angles, with the increase in the speeds, it was observed that the induced reaction force at driver’s end was 68 kN at 0kmph and it was increased up to 52% at 36kmph. In addition, the internal energy was 5 kJ at 0kmph and it increased up to 85% at 36kmph.

- In the dynamic rollover crash test of the Toyota RAV4, for 20 cm drop height and varying rollover angles, with the increase in the speeds, it was observed that the induced reaction force at driver’s end was 78 kN at 0kmph and it was increased up to 57% at 36kmph. In addition, the internal energy was 10 kJ at 0kmph and it increased up to 75% at 36kmph.

- In the dynamic rollover crash test of the Toyota RAV4, for 30 cm drop height and varying rollover angles, with the increase in the speeds, it was observed that the induced reaction force at passenger’s end was 86 kN at 0kmph and it was increased up to 47% at 36kmph. In addition, the internal energy was 10 kJ at 0kmph and it increased up to 76% at 36kmph.

- The design of experiment (DOE) study indicated that for a given drop height, maximum force and maximum energy was obtained at highest speed (36 kmph) and at roll angle 155°.

- The DOE study, also indicated that for a given roll angle, maximum force and maximum energy were obtained at height drop (30 cm) and highest speed of platform (36 kmph).

- The DOE study also indicated that for a given speed of platform, maximum force and maximum energy were obtained at highest speed of platform (36 kmph) and roll angle of 155°.
• The DOE results produced showed that among the three parameters, the speed of the platform had the highest effect, and the roll angle had the lowest effect, on both generated force and energy.

Overall, from all the results from this investigation, it is recommended that a drop height of 30 cm, a Roll angle of 155°, and speed of 36 kmph to be utilized in the unconstrained dynamic rollover test of vehicle. It is also recommended that this test procedure, with the identified parameters, to be adopted as a federal regulatory standard test procedure.
6.2 RECOMMENDATIONS

The following recommendations are suggested for the future in extending current study:

- The same vehicle can be subjected to constrained rollover using Jordon Rollover System for a better analyzing of the crash parameters.

- Roof structure can be reinforced by using alloys and vehicle Intrusion parameters can be evaluated and optimized by using crashworthiness techniques.

- Static and dynamic rollover crash tests can be conducted along with finite element dummies models at driver, far side and rear seats to evaluate injury criteria to optimize occupant’s safety in rollover crashes.

- Constrained and unconstrained rollover crash tests can be tested using the laden weight.

- Static and dynamic rollover crash response of finite element models tested using ECE R66 European crashworthiness testing standards.
REFERENCES
REFERENCES


