ANALYSIS OF 3+2 POINT SEAT BELT CONFIGURATION AND OCCUPANT RESPONSES IN ROLLOVER CRASH OF A PICK-UP TRUCK

A Thesis by

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

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Dr. Hamid M Lankarani, Committee Chair

We have read this thesis and recommend its acceptance:

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Dr. Kurt Soschinske, Committee Member

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Dr. Krishna K Krishnan, Committee Member

DEDICATION

WITH LOVE TO MY PARENTS AND SISTER

ACKNOWLEDGMENTS

I extend my sincere gratitude and appreciation to all people who made this Thesis achievable. Firstly, I would like to express my deepest thanks and gratitude to my advisor Dr. Hamid M Lankarani for his outstanding and constant support, patience and guidance during my entire graduate studies. Working with him was a memorable experience.

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Last but certainly not the least; I am forever indebted to the unconditional love and tireless sacrifice of my parents and my loving sister.

ABSTRACT

This Thesis studies the effectiveness of 3+2 Point Seat Belt system in making the car environment safer. The new and enhanced 3+2 Point Belt has conventional 3 Point Belt and an additional shoulder Belt conveyed from other side of the occupant. This provides additional pulling force of occupant towards Seat which minimizes him/her moving freely and hitting inside the vehicle compartment when the vehicle makes a roll of 45^0 or more. It also restrains the occupant from ejecting out of the vehicle.

The test simulates the Rollover situation with the occupant secured by 3+2 or 3 Point Seat Belts. The rollover situation on a Dolly structure is modeled using Mathematical Dynamical Model (MADYMO) code with the use of Easi-Crash CAE software tool. The test simulation is produced by giving required velocities and accelerations to the vehicle in accordance to Dolly Rollover (FMVSS 208). The results are then compared and analyzed to validate the effectiveness of 3+2 Point Seat Belt over 3 Point Seat Belt.

The main areas of interest of this thesis are:

a. Analysis of Occupant's responses (Kinematics) from the MADYMO simulation
b. Evaluation of effectiveness of the restraint systems like 3+2 and 3 Point Seat Belts in attenuating the injuries incurred by occupants
c. Evaluation of injury factors like Head Injury Criteria, Acceleration, Nij values.etc.

Hybrid III 50th percentile male dummy is used to study the occupant responses. The MADYMO results for the Dolly Rollover test is analyzed by comparing the injury parameter standards and specifications of NHTSA.

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1 INTRODUCTION

1.1 MOTIVATION

"Rollovers are dangerous incidents that have a higher fatality rate than other types of Automobile crashes"

In this modern era, the public's main priority is to save time with added comfort during their travel. Automobiles are the better choice for people to meet these necessities. The advantage of Automobiles is that we have ready mobility in a private and secure environment. Whereas, the negative aspect is that it is also a contributor to serious public losses. Motor vehicle crash is the leading cause of death for children greater than 3 years of age and is the leading cause of life lost in USA, far exceeding cancer and cardiovascular disease like stroke and heart attack. In the year 2000, there were 41,821 Americans killed in or by motor vehicles.

Automotive manufacturers have improved the safety of vehicles considerably in frontal, side and rear collisions. This led to the all-time lowest fatality rate in year 2000 with only 1.5% of total motor vehicle crashes. While the total number of highway fatalities has remained relatively stable over the past decade, the number of rollover deaths has risen substantially. According to National Highway Traffic Safety Administration (NHTSA)'s National Center for Statistics and Analysis, from 1991 to 2001, the number of passenger vehicle occupants killed in all motor vehicle crashes increased 4%, while fatalities in rollover crashes increased 10%. In the same decade, passenger car occupant fatalities in rollovers declined 15% while rollover fatalities in light trucks increased 43%. In 2001, 10,138 people died in rollover crashes, where this represents 32% of occupant fatalities for the year. Safety in rollover accidents, however, has been given more attention in recent years because the number of rollover crashes has only decreased by little more than half of a percent in the last decade. According to NHTSA, the risk of serious or fatal injury is greater in a rollover than in any other mode of crash.

1.2 ROLLOVER CRASH STATISTICS

Rollovers are dangerous incidents and have a higher fatality rate than other kinds of crashes. Of the nearly 11 million passenger car, SUV, pickup and van crashes in 2002, only 3% involved a rollover. However, rollovers accounted for nearly 33% of all deaths from passenger vehicle crashes. In 2002 alone, more than 10,000 people died in rollover crashes. The majority of them (72%) were not wearing safety Belts**.**

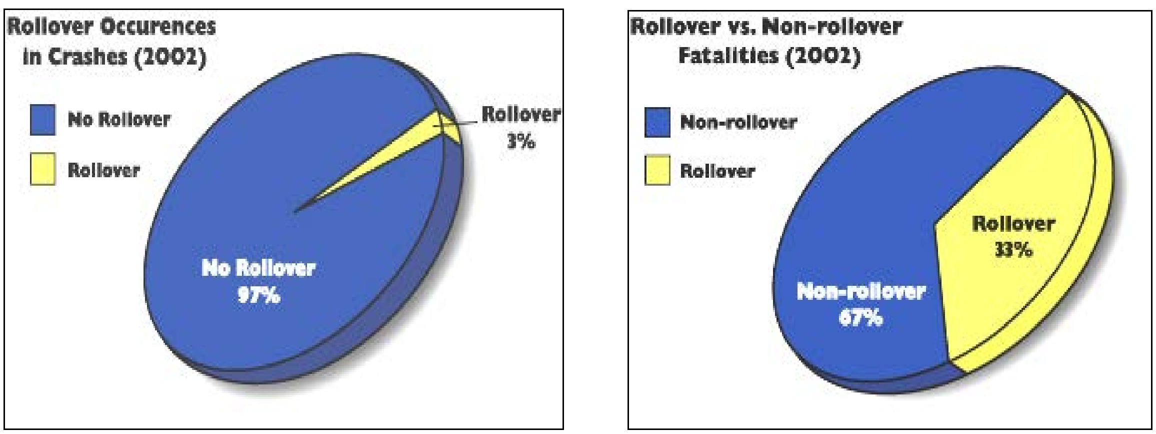


Figure 1 Rollover Occurrences and Fatalities

Source: NHTSA, 2001

Over 9,000 people are killed annually in rollover crashes. In 2002, 10.5% of all fatal crashes were rollovers, though only 3% of all crashes were rollovers. Almost 50% of fatalities occurring in SUVs, pickup trucks, and minivans are due to rollovers. This makes rollover a serious threat for all vehicles, but especially larger utility vehicles. Figure 2 illustrates the dangers of rollover accidents.

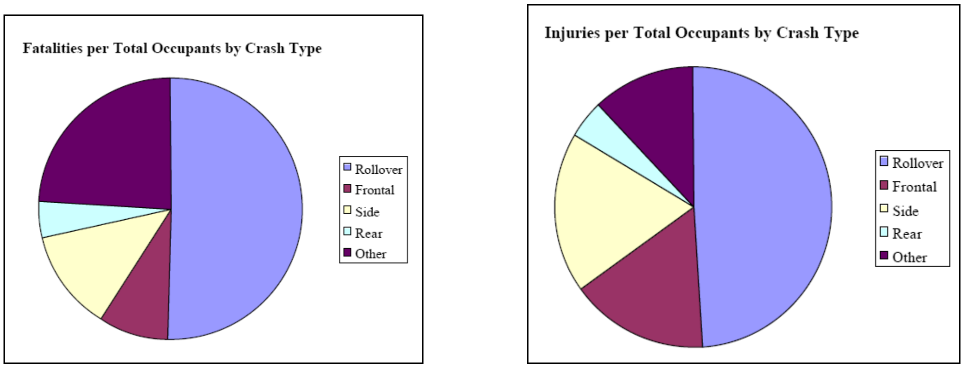


Figure 2 Fatalities and Injuries by Crash Type

Source: NASS and FARS Crash Databases (1995-1999)

Pickup trucks and SUVs are heavier than passenger cars, which make occupants safer in multi-vehicle crashes. However, since the center of gravity is higher in heavier vehicles, they are more likely to roll over than passenger cars. As shown in Figure 3, the rate of rollover per 100 crashes in SUVs and pickup trucks is higher than in smaller vehicles.

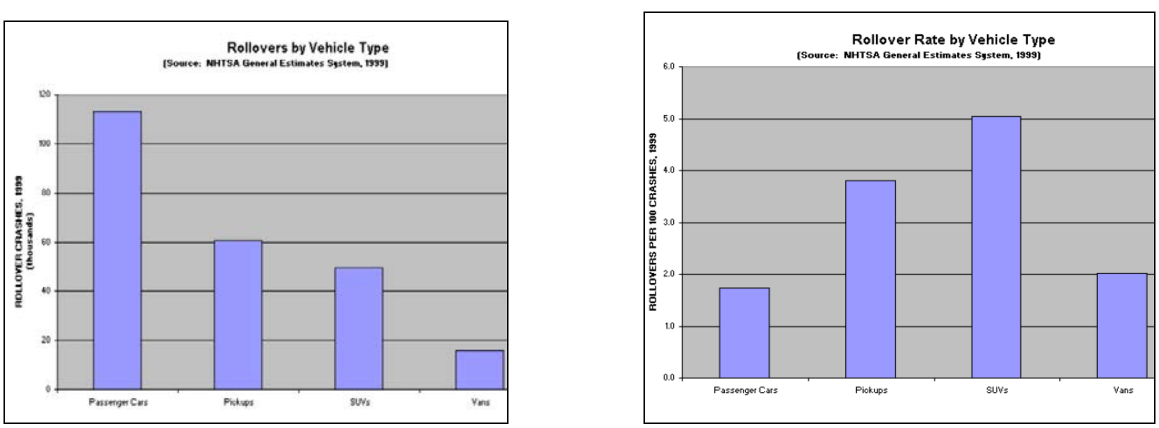


Figure 3 Rollover Crashes by Vehicle Type

Source: NHTSA, 1999

All vehicles will rollover if given appropriate conditions. As Figure 3 illustrates, since there are more passenger cars on the road than any other vehicle type, the total occurrence of rollovers of passenger cars is still the largest.

The market for larger vehicles, including SUVs and pickup trucks has been growing rapidly in the last five to ten years. Just about every car manufacturer has now added SUV models to their fleet. This leads to increased risk for the occupants of these SUVs. According to a Traffic Safety Facts survey published by NHTSA, 35.2% of fatal crashes involving utility vehicles were rollovers.

1.3 SIGNIFICANCE OF COMPUTER SIMULATION

Ensuring passenger safety in rollover crashes is a difficult challenge for automotive manufacturers. A rollover is a chaotic and unpredictable event, so designing safety features for all sizes of occupants is complicated and requires extensive testing.

Computer simulation is becoming an irreplaceable tool in the design process. Simulation allows manufacturers to test safety features and designs in crashes without producing costly prototypes until the design has been fully tested.

Advances in numerical simulation techniques and computer capabilities have made crash simulations another important tool for investigating crash safety. Finite element models of vehicles have been increasingly used in preliminary design analysis, component design, and vehicle crashworthiness evaluation. As these vehicle models are becoming more sophisticated over the years in terms of their accuracy, robustness, fidelity, and size, the need for developing multi-purpose models that can be used to address safety issues for a wide class of impact scenarios becomes more apparent.

A computer model can be developed to provide information about vehicle crashworthiness in a larger number of crash scenarios. These scenarios include a range of collision partners, collision speeds, occupant height and age, and occupant injury tolerance levels. The data obtained from simulations can provide complete understanding of the impact of different characteristics on vehicle crashworthiness, and vehicle designers could use the information to create a safer truck or passenger car.

Today, with the availability of lower cost super computers based on Symmetric Multi-Processor (SMP) and Massively Parallel Processor (MPP) technologies, simulations of different impact scenarios be made more elaborate and efficient.

From an engineering perspective, Crashworthiness is the ability of the vehicle to prevent occupant injuries in the event of an accident. Today's vehicles are designed more Crashworthy than ever, there by dictating the need for better designs. Still, on an average about 30,000 occupants die in crashes on U.S. roads each year, most of them in Rollover crashes. Modern car/truck designs include a strong occupant compartment, or "safety cage", less prone to Rollover designed with less Static Stability factor in a controlled manner. Good structural designs confine crash damage to the crush zones. The occupant compartment should remain intact as the crush zones absorb all the energy and minimizing crash forces inside the compartment. The injury to a passenger also depends on how well the vehicle is equipped with occupant restraint systems. So the level of safety performance of the vehicles has to be assessed.

One aspect of automotive safety is Rollover crash. The purpose of this research is to look at various issues that govern the crash compatibility of a car in a Rollover scenario. This can be achieved by modeling the crash scenario using simulation software. Valuable data can be obtained by computer simulation analysis, which is quite tedious and expensive to be analyzed by full-scale actual tests.

1.4 BACKGROUND

In recent years, cars have gotten much safer. One reason is that safety is now selling points in new trucks, people actually seek out and buy safer trucks. In the United States, NHTSA test crashes cars/trucks and analyzes data with a goal of improving their safety. Vehicle manufacturers are required to certify that their products meet the Federal Motor Vehicle Safety Standards (FMVSS). These rules cover everything from how bright the turn signal bulbs must be to the crash-testing requirements. Manufacturers have to be certain that if the NHTSA goes to any dealer in the United States, buys any truck and crashes it at the federal specifications, the car will pass all of the FMVSS requirements.

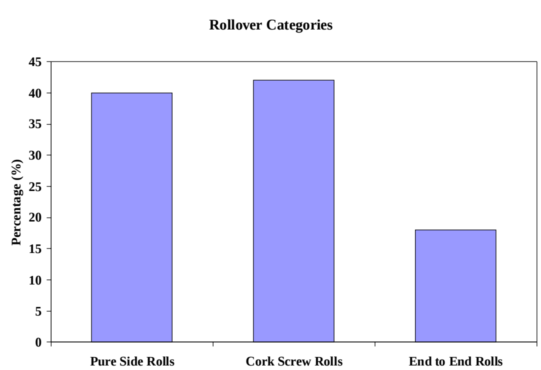
These Federal safety standards are regulations written in terms of minimum safety performance requirements for motor vehicles or items of motor vehicle equipment. These requirements are specified in such a manner "that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur."

The NHTSA has a legislative mandate under Title 49 of the United States Code, Chapter 301, Motor Vehicle Safety, to issue Federal Motor Vehicle Safety Standards (FMVSS) and regulations to which manufacturers of motor vehicle and equipment items must conform and certify compliance. FMVSS 209 was the first standard to become effective on March 1, 1967. A number of FMVSS became effective for vehicles manufactured on and after January 1, 1968.

The NHTSA started their New Car Assessment Program (NCAP) in 1978 with the primary purpose of providing consumers with a measure of the relative safety potential of vehicles in frontal crashes. NCAP now supplies consumers with important comprehensive information, including frontal, side and rollover crash test results, to aid them in their vehicle purchase decisions. The ultimate goal of NCAP is to improve occupant safety by providing market incentives for vehicle manufacturers to voluntarily design their vehicles to better protect occupants in a crash.

1.5 DOLLY ROLLOVER (FMVSS 208)

The following graph shows the details of Rollover types in vehicles and the number of rolls the vehicle makes during a crash scenario.



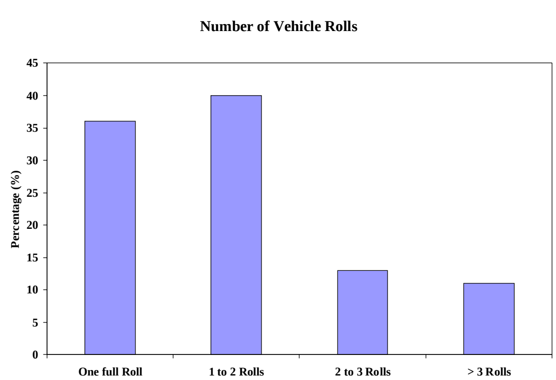


Figure 4 Rollover Characteristics

Source: NHTSA, 2001

The figure shows that Pure Rolls in the lateral side of the vehicle due to cornering and Cork Screw Rolls due to the extreme maneuvering are the major types of Rollover occurrences. Also, it suggests that in most of the Rollover crashes, the vehicle makes more than one complete roll. This proves that the Rollover crash is fatal.

The NHTSA developed a test standard called Dolly test, designed to enhance and measure Occupant protection. FMVSS 208 specifies performance requirements for the protection of vehicle occupants in crashes. Its purpose is to reduce the number of deaths of vehicle occupants, and the severity of injuries, by specifying vehicle crashworthiness requirements in terms of forces and accelerations measured on anthropomorphic dummies in test crashes, and by specifying equipment requirements for active and passive restraint systems.

The test consists of launching a vehicle into a lateral roll at 30 mph with the Hybrid III driver side leading from a dolly fixture. The vehicle is initially inclined at 23^0 on the FMVSS 208 dolly. The FMVSS 208 rollover provides specific dolly configuration, speed, and dolly deceleration requirements. In addition, this method is used in a variety of different dolly and speed configurations to produce the desired rollover event. The test is often conducted in conjunction with the lateral curb and corkscrew rollover methods. FMVSS 216 and other Static tests are performed to cover Roof Crush Resistance and Stability factor requirements.

For passengers, head injuries are the most common crash injury and the leading cause of death in crashes. The most common way the brain can be injured is by acceleration, which usually produces a closed head injury where there is usually no break of the skin or an open wound. This happens when the head suddenly changes its motion. For closed head impact, without skull fracture, a transient force produces a proportional acceleration of the head. Since the acceleration is a measurable quantity on a moving body during impact, the earliest experimental determination of head injury was related to the translational acceleration. Head injury is judged from the amplitude of injury assessment parameters, which are transformed from physical measurements such as force, acceleration, velocity or displacement. The pioneering research of Holbourn resulted in an engineering interpretation of the mechanism of head injury for blows of short duration or impact. He proposed that injury is proportional to the force multiplied by the time over which it acts.

Gurdjian subsequently defined the Head Injury Criteria (HIC) as,

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

where, a (t) - resultant acceleration of the head center of gravity in G's,

t_1 - initial integration time, expressed in seconds,

t_2 - final integration time, expressed in seconds.

Identifying the time interval, t_2 - t_1, which results in the largest functional value, performs this maximization. Injury is defined as any HIC value exceeding 1000. This criterion was adapted in 1967. Generally, a maximum window size of 36 ms is used in the automotive industry.

1.6 RESEARCH OBJECTIVES

The purpose of the research presented in this report is to analyze the Rollover crash of a Chevy-1500 pickup truck using computer analysis software and to evaluate the effectiveness in using the 3+2 Point Seat Belt system over 3 Point Seat Belt system. The compatibility of the vehicle during Rollover crash is to be tested by using Dolly type Rollover testing method. The NCAP and Insurance Institute for Highway Safety (IIHS) developed the testing conditions. The crash analysis is to be performed using non-linear FE software LS-DYNA and the occupant response in the crash is to be evaluated using the MADYMO code. The Crash injuries of Hybrid III dummy are to be compared and evaluated between the two Seat Belt systems.

2 CRASH TESTING AND SIMULATION SOFTWARES

2.1 VEHICLE KINEMATICS

More than 90% of vehicle rollovers occur along the longitudinal vehicle axis (Digges 1991). In the NASS-CDS database, different definitions are used to describe various rollover types. NASS-CDS definitions from the coding manual include:

Trip-over: When the lateral motion of the vehicle is suddenly slowed or stopped inducing a rollover. The opposing force may be produced by a curb, pot-hole, or pavement that the vehicle wheels dig into.

Fall-over: When the surface on which the vehicle is traveling slopes downward in the direction of vehicle movement so that the center of gravity (cg) becomes outboard of its wheels. The distinction between this code and turn-over is a negative slope.

Flip-over: When a vehicle is rotated around its longitudinal axis by a ramp-like object such as a turned down guardrail or the back slope of a ditch. The vehicle may be in yaw when it comes in contact with a ramp-like object.

Bounce-over: When a vehicle rebounds off a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected.

Turn-over: When centrifugal forces from a sharp turn or vehicle rotation are resisted by normal surface friction (most common for vehicle with higher cg). The surface includes pavement surface and gravel, grass, dirt and there is no furrowing, gouging at the Point of impact. If rotation and/or surface friction causes a trip, the rollover is classified as a turn-over.

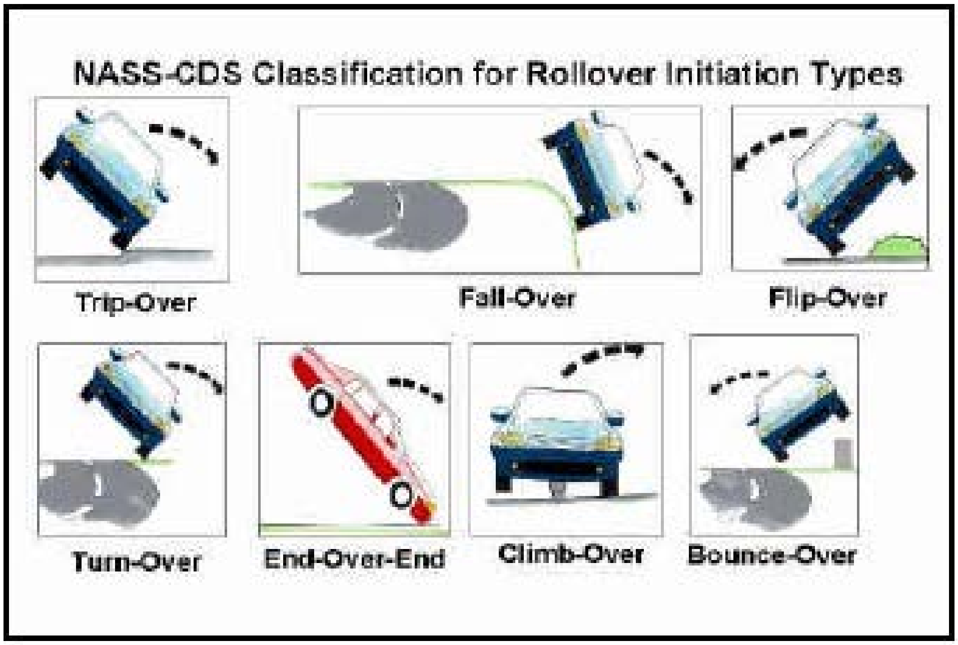


Figure 5 Classification of Rollover initiation

Source: NHTSA

Collision: Rollover occurs when there is an impact with another vehicle. The rollover must be the immediate result of an impact between the vehicles.

Climb-over: When vehicle climbs up and over a fixed object (e.g., guardrail, barrier) that is high enough to lift the vehicle completely off the ground. The vehicle must roll on the opposite side from which it approached the object.

End-over-end: When a vehicle rolls primarily about its lateral axis (pitch motion).

Using NASS-CDS definitions, Parenteau et al. (2003) found that trip-over rollovers had the highest frequency at 57% for passenger cars and 52% for light truck vehicles (LTV's). It is not surprising that drivers were most seriously injured in trip-overs, followed by a fall-over.

When looking at the object contacted, more than 90% of trip-overs resulted after contact with the ground. Though bounce-overs were not frequent, the risk of serious injury was high.

2.2 NHTSA / CRASHWORTHINESS

The Highway Safety Act of 1970 established the National Highway Traffic Safety Administration (NHTSA), under the U.S. Department of Transportation. It is responsible for reducing deaths, injuries and economic losses resulting from motor vehicle crashes which is accomplished by setting and enforcing safety performance standards.

Every year the National Highway Traffic Safety Administration (NHTSA) evaluates crash safety of cars/trucks. NHTSA chooses new vehicles, which are predicted to have high sales volume, vehicles which have been redesigned with structural changes, or have improved safety equipment for testing such as airbag. These vehicles are purchased from dealerships, just as a consumer would, and not supplied by the manufacturer. Only one of each model is tested. This is done to compare how well different vehicles protect passengers in automobile collisions. Results are given in a one-to-five star rating, with five stars indicating the most protected, and one star, the least. These crash test ratings are only meaningful when comparing vehicles in the same weight class.

2.3 HISTORY OF ROLLOVER TESTS / FMVSS 208 REGULATION

In order to reduce deaths and injuries resulting from traffic accidents, the National Traffic and Motor Vehicle Safety Act was enacted on September 9, 1966. This law directs the U.S. Secretary of Transportation to establish Federal Motor Vehicle Safety Standards (FMVSS), to which manufactures of passenger cars, multipurpose passenger vehicles, trucks, trailers, buses, school buses, motorcycles, and items of motor vehicle equipment must conform and certify compliance. The law defines a FMVSS as a "minimum standard for motor vehicle performance, or motor vehicle equipment performance, which is practicable, which meets the need for motor vehicle safety, and which provides objective test criteria". The law further defines motor vehicle safety to mean the performance of motor vehicles or items of motor vehicle equipment in such a manner "that the public is protected against unreasonable risk of accidents occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event accidents do occur".

In the U.S., FMVSS 208 for Dolly test is used to evaluate occupant kinematics in a rollover. The test consists of launching a vehicle into a lateral roll at 30 mph with the Hybrid III driver side leading from a dolly fixture. The vehicle is initially inclined at 23^0 on the dolly. Historically, the 208 dolly test method was selected as it ensures a vehicle roll. The intent of the test is to investigate the effects of roof strength and the kinematics of belted and unbelted occupants during a rollover. However, the test was found unlikely to represent more than 1% of the field conditions due its severity and the initial launch angle of the vehicle (Orlowski et al. 1985, Parenteau et al. 2003).

The rising market of SUVs and Pickup trucks increased the attention of automotive rollovers. Since the FMVSS 208 dolly test was instated in 1969, researchers have been attempting to create a new dynamic rollover test that is realistic and repeatable. Some possibilities that have been tested include tripping a vehicle laterally in dirt, on a curb, a curved rail, or a ramp, or by using an automatic steering device to input severe steering maneuvers. There have also been numerous studies concerning the FMVSS 208 dolly test. The dolly test is used in the federal standard because it reliably rolls a vehicle laterally, however the results are not repeatable. In papers dating back to 1972, the high variability of the dolly test was documented (Cooper et al, 2001). In a study done by Wilson (1972), four identical dolly tests were performed. The vehicles in these tests rolled anywhere from 2.5 to 3.75 times. Two additional studies presented in Cooper et al's (2001) research showed that the vehicles rolled a variable number of times as well. Research has shown that the FMVSS 208 dolly test is useful in creating a lateral roll, which over 90% of all rollover crashes is, but it is not repeatable.

Several studies have been conducted presenting new dynamic Rollover tests; however each test focuses on one segment of the rollover event. Cooper et al (2001) created a test to more closely examine the roof to ground contact in a rollover. That test device worked by beginning the roll of a vehicle with the roof-to-ground contact instead of the tripping mechanism. The vehicle being tested was suspended and rotated laterally from the back of a semi-trailer equipped with a hanging fixture. The semi-trailer was then accelerated until it reached the initial speed of the roll. When this speed was reached, the vehicle was dropped onto its roof and allowed to continue the rolling motion unhindered.

The unpredictability of the first contact between the roof and ground in the FMVSS 208 dolly test makes instrument placement very difficult, which can lead to unusable measurements. Since the roof-to-ground contact is predetermined in the Cooper et al (2001) test, there are several options not available in previous dynamic tests. For instance, cameras can be attached to the fixture holding the vehicle to take close up video footage of the roof-to-ground contact. If the semi-trailer can decelerate at approximately the same rate as the rolling vehicle, the cameras can continue to record the entire rolling motion. Also, instrumentation can be placed exactly where readings are wanted.

A test to explore occupant kinematics prior to a tripped rollover was studied by Pywell et al (1997) from the GM Safety Center and Exponent. These researchers simulated tripped rollovers by attaching a vehicle to a dolly that accelerated a vehicle to a constant lateral speed. Two tests were conducted using a Chevy Blazer with a hook attached to its frame on one side. The dolly traveled on a track that ended at a concrete roll platform positioned at the same height as the surface of the dolly. A curb-trip rollover was simulated by decelerating the moving sled rapidly just prior to tripping the Blazer with a wire loop that caught the hook attached to the Blazer's frame. A soil tripped rollover was simulated by gradually decelerating the dolly and tripping the wheels with a soft honeycomb-like material.

Autoliv North America created a dynamic test to research safety system effectiveness in a rollover (Rossey, 2001). Their test device, called the Deceleration Rollover Sled (DRS), was similar to the test created by Pywell et al (2001) in that the test vehicle was accelerated to a constant speed on a platform. In this test, however, the platform was decelerated by applying brakes to the bottom of the DRS. Instead of allowing the vehicle to roll from the platform onto a test surface; the vehicle was secured to the platform using tethers. These tethers could be adjusted to allow as much or as little of the tip-over phase as desired. The benefit of using brakes to decelerate the DRS was the ability to change the type of rollover being tested without changing the test setup.

This test is useful in determining what affect the trip type has on the rollover.

A study conducted by Moffatt et al (1997) examined occupant head excursion in a rollover. These researchers explored the kinematics of dummies and humans in the airborne phase of a rollover by rotating a Seat Belted dummy or volunteer in a Seat-like fixture around a central axis. This simulated the rollover of the passenger compartment.

Occupant head excursion in both passenger side and driver side leading rollovers was measured. These measurements were used to compare occupant motion in a rollover with variations in Seat Belt configurations.

Studies have also been conducted in order to recreate actual rollover accidents. In one such study, Larson et al (2000) presented a dynamic test to study a rollover from the trip stage on. Their test device, called the Roller Coaster Dolly (RCD) and similar to the dollies discussed above, was used to throw an unoccupied vehicle off the road with certain initial conditions to initiate a rollover. The RCD was used to recreate soil-trip and furrow type rollover accidents. They also created an automatic steering device to recreate on-road rollover accidents and examine steering inputs that cause these rollovers. Their tests were useful in recreating an accident to explain the cause of the rollover.

Because a rollover is such a complex situation, with many possible causes and outcomes, the dynamic tests that seem to be repeatable, are only valid in one segment of the entire event. For instance, the Cooper et al test (2001) could not be used to research the dummy kinematics in a pre-roll situation, and the Pywell et al test (1997) could not be used as efficiently as Cooper's to study the initial roof-to-ground contact. For this reason, a regulation utilizing a dynamic test is still under investigation.

Standard No. 208 - Occupant Crash Protection: Applies to passenger Cars, Multipurpose Passenger Vehicles, Trucks, Buses, Pressure vessels, and Explosive devices. This standard originally specified the type of occupant restraints required. It was amended to specify performance requirements for anthropomorphic test dummies seated in the front outboard Seats of the Vehicles, including the active and passive restraint systems. The purpose of the standard is to reduce the number of fatalities and the number and the severity of injuries to occupants by specifying vehicle crashworthiness requirements in terms of forces and accelerations measured on anthropomorphic dummies in test crashes, and by specifying equipment requirements for active and passive restraint systems. Generally the requirements are as follows:

Passenger Cars (Effective 1-1-68) - Lap or lap and shoulder Seat Belt assemblies for each designated Seating position. Except in convertibles, lap and shoulder Seat Belt assemblies are required in each front outboard Seating position.

Passenger Cars (Effective 1-1-72), Multipurpose Passenger Vehicles, Trucks and Buses - Options A and B only (Effective 1-1-72), Passenger cars, multipurpose passenger vehicles and trucks with a gross vehicle weight rating of 4,536 kg (10,000 lbs.) or less, and buses (driver's Seat only) shall have:

- A complete passive protection system, or
- Lap Belts, Belts warning and meeting 48 km/h (30 mph) crash test requirements, or
- Lap or lap and shoulder Belts, Seat Belts warning: outboard Seats shall have a single-Point pushbutton release and emergency-locking or automatic-locking Seat Belt retractors

Passenger Cars (Effective 1-1-73) - Requirements same as above except upper torso restraints shall have an emergency-locking retractor.

Multipurpose Passenger Vehicles, Trucks and Buses (Effective 9-1-95) - The lap portion of each Seat Belt in a forward - facing Seat or a Seat that can be adjusted to forward-facing shall have a lap Belt portion that is lockable.

Front, outboard designated Seating positions for Passenger Cars and Multipurpose Passenger Vehicles, Trucks and Buses as listed below with a Gross Vehicle Weight Rating of 3,856 kg (8500 lbs.) or less and Unloaded Vehicle Weight of 2,495 kg (5,500 lbs.) or less.

Passenger Cars (Effective 9-1-86), Multipurpose Passenger Vehicles, Trucks and Buses (Effective 9-1-84) shall meet passive restraint phase-in requirements.

Multipurpose Passenger Vehicles, Trucks and Buses (Effective 9-1-91) shall meet 48 km/h (30 mph) crash test requirements with Seat Belts fastened.

Passenger Cars (Effective 9-1-89) shall meet passive restraint requirements.

Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Buses (Effective 6-22-95 until 9-1-2000) - Vehicles with no rear Seats or rear Seats too small to accommodate a rear-facing infant Seat may be equipped with an air bag cut-off switch for the right front passenger air bag.

Passenger Cars (Effective 9-1-96), Multipurpose Passenger Vehicles, Trucks and Buses (Effective 9-1-97) shall meet phase-in requiring air bags.

Passenger Cars (Effective 9-1-97), Multipurpose Passenger Vehicles, Trucks and Buses (Effective 9-1-98) shall be equipped with air bags.

Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Buses (Effective 2-25-97) shall be equipped with a warning label.

Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Buses (Effective 3-19-97) - For the unbelted dummy test condition, manufactures have the option to certify vehicles using the sled test specified in the standard versus the 48 km/h (30 mph) vehicle-into-barrier crash test.

All outboard designated Seating positions: Passenger Cars, except convertibles (Effective 12/11/89), Convertibles (Effective 9-1-91), Multipurpose Passenger Vehicles and Trucks with a Gross Vehicle Weight Rating of 4,536 kg (10,000 lbs.) or less (Effective 9-1-91) shall be equipped with integral lap and shoulder Belts at every forward facing, outboard designated Seating position.

2.4 TESTING METHOD

2.4.1 DOLLY TEST (FMVSS 208)

The curb trip test that is well known among the occupant protection circle is the FMVSS 208 - Dolly Rollover test. This was a part of SAE J2114.

The test setup (Figure 6) consists of positioning a test vehicle on a dolly fixture, which is inclined at 23^0 angle. A curb of 102mm holds the tires (and vehicle) in place. A cable is generally used to tow (move) the fixture at 30mph (48kmph). A stopper is used to arrest the motion of the fixture resulting in inducing a curb-trip rollover to the vehicle.

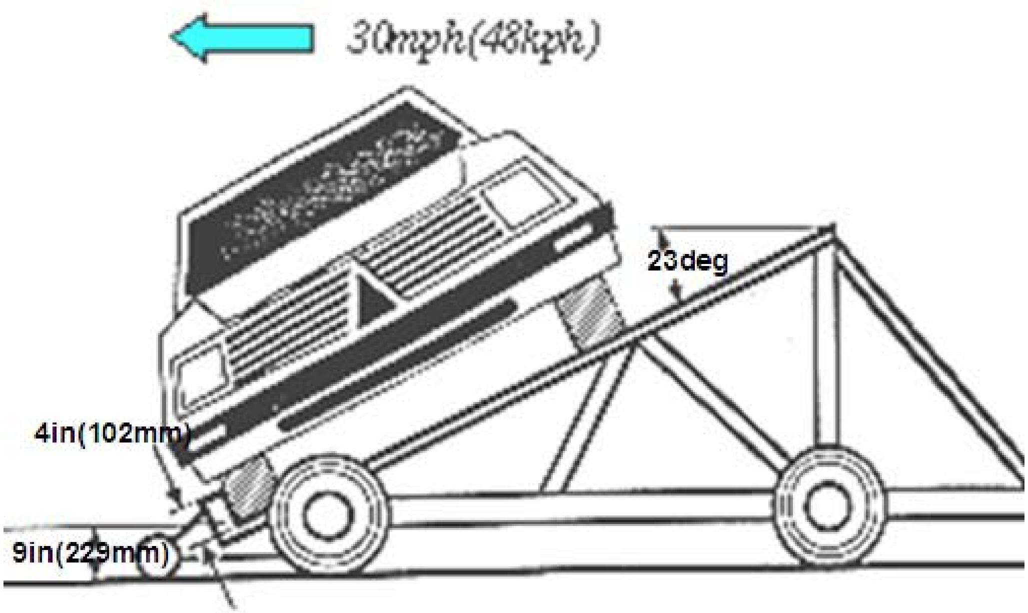


Figure 6 Dolly Test setup

Photo Courtesy: NHTSA

The main advantage of this test is its ability to generate a rollover. This can be an advantage especially for small vehicles with low center of gravity.

A PC-crash model of the same was able to capture a very general trend of the kinematics. However, the MADYMO model was found to be a better tool again due to suspension complexity. A component level pendulum test of the suspension was developed to generate input data for the modeling.

The first part of the rollover involves the vehicle leaving the dolly, the second is the rigid-body rotation followed by ground contact and subsequent rollover. In general, MADYMO is able to replicate the overall kinematics well. However, the model does not capture the very first part of the roll-rate change. This is represented by the first horizontal part of the curve for both tests. Again, suspension deformation modeling has a part to play.

2.4.2 CHALLENGES IN SIMULATING ROLLOVER

Rollovers are more difficult to simulate than frontal, side, and rear collisions because of the number of parameters that contribute to the motion. Many theories and models have been used to simplify a rollover in order to better understand this motion. The most advanced model possible is a detailed finite element mesh of vehicle and occupant (Chou et al, 1998).

Niii et al (1995) simulated a rollover of a large bus using a finite element model in 1995. There have been several other suggestions of rollover simulation research, however as yet no simulations of smaller vehicles in a rollover have been successfully validated and published (Chou et al, 1998).

There are many challenges involved in successfully completing a finite element simulation of a rollover. A good tire and suspension model need to be incorporated into the model for it to be realistic. The mesh must include an appropriate ground interaction definition. The exact impact area in a rollover is unknown; therefore in order to ensure the contact will occur on the defined area, a larger contact area than would be involved in the impact may need to be defined.

A rollover simulation using a detailed finite element model will be costly in terms of CPU time and resources. Frontal, side and rear collisions are completed in about 150 milliseconds, while a rollover can last up to 5 seconds. If the time step were increased proportionally to decrease the computation time, the accuracy of the simulation would degrade. Another reason a rollover simulation requires more CPU time than other collision types is the mesh size. The mesh needs to be controlled in order to lessen the amount of calculation needed, however the mesh must be fine enough in order to retain accuracy. Chou et al (1998) estimate the maximum number of nodes should be 15,000 based on experience.

One method of decreasing CPU time suggested by Chou et al (1998) is using a rigid body model during airborne phases of the roll and a finite element model when the vehicle strikes the ground. These researchers suggest using the finite element code to switch between material types or between rigid body and deformable mesh options during the simulation. This approach is similar to that used by Frimberger and Wolf (2001) in their simulation in which a rigid body vehicle model was created in ADAMS, then occupant and Seat Belt models were added using MADYMO. Finally, the deformation phase of the rollover was simulated using PAM - CRASH. This three-part simulation separated the rollover event into its constituent phases and optimized each of the software in order to decrease the simulation time. A more efficient method of doing this would be to use

PAM-CRASH or another finite element code to do the switch, thereby completing the entire simulation within one program.

The simulation validated by Marzougui et al (1996) demonstrated another potential method of decreasing the CPU time necessary for finite element simulations of crash testing and occupant safety. With the use of solver parallelization, the simulation required 35 hours on 10 processors, instead of the days needed on a single processor. As technology continues to evolve, the time constraints of running simulations will decrease.

Another factor that will add complexity to simulating a rollover is the inclusion of safety features, i.e. dummies, Seats, Seat Belts or airbags. During simulation, the dummy will interact with the interior of the vehicle, the Seat Belt, the Seat, and the airbag and the airbag will interact with the dummy and the interior of the vehicle. All of these interactions need to be defined separately. A fully integrated model may take several days or even weeks to run depending on the capability of the system used to run the simulation (Chou et al, 1998).

For safety research to be conducted using a finite element model, crash sensing devices need to be included in the simulation. These must include sensing algorithms as well as angular rate sensors to deploy a safety device, such as an airbag, at the appropriate time (Chou et al, 1998). Each of these components increases the complexity of the simulation.

The dummies currently used in rollover crash research are from the Hybrid III family. These dummies were specifically designed for use in frontal crash research. During several full-scale crash test studies, the Hybrid III dummies' properties in rollover collisions, such as neck stiffness, have been questioned (Moffatt et al, 1997).

In simulations, the treatment of the interaction between the dummy and Seat Belt models has also been questioned. The Seat Belt does not slide relative to the dummy in a frontal collision; however in a rollover sliding is expected. A different contact interface between the Belt and the dummy must be defined in a rollover than in a frontal collision (Chou et al, 1998).

2.5 SIMULATION SOFTWARES

This section reviews the various CAD, Finite element analysis and Occupant safety simulation tools utilized in the analysis of Rollover crash of Chevy-1500 truck FE model.

2.5.1 LS-DYNA

LS-DYNA is a general-purpose, explicit finite element program used to analyze the nonlinear dynamic response of three-dimensional inelastic structures. Its fully automated contact analysis capability and error-checking features have enabled users worldwide to solve successfully many complex crash and forming problems. It has been widely used to study automotive crash. Default input parameters are chosen to give efficient crash simulation results.

An explicit time integration scheme offers advantages over the implicit methods found in many FEA codes. A solution is advanced without forming a stiffness matrix (thus saving storage requirements). Complex geometries may be simulated with many elements that undergo large deformations. For a given time step, an explicit code requires fewer computations per time step than an implicit one. This advantage is especially dramatic in solid and shell structures. In extensive car crash, airbag and metal forming benchmark analyses, the explicit method has been shown to be faster, more accurate, and more versatile than implicit methods.

LS-DYNA has over one hundred metallic and nonmetallic material models like Elastic, Elastoplastic, Elasto-viscoplastic, Blatz Ko Rubber, Foam models, Linear Viscoelastic, Glass Models, Composites, etc.

The fully automated contact analysis capability in LS-DYNA is easy to use, robust, and validated. It uses constraint and penalty methods to satisfy contact conditions. These techniques have worked extremely well over the past twenty years in numerous applications such as full-car crashworthiness studies, systems/component analyses, and occupant safety analyses. Coupled thermo-mechanical contact can also be handled. Over twenty-five different contact options are available. These options primarily treat contact of deformable to deformable bodies, single surface contact in deformable bodies, and deformable body to rigid body contact. Multiple definitions of contact surfaces are also possible. A special option exists for treating contact between a rigid surface (usually defined as an analytical surface) and a deformable structure. One example is in metal forming, where the punch and die surface geometries can be input as IGES or VDA-surfaces which are assumed rigid. Another example is in occupant modeling, where the rigid-body occupant dummy (made up of geometric surfaces) contacts deformable structures such as airbags and instrument panels.

Some of the prime application areas of LS-DYNA are as follows:

- Crashworthiness simulations: automobiles, airplanes, trains, ships, etc

- Occupant safety: Airbag/Dummy interaction, Seat Belts, Foam Padding, etc

- Bird strike, Biomedical applications and many more

- Metal forming: rolling, extrusion, forging, casting, spinning, ironing, superplastic forming, sheet metal stamping, profile rolling, deep drawing, hydroforming (including very large deformations), and multi-stage processes

LS-DYNA runs on leading UNIX workstations, Supercomputers, and MPP (Massively Parallel Processing) machines. Computer resource requirements vary depending on problem size. Simulations with more than 1,200,000 elements have been run using 250 million words of memory and 3.5 GB of disk space.

2.5.2 MADYMO PROGRAM

MADYMO (Mathematical Dynamical Model) 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. It is used extensively in industrial engineering, design offices, research laboratories and technical universities.

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, Figure 6. It is not necessary to include both in a model, i.e. a model with either finite elements or multibodies can be used.

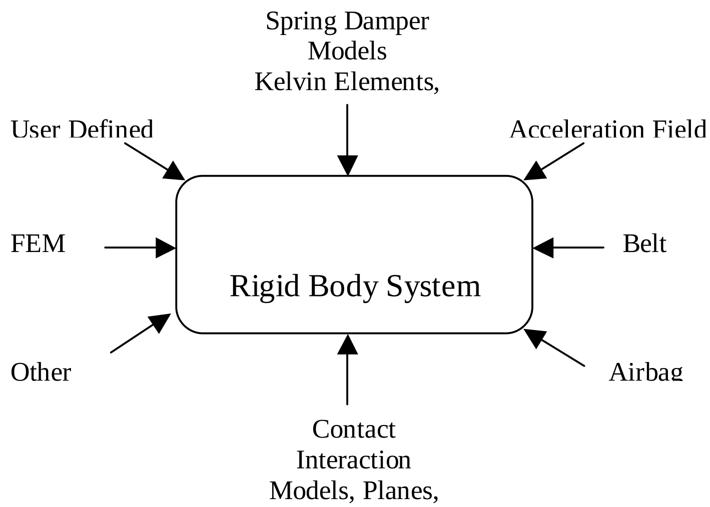


Figure 7 MADYMO 3D structures

The multi-body algorithm in MADYMO yields the second time derivatives of the degrees of freedom in explicit form. The number of computer operations is linear in the number of bodies if all joints have the same number of degrees of freedom. This leads to an efficient algorithm for large systems of bodies. At the start of the integration the initial state of the systems of bodies has to be specified (initial conditions). Several different Kinematic joint types are available with dynamic restraints to account for joint stiffness, damping and friction. Joints can be unlocked or removed based on a user-defined criterion.

In MADYMO a finite element module is available. The finite element method divides the actual continuum into finite volumes, surfaces or line segments. The continuum is then analyzed as a complex system, composed of relatively simple elements where continuity should be ensured along the interface between elements. These elements are interconnected at a discrete number of Points, the nodes. The initial nodal positions and velocities, the nodes corresponding to each element, the connectivity, as well as the element properties, e.g. the material behavior, must be specified at the start of the simulation. Material models are available for metals, fabrics, foams, composites, rubbers and honeycomb.

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 multibody system the number of bodies and their configuration and for each structure, the finite element mesh, the element types and the material properties must be specified.

An input data file is then set up which specifies the configuration, the mass distribution and the general properties of the multibody systems (joint characteristics) and the finite element structures.

The acceleration field model calculates the forces at the centers of gravity of bodies or finite elements due to a homogeneous acceleration field. This model is particularly useful for the simulation of the acceleration forces on a vehicle occupant during an impact. It is not necessary to apply an acceleration field to all bodies. Three types of massless spring-damper elements are available. The Kelvin element is a uniaxial element, which simulates a spring parallel with a damper. The Maxwell element is a uniaxial element, which simulates a spring and damper in series. Non-linear spring characteristics as well as velocity dependent damping can be defined. The Point-restraint can be considered as a combination of three spring-damper elements each parallel to one of the axes of an orthogonal coordinate system.

Planes, ellipsoids, cylinders and facet surfaces can be attached to a body to represent its shape. These surfaces are also used to model contact with other bodies or with finite elements. The contact surfaces are of major importance in the description of the interaction of the occupant with the vehicle interior. The elastic contact forces, including Hysteresis, are a function of the penetration of the contact surfaces. In addition to elastic contact forces, damping and friction can be specified.

The Belt model accounts for initial Belt slack or pre-tension and rupture of Belt segments. Elastic characteristics can be specified separately for each Belt segment and slip of Belt material from one segment to another is accounted for. A special Belt segment is available for fuse Belts. Slip rings, retractors and pretensioners with webbing grabber can be applied.

The final section of the input file deals with the output required from the simulation. The output generated by MADYMO is specified through a set of output control parameters. A large number of standard output parameters are available, such as accelerations, forces, torques and kinematic data. MADYMO offers in addition to standard output quantities, the possibility 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). Special output can be obtained through user-defined output routines. Results of the simulation are stored in a number of output files, which are accessible by post-processing programs.

Once a given crash situation is 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. Thus MADYMO package proves to be an extremely useful tool in enhancing vehicle safety.

Multibody Systems: A multibody system is a system of bodies. A kinematic joint can interconnect any pair of bodies of the same system; kinematic joints cannot connect bodies of different systems. The MADYMO multibody formalism for generating the equations of motion is suited for multiple systems of bodies with a tree structure and systems with closed chains. Systems with closed chains must be reduced to systems with a tree structure by removing every chain in a kinematic joint. Removed joints are subsequently taken into account by a closing joint. For each (reduced) system, one body can be connected to the inertial space by a kinematic joint, or the motion relative to the inertial space of one body can be prescribed as a function of time.

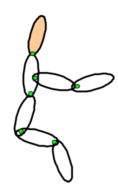


Figure 8 Single and Multibody systems with tree structure

Kinematic Joints: A Kinematic joint restricts the relative motion of the two bodies it connects. In MADYMO, 12 types of joints are available such as spherical, translational, revolute, cylindrical, planar and universal joints. Figure 10 shows the different types of joints differentiated by their relative motion between bodies. The type of Kinematic joint, geometry (i.e., locations of centers of gravity of the bodies and the kinematic joints), mass distribution of bodies, initial conditions and in addition the shape of bodies may be needed for contact calculations or post-processing purposes.

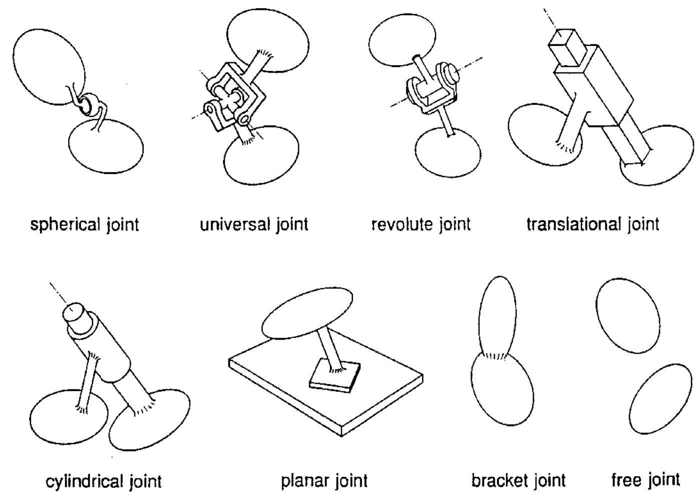


Figure 9 Types of Kinematic joints

The constraints imposed by a kinematic joint cause a load on the pair of interconnected bodies, the constraint load. Due to this load the relative motion of the pair of bodies is restricted to a motion that does not violate the constraints imposed by the kinematic joint. The constraint loads on the separate bodies are equal but opposite loads. Figure 11 shows the constraint load in a spherical joint. Constraint loads can be used to assess the strength of the joint.

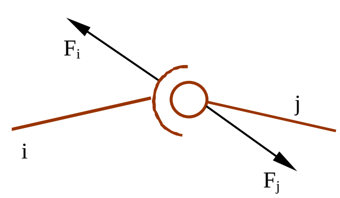


Figure 10 Constraint load in Spherical Joint

Dummy database: Biodynamic simulations are done using well-validated Anthropomorphic Test Dummy (ATD) databases. Databases of 2D and 3D ATD models are available in MADYMO. The standard models of Hybrid III dummies are the 5^{th} percentile female, the 50^{th} percentile male, the 95^{th} percentile male, 3-year-old child and 6-year-old child models. The size and weight of the average American adult male is represented by Hybrid III 50^{th} 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 5^{th} percentile small female and the 95^{th} percentile large male. In this research, the 50^{th} percentile male Hybrid III dummy is used. The model of the 50^{th} percentile dummy consists of 69 bodies, with 6 left and right ribs. The reference joint is chosen in the lower torso. For the neck and spine joints the flexion-torsion restraint model is chosen. For all other joints the cardan restraint model is used. The data for the dimensions of the ellipsoids are determined from technical drawings at TNO. The resulting shape of the dummy model is presented in Figure 12. It is possible to adjust the dimensions if necessary for a more adequate description of the contacts.

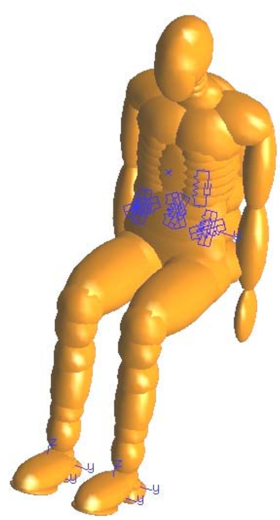


Figure 11 Isometric view of Hybrid III dummy (50^{th} Percentile)

Injury Parameters: The field of Injury Biomechanics deals with the effect of mechanical loads, in particular impact loads on the human body. Due to this mechanical load, a body region will experience a mechanical or physiological change which is called as the Biomechanical response. An injury will occur if the biomechanical response is of such a nature that the biological system deforms beyond a recoverable limit, resulting in damage to anatomical structures and alteration in normal function. The mechanism involved is called the injury mechanism and the severity of the resulting injury is named as the injury severity. An injury criterion is a physical parameter or a function of several physical parameters, which correlates 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). The AIS distinguishes the following levels of injury:

Table 1 Abbreviated Injury scale (AIS) Number

Abbreviated Injury Scale (AIS) number	**Injury Severity**
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum Injury (Cannot be survived)
9	Unknown

The AIS is a so-called “threat to life” ranking.

Most injury criteria are based on accelerations, relative velocities or displacements, or joint constraint forces. These qualities must be requested with standard output options. MADYMO performs mathematical evaluation of the time history signal to calculate the following different injury parameter calculations:

- Gadd Severity Index (GSI)
- Head Injury Criterion (HIC)
- Neck Injury Criteria (NIC)
- ms Criterion (3MS)
- Thoracic Trauma Index (TTI)

2.5.3 MSC/ PATRAN

MSC/PATRAN provides an open, integrated, CAE environment for multi-disciplinary design analysis. With this analysis, one can use it to simulate product performance and manufacturing processes early in the design-to-manufacture process. MSC/PATRAN includes a world-class pre and postprocessor with analysis modeling, analysis data integration, analysis simulation, and results evaluation capabilities. With a menu-driven graphical interface and online help, MSC/PATRAN represents the industry's most advanced and easy-to-use pre and post processing solution.

MSC/PATRAN provides direct access to geometry from the world's leading CAD systems and data exchange standards. Using sophisticated geometry access tools, MSC/PATRAN addresses many of the traditional barriers to shared geometry including topological incompatibilities, solid body healing, mixed tolerances, and others. Once accessed, MSC/PATRAN provides a wealth of tools to manipulate geometry, plus tools for building new geometry.

Powerful yet flexible meshing is available in MSC/PATRAN, with capabilities that range from fully automatic solid meshing to detailed node and element editing. Loads and boundary conditions can vary and may be associated with the design geometry or with the analysis model. Extensive model verification techniques locate errors and further increase the efficiency of the analysis process.

The powerful results visualization tools of MSC/PATRAN enable you to identify critical information, including minimums, maximums, trends, and correlations. Isosurfaces and other advanced visualization tools help speed and improve results evaluation.

Preferences are available for MSC/NASTRAN, and other leading analysis solvers like LS-DYNA, ABAQUS, etc. The MSC/PATRAN fully integrated product family includes analysis products available for structural analysis, advanced structural analysis, thermal analysis, fatigue simulation, composite laminate modeling, analysis management, and materials selection.

3 CRASH ANALYSIS OF CHEVY PICKUP TRUCK

3.1 STUDY OF THE FE VEHICLE MODEL

Finite element models of vehicles have been increasingly used in preliminary design analysis, component design, and vehicle crashworthiness evaluation. As these vehicle models are becoming more sophisticated over the years in terms of their accuracy, robustness, fidelity and size, the need for developing multipurpose models that can be used to address safety issues for a wide class of impact scenarios becomes more apparent. Several vehicle models have been developed at the U.S. Department of Transportation over the past years.

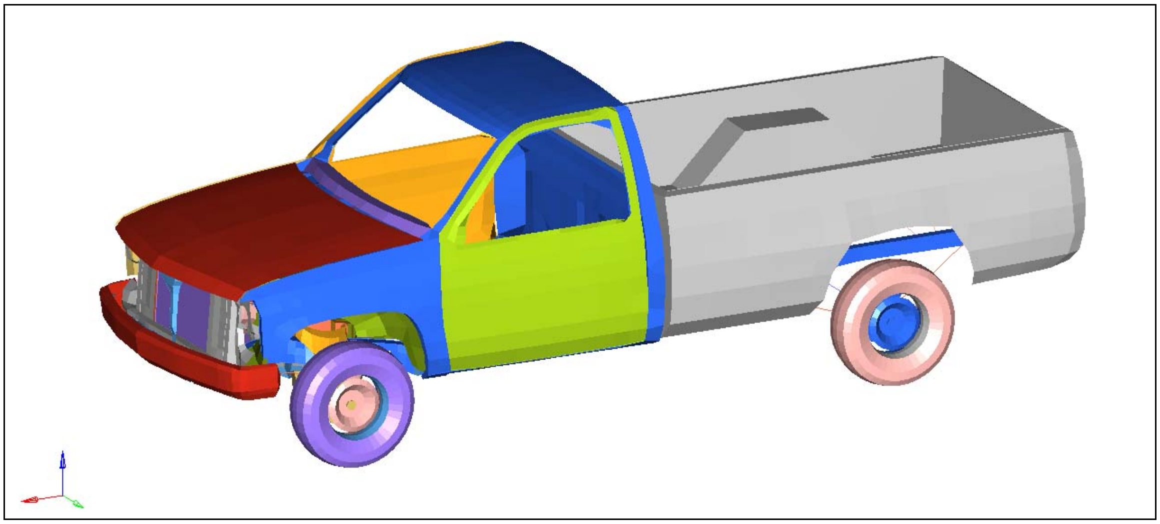
The Chevy C-1500 truck is a multi-purpose Pickup truck with a total length of 5.4 meters (212.6 inches) and a wheelbase of 3.34 meters (131.5) inches. The engine is a 4.3-liter Vortec V6 with Electronic Fuel Injection coupled to a manual transmission with a rear wheel drive configuration.

A detailed multi-purpose finite element model of a 1994 Chevy C-1500 Pick-up truck was developed at the NHTSA's National Crash Analysis Center (NCAC). The model is the first of its kind developed specifically to address vehicle safety issues, including front and side performance. In addition a reduced version of the C-1500 detailed model was developed as a "bullet" model to test various components of the detailed model. The overall goal for the reduced model was to be computationally effective. To achieve that goal, the model size was limited to around 10,000 elements.

Figure 13 shows the vehicle model of Chevy pickup truck. The frontal portion was modeled in detail while the center and rear portions of the vehicle were modeled with a coarse mesh or beam elements. Since the central and the rear portions of the vehicle do not undergo deformations in a frontal impact, modeling these parts with coarse mesh or beam elements does not effect the accuracy of the results as long as the overall mass distribution and inertia of the model are consistent with those of the actual model.

3.2 FINITE ELEMENT MODEL DESCRIPTION

The FE model is developed using the dimensions from the real time model by a process called as digitizing. The truck is first disassembled and grouped into seven main groups, the frame, front inner, front outer, cabin, doors, bed and miscellaneous. The three dimensional geometric data of each component is then obtained by using a passive digitizing arm connected to a desktop computer. The surface patches generated from specified digitized data is stored in AutoCAD in IGES format. These IGES files are then imported into PATRAN for mesh generation and model assembly.



* - Left and Right Windows deleted

Figure 12 Finite Element model of the Chevy C-1500 Truck

The model is translated from PATRAN, which outputs a neutral file, into an LS-DYNA3D input file. Considerable detail is included in the rail frame, and front structures including bumper, radiator, radiator assembly, suspension, engine, side door and cabin of the vehicle. These parts are digitized as detailed as possible, minimizing any loss in the part's geometry.

Table 2 Vehicle Model Summary

Number of Parts	61
Number of Nodes	10,447
Number of Shell Elements	10,157
Number of Hexahedron Elements	1657
Number of Beam Elements	40

Table 3 Material Models

MADYMO Material model	LS-Dyna 3D Material Type
Rate-Dependent tabular Isotropic Elastic-Plastic	24
Rigid	20
Blatz – Ko Rubber	7
Elastic	1

The weight ratio is typical for a pickup truck, with 60% of the weight on the front axle and 40% on the rear. An internal pressure curve is assigned to the tires resulting in an inflation pressure of 220 KPa (32 psi).

The rate dependent tabular isotropic elastic-plastic material model is used for the shell elements whereas all hexahedron elements either use the elastic material model or the Blatz-Ko rubber material model. Two types of shell elements used in the model, viz. quadrilateral shell and triangular shell. The FE vehicle model components are connected to each other using the spot welds and rigid body constraint options in LS-DYNA3D. The contact and friction between the components of the truck are modeled with one single surface-sliding interface also known as "automatic single surface contact" for beam, shell and solid elements with arbitrary segment orientation.

Parts are connected using three different types of connections, slidelines, constrained nodes or joints. Two types of nodal constraint, group nodal constraint and spot weld are used. Group nodal constraint assigns the same degree of freedom to a group of nodes, forcing all the constrained nodes to move together and in the same direction. The second type of nodal constraint is the spot weld, which can be treated as two nodes connected by a rigid beam. The nodes can move in space in translation and in rotation, but cannot translate or rotate relative to each other. Two types of joints, spherical and revolute, are used to connect the front suspension of the truck model.

3.3 MODELING INTERIOR AND EXTERIOR OF CHEVY C-1500 PICKUP TRUCK

In crashworthiness research, simulations are often used to evaluate the feasibility, effectiveness and potential limitations of proposed test procedures and safety countermeasures. Computer modelling allows researchers to augment test data by simulating crashes over a wider range of conditions that would otherwise be feasible. The capabilities are effectively utilized depending on how well the real time scenario is implicated into the modelling.

Providing crash protection for the occupants is an integral part of vehicle development. Increasingly sophisticated legislative crash tests, with occupant injury measurements as the pass/fail criterion, demand that detailed modelling be undertaken at an early stage in the design to avoid costly late changes. Accurate multibody occupant models can be developed in the MADYMO program code thereby allowing us to carry out predictive occupant simulation and contribute to the design process in the early stages.

The occupant compartment of pickup truck is modeled in MADYMO. The FEM model of Chevy 1500 pickup truck, modeled by National Crash Analysis Centre (NCAC) is converted into facet surfaces in the MADYMO. So by this, we retain the accuracy of the FEM model dimensions in MADYMO too. In this model, only the outer case of the truck is retain and all other integral parts like engine, axle, suspension, radiator is removed which are not going to be in contact either with ground or occupant, so they don't affect the kinematics of rollover. Vehicle is modeled with open window with a consideration that once vehicle impacts ground, window will be break off and also it helps to simulate the occupant ejection if any in this rollover. Model is kept as simple as possible giving the exact shape and dimensions to it.

The occupant is the 50th percentile Hybrid 3rd dummy.

4 DEVELOPMENT OF OCCUPANT VEHICLE MODEL

4.1 ROLLOVER MODELING METHODOLOGY

The following figure gives the methodology to Analyze 3+2 Point Seat Belt configuration and Occupant Responses in Rollover Crash of a Pick-Up Truck:

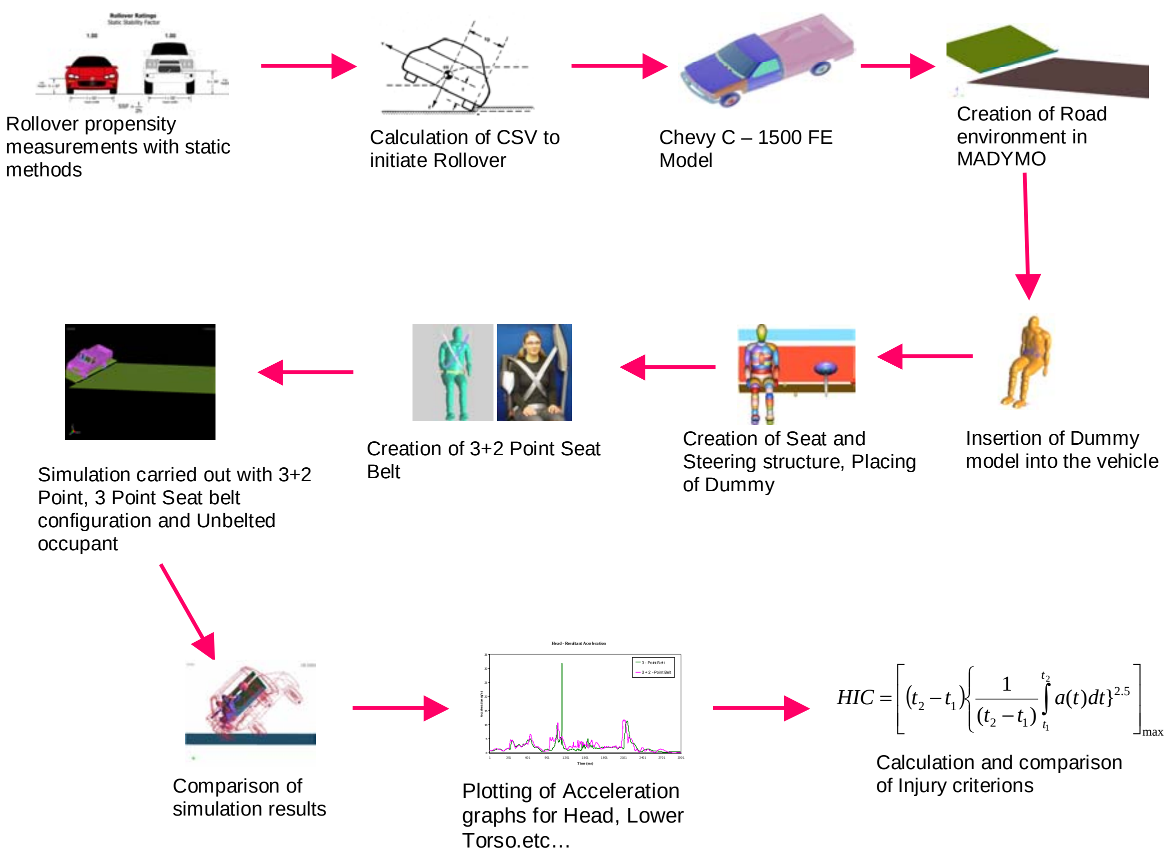


Figure 13 Rollover modeling Methodolgy

4.2 VEHICLE ENVIRONMENT

The Dolly Rollover situation is modeled in MADYMO using the Dyna model of the vehicle. The following table gives the different models used and their characteristics:

Model	Modelled in	Shape	Number of Parts
Vehicle (Chevy C-1500 Pick-up Truck)	LS Dyna - FE Model	Nodes and Elements	61 Parts 10447 Nodes 10157 Elements
Hybrid III Dummy	MADYMO	Ellipsoids	69 Bodies
Seat structure	MADYMO	Planes	3 Planes
Steering Column	MADYMO	Ellipsoids	3 Bodies
Seat Belt	MADYMO	Belt Segments	3 Parts (3+2 Point) 2 Parts (3 Point)
Road Environment	MADYMO	Planes	3 Planes

Table 4 Different models and their characteristics

4.2.1 DUMMY DATABASE

The dummy’s job is to simulate a human being during a crash, while collecting data that would not be possible to collect from a human occupant. A dummy is built from materials that mimic the physiology of the human body. For example, it has a spine made from alternating layers of metal discs and rubber pads. The dummies come in different sizes, and they are referred to by percentile and gender. The 50th percentile male dummy represents the median sized male. This is the dummy most commonly used in crash testing. It weighs 172lbs (78kg) and is 69inches (5ft 9inches or 1.75m) tall.

The real time dummies have steel skeleton with rubber skin and are packed with sensing equipment such as accelerometers, load sensors and motion sensors. The MADYMO model of the 50th percentile dummy consists of 69 bodies, with 6 left and right ribs. The reference joint is chosen in the lower torso. For the neck and spine joints, the flexion-torsion restraint model is chosen. For all other joints, the cardan restraint model is used.

4.2.2 INSERTING AND POSITIONING THE DUMMY

In order to use this dummy in a rollover simulation, the dummy model file needed to be merged with the model of the pickup truck. The model of the pickup truck with the equivalent stiffness and damping applied to the tires, as described in Chapter 3, was used for this task. To merge the two models, the dummy file was opened using the MADYMO Crash simulation software Editor (EasiCrash MADYMO – ECM) and the "Merge" command was used to simultaneously open the pickup truck rollover file. When prompted, the units of the pickup truck rollover file were converted by ECM from millimeters, kilograms and milliseconds to MKS in order to merge the files correctly.

The dummy needed to be positioned within the vehicle because the two files were created separately. The pickup truck was rotated 23^0 back to a horizontal position to simplify the positioning operations. The extraneous materials and elements from the original dummy file were also deleted before moving the dummy. The floor and roof elements of the vehicle frame, the Seat Belts and their connections, and the airbag were excluded from the rollover simulation. The dummy, Seat, and footrest elements remained in the model.

The positioning of the dummy could not be completed using the “Create/Modify/Delete” command in ECM due to the rigid body centers of gravity. The centers of gravity were defined using nodes that were not connected to the material parameters of the model. This type of node is called a free node and when defined as a center of gravity of a dummy body part, it is stored in the position file. The “Translate” command in ECM was used to complete the positioning of the dummy.

Once the dummy was positioned correctly into the driver's side of the pickup truck, the truck and dummy were rotated back onto the tilt table together. The windows of the vehicle are not displayed in order to view the dummy occupant and moreover, due to the rollover, the Windows break on contact with the hard ground.

Every possible new contact definitions are to be considered between parts of the dummy and the interior of the vehicle so that the dummy would not penetrate any vehicle surface. The contact definitions retained from the dummy file were the contacts between the dummy torso and the Seat, the head and chest of the dummy, and the feet of the dummy and the footrest. These contacts were all specified as body-to-plane contact. The force-deflection curves for these contacts are previously established and were left unchanged.

The new contacts needed to be defined using surface/surface contacts. Contact definitions were needed between the various dummy segments and each other and the vehicle interior. A contact definition between the dummy's feet and the floor of the passenger compartment was needed. If the dummy was ejected, contact between the entire dummy and the road surface would also be needed.

The surface/surface contact definition, like the nodes/surface definition, uses a penalty method that compares masses of the slave node and the master element in each contact pair. The mass used for contacts is calculated by the MADYMO solver from the density and thickness of a material. In the original dummy simulation, no contacts using the nodal masses were defined, and the user-defined mass of the center of gravity of each rigid body part was used to calculate the motion.

The resulting shape of the dummy position is presented in Figure 16. It is possible to adjust the dimensions if necessary for a more adequate description of the contacts.

4.2.3 BELT MODEL

Restraint systems are designed to minimize occupant injuries and are activated when a crash is detected. Directly after detection, a setting for the actuators of the restraint system is chosen out of a limited set. These settings are designed with crash tests and numerical modeling.

Figure 14 Display of 3+2 Point Seat Belt

Photo Courtesy: AutoLiv Inc

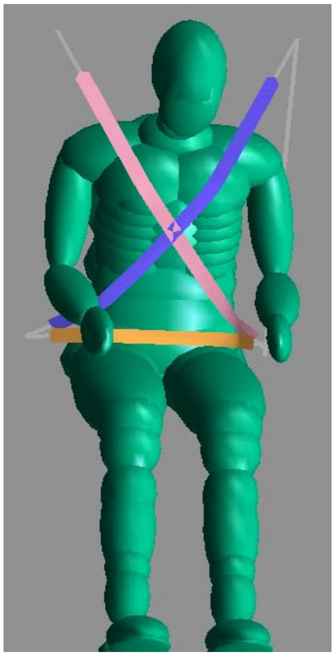


Figure 15 50th Percentile Hybrid III Dummy with 3+2 Point Seat Belt

The main focus of this Thesis is the use of 3+2 Point Belt system used in restraining the Dummy. The new and enhanced 3+2 Point Belt system in addition to the conventional 3 Point Belt has an additional shoulder Belt be conveyed from the other side of the occupant too. The MADYMO model of the occupant secured with the 3+2 Point Seat Belt configuration is shown in Figure 15. This provides additional pulling force of the occupant towards the Seat which prevents him/her from rolling and hitting inside the vehicle structure when the vehicle makes a roll of 45^0 or more. It also restrains the occupant from ejecting out of the vehicle.

The Belt system modeled has MADYMO Belt segment. The end of the Belt is attached to the vehicle system. The only disadvantage of this type of Belt system is one cannot simulate Belt slip, which is a real scenario problem. The test simulates the rollover situation with both 3+2 Point Seat Belt and 3 Point Seat Belt configurations.

4.2.4 VEHICLE SEAT

The Vehicle Seat is modelled with three planes namely, Seat cushion, Seat back and Head rest. Seat cushion and Seat back are given same cushion property. The following figure gives the view of placing Dummy on the Vehicle seat in MADYMO.

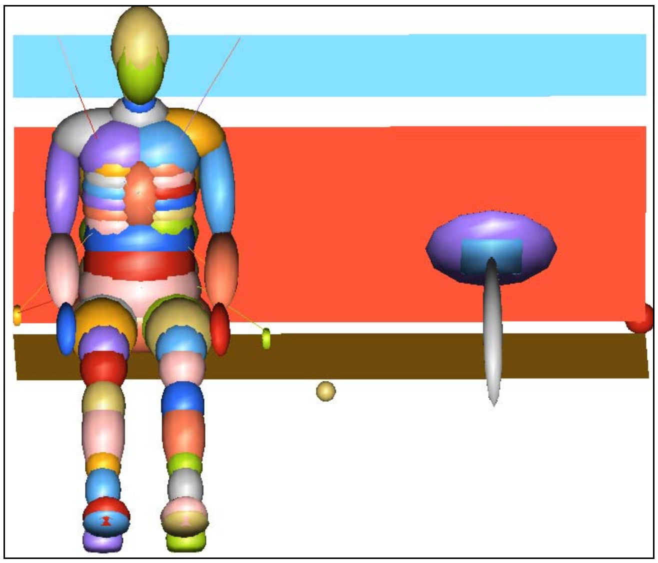


Figure 16 Seat model with the Dummy placed in position

4.2.5 STEERING MODEL

The model consists of one multibody system. Figure 16 shows the setup. The steering column is connected to the inertial space by a bracket joint. This joint may be replaced by another type of joint so that the steering column deformation can be simulated. This system consists of three bodies steering column, steering wheel and airbag holder. In this analysis, we don't use airbag. Bracket joint is defined between steering wheel and column.

4.2.6 TIRE AND SUSPENSION MODEL

Tires and suspension plays a major role in the Kinematics of vehicle rollover. So they should be modeled with at most care. The tires of vehicle can be modeled as ellipsoid or we can use the magic formula, a set of equations describing tire mechanism, to simulate the tire's rolling and cornering stiffness characteristics. But in this thesis they are modeled as facet surface. It was difficult to model suspension separately, because of its complexity and too much of work. So, the suspension spring rate and damping is included in the characteristic of tire facet surface. Figure 17 shows the idealized model of automobile suspension system. There is no joint between the tire and the vehicle body, the whole vehicle behave as one rigid system, with just loading and unloading function.

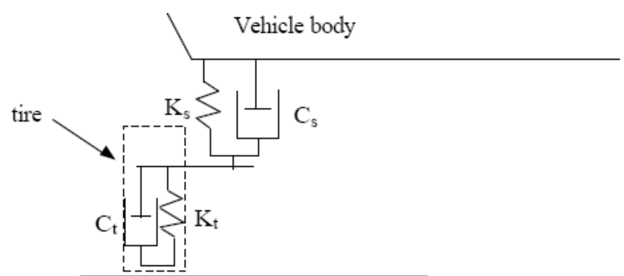


Figure 17 Suspension and Tire simplification

4.2.7 MODEL OF ROAD SURFACE AND SOIL REPLICA

The road surface was modeled with three planes as follows:

<u>Road:</u> A plane representing the road surface in the real time environment. This plane is horizontal to the ground. The vehicle after displaced from the Dolly rolls over the road and comes to rest on the road.

Dolly: A plane which is inclined to 23^0 from the ground to produce the lateral force on the Vehicle. The vehicle rests initially on the Dolly before it is rolled over. In real time, the dolly is the inclined structure on which the vehicle to be rolled over is placed.

Curb: There is another plane which is very small compared to the Dolly and the Road planes. The Curb plane is placed horizontally at the end of the Dolly plane. When the dolly is stopped suddenly, the vehicle will slide down the Dolly. At this time, the Curb plane acts as a tripping mechanism which initiates Rollover of the Vehicle. The FMVSS 208 specification for the curb height is 102mm.

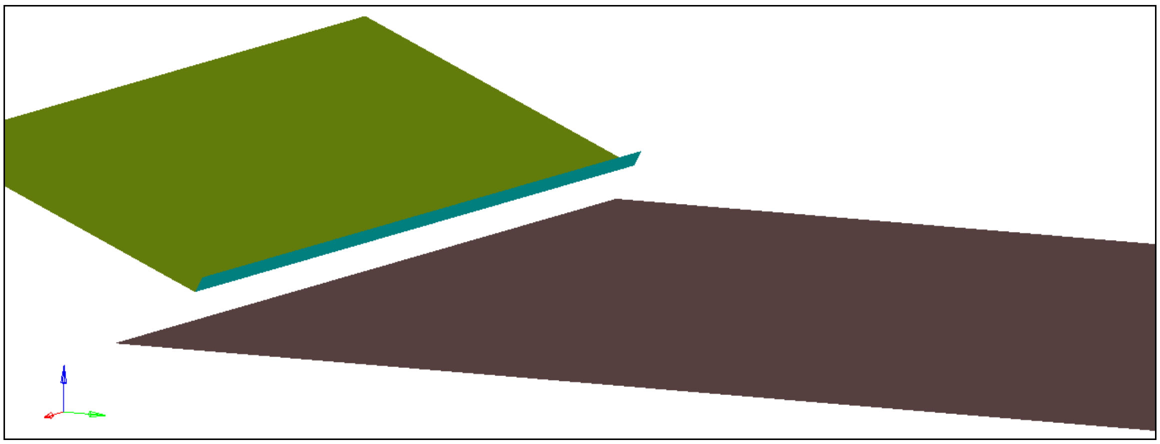


Figure 18 MADYMO model of the Road with Dolly and Soil Replica

4.2.8 MADYMO CONTACT

There are two contact models available, the elastic and the kinematic contact model. The elastic model is available for all contact types and the contacting surfaces can penetrate. The corresponding elastic contact force depends on the penetration. This dependency must be specified as a force-penetration characteristic, a stress-penetration characteristic or a penalty factor. For the kinematic contact model, the contacting surface cannot penetrate. In my study, all the contacts are elastic contacts. Important contacts used are PLANE - VERTEX and ELLIPSOID - VERTEX contact. The first one is for contact between the vehicle and the ground, where the vehicle is facet surface and ground is plane. The second one is between occupant and vehicle interior, where occupant is ellipsoid and vehicle interior is facet surface.

After the vehicle modelling is done and before we run any rollover analysis, it is tested for rollover propensity. We conduct the following tests - Static Stability Test, Tilt Table Test and Side Pull Test which is discussed in the following page.

4.3 STATIC STABILITY TEST

Many researchers have used the static stability factor in past and found to have a good correlation with practical test. Basically, SSF is a measure of how top-heavy a vehicle is. A vehicle's SSF is calculated using the formula:

$SSF = t / (2*h_{cg})$

where, t = Track Width

h_{cg} = height of the center of gravity of the vehicle

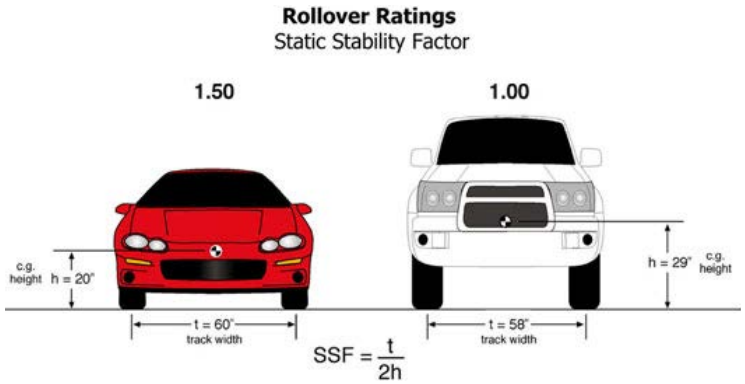


Figure 19 Static Stability Test terminologies

For Chevy C-1500 pickup truck,

Track Width (t) = (1.6 + 1.646) / 2 = 1.628m and h_{cg} = 0.665m

Substituting these values, we get, SSF = t / 2*h_{cg} = 1.628 / 2*0.665 = 1.224

STATIC STABILITY FACTOR = 1.224

As SSF is calculated by static cg height and track width, it doesn't consider change in cg height due to vehicle's suspension and tires.

4.4 TILT TABLE TEST

Tilt table test involves placing the vehicle on a flat platform, which is tilted along an axis parallel to vehicle's longitudinal axis and the vehicle's rollover stability is characterized by the angle at which the upper side of the vehicle loose contact with the platform. The tilt table attempts to simulate the lateral acceleration by tilting the table on one side, this causes the component of gravity to act in both lateral and vertical direction relative to the vehicle. The test setup is shown in the Figure 20.

When there is no contact between the tire and table, the contact force for this tire becomes zero. At this Point, the angle of the table is measured.

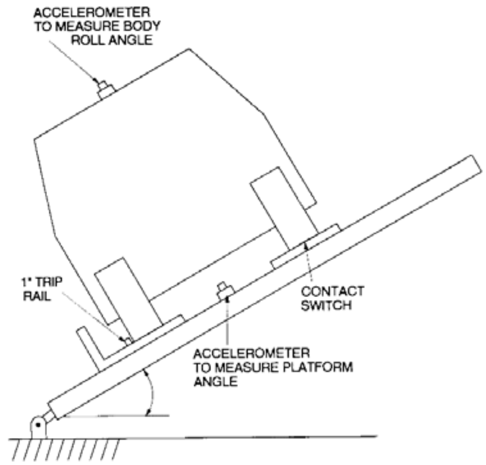


Figure 20 Tilt Table Ratio setup

For an idealized vehicle without suspension movements, the TTR is the same as the SSF. The suspension movements of actual vehicles reduce the TTR about 10 to 15% relative to the SSF.

4.5 SIDE PULL TEST

It involves applying a horizontal (lateral) force to the vehicle through its cg, sufficient to just lift the vehicle's wheels opposite the pull force off the ground. The side pull test setup is shown in Figure 21. The Side Pull Ratio (SPR) is determined by the formula: SPR = (Lateral Force) / (Vehicle Weight). At the time when the vehicle looses contact between the front left tire and ground, the lateral force is measured. Then, the value is substituted in the above formula with the weight of the vehicle to get the SPR value. The advantage of this test over Static Stability and Tilt Table Test is that it calculates the force while vehicle is being rolled, so the contribution of the motion of vehicle's cg due to suspension kinematics and tire compliance is more accurately considered.

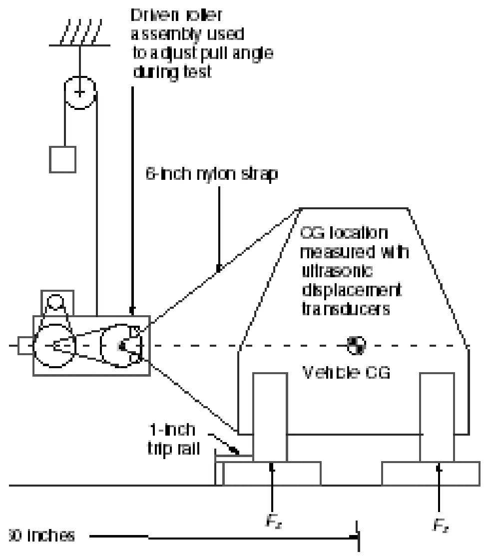


Figure 21 Side Pull ratio setup

For an idealized vehicle without suspension movements, the TTR and SPR is the same as the SSF. The suspension movements of actual vehicles reduce the TTR and SPR about 10 to 15% relative to the SSF.

4.6 CRITICAL SLIDING VELOCITY (CSV)

It is a measure of minimum lateral velocity of a vehicle needed to initiate a quarter turn rollover when the vehicle is tripped in the lateral direction. The equation for calculating CSV is as given below,

$$CSV = \sqrt{\frac{2gI_{oxx}}{Mh_{cg}^2}\left(\sqrt{\frac{TW^2}{4}+h_{cg}^2}-h_{cg}\right)}$$

$$\text{where,} \quad I_{oxx} = I_{xx} + M\left(\frac{TW^2}{4}+h_{cg}^2\right)$$

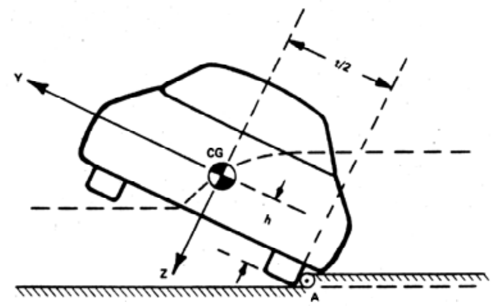


Figure 22 Critical Sliding Velocity

CSV can be predicted if track width, CG height and Radius of Gyration of the Roll are known. For Chevy C-1500, t = 1.628m

h = 0.665m

Mass of the vehicle = 1839kg

$I_g = mk^2 = 762kgm^2$. So, the value of $k^2 = 0.42$

The Tilt table angle for Dolly Rollover test is 23^0 and the angle between line Y and the table is calculated from Figure 23. This comes out to be 39.24^0. So, substituting all these values in the CSV formula above gives its value to be 2.85m/s. This is the minimum sliding velocity required to quarter turn the Chevy C-1500 Pickup truck.

CRITICAL SLIDING VELOCITY = 2.85m/s

5 OCCUPANT IMPACT RESPONSE

5.1 DOLLY ROLLOVER

The Dolly Rollover test involves towing a vehicle sideways into a simulated curb fixture. It is used for airbag system design and occupant protection considerations. The curb height and test speed can be adjusted to induce the desired rollover conditions. Figure 24 shows the test configuration in MADYMO. In this test, the lateral velocity of 18mph (8m/s) is applied to the vehicle and occupant. This value is achieved by using the Critical Sliding Velocity equation by Jones, mentioned in Page 55.

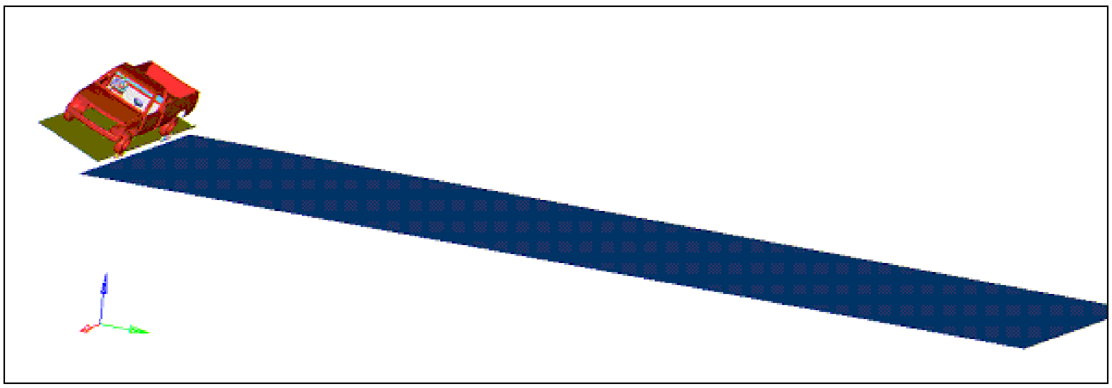


Figure 23 Dolly Rollover - MADYMO model

5.1.1 3+2 POINT SEAT BELTED OCCUPANT

<u>Simulation facts:</u>

- 0.35s = Left wheel hits curb plane
- 0.35 - 1.09s = Vehicle in air due to impact with curb plane
- 1.12s = Roof hits ground

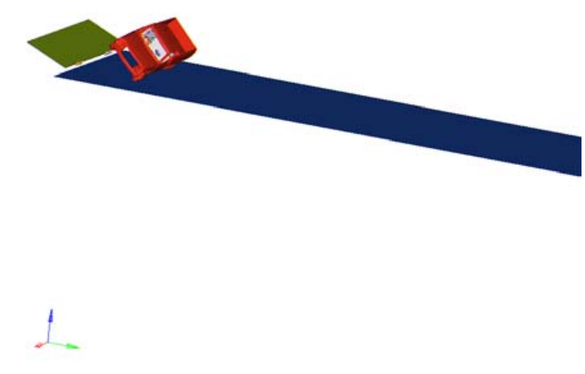
- 1.53s = Right side of the vehicle contacts the ground
- 2.75s = Vehicle rolls from roof to right side of vehicle completing one full revolution

When the vehicle hits the curb at 350ms, the occupant is forced to roll towards left side and hits vehicle interior giving increased lower torso and upper torso acceleration. But, the values are not the peak ones, since the occupant is restrained by 3+2 Point Seat Belt system and pulled more towards the seat arresting any free movement inside the vehicle compartment. From 350ms to 1085ms, vehicle is not in contact with ground and makes 1/2 rotation in air and roof hits ground at 1120ms. The lap/shoulder/additional 3+2 Point Belts prevent the head from hitting the ground through deforming roof at 1133ms. Peak head acceleration at this time is reduced to 13g's when compared with that of 33g's in case of 3 Point belted occupant. At this point, the lower torso gets spike in acceleration as shown in Figure 27. Simulation stops at 3000ms with vehicle resting on right side. Figure 29 shows the vehicle center of gravity acceleration which has shows 3 spikes in value - one when tire hits curb, the other when roof hits ground first time and the last one when the vehicle rests on the ground with all the 4 tires. In Figure 25, it is seen that the Head acceleration is reduced 1/3 that of the 3 Point belted occupant and maintains almost constant value throughout the simulation with no huge change in values. Thus, the head is prevented from any contact with the vehicle interior, therefore, reducing the Head injury criterion (HIC) value to 114 (3+2 Point Belt) from 281 in case of 3 Point seat Belt. Upper Torso acceleration behaves similarly as Lower Torso. Vehicle completes 0.75 turn in 3000ms as shown in Figure 24. Table 5 shows neck compressive, neck tension-extension and neck tension-flexion within safe limits.

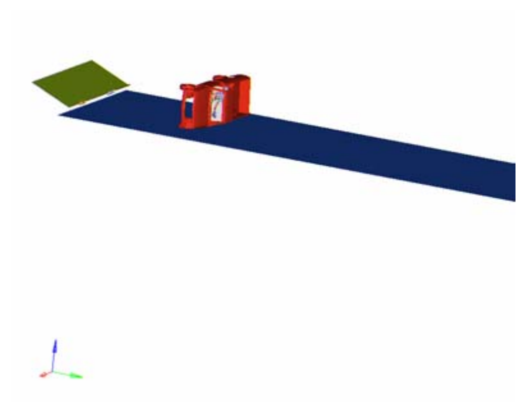
Figure 24 Simulation with Time interval of 250 ms (3+2 Pt Seat belted Occupant)

Simulation Time: **0 ms**

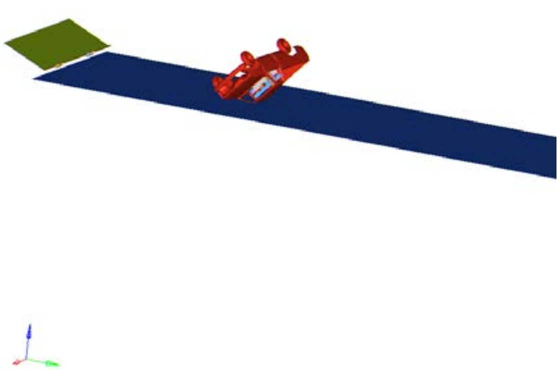
Simulation Time: **250 ms**



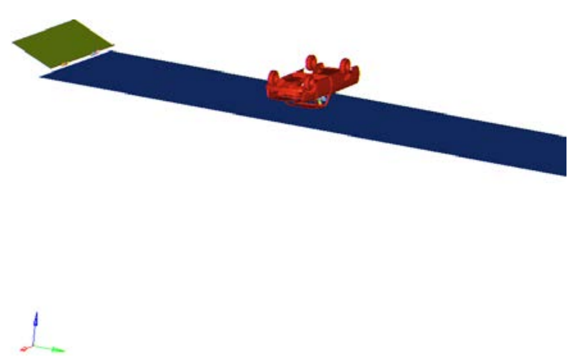
Simulation Time: **500 ms**



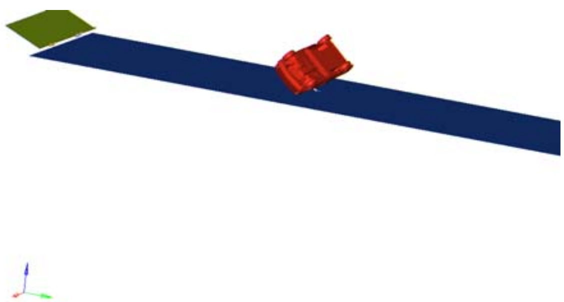
Simulation Time: **750 ms**



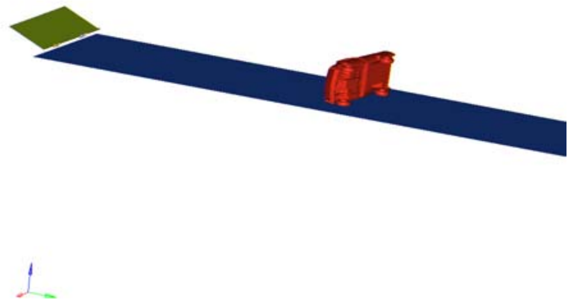
Simulation Time: **1000 ms**



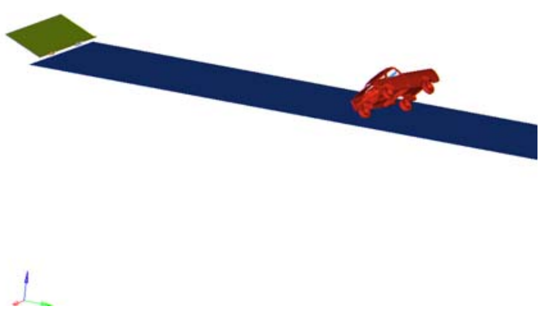
Simulation Time: **1250 ms**



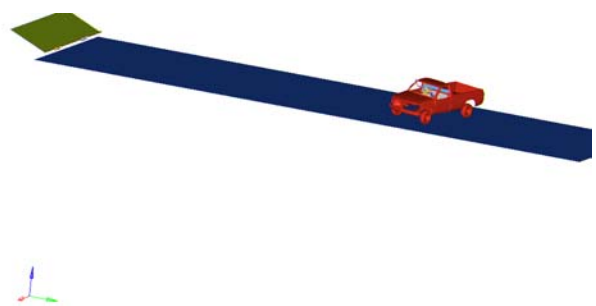
Simulation Time: **1500 ms**



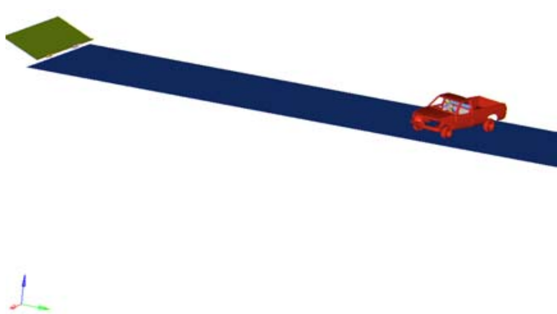
Simulation Time: **1750 ms**



Simulation Time: **2000 ms**



Simulation Time: **2250 ms**



Simulation Time: **3000 ms**

Resultant Accelerations (With 3+2 – Point Belt system)

Head

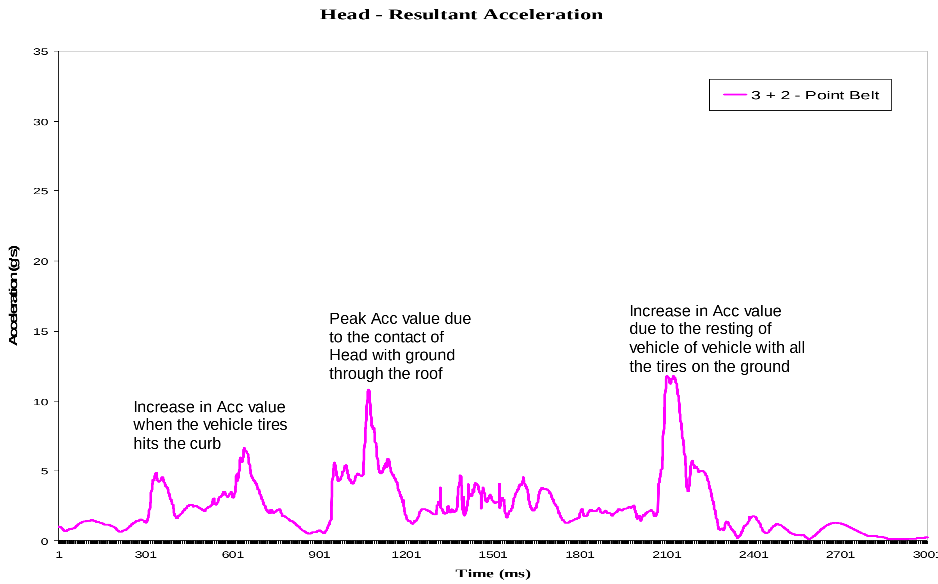


Figure 25 Resultant Acceleration – Head (3+2 Point)

Inference:

The equipment of 3+2 Point Belt system has trimmed down the Head acceleration values throughout the cycle of 3000ms when compared to the 3 Point Belt system. The comparison plot is shown on Page 83. The sudden increase in the value of Head Acceleration at 350ms is due to the Left Wheel hitting the Curb plane. From 350ms to 1,085ms, vehicle is not in contact with ground, makes 1/2 rotation in air and roof hits ground at 1,120ms. Peak head acceleration at this time is 13g's which is well below the value with 3 – Point Seat Belt of 33g's. This is due to the 3 +2 – Point Belt system, where the occupant is pulled towards the Seat with more pulling force. So, the head of the occupant is restricted from hitting the crushed roof. At 2100ms is the elevated acceleration value which is due to the resting of the vehicle on ground with all the 4 tires.

Lower Torso

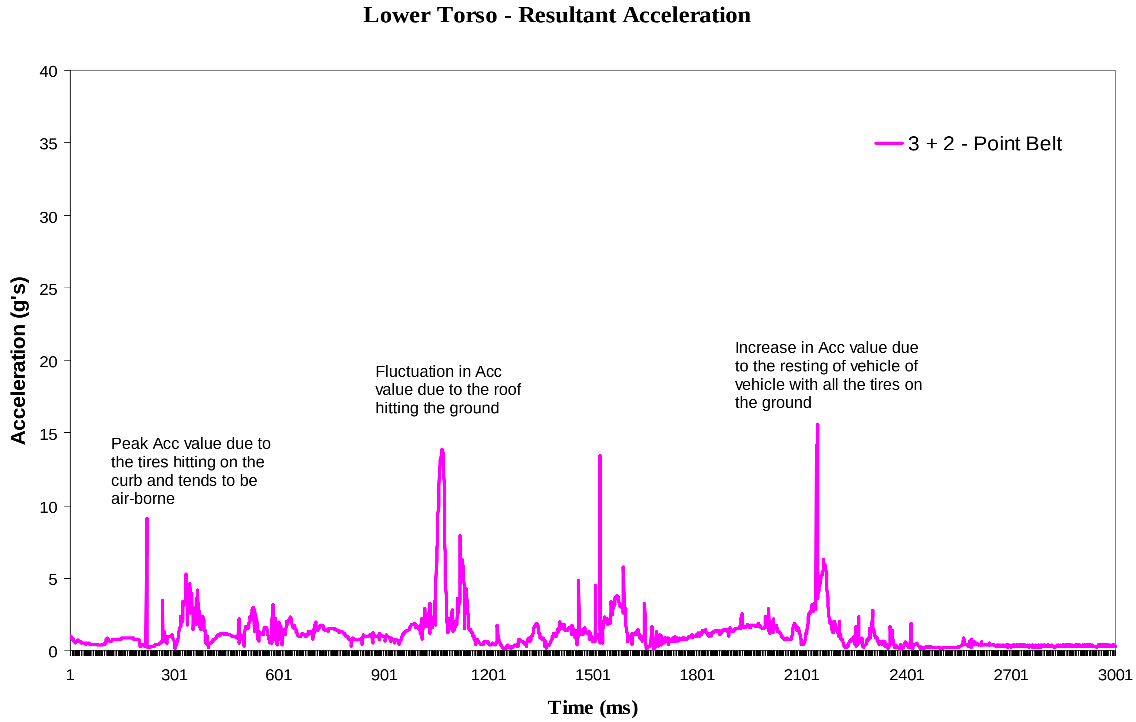


Figure 26 Resultant Acceleration - Lower Torso (3+2 Point)

Inference:

Vehicle hits the curb at 0.35s, occupant is forced to roll towards left side and hits vehicle interior giving elevated lower torso acceleration at 350ms. The acceleration values at 400ms to 1100ms are almost constant as the vehicle was in airborne roll along the left side of the truck. The acceleration spike at 1100ms is due to the sudden change in Momentum when the truck land by its roof. When the vehicle hits flat with the right door, the lower torso acceleration reaches another elevated value at 1500ms. At 2100ms is the Peak acceleration value which is due to the resting of the vehicle on the ground. Whereas, this value is much less when compared to the 3 – Point Belt system.

Upper Torso

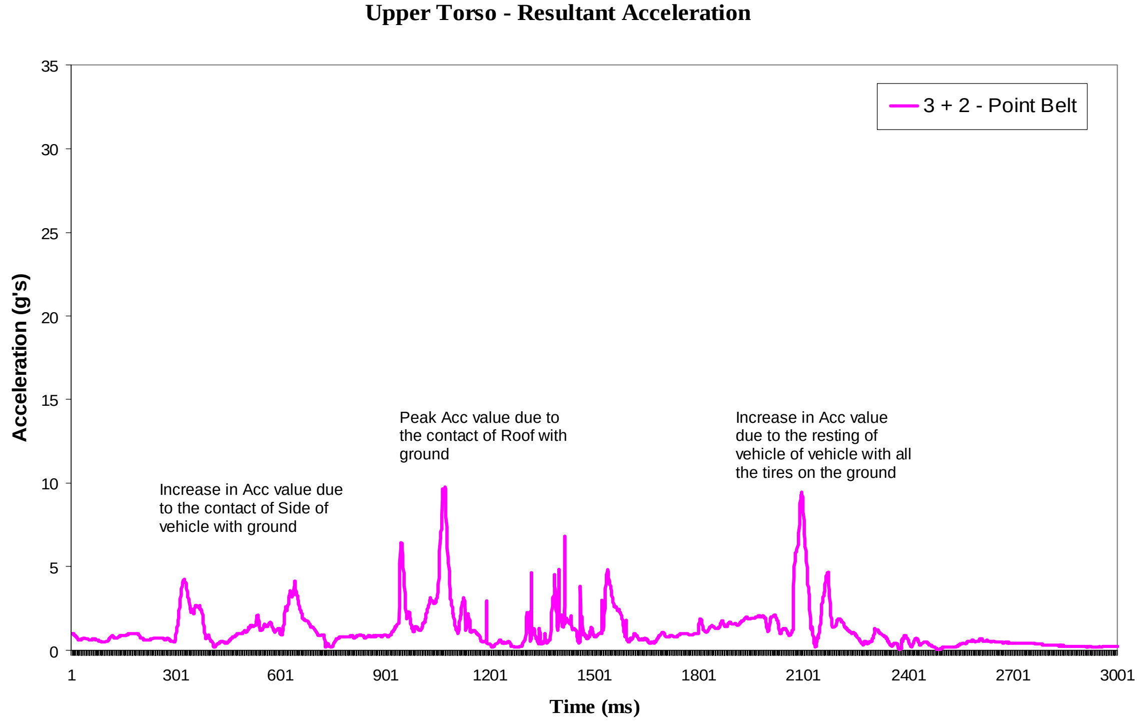


Figure 27 Resultant Acceleration - Upper Torso (3+2 Point)

Inference:

When the vehicle hits curb at 350ms, the occupant is forced to roll towards left side and hits vehicle interior giving increase in both upper torso and lower torso accelerations. Even though there is movement of the upper torso inside the vehicle compartment due to the airborne roll, the occupant is protected from severe injuries due to the 3+2 Point Seat belt. The peak acceleration spike at 1100ms is due to the sudden change in Momentum when the truck land by its roof. When the vehicle hits the ground flat with its right door, the lower torso acceleration reaches another elevated value at 1500ms. At 2100ms there is another spike in acceleration value which is due to the resting of the vehicle on the ground with all the 4 tires.

Center of Gravity of the Vehicle

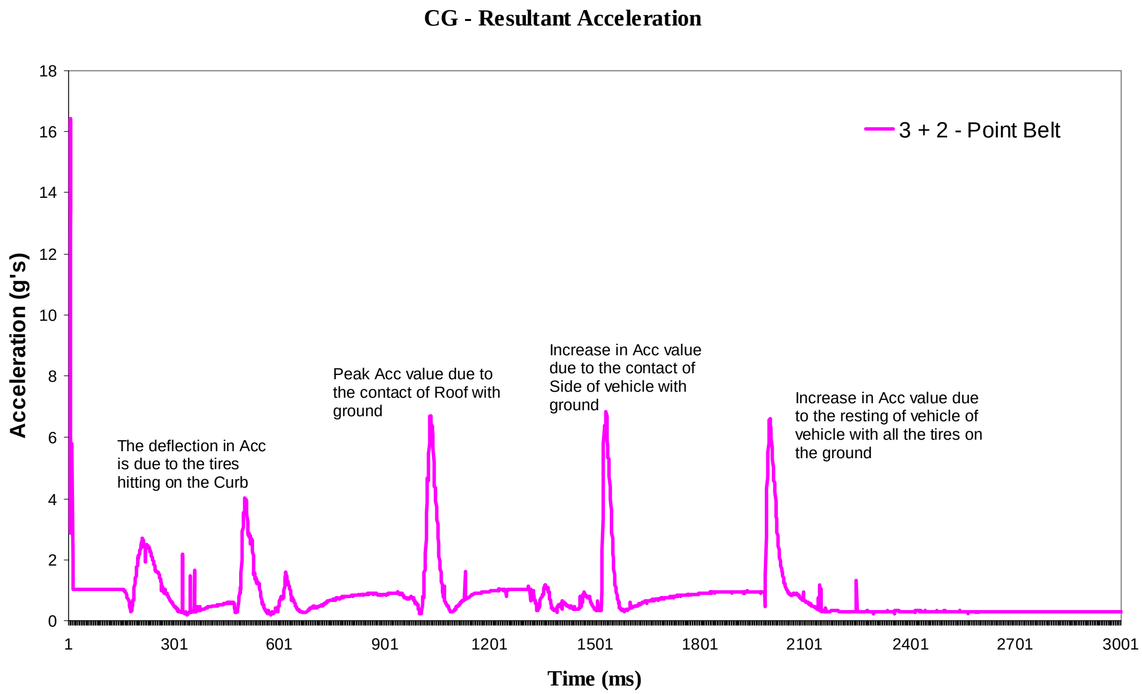


Figure 28 Resultant Acceleration - Center of Gravity of the Vehicle (3+2 Point)

Inference:

There are 3 sudden rises in acceleration values of the Centre of Gravity of the truck. The truck is given an initial velocity of 18mph and the Peak acceleration occurs at this point. When it hits the curb of 102mm on the dolly, which is used as a tripping mechanism, there is an increase in acceleration at that time. When the roll angle changes and the roof of the truck hit the ground, there is another acceleration spike. At 2000ms, the acceleration value reaches 7g's as the vehicle rests on the ground with all the 4 tires. Then, the CG of the vehicle moves flat on the ground with constant acceleration till the simulation ends.

Table 5 Injury Parameters (3+2 Point Seat Belt)

Injury Parameters

Neck Injury Criteria (N_{ij})	3+2 – Point Seat Belt system
N_{te}	0.151
N_{tf}	0.447
N_{ce}	0.218
N_{cf}	0.129

5.1.2 3 – POINT SEAT BELTED OCCUPANT

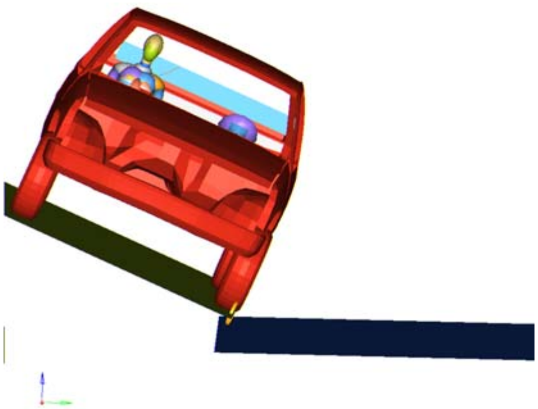
Simulation facts: Are same as 3+2 – Point Seat Belted occupant

- 0.35s = Left wheel hits curb plane
- 0.35 - 1.09s = Vehicle in air due to impact with curb plane
- 1.12s = Roof hits ground
- 1.53s = Right side of the vehicle contacts the ground
- 2.75s = Vehicle rolls from roof to right side of vehicle completing one full revolution

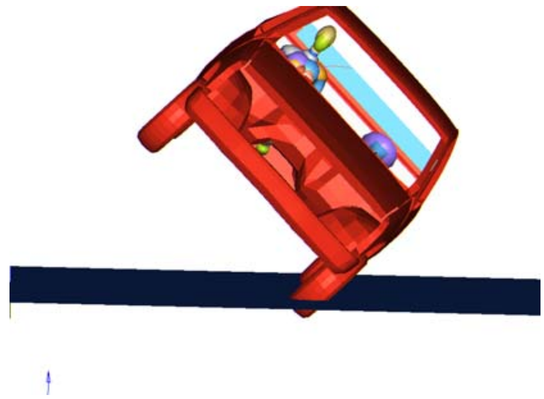
Here the configuration is with the conventional 3 – Point Seat Belt. Vehicle hits curb at 350ms, the occupant is forced to roll towards left side and hit vehicle interior giving peak in lower torso acceleration. Even upper torso acceleration is high almost 34g's. From 350ms to 1090ms, vehicle is not in contact with ground, makes 1/2 rotation in air and roof hits ground at 1,120ms. Through deforming roof, the head hits ground at 1,130ms. Peak head acceleration at this time is as high as 33g's. Even though the occupant is restrained, lap/shoulder Belt could not stop head hitting ground because of roof deformation. Due to the head hitting some of the interior parts of the vehicle compartment, the Head Injury Criterion (HIC) value is as high as 281 (3 Point Seat belt) when compared with the value of 114 in case of 3+2 Point Seat belt. Even the upper torso gets spike in acceleration as shown in Figure 32. After this, the vehicle rolls almost quarter turn, making occupant in inverted position but is held to Seat by lap/shoulder Belt. Simulation stops at 3000ms with vehicle resting on all the 4 tires. Figure 33 shows the vehicle center of gravity acceleration, it shows 3 rises in values - one when tire hits curb, the other when roof hits ground first time and the last one being when the vehicle rests on ground with all the 4 tires. In Figure 31, it is seen that lower torso acceleration is high from 1130 to 1370ms as roof touches and slides on the road, giving no Seat cushion support to lower torso. Chest acceleration behaves similarly as lower torso. Vehicle completes 0.75 turn in 3000ms as shown in Figure 29. Table 6 shows neck compressive-extension, neck compressive-flexion, neck tension-extension and neck tension-flexion all within safe limits. Even though the occupant do not eject out of the vehicle, the body parts are injured more when the occupant is secured by 3 Point Seat belt when compared to that of the 3+2 point Seat belt configuration.

Figure 29 Simulation with Time interval of 300 ms (3 Point Seat belted Occupant)

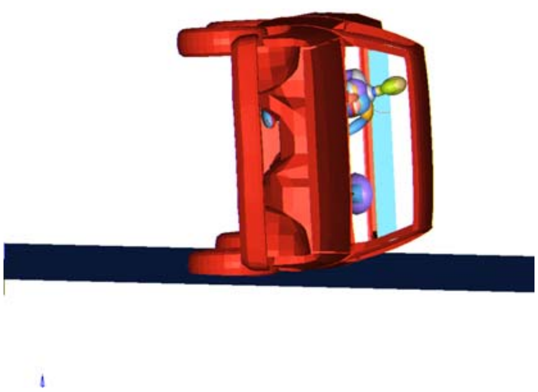
Simulation Time: **0 ms**



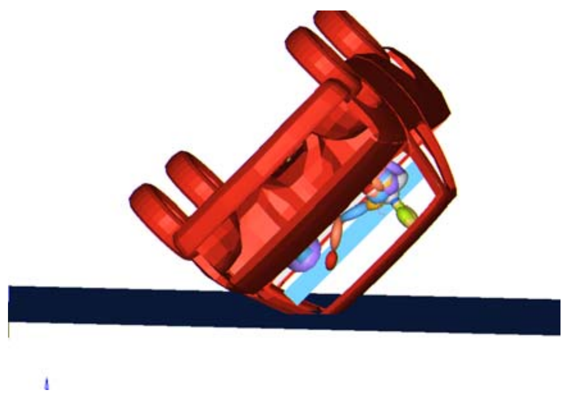
Simulation Time: **300 ms**



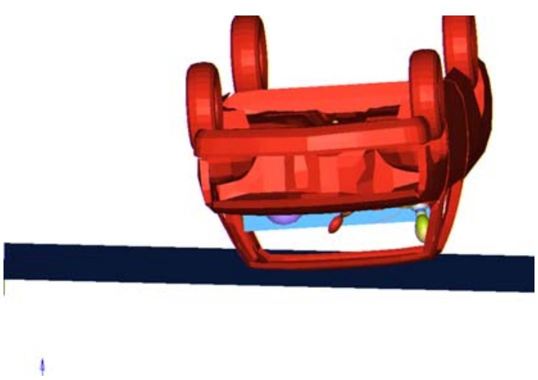
Simulation Time: **600 ms**



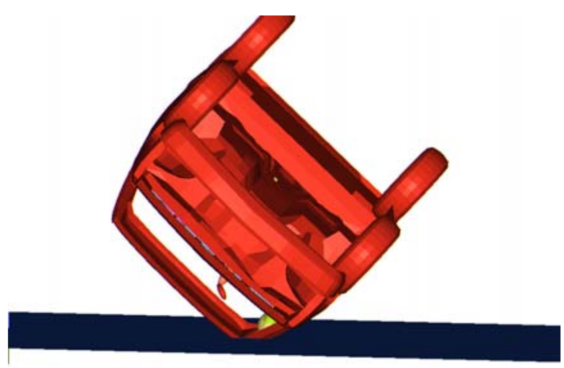
Simulation Time: **900 ms**



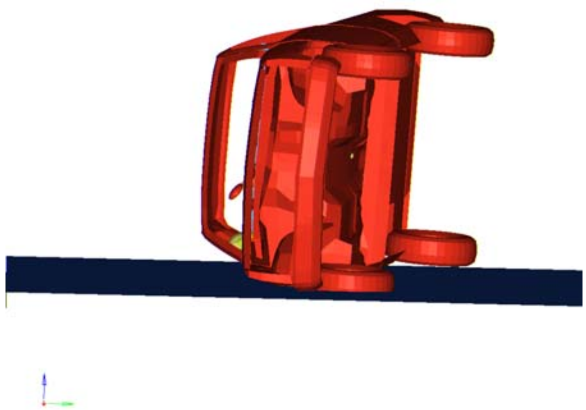
Simulation Time: **1200 ms**



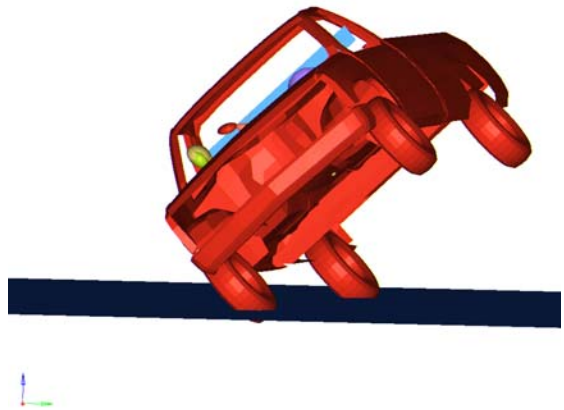
Simulation Time: **1500 ms**



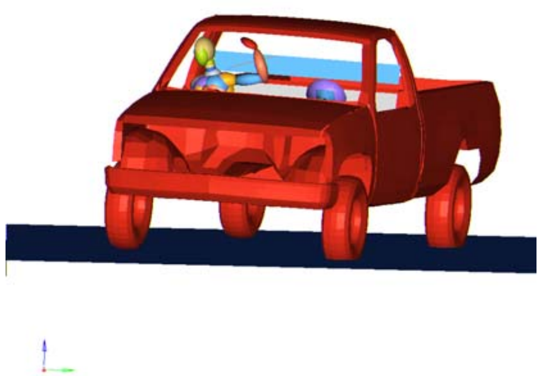
Simulation Time: **1800 ms**



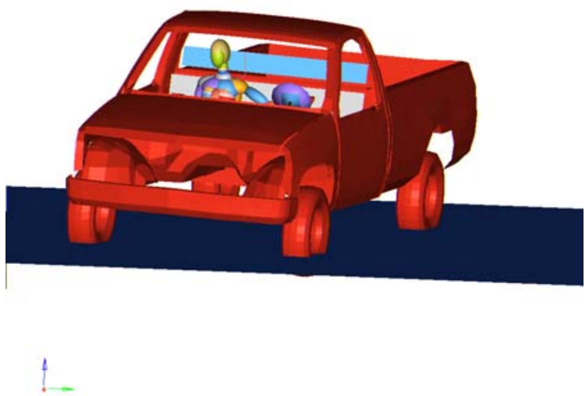
Simulation Time: **2100 ms**



Simulation Time: **2400 ms**



Simulation Time: **2700 ms**



Simulation Time: **3000 ms**

Resultant Accelerations (With 3 – Point Belt system)

Head

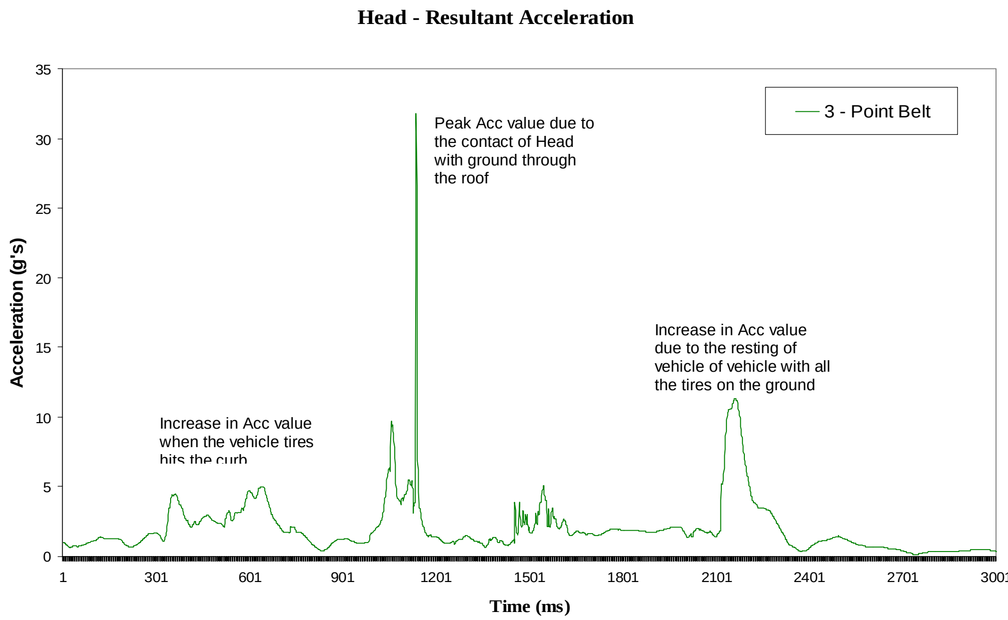


Figure 30 Resultant Acceleration - Head (3 Point)

Inference:

The sudden increase in value of Head Acceleration at 350ms is due to the left wheel hitting the Curb plane. From 350ms to 1090ms, the vehicle is not in contact with ground, makes 1/2 rotation in air and roof hits ground at 1,120ms. Through deforming roof, the head hits ground at 1130ms. Peak head acceleration at this time is 33g's. This value is well above the value with 3+2 Point Seat Belt system which is 13g's. This is because, even though the occupant is secured by 3 Point Seat belt, still the free movement of the occupant exists inside the vehicle compartment. At 2100ms is the elevated acceleration value which is due to the resting of the vehicle on the ground with all the 4 tires.

Lower Torso

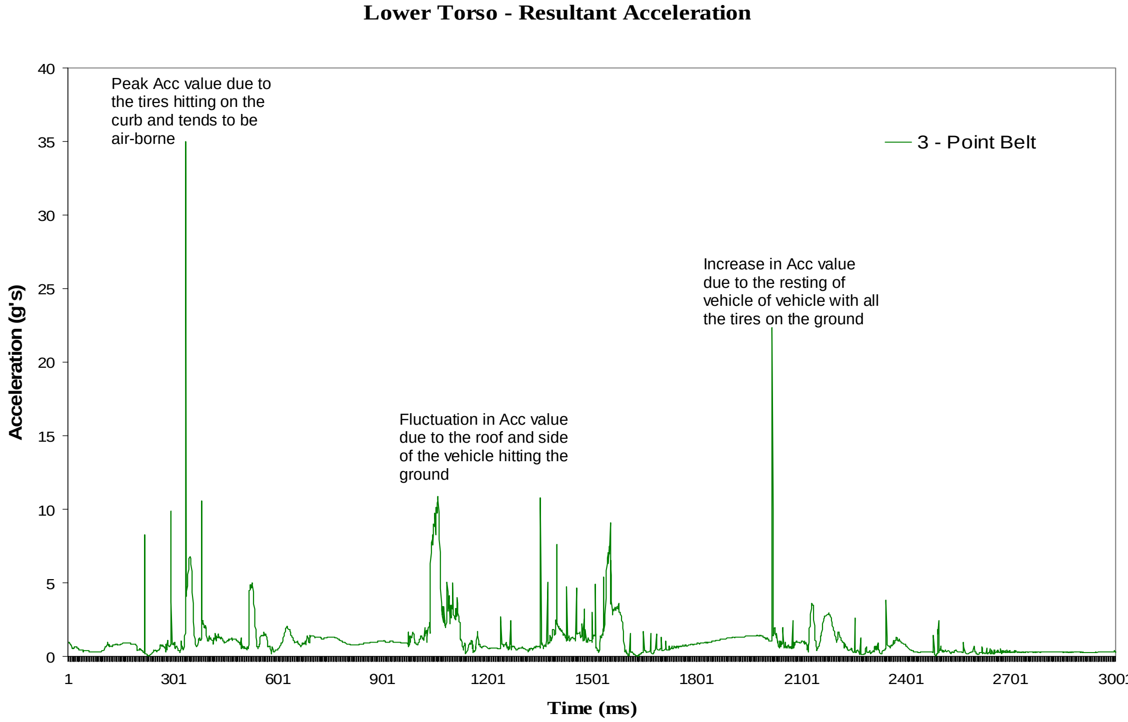


Figure 31 Resultant Acceleration - Lower Torso (3 Point)

Inference:

Vehicle hits the curb at 350ms and the occupant is forced to roll towards left side and hit the vehicle interior giving peak in lower torso acceleration. The acceleration values at 400ms to 1100ms are almost constant as the vehicle experiences air - borne roll along the left side of the truck. When the truck lands by its roof, there is a sudden change in momentum which gives another Acceleration spike at 1100ms. When the vehicle hits flat with the right door, the lower torso acceleration reaches another elevated value at 1350ms. At 2100ms, the elevated acceleration value is due to the resting of the vehicle on the ground. This value is also high when compared to the 3+2 Point Belt system.

Upper Torso

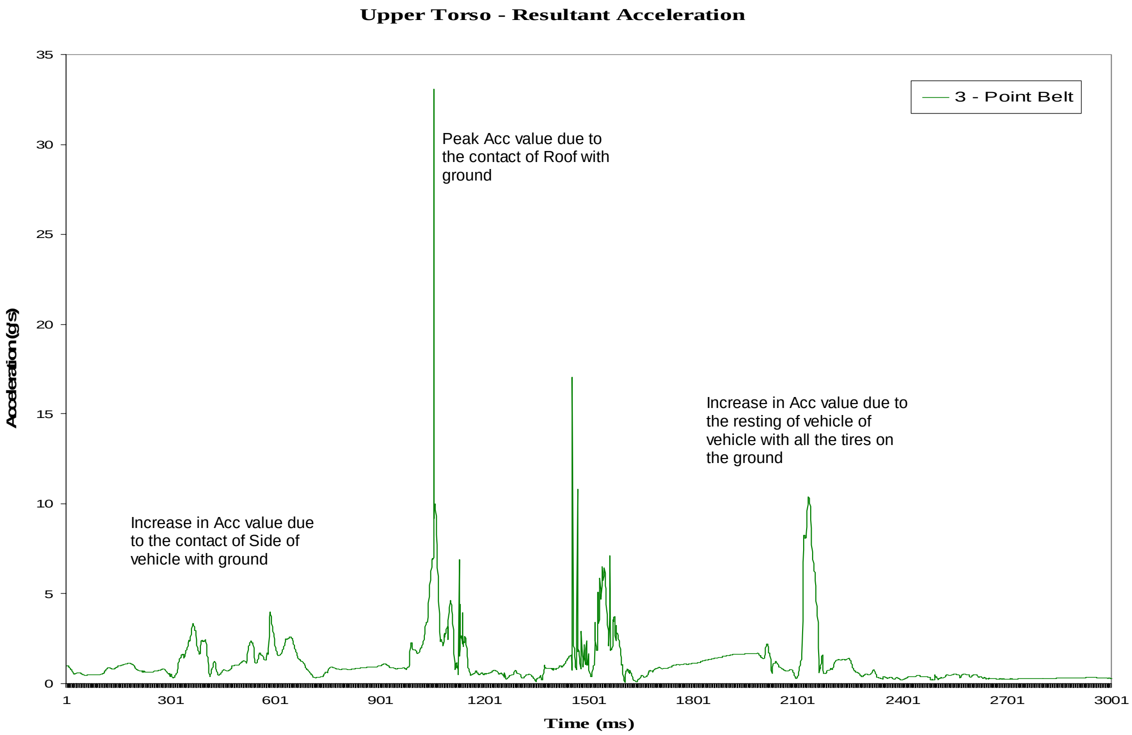


Figure 32 Resultant Acceleration - Upper Torso (3 Point)

Inference:

When the vehicle hits curb at 350ms, the occupant is forced to roll towards left side and hits vehicle interior giving increase in both upper torso and lower torso accelerations. The acceleration values at 400ms to 1100ms are almost constant as the vehicle experiences air - borne roll along the left side of the truck. The peak acceleration spike at 1100ms is due to the sudden change in Momentum when the truck land by its roof. When the vehicle hits the ground flat with its right door, the lower torso acceleration reaches another elevated value at 1500ms. At 2100ms there is another spike in acceleration value which is due to the resting of the vehicle on the ground with all the 4 tires.

Center of Gravity of the Vehicle

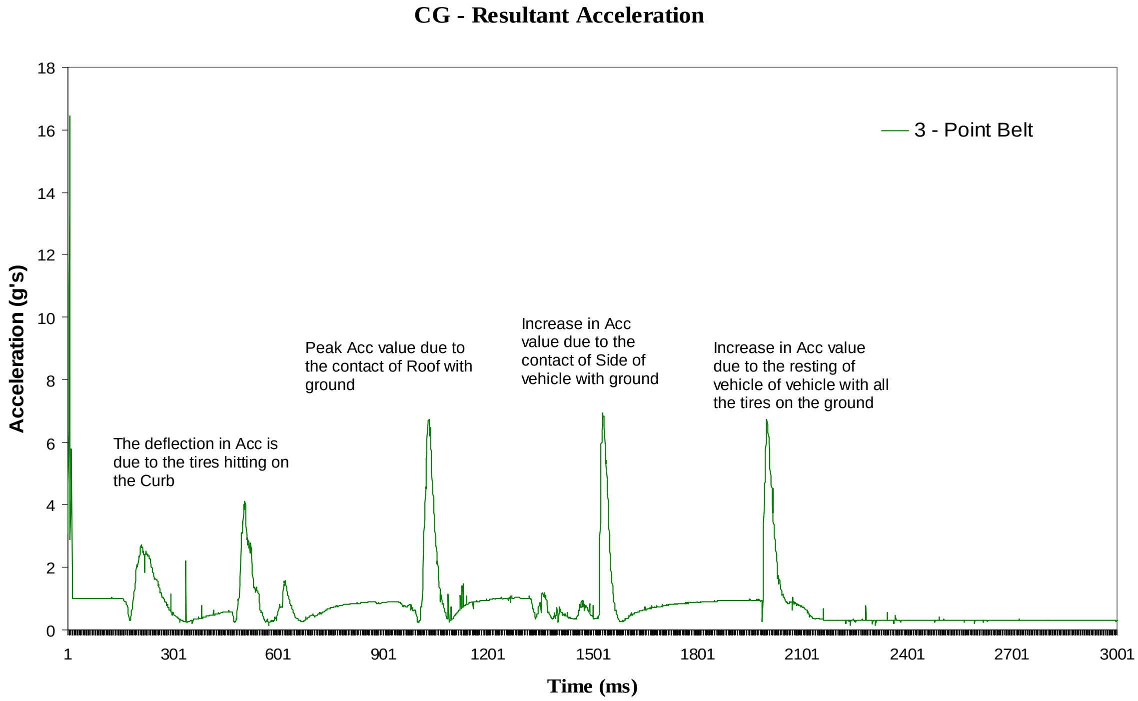


Figure 33 Resultant Acceleration – Center of Gravity of the Vehicle (3 Point)

Inference:

There are 3 sudden rises in acceleration values of the Centre of Gravity of the truck. The truck is given an initial velocity of 18mph and the Peak acceleration occurs at this point. When it hits the curb of 102mm on the dolly, which is used as a tripping mechanism, there is an increase in acceleration at that time. When the roll angle changes and the roof of the truck hit the ground, there is another acceleration spike. At 2000ms, the acceleration value reaches 7g's as the vehicle rests on the ground with all the 4 tires. Then, the CG of the vehicle moves flat on the ground with constant acceleration till the simulation ends.

Table 6 Injury Parameters (3 Point Belt)

Injury Parameters

Neck Injury Criteria (N_{ij})	3 – Point Seat Belt system
N_{te}	0.212
N_{tf}	0.039
N_{ce}	0.218
N_{cf}	0.129

5.1.3 EVALUATION BETWEEN 3 POINT AND 3+2 POINT BELT SYSTEM

Simulation (Combined 3+2 and 3 Point Belt system)

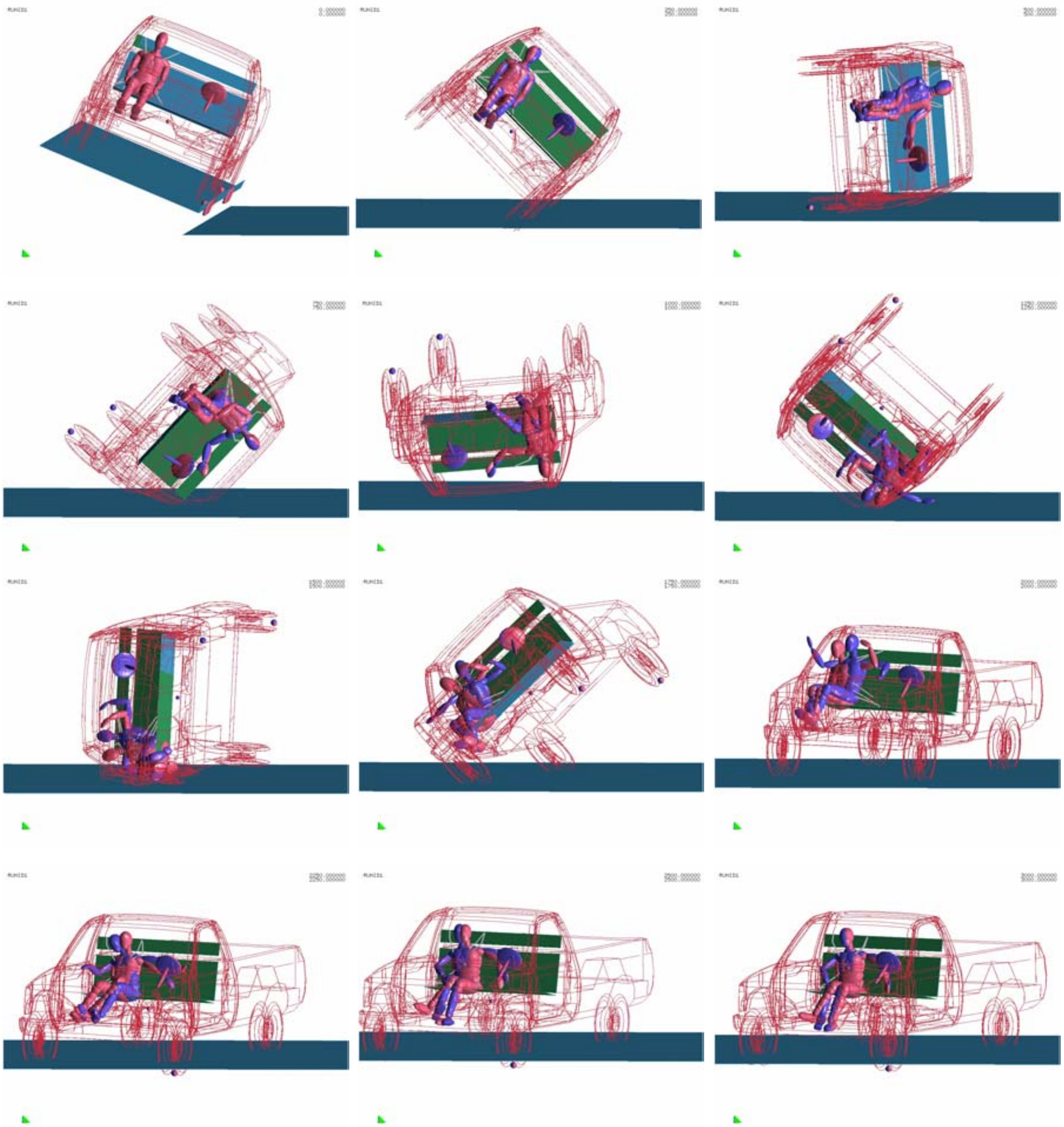


Figure 34 Combined simulation of 3+2 and 3 Pt Seat belted occupant

Key:

- *Pink Occupant: Secured by 3+2 Point Seat Belt configuration*
- *Purple Occupant: Secured by 3 Point Seat Belt configuration*

Resultant Accelerations (Combined 3+2 and 3 Point Belt Systems)

Head

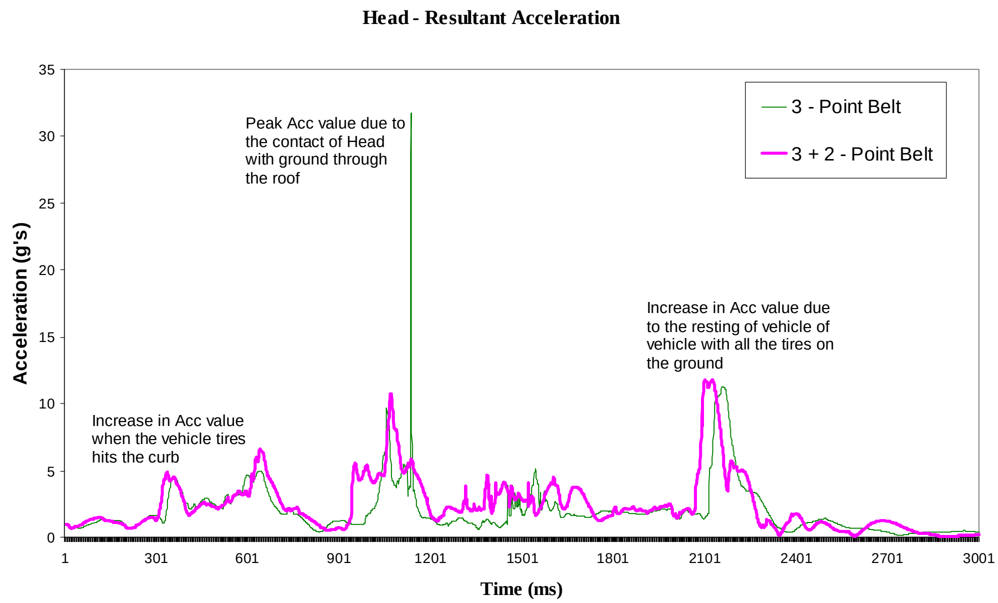


Figure 35 Resultant Acceleration – Head (3+2 and 3 Point Combined)

Inference:

The comparison plot shown above depicts that the Peak Acceleration is reduced drastically from 30g (3 Point Belt) to 10g (3+2 Point Belt). This 3 fold decrease in acceleration is due to the additional pulling of the occupant towards the seat by the 3+2 Point belt. When the roof hits the ground, the occupant tends to travel towards the roof and sideward inside the vehicle compartment. The additional pulling force by the enhanced 3+2 Point Belt prevents the occupant from his/her free movement inside the vehicle which in turn, prevents the occupant from hitting the roof of the vehicle which is too dangerous. This reduced acceleration in the given time period gives much reduced HIC value of 114 which is very less when compared to 281 in case of 3 Point Seat Belt.

Lower Torso

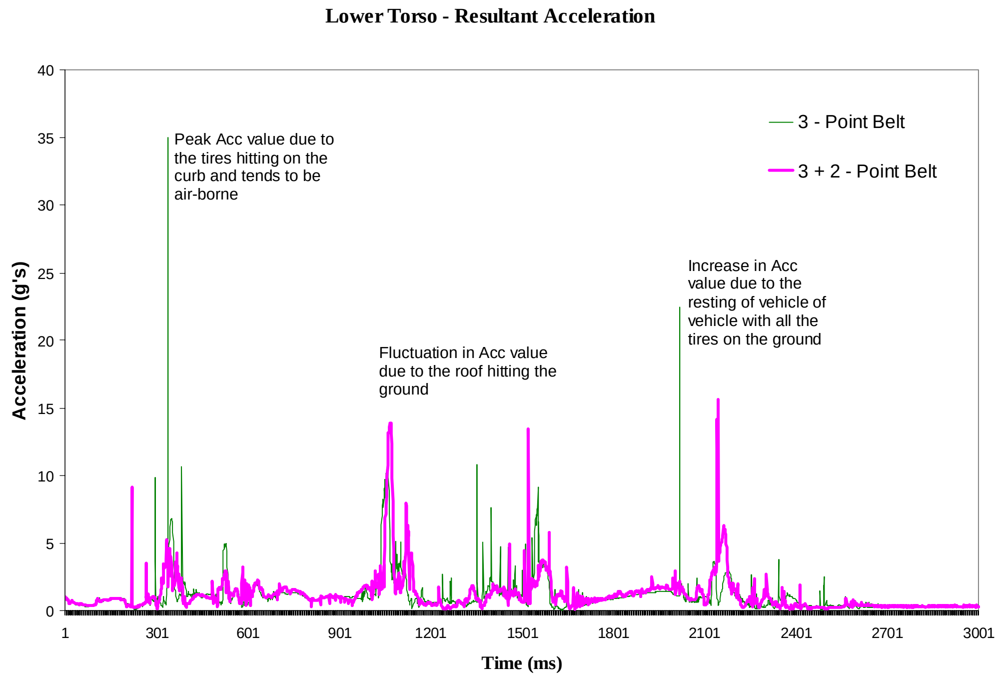


Figure 36 Resultant Acceleration – Lower Torso (3+2 and 3 Point Combined)

Inference:

From the above graph, the Lower Torso's Resultant Acceleration is reduced much at all points of the crash scenario with 3+2 Point Seat Belt. When the vehicle hits the curb at 350ms, the occupant is forced to roll towards left side and hits vehicle interior giving peak value of 35g's at 350ms. Whereas, due to the additional pulling force by the 3+2 Point Seat belt, the occupant is forced into the seat and the acceleration is reduced to as much as 5g's at this point. The acceleration values at 400ms to 1100ms are almost constant as the vehicle experience air - borne roll along the left side of the truck. Since there was reduced rise and fall of the occupant inside the vehicle compartment with 3+2 Point Belt, there is a reduced acceleration rises and rebounds also when the vehicle hits the ground and comes to the stop at 2100ms.

Upper Torso

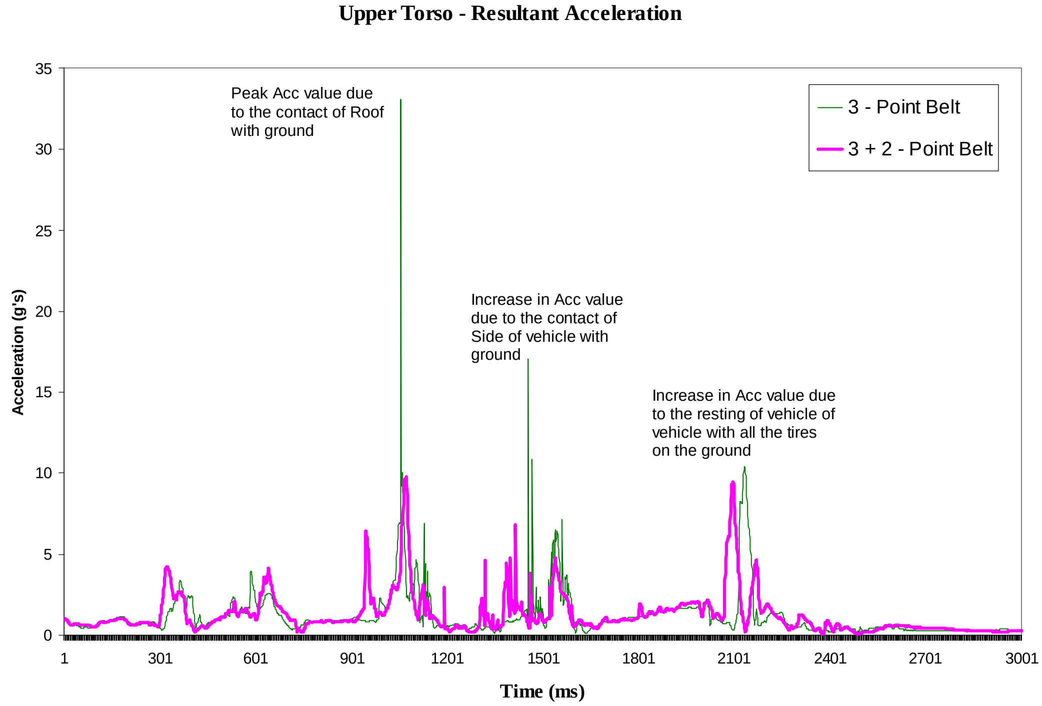


Figure 37 Resultant Acceleration – Upper Torso (3+2 and 3 Point Combined)

Inference:

When the vehicle hits the ground by its roof, the sudden change in momentum reflects the Acceleration spike at 1100ms. With 3+2 Point Belt, this value is reduced to 9.5g's when compared to that of 33g's in case of 3 Point Seat Belt configuration. This is because, the lateral movement of the occupant is controlled with 3+2 Point Belt as the belt's end points originate on top of the seat on either side of the shoulders of the occupant. When the vehicle hits flat with the right door, the lower torso acceleration reaches another elevated value of 17g's at 1500ms. Whereas, in case of 3+2 Point Belted occupant, this value is significantly reduced to around 5g's as the occupant is restricted from moving laterally toward the right door which prevents him/her to crash with the right door.

Center of Gravity of the Vehicle

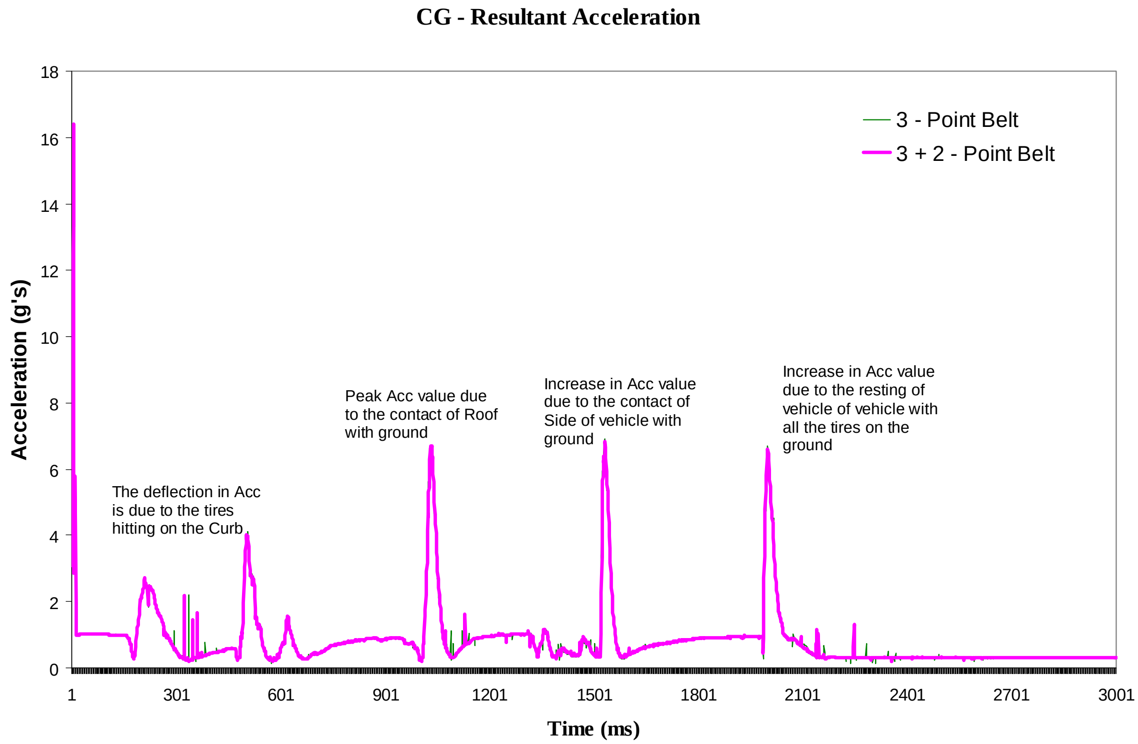


Figure 38 Resultant Acceleration – CG of the Vehicle (3+2 and 3 Point Combined)

Inference:

There are 3 sudden rises in acceleration values of the Centre of Gravity of the truck. The truck is given an initial velocity of 18mph and the Peak acceleration occurs at this point. When it hits the curb of 102mm on the dolly, which is used as a tripping mechanism, there is an increase in acceleration at that time. When the roll angle changes and the roof of the truck hit the ground, there is another acceleration spike. At 2000ms, the acceleration value reaches 7g's as the vehicle rests on the ground with all the 4 tires. Then, the CG of the vehicle moves flat on the ground with constant acceleration till the simulation ends.

Injury Parameters

Table 7 Injury Parameters (Comparison between 3+2 Point Belt and 3 Point Belt)

Neck Injury Criteria	3+2 – Point Seat Belt system	3 – Point Seat Belt system
N_{te}	0.151	0.212
N_{tf}	0.447	0.039
N_{ce}	0.211	0.218
N_{cf}	0.109	0.129

5.2 IMPLICATION

From the graphs and tables discussed in the previous pages, it clearly indicates that the Acceleration spikes, Injury parameters are all decreased considerably if the occupant is secured by the 3+2 Point Seat belt rather than with a 3 Point Seat belt configuration. From Figure 34, with 3+2 Point Seat belt, it is proved that the occupant is restricted from hitting the ground through the deformed roof and he is arrested from any free movement inside the vehicle compartment which prevents him/her from being hit on the vehicle parts thus reducing the injury criterion values. All four N_{ij} values are within the safe limit. Head injury criterion (HIC) is reduced to 114 with 3+2 Point Belt when compared with that of 281 in case of 3 Point belted occupant. The body parts are safely secured with 3+2 Point Belt, thus, injuries are reduced by preventing the occupant from hitting foreign objects like road surface, rocks.etc…

OCCUPANT DONOT EJECT OUT OF THE VEHICLE

6 CONCLUSIONS AND RECOMMENDATIONS

Since Rollover is a public threat that is receiving a lot of attention in case of SUVs and pickup trucks whose centers of gravity are higher than in smaller passenger cars and have an increased risk of rolling over, the purpose of this study concentrated to investigate the dynamics of occupants of the Light Pick-up truck involved in rollover. Also of importance were the evaluation of different injury criterions and the extent of the effects of safety restraint systems like 3+2 Point and 3 Point Belt systems in reducing the injuries incurred by the occupants of rolled over vehicles.

6.1 CONCLUSION

The simulation shows that the vehicle parts such as side door panel, roof and ground seem to harm more while ground and roof are dangerous. Roof injury can be reduced by preventing roof to deform in the liable volume. Ground injury of the occupant can be avoided by preventing the ejection. Injury due to seat can be prevented by redesigning seat and using better cushion properties. Avoiding Neck injury can be obtained by not letting neck to move by providing side as well as roof airbag. Leg injury can be reduced by having softer interior especially for door interior.

Vehicle crashworthiness research is becoming more and more reliant on computer simulations. The automotive industry is using computational tools in order to decrease the design time required to make new models available to the public. The use of simulations saves manufacturers time and resources by decreasing the number of prototypes built and tested when making new designs.

During this research, the current standards and regulations dealing with rollover, and previous research, testing, and simulations of rollover crashes were reviewed. FE analysis and vehicle crash simulation software algorithms were described. The modeling techniques used in the simulation of an FMVSS 208 - Dolly Rollover test of a pickup truck were described and results of those simulations were shown. A modeling strategy for adding a dummy occupant to the rollover simulation was also discussed.

From the results presented in this thesis, it can be concluded that:

- The enhanced 3+2 Point Seat Belt is more safe to the occupants than the existing 3 Point Seat Belt system

- The injury criterions are very much reduced with 3+2 Point Seat Belt

- The HIC value is reduced from 281 (3 Point Belt) to 114 (3+2 Point Belt)

- The 3+2 Point Seat Belt is very effective in Rollover crashes which are unpredictable and very dangerous. The occupant is protected from the free movement inside the vehicle compartment and avoids his/her contact with the vehicle interior.

- The simplification of the suspension as a system of springs and dampers saves CPU time while achieving accurate results

- Defining a sensor to switch the entire vehicle from a rigid body to a deformable body and back again during the simulation saved CPU time without affecting the accuracy

- The MADYMO / LS-Dyna solver is capable of handling the computational complexity of a rollover event. It is recommended that any future work on vehicle rollovers be conducted using the Coupling technique between MADYMO and LS-Dyna crash programs as accurate results like crushing of the roof against the ground can be attained.

- The greatest decrease in Kinetic energy in the rollover dolly test occurred during the first impact with the ground.

- If a suspension is weak and breaks when the tires first contact the ground, the vehicle will continue rolling at a higher lateral speed and the first tire contact will not decrease the kinetic energy of the vehicle significantly.

- When the mass of the vehicle was increased, the rotational velocity decreased and the vehicle experienced more damage.

As a summary, in case of the Dolly Rollover, the lateral velocity to the vehicle is 18mph. The injuries to neck, head, left and right legs are reduced by using 3+2 point Belt system instead of the 3 Point Belt system. N_{ij} values are also in the safe limit area. Vehicle completes one full roll in the simulation. Occupant do not eject out of the vehicle.

6.2 FUTURE WORK

This research presents many possibilities for further rollover research using FE analysis software. Possible areas for this future work are briefly described here in the following pages:

6.2.1 SUSPENSION DESIGN

The suspension characteristics influence a vehicle's dynamic results in a rollover. A detailed investigation is needed to determine the best suspension design to protect an occupant involved in a rollover crash. Hence, the concept for the newer Suspension design mentioned below was proposed with this Thesis:

"Innovative design of Rear axle for Automobiles to virtually eliminate

Rollover crashes"

The Rollover in a Vehicle is caused due to the extreme lateral force experienced on the tires during cornering or unusual maneuvers. The friction created between the Tire surface and the Road surface trips the vehicle to Rollover. So, an ideology was created to reduce the lateral force by creating a shock absorbing action in the lateral axle. This could absorb all the lateral shocks similar to the existing shock absorbers which absorb the perpendicular shocks on road surfaces. So, the lateral force gets nullified and the vehicle is less prone to be tripped by friction. This would create newer Vehicles travel at high speeds and still can hold out extreme maneuvers.

6.2.2 ADVANCED METHODS

It is recommended that any future work on vehicle rollovers be conducted using the Coupling technique between MADYMO and LS - Dyna crash programs as accurate results like crushing of the roof against the ground can be attained. The friction coefficients for contacts could be measured experimentally, the simplification of the suspension could be calculated with measurements from the real truck and the mass of the model could be adjusted to be realistic.

6.2.3 TESTING METHODS

The current rollover standards are insufficient to ensure drivers and passengers involved in rollover crashes are protected. Dynamic rollover tests are being researched to replace the FMVSS 208 Dolly test. Other rollover tests could be designed or tested within FE simulations to determine the effectiveness of a test before a full-scale test is created.

Recreating rollover accidents could also be an application of a finite element simulation. If the ground properties and vehicle characteristics from an accident are known, reconstructing the accident by simulation to determine causes of the accident and any occupant injuries could be achieved to acquire real time test conditions.

6.2.4 DUMMY

In order to successfully complete a rollover simulation of a vehicle including a dummy occupant, the dummy model needs to be investigated further. It is recommended a double precision solver be used to study any simulations involving a dummy contacting more than one surface. Once the simulation of a rollover including a dummy occupant is successfully completed using a double precision solver, the arena of occupant safety can be fully explored. The causes and effects of occupant injury could be investigated without harming a human volunteer. The effectiveness of safety devices such as Seat Belts and Airbags in a rollover accident could be investigated without building and destroying multiple prototype vehicles. Finite element Dummy of a human being could replace the Hybrid III dummy to create a more accurate test. Vehicle parameters such as roof strength or pillar design could also be investigated with fewer prototypes.

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