NCAC
THE NATIONAL CRASH ANALYSIS CENTER

Sensitivity Study of Vehicle Rollovers to Various Initial Conditions

Finite Element Model Based Analysis

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Abstract – The Automotive Safety Research Institute (ASRI) has commissioned a series of dynamic rollover tests using the Jordan Rollover System (JRS). The Jordan Rollover System (JRS) has the flexibility of closely controlling the initial conditions of the test vehicle being subjected to a rollover. The controlled conditions include drop height, roll velocity, roadway velocity and angular orientation at drop. A previous series of dynamic rollover tests sponsored by the Santos Family Foundation were conducted under a constant set of initial conditions. The ASRI proposed this study in order to compare these test conditions with other alternatives.

The baseline conditions for the Santos tests were: Roll angle of 145° at impact; Pitch angle of 5°; Yaw angle of 10°; Roadbed speed of 24kph; Vertical drop of 10cm and roll velocity of 190deg/sec. This test procedure produced severe roof damage on some, but not all of the vehicles tested. However, the new static test standard (FMVSS216) doubles the minimum allowable roof strength as measured by a static test. This change in the standard should permit vehicles to withstand more severe rollover conditions. A purpose of this research is to investigate how changes in the initial rollover conditions on the JRS would affect the roof loading and dynamics of a vehicle with a strong roof for both the driver and passenger sides of the vehicle.

The approach used in this study makes use of Finite Element Analysis. A FMVSS No 216 validated Finite Element model of a 2003 Ford Explorer. In order to exclude crushing factors, a strong roof structure was adopted and made of high strength steel without failure and plasticity.

In this initial study, the angle of impact was held constant at the baseline conditions. The initial rollover parameters of road speed, roll rate and drop height were changed one at a time in order to study their effects on vehicle rollover behavior and loading of the roadbed.

The following observations were made based on simulation results:

1- Roadbed speeds of 0, 9, 18, 24, 30 and 36kph were investigated. A minimum roadbed speed of 24kph was necessary to produce roof contact on the near and the far sides. For roadbed speeds lower than 24kph, the far side impact was not significant.

2- Roll rates of 190, 360 and 540deg/sec were investigated. As the roll rate increases, the roadbed force measured at the near side impact decreases. The roadbed force effect at the far side impact sustains for a longer time in order to manage the additional energy in the system. After the near side hit is completed, the roadbed speed controls the roll rate.

3- Three drop heights of 10, 20 and 30cm were investigated. The increase in potential energy increases the force that is managed by both sides of the roof. The drop heights have shown no effect on the roll velocity.

Introduction

FMVSS No 216 specifies a quasi-static test procedure that measures the force required to push a metal plate into the roof at a constant rate [1]. It requires a reaction force equal to 1.5 times the weight of the vehicle be reached within 5 inches of plate displacement. In 1991, the standard was extended to apply to light trucks and vans with Gross Vehicle Weight Ratings (GVWR) less than 6,000 lbs [2]. In May 2009, the rule doubled the amount of force the vehicle's roof structure must withstand in the specified test, for vehicles of a Gross Vehicle Weight Rating (GVWR) of 2,722kg (6,000 lbs) or less, to 3.0 times the vehicle's unloaded weight. The rule requires, as well, that all vehicles must meet the specified force requirements in a two-sided test, instead of a single-sided test, i.e., the same vehicle must meet the force requirements when tested first on one side and then on the other side of the vehicle. NHTSA adopted this upgraded quasi-static requirement for now and is conducting research for a dynamic test standard [3].

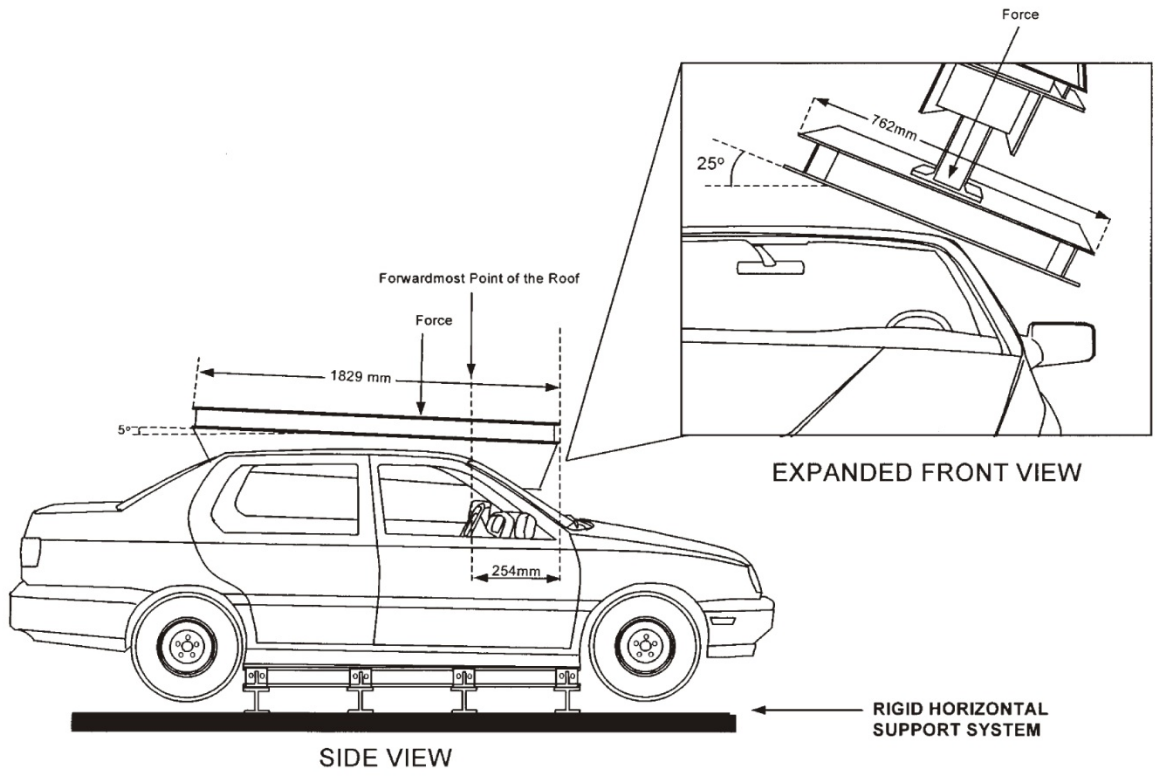


Figure 1. FMVSS No 216 Test setup [1]

The Insurance Institute of Highway Safety (IIHS) has developed its own rollover crashworthiness rating. The IIHS indicated that the boundary for a good rating in their program will be a Strength to Weight Ratio (SWR) of 4.0 in a one-sided platen test condition similar to the existing FMVSS No 216 test procedure. For an acceptable rating, the minimum SWR is 3.25. A marginal rating value is 2.5. Anything lower than that is rated as poor. This rating system is based on the institute research showing that occupants in rollover crashes benefit from stronger roofs [4].

In developing the upgraded FMVSS 216 NHTSA considered, several dynamic rollover tests.

The FMVSS No. 208 dolly rollover test was originally developed only as an occupant containment test and not to evaluate the loads on specified vehicle roof components [3]. The vehicle is rolled laterally off the inclined ramp of a dolly moving at 30mph. The vehicle typically rolls one to four times and, to pass the test, no part of an unrestrained dummy in the vehicle may be ejected. The National Highway Traffic Safety Administration (NHTSA) believed that this test lacks sufficient repeatability to serve as a structural component compliance requirement [3].

The Controlled Rollover Impact System (CRIS) test is achieved by mounting a vehicle on a spit at the back of a moving tractor-trailer. It is rolled as the truck drives along a flat surface at a given speed and is dropped so that it lands on its roof while rolling. After release, the vehicle continues to roll to rest [5]. CRIS is considered to produce repeatable vehicle and occupant kinematics for the initial vehicle-to-ground contact but NHTSA have no indication that this procedure is repeatable after the initial ground contact [3].

The Jordan Rollover System (JRS) test is attained by mounting a vehicle on an axis that permits it to roll and be dropped. As the vehicle is rotated, a roadway segment is run underneath and the vehicle is dropped so that its roof strikes the road as it would in an actual rollover. After both sides of the roof have impacted the roadway, the vehicle is then lifted by the spit so that it will sustain no further damage to the vehicle sides or undercarriage. Subsequent rolls can be conducted by resetting and running the JRS test a second time [5, 6]. NHTSA believes there is lack of real-world data in order to determine the JRS test parameters for different vehicles [3].

In this research, the JRS initial conditions were the base parameters. Only 3 quarter turns were simulated since we are interested in loading the near and far sides structure of the roof and the vehicle dynamics during the impacts.

Research Approach

Finite Element (FE) modeling was used in this analysis. FE modeling has been indispensable in the development of component design, and vehicle crashworthiness evaluations. This study utilizes commercial FE code, LS-DYNA to simulate roof strength for multiple loading conditions [10].

FE Model

The full vehicle FE model used in this study was developed at the National Crash Analysis Centre (NCAC) under a co-operative agreement between Federal Highway Administration and National Highway Traffic Safety Administration and The George Washington University. The FE model of a 2003 Ford Explorer has been validated to several sub-system tests and to a full frontal rigid barrier test conducted by NHTSA. The validation report and the FE model are available from the NCAC website (www.ncac.gwu.edu/vml/models.html) [11].

FMVSS 216 Validation

Further model validation was carried using FMVSS No 216 test set up with two different pitch angles. The FE model was verified against two FMVSS No 216 tests conducted by NHTSA to establish the baseline performance for this vehicle. The first test (NHTSA test number C0139) was conducted as per the FMVSS No 216 protocol platen angles of 5 degree pitch and 25 degree roll [7]. The second test (NHTSA test number C0140) was conducted at platen angles of 10 degree pitch and 45 degree roll to investigate the change in roof crush resistance [8]. The platen reaction force versus roof deformation from the NHTSA tests and the corresponding FE simulations are shown in Figure2. The reaction force is presented as a percentage of the unloaded vehicle weight. The FE model shows good correlation in both tests.

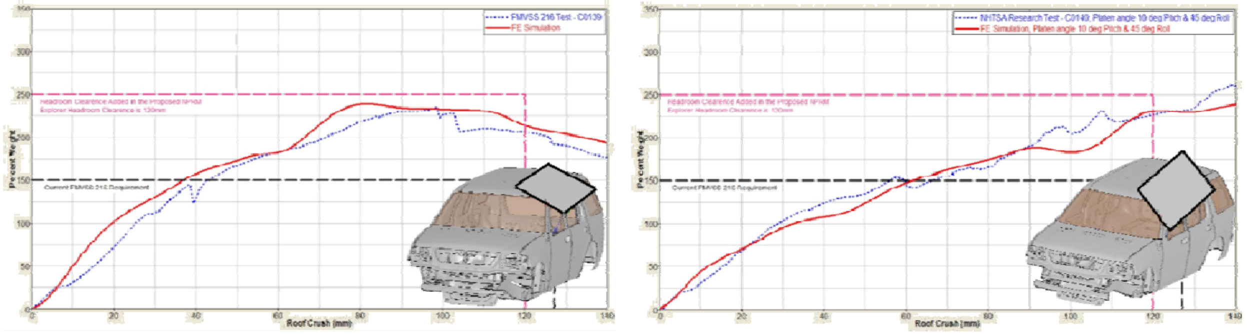


Figure2. Force-Crush Comparison Tests C039 & C040 and FE Simulations [8]

FE model set up

Once completed, the model was given initial conditions similar to the JRS common values [6]. The FE model had some differences from the JRS test. The FE model was free of any outside structure constraints, the roadbed was considered moving at a constant speed and the roof structure was strengthened by eliminating the plastic deformation in steel. These assumptions were made in order to investigate solely the sensitivity effects on future strong roofs that would meet the new regulations and to exclude any interactions with the vehicle's surroundings (i.e. spit interactions). The front and side views are shown in Figure3.

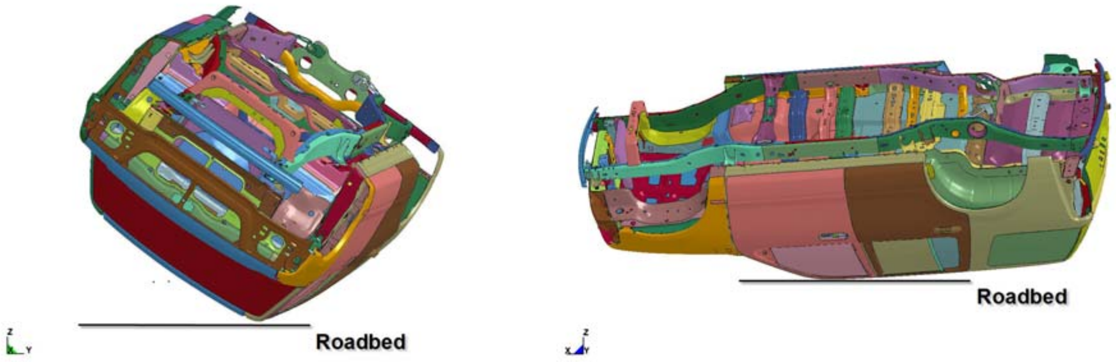


Figure3. FE model front and side views setup

Rollover simulations usually take long computational times. Therefore, in order to reduce the model size and simulation run time, some components of the vehicle were removed. The suspensions, drivetrain and engine were selected because they have minimal influence on the roof strength. The weight and inertia of these parts were replaced by adding concentrated mass and inertia to six points at the ladder frame. LS-DYNA provides *ELEMENT_INERTIA [10] for this kind of purpose. The inertial properties of the removed parts were determined and divided into the engine, the transmission, the front suspension, and the rear suspension sections. These sections were replaced and applied to nodes attached to the ladder frame at the mounting points of the removed components. Vehicle weight was dropped from 2237.8 kg to 719.7 kg. Several iterations were conducted in order to calibrate the model and the element inertias in order to closely match the original model. These components reduced the number of elements from 619161 to 420517, which had subsequent effects on run time. The values are shown in Table1 and the full and the reduced models are compared in Figure4 [9].

Model Description	**Mass**	**I_{11}**	**I_{22}**	**I_{33}**
Full Vehicle Model	2237.8 kg	725.97 kg×m^2	3805.4 kg×m^2	4063.8 kg×m^2
Reduced Vehicle Model	2254.7 kg	604.9 kg×m^2	3884.0 kg×m^2	4073.7 kg×m^2

Table1. Inertial properties of the original and the reduced models [9]

The roadbed was represented by *RIGIDWALL [10] in order to exclude any variations occurring from the ground. The roadbed speed was maintained fixed during this representation using the MOTION [10] option since it excludes any variability. The roadbed was 2.6m wide and 2.8m long.

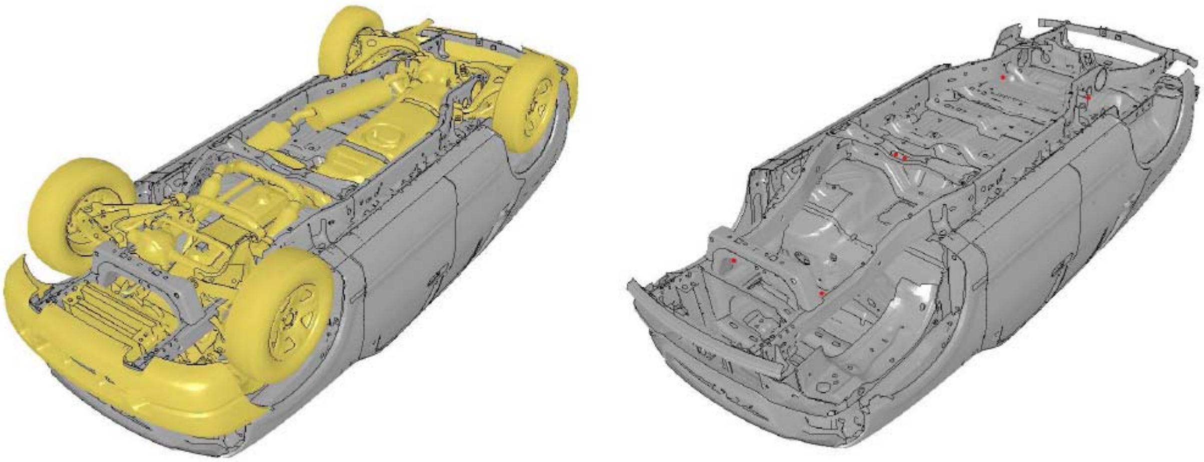


Figure4. Full and Reduced models. Yellow parts are the removed components; Red elements are the added mass with inertias [9]

To represent future vehicles that are going to meet the new FMVSS No 216 requirements, all roof components were switched to pure elastic properties. This includes the A- B- C- D-pillars, roof rails, roof cross members and roof outer sheet metal. These components are show in Figure5. They made the roof structure stronger than the original model and eliminated structural plastic deformation during the sensitivity assessment. The Strength to Weight Ratio (SWR) is measured to be 3.9 times the vehicle’s unloaded weight .

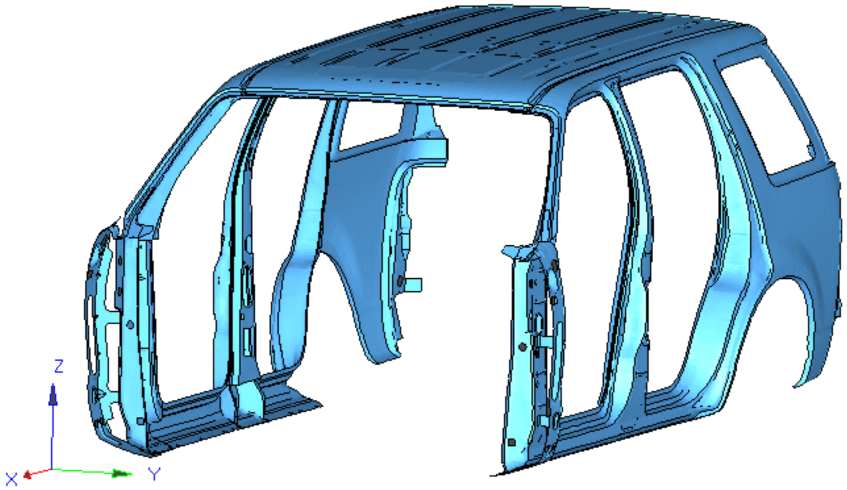


Figure5. Roof structure components switched to elastic steel material to represent futuristic strong roof

This representation was considered sufficient for the purpose of analyzing the near and far sides of the roof. The near side of the vehicle is set to be the passenger side and the far side is the driver side in this study. Finally, the simulation time of 350ms was sufficient to cover 3 quarter turns of the rollover.

Selecting the initial conditions was based on the Santos test protocols for the JRS tests. These values were considered as baseline model in this study. The approach is based on performing a sensitivity study with multiple initial parameter variations on the validated FE model. The design parameters addressed were the roadbed speeds of 0, 9, 18, 24, 30 and 36kph, roll rates of 190, 360 and 540deg/sec, and drop heights of 10, 20 and 30cm. The sets of simulations were compared with each other.

Parametric Study and Baseline Model Comparison

The baseline variables were: Roll angle of 145° at impact; Pitch angle of 5°; Yaw angle of 10°; Roadbed speed of 24kph; Vertical drop of 10cm and roll velocity of 190deg/sec. The baseline values of the JRS produced extensive roof crush in some vehicles but not in others.

The first set of parameters varied was the roadbed speeds. Roadbed speeds of 0, 9, 18, 30, and 36kph were investigated. A summary is shown in Table2.

	Roadbed Speed	Roll Rate	Drop Height	Initial Roll Angle
	km/h	degree/sec	cm	degree
	0	190	10	145
	9	190	10	145
	18	190	10	145
Baseline	24	190	10	145
	30	190	10	145
	36	190	10	145

Table2. Different roadbed speed simulations

Roadbed normal forces for different roadbed speeds are compared with respect to roll angle as shown in Figure6. The initial roll angle of 145° is where the loading begins. A minimum roadbed speed of 24kph was necessary to produce roof contact on both the near and the far sides. The roadbed normal forces for roadbed speeds of 24, 30, and 36kph were about 40KN measured at the near side (passenger or leading side), however, the load peaks around 60KN at the far side (driver or trailing side). For roadbed speeds lower than 24kph, the far side impact was not significant or complete. The roadbed normal forces for roadbed speeds of 9kph and lower were higher at the near side but lower at the far side. For roadbed speed of 18kph, the far side did not withstand high loading and the roadbed normal force curve did not converge to higher speed curves.

This behavior corresponds closely to the following findings. For a stationary roadbed, the roof crush was similar to a drop test. This is because the roll angular velocity could not alone maintain sufficient speed for the vehicle to roll on its far side. For different roadbed speeds, the affect of the roll rate of the vehicle depended on the speed. For roadbed speeds lower than the initial roll rate times the shortest distance between the point of contact and the axis of rotation, the vehicle roll rate was decelerated. For higher speeds, the vehicle roll rate was increased, as shown in Figure7. When the vehicle was upside down (i.e. roll angle =180°), the distance between the point of contact and the axis of rotation was the shortest. This condition decreases the roll rate. This distance increases again when the roadbed contacts the far side of the vehicle which, in turn, increases the roll rate.

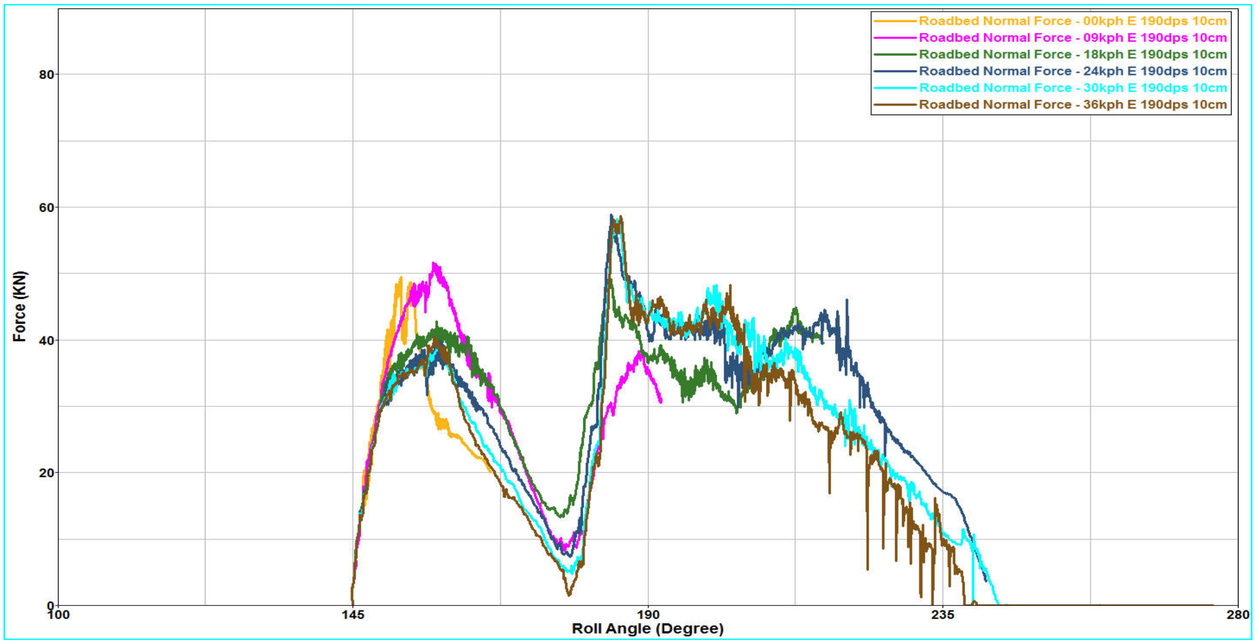


Figure6. Roadbed normal force Vs Roll Angle for different roadbed speeds

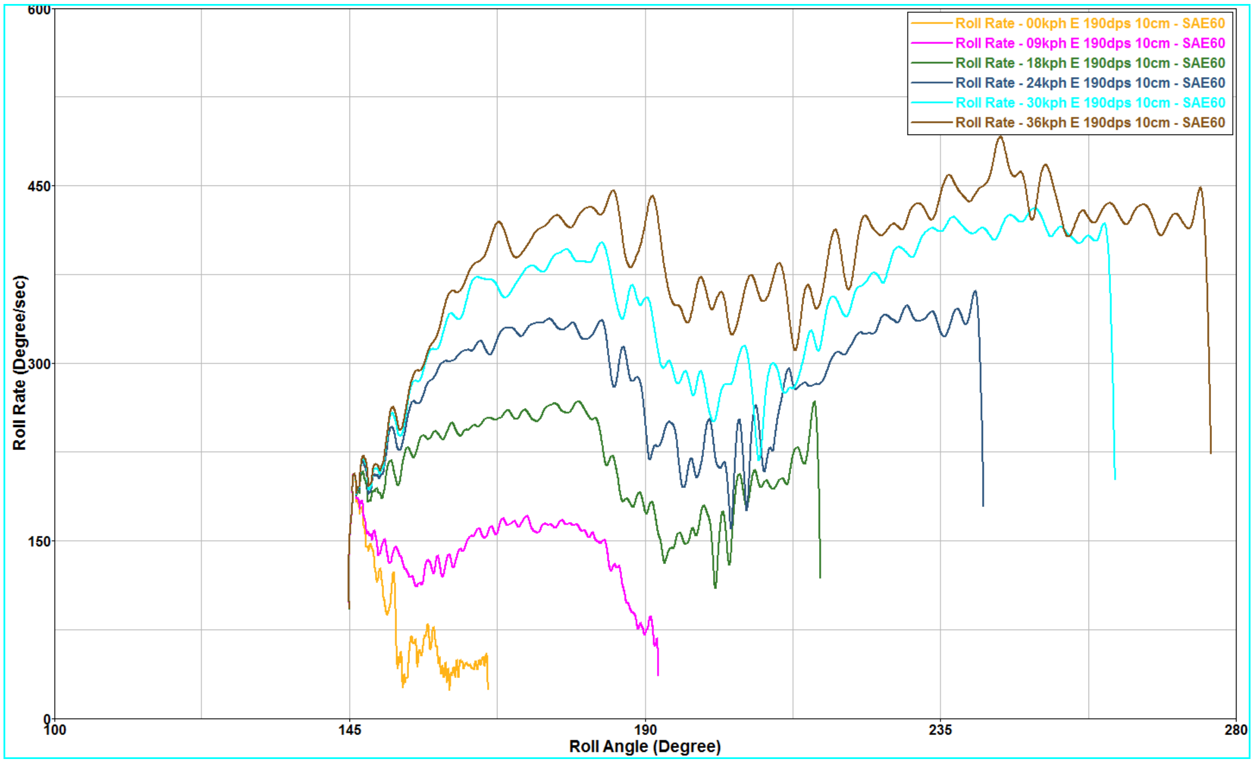
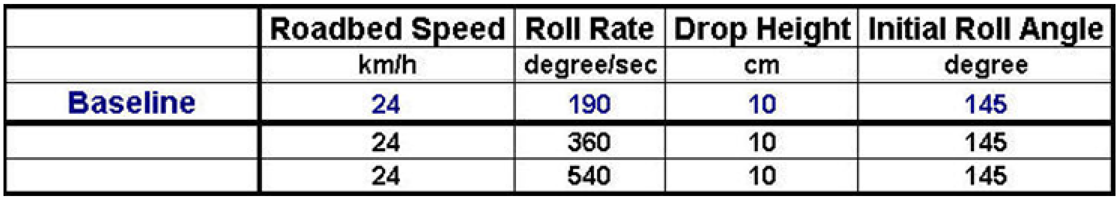


Figure7. Roll Rate Vs Roll Angle for different roadbed speeds (SAE 060 filtered)

The second set of parameters varied was the roll rate. Roll rates of 190, 360, and 540deg/sec were investigated. A summary is shown in Table3.



	Roadbed Speed	Roll Rate	Drop Height	Initial Roll Angle
	km/h	degree/sec	cm	degree
Baseline	24	190	10	145
	24	360	10	145
	24	540	10	145

Table3. Different roll rate speed simulations

Roadbed normal force for different roll rates are compared with respect to roll angle as shown in Figure8. As the roll rate increases, the roadbed force measured at the near side impact decreases. The vehicle has a tendency to bounce off the ground at initial contact for higher rotational speeds. The roadbed force effect at the far side impact sustains for a longer time in order to manage the additional energy in the system.

Similar to roadbed speeds findings, the roll rate changes based on roadbed speed. This is influenced by the initial roll rate times the shortest distance between the point of contact and the axis of rotation. The vehicle roll rate of 190deg/sec is increased to match the roadbed speed and decreased for the 360 and 540 deg/sec. After the near side hit is completed, the roadbed speed controls the roll rate as shown in Figure9. This behavior is similar to all three roll rates simulated.

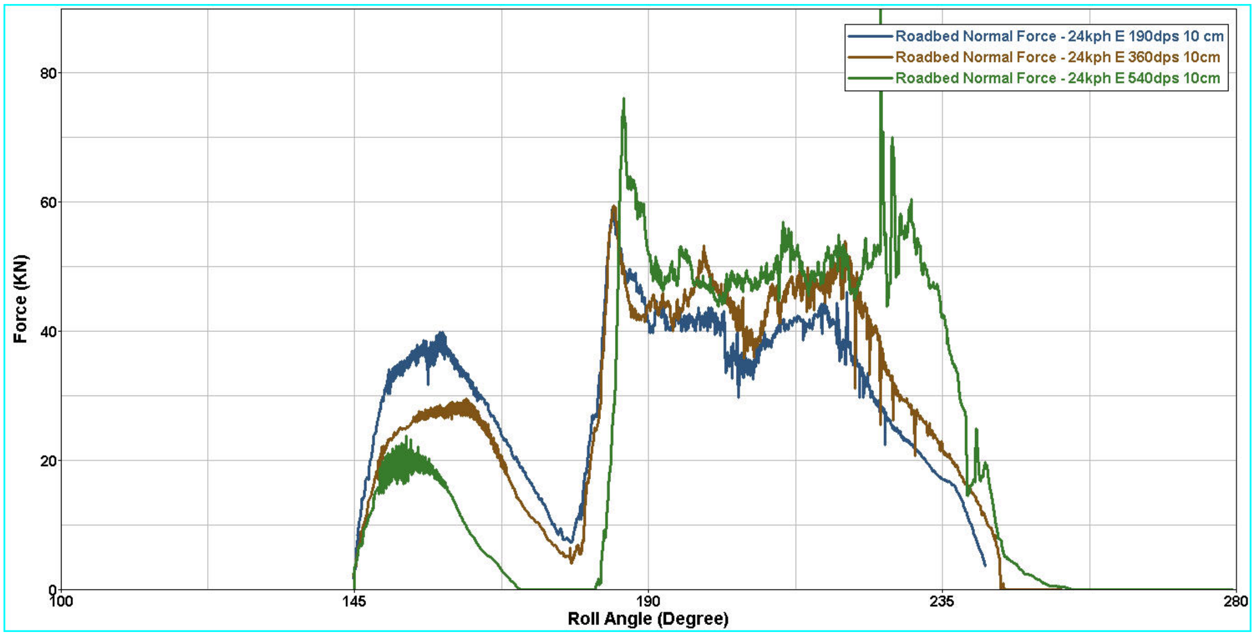


Figure8. Roadbed normal force Vs Roll Angle for different roll rate speeds

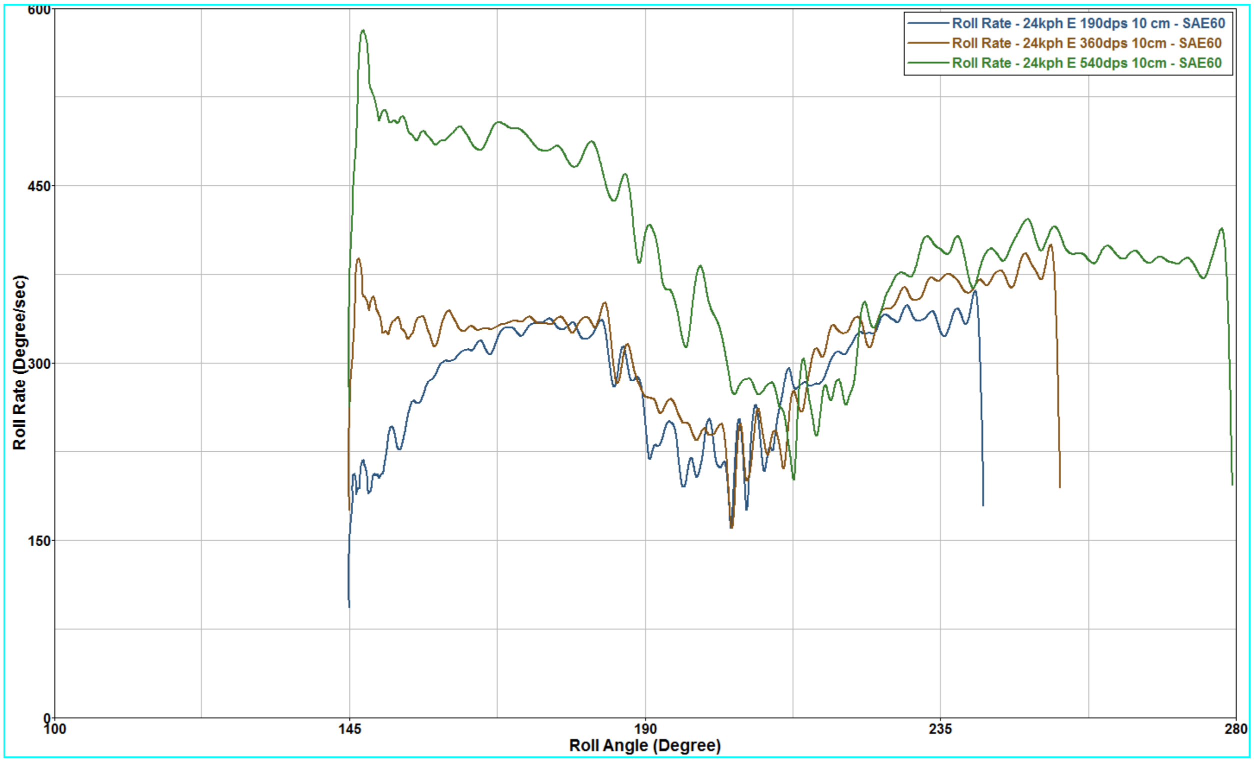


Figure9. Roll Rate Vs Roll Angle for different roll rate speeds (SAE 060 filtered)

The third set of parameters varied was the drop height. Heights of 10, 20, and 30cm were investigated. A summary is shown in Table4.

	Roadbed Speed	Roll Rate	Drop Height	Initial Roll Angle
	km/h	degree/sec	cm	degree
Baseline	24	190	10	145
	24	190	20	145
	24	190	30	145

Table4. Different drop height simulations

Roadbed normal forces for different drop heights are compared with respect to roll angle as shown in Figure10. As the drop height increases, the roadbed force measured at the near and far sides increases. This is attributed to the increase in potential energy that has to be managed by both sides of the roof.

Figure11 shows the roll rate versus the roll angle. The different curves lie on top of each other. Therefore, the drop heights show no effect on the roll rate.

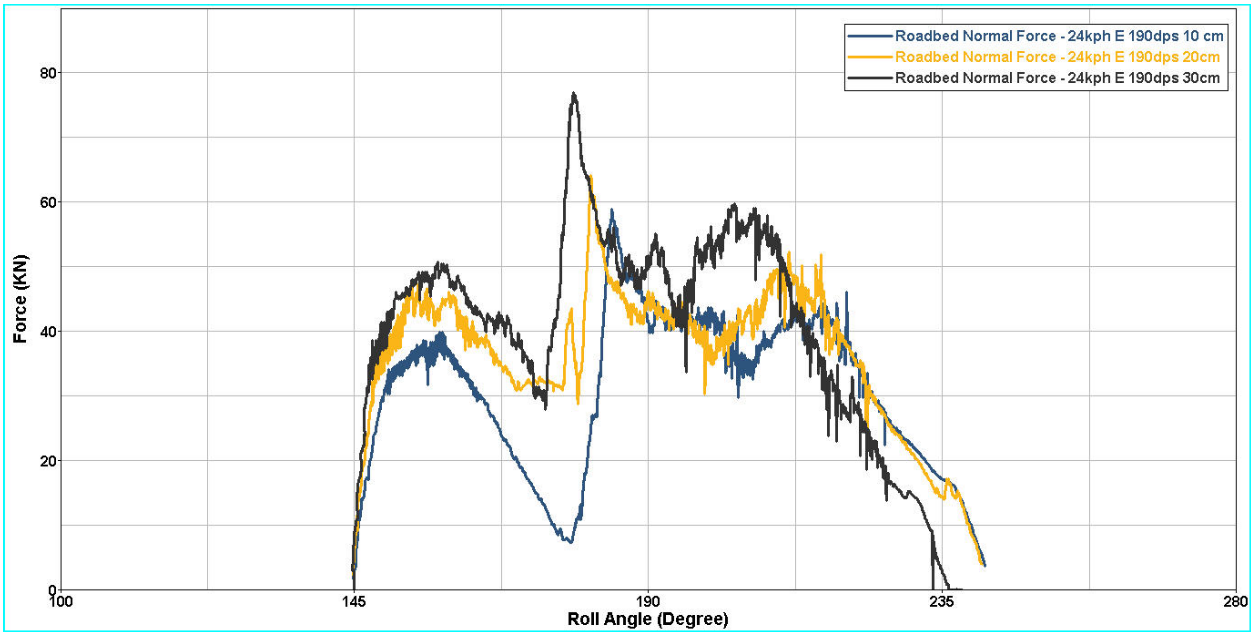


Figure10. Roadbed normal force Vs Roll Angle for different drop heights

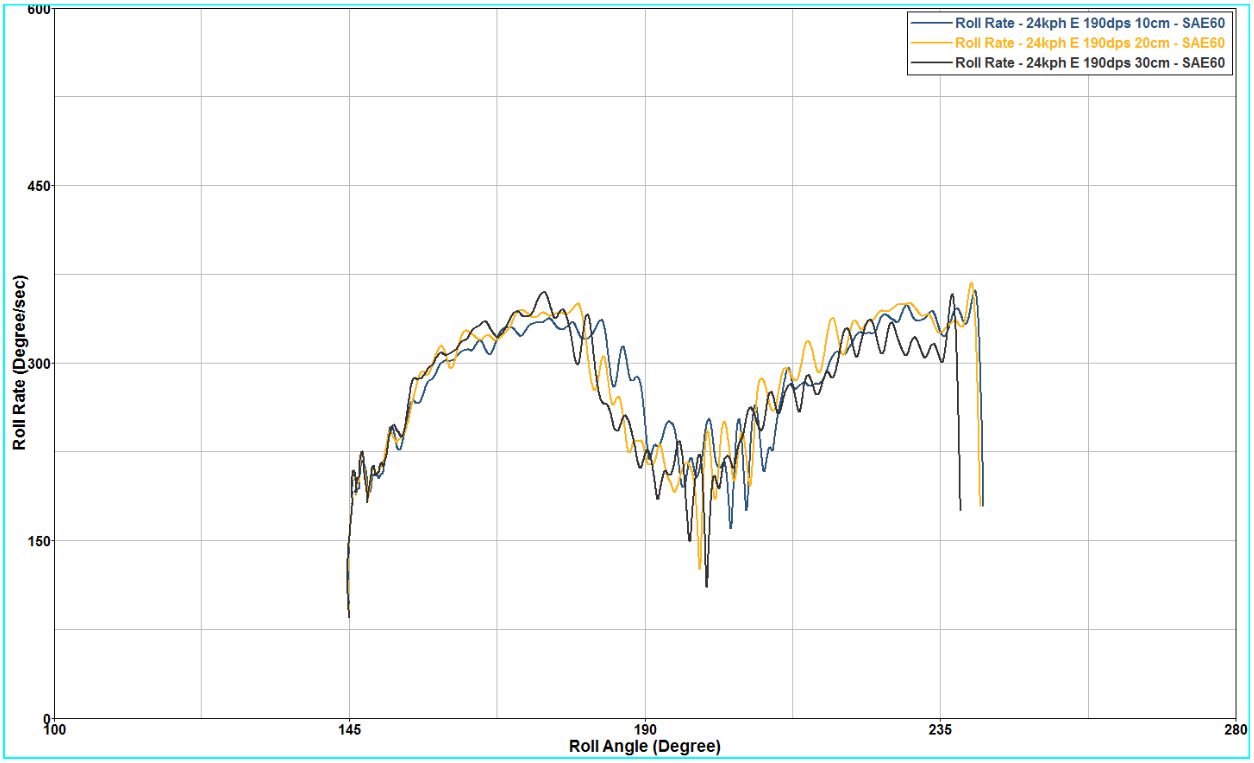


Figure11. Roll Rate Vs Roll Angle for different drop heights (SAE 060 filtered)

Summary

The focus of this study was to evaluate parameters sensitivity in the initial rollover conditions on the JRS. The parameters would affect the roof loadings and dynamics of the vehicle with a strong roof. An elastic roof structure was assumed. FE model were used to address this study. The FE model was validated and reduced in order to reasonably evaluate the sensitivity study. The simulation results showed that the roadbed speeds of 24kph is important for a 3 quarter turns rollover. The roadbed speed influences the roll rate after initial contact. The increase in roll rate resulted in a decrease roadbed normal force on the near side of the impact but an increase at the far side. The roadbed speed controls the roll rate after the near side impact is completed.

This study is limited by the assumption made. Further work is recommended to identify more variables that match the majority of the real rollover world accidents. In addition, other dynamic rollover parameters should be investigated like different roll angle, changing multi-parameters at the same time, as well as studying the effect of the JRS structure to the roof crush.

References

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