Selective Sensitivity Study of the Jordan Rollover System – Comparison with the Un-Constrained Model for Different Test Bed Mass and Yaw Angle

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This working paper summarizes recent efforts and findings derived from NCAC research. It is intended to solicit feedback on the approach, scenarios analyzed, findings, interpretations, and implications for practice reported by the research team. The statements contained herein do not necessarily reflect the views or policy of the FHWA. Please forward comments or questions to the authors noted above. These efforts will ultimately be documented and made available to advance research efforts related to this topic and guidance for practice.

ABSTRACT
In this paper, finite element analysis was used to compare the dynamic rollover performance of a mid-sized SUV with a strengthened roof in a Jordan Rollover System (JRS) test with an Un-Constrained (U-C) rollover under the same initial conditions. The JRS has the ability to closely control the initial conditions of a vehicle being subjected to a rollover test. This research was proposed to study the ability of the JRS to emulate the vehicle kinematics and roof crush resulting from an actual rollover. An additional sensitivity study for the test bed mass and yaw angle was performed.

The model was given initial conditions at impact similar to the JRS common values. These conditions were: roll angle of 145°; pitch angle of 5°; yaw angle of 10°; test bed speed of 24 km/h; vertical drop height of 10 cm; and roll velocity of 190°/s. The finite element model of a 2003 Ford Explorer was used in this study and was validated towards several full-scale tests. The roof was then strengthened to meet new federal roof regulations.

Computer simulations comparing a JRS test with an Un-Constrained rollover showed that during the pure roof crush phase, both models behave similarly. Afterwards, some variations occur but the differences are less than 5%. For different test bed mass, the only significant difference between the model results was the final test bed speed. Finally, increasing the yaw angle on a JRS test showed a decrease in the roll rate and intrusion characteristics of less than 5%.
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INTRODUCTION

Although rollover accidents account for only 2.4% of all vehicle crashes, 33% of passenger vehicle occupant fatalities were in this type of crash mode [1]. Therefore, the protection in a rollover is significant even if rollover is not the most frequent crash type. Much research has been involved in understanding rollover accidents and the resulting occupant injuries, although to date there is no dynamic rollover test method in use to evaluate rollover safety in government safety standards. However, promising dynamic rollover test devices are being evaluated in the U.S. [2] and Australia based on the Jordan Rollover System [3].

Federal Motor Vehicle Safety Standard (FMVSS) No. 216 specifies a quasi-static test procedure that measures the force required to push a metal platen into the roof at a constant rate [4]. It requires a reaction force equal to 1.5 times the weight of the vehicle to be reached within 127 mm (5 inches) of plate displacement. This is also called a strength-to-weight ratio (SWR) of 1.5. In 1991, the standard was extended to apply to light trucks and vans with gross vehicle weight ratings (GVWR) less than 2,722 kg (6,000 lbs) [5]. In May 2009, the rule was amended for vehicles of GVWR of 2,722kg (6,000 lbs) or less to double the SWR to reach 3.0 and limit displacement to the point where the roof would contact a seated occupant’s head. The rule also required that all vehicles must meet the specified force requirements on both sides when tested sequentially and maintained the roof crush limit of 127 mm [6]. The National Highway Traffic Safety Administration (NHTSA) is conducting research toward achieving a dynamic test standard that provides a sufficiently repeatable test environment [7].

The Insurance Institute of Highway Safety (IIHS) has adopted its own rollover crashworthiness rating. The IIHS set the boundary for a “good” rating in their program at an 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 requires an SWR of at least 2.5. IIHS rates anything lower than that as “poor.” This rating system is based on the institute research showing that occupants in rollover crashes benefit from stronger roofs [8].

FMVSS No. 216 contains a provision that excludes vehicles that conform to the rollover test requirements of FMVSS No. 208 by means that require no action by vehicle occupants. 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 [6].

NHTSA has concluded that the development of a dynamic rollover test is a priority and has initiated research toward achieving a dynamic test standard that provides a sufficiently repeatable test environment [2, 7].

NHTSA’s principal research contractor for developing a dynamic rollover test is the University of Virginia. A dynamic rollover test device as described by Kerrigan [9] has been installed and is now being operated by NHTSA’s research contractor. This rollover test device employs concepts that were patented in the Jordan Rollover System (JRS) [10]. Further studies that compare the response of a vehicle constrained by the test device with the response of an Un-Constrained vehicle are warranted.
The study in this paper is intended to assist the safety community in assessing the performance of the rollover test device that is of interest to NHTSA.

The Jordan Rollover System (JRS) is a versatile and repeatable rollover test system developed to evaluate the performance of the roof structure and occupant restraint system during rollover. The JRS mounts a vehicle on an axis that permits it to roll as it is dropped. The constraints with this mounting are in the longitudinal and lateral directions. As the vehicle is rotated, a roadway segment runs underneath so that the vehicle’s roof strikes the road as it would in an actual rollover. After both sides of the roof have struck the roadway, the vehicle is caught so that it will sustain no further damage. Subsequent rolls can be conducted by resetting and running the JRS test a second time [10]. The Center for Injury Research ran a series of three identical Subaru Foresters and reported that the variation is not more than 10 percent [11]. Other research that demonstrated repeatability of the JRS included physical tests [11] and computational simulations [12, 13, 14].

In this research, the finite element (FE) model of the JRS was developed. The JRS model constrains a vehicle during rollover in the same way as the JRS machine and provides the basis for a comparison with an Un-Constrained (U-C) rollover. The model addresses the influence of the machine constraints (tower pivots and test bed mass) on the dynamic roof deformation. Other parameters were not included in this study since they were already performed in previous papers using the U-C model setup [13, 14]. The comparison was performed using a model of a 2002 Explorer with a strengthened roof. Further comparisons were performed by varying the test bed mass and yaw angle.

The research approach and method section provides an overview of the FE vehicle model validation and the model setup. The results section includes the comparison between the JRS and the U-C models and the effects of the test bed mass and the yaw angle. A discussion about the findings concludes this research.

**RESEARCH APPROACH AND METHOD**

FE modeling was used for this work since it has proven to be indispensable in the development of component design and vehicle crashworthiness evaluations. This study utilized LS-DYNA commercial FE code to simulate roof strength for multiple loading conditions [15]. LS-DYNA version 971s R5 was used on a massive parallel processor (MPP) system. In order to carry the sensitivity study, a parameter was changed one at a time to address its effect on the rollover test outcome.

**Vehicle Model Validation**

The full vehicle FE model used in this study was developed at the National Crash Analysis Center (NCAC) under a co-operative agreement between the Federal Highway Administration, the 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 [16]. Additional validation work was performed to validate the FE model to the following tests: Canada Motor Vehicle Safety Standard (CMVSS) 212-301, side new car assessment program (SNCAP), and offset deformable barrier IIHS tests.

Additional component FE model validation was carried out using two FMVSS No. 216 quasi-static tests conducted by NHTSA with different roll and pitch angles. The first test (C0139) was conducted using the FMVSS No. 216 protocol platen angles of 5 degree pitch and 25 degree roll. The second test
(C0140) was conducted similarly to the roof crush protocol with different platen angles of 10 degree pitch and 45 degree roll. The aim of the second test was to investigate the change in roof crush resistance. The platen reaction force versus roof deformation from the NHTSA tests and the corresponding FE simulations are shown in Figure 1. The reaction force is presented as a percentage of the unloaded vehicle weight. The FE model shows good correlation for both tests. There has been no dynamic roof testing of the Explorer that would permit correlation of the FE model with dynamic test results.

**FIGURE 1** Force-Crush comparison tests C039 & C040 and FE simulations

**FE Model Setup**

The initial conditions selected were based on common values used for testing [10]. These values are: a roll angle of 145°; a pitch angle of 5°; a yaw angle of 10°; test bed speed of 24 km/h; a vertical drop height of 10 cm; and a roll velocity of 190°/s. Only the first roof-to-ground contact was simulated since the interest was on loading the near and far side structures of the roof. This study used a full vehicle model instead of a selected stripped vehicle as an actual JRS test or a reduced FE model that was studied by the author [13] and others in previous analyses [17, 18].

The JRS model is simplified in this research and is made of 2 supporting towers, a spit, a test bed, and a set of translational, revolute, and cylindrical joints. The spit consists of 2 arm links that are attached at one end to the vehicle rails and on the other end to a tubular axis that runs underneath the full vehicle model. Each tower has three joints in series to model the end constraints of the JRS test. A translational joint is mounted on the structure tower to allow the vertical motion of the system. A revolute joint is sandwiched between the translational joint and the cylindrical joint. The cylindrical joint is attached at the end of the spit. The revolute joints allow the vehicle to pitch while the cylindrical joints allow the vehicle to spin and slide. The joint mechanisms are made of rigid components to capture the physical mass and they are constrained by using the *CONSTRAINED_JOINT option in LS-DYNA with no friction allowed in the joints [15]. The system is shown in Figure 2. The spit and the joints weigh 66 kg.
The vehicle-spit assembly was positioned in order to have the roll, pitch and yaw angles as specified in the initial conditions. The initial rotational velocity of 190°/s was given to the assembly around an axis passing through the center of gravity (C.G.) of the vehicle. To maintain the initial contact conditions specified earlier, the drop height was addressed by giving the vehicle assembly a vertical velocity that corresponds to a 10 cm drop height based on a free fall motion. Equation 1 converts the potential energy into kinetic energy.

\[ V_Z = \sqrt{2 \times g \times h} = \sqrt{2 \times 9.81 \times 0.1} = 1.4 \text{ m/s} \]  

Equation 1

The test bed used in this study was made larger than the original JRS moving test bed in order to cover the full length of the vehicle. The 4.8 m long and 4.8 m wide test bed was made of a steel structure on the bottom and a 25.4 mm (1 in) thick wood surface on the top. The test bed had one axis of motion. It was given a translational initial velocity of 24 km/h (6.67 m/s; 15 mph) and no external mechanisms affected its motion during the roof-to-test bed contact.

The test bed is made of plywood. A dynamic coefficient of friction of 0.2 was used between the vehicle roof and the test bed. The static coefficient of friction listed in handbooks between steel and wood ranges from 0.2 to 0.6 [19]. The lower value was selected because the motion involves both rolling and sliding. In a separate study, the friction coefficient was varied between 0.2 and 0.8 and the variation did not produce marked difference in the vehicle’s response.

**Strengthened Roof**

In order to study the effect of a strengthened roof on the kinematic results under different impact configurations, all roof components were replaced by steel materials that were purely elastic in this paper. This included the A- B- C- and D-pillars, roof rails, roof cross members, and roof outer sheet metal. *MAT_ELASTIC in LS-DYNA was used with steel properties [15]. The material changes made the roof structure stronger than the original model and eliminated structural plastic deformation. The revised SWR of the new model was measured to be 3.25 times the vehicle’s unloaded weight. This strengthened roof meets the new federal roof regulation of 3.0 SWR.

**Un-Constrained Model**

The U-C model is based on the JRS model except it has no outside constraints contributing to the vehicle. The support towers were removed from the analysis. To maintain a similar mass comparison of the moving parts with the JRS model, the masses of the revolute and translational joints were added at
the end of the spit. This provided similar mass and inertial effects. The JRS and U-C models are compared side by side in Figure 3.

![FIGURE 3 JRS and Un-Constrained model comparison](image]

This representation was considered sufficient for the purpose of analyzing the near and far sides of the roof. The near side of the vehicle was set to be the passenger side and the far side was the driver side in this study. Finally, the simulation time of 400 ms was sufficient to cover the first roof-to-ground contact of the rollover.

RESULTS

The test bed normal force, roll rate, dynamic intrusion value, and speed are discussed in this section. All plots have the horizontal axis as a function of the roll angle (RA) in degrees since it gives a perspective of vehicle position. The plots are divided into 2 zones. The first has a pure roof crush zone while the second has a combined roof crush and hood contacting the test bed zone.

Jordan Rollover System - Un-Constrained Models Comparison

The test bed normal force is measured at the test bed for both models and compared in Figure 4. The loading pattern on the test bed is similar to actual JRS tests. The plots are shown from 140° to 240° RA. Both curves follow the same pattern until about 195° RA. Then a slight divergence is noticed. The U-C model tends to move freely while the JRS model has the tower constraints preventing it from yawing. At about 205° RA, the measured force spikes for both runs because the hood contacts the test bed.

Figure 5 shows the pitch angle comparison for both models. The difference in pitch angle starts to increase at 195° RA when the far side crush increases gradually. The value of this difference before the hood interacts with the test bed is 14% (1.14°). The roll rate follows a similar pattern until the hood interacts with the test bed; thereafter the roll rate for the U-C model slows down more than the JRS model. The roll rate curves are shown in Figure 6.
The intrusion characteristics are measured from the inside of the top A-pillar with respect to the C.G. of the vehicle. The dynamic intrusion is the total length change and the intrusion speed is the resultant speed of the roof deformation, both with respect to the C.G. These measurements are extracted for both near (passenger) and far (driver) sides and they are shown in Figure 7. The near side dynamic intrusion is shown in Figure 7(a) where the maximum difference in the peak values is less than 0.5%. The far side dynamic intrusion is shown in Figure 7(b) where the maximum difference in the peak values is 4.5%.
The additional intrusion of the vehicle roof in the JRS over the U-C model is caused by a timing delay of hood contact with the test bed. This delay causes the roof loading to continue until the vehicle starts to decelerate vertically as the hood and test bed come in contact. It is noticed that the maximum intrusion happens during the combined effect of roof crush and the hood contact with the test bed. The intrusion
speeds for both sides of the vehicle are shown in Figure 7(c) and 7(d). The maximum intrusion speed for
the near side crush happens close to impact at about 148° RA while the far side crush happens at 185° RA. The difference in maximum intrusion speed for both sides is less than 2%.

Test Bed Mass Effect

In the dynamic test machine it is desirable for simplicity to keep the moving roadway mass constant. However, the vehicles tested may have a wide range of weights. It is of interest to determine how differences between the vehicle mass and the roadway mass affect the rollover. Four different test bed masses were analyzed while keeping the other initial conditions the same. The test bed mass was assumed to be factor of the vehicle mass, and they were: one half, one, two, and four times the vehicle’s original mass. This assumption was made to identify the effect of test bed mass when testing the range from light small cars to heavy SUV’s. The road top surface was kept the same with 25.4 mm (1 in) thick wood and the structure mass was changed to meet the target values.

The test bed normal force comparison is shown in Figure 8. The curves during the near side crush are identical. During the far side crush, some minor differences occur at the beginning of the crush and more differences happen after 215° RA but it is considered within the corridor of errors. The roll rate comparison is shown in Figure 9. Similarly, minimum differences are noticed up to 180° RA but the roll rate values increase with the increase of the test bed mass after 180° RA. The increase in roll rate values is less than 7% (maximum is about 15 degree/sec) during the far side impact for 2 consecutive test bed mass models (i.e. half and one times, or 1 and 2 times or 2 and 4 times the vehicle mass).

![Test Bed Normal Force vs. Roll Angle](image)

FIGURE 8 Test bed normal force vs. roll angle (JRS with 4 different test bed masses)
FIGURE 9 Roll rate vs. roll angle (JRS with 4 different test bed masses)

The intrusion characteristics are shown in Figure 10. The near side dynamic intrusion is shown in Figure 10(a) where the maximum difference is less than 1%. The far side dynamic intrusion is shown in Figure 10(b) where the maximum difference is less than 3%. The intrusion speeds for both sides of the vehicle are shown in Figure 10(c) and 10(d). The maximum intrusion speed for the near side happens close to impact at 148° RA while for the far side it happens at 185° RA. The maximum difference in intrusion speed for the near side is less than 1% while for the far side it is less than 2%. There is a second peak for the 2 times test bed mass (4496 kg) that starts at 200° RA, which is caused by the localized vehicle test bed contact instability. This is shown by the noise measured at the test bed normal force in Figure 8. The other peaks that happen late during the rollover are caused by the roof rebound since the measured intrusion speed is a positive value because it is a resultant measurement. The maximum dynamic intrusion and intrusion speed differences are very minimal and can be ignored.

The deceleration of the test bed structure is shown in Table 1. For the test bed with half of the vehicle mass, the percentage speed decrease of the test bed structure is 30.1% while the others are 15.7%, 8.0%, and 4% for one times, 2 times, and 4 times vehicle mass, respectively. The differences in the final velocity are based on the amount of energy carried by each test bed mass with its initial speed. The heavier the test bed is, the smaller its deceleration is. This explains the roll rate variation in Figure 9 since the roll rate changes are based on the test bed speed.
Although the variation in roadway mass resulted in substantial changes in the final velocity of the roadway, the effects on the vehicle maximum dynamic intrusion and intrusion speed were minimal.

<table>
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<tr>
<th>Model</th>
<th>C.G. Initial Speed (m/s)</th>
<th>C.G. Final Speed (m/s)</th>
<th>Percentage Decrease (%)</th>
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<tbody>
<tr>
<td>Test bed 1124 kg</td>
<td>6.777</td>
<td>4.683</td>
<td>30.1%</td>
</tr>
<tr>
<td>Test bed 2248 kg</td>
<td>6.777</td>
<td>5.651</td>
<td>15.7%</td>
</tr>
<tr>
<td>Test bed 4496 kg</td>
<td>6.777</td>
<td>6.165</td>
<td>8.0%</td>
</tr>
<tr>
<td>Test bed 8992 kg</td>
<td>6.777</td>
<td>6.431</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

**Yaw Angle Effect**

Four different yaw angles were analyzed with an increment of 5° while maintaining the other initial conditions the same. The yaw angles performed in this study are: 5°, 10°, 15°, and 20°. The test bed normal force comparison is shown in Figure 11. The curves during the near side crush are identical until 172° RA. Then, some minor differences occur until 182° RA where the maximum force measured locally for the far side crush is less than 8%. At around 205° RA, the hood interaction with the test bed happens sooner for higher yaw angles. The roll rate comparison is shown in Figure 12. It is noticed that the higher the yaw angle is, the lower the roll rate value is. The decrease in roll rate values is less than 7.5% for 2 consecutive yaw angle models (i.e., 5° and 10°, or 10° and 15°, or 15° and 20° yaw angles).
The intrusion characteristics are shown in Figure 13. The near side dynamic intrusion is shown in Figure 13(a) where the maximum difference is less than 2%. The far side dynamic intrusion is shown in Figure 13(b) and the maximum difference is less than 3.5%. The intrusion speeds for both sides of the vehicle are shown in Figure 13(c) and 13(d). The maximum intrusion speed for the near side happens close to
impact at 148° RA while for the far side it happens between 182° and 186° RA. The maximum speed difference for the near side is less than 1.1% while for the far side it is less than 5%.

FIGURE 13 Dynamic intrusion characteristics vs. roll angle for near and far sides (JRS with 4 different yaw angles)

CONCLUSIONS
The Jordon Rollover System (JRS) comparison with an Un-Constrained (U-C) model is presented in this study using an Explorer finite element vehicle model that was tested with a standard set of initial conditions. Additional sensitivity studies of the JRS with different test bed mass and yaw angle were performed.

Based on the FE analysis performed using the JRS and the U-C models, the difference between the test bed normal forces were negligible up to a 195° roll angle. For the crush characteristics, the dynamic intrusion difference was less 4.5%, and the intrusion speed difference was less than 2%. Both models generally produced similar results. The constraint imposed by the JRS tends to limit the pitch angle motion after about 195 degrees of roll. A consequence of this constraint is a difference in the vehicle orientation at the time the hood contacts the roadway. The degree to which the hood contact orientation can influence other safety performance measurements requires further study.

For test bed mass variation between 0.5 to 4 times the vehicle mass, the test bed normal forces and the intrusion characteristics differences were less than 3%. The final test bed speed dropped by 29.1%, 15.4%, 7.9% and 4% for the test bed mass of half, one times, 2 times, and 4 times the vehicle mass, respectively. Based on the data reviewed in this study, the roll rate and intrusion speed were mainly the
two affected results. During the far side crush, the roll rate values increased by less than 7% with the increase of two consecutive test bed mass (i.e. half and one times, or 1 and 2 times or 2 and 4 times the vehicle mass).

For different yaw angles, there was no difference of the test bed normal force for the near side. For the far side, the hood contact with the test bed occurs earlier for a higher yaw angle. The timing of the load distribution between the crushed roof and the hood contact with the test bed affects the vehicle orientation. The intrusion characteristics values were less than 2% for the near side and less than 5% for the far side.

REFERENCES

