Investigation of Conditions for Repeatability/Reproducibility of Vehicle Rollover Crash Tests with Devices Based on the Jordan Rollover System

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Abstract

Vehicle rollovers are particularly dangerous crash modes being responsible for a considerable percentage of the entire vehicle occupant fatalities. Test devices based on the functional principles of the Jordan Rollover System (JRS) may help researchers in investigating what happens to occupants during vehicle rollovers. Repeatability and reproducibility of test outcomes are both paramount requirements for any future successful rollover crash test protocol. Apart from the initial testing conditions, test outcomes may be affected by some boundary conditions as well. Thus, a standardised rollover testing protocol should impose a strict control also on those boundary conditions that could influence the test outcomes.

This research aimed at identifying whether and to what extent some initial and boundary conditions may affect the repeatability and reproducibility of the test results. Such investigation, which was carried out using computer simulations of crash tests with the UNSW JRS, indicated that two conditions which can influence the test outcomes are the roadbed-to-vehicle friction and the initial offset of the roadbed bottom skids from the ground supports.

Introduction

Based on a statistical study on the three Australian states of News South Wales, Victoria and Northern Territory, vehicle rollovers were responsible for around 35 percent of all occupant fatalities that occurred in single-vehicle crashes during the period 2000-2007 (Fréchède, McIntosh, Grzebieta, & Bambach, 2011). Understanding the mechanisms that cause severe injuries during vehicle rollovers is essential to develop effective design countermeasures. A repeatable rollover crash test procedure would be ideal to allow researchers to investigate injury mechanisms during vehicle rollovers. Test devices based on the working principles of the Jordan Rollover System (JRS) (Friedman & Jordan, 2008) appear to be good candidates for conducting repeatable rollover crash tests (Chirwa, Stephenson, Batzer, & Grzebieta, 2010).

In general, the JRS testing principle aims to replicate real-world vehicle rollovers by dropping a vehicle that is spinning around its longitudinal axis onto an approaching sled, or roadbed, which moves at a pre-defined initial speed. The front and rear ends of the tested vehicle are hinged to two separate control arms, which are free to rotate independently and allow the vehicle to drop from an assigned initial height. Testing of a small passenger car (Toyota Yaris) with the University of New South Wales (UNSW) JRS (Grzebieta et al., 2013) is shown in Figure 1.

A recent investigation that was conducted through a subjective assessment of the experimental results indicated that a good level of repeatability was achieved from two rollover crash tests that were conducted using the University of Virginia (UVA) Dynamic Rollover Test System (DRoTS) (Seppi, Toczyski, Crandall & Kerrigan, 2106), which is a JRS-based testing device (Kerrigan et al., 2011). However, in previous research by Mongiardini et al. (2014), substantial differences in the measured roll rate and roadbed load were identified between two rollover crash tests with a small passenger car. These tests were conducted under the same nominal conditions but using different JRS-based devices, i.e., the UVA DRoTS and the UNSW JRS.
Apart from the testing Initial Conditions (IC’s), test outcomes may be affected by some Boundary Conditions (BC’s) as well. Thus, to achieve testing repeatability and reproducibility, it is important to identify also those BC’s that would determine the test outcomes and impose a rigorous control on those conditions in any future standardised rollover testing protocol. Thus, the objective of this research was to identify relevant IC’s/BC’s that would affect the repeatability and reproducibility of test results. The investigation was conducted using detailed computer simulations of full-scale rollover crash tests on a small passenger vehicle with the UNSW JRS.

**Methods**

The two rollover crash tests that were previously conducted using the UVA DRoTS and the UNSW JRS were used as baselines during the comparisons of the simulation results. Finite Element (FE) simulations of full-scale vehicle rollover crash tests with the UNSW JRS were carried out to analyse whether and to what extent the test outcomes would be affected when varying selected testing IC’s/BC’s. Initially, two simulations were performed to demonstrate that the minor differences between the IC’s of the two baseline experimental tests cannot justify all the dissimilarities in the test outcomes. These two simulations were conducted at the same IC’s that were recorded for the corresponding baseline tests. Subsequently, a preliminary parametric study was conducted for the following two IC’s/BC’s of interest: (a) roadbed-vehicle friction and (b) initial roadbed offset from the ground supports. A summary of the IC’s/BC’s for each of the simulated scenarios is shown in Table 1.

Simulations were performed using LS-DYNA, a non-linear explicit FE solver that is highly suitable for simulating crash events (LSTC, 2015). A validated FE model of the UNSW JRS coupled with a detailed vehicle model of a 2010 Toyota Yaris was used as a basis for all the simulations (Mongiardini, Grzebieta, Mattos, & Bambach, 2016). The FE model is shown in Figure 2.
Table 1: Matrix of simulated scenarios to investigate relevant IC’s/BC’s

<table>
<thead>
<tr>
<th>Configuration Name</th>
<th>IC’s Values</th>
<th>BC’s Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll Angle (deg)</td>
<td>Pitch Angle (deg)</td>
</tr>
<tr>
<td>IC_JRS_B13037</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>IC_UVA_1519</td>
<td>181.0</td>
<td>-12.9</td>
</tr>
<tr>
<td>Offset_10mm</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Offset_7.5mm</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Offset_5mm</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Offset_2.5mm</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Offset_0mm</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Low_Fric</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Mid_Fric</td>
<td>-179.3</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* Static Friction / Dynamic Friction
§ Equivalent Drop Height Based on Vehicle Speed

Results

Role of the different IC’s between the tests

Two scenarios with IC’s from either the two experimental tests with the UNSW JRS and the UVA DRoTS were simulated, as summarised in the section JRS/DRoTS in Table 1. In the simulated scenario IC_UVA_1519, the testing IC’s from the UVA test were imposed to the FE model with the UNSW JRS. When imposing those IC’s, the simulation did not indicate any significantly better correlation towards the results of the test with the UVA DRoTs. The graphs of the simulated vertical roadbed load and the simulated vehicle roll rate/roll angle are shown in Figures 3 and 4, respectively. The simulated curves for the modelled scenario with the IC’s of the test with the UVA DRoTS were practically similar to the curves for the simulated scenario with the IC’s of the test with the UNSW JRS. In other words, independently from the different IC’s, both simulated scenarios were in significant disagreement with the corresponding curves from the actual experimental test with the UVA DRoTS. This indicated that the different IC’s between the tests with the UNSW JRS and the UVA DRoTS were not the main reason for the different test outcomes. Therefore, the observed different outcomes for the two tests were likely caused by differences in either some of the BC’s or some of the IC’s other than those normally controlled or imposed in the...
test setup. The most likely IC and BC that may justify the observed different test outcomes were then identified to be the initial offset of the roadbed from the ground supports and the vehicle-roadbed friction, respectively.

Figure 3: Simulated roadbed load – simulations at same IC’s of each of the two tests (compared to experimental results).

Figure 4: Simulated vehicle roll rate and rotation – simulations at same IC’s of each of the two tests (compared to experimental results).

Sensitivity analysis on selected IC’s/BC’s

A preliminary parametric study was then conducted to investigate the potential role of the following two IC’s/BC’s of interest on the test outcomes: (a) initial roadbed offset from the ground support and (b) roadbed-vehicle friction.

Initial roadbed offset from ground supports

In previous research related to the development of the FE model of the UNSW JRS, the initial offset of the roadbed from the ground supports was found to have a considerable role on the impact force measured by the load cells that are embedded in the roadbed (Mongiardini et al., 2016). Simulations showed that a larger initial offset between the roadbed and the ground supports can cause a higher peak load as well as a longer fluctuation of the impact force measured by the roadbed load cells. Both these effects are a consequence of the roadbed bottoming out on the ground supports, which ultimately causes the roadbed upper wood surface to apply an inertial force onto the load cells that are located immediately underneath. A smaller roadbed-support offset would likely reduce such
inertial load, thus reducing the initial spike of the measured roadbed impact force. To further assess the influence of the roadbed-support initial offset on the force measured by the load cells, a series of simulations were then performed as part of this research by varying such offset between 10 mm and 0 mm, as summarised in the section Roadbed Offset in Table 1.

The simulated roadbed load from each investigated scenario as well as the experimental load that was measured during the tests with the UNSW JRS and the UVA DRoTS are shown in Figure 5. The corresponding peak loads are summarised in Table 2. Simulations confirmed that a reduction of the roadbed-support initial offset in the test with the UNSW JRS would have likely contributed to create a roadbed load much more similar to that measured in the test with the UVA DRoTS. In fact, a reduced initial offset between the roadbed and the ground rollers seems to contribute to reducing the first peak load, especially for offset values equal or less than 5 mm. Another general trend that was noticed is that the smaller the roadbed initial offset from the ground supports, the earlier the first peak load occurs. Such phase shift of the first peak load can be justified by an earlier bottom out of the roadbed in the case of a smaller offset.

![Decreasing peak load for smaller roadbed offsets](image)

**Figure 5: Simulated roadbed load varying the roadbed initial offset from ground support (compared to experimental results).**

**Table 2: Simulated peak loads varying the initial roadbed offset from the ground supports**

<table>
<thead>
<tr>
<th>Roadbed Offset</th>
<th>1st Peak Value (kN)</th>
<th>1st Peak Time (ms)</th>
<th>Difference to UVA Test</th>
<th>2nd Peak Value (kN)</th>
<th>2nd Peak Time (ms)</th>
<th>Difference to UVA Test</th>
<th>3rd Peak Value (kN)</th>
<th>3rd Peak Time (ms)</th>
<th>Difference to UVA Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>101.5</td>
<td>34.0</td>
<td>[45]</td>
<td>109.9</td>
<td>16.3</td>
<td>[54]</td>
<td>87.9</td>
<td>19.3</td>
<td>[67]</td>
</tr>
<tr>
<td>7.5 mm</td>
<td>86.5</td>
<td>19.0</td>
<td>[40]</td>
<td>102.0</td>
<td>8.4</td>
<td>[51]</td>
<td>81.0</td>
<td>12.4</td>
<td>[61]</td>
</tr>
<tr>
<td>5 mm</td>
<td>74.8</td>
<td>7.2</td>
<td>[35]</td>
<td>77.3</td>
<td>-16.4</td>
<td>[46]</td>
<td>88.4</td>
<td>19.8</td>
<td>[65]</td>
</tr>
<tr>
<td>2.5 mm</td>
<td>51.6</td>
<td>-16.0</td>
<td>[31]</td>
<td>57.1</td>
<td>-36.5</td>
<td>[49]</td>
<td>73.4</td>
<td>4.8</td>
<td>[67]</td>
</tr>
<tr>
<td>0 mm</td>
<td>40.7</td>
<td>-26.8</td>
<td>[32]</td>
<td>63.3</td>
<td>-30.3</td>
<td>[47]</td>
<td>71.3</td>
<td>2.7</td>
<td>[79]</td>
</tr>
</tbody>
</table>

*Values in square brackets indicate the peak time.
Further, for offset values smaller than 5 mm, the simulated roadbed load becomes more constant throughout the impact, which is another behaviour similar to what observed in the experimental test with the UVA DRoTS. This plateau of the simulated load curve is particularly evident for initial roadbed offsets from the ground supports equal to 0 mm and 2.5 mm.

In general, an initial offset between 2 mm and 4 mm seems to provide a marginally better match between the simulated roadbed load and the load measured during the test with the UVA DRoTS. However, it should be noted that the load simulated with a roadbed initial offset within the mentioned range appears to be lower than the load that was measured during the experimental test with the UVA DRoTS.

**Roadbed-vehicle friction**

The FE model of the UNSW JRS was used to simulate the rollover tests for scenarios with either a low or a medium level of friction between the roadbed and the vehicle, as summarised in the section *Roadbed Friction* in Table 1. A comparison of the simulated vehicle roll rate and roll rotations for these two investigated scenarios is provided in Figure 6.

![Figure 6: Simulated vehicle roll rate and rotation – scenarios with low and medium roadbed friction (compared to experimental results).](image)

Simulations showed how an increased level of roadbed-vehicle friction would cause a roll rate and a corresponding rotation very similar to those that occurred in the test with the UVA DRoTS; whereas, at low level of roadbed-vehicle friction, the simulated vehicle roll rate and rotations matched well the experimental curves from the test that was conducted with the UNSW JRS.

Further, simulations confirmed the effect of the roadbed-vehicle friction on the vehicle stability during the test, as summarised in Figure 7. The vehicle clearly showed a tendency to bounce off the roadbed in the case of a higher roadbed-vehicle friction in a way very similar to what occurred in the test with the UVA DRoTS. On the other hand, in the case of a low roadbed-vehicle friction, a relative roadbed-vehicle sliding kept the vehicle in contact with the roadbed until the roadbed moved completely downstream, which is exactly what happened in the test with the UNSW JRS.
Conclusions

The objective of this study was to identify relevant IC’s/BC’s that could affect the repeatability and reproducibility of rollover crash tests conducted using JRS-based devices. Detailed FE models of the UNSW JRS and a small passenger car were used to simulate how test outcomes would change when varying selected IC’s/BC’s. The results from the simulated scenarios were then compared against each other as well as against the outcomes from two experimental tests that were conducted under the same nominal conditions using similar JRS-based devices.

Initially, simulations confirmed that the slightly different IC’s between the tests with the UNSW JRS and the UVA DRoTS cannot explain alone the identified differences in the test outcomes in terms of both vehicle kinematics and roadbed load. Further, simulations indicated that IC’s/BC’s such as the initial roadbed offset from the ground and the roadbed-vehicle friction can significantly affect test outcomes. An initial roadbed offset from the ground supports may add a significant inertial component to the load measured by the roadbed load cells; whereas the roadbed-vehicle friction can considerably affect the vehicle roll rate. To improve repeatability and reproducibility of test results, it is then suggested that standard values should be considered for these IC’s/BC’s in any future rollover crash test protocol for JRS-based devices. Also, it is proposed that a baseline test would be used for calibrating JRS-based devices. A baseline test would facilitate the process of assessing whether a testing device would be able to reproduce results that are comparable to other similar devices. Obviously, the protocol for such baseline calibration test should impose specific values as well as corresponding uncertainty ranges for both the roadbed-vehicle friction and for the initial clearance between the roadbed and the ground supports. The IC’s/BC’s of the rollover crash test initially conducted by UVA using the DRoTS would be reasonable for a baseline test that aims to calibrate rollover test devices with a small passenger car.

The conclusions found throughout this research are purely based on results obtained using computer simulations. Despite the accuracy of the simulations have been proven through a previous accurate validation of the model, a final confirmation of the main findings from this research should be obtained by means of one or more targeted experimental tests in the future. Also, all the simulated scenarios in this research considered the specific UNSW-JRS configuration, with both control arms that hold the vehicle during the test working under tension. However, the UVA DRoTS has
opposite control arms, with the arm that is connected to the front of the of the vehicle working under compression and the other arm working under tension. Further investigation should be carried out to assess any potential influence that such different configuration of the front control arm may have. Finally, the findings that have been described in this paper should be considered as a part of a preliminary investigation. Future investigation should be carried on to identify any other IC’s/BC’s that may play a relevant role in determining the outcomes of rollover crash tests conducted using JRS-based devices. Examples of IC’s/BC’s that should be investigated include the initial pitch angle at impact or an undesired offset of the vehicle roll axis.

References


