Comparing vehicle rollover crash test rigs: JRS vs. DRoTS

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Abstract - To date, there is no standard vehicle rollover crashworthiness test procedure accepted by any regulatory authority that is capable of providing repeatable results in a similar manner to frontal and side impact crash tests. It appears that rigs based on the principles of the Jordan Rollover System (JRS) may be capable of replicating in a repeatable manner both the vehicle kinematics and the roof deformation for typical rollover scenarios. However, the capability of such rigs to provide consistent results in repeated tests conducted within different facilities, i.e., reproducibility, has not yet been proven. This research paper investigates the reproducibility of testing conducted with a second evolved version of the JRS, namely the UNSW JRS, which was developed for the University of New South Wales in co-operation with US researchers. Also, the paper describes the test setup requirements along with some difficulties that were experienced during the test rig's calibration. Reproducibility of testing with the UNSW JRS was assessed by replicating a baseline test previously performed at the University of Virginia using the Dynamic Rollover Test System (DRoTS), which is a rig with the same functionality as the UNSW JRS. The test with the UNSW JRS rig was performed under the same initial conditions and with the same type/model of vehicle used in the baseline test. Promising results were obtained from the comparison of the two tests independently carried out with the UNSW JRS rig and the UVA DRoTS rigs. The rigs have demonstrated to be potentially capable of performing reproducible rollover crash tests. This finding is a step toward a potential adoption of such rigs into a reliable dynamic rollover testing protocol for assessing vehicle crashworthiness.

Keywords: Passenger Vehicles, Vehicle Rollovers, Jordan Rollover System, Dynamic Testing, Crashworthiness.

INTRODUCTION

To date, there is no standard rollover crashworthiness test procedure accepted by any regulatory authority that is capable of providing repeatable test results in a similar manner to frontal and side impact crash tests. The adoption of a reliable and repeatable rollover crash test protocol would permit researchers, regulators, and manufacturers to explore and understand how serious occupant injuries typically occur during real-world vehicle rollover crashes. Further, if such a rollover testing protocol is shown to be effective for vehicle design purposes, it could also be implemented into consumer-rating programs to assess the performance of devices that may prevent or mitigate injuries during a rollover, such as on-board retention and airbag systems. A review of various rollover crashworthiness tests and dynamic test rigs conducted by Chirwa *et al.* indicated rigs based on the principle of the Jordan Rollover System (JRS) as the best candidate to date [1]. The original JRS test rig was designed by the Center for Injury Research (CfIR) [2] as a tool used by forensic engineers to evaluate the potential for occupant injury due to ejection and roof crush as well as the effectiveness of side curtain airbags and seatbelts during rollovers [3].

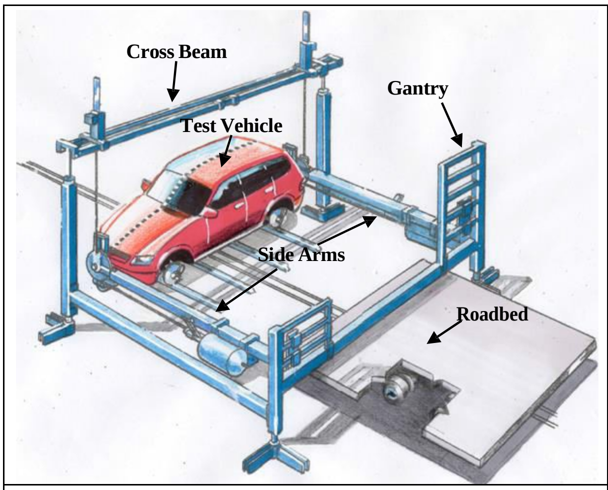
Apart from being capable of replicating the dynamic loads, kinematics, and deformation that a vehicle is subject to during a real-world rollover event, a paramount characteristic for a successful dynamic rollover test rig is the capability of providing consistent results in repeated tests conducted within either the same laboratory or in different facilities. So far, there appear to be two potential candidate test rigs that may be capable of repeatable rollover testing, namely the University of New South Wales's (UNSW) JRS rig located at the Crashlab facility in Sydney, Australia [4], and the Dynamic Rollover Test System (DRoTS) located at the University of Virginia (UVA) [5]. Both rigs are based on the same functional principles of the original version of the JRS test rig. During the rollover test, the rig initially supports the vehicle in an elevated position through hinged connections at both the vehicle front and rear ends. The vehicle is then given an initial rotational velocity along its longitudinal axis and then dropped onto a moving roadbed passing underneath it. After the vehicle drops off the upstream edge of the moving roadbed, it is captured and held by the rig supports to prevent any additional roof damage that may be caused by a second impact against the laboratory floor.

The rollover crash test principles on which the JRS is based have already proven to be capable of providing repeatable results for tests performed with the same rig and in the same facility [3,6,7,8]. However, the capability of rigs based on the JRS functionality to provide consistent results in repeated tests conducted within different facilities, i.e. reproducibility, has not yet been proven. This research paper investigates the reproducibility of testing conducted with the UNSW JRS, which is a rig developed in a joint effort between researchers at UNSW and various institutions in the USA [4,9]. This rig will be referred to as the UNSW JRS in the remainder of the paper. Also, the paper describes a difficulty that was initially experienced during the preliminary capability assessments and acceptance procedures of the test rig as well as the solution adopted to overcome this initial issue.

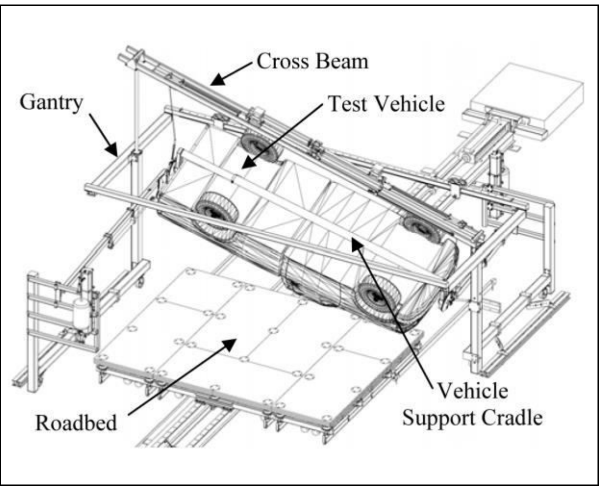
To assess testing reproducibility, a rollover baseline crash test previously carried out by UVA researchers on a Toyota Yaris using the DRoTS rig [7,8] was replicated using the UNSW JRS rig under the same test initial conditions and with the same type of vehicle [10]. Since the designs and functionality of both UNSW JRS and UVA DRoTS rigs are essentially based on the same principles, tests performed using one rig should nominally be reproduced with the other rig within acceptable experimental test tolerances. Hence, testing reproducibility could be assessed by comparing the results between these two tests.

UNSW JRS AND UVA DROTS RIGS

Both the UNSW JRS and UVA DRoTS rigs are based on the same functional principles previously described in the Introduction. With respect to the original JRS design, in both rigs the vehicle roll motion and the roadbed translation are independently driven. An overview of each rig is provided in the schematics of Figure 1. The vehicle yaw angle, which is kept constant throughout the entire test, is obtained by rotating the gantry with respect to the roadbed direction of motion. To guarantee free vehicle pitch motion during the test, in both rigs the vehicle's front and rear ends are attached to independent control arms. The main difference between the two rigs, which were designed and built independently, is that in the DRoTS one side-control arm is subject to compression while the other is under tension, whereas both side arms are under tension in the UNSW JRS. Both test rigs use the same type of sensors and data are analysed with similar post-processing methods. For both rigs, the test protocol requires all the sensor data to be digitally filtered using the procedure suggested in the Society of Automotive Engineers (SAE) J211 standard [11]. For data measured by the gyroscope mounted on the test vehicle a Channel Filter Class (CFC) 180 was used, whereas measurements from all the other sensors were filtered using a CFC 60.



UNSW JRS



UVA DRoTS [5]

Figure 1. Schematics of UNSW JRS and UVA DRoTS Rigs.

REPLICATION OF UVA TEST USING THE UNSW JRS

The rollover crash test performed at Sydney's Crashlab [12] with the UNSW JRS (Test B13037) used the same vehicle make, model, and year of the baseline test previously performed at UVA with the DRoTS rig (Test 1519), i.e., a 2010 four-door Toyota Yaris [7,8]. The target initial impact conditions for the UNSW JRS test matched the actual initial impact conditions measured at the beginning of UVA's baseline Test 1519.

In both tests with the UNSW JRS and the UVA DRoTS, the driver position was on the far side of the vehicle during the rollover. The only difference between the two tests was in the vehicle driver configuration: right-seated driver for the vehicle tested using the UNSW JRS and left-seated driver for the vehicle tested using the UVA DRoTS. The actual initial impact conditions for UNSW's Test B13037 and UVA's Test 1519 were very similar, as summarised in Table 1. Note that, in order to account for the opposite driver position, the vehicle tested in UNSW's Test B13037 was given a roll motion in the opposite direction with respect to UVA's Test 1519. For the same reason, also the roadbed direction of motion was opposite in the two tests.

Table 1. Actual Initial Impact Test Conditions - UNSW Test B13037 and UVA Test 1519

		UNSW Test B13037	UVA Test 1519
Angles	Roll (deg)	-179.3	181.0
	Pitch (deg)	-11.5	-12.9
	Yaw (deg)	90.0	90.0
Velocities	Roll Rate (deg/sec)	-263.7	268.0
	Pitch Rate (deg/sec)	-4.9	-5.2
	Vertical Velocity (m/s)	2.12	2.11
	[Equivalent Drop Height (mm)]	[228.8]	[227.7]
	Roadbed Velocity (km/h)	29.6	30.2
Mass	Test Vehicle(*) (kg)	1,200.0	1,173.9
	Roadbed (kg)	1,865	1,789

(*) Vehicle mass includes: (a) instrumentation, (b) cradle, and (c) cantilevered load of JRS arms

Vehicle-cradle attachment and initial failure

The test vehicle was attached to the UNSW JRS through a rigid cradle structure, which was welded to the front and rear ends of the test vehicle, as shown in Figure 2. The front and rear ends of the cradle were connected to the pulley located at the free extremity of the corresponding control arm of the UNSW JRS rig.

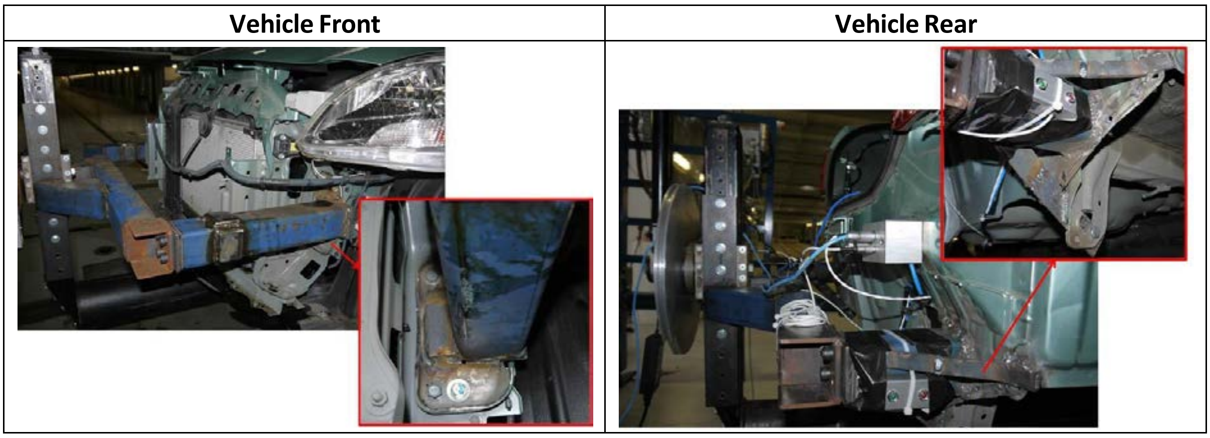


Figure 2. Cradle Attachment to Vehicle in UNSW JRS Test B13037.

Synchronisation between the vehicle roll and drop motions and the translation of the approaching roadbed sled is established through calibration runs prior to the actual crash test. Through this calibration, it is possible to precisely set the values of the vehicle roll angle and roll rate at which the initial impact has to occur. Note that, in order to prevent an impact during the calibration runs, the dropping vehicle is caught at about 200 mm above the roadbed level. A partial failure of the vehicle-cradle connection occurred during the initial calibration test.

Initially, the front extremity of the cradle was welded to the two vehicle sacrificial beam elements that normally support the front bumper, which are designed to collapse in a controlled manner during a frontal impact for optimising the energy absorption. As a consequence of this intrinsic weakness, the vehicle sacrificial beams collapsed during the initial calibration run conducted before the actual rollover test. These beam elements bent under the load impulsively applied to the cradle when the free-falling vehicle was caught to prevent the vehicle from impacting the roadbed. The failure of the initial design of the cradle-to-vehicle connection during the calibration run is shown in Figure 3. Although during the actual crash test the vehicle is caught by the two JRS suspensions only at the end of the impact, such a weak cradle-to-vehicle connection could have still partially failed during the test. Such a failure could have potentially affected the free roll motion of the vehicle. Thus, in order to prevent this type of failure during the actual rollover test, it was decided to extend the steel tubes of the cradle connection so that they could be welded directly to the stronger vehicle front rails. With this modified vehicle-cradle connection, the UNSW JRS was capable of performing the test under the replicated UVA initial conditions.

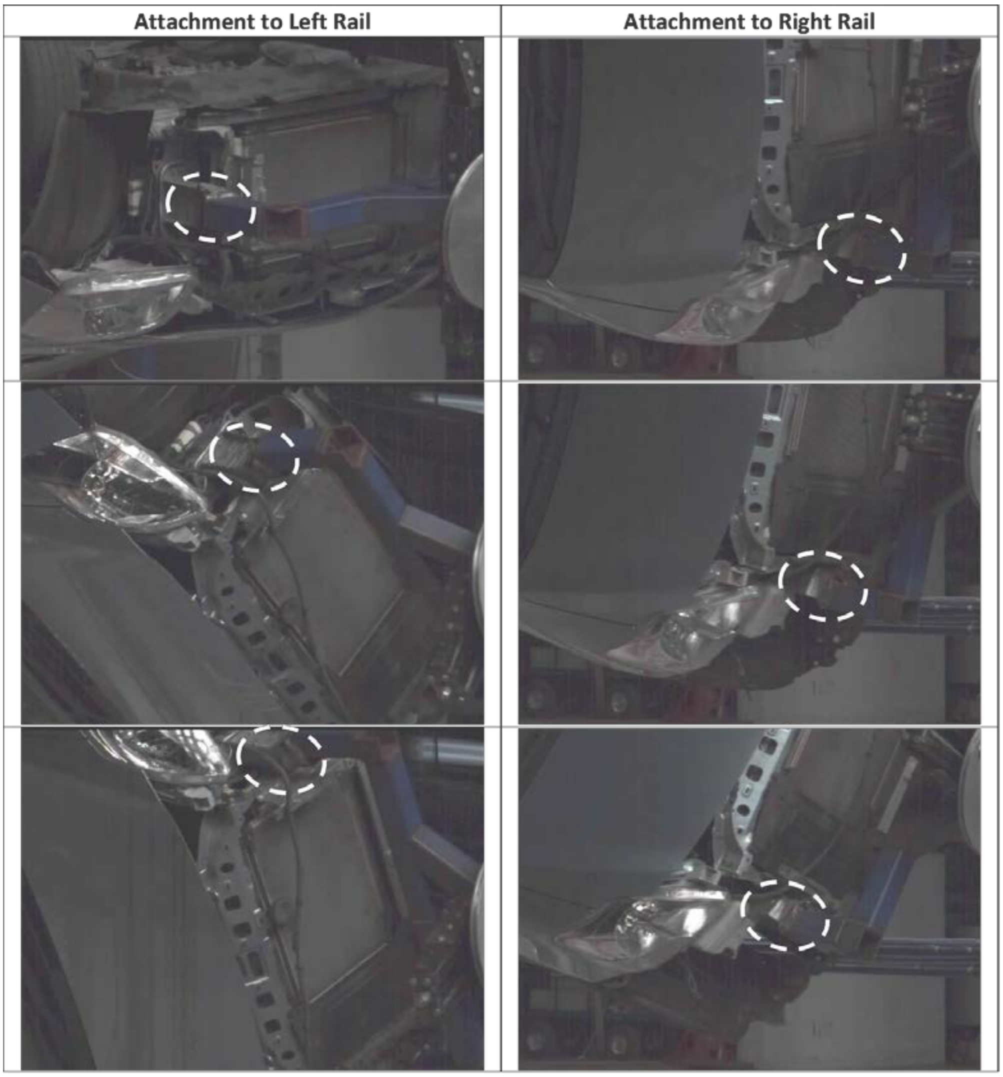


Figure 3. Failure of Initial Cradle-to-Vehicle Front Connection in UNSW JRS Test B13037.

The following sections provide a comparison between the results of the two rollover crash tests performed using the UNSW JRS and the UVA DRoTS rigs, respectively. To assess the reproducibility of these two rollover dynamic tests, their results were compared in terms of: (a) roadbed impact load, (b) vehicle kinematics, and (c) vehicle permanent deformation.

Roadbed load

Figure 4 compares the plots of the total vertical force as measured by the roadbed load cells during the rollover tests performed using the UNSW JRS and the UVA DRoTS rigs, respectively. A higher peak roadbed force equal to 122.4 kN was measured in UNSW's Test B13037 compared to a peak load of 94.4 kN in UVA's Test 1519. However, the comparison of the load impulses shown in Figure 5 clearly indicates that, overall, a slightly higher roadbed average vertical load occurred in the test with UVA DRoTS rig throughout the entire duration of the two crash tests.

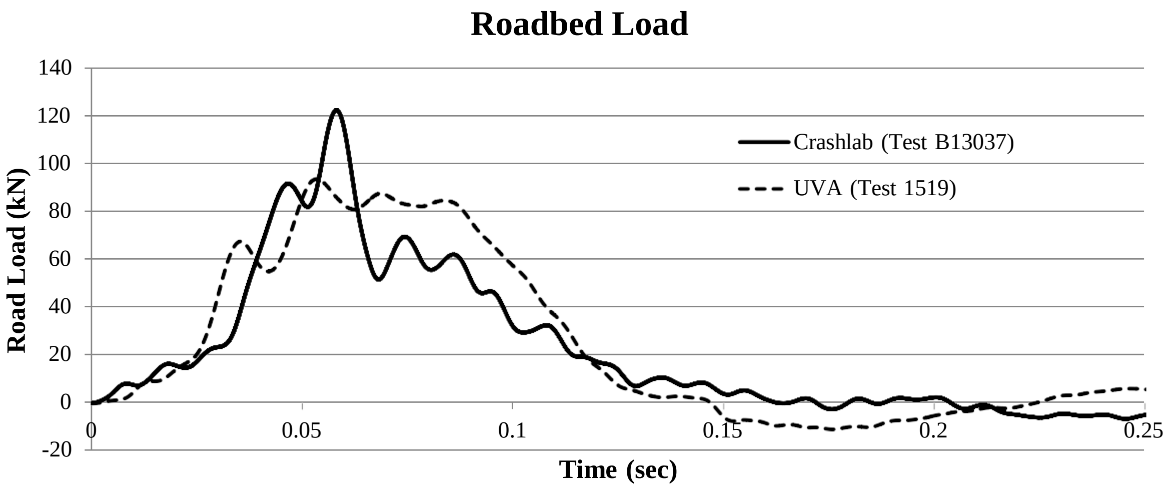


Figure 4. Roadbed Vertical Force – UNSW Test B13037 vs. UVA Test 1519.

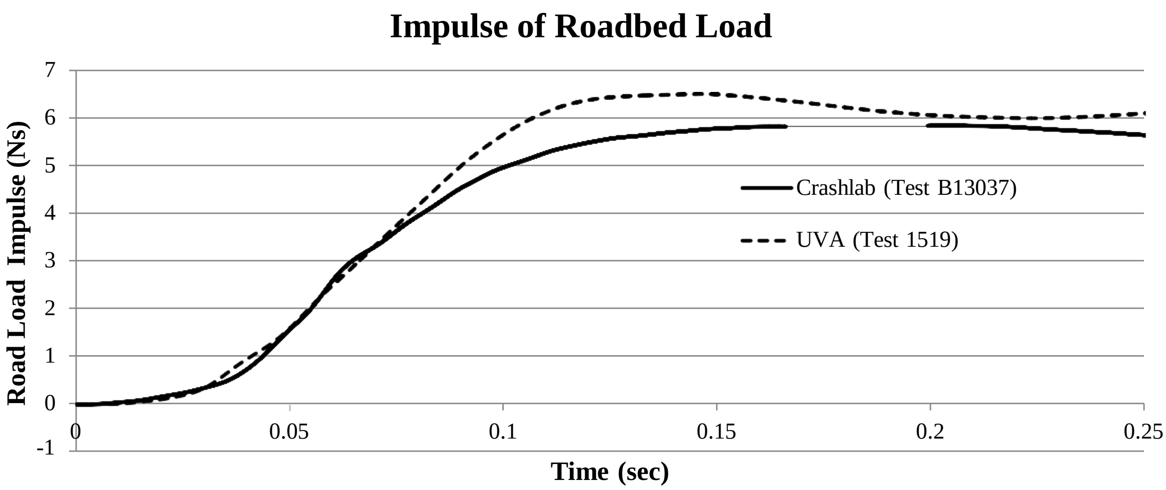


Figure 5. Impulse of the Roadbed Vertical Force – UNSW Test B13037 vs. UVA Test 1519.

Vehicle kinematics and dynamic deformation

A visual comparison of the vehicle kinematics and dynamic deformation during UNSW's Test B13037 and UVA's Test 1519 is shown in the sequential frames of Figure 6. Overall, a similar vehicle dynamic deformation occurred during the tests with the UNSW JRS and UVA DRoTS rigs. However, some differences between the two tests can be noticed in terms of the vehicle kinematics.

Vehicle kinematics

The main noticeable difference in the vehicle kinematics was that the vehicle bounced up at the end of UVA's Test 1519whereas considerable relative sliding between the vehicle and the roadbed occurred in the last phase of Test B13037 with the UNSW JRS rig. Such relative sliding between the vehicle and the roadbed in UNSW's Test B13037 was likely caused by a lower surface friction of the roadbed used with the UNSW JRS compared to the friction of the UVA DRoTS's roadbed.

Further, the vehicle roll rate consistently decreased in the test with the UNSW JRS rig, whereas the vehicle roll motion accelerated during the first phase of the test with the UVA DRoTS rig, as clearly shown in the comparison in Figure 7. For both tests, the vehicle roll rate was measured using a gyroscopic sensor mounted close to the vehicle's centre of gravity. Consequently, the vehicle roll angle in UNSW's Test B13037 resulted to be consistently smaller than in UVA's Test 1519, as shown in Figure 8. Also in this instance, a higher friction of the roadbed surface may explain the vehicle roll acceleration (i.e., increase of the roll rate) that occurred during the test with UVA DRoTS rig. Since at the beginning of the impact the roadbed was purposely assigned a travelling speed higher than the vehicle peripheral speed, it continuously transferred part of its momentum to the vehicle throughout the first part of the test with the UVA DRoTS rig. During the first half of the test with the UVA DRoTS rig, the energy transferred to the vehicle was greater than the energy dissipated through the crushing of the vehicle roof, thus resulting in a rotational acceleration of the test vehicle. On the other hand, during the test with the UNSW JRS rig, limited or no energy at all was transferred from the roadbed to the vehicle roll motion due to the previously mentioned relative sliding. In the UNSW JRS test, the energy dissipated from the roof crushing was not balanced by an energy input from the faster roadbed and the vehicle rotational rate decreased from the initial impact.

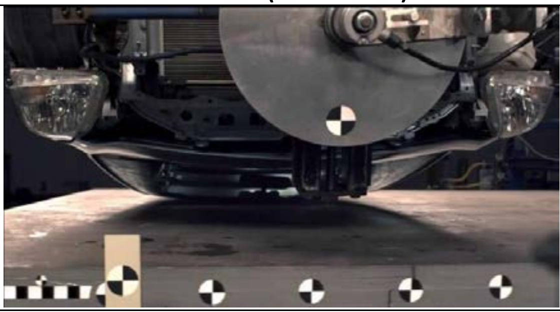
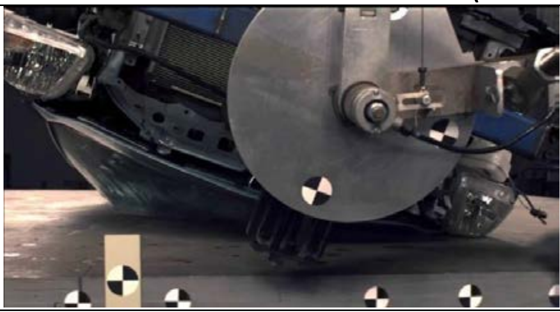
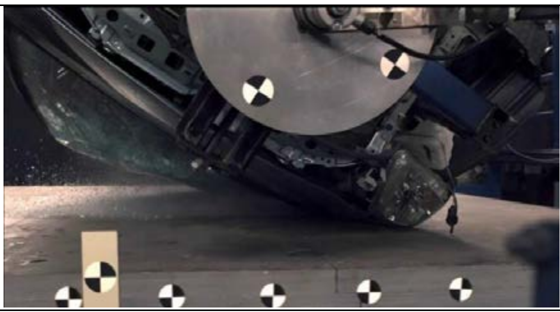
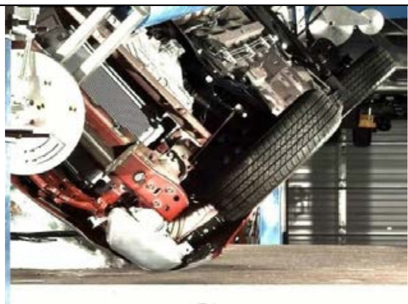
UNSW JRS (Test B13037)	**UVA DROT (Test 1519) (*)**
	
t = 0 ms (Initial Impact)	
	
t = 84 ms	
	
t = 164 ms	
	
t = 254 ms	
	
t = 334 ms	
(*) Pictures mirrored on vertical plane to compensate for opposite direction of vehicle roll motion (Driver position in vehicle tested w/ UVA DRoTS was on the left side)	

Figure 6. Vehicle Kinematics and Dynamic Deformation (Front View) – UNSW Test B13037 vs. UVA Test 1519.

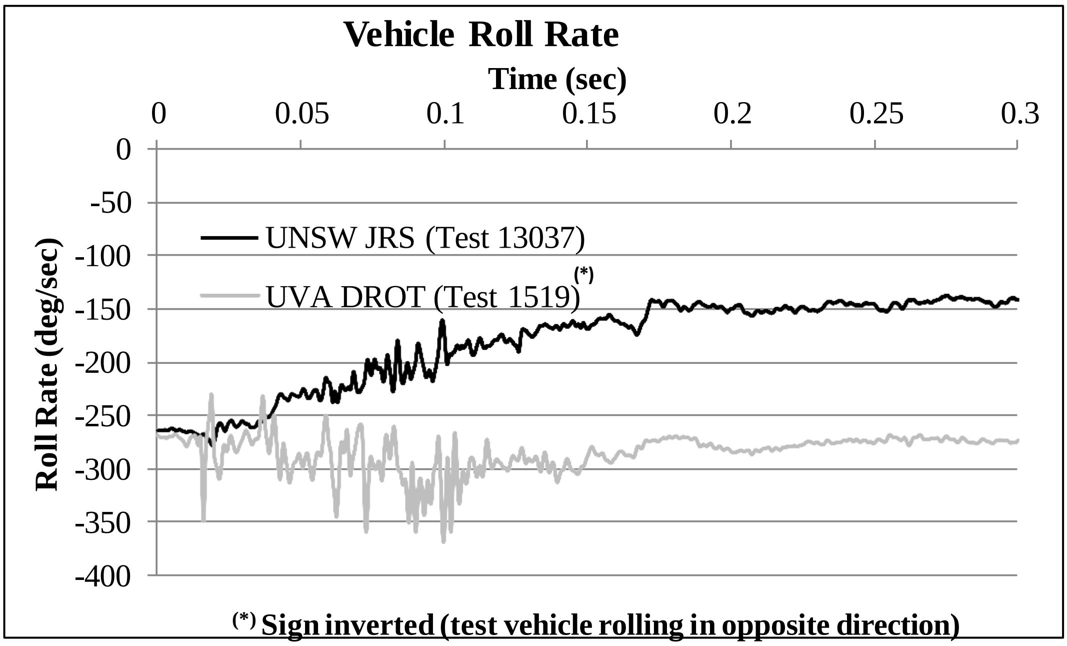


Figure 7. Vehicle Roll Rate – UNSW Test B13037 and UVA Test 1519.

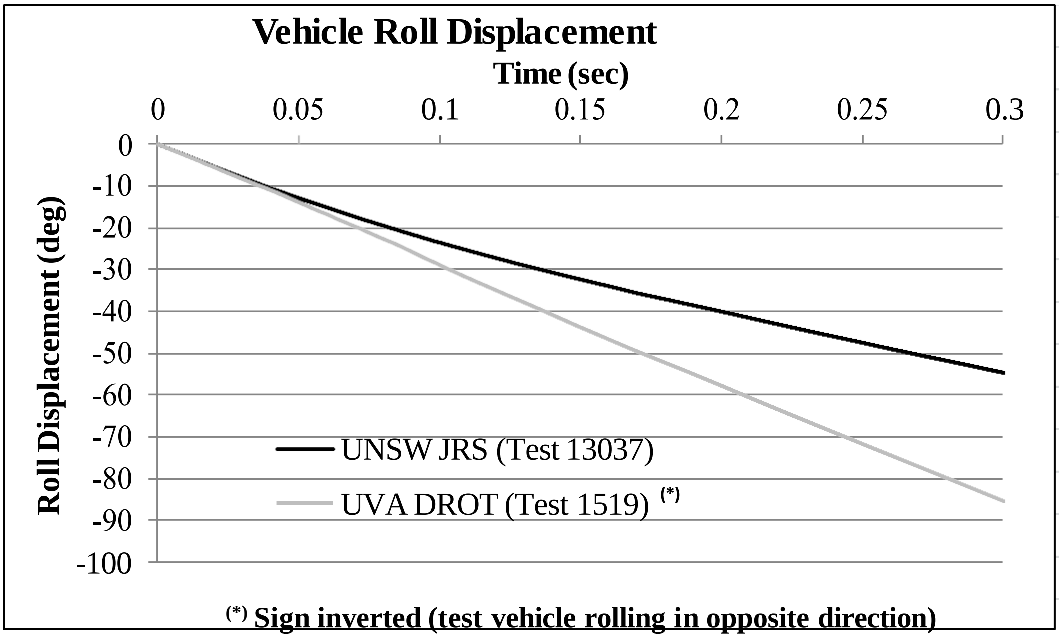
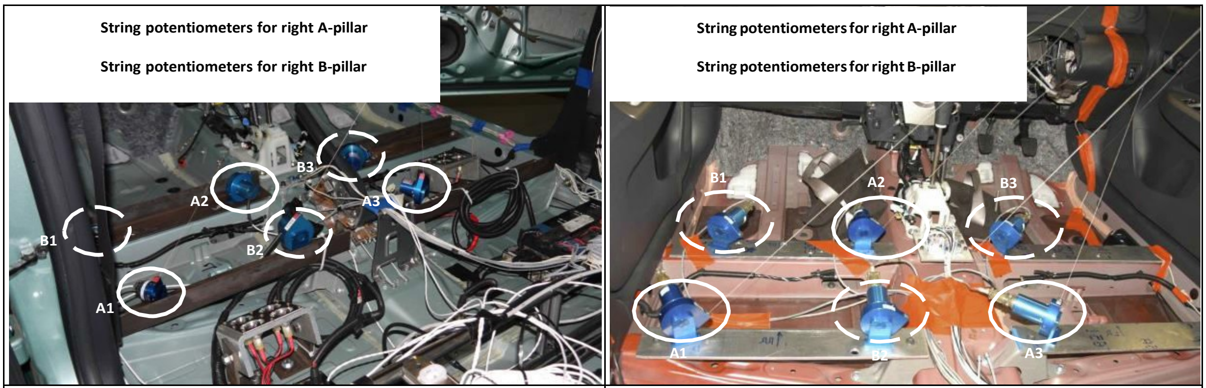


Figure 8. Vehicle Roll Displacement – UNSW Test B13037 and UVA Test 1519.

Dynamic crush of A- and B- pillars

In both tests with the UNSW JRS and the UVA DRoTS rigs, the dynamic deformations of the upper A- and B- pillars on the vehicle far-side were measured using two sets of three string potentiometers. All the string potentiometers were positioned on the vehicle floor, in locations corresponding to the floor attachment of either the front driver's or the front passenger's seat, as indicated in Figure 9. The locations where the end of the potentiometer strings were attached to either the vehicle A- or B- pillar are indicated in Figure 10. Such a configuration with a set of three string potentiometers attached to the same pillar location was initially adopted by UVA to allow for a calculation of the pillar displacement in the vehicle relative coordinate system via trilateration. For the sake of convenience, in this paper only the displacements measured by each of the three potentiometers for each pillar were compared.

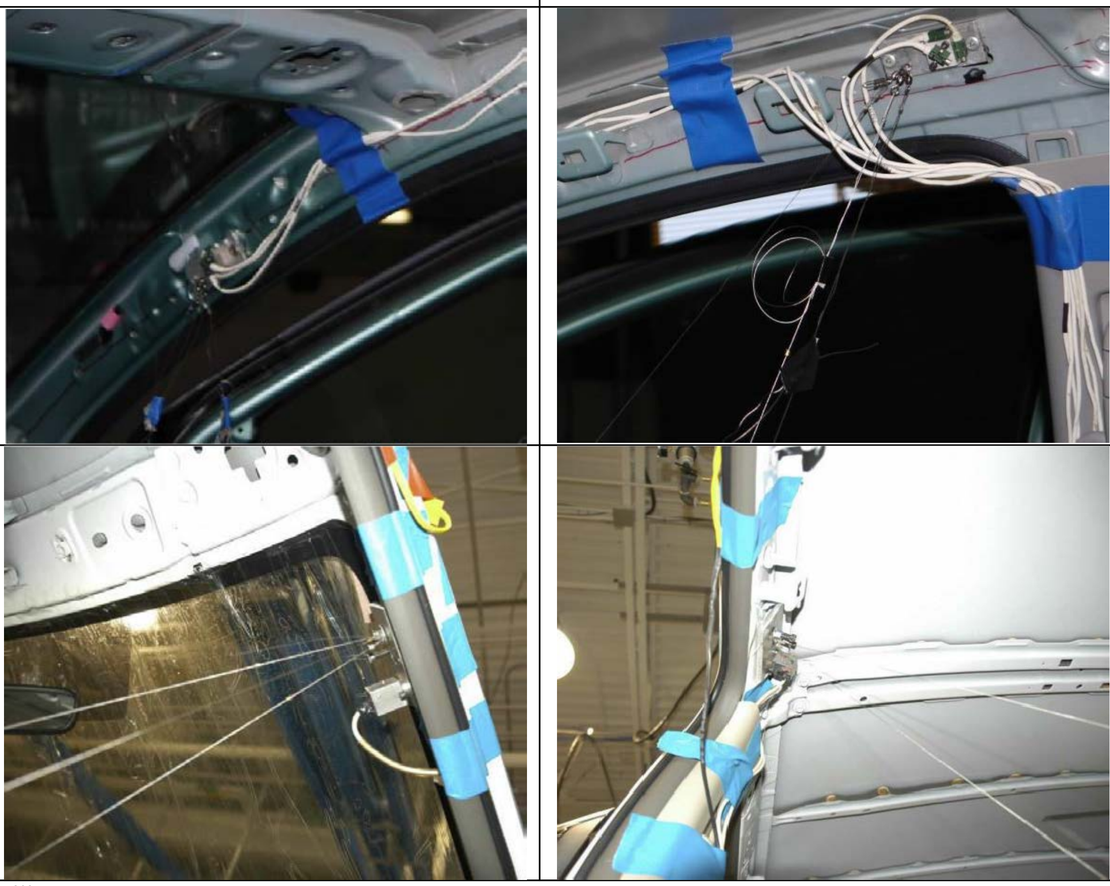


UNSW Test B13037	UVA Test 1519* [8]

(*) Image mirrored on vertical plane to compensate for opposite driver position

Figure 9. String Potentiometers Positioned on Vehicle Floor.

A-Pillar	B-Pillar



(*) Images mirrored on vertical plane to compensate for opposite driver position

Figure 10. Attachment of String Potentiometers to Vehicle Pillars.

The comparison of the displacements measured by the string potentiometers in the tests with the UNSW JRS and UVA DRoTS is shown in Figure 11. An analysis of these displacements indicated a similar trend between the two tests in terms of both the duration and the shape of the curves. However, it is clear that in the test with the UVA DRoTS a slightly larger deformation of the A-pillar as well as a slightly smaller deformation of the B-pillar occurred. Both differences in the crush of A- and B- pillars may have been caused by the slightly larger initial pitch angle at the beginning of UVA's Test 1519. The larger crush of the driver A-pillar in the test with the UVA DRoTS rig is reflected in a prolonged and almost constant roadbed force compared to a shorter and decaying roadbed load measured in the test with the UNSW JRS rig, as shown in Figure 4.

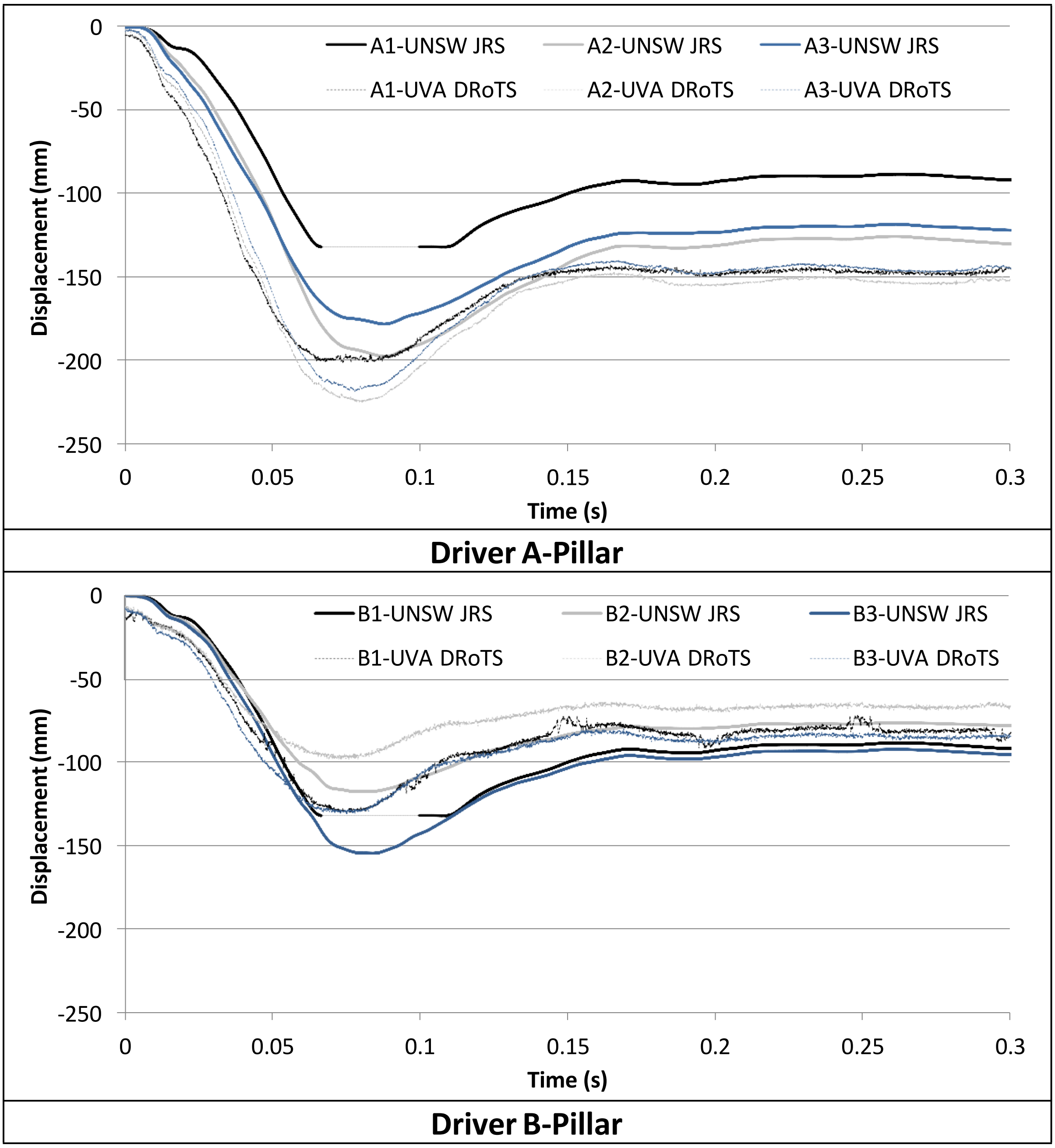


Figure 11. Displacement of String Potentiometers Attached to Far-Side Vehicle A- and B-Pillars.

The larger B-pillar crush in the test with the UNSW JRS rig may also have been caused by a weaker resistance of the front driver door due to a slip-off of the side window's upper edge from the door frame, which did not break during the entire test. On the other hand, in the test with the UVA DRoTS rig, the upper edge of the driver side window stayed connected to the door frame until it shattered. Further, the ultimate strength of the side window in UVA Test 1519 may have been slightly increased by the plastic film that was covering it in order to prevent pieces of broken glass to spread through the laboratory during their test.

Vehicle permanent deformation

Photographs of the vehicle overall permanent deformation as well as a digital scan of the deformed roof for the vehicle used in the tests with the UNSW JRS and the UVA DRoTS are shown in Figure 12. Both digital scans were taken from the interior of the vehicles after the corresponding test. A visual comparison of these scans indicates that the roof collapsed in a similar fashion in both tests: a plastic hinge formed on the roof front header at about three quarters of the roof width from the impacted far side, i.e., the driver's side. In both UNSW's Test B13037 and UVA's Test 1519, the asymmetric location of this plastic hinge was caused by a larger crush of the far-side A-pillar compared to the corresponding pillar on the far-side. The extent of such a plastic hinge at the roof header resulted to be slightly smaller for the vehicle tested with the UNSW JRS rig. This smaller plastic hinge was a direct consequence of a smaller amount of crush of the far-side A-pillar that occurred in UNSW's Test B13037. This was probably due to the vehicle-roadbed relative sliding during the last phase of the rollover test, which was discussed in the previous section.

UNSW Test B13037	UVA Test 1519* [7,8]

(*) **Images mirrored on vertical plane to compensate for opposite driver position**

Figure 12. Permanent Deformation: Tested Vehicle (Top) and Roof Digital Scan from Vehicle Interior (Bottom).

REPRODUCIBILITY ASSESSMENT

The results obtained with the UNSW JRS rig are similar to those from an analogous test previously performed by UVA using the DRoTS rig. In both UNSW's Test B13037 and the analogous UVA's Test 1519, the vehicle roof deformation was similar in terms of both shape and magnitude. Similarly, there was a good match between the impact loads measured by the sensors embedded in the moving roadbeds during both rollover tests. However, a couple of dissimilarities were found regarding the vehicle kinematics observed in the two tests conducted using the UNSW JRS rig and the UVA DRoTS, respectively.

An analysis of the vehicle roll rate measured during each test indicated an opposite trend in the first phase of the rollover crash: a vehicle roll deceleration upon impact with the roadbed in UNSW's Test B13037 versus an initial vehicle roll acceleration in the analogous test with the UVA DRoTS rig. A higher roadbed coefficient of friction in the baseline test conducted using the UVA DRoTS rig has been identified as the likely cause for the initial rotational acceleration of the test vehicle as well as its subsequent bouncing over the moving roadbed. The roadbed friction is an easily controllable parameter in a test environment. As such it is believed that the mentioned dissimilarities in terms of vehicle kinematics would likely not arise in future tests conducted using the UNSW JRS and the UVA DRoTS as far as roadbeds with comparable friction characteristic are used. Under this assumption of a standard roadbed friction during testing and considering the many similarities observed in the results between UNSW's Test B13037 and UVA's Test 1519, it appears to be reasonably possible to reproduce the same test in different laboratories with rigs based on the JRS principle.

Further, another factor that may have contributed to a larger tangential force exchanged between the roadbed and the vehicle during UVA's Test 1519 could be the configuration of the control arm connected to the vehicle front end. In the DRoTS rig the control arm that is connected to the vehicle front end was positioned such that it went into compression, thus potentially causing an additional vertical force pushing the vehicle down on the roadbed. Additionally, the front control arm of the DRoTS rig transferred the compressive load to the gantry to which it was attached. This transferred load caused an initial large elastic deformation of the gantry, which could have subsequently released a load back to the vehicle thus initiating its bouncing during the second phase of the test. An additional vertical load due to the compressive configuration of the front control arm in the DRoTS rig seems to be consistent with the longer and constant vertical force measured by the roadbed during UVA's Test 1519 in comparison to the shorter and decaying roadbed load measured in the test with the UNSW JRS rig. However, a higher roadbed peak load occurred in the test with the UNSWJRS rig. Further analysis needs to be performed to confirm such speculations.

Finally, the opposite driver's configuration for the two tested vehicles (i.e., left hand-side for UVA's Test 1519 and right -hand-side for UNSW's Test B13037) may have resulted in some differences in the inertial properties of the two vehicles as well.

CONCLUSIONS AND DISCUSSION

The comparison of the UNSW JRS test results against the DRoTS baseline test results indicated that the two rigs are potentially capable of providing similar outcomes within a reasonable tolerance expected from experimental crash tests. The shape of the roof damage was basically identical between the two tests, with only a marginally smaller deformation occurring in the UNSW JRS test. However, some differences between the tests performed with the two rigs were noticed in terms of vehicle kinematics. In the first phase of each test with the respective similar rig an opposite trend was noticed for the vehicle roll motion, with a roll acceleration occurring at the beginning of the test with the UVA DRoTS. Also, in the test with the UVA DRoTS the vehicle eventually bounced over the roadbed. Friction between the vehicle and roadbed was identified as the likely ultimate reason for these differences in terms of vehicle kinematics. The different configuration of the control arms between the two test rigs may have affected the vehicle kinematics as well.

Overall, promising results were obtained when replicating with the UNSW JRS rig a baseline test previously carried out in similar conditions with another completely independently-constructed test rig (i.e., the DRoTS). The comparison of the results between the two tests demonstrates that it is possible to carry out reproducible rollover crash tests with rigs based on the JRS functional concepts. Further, previous investigations carried out on repeated tests using the original version of the JRS rig as well as the UVA DRoTS indicated a good repeatability of the test results. Hence, test devices based on the JRS functional principles can definitively be considered as suitable candidates by designers, regulators, and consumer groups for future repeatable and reproducible vehicle rollover crash testing. Such dynamic rollover testing protocol may provide researchers with a tool to investigate the causes for the serious occupant injuries that typically occur during vehicle rollovers.

Further improvements in the reproducibly of vehicle dynamic rollover testing with rigs based on the JRS functional principles may be achieved by setting common inter-laboratory standard test procedures related to various test parameters, such as the roadbed friction, dimensions, weight, and propulsion method as well as the positioning and attachment of the cradle to the test vehicle.

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