Repeatability of a dynamic rollover test system

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ABSTRACT
Objective: The goal of this study was to characterize the rollover crash and to evaluate the repeatability of the Dynamic Rollover Test System (DRoTS) in terms of initial roof-to-ground contact conditions, vehicle kinematics, road reaction forces, and vehicle deformation. 
Methods: Four rollover crash tests were performed on 2 pairs of replicate vehicles (2 sedan tests and 2 compact multipurpose van [MPV] tests), instrumented with a custom inertial measurement unit to measure vehicle and global kinematics and string potentiometers to measure pillar deformation time histories. The road was instrumented with load cells to measure reaction loads and an optical encoder to measure road velocity. Laser scans of pre- and posttest vehicles were taken to provide detailed deformation maps.
Results: Initial conditions were found to be repeatable, with the largest difference seen in drop height of 20 mm; roll rate, roll angle, pitch angle, road velocity, drop velocity, mass, and moment of inertia were all 7% different or less. Vehicle kinematics (roll rate, road speed, roll and pitch angle, global $Z'$ acceleration, and global $Z'$ velocity) were similar throughout the impact; however, differences were seen in the sedan tests because of a vehicle fixation problem and differences were seen in the MPV tests due to an increase in reaction forces during leading side impact likely caused by disparities in roll angle (3° difference) and mass properties (2.2% in moment of inertia [MOI], 53.5 mm difference in center of gravity [CG] location).
Conclusions: Despite those issues, kinetic and deformation measures showed a high degree of repeatability, which is necessary for assessing injury risk in rollover because roof strength positively correlates withinjury risk (Brumelow 2009). Improvements of the test equipment and matching mass properties will ensure highly repeatable initial conditions, vehicle kinematics, kinetics, and deformations.

Introduction
Vehicle rollover crashes are a major occupant safety concern and have long been studied in a variety of ways, including corkscrew ramp methods, side curb tripping methods, and dolly rollover tests to understand vehicle response, occupant/vehicle interaction, and injury mitigation strategies. However, currently no dynamic testing standard is used in government or consumer test protocols in part because sufficient levels of test-to-test repeatability have not yet been demonstrated (Office of the Federal Register 1999).

In an attempt to improve repeatability of rollover crash tests, a variety of rollover test methods that controlled either the impact conditions or the trip conditions like the controlled rollover impact system (CRIS; Cooper et al. 2001), the Jordon rollover system (JRS; Friedman et al. 2003), and the deceleration rollover sled (DRS; Rossey 2001) were developed. However, test methods of fixtures that claimed to be repeatable such as the CRIS and JRS were based on little evidence (Bish et al. 2008; Moffatt et al. 2003); for example, repeatability of the JRS system was based on visual comparison, peak values of reaction forces, and max roof intrusion measures rather than on quantitative comparison of data signals between tests. Kerrigan, Dennis, et al. (2011) looked at 5 different metrics (touchdown conditions, input kinematics, vehicle kinematic response, vehicle deformation, and dummy response) and some objective rating techniques to suggest that repeatability of the DRS was observed when vehicle inertial properties were similar.

The dynamic rollover test system (DRoTS; Kerrigan, Jordan, et al. 2011) was developed as a research tool to examine some of the conditions that occur in real rollover crashes in a controlled, repeatable laboratory environment. This study performed a similar analysis to the DRS study as described by Kerrigan, Dennis, et al. (2011) in which repeatability of initial conditions, vehicle kinematics, road reaction forces, and vehicle deformations were analyzed to assess the test-to-test repeatability of crash tests performed with DRoTS.

Methods
Four rollover impact tests were performed with 2 pairs of replicate vehicles (tests 1519 and 1546: subcompact sedan, tests 1662 and 1684: compact multipurpose van [MPV]) using DRoTS (Figure A1, see online supplement). A brief description of the test fixture and method are provided here, with details pertaining to these tests, but more detail regarding both have been previously described (Kerrigan, Jordan, et al. 2011; Kerrigan et al. 2013). The fixture was designed to simulate interaction between
the vehicle and the ground (or road) between vehicle roll angles of 90° to 270° of the first full roll of a rollover crash. The fixture consisted of a gantry that held each vehicle in a pretest orientation, rotated it (about an axis fixed relative to the car) to a test roll angle and angular velocity, and dropped the rotating vehicle onto a moving road surface that was propelled by a deceleration sled system. The fixture permitted specification of the following parameters at touchdown: vehicle roll angle, pitch angle, roll rate, vertical velocity, and road velocity. During the interaction with the road, each vehicle was free to rotate about the predetermined roll axis and about an axis parallel to the direction of road motion (similar to pitch) but was not permitted to rotate about an axis perpendicular to the ground (similar to yaw). Further, the vehicle was free to translate in the vertical and longitudinal directions, and lateral translations were simulated by constraining the roll axis to remain in a plane (which was mutually perpendicular to the road and the direction of road motion) and implementing a translating road surface. After interacting with the road, each vehicle’s vertical and rotational motions were arrested and the road surface was decelerated.

**Vehicle preparation**

After receiving each vehicle the 4-wheel mass distribution and total mass were recorded using 4 weighing scales. Because mounting hardware, instrumentation, and data acquisition were to be added to each vehicle, vehicle components were removed and fluids were drained to achieve a target mass and mass distribution for each vehicle:

- **Tests 1519 (sedan1) and 1546 (sedan2)**—As much mass was removed as possible to accommodate the 139.3 kg cradle and 41.2 kg mounting hardware without compromising the vehicle structure.
- **Test 1662 (MPV1)**—Two approximately 50th percentile male occupants (to simulate 50th percentile male dummies) and all instrumentation and data acquisition components were added to MPV1 to obtain a target mass and mass distribution for MPV1/2. For MPV1, the occupants, associated data acquisition, and vehicle front seats were removed and the goal mass and distribution were then achieved after removing internal components and adding ballast to accommodate difference in mass.
- **Test 1684 (MPV2)**—Target mass and mass distribution were matched closely to MPV1 with dummies positioned in the driver and right passenger front seats. To interface test vehicles to the DRoTS fixture, custom hardware (Figure A2, see online supplement) was fabricated to rigidly attach the DRoTS cradle to the front and rear bumper beam mounts after removing the fascia and bumper beams (bumper beams were maintained and modified for sedan1 and sedan2).

**Instrumentation**

Data acquisition systems and related components, instrumentation, cameras, lights, and imaging system components were added to each vehicle to facilitate data acquisition and photography. Each vehicle was instrumented with a custom inertial measurement unit consisting of 9 accelerometers and 6 angular rate sensors to facilitate calculation of the vehicle angular acceleration by standard 9-accelerometer-package processing techniques (DiMasi 1995). Other vehicle sensors included 6 string potentiometers extended from the vehicle floor to mounting plates installed on the roof rail near the driver’s side A- and B-pillars using existing holes in vehicle frame to not influence roof structural integrity. Twenty uniaxial load cells were mounted in the roadbed to measure forces normal to the roadbed surface. An optical encoder was attached to the road propulsion system and used to measure the road velocity. All sensor data were sampled at 10 kHz.

**Test procedure**

Once vehicle preparation was completed, it was attached to the DRoTS control arms, final adjustments to the test fixture were made, and ballast was added if needed to ensure rotational stability. The moment of inertia (MOI) was calculated by conducting a roll-only (noncontact) test while collecting the force needed to rotate the vehicles and the angular roll rate of the vehicle. Then speed tests were run to adjust timing of roll initiation and drop release to ensure accurate touchdown conditions. Touchdown conditions of the second sedan test were chosen to match the first sedan test (Kerrigan et al. 2013). MPV test conditions were based on a reconstruction of a NASS-CDS case number 2008-03-108.

Before the final test a coordinate measurement machine (Titanium Arm, FARO Technologies, Lake Mary, FL) was used to facilitate kinematics data processing. Additionally, the exterior of each vehicle was scanned with a commercial laser scanner (Focus 3D, FARO Technologies) to obtain a point cloud description of the vehicle body (pre- and posttest) for deformation measures.

**Data processing**

**Kinematics data processing**

All sensor data were filtered and debiased and were time shifted such that time \( t = 0 \) corresponded to the time of touchdown. Road and control arm load cells, vehicle accelerometers, and string potentiometers were filtered to CFC60 and vehicle angular rate sensors were filtered to CFC180 (Society of Automotive Engineers [SAE] 1995). The filtered and debiased inertial measurement unit signals were used to compute vehicle and global center of gravity (CG) linear and angular accelerations, velocities, and displacements using rigid-body kinematics in conjunction with a method of computing vehicle-to-global coordinate transformation time histories formulated by Beard and Schlick (2003). Complete kinematic data analysis processing has been previously outlined in detail (Kerrigan et al. 2013). The vehicle coordinate system follows SAE J1733 standard vehicle coordinate system for left-hand-driven vehicles (+X-axis from rear bumper to front bumper, +Y-axis from driver side to passenger side, +Z-axis from roof to floor). The global coordinate system was +X’-axis is direction of road travel, +Z’-axis is directed toward the ground, and +Y-axis is a cross product of +Z-axis with +X’-axis.

**Deformation data processing**

A trilateration algorithm was applied to string potentiometer data from the sedan tests to determine the component-wise
Table 1. Measured touchdown parameters and mass properties.

| Test Numbers | Pitch angle (°) | Pitch rate (°/s) | Roll angle (°) | Roll rate (°/s) | Road speed (m/s) | Vertical velocity (m/s) | Drop height (mm) | Mass as tested (kg) | MOI (kg m²) | % Difference |
|--------------|----------------|------------------|---------------|----------------|-----------------|-----------------------|-----------------|-------------------|-------------|---------------|
| 1519 (sedan1) | −12.8          | 5                | 181.0         | 268            | 8.38            | 1.91                  | 247             | 1,733.9           | 379         | −7.7          | 133          | 0              |
| 1546 (sedan2) | −11.9          | 1                | 181.0         | 274            | 8.52            | 1.84                  | 234             | 1,816.1           | 378         | −7.5          | 2            | 2              |
| 1662 (MPV1)  | 0              | −3               | −143.2        | −245           | 7.54            | 1.67                  | 158             | 2,260.2           | 980         | 3            | 7            | 7              |
| 1684 (MPV2)  | 0              | −3               | −146.2        | −248           | 7.54            | 1.55                  | 138             | 2,257.6           | 1,002       | 14            |              |                |

Pitch and roll angles are expressed in the SAE vehicle coordinate system with negative front-down pitch and positive roll angles in the passenger side leading direction for left-hand-driven vehicles.

Results

Touchdown conditions

For sedan1 and sedan2, most touchdown conditions closely matched test parameters with respect to one other. The largest percentage difference was calculated at 7% for pitch angle at touchdown; all other parameters were within 5% difference (Table 1). Touchdown conditions for MPV tests were also very similar. The largest variations in test parameters were the drop height (14% or 20 mm) and vertical velocity (7% or 0.12 m/s) due to a 2% difference in roll angle (Table 1).

Kinematic results

Selected vehicle kinematic data for all tests are presented (Figures 1 and 2), which corresponds to the vehicle motions (Figure 3); complete kinematic data are shown in the Appendix (Figures A3–A6, see online supplement). Despite having very similar roll rates initially, sedan2 showed an increase in roll rate beginning at 70 ms relative to sedan1, with roll rates exceeding 50°/s (17%) more than sedan1 throughout the impact. Road velocities remained similar until 116 ms, where sedan1 slows down slightly and remains consistently slower than sedan2.

Similar roll rates were seen initially in MPV tests; however, MPV1 had a greater roll rate during the first 130 ms after touchdown with the peak difference between tests exceeding 39°/s (6%) around 128 ms. Road velocities remained similar until 116 ms, where MPV2 slows down faster than MPV1.

Boundary condition results

Road reaction forces were similar for both paired tests, but data acquisition problems affected the response data for MPV tests. The road’s data acquisition system ceased functioning at approximately 155 ms in MPV1. As a result, load time history data are truncated there (Figure 4). In MPV2, the data acquisition system temporarily failed at about 163 ms, which was evidenced by all of the load cells temporarily reading negative rail. Despite

Figure 1. Vehicle X angular velocity and road velocity, sedan1 vs. sedan2 (top) and MPV1 vs. MPV2 (bottom).

Figure 2. Global Z’ acceleration, sedan1 vs. sedan2 (top) and MPV1 vs. MPV2 (bottom).
these problems, peak loads differed by less than 7,000 N (4%) and 2 ms. The peak force in MPV1 was slightly higher than in MPV2 (177.4 kN vs. 170.7 kN). The peak force occurred within 2° of the same roll angle (189.6 vs. 187.9). For sedan tests, peak loads differed by 11.7% (94.4 kN vs. 84.0 kN) and 4 ms, which occurred within 1.3° of the same roll angle (196.2 vs. 194.9).

**Deformation results**

The peak resultant deformation at the top of the A-pillar for sedan1 was 222 mm at 86 ms and for sedan2 it was 219 mm at 86.1 ms: a 0.4% difference in magnitude and only 0.1 ms difference in timing (Figure 5). Throughout the loading of the A-pillar, deformations remained mostly in the vehicle's Y–Z plane, with peak Z deformations (168 vs. 163 mm) slightly higher than peak Y deformations (146 vs. 148 mm). Differences in peak deformation between the tests were largest (31%) in the X direction because small deformations occurred in opposite directions, with Y and Z peak deformation differences remaining relatively low (1–3%). Although the percentage difference was large, the difference in displacement between peaks was only 7 mm.
The maximum resultant deformation at the B-pillar for sedan1 was 132 mm at 84 ms and for sedan2 it was 150 mm at 86.8 ms: a 13% difference in magnitude and 2.8 ms difference in timing (Figure 5). Throughout the loading of the B-pillar, deformations remained mostly in the vehicle's Y–Z plane, with Z deformations slightly higher than Y deformations up until around 62 ms. After 62 ms, Y deformations exceed Z deformations, reaching peak values of 105–123 mm at around 86 ms, whereas Z deformations peaked to 86 mm at 59 ms and 92 mm at 77 ms. Differences in peak deformation between the tests were largest (57% or only 15 mm) in the X direction because small deformations occurred in opposite directions, with Y and Z peak deformation differences remaining relatively low (16 and 7%).

Contour plots depicting the shortest distance between the original (pretest) and deformed (posttest) surfaces are plotted on the deformed surfaces for MPV tests (Figure A7, see online supplement). The shortest distance deformation maps show highly similar final deformations between the 2 vehicles, with portions of the passenger side A-pillar and A/B roof rail sustaining permanent deformations approaching 120 mm. Significant outward deformations were seen near the centerline of the vehicle roof (approaching 80 mm), but the leading side roof rail only sustained minimal outward deformations.

Discussion

Sedan1 vs. Sedan2

For sedan1, the mechanism that releases the vehicle from a fixed to a free-fall state, just before the initial roof to ground contact, had a failure (Kerrigan et al. 2013). As a result of this problem, the drop release system was redesigned before performing the next test; however, differences between actual touchdown conditions of the sedan tests were 7% or less.

During the sedan1 test, video images of the front bumper (Figure A8, see online supplement), which was used to fix the vehicle to the test fixture cradle, showed abrupt movement in the vehicle local Y-direction relative to the vehicle frame. Video analysis showed sudden movement at 83 ms followed by another sudden shift at 95 ms. Abrupt changes in the vehicle local X angular velocity data were also seen at similar times, where at approximately 83 ms the vehicle angular rate decreased for a few milliseconds (deviating from increasing rate data in sedan2) and then increased until 95 ms when it began to decrease again (Figure 1). Additionally, other kinematic descriptions showed deviation after 83 ms; global Z' accelerations were not affected and nearly identical (Figure 2), whereas global X' accelerations were strongly correlated up until this time (Figure A4) and vehicle Z angular rate data deviate after 95 ms (Figure A3). The bumper beam's motion relative to the vehicle caused the roll axis to move away from the vehicle's center of gravity, which resulted in an imbalance of the vehicle's rotation. The imbalanced rotation resulted in a higher roll moment of inertia, which explains the reduced roll rate after the motion in sedan1.

Overall, the total vertical force and deformation data showed strong correlations between repeated tests; however, differences were seen starting at 50 ms, when the vertical force in sedan1 surpassed the peak force in sedan2 for 40 ms. This increase in force was likely due to the larger pitch angle (−12.8° vs. −11.9°) and drop height (247 mm vs. 234 mm) during sedan1, which would cause the increased global Z' CG velocity (Figure A4) and vehicle angular Y velocity (Figure A3) after 60 ms. The bumper motion, which was hypothesized to have caused the variation in kinematics, did not appear to cause variations in the contact force and vehicle deformation.

Because the resulting kinematics seem to be well correlated before 83 ms, a shift of the vehicle CG from the roll axis accounts for the changes seen after 83 ms, and no variations or divergences were observed in the force or deformation data at that time, it was expected that vehicle response during a DRoTTS test would be more repeatable if the roll axis is maintained.

MPV1 vs. MPV2

To resolve the issue identified in sedan1, after the small sedan test series, all future test vehicles utilized direct connection, through custom hardware, between the vehicle frame rails and the DRoTTS cradle, without use of the bumper beam. The MPV tests initiated impacts on the leading side and then had a trailing side impact as noticed by the bimodal shape of the vertical force data (Figure 4), whereas the sedan tests only had trailing side impacts. Unlike the sedan tests, initial conditions of the MPV tests exceeded a 7% difference in drop height alone (14%, 158 vs. 138 mm), whereas all other touchdown conditions were 7% or less.

MPV1 endured a slightly higher increase in roll rate during the interaction between the road and the leading side of the vehicle. The maximum difference in roll rate between both vehicles was 39°/s, which occurred at 128 ms. Despite the 39°/s difference, upon initiation of the trailing side impact, both vehicles roll rates decreased to the same level and generally tracked each other without significant variation for the remainder of the test. It was hypothesized that a higher roll rate achieved by the first vehicle during the initial contact phase was related to a 2.2% difference in moment of inertia (980 kg m² in MPV1 and 1,002 kg m² in MPV2). Because the vehicle's roll rate increased initially as a result of frictional forces from the faster moving road (road speed was 7.5 m/s, whereas tangential speed of the vehicle was only 5.4 m/s), a greater increase in roll rate would be expected in the case where the vehicle had a lower moment of inertia. Because the roll angle was slightly (3°) higher at touchdown in the case of MPV2, the increased roll rate in MPV1 resulted in the 3° difference gradually becoming a 0° difference by 310 ms. However, from a simplified energy analysis, the increase in rotational energy of MPV1 (7771 J) during the leading side impact was 13% larger than the increase in rotational energy of MPV2 (6857 J), which could not be produced by the 2.2% difference in MOI between tests. The impact force exerted on MPV1 during the leading side contact was consistently larger than the force exerted on MPV2 with a max difference of 17 kN until the trailing side contact of MPV2, which occurred 119 ms later (Figure 4). This was likely due to MPV1 landing earlier during its rotation, which caused a stiffer load path than for MPV2. As the vehicles continued to roll, the force experienced on both diminished at the same rate because the effective distance from the CG to the roof decreased faster than the vehicles were falling, limiting the contact between the roof and the road. During the trailing side impact, both vehicles experienced a similar loading rate and peak force. The offset of the leading side impact force and the difference in MOI were the likely cause for MPV1 to initially
achieve a higher roll rate than MPV2, which allowed MPV1 to impact the trailing side at a similar time to MPV2.

Road motion showed very good repeatability between the MPV tests (Figure 1). The rate of deceleration of the road as a result of vehicle loading was very similar between the 2 tests; however, the road slowed down less in the case of MPV1 than in MPV2 during trailing side impact. This result was consistent with the hypothesis that the increased roll rate in MPV1 was the result of the lower vehicle moment of inertia. Because the moment of inertia was smaller in MPV1, less energy was required to increase the roll rate by the same amount compared to MPV2 and thus the road slowed down less in MPV1 (because it gave up less of its energy to the roll).

Additionally, differences in CG location may have caused differences seen in selected data channels. Due to supplemental studies performed in MPV2, anthropomorphic test devices were positioned in the driver and right front passenger seats and different vehicle components were not removed as they were in MPV1. Although efforts were made to reduce differences in mass and mass distribution, the CG location moved 53.5 mm (44 mm X-direction, −11.4 mm Y-direction, −28.2 mm Z-direction) relative to MPV1. The CG moved because the masses used as ballast in place of the occupants in MPV1 were added to the floor but not as high as the occupants; thus the CG in MPV2 was higher (as the −28 mm in Z shows). This supports the findings of Kerrigan, Dennis, et al. (2011), in which variation of vehicle CG location may have a significant effect on vehicle response.

Though dynamic deformation data was not collected for both MPV tests, deformation contours of both tests showed very similar deformation patterns and values (Figure A7). Passenger roof rail deformation in MPV1 (contour levels between 97 and 120 mm) matched closely to final resultant dynamic deformation at the A-pillar (92 mm) and B-pillar (107 mm). Between MPV tests, MPV1 showed slightly larger deformations in the passenger roof rail, which correlates to slightly higher peak reaction forces on the trailing side for MPV1 (177 vs. 171 kN).

**DRoTS performance comparison**

MPV tests were not seen to exhibit any mechanical abnormalities during impact, whereby proper fixation of the vehicles solved the problem that occurred with the sedan1 test and the DRoTS showed very repeatable results. As opposed to repeatability studies of the CRIS and JRS fixtures, complete time history data of vehicle kinematic, kinetic, and deformations responses of replicate tests were presented and showed high levels of repeatability. Even compared to the DRS study, dynamic and static deformations as well as vertical reaction force–time histories provided more detail about the repeatability of the vehicle response in a DRoTS test.

Similar to the analysis conducted by Kerrigan, Dennis, et al. (2011), an objective rating method should be used to correlate data signals in repeated tests to quantitatively distinguish repeatability of vehicle responses. However, previous evaluations have subjectively defined repeatability because a repeatability benchmark in rollover does not exist. This was seen in the JRS studies where repeatability of the system was based on visual comparison and peak values of reaction forces and max roof intrusion measures rather than quantitatively comparing data signals between tests. Although the DRS study used an objective rating method, a threshold for repeatability was not established, which led to subjective conclusions. The use of subjective analyses, as presented, was sufficient for comparing vehicle responses between pairs of tests, but to compare between test methods (vs. DRS or vs. JRS) and to establish a repeatability benchmark, an objective rating will be necessary and should be considered for future use. This study subjectively shows that the DRoTS can be used to repeatedly evaluate rollover crashworthiness; therefore, an objective approach would strengthen these findings and would allow for evaluating repeatability of DRoTS relative to other test modes.

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