Repeatability of a Dynamic Rollover Test System

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Abstract – Rollover accidents have the highest serious to fatal injury rates of any accident mode. Research and development on rollover occupant protection has been frustrated by the lack of a low cost, controlled, repeatable, dynamic test. The most widely used tests, dolly and CRIS system rollovers, do not meet all of these conditions, but the Jordan Rollover System (JRS) does. This study demonstrates JRS repeatability using three identical production vehicles with anthropomorphic test dummies. The first test of each vehicle used string potentiometers to measure roof performance. The second used both string potentiometers and an instrumented test dummy. The JRS test parameters, roof structural performance, and Hybrid III dummy injury measures were all shown to be highly repeatable with variation generally not more than 10 percent. The dummy and vehicle repeatability was on par with the repeatability shown in similar crash test studies conducted by IIHS and NHTSA.

Keywords: Rollover, Roof Crush, Jordan Rollover System, Testing, Repeatability, Crashworthiness

INTRODUCTION

There are currently two consumer information, crash test programs conducted by the National Highway Traffic Safety Administration, and the Insurance Institute for Highway Safety. Both programs conduct dynamic testing of production vehicles in order to determine their crashworthiness using a variety of test parameters. Both groups have previously published articles illustrating the repeatability of the portion of their test programs dealing with frontal crashes [1],[2]. While there are no generally accepted standards for determining repeatability in automotive crash testing, these studies set a de facto acceptable level.

The first test series was a series of 35 mph frontal barrier crash tests of fourteen 1982 Chevrolet Citations with dummies conducted for NHTSA by three test facilities.[3] The tests were at three different test sites on vehicles that were manufactured consecutively on the same production line in the same assembly plant to achieve maximum possible uniformity.

The authors state that, “the number variation from the sites participating in the RTP is approximately 10 percent.” However, the sample standard deviation of the driver HICs was 20 percent of the average value while it was 11 percent for the passenger HICs. Time shifts in the data were also found to be roughly 10 percent of the duration of the event.

The authors described variation in the vehicle responses: “An examination of the vehicle engine cradle revealed that different load paths developed during the crash event. . . . the bending at the cutout of the engine cradle members varied.” In some vehicles, both left and right side buckled, some on the left and others only the right member buckled. In addition, the buckling of the floor pan and toe board varied from vehicle to vehicle and the separations between floor pan sections varied as did the separations at the rocker panel areas. Weld failures also occurred in the floor pan, some welds pulled parent metal, others failed at the weld joint.

These observations illustrate the differences in vehicle crash performance even when they are all assembled sequentially and are as identical as the manufacturer could make them on a regular assembly line. The authors also cited differences among test facilities, procedures, and dummies as contributing to the differences in the test results. Although not explicitly stated, the authors implied that variation of less than 10 percent in critical measurements was an acceptable level of repeatability.

This level has been generally accepted in that NCAP testing has been used to rate vehicles for the last 27 years and presented to the public as a useful comparative measure of vehicle safety.

The Insurance Institute for Highway Safety (IIHS) also conducted a study of repeatability of its frontal offset crash tests.[4] In these tests of two specimens of each of seven vehicle models, the weights of the test vehicles, impact speeds, and degree of overlap were very well controlled.

They noted significant differences in the peak longitudinal accelerations of the vehicles, but attributed them to instrumentation rather than actual performance differences. The velocity curves as a function of time during the impacts were quite close. They found some differences in intrusion in the vehicles' interiors. The largest differences were in larger passenger cars and averaged roughly 25 percent of the total intrusion which averaged about 15 cm. The largest differences were only about 8 cm. With one exception, the average difference in steering wheel intrusion was 2 cm out of an average of 11 cm. These differences may be more a function of vehicle differences than test variability.

The differences in HICs and chest deflections between the two tests of each of four cars tested and reported both averaged 11 percent. Leg and foot measures had greater differences. The authors concluded:

> "In summary, because differences between intrusion measurements, restraint system observations, and dummy injury measures in repeated tests generally were small compared with differences between rating categories, the Institute's overall crashworthiness evaluations would not be expected to change as a result of repeated tests. In cases where there is somewhat greater variability, a rating change of more than one category appears unlikely. Thus, the repeatability of modern vehicle performance in a frontal offset crash test is sufficient for making evaluations of the crash protection provided by different designs."

In effect, IIHS seems to also endorse the position that variation of roughly 10 percent in key measurements made in crash tests indicates an acceptable level of variation in tests deemed to be repeatable.

The Jordan Rollover System, JRS, has been described in several research papers [5-13]. The system was designed to conduct repeatable, dynamic rollover crash tests in a laboratory setting, controlling and measuring rollover roof impacts in a variety of possible test configurations. The design minimizes consequential parameters that can affect the orientation of the vehicle at the roof impact increasing repeatability of the impact conditions and the loadings on the test article.

An initial JRS repeatability study was conducted using a simple welded tube frame, with a replaceable roof structure, simulating a pickup truck.[14] This study examined the repeatability of the test fixture looking at both the speed of the roadway at impact and vertical road load applied to the roof structure. Both of these parameters were found to be highly repeatable. The road speed in the three tests averaged 13.6 mph with a variation of less than 5 percent. The vertical road loads had a variation of approximately 10 percent. The tests achieved very similar impacts to the test articles. The study also examined the affects on the roof structure of the vehicle. The deformation patterns were very similar from vehicle to vehicle. The largest difference between the vehicles was due to a single spot weld failure at the top of the buck's A-pillar structure. Overall, this study found the fixture to be highly repeatable and illustrated the effects of having variations in the test article.

The initial study utilized a replaceable roof buck to examine repeatability of the fixture. However, it was desired to conduct a study looking at repeatability utilizing production vehicles and Hybrid III test dummies. This study would need to look at the structural response of the test articles under the similar loading environment provided by the JRS fixture and also examine the response of the test dummy both in injury measure and motion.

TEST DESCRIPTION

A test must be repeatable and reproducible. The former is defined as the degree to which the results of tests of essentially identical objects produce the same performance measures and results. The latter is defined as the degree to which the results of tests of essentially identical objects produce the same performance measures and results regardless of which test instrument, location, time and personnel are involved in the testing. We can test the repeatability of the JRS, but because there is only one such test instrument, we can test reproducibility in only a limited way. The testing discussed herein was conducted over several months to attempt to examine reproducibility.

The problem of obtaining repeatable test results is complicated by the fact that, the object being tested – an automobile – is a complex welded and bolted assembly with deformable exterior surfaces, large masses attached by compliant elements, and soft interior upholstery. Even if one obtains essentially identical test vehicles, there may be variation in materials, construction quality, and welds that are difficult to assess but that may affect test results. Because of this variation, manufacturers routinely insist on a margin of 20 to 25 percent above the minimum requirement in compliance test results to account for variation in vehicle options and manufacturing quality.

Repeatability test results may be confounded by the complexity of the test and test instruments, the variability of objects being tested, and the difficulty of accurately controlling test conditions. There is a considerable amount of literature on repeatability (and on reproducibility), but it is difficult to apply the standard formalism to the problem of automotive crash testing because of the complexity of the test and test measurements that are typical of such tests.

The FMVSS 208 dolly rollover test is considered repeatable in the sense that the initial conditions of the test – speed of launch, can be very carefully controlled. On the other hand, once the vehicle is released from the dolly, its motion is generally thought to be somewhat random or chaotic regardless of how carefully the initial conditions are controlled. The JRS was designed with these facts in mind.

The JRS is a highly controlled, flexible test device used to evaluate the dynamic performance of a light vehicle's rollover occupant protection system and in particular a vehicle's dynamic roof crush performance under typical rollover conditions. The JRS has proven itself in more than 30 tests of passenger cars, sport utility vehicles and pickups.

The JRS is a simple, straightforward system for rotating a vehicle about its longitudinal axis and dropping it in coordination with the motion of a road segment that is moving beneath it. From the standpoint of Newtonian physics, this is completely equivalent to having the vehicle move laterally at the speed of the road segment and falling on a fixed road. Because the vehicle is rolling as it falls, there is little transfer of momentum between the vehicle and the road segment in the direction of the road segment's motion as shown by direct measurements. As the road segment moves beneath the test article, the roof structure strikes the road surface after which the vehicle is caught before any further contact or damage to the roof structure can occur. The test of a particular vehicle may be repeated under the same or different initial conditions to simulate a second (or more) roll(s) of the vehicle. The road speed, vehicle rotation speed, drop height and roll, pitch and yaw angle at first impact are fully controlled and adjustable to emulate the conditions of actual rollovers.

The value of the JRS is its ability to accurately simulate roof impacts in individual rolls of a motor vehicle (either a complete vehicle or a body in white) under a wide variety of realistic, initial conditions. After the planned roof impacts, the JRS prevents further damage to the vehicle. It also involves a variety of detailed measurements including roof intrusion and intrusion speed at a variety of locations and impact force to the roof on the road surface, both vertically and laterally. This system is the first time that it has been possible to directly measure the force of the vehicle roof impact on the road. The JRS can also measure the center of gravity falling height above the road, falling velocity and acceleration.

An instrumented anthropomorphic test dummy can be used in the JRS in which case dummy injury measures, motion and the effects of the occupant protection equipment; belts, airbags, padding, etc., can be examined. All of the measurements can be made as a function of time or vehicle roll angle.

In the present repeatability series, three 2003-2004 Subaru Foresters that were essentially identical in body style and equipment were tested. All three were used vehicles and one had frontal crash damage that had been repaired but that did not involve the vehicle from the firewall and A-posts rearward. None of the cars had sun roofs and all had roof racks. All had four cylinder engines with automatic transmissions and weighed 7,121 kg, 7,157 kg and 7,150 kg, respectively, as tested. Two tests of each vehicle were conducted: the first without dummies but with additional instrumentation, the second with a fully instrumented Hybrid III dummy restrained in the driver (initially trailing) seat.

TEST RESULTS

Roll 1

The first test of each Forester was conducted with the following target parameters: a road speed of 29 km/hr, an impact roll angle of 145 degrees, a vehicle roll rate of 210 degrees per second, 10 degrees of pitch and yaw, and a 102 mm drop height to the leading side of the roof. The yaw angle was fixed throughout the test and the variation in the remaining parameters is shown in Table 1. These parameters are linked in that changes in roll angle and pitch angle will affect drop height, etc. Photographs of the three vehicles before and after the first rolls are shown in Figure 1 and 2.

Table 1. Measured Initial Test Conditions for Roll 1

Test Vehicle	Road Speed (km/hr)	Drop Height (mm)	Impact Roll Angle (deg)	Pitch Angle (deg)	Roll Rate (deg/sec)
1	29.0	86	147	10.3	223
2	28.7	103	147	10.2	182
3	28.5	116	146	10.2	208
Standard Deviation / Average	1%	15%	1%	1%	10%

Figure 1. Photographs of the Three Subaru Foresters before the First Roll on the JRS.

The vertical and lateral loads for the first roll on the three test vehicles are shown in Figure 3 and 4. The vertical load data traces show two distinct peaks for each vehicle. These are the near and far side impacts with the roof structure. For the three vehicles, the peak, near side vertical road loads are 46,634 N, 45,907 N and 53,999 N. These results have an average value of 48,846 N, a standard deviation of 4,477 N and a variation of 9 percent (standard deviation divided by the average value). For the three vehicles, the peak, far side vertical road loads are 65,490 N, 65,674 N and 67,980 N.

These results have an average value of 66,381 N, a standard deviation of 1,388 N and a variation of 2 percent. The impact loads from the fixture onto the test articles are very similar from test to test. The greatest variation comes from test vehicle 3, which was the repaired vehicle mentioned earlier. For the two used, but undamaged vehicles, the vertical load traces are virtually identical.

Figure 2. Photographs of the Three Subaru Foresters Following the First Test on the JRS.

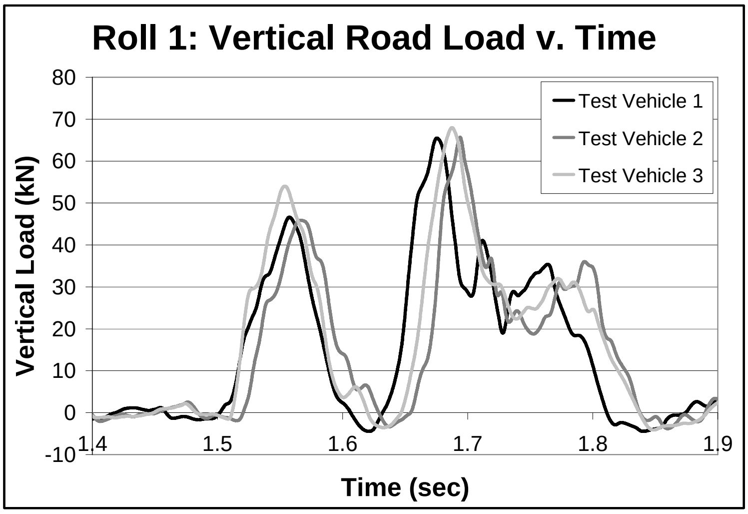

Figure 3. Vertical Road Loads for Roll 1.

The lateral load data traces are shown in Figure 4. The distinctive peaks seen in the vertical road load traces are not as obvious in the lateral data. Using the same timing of the near and far side roof impact from the vertical load data, the following is determined. For the three vehicles, the peak, near side lateral road loads are 3,838 N, 3,210 N and 3,699 N. These results have an average value of 3,582 N, a standard deviation of 330 N and a variation of 9 percent. For the three vehicles, the peak, far side lateral road loads are 3,145 N, 3,619 N and 3,173 N. These results have an average value of 3,312 N, a standard deviation of 266 N and a variation of 8 percent. These values are similar from test to test and are a small percentage of the weight of the vehicle illustrating the low level of lateral loading in the system.

The vehicles had limited deformation in these tests. For this vehicle, the B-pillar is very strong [15], acting as a roll bar for this vehicle. By contrast, the A-pillar and windshield header displayed weakness with buckles forming in the windshield header several inches inboard of the top of the A-pillar and further toward the middle. This effect is reflected in the larger amount of A-pillar deformation as compared to the B-pillar. In addition, the B-pillar strength limited the A-pillar intrusion. The crush at the front of the roof resulted in some distortion of the roof panel. All three vehicles showed similar patterns of roof damage, see Figure 2.

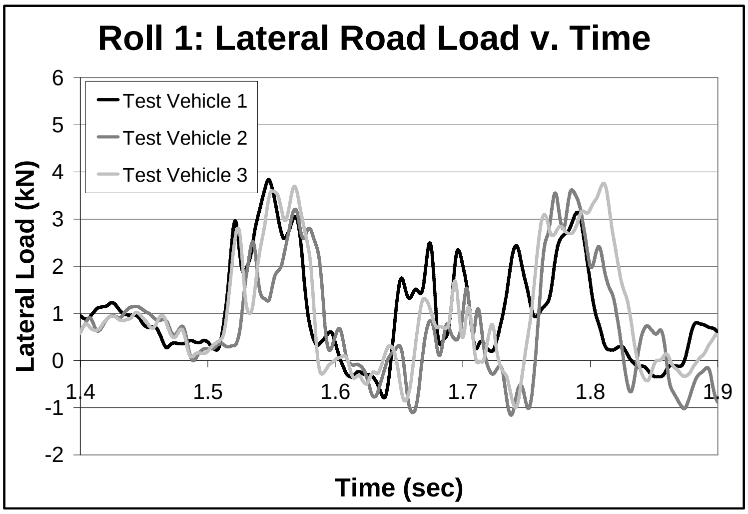

Figure 4. Lateral Road Loads for Roll 1.

String potentiometers were used to measure the intrusion of the roof structure at several points. The string potentiometers were attached to the roof of the vehicle and anchored at the approximate longitudinal roll axis of the vehicle. Thus, the intrusion and intrusion velocity mentioned here is the amount directed towards the roll axis. These values are conservative. The maximum, dynamic roof deformation and residual roof deformation are shown in Figures 5 and 6. The standard deviation of the maximum dynamic crush at the top of the A-pillar, mid roof rail, top of the B-pillar and windshield header inboard of the A-pillar were 7.6, 11.5, 6.2 and 13.4 mm respectively. These standard deviations were 7, 18, 17 and 18 percent of the average and 6, 9, 5 and 11 percent of the NHTSA's acceptable roof crush of 127 mm. The residual results are similar.

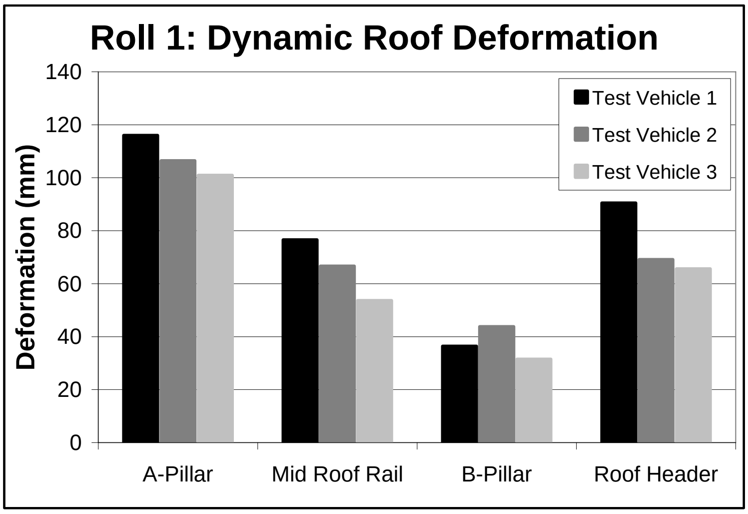

Figure 5. Maximum Roof Crush During the First Roll.

Roof intrusion speed, shown in Figure 7, provides a better measure than gross intrusion of the potential for head or neck injury [16]. The A pillar intrusion speed of 8.2 km/hr is more than twice that of the B pillar measured at 3.7 km/hr. The standard deviation of the maximum intrusion speed at the top of the A-pillar, mid roof rail, top of the B-pillar and windshield header inboard of the A-pillar were 0.4, 0.8, 0.4 and 1.3 km/hr respectively. These standard deviations were 5, 16, 12 and 21 percent of the average.

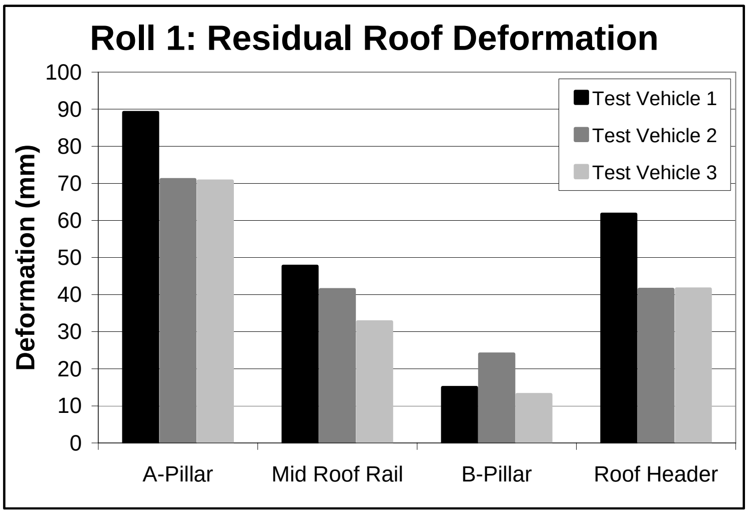

Figure 6. Residual Roof Crush Following the First Roll.

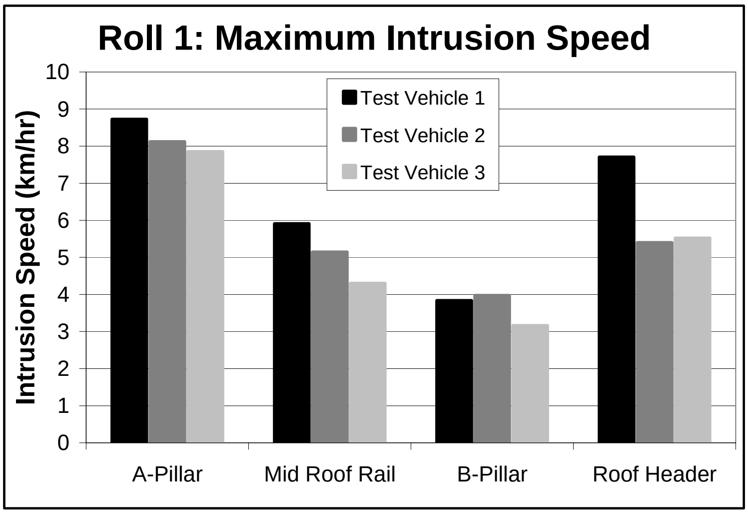

Figure 7. Maximum Roof Intrusion Speed During the First Roll.

Roll 2

The second test of each of the three Foresters was conducted with an instrumented Hybrid III 50th percentile male dummy restrained by the available lap/shoulder belt in the driver position (the initially trailing side in these tests where maximum roof crush generally occurs). The dummies were positioned according to the procedures set forth in FMVSS 208 at the mid seating position, but no additional restraints were placed on the dummy to constrain it during the test. In this roll, the following target parameters were used: a road speed was 19.3 km/hr, an impact roll angle of 145 degrees, a vehicle roll rate of 160 degrees per second, 10 degrees of pitch and yaw, and a 102 mm drop height to the leading side of the roof. The yaw angle was fixed throughout the test and the variation of the remaining parameters is shown in Table 2. Photographs of the three vehicles following the second roll are shown in Figure 8.

The vertical and lateral loads for the second roll on the three test vehicles are shown in Figure 9 and 10. These are similar to the traces from the first roll. For the three vehicles the peak, near side vertical road loads are 47,927 N, 47,754 N and 42,335 N. These results have an average value of 46,005 N, a standard deviation of 3,180 N and a variation of 7 percent. For the three vehicles the peak, far side vertical road loads are 70,087 N, 61,883 N and 58,499 N. These results have an average value of 63,490 N, a standard deviation of 5,958 N and a variation of 9 percent.

Table 2. Measured Initial Test Conditions for Roll 2

Test Vehicle	Road Speed (km/hr)	Drop Height (mm)	Impact Roll Angle (deg)	Pitch Angle (deg)	Roll Rate (deg/sec)
1	20.5	108	150	11.1	139
2	19.9	85	143	9.8	148
3	20.0	115	149	10.3	156
Standard Deviation / Average	2%	15%	3%	6%	6%

Figure 8. Photographs of the Three Subaru Foresters Following the Second Roll on the JRS.

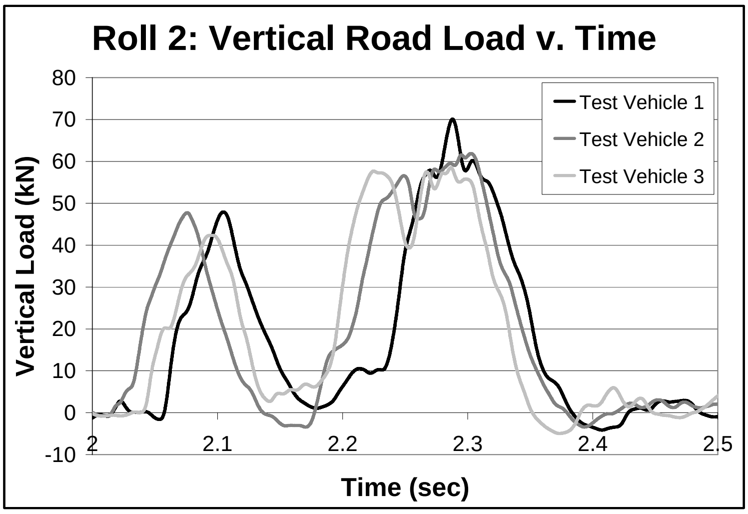

Figure 9. Vertical Road Loads for Roll 2.

The lateral load data traces are shown in Figure 10. Using the same timing of the near and far side roof impact from the vertical load data, the following is determined. For the three vehicles, the peak, near side lateral road loads are 2,289 N, 1,826 N and 1,707 N. These results have an average value of 1,941 N, a standard deviation of 308 N and a variation of 16 percent. For the three vehicles, the peak, far side lateral road loads are 2,766 N, 1,345 N and 1,507 N. These results have an average value of 1,873 N, a standard deviation of 778 N and a variation of 42 percent.

For the second roll, the inclusion of the Hybrid III test dummy required removing some string potentiometers to prevent interaction. The maximum dynamic roof deformation and residual roof deformation are shown in Figures 11 and 12. These values are not cumulative values from the first roll. The deformation presented in these graphs is only the deformation from the second roll. The standard deviations of the maximum, dynamic crush at the top of the A-pillar, top of the B-pillar and windshield header inboard of the A-pillar were 10.0 mm, 7.8 mm and 25.9 mm respectively. These standard deviations were 11, 13 and 27 percent of the average and 8, 6 and 20 percent of the NHTSA's acceptable roof crush of 127 mm. The residual results are similar.

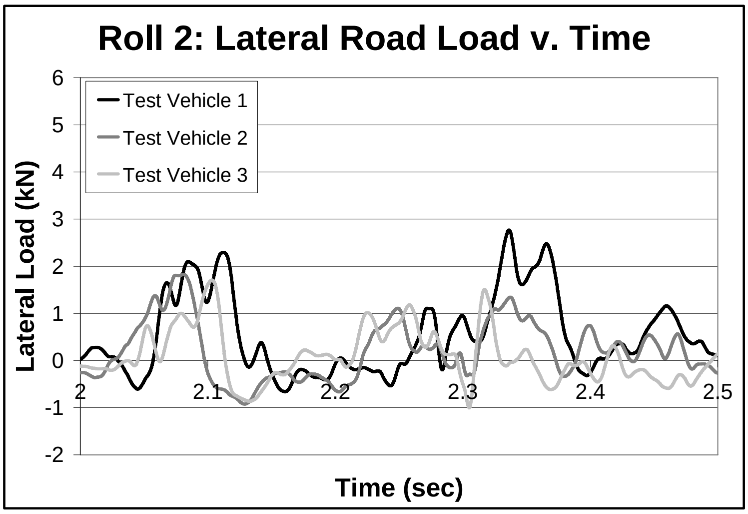

Figure 10. Lateral Road Loads for Roll 2.

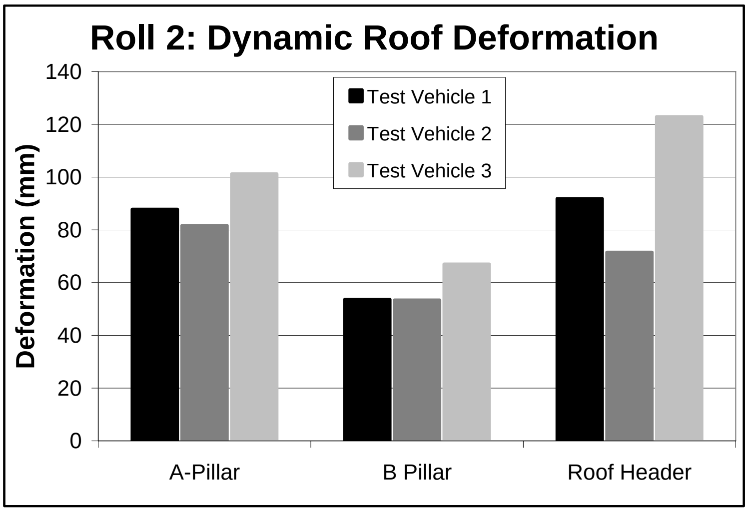

Figure 11. Maximum Roof Crush During the Second Roll.

Roof intrusion speed for the second roll is shown in Figure 13. The standard deviation of the maximum intrusion speed at the top of the A-pillar, top of the B-pillar and windshield header inboard of the A-pillar were 1.3 km/hr, 0.1 km/hr and 1.4 km/hr respectively. These standard deviations were 14, 2 and 20 percent of the average.

The somewhat greater variation in the second roll was caused by slight differences in damage from the initial roll. Even with this initial damage, the variation is relatively small. This initial damage will cause greater variability in dummy response. However even with this, the dummy response was very similar and repeatable from test to test.

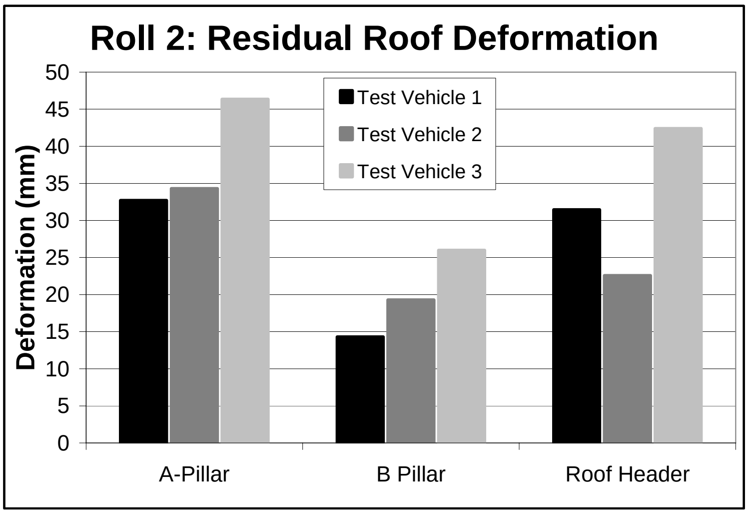

Figure 12. Residual Roof Crush Following the Second Roll.

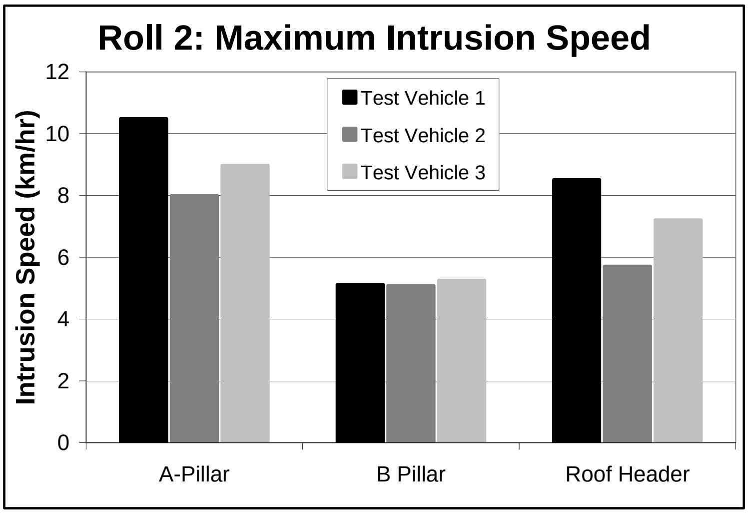

Figure 13. Maximum Roof Intrusion Speed During the Second Roll.

The dummy neck injury measures are shown in Figure 14. The compressive neck loads are 4,240, 4,104 and 3,573 N. The standard deviation was 352 N. The standard deviation was 9 percent of the average. The Neck Injury Criteria, Nij [17], are 0.85, 0.76 and 0.92. The standard deviation was 0.08. The standard deviation was 10 percent of the average.

The motion of the dummy was monitored by several sensors including lap and torso belt loads and string potentiometers on the dummy head, hip and under the Hybrid III dummy. The lap belt loads through the impact phase of the test are shown in Figure 15. The data traces show a similar response in both time and magnitude from test to test. The peak lap belt loads for each test are 614 N, 502 N and 558 N. The standard deviation was 56 N. The standard deviation was 10 percent of the average.

The vertical motion of the test dummies through the impact phase of the test are shown in Figure 16. The data traces show a similar response in both time and magnitude from test to test. The peak lap belt loads for each test are 91 mm, 81 mm and 77 mm. The standard deviation was 7 mm. The standard deviation was 9 percent of the average. The other measures of dummy motion are similar to those illustrated here.

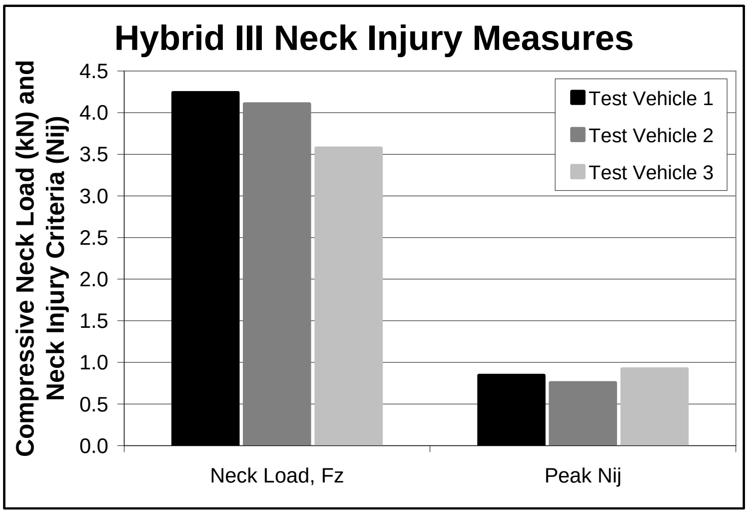

Figure 14. Hybrid III Neck Injury Measures: Compressive Neck Load and Neck Injury Criteria.

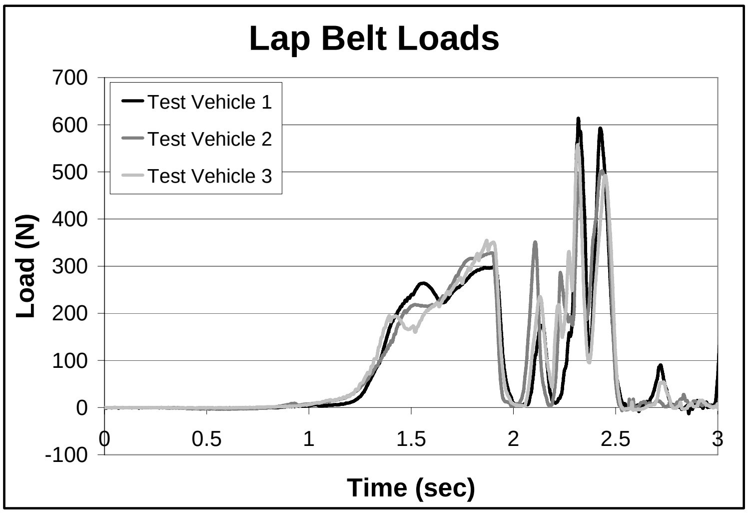

Figure 15. Lap Belt Loads.

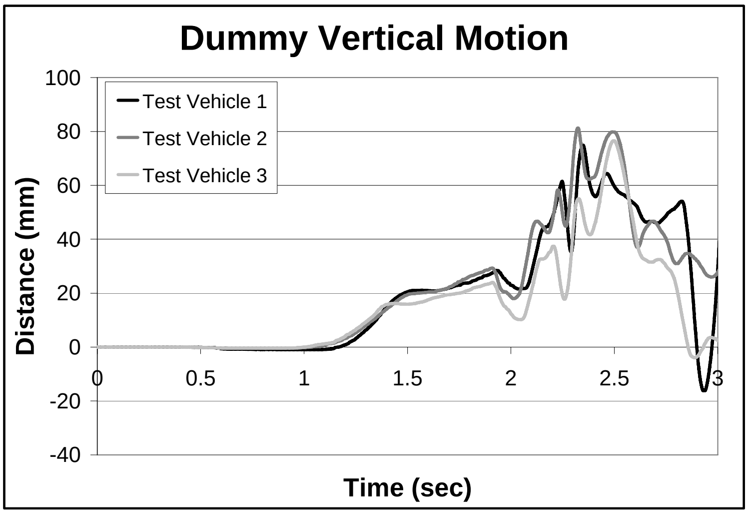

Figure 16. Hybrid III Vertical Motion.

CONCLUSIONS

The Jordan Rollover System has been shown to be repeatable in two test series. This fact is primarily due to the design of the fixture, which was created to minimize the number of setup parameters that are necessary to run a repeatable rollover test. With the current test setup, the test to test variation is small in most cases, less than 10 percent, with the largest variation coming in drop height. Further fixture improvements can reduce these levels even further. However, the loading environment on the test article was very similar even with this variation. The test articles all underwent similar severity impacts, resulting in vertical loads with less than 10 percent variation. The variation was much lower than this in the first roll. Slight differences in vehicle damage caused a slightly higher load variation in roll 2.

Vehicle to vehicle differences seemed to have the greatest effect on load variation. This fact is seen by the slightly higher variation in roll 2. In both rolls there is a higher variation in structural vehicle performance in the roof header than the roof rail locations. The structural strength in the location of string potentiometer mounting can alter the variation.

These differences in fixture setup and vehicle variation had a very small impact on dummy injury measures. For both the compressive neck load and the neck injury criteria, Nij, the standard deviation was 10 percent of the average value. These levels are on par if not better than current dynamic test, consumer information programs illustrating the applicability of JRS testing for both consumer information applications and general safety research testing.

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