8

VEHICLE AND OCCUPANT RESPONSE IN ROLLOVER CRASH TESTS

Louise Obergefell, Ints Kaleps
Armstrong Laboratory, Dept. Air Force
Arnold Johnson
National Highway Traffic Safety Administration

This paper was presented at the 19th Annual Workshop on Human Subjects for Biomechanical Research. It has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

ABSTRACT

Over a period of several years, The National Highway Traffic Safety Administration (NHTSA) has sponsored a total of twenty-four full-scale rollover crash tests to investigate vehicle and occupant dynamics during rollover crashes. A variety of pickup trucks, vans and automobiles were tested with a fully instrumented dummy seated in either the driver's or passenger's front seat. For some tests, the dummy was unrestrained and for others the dummy was restrained by the test vehicle's regular belt restraint system. For most of the tests, a specially designed NHTSA Rollover Test Device (RTD) was used to impart to the test vehicle both an initial linear velocity and a rolling motion about the vehicle's longitudinal axis. In five of the tests, the rolling motion was initiated by vehicle impact with a guardrail or curb. Data for all these tests were collected from electrical sensors mounted on the vehicle and the dummy and also from high speed cameras mounted both inside the vehicle and on the ground. Many of the vehicles, especially the pickup trucks, experienced severe roof crush in the tests. Frequently, high neck forces were measured during the roof crush, indicating that the dummy provided momentary roof support and modified the damage to the vehicle. Also, independent of severe roof crush, the dummy often experienced impacts to the top of the head. Although the impact forces to the top of the head may have been large, both with and without roof crush, the data shows that the opposing neck forces are also large. These counteracting forces minimize the head accelerations and resulting Head Injury Criteria (HIC) value. In rollover crashes head contact with the vehicle roof may be sustained for a relatively long time, leading to static loading in the neck. For such loading, an injury criteria based on neck forces or moments may be required to indicate potential injury. Further, a rollover test dummy would require more realistic neck flexion and compression to adequately indicate the potential for either neck or head injury and would require an articulated spine to more realistically simulate occupant kinematics. Other findings regarding vehicle and occupant dynamics during rollover are also discussed.

INTRODUCTION

Rollover accidents are receiving increasing attention in the field of automobile safety by the NHTSA. Since 1983 twenty-four full-scale rollover tests have been sponsored by NHTSA to investigate vehicle and occupant dynamics during rollover events. The tests were also conducted to provide data for predictive computer simulations of both the vehicle and occupant motions. References 1, 2 and 3 provide results of such predictive simulations. Table I contains a list of the full-scale tests conducted. All of the tests were conducted at the Transportation Research Center of Ohio (TRC), except for the first test in 1983 which was conducted at the Southwest Research Institute (SWRI). Except for the Dodge Aries test on 3 November 1983, all the tests have the test date as the test number which appears in the films and pictures of the tests. The complete test conditions and results are included in the test reports that are available from NHTSA. The tests can be identified by the test date and the NHTSA data tape number. In nineteen of the tests a RTD[4] was used to initiate the rolling motion. The remaining tests consisted of three guardrail and two pole impact tests. In this report, the main focus is on the RTD tests.

TEST CONFIGURATION

The specific test conditions for each test are listed in Table I. Most of the vehicles were small pickup trucks and light vans. These vehicles were chosen because they are involved in a high frequency of rollover accidents. The particular vehicles used were chosen based on availability, previous testing experience with the vehicle, and other testing considerations. In most of the tests, a Hybrid III dummy was placed in the driver's seat and restrained by a three-point seat belt. The first impact side refers to which side of the vehicle struck the ground initially. The motion of a vehicle during a rollover is affected by the mass properties of a vehicle. To better understand how these properties affect rollover dynamics, the weight, center of mass location, and moments of inertia of each test vehicle in the last seventeen tests were measured. These measurements were made with the vehicle fully instrumented as it was in the test. The mass properties were measured both before and after the test to determine whether and how much the vehicle damage may have affected the mass properties.

The vehicles in the RTD tests were mounted on the RTD, as shown in Figure 1, at an initial roll angle of 30 degrees. The vehicle was mounted with its frame directly supported on the platform to avoid effects from the tires and suspension system, providing better repeatability between tests. The RTD was towed by cable along a guide-rail and accelerated to a specified initial constant velocity. On reaching the test initiation point, the launch sequence was started. First, chains attaching the vehicle to the platform were released, the pneumatic cylinders were actuated producing angular rotation of the platform and vehicle, and the RTD was decelerated. This resulted in the vehicle being thrown clear of the RTD with an initial linear and angular

Table I
Rollover Test Conditions

Test Date	Vehicle	Test Type	Data Tape #	Vehicle Crab Angle (deg)	First Impact Side	Speed (mph)[a]	Surface	Dummy Position	Restraint
850108	Ford Pinto	RTD	c	-45	Left	17	Concrete	Driver	3-Point
850523	Plymouth Reliant	RTD	V1546	-45	Left	21	Concrete	Driver	3-Point
851113	Honda Accord	RTD	V878	-45	Left	21	Concrete	Driver	None
860110	Chevy Celebrity	RTD	V888	-45	Left	23	Concrete	Driver	None
860321	Dodge Omni	RTD	V920	-45	Left	23	Concrete	Passenger	None
860505	Mercury Zephyr	RTD	V939	-60	Left	23	Concrete	Passenger	None
880630	Nissan Pickup	RTD	V1274	-45	Left	30	Concrete	Driver	3-Point
880714	Dodge Caravan	RTD	V1266	-45	Left	30	Concrete	Passenger	3-Point
880817	Chevy Pickup	RTD	V1267	-45	Left	30	Concrete	Passenger	None
880923	Ford Bronco	RTD	V1255	-45	Left	30	Concrete	Driver	None
890530	Nissan Pickup	RTD	V1289	-45	Left	30	Mat	Driver	3-Point
890918	Dodge Colt	RTD	V1471	0	Right	30	Mat	Driver	None
891025	Dodge Caravan	RTD	V1391	45	Right	30	Mat	Passenger	3-Point
891113	Ford Bronco	RTD	V1392	90	Right	30	Mat	Driver	3-Point
891116	Nissan Pickup	RTD	V1393	90	Right	30	Mat	Driver	3-Point
891122	Nissan Pickup	RTD	V1394	90	Right	30	Mat	Driver	3-Point
891129	Pontiac Grand Am	RTD	V1395	90	Right	b	Mat	Driver	3-Point
900827	Dodge Ram	RTD	V1521	90	Right	30	Mat	Driver	3-Point
900905	Ford Ranger	RTD	V1520	90	Right	30	Mat	Driver	3-Point
831103	Dodge Aries	Guardrail	c	0	Right	60.3	Dirt & Grass	Passenger	3-Point
900910	Nissan Pickup	Guardrail	V1531	0	Right	58.4	Grass	Driver	3-Point
901010	Dodge Caravan	Guardrail	V1530	0	Right	50.5	Grass	Driver	3-Point
900820	Dodge Caravan	Pole	V1516	-90	Left	30	Concrete	Driver	3-Point
900914	Nissan Pickup	Pole	V1522	-90	Left	30	Concrete	Driver	3-Point

a. For the RTD test, speed refers to the speed of the RTD.
b. Rollover Test Device failure. Data unavailable.
c. Data tapes are not available for these tests. However, the test report and the high speed films are available from the NHTSA.

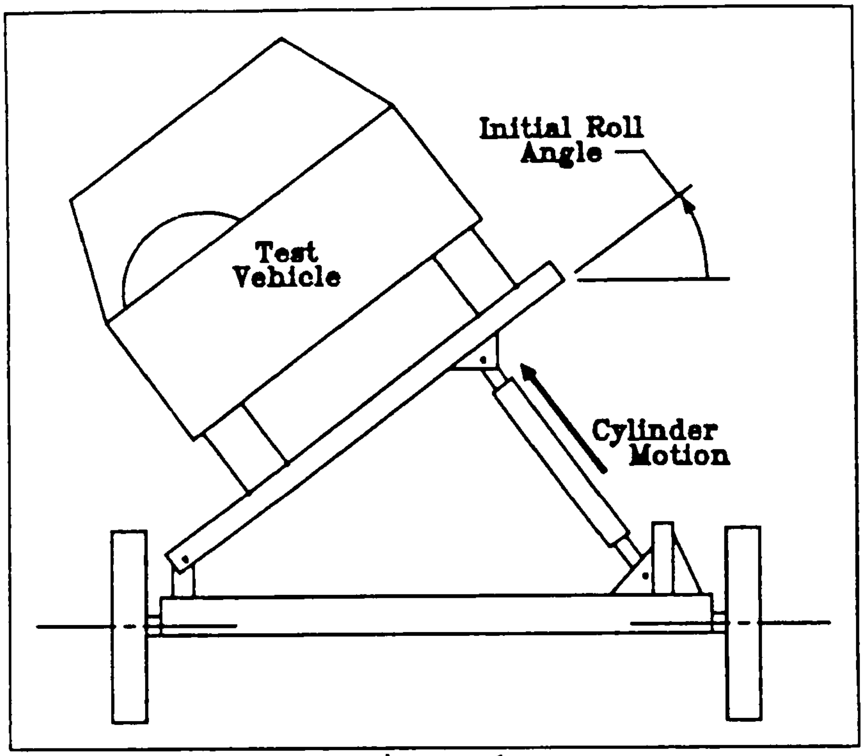

Figure 1
Test Vehicle Mounted on the Rollover Test Device

velocity. The RTD wheels were designed so that they can be rotated to allow the RTD and the test vehicle to be crabbed at an initial yaw angle (Figure 2). This feature of the RTD permits its use over a wide range of rollover crashes. In the initial ten RTD tests on a concrete surface, many of the vehicles did not complete a full roll. Since accident investigation data show that the greater amount of roll, the greater potential for injury, a rubber mat was installed on the surface in order to increase friction and therefore increase the likelihood of multiple rolls, as well as to standardize the properties of the initial impacting surface. The RTD was originally designed to handle small to mid-sized automobiles. For the RTD to handle test vehicles of greater weight and to provide greater angular velocity, the original pneumatic cylinders were replaced with larger cylinders after the sixth RTD test. Also, throughout the testing process a number of modifications were made to the RTD pneumatic and electrical systems to increase the angular acceleration imparted to the vehicle[5]. The RTD structure was also upgraded to improve stability, including larger axles and wheels which were used in the last two RTD tests. These additional modifications improved the RTD's operation and increased the test vehicle's angular velocity at release.

Instrumentation

The RTD was instrumented to collect the three-dimensional acceleration of the RTD and the platform displacement at each cylinder. Also, limit switches were used on both sides of the vehicle to measure the vehicle/RTD separation times. All the vehicles were instrumented to collect the three-dimensional vehicle center of mass accelerations and angular velocities.

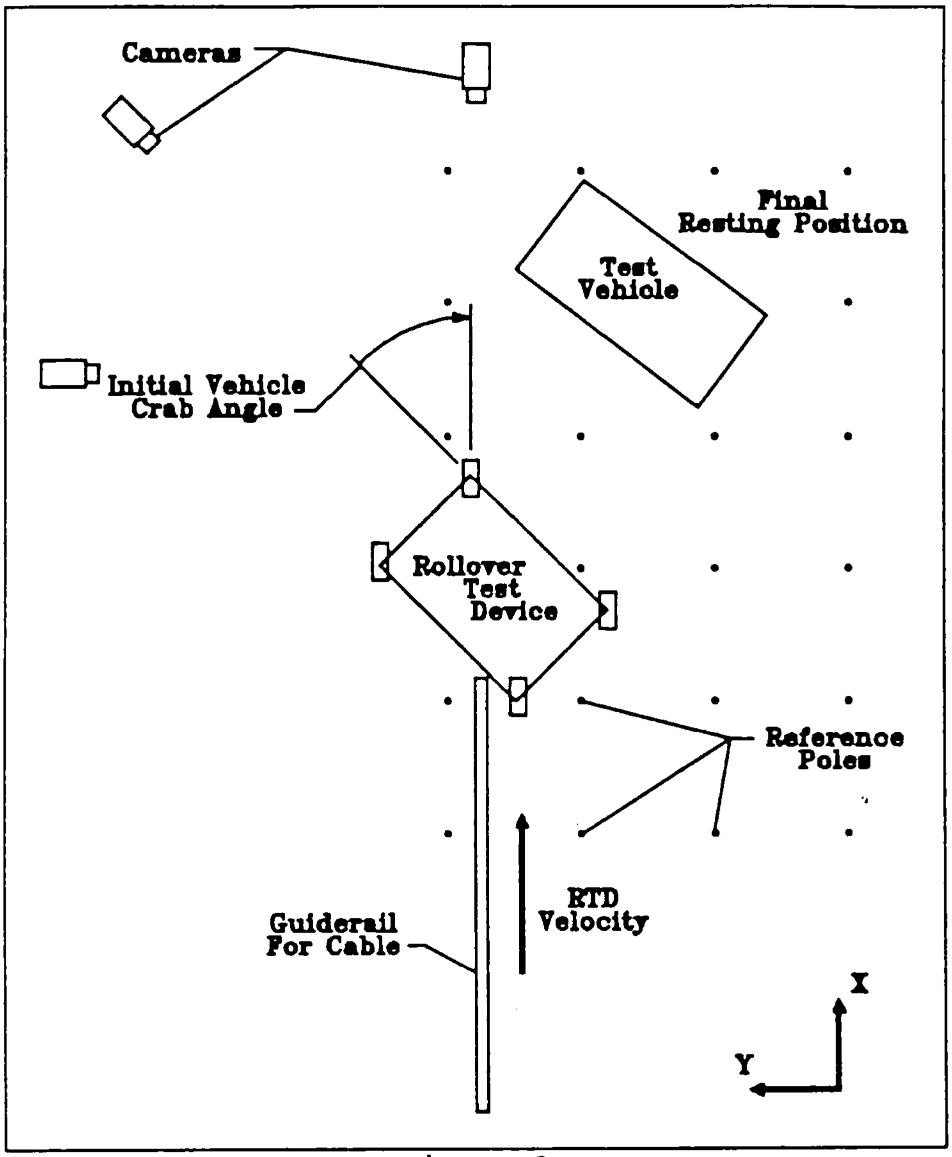

Figure 2
RTD Test Layout

Also collected were the suspension displacements at all four wheels. Part 572 (Hybrid II) dummies were used in the first three tests and Part 572E (Hybrid III) dummies were used in the subsequent tests. The dummies were instrumented to collect three-dimensional head, chest and pelvis accelera-tions, three-dimensional neck forces and moments, and chest displacement. Femur loads were also measured in some of the earlier tests. When the dummy was restrained, the belt displacement at the belt feed-out point was also measured.

Photography

High speed cameras were used to film both the vehicle and dummy motion. Typically, three exterior cameras were used in the RTD tests as shown in Figure 2 to film the vehicle motion. A panning camera was also used to provide a real time film of the vehicle motion. Whenever possible, two interior cameras were used to film the dummy motion. The front interior camera was mounted laterally opposite to the dummy in a position unlikely to affect the dummy's motion. Usually this camera was mounted to the floor, in front of the seat and aimed up towards the dummy. The second interior camera was mounted in the back seat or compartment with the field of view covering the whole front seat compartment in case the dummy moved laterally across the vehicle. This camera was not used in the tests using pickup trucks, due to potential damage to the camera. Break-away reference poles were placed throughout the test areas to provide a gauge for measuring the vehicle motion from the films.

TEST RESULTS

Vehicle Response

In the RTD tests the vehicles first landed on their side. As the RTD was improved to be more rugged and to provide greater angular motion to the test vehicles, the vehicles tended to land higher up on the side and closer to the roof. Many of the vehicles continued to roll about their longitudinal axis after this initial impact. A maximum roll of two complete revolutions was obtained in two of the RTD tests. Table II lists the general vehicle motion and the major damage to the vehicles. In many of the tests, especially those with pickup trucks, the A-pillar and B-pillar on the impact side collapsed during the first impact with the ground. The Dodge Caravan, in the 880714 test (Figure 3), landed on its side and slid without rolling any further. Although the maximum crush appears to be relatively small, 7.4 inches, the whole van structure was deformed, while in the other van tests only the roof sustained serious damage. As the vehicles continued to roll, the roof collapsed as it contacted the ground. The entire cab of many of the pickup trucks collapsed. Figure 4 shows an example of this extensive damage to a pickup truck. Many of the vehicles slid to a stop on their roof, while some still had enough angular kinetic energy to roll back onto their wheels. Many of the vehicles that came to a rest on their wheels stopped rolling because one or more of the tires blew out, absorbing energy. Other vehicles' suspension systems caused the vehicle to bounce and continue rolling. These results suggest that the primary factor that affected the amount of roll was the energy absorbed in the vehicle deformation.

In general the accelerations experienced by the vehicles in all three types of rollover tests were low compared to accelerations in other types of crashes, such as frontal and side impact. The accelerations experienced in the RTD tests increased in the later tests. This is most likely due to the improvements made to the RTD which increased the rotational energy imparted to the vehicle upon its release.

Table II
Vehicle Motion and Damage

Test Date	Vehicle	# of 1/4 Rolls	Distance Traveled (ft)[a]		Vehicle Damage	Maximum Crush (in)
			X	Y		
850108	Ford Pinto	4	29	3	Hood bent up	-4.2 hood
850523	Plymouth Reliant	6	25	11	Roof crush	3.8 roof
851113	Honda Accord	2	25	11	Roof crush	3.9 roof
860110	Chevy Celebrity	4	84	12	Minor	
860321	Dodge Omni	2	74	8	Roof crush	5.1 roof
860505	Mercury Zephyr	2	89	9	Roof crush	7.5 roof
880630	Nissan Pickup	6	110	5	Roof collapse	14.5 roof
880714	Dodge Caravan	1	124	8	Left side crush	7.4 side
880817	Chevy Pickup	4	189	-1	Roof crush	3.6 roof
880923	Ford Bronco	2	136	5	Roof & left side crush	10.9 roof, 7.5 side
890530	Nissan Pickup	2	123	5	Complete roof collapse	13.9 roof
890918	Dodge Colt	2	116	-23	Windshield & right side crush	4.1 roof, 5.1 side
891025	Dodge Caravan	8	130	-16	Roof collapse	15.3 roof
891113	Ford Bronco	8	105	10	Complete roof & right side collapse	14.5 roof, 7.4 side
891116	Nissan Pickup	4	137	6	Complete roof collapse	14.1 roof
891122	Nissan Pickup	4	92	8	Complete roof & left side collapse	17.2 roof
891129	Pontiac Grand Am	2	117	27	Roof crush	6.8 roof
900827	Dodge Ram	4	90	5	Complete roof collapse	15.6 roof
900905	Ford Ranger	2	126	1	Complete roof collapse	18.5 roof
831103	Dodge Aries	16				
900910	Nissan Pickup	4	210	-8	Roof & left side crush	11.5 roof
901010	Dodge Caravan	0[b]	158	-27	Minor	
900820	Dodge Caravan	1	n/a	n/a	Complete left side & roof cave-in	25.4 side
900914	Nissan Pickup	2	n/a	n/a	Roof collapse & left rear wheel lost	23.2 roof

a. Distance measured from knock-out block, which is the point where vehicle release sequence is started.
b. Net number of quarter rolls. Vehicle made one quarter roll followed by a second quarter roll in the opposite direction, ending in an upright position.

Figure 3
Test 071488 Dodge Caravan Damage

Occupant Response

Because of the varied conditions of the rollover tests that were conducted, the occupant motions were diverse. Although the general occupant responses were varied, the contacts with the vehicle surfaces were somewhat predictable. Head contacts with the roof occurred in virtually all the tests. Also door contacts by the chest and the legs were also frequent. In many of the RTD tests the roof collapsed, trapping the dummy head and body and restricting most movement. In two of the unrestrained tests, 880817 and 890918, the body fell to the opposite side of the vehicle. Because of the number of rolls and lack of roof deformation in the 880817 test, the dummy continued to bounce around the truck cab. In the 890918 test the roof collapsed, trapping the dummy against the seat. In most of the tests, the lap belt or steering wheel kept the dummy's body in its seat. Typically in the RTD tests with the dummy positioned on the impact side seat, the roof and side bent in on impact with the ground. The deforming surfaces impacted the dummy head and shoulder forcing the dummy laterally across the vehicle. The tests with the dummy positioned on the side opposite the initial

Figure 4
Test 900905 Ford Ranger Pickup Damage

impact were usually more dramatic. The roof would begin its collapse opposite of the dummy, would continue collapsing in a wave across the vehicle, and eventually trap the dummy head and body against the door. When the last portion of the roof collapsed, the trapped head would be crushed by the roof. At this point the dummy head often provided some roof support, hindering further roof crush. In the 891122 and 900905 tests, the head was pushed out the window by this roof movement. The shoulder belts seem to have little effect on the dummy motion, because of the lateral motion of the body. Also, as a result of the vehicle motion, the belts may have unlocked during the tests. The vehicles' rolling motion and the collapse of the roof generally kept the dummy's body upright.

Table III shows that the resulting head accelerations and Head Injury Criteria (HIC) levels are often low, even though many of the tests were very severe. In only three of the RTD tests is the HIC level above 1000. In many cases, when the head and body became trapped, the head was loaded by the roof but it could not move with respect to the body resulting in large neck loads. Therefore, the neck loads may more accurately reflect the

Table III
Occupant Head Accelerations & Neck Loads

Test Date	Vehicle	HIC	Maximum Head Acceleration (g)			Maximum Neck Force (lb)		
			X	Y	Z	X	Y	Z
850108	Ford Pinto	a	a	a	a	c	c	c
850523	Plymouth Reliant	104	17.5	98.9	32.3	c	c	c
851113	Honda Accord	132	105.3	79.7	11.1	c	c	c
860110	Chevy Celebrity	15	9.1	14.8	13.5	104.4	d	552.3
860321	Dodge Omni	40	11.4	30.7	20.9	118.1	d	754.8
860505	Mercury Zephyr	58	55.4	14.9	18.1	171.0	d	492.9
880630	Nissan Pickup	229	15.6	77.2	21.0	63.0	134.8	243.9
880714	Dodge Caravan	18	5.9	9.4	18.6	22.5	72.0	155.4
880817	Chevy Pickup	55	28.6	41.4	21.4	81.6	131.4	591.1
880923	Ford Bronco	240	14.0	77.0	34.2	45.0	204.8	263.1
890530	Nissan Pickup	156	24.3	50.1	31.3	362.5	244.6	1156.8
890918	Dodge Colt	81	18.9	44.3	119.6	153.5	209.9	787.9
891025	Dodge Caravan	220	12.2	89.7	27.0	120.2	246.9	1031.7
891113	Ford Bronco	2140	24.7	63.2	399.7	283.9	655.2	2152.7[b]
891116	Nissan Pickup	1049	81.2	58.1	142.5	1330.2	803.7	2116.6[b]
891122	Nissan Pickup	774	34.9	110.9	147.8	1174.2	1197.8	2960.2[b]
891129	Pontiac Grand Am	89	12.8	a	a	152.9	154.6	a
900827	Dodge Ram	3015	174.6	86.6	250.2	2421.3	667.8	2644.6[b]
900905	Ford Ranger	938	175.9	246.9	122.3	3054.5	716.1	2807.5
831103	Dodge Aries	a	a	a	a	c	c	c
900910	Nissan Pickup	42	11.9	20.4	44.3	283.3	242.3	942.2
901010	Dodge Caravan	154	23.3	46.1	30.3	82.4	113.8	259.9
900820	Dodge Caravan	1328	230.7	190.9	163.4	2098.8	2889.1	2128.5
900914	Nissan Pickup	426	24.5	71.5	48.9	149.5	222.9	946.8

a. Data unavailable.
b. Exceeded channel's full scale.
c. The Part 572 dummy used does not have a neck load cell.
d. Neck load cell measured limited axes in early Hybrid III dummy.

severity of the event. The neck forces in Table III show that the HIC levels and head accelerations do not always fully indicate the severity of the occupant's response. For example, the HIC levels in tests 890530 and 891025 are 156 and 220 respectively, while the neck loads exceeded 1000 lbs. Even more dramatic is test 891122 where the HIC level is 774 and the neck experienced forces close to 3000 lbs and torques in excess of 200 in-lbs.

CONCLUSIONS

These tests were conducted to develop rollover testing methodologies, identify procedural and vehicle structural problems, and provide information on occupant dynamics during automobile rollover accidents for use in validating computer simulations. Because the twenty-four tests were conducted under several different programs over a period of more than six years, they do not form a consistent study to which statistical methods can be applied. They do provide a large amount of data on vehicle and occupant response during rollover, along with insights into what factors influence the rollover event. From this information, guidelines can be drawn for developing improved rollover tests.

In the tests conducted it was found that the vehicle rollover motion is very unpredictable due to its sensitivity to many factors. These factors include the vehicle mass properties, the initial conditions, the point of first impact, the ground surface properties, the deformation characteristics of each vehicle component that impacts the ground, and failure of any vehicle components such as tire blow out or roof collapse. In the two tests with the same test conditions, 891116 and 891122, the results were similar in some respects, such as the amount of roll and the type of roof crush, but other results were considerably different, such as the distance traveled and the vehicle accelerations. The dummy responses showed even more differences. This partially demonstrates the difficulty in developing a standard, highly repeatable rollover test.

With the upgrades that were made to it during the span of these tests, the RTD easily handles the vehicles used and imparts enough angular velocity to the vehicles to ensure rolling motion. Although the realism of these tests may be questionable, the RTD provides a reasonably controllable method for providing consistent initial roll and linear velocity, over a physically reasonable range for road vehicles. The guardrail impact tests are more plausible events, but rollover is not always assured as demonstrated in the 901010 test. The pole impact tests were even more unpredictable and extremely difficult to control.

The occupant motions showed that, although the lap belt probably restrained the dummy in its seat, the shoulder belt rarely affected the dummy's motion. Unless a rollover includes accelerations of the proper magnitudes and directions, the occupant may not load into the shoulder belt and the shoulder belt may not remain locked.

Most of the tests resulted in significant roof crush. The pickup trucks especially showed a tendency for the cab roof to completely collapse, with the seat back, window sill, or even dummy head limiting further deformation. Often the body was trapped by the roof crush. In these cases the head/neck system was vulnerable to large loads from the roof. These loads did not always result in high head accelerations; therefore, it is important that neck loads be measured in rollover testing.

These tests provide greatly needed data on vehicle and occupant dynamics during automobile rollover from three different testing procedures. They demonstrated the variability of rollover results, the difficulty in controlling the test conditions, the tendency for significant roof crush, and the danger to the head and neck region of the body.

REFERENCES

1. Kaleps, I., Obergefell, L.A. and Ryerson, J.R., "Simulation of Restrained Occupant Dynamics During Vehicle Rollover," DOT Report No. HS-807-049, June 1986.

2. Obergefell, L.A., Rizer, A.L. and Kaleps, I., "Simulations of Rollover Tests," DOT Report No. HS-807-372, May 1988.

3. Rizer, A.L., Obergefell, L.A., and Kaleps, I., "Simulations of Vehicle Dynamics During Rollover," DOT Report No. HS-807-587, May 1989.

4. Segal, D. and Kamholz, L., "Developments of a General Rollover Test Device," DOT Report No. HS-806-550, September 1983.

5. Stultz, John C., "Modifications to the NHTSA General Purpose Rollover Test Device," Transportation Research Center of Ohio, January 1989.

DISCUSSION

PAPER: **Vehicle & Occupant Response in Roll-over Crash Tests**

SPEAKER: Louise Obergefell, Wright Patterson AFB

QUESTION; Jeff Pike, Ford Motor Co.

You mentioned towards the end that the test program was designed to represent a number of different types of crashes rather than a single crash so that they were all comparable. Could you give a little more detail if the tests were designed to represent a type of crash that was typical or some type of extreme.

A: They are really designed to determine what's likely to happen to an occupant in roll-overs especially in developing computer simulation capabilities. So we were really were just looking for tests that had rollovers with comparable angular velocities and accelerations that would be in the real world. They weren't set up to match any particular real world event and of course with RTD your initial conditions are quite questionable. I think the range, especially the angular velocities, are in the right range.

Q: Would you know if any of the tests were comparable to some of the existing standardized test conditions.

A: Unfortunately, I'm not familiar with the standardized testing procedures.

Q: Ed Kennedy, Consulting Engineer

I question your third conclusion where the shoulder belt did not effect the dummy and you made a statement that you didn't think it was activated because of low g's. Did you compare the g's of the vehicle at the time the dummy was moving?

A: Yes, we have the acceleration levels, we looked at those and we've also looked at the shoulder belt payouts and in most cases the belts weren't locking.

Q: And were the g's above .5 g? In which case the belts should have locked. I question what you had in the belt system then.

A: They were the standard belt systems that were in the vehicles. You have to remember the g's usually are in the Y-direction.

Q: Well, it'll activate in any direction, I question that because I can't accept...

A: I can understand that and it made us wonder but we were still getting payout...

Q: The occupant isn't going to have any less g's than the vehicle and if the vehicle is over .5g, then the occupant should be locked in.

A: Typically what we would see is belt payout all through the event, in and out, usually the dummy isn't loading it so it's hard to tell perhaps was locked ...that was still in the free play of the inertial mechanism. But we didn't have any instrumentation measuring locking so we're drawing our conclusion from seeing the belt displacement.

Q: Mike Walsh, Hartley Associates

I get the impression the 24 roll-overs were done being very closely tied in with simulation. How did your simulation efforts over those long time periods compare with the experimental data?

A: We've done a number of simulations especially with the earlier tests. We've gotten very good comparison with the occupant simulations, we're still working on the later simulations, especially with the pickup trucks. We've done a lot of simulations with the cars; we're also looking at simulating actually the vehicle motion and with the ATB and CVS model and in general, we've gotten reasonable results.