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Summary of Rollover Crash Tests

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This technical report has been reviewed and is approved for publication.

FOR THE DIRECTOR

F. Wesley

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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 (contract # DTNH22-87-X-07477) 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 a 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 from high-speed cameras mounted both inside the vehicle and on the ground. The testing procedures are described along with the modifications to the procedures to improve control and consistency of the rollover. A summary of the general test results is presented, on the vehicle and occupant motions, and the vehicle damage. Finally the lessons learned about this type of testing are presented, along with recommendations for future testing.

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SUMMARY

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 (contract # DTNH22-87-X-07477) 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 a 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 from high-speed cameras mounted both inside the vehicle and on the ground. The testing procedures are described along with the modifications to the procedures to improve control and consistency of the rollover. A summary of the general test results is presented, on the vehicle and occupant motions, and the vehicle damage. Finally the lessons learned about this type of testing are presented, along with recommendations for future testing.

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INTRODUCTION

Rollover accidents are receiving increasing attention in the field of automobile safety by the National Highway Traffic Safety Administration (NHTSA). There were more than 9,600 rollover fatalities in passenger cars, pickup trucks, passenger vans, and utility vehicles in 1989. Of these fatalities, thirty-eight percent were not ejected, with most being killed by impact with the interior of the vehicle. Of special concern are small pickup trucks and light vans, because of the high frequency of their involvement in rollover crashes. Over several years a number of full-scale rollover tests have been sponsored by NHTSA to investigate vehicle and occupant dynamics during rollover events. The tests were also set up to provide data for predictive computer simulations of both the vehicle and occupant motions. References [1], [2] and [3] provide results of such simulations. Table 1 contains a list of the full-scale tests conducted. All of the tests were conducted at Transportation Research Center of Ohio (TRC), except for the first test in 1983 which was conducted at Southwest Research Institute (SWRI). For each test the NHTSA data tape number is given with the type of test and its date. 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. This report contains a general summary of the testing procedures and results for all these rollover tests. In nineteen of the tests a Rollover Test Device (RTD)[4] was used to initiate the rolling motion. The remaining tests consisted of three guardrail and two pole impact tests. Most of the vehicles were small pickup trucks and light vans. These vehicles were chosen because of the high frequency in which they are involved in rollover accidents. The particular vehicles used were chosen based on availability, previous testing experience with the vehicle, and other testing considerations.

Table 1. Rollover Tests

Test #	Vehicle	Test Type	Data Tape #	Date
G1	1981 Dodge Aries 4-Door	Guardrail	a	11-03-83
D1	1975 Ford Pinto	RTD	a	01-08-85
D2	1981 Plymouth Reliant K	RTD	V1546	05-23-85
D3	1984 Honda Accord	RTD	V878	11-13-85
D4	1982 Chevrolet Celebrity	RTD	V888	01-10-86
D5	1979 Dodge Omni Hatchback	RTD	V920	03-21-86
D6	1982 Mercury Zephyr	RTD	V939	05-05-86
D7	1988 Nissan Standard Pickup	RTD	V1274	06-30-88
D8	1988 Dodge Caravan	RTD	V1266	07-14-88
D9	1988 Chevrolet Standard Bed Pickup	RTD	V1267	08-17-88
D10	1988 Ford Bronco	RTD	V1255	09-23-88
D11	1989 Nissan Standard Pickup	RTD	V1289	05-30-89
D12	1989 Dodge Colt Hatchback	RTD	V1471	09-18-89
D13	1989 Dodge Caravan	RTD	V1391	10-25-89
D14	1989 Ford Bronco II	RTD	V1392	11-13-89
D15	1989 Nissan Standard Pickup	RTD	V1393	11-16-89
D16	1989 Nissan Standard Pickup	RTD	V1394	11-22-89
D17	1989 Pontiac Grand Am	RTD	V1395	11-29-89
P1	1988 Dodge Caravan	Pole	V1516	08-20-90
D18	1988 Dodge Ram Pickup	RTD	V1521	08-27-90
D19	1988 Ford Ranger Pickup	RTD	V1520	09-05-90
G2	1988 Nissan Standard Pickup	Guardrail	V1531	09-10-90
P2	1988 Nissan Standard Pickup	Pole	V1522	09-14-90
G3	1988 Dodge Caravan	Guardrail	V1530	10-10-90

a. Data tapes are not available for these tests. However, the test report and the high-speed films are available from the NHTSA.

TEST CONFIGURATIONS

The vehicles in the RTD tests were mounted on the RTD, as shown in Figure 1, with an initial roll angle of 30 degrees. The RTD was towed by cable along a guide-rail to obtain a specified initial velocity. After reaching the start 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 velocity. 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 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. Figure 3 shows the 1988 Ford Bronco from test D10 mounted on the RTD with -45° yaw. 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.

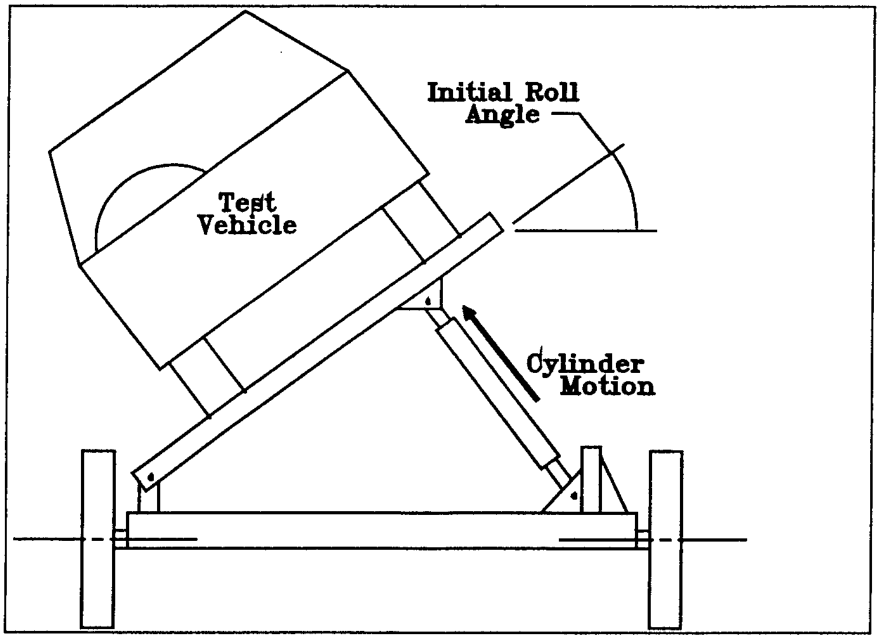

Figure1. Test Vehicle Mounted on the Rollover Test Device

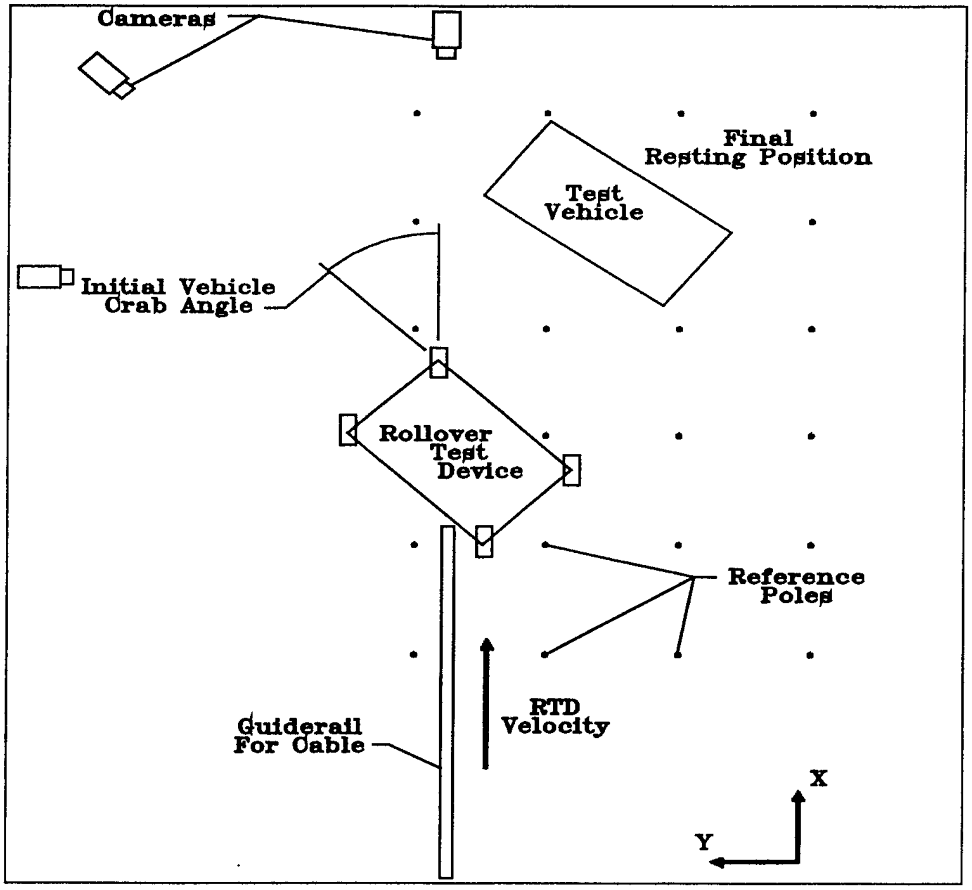

Figure 2. RTD Test Layout

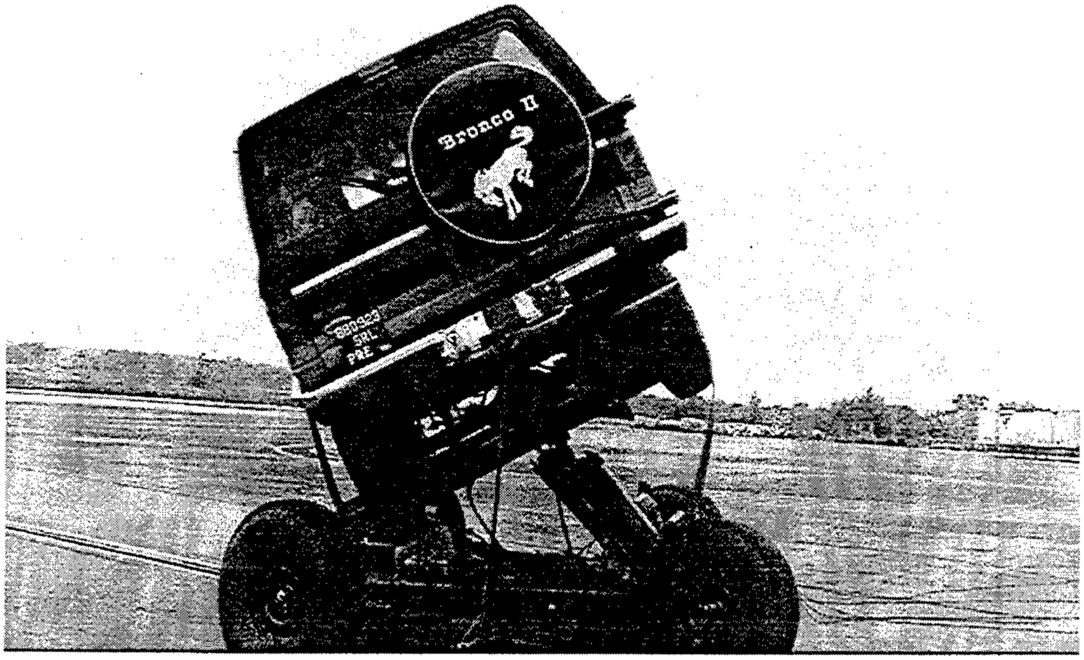

Figure 3. Ford Bronco Mounted on RTD With -45° Yaw

In the guardrail impact tests, the vehicle was towed by cable about a pulley to obtain the specified initial velocity. A stationary cable was used to control any lateral movement of the vehicle. Several feet in front of the guardrail, the vehicle was released from the towing cable and allowed to run up the turned down end of the guardrail (Figure 4). The guardrail was positioned to be 15 inches offset from the vehicle centerline on the driver's side. The guardrail forced the vehicle upward and induced a rolling moment. A grass surface surrounded the guardrail. The complete test layout for the G2 and G3 guardrail impact tests is depicted in Figure 5. A similar test layout was used for the G1 guardrail impact test which had a dirt and grass test area.

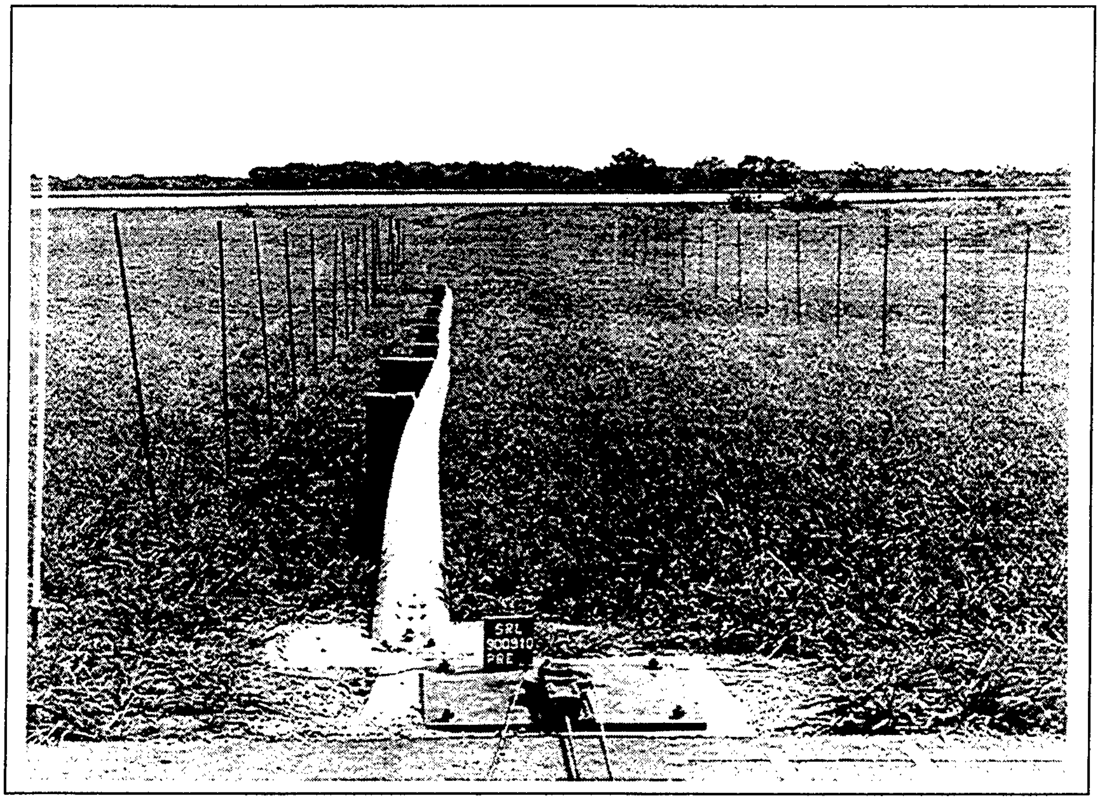

Figure 4. Guardrail Construction

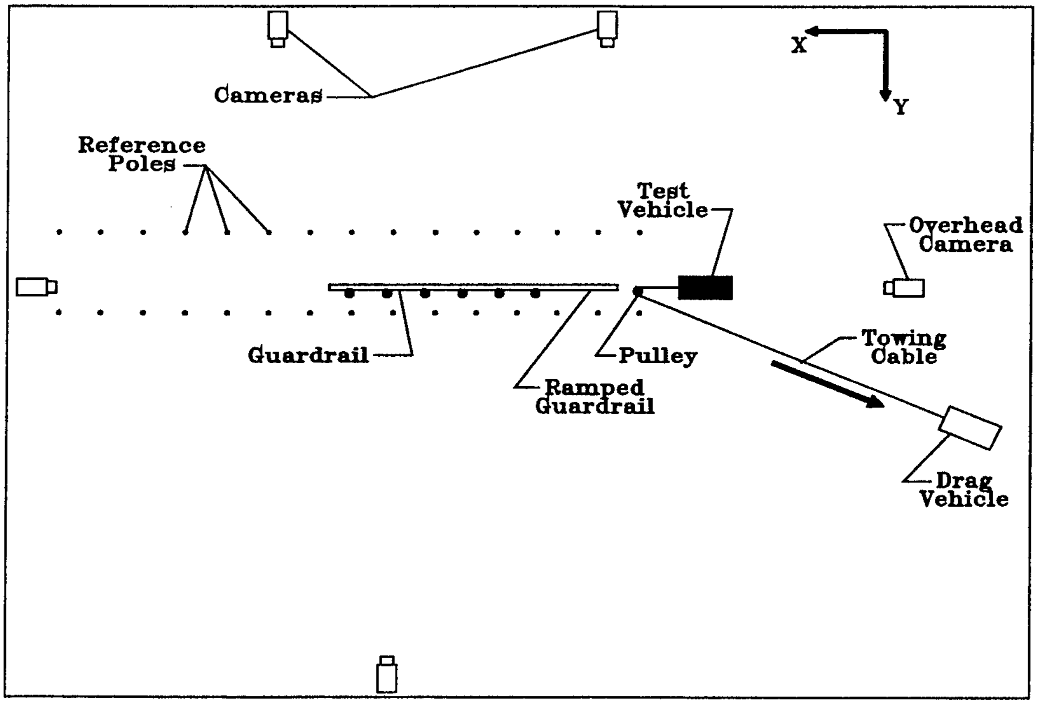

Figure 5. Guardrail Impact Test Layout

In the pole impact tests, the vehicle was towed laterally by cable on an asphalt surface to obtain the specified initial velocity. The surface was soaped to allow the vehicle's wheels to slide without the vehicle becoming unstable. Immediately prior to impact, the vehicle was released from the cable. The initial impact was between the driver's side wheels and two eight-inch-high steel plate curbs. As shown in Figure 6, the curbs were positioned to initiate the vehicle's roll. A 12-inch diameter instrumented steel pole was positioned 75.5 inches beyond the curbs. The pole was placed approximately aligned with the vehicle's longitudinal center of mass and at a distance from the curbs that would cause the vehicle to impact the pole during its rolling motion.

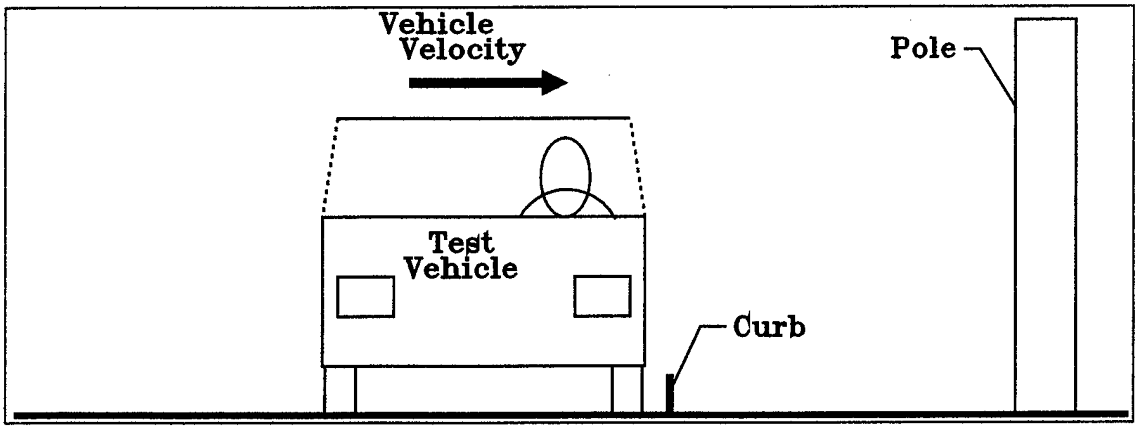

Figure 6. Pole Impact Test

The specific test conditions for each test are listed in Table 2. 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.

Table 2. Rollover Test Conditions

Test #	Vehicle	Vehicle Crab Angle (deg)	First Impact Side	Speed (mph)[a]	Surface	Dummy Position	Restraint
D1	Ford Pinto	-45	Left	17	Concrete	Driver	3-Point ?
D2	Plymouth Reliant	-45	Left	21	Concrete	Driver	3-Point Friction
D3	Honda Accord	-45	Left	21	Concrete	Driver	None
D4	Chevy Celebrity	-45	Left	23	Concrete	Driver	None
D5	Dodge Omni	-45	Left	23	Concrete	Passenger	None
D6	Mercury Zephyr	-60	Left	23	Concrete	Passenger	None
D7	Nissan Pickup	-45	Left	30	Concrete	Driver	3-Point D-Ring
D8	Dodge Caravan	-45	Left	30	Concrete	Passenger	3-Point Friction
D9	Chevy Pickup	-45	Left	30	Concrete	Passenger	None
D10	Ford Bronco	-45	Left	30	Concrete	Driver	None
D11	Nissan Pickup	-45	Left	30	Mat	Driver	3-Point D-Ring
D12	Dodge Colt	0	Right	30	Mat	Driver	None
D13	Dodge Caravan	45	Right	30	Mat	Passenger	3-Point D-Ring
D14	Ford Bronco	90	Right	30	Mat	Driver	3-Point Friction
D15	Nissan Pickup	90	Right	30	Mat	Driver	3-Point D-Ring
D16	Nissan Pickup	90	Right	30	Mat	Driver	3-Point D-Ring
D17	Pontiac Grand Am	90	Right	b	Mat	Driver	3-Point, 2 belts
D18	Dodge Ram	90	Right	30	Mat	Driver	3-Point ?
D19	Ford Ranger	90	Right	30	Mat	Driver	3-Point Friction
G1	Dodge Aries	0	Right	60.3	Dirt & Grass	Passenger	3-Point Friction
G2	Nissan Pickup	0	Right	58.4	Grass	Driver	3-Point D-Ring
G3	Dodge Caravan	0	Right	50.5	Grass	Driver	3-Point Friction
P1	Dodge Caravan	-90	Left	30	Concrete	Driver	3-Point Friction
P2	Nissan Pickup	-90	Left	30	Concrete	Driver	3-Point D-Ring

a. For the RTD test, speed refers to the speed of the RTD.

b. Rollover Test Device failure. Data unavailable.

Instrumentation

When used, 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. The pole in the pole impact tests was instrumented to measure the forces acting on it. Figure 7 shows the location of the four pole load cells. All the vehicles were instrumented to collect the three-dimensional vehicle center of mass accelerations and angular velocities. Also collected were the suspension displacements at all four wheels. The locations and coordinate systems for the vehicle instrumentation are listed in Table 3. 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 accelerations, three-dimensional neck forces and moments, and chest displacement. Femur loads were also measured in some of the earlier tests. The locations and coordinate systems for the dummy instrumentation are listed in Table 4. When the dummy was restrained, the belt displacement at the belt feed-out point was also measured. A description of the data filtering used for these tests is included in Appendix A.

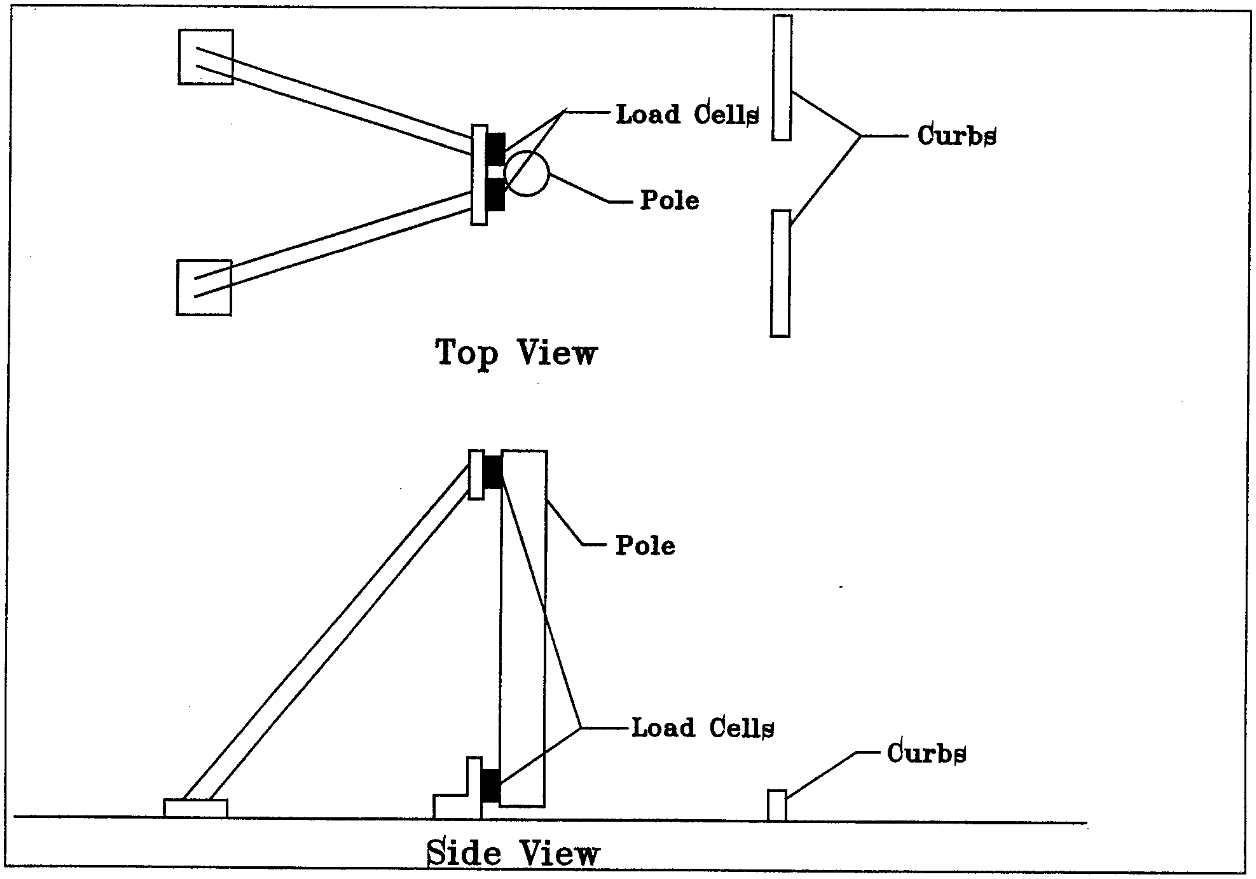

Figure 7. Pole Load Cell Locations

Table 3. Vehicle Instrumentation

Vehicle Accelerometer
Located near vehicle center of gravity
X: + forward
Y: + leftward
Z: + upward

Vehicle Angular Rate Gyro
Located near vehicle center of gravity
Roll : + to right when facing forward
Pitch: + front downward
Yaw : + Counterclockwise when facing downward

Suspension Potentiometer
Located at axle close to wheel
Displacement: + outward

Belt Potentiometer
Located close to payout point
Displacement: + outward

Table 4. Dummy Instrumentation

Head, Chest, and Pelvis Accelerometers
Longitudinal X: + forward
Lateral Y: + leftward
Vertical Z: + upward

Neck Load Cells
Forces
Longitudinal X: + head forward
Lateral Y: + head rightward
Vertical Z: + head upward, neck tension

Moments
About longitudinal X: + right ear to right shoulder
About lateral Y: + head rotating forward
About vertical Z: + head rotating leftward

Chest Potentiometer
Longitudinal displacement: + outward

Femur Load Cell
Axial force: + tension

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. Four exterior cameras were used in the pole impact tests, including an overhead camera not shown in Figure 8, and five cameras were used in the guardrail impact tests (Figure 5). 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 focusing 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 the lack of a safe mounting position. Break-away reference poles were placed throughout the test areas to provide a gauge for measuring the vehicle motion from the films.

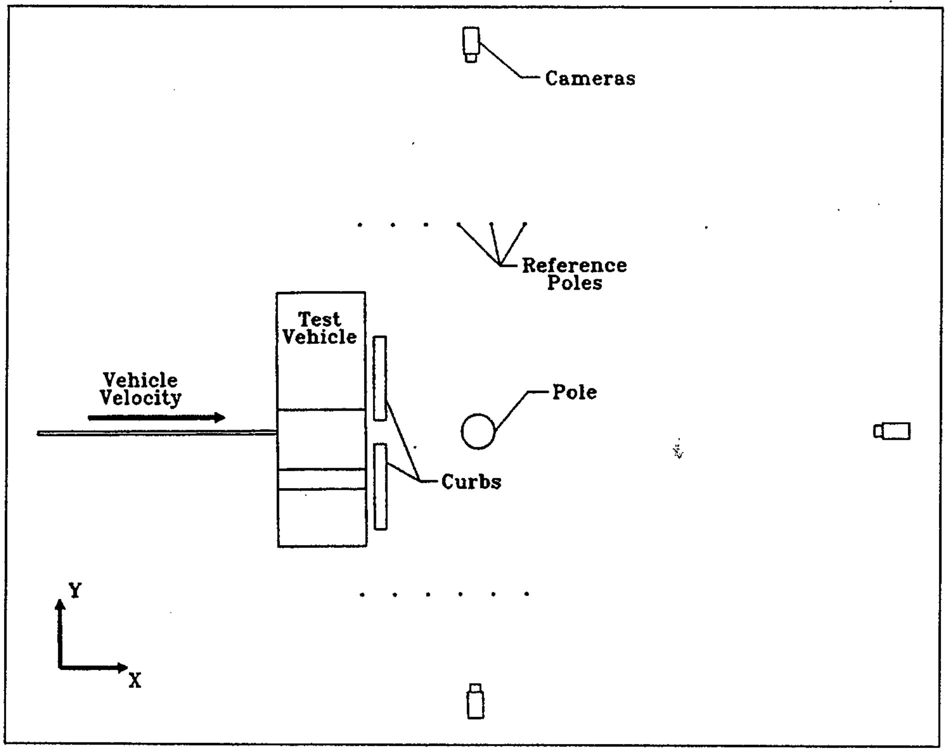

Figure 8. Pole Impact Test Layout

Vehicle Mass Properties

The motion of a vehicle during a rollover is affected by the mass properties of a vehicle. To study the effects of these properties, 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 how the vehicle damage affects the mass properties. Table 5 contains these mass properties for the vehicles before testing and Table 6 contains the properties after testing. The coordinate system used for the vehicle measurements is defined as positive X pointing forward, positive Y pointing left, and positive Z pointing up.

Table 5. Vehicle Mass Properties Before Testing

Test #	Vehicle	Weight (lb)	Center of Mass (in)			Moments of Inertia (ft-lb-s^2)		
			X[a]	Y[b]	Z[c]	X	Y	Z
D7	Nissan Pickup	3140	50.8	-0.8	23.6	335.9	1706.0	1812.0
D8	Dodge Caravan	3424	47.9	0.6	25.8	514.5	2160.0	2288.7
D9	Chevy Pickup	4087	53.5	-0.4	27.6	513.7	2615.4	2782.5
D10	Ford Bronco	3810	48.9	-0.4	28.6	424.6	1965.2	1928.0
D11	Nissan Pickup	3156	52.0	-0.1	23.0	336.3	1963.4	1986.1
D12	Dodge Colt	2422	39.5	-0.4	20.3	281.2	1209.2	1239.5
D13	Dodge Caravan	3512	48.5	-0.6	24.9	603.4	2426.4	2420.4
D14	Ford Bronco	3927	51.8	0.1	28.9	414.1	2056.2	1965.3
D15	Nissan Pickup	3110	51.6	0.0	23.6	381.0	2058.7	1913.8
D16	Nissan Pickup	3173	51.9	-0.2	23.8	363.4	1887.1	1880.5
D17	Pontiac Grand Am	2836	41.7	-1.0	21.6	321.9	1645.8	1664.7
D18	Dodge Ram	3109	53.0	-0.6	21.6	328.5	1933.7	2004.7
D19	Ford Ranger	3084	51.0	-0.2	24.5	322.0	1872.3	1971.0
G2	Nissan Pickup	3091	50.8	-0.2	22.8	335.2	1808.5	1922.4
G3	Dodge Caravan	3691	49.3	-1.2	24.8	568.3	2483.7	2548.5
P1	Dodge Caravan	3614	49.1	0.2	24.7	552.0	2511.6	2569.1
P2	Nissan Pickup	3164	51.2	-0.7	22.7	354.7	1896.7	2007.6

a. Distance from front axle. b. Distance from center line. c. Center of mass height, measured from the ground.

Table 6. Vehicle Mass Properties After Testing

Test #	Vehicle	Weight (lb)	Center of Mass (in)			Moments of Inertia (ft-lb-s^2)		
			X^a	Y^b	Z^c	X	Y	Z
D7	Nissan Pickup	3070	51.6	-1.8	22.9	323.1	1671.9	1743.3
D8	Dodge Caravan	3341	48.6	0.7	25.6	541.7	2132.0	2183.9
D9	Chevy Pickup	4092	53.0	-0.5	26.6	538.8	2648.8	2678.8
D10	Ford Bronco	3712	48.5	-0.2	28.0	422.3	1913.8	1860.2
D11	Nissan Pickup	3124	53.5	0.0	22.6	328.8	1891.0	1901.3
D12	Dodge Colt	2369	39.7	-0.7	20.1	258.8	1168.5	1285.5
D13	Dodge Caravan	3466	49.3	-1.2	24.5	528.7	2338.8	2284.7
D14	Ford Bronco	3838	52.0	2.8	26.5	403.1	1923.5	1934.5
D15	Nissan Pickup	3053	51.3	0.1	22.5	329.3	1848.2	1814.8
D16	Nissan Pickup	3110	50.9	0.6	21.6	325.6	1790.2	1844.3
D17	Pontiac Grand Am	2829	41.5	-0.7	18.8	325.5	1654.8	1646.1
D18	Dodge Ram	3047	53.3	1.3	19.1	313.1	1841.9	1977.9
D19	Ford Ranger	3020	51.2	-0.6	23.5	288.8	1837.1	1950.1
G2	Nissan Pickup	3092	51.2	-0.6	21.8	333.4	1764.0	1895.7
G3	Dodge Caravan	3690	48.8	-0.5	22.3	581.4	2435.4	2557.2
P1	Dodge Caravan	3596	49.0	-6.6		508.0	2264.9	2353.2
P2	Nissan Pickup	3070	51.2	-5.0	20.7	315.8	1842.0	1985.4

a. Distance from front axle. b. Distance from center line. c. Center of mass height, measured from the ground.

TEST RESULTS

Summary data from the tests is presented here to provide general information on the tests. More complete results can be obtained from the films, data tapes and test reports from each test.

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 tests. Table 7 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. As the trucks continued to roll, the roof collapsed as it contacted the ground. Most of the pickups slid to a stop on their roof, while some still had enough angular kinetic energy to roll back onto their wheels. The Dodge Caravan in test D8 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 (Figure 9), while in the other van tests only the roof sustained serious damage. 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.

Table 7. Vehicle Motion and Damage

Test #	Vehicle	# of 1/4 Rolls	Distance Traveled (ft)[a]		Vehicle Damage	Maximum Crush (in)
			X	Y		
D1	Ford Pinto	4	29	3	Hood bent up	-4.2 hood
D2	Plymouth Reliant	6	25	11	Roof crush	3.8 roof
D3	Honda Accord	2	25	11	Roof crush	3.9 roof
D4	Chevy Celebrity	4	84	12	Minor	
D5	Dodge Omni	2	74	8	Roof crush	5.1 roof
D6	Mercury Zephyr	2	89	9	Roof crush	7.5 roof
D7	Nissan Pickup	6	110	5	Roof collapse	14.5 roof
D8	Dodge Caravan	1	124	8	Left side crush	7.4 side
D9	Chevy Pickup	4	189	-1	Roof crush	3.6 roof
D10	Ford Bronco	2	136	5	Roof & left side crush	10.9 roof, 7.5 side
D11	Nissan Pickup	2	123	5	Complete roof collapse	13.9 roof
D12	Dodge Colt	2	116	-23	Windshield & right side crush	4.1 roof, 5.1 side
D13	Dodge Caravan	8	130	-16	Roof collapse	15.3 roof
D14	Ford Bronco	8	105	10	Complete roof & right side collapse	14.5 roof, 7.4 side
D15	Nissan Pickup	4	137	6	Complete roof collapse	14.1 roof
D16	Nissan Pickup	4	92	8	Complete roof & left side collapse	17.2 roof
D17	Pontiac Grand Am	2	117	27	Roof crush	6.8 roof
D18	Dodge Ram	4	90	5	Complete roof collapse	15.6 roof
D19	Ford Ranger	2	126	1	Complete roof collapse	18.5 roof
G1	Dodge Aries	16	N/A	N/A	N/A	N/A
G2	Nissan Pickup	4	210	-8	Roof & left side crush	11.5 roof
G3	Dodge Caravan	0[b]	158	-27	Minor	
P1	Dodge Caravan	1	N/a	n/a	Complete left side & roof cave-in	25.4 side
P2	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.

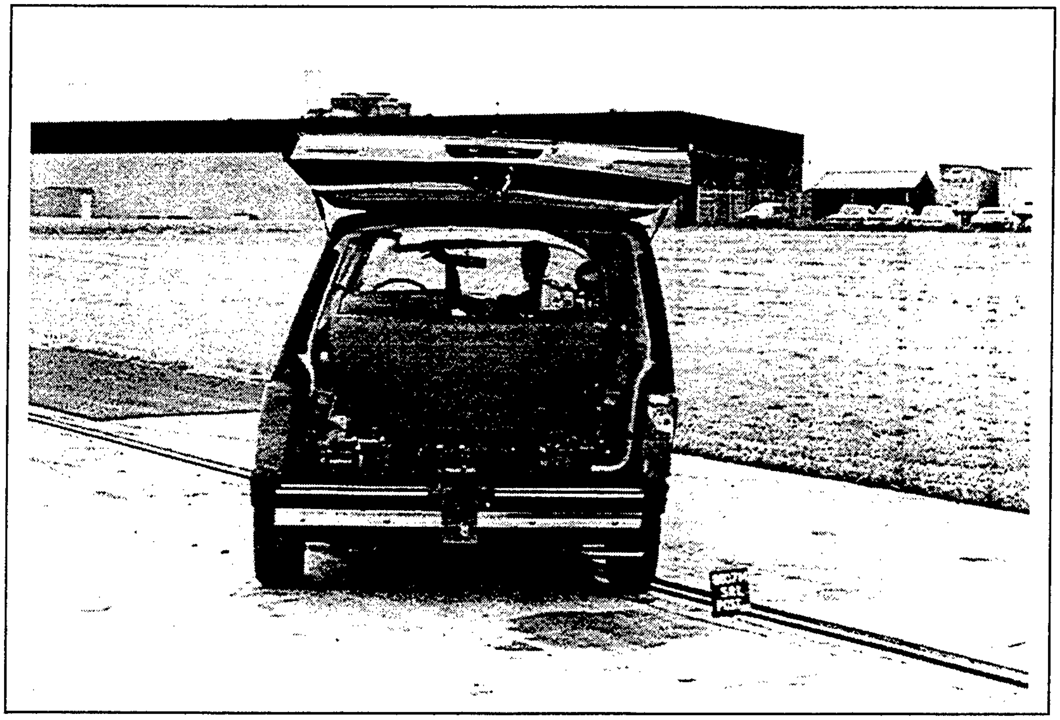

Figure 9. Test D8 Dodge Caravan Damage

The Nissan Pickup in the G2 guardrail test rolled onto its right side after impacting the guardrail. It slid on its side and roof on the wet grassy surface, and finally rolled completely over, landing on its wheels and coming to a stop. On the other hand, the Dodge Caravan in the G3 test rolled onto its right side after impacting the guardrail and slid along the guardrail. As it came to the end of the guardrail, the vehicle's right wheels caught the grass or a soft spot in the surface. This yawed the vehicle to the right and then the forward momentum of the vehicle forced the vehicle back onto its wheels. The wet grass in both of these guardrail tests may have resulted in a low coefficient of friction and the minimal rolling.

In setting up the pole impact tests, several trial tests were conducted with previously tested Dodge Caravans. These trial tests were used to determine the curb height and velocity needed to initiate roll of the vehicle, and the distance between the curb and pole required for the vehicle to impact the pole on the driver's side roof. The results of the trial tests varied from the vehicle skipping the curbs and barely rolling before pole impact to the vehicle bouncing up from the curbs, rolling completely to its side and landing on the curb without reaching the pole. In the trial tests, the curb height was increased from 5 to 8 inches to catch the wheel rim, and the curb material was changed from concrete to steel to avoid curb failure. Also the impact velocity was varied to investigate its effects. The curb in the P1 pole impact test did initiate significant roll and the Caravan impacted the pole after rolling approximately 45°. The driver's side and roof sustained major damage as the vehicle wrapped itself around the pole (Figure 10). The same conditions were used in the P2 pole impact test, but the Nissan Pickup behaved differently. Upon impact with the curb, the truck flew more than six feet into the air and quickly rolled completely upside down. As the vehicle started to come down, the right passenger side hit the pole, causing the pickup to yaw about the pole. The pickup landed upside down on top of its rear wheel, which broke free during the curb impact (Figure 11). The maximum loads on the pole are listed in Table 8. In both tests the impacting wheels suffered major damage, as they were bent at the axle. These results demonstrate the difficulty in predicting the vehicle response in this test configuration and the resulting difficulty in choosing the test conditions. When the curb was not high enough or the velocity was too high, the wheels skipped the curb and no rolling motion occurred. Other conditions caused the wheels to be stopped, transferring all the linear kinetic energy to angular kinetic energy, and the vehicle would fly into the air, rolling rapidly with little forward motion. The ideal vehicle response would have been for the wheels to skip the curb, while slowing down enough for the rest of the vehicle to roll over them, initiating enough rolling motion to tip the vehicle just before impact with the pole.

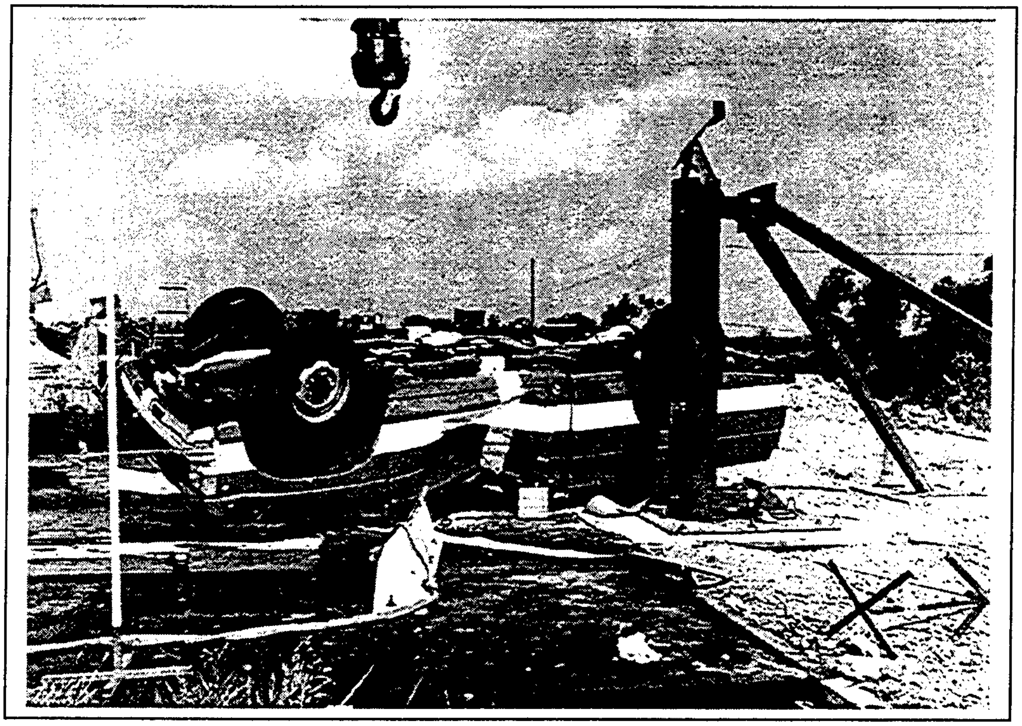

Figure 10. Dodge Caravan Pole Impact Test Final Position

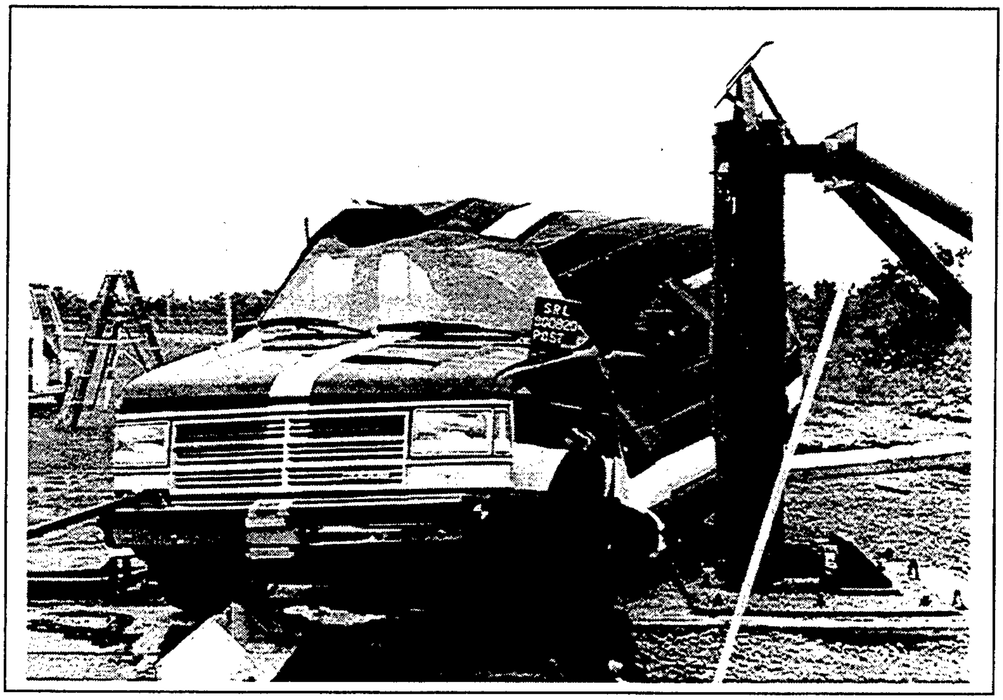

Figure 11. Nissan Pickup Pole Impact Test Final Position

Table 8. Maximum Pole Loads

Test #	Vehicle	Maximum Pole Load (lb)			
		Top Left	Top Right	Bottom Left	Bottom Right
P1	Dodge Caravan	-5,400	-5,800	-10,100	-5,300
P2	Nissan Pickup	-1,900	-4,000	-4,000	-5,000

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. Table 9 lists the maximum accelerations measured at the vehicle center of mass during the rollover tests. The accelerations experienced in the RTD tests increased in the later tests. This is most likely due to the improvements made to the RTD that increased the rotational energy imparted to the vehicle upon its release. As demonstrated by the vehicle accelerations, the pole impact tests were very severe, while the guardrail impact tests were less severe than the other tests. The maximum vehicle angular velocities in Table 9 are less revealing, varying greatly between tests with little relationship to the number of rolls made by the vehicle.

Table 9. Vehicle Accelerations and Angular Velocities

Test #	Vehicle	Maximum Center of Mass Acceleration (g)			Maximum Center of Mass Angular Velocity (deg/sec)		
		X	Y	Z	X	Y	Z
D1	Ford Pinto	a	a	a	a	a	a
D2	Plymouth Reliant	9.2	17.1	15.2	349.7	73.0	40.3
D3	Honda Accord	8.4	19.3	8.4	1152.1	121.4	88.0
D4	Chevy Celebrity	5.6	62.9	13.3	a	108.0	73.5
D5	Dodge Omni	5.7	12.0	14.8	206.0	93.5	80.6
D6	Mercury Zephyr	3.9	9.8	7.5	149.4	88.5	15.5
D7	Nissan Pickup	4.2	12.9	14.1	296.9	203.9	125.3
D8	Dodge Caravan	5.5	10.9	11.5	276.1	139.8	120.1
D9	Chevy Pickup	10.3	9.0	26.6	292.4	248.5	125.2
D10	Ford Bronco	18.4	11.3	13.4	a	137.1	64.2
D11	Nissan Pickup	11.0	12.9	17.9	408.7	117.8	56.9
D12	Dodge Colt	17.9	17.8	12.9	233.9	344.6	275.5
D13	Dodge Caravan	20.6	28.9	20.5	319.3	78.9	46.2
D14	Ford Bronco	26.4	37.9	44.9	449.4	159.5	98.0
D15	Nissan Pickup	11.6	14.9	20.6	380.1	203.8	183.5
D16	Nissan Pickup	27.1	15.4	20.8	452.8	225.2	a
D17	Pontiac Grand Am	9.2	9.2	13.4	230.7	103.1	120.2
D18	Dodge Ram	12.6	36.0	24.9	623.2	195.7	164.5
D19	Ford Ranger	51.2	17.7	21.4	226.4	50.3	81.2
G1	Dodge Aries	a	a	a	a	a	a
G2	Nissan Pickup	7.6	13.9	9.0	316.2	38.0	75.2
G3	Dodge Caravan	18.4	15.4	14.8	161.9	46.0	154.7
P1	Dodge Caravan	26.7	54.2	30.0	690.4	489.8	711.5
P2	Nissan Pickup	11.8	31.2	12.4	433.9	158.5	155.1

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, as shown in Table 10. Head contacts with the roof occurred in virtually all the tests. 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, D9 and D12, the body fell to the opposite side of the vehicle. Because of the number of rolls and lack of roof deformation in the D9 test, the dummy continued to bounce around the truck cab. In the D12 test the roof collapsed, trapping the dummy against the seat. In the remaining 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 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 tests D16 and D19, 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 low vehicle accelerations, the belts did not lock up. The vehicles' rolling motion and the collapse of the roof generally kept the dummy's body upright. The dummy's motion in the P2 test was similar to the RTD tests, but in the P1 test, the dummy and its seat were completely crushed by the pole. The body motions in the guardrail tests were very benign.

Table 10. Occupant Contacts

Test #	Vehicle	Dummy Contacts				
		Head	**Chest**	**Left Knee**	**Right Knee**	**Ejection**
D1	Ford Pinto	L Door & Camera	L Door	L Door	Steering Column	-
D2	Plymouth Reliant	Roof & L Side Headliner	L Door & B-Pillar	L Door	Steering Column	-
D3a	Honda Accord	Roof, R Seat & L Side Header	L Door & Window	L Door	-	-
D4	Chevy Celebrity	Roof & L Side Headliner	L Door & Window	L Door	-	-
D5	Dodge Omni	Roof & Header	Header	-	-	-
D6	Mercury Zephyr	L Window, Sill & Seat	Header	-	-	-
D7	Nissan Pickup	Roof & L Side Headliner	L Door	-	-	-
D8	Dodge Caravan	R B-Pillar	R Door	-	-	-
D9	Chevy Pickup	Seatback & Roof	-	Knee Blocker	R Door	-
D10	Ford Bronco	Roof & L Side Headliner	-	Knee Blocker	R Door	-
D11	Nissan Pickup	Roof & L Side Headliner	L Door	-	-	L Arm - L Window
D12	Dodge Colt	Roof	-	Instrument Panel	Passenger Front Seat	-
D13	Dodge Caravan	Roof & B-Pillar	-	-	R Door	R Arm - R Window
D14	Ford Bronco	L B-Pillar & Roof	Roof & China	L Door	-	-
D15	Nissan Pickup	Roof	Head	L Door & Steering Wheel	Steering Wheel	-
D16	Nissan Pickup	Roof, Window Sill & Ground	Roof	L Door & Steering Column	-	Head & L Arm - L Window
D17	Pontiac Grand Am	Roof	-	Steering Wheel & L Door	Steering Wheel	-
D18	Dodge Ram	Roof	L Door	L Door	Steering Column	L Hand – L Window

Table 10 (continued). Occupant Contacts

Test #	Vehicle	Dummy Contacts				
		Head	**Chest**	**Left Knee**	**Right Knee**	**Ejection**
D19	Ford Ranger	Roof & Ground	Roof	L Door	Steering Column	Head – L Window
G1	Dodge Aries	Roof, R Window & Seatback	Driver Seat & R Door	R Door	R Door	-
G2	Nissan Pickup	Roof	-	-	Steering Column	-
G3	Dodge Caravan	L Window	L Door	L Door	Center Console	-
P1	Dodge Caravan	L B-Pillar & Roof	L Door & Passenger Seat Back	L Door	-	-
P2	Nissan Pickup	Roof, L B-Pillar & L Door	L Door	L Door	Steering Wheel	-

Table 11 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 and one of the pole impact tests is the HIC level above 1000. The chest accelerations are comparably low. 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 severity of the event. The neck forces and torques in 0 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 D11 and D13 are 156 and 120 respectively, while the neck loads exceeded 1000 lbs. Even more dramatic is test D16 where the HIC level is 774 and the neck experienced forces close to 3000 lbs and torques in excess of 200 in-lbs. (Table 12).

Table 11. Occupant Head & Chest Accelerations

Test #	**Vehicle**	**HIC**	**Maximum Head Acceleration (g)**			**Maximum Chest Acceleration (g)**		
			X	**Y**	**Z**	**X**	**Y**	**Z**
D1	Ford Pinto	a	a	a	a	a	a	a
D2	Plymouth Reliant	104	17.5	98.9	32.3	15.7	103.0	14.2
D3	Honda Accord	132	105.3	79.7	11.1	77.8	26.7	15.9
D4	Chevy Celebrity	15	9.1	14.8	13.5	8.3	23.5	7.8
D5	Dodge Omni	40	11.4	30.7	20.9	5.6	16.5	9.7
D6	Mercury Zephyr	58	55.4	14.9	18.1	8.6	9.1	7.1
D7	Nissan Pickup	229	15.6	77.2	21.0	8.3	27.9	14.4
D8	Dodge Caravan	18	5.9	9.4	18.6	9.8	11.0	14.0
D9	Chevy Pickup	55	28.6	41.4	21.4	13.9	24.9	12.5
D10	Ford Bronco	240	14.0	77.0	34.2	57.6	116.3	a
D11	Nissan Pickup	156	24.3	50.1	31.3	13.5	15.0	18.0
D12	Dodge Colt	81	18.9	44.3	119.6	7.8	11.2	15.9
D13	Dodge Caravan	220	12.2	89.7	27.0	8.0	5.5	19.8
D14	Ford Bronco	2140	24.7	63.2	399.7	33.6	29.9	77.3
D15	Nissan Pickup	1049	81.2	58.1	142.5	35.4	25.1	90.3
D16	Nissan Pickup	774	34.9	110.9	147.8	22.8	21.7	77.9
D17	Pontiac Grand Am	89	12.8	a	a	14.5	6.6	30.9
D18	Dodge Ram	3015	174.6	86.6	250.2	58.9	24.7	313.4
D19	Ford Ranger	938	175.9	246.9	122.3	28.1	45.5	51.6
G1	Dodge Aries	a	a	a	a	a	a	a
G2	Nissan Pickup	42	11.9	20.4	44.3	11.9	11.2	21.7
G3	Dodge Caravan	154	23.3	46.1	30.3	9.3	21.9	18.7
P1	Dodge Caravan	1328	230.7	190.9	163.4	72.0	99.6	57.5
P2	Nissan Pickup	426	24.5	71.5	48.9	25.5	52.9	15.1

a. Data unavailable

Table 12. Neck Loads

Test #	Vehicle	Maximum Neck Force (lb)			Maximum Neck Moment (in lb)		
		X	Y	Z	X	Y	Z
D1	Ford Pinto	C	c	c	c	c	c
D2	Plymouth Reliant	C	c	c	c	c	c
D3	Honda Accord	C	c	c	c	c	c
D4	Chevy Celebrity	104.4	d	552.3	d	18.1	d
D5	Dodge Omni	118.1	d	754.8	d	28.7	d
D6	Mercury Zephyr	171	d	492.9	d	42.4	d
D7	Nissan Pickup	63	134.8	243.9	325.6	260.9	168.4
D8	Dodge Caravan	22.5	72	155.4	133.4	122.6	55.5
D9	Chevy Pickup	81.6	131.4	591.1	25.8	35.6	15.2
D10	Ford Bronco	45	204.8	263.1	80.4	19.5	8.5
D11	Nissan Pickup	362.5	244.6	1156.8	104.5	45.1	32
D12	Dodge Colt	153.5	209.9	787.9	44.4	22.4	32.3
D13	Dodge Caravan	120.2	246.9	1031.7	95.2	27.1	12.7
D14	Ford Bronco	283.9	655.2	2152.7b	222.6	69.7	57
D15	Nissan Pickup	1330.2	803.7	2116.6b	173.8	229.8	69.5
D16	Nissan Pickup	1174.2	1197.8	2960.2b	234.9	79.6	63.5
D17	Pontiac Grand Am	152.9	154.6	a	65.1	29.1	19.7
D18	Dodge Ram	2421.3	667.8	2644.6b	158.8	357.8b	64.6
D19	Ford Ranger	3054.5	716.1	2807.5	280.1	252.8	79.5
G1	Dodge Aries	C	c	c	c	c	c
G2	Nissan Pickup	283.3	242.3	942.2	26.1	20.1	6.6
G3	Dodge Caravan	82.4	113.8	259.9	26.9	14.9	15.3
P1	Dodge Caravan	2098.8	2889.1	2128.5	77.4	20.1	11.5
P2	Nissan Pickup	149.5	222.9	946.8	39.2	26.1	15

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.

CONCLUSIONS

These tests were conducted to develop consistent 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 make up a complete study in which statistical comparisons can be made between and among tests. They do provide a large amount of data on rollover, along with insights into what can happen during rollover and what factors need to be considered when developing 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, D15 and D16, 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 some rolling motion. Although the realism of these tests may be questionable, the RTD provides a somewhat controllable method of initiating roll and linear velocity, with conditions that are not unreasonable. The guardrail impact tests are more plausible events, but rollover is not always assured, as demonstrated in test G3. For future tests using the guardrail, it is recommended that the grass surface be compacted and leveled, to provide more consistent test conditions. The pole impact tests were highly unpredictable and need to be completely redesigned. The suspension system dynamics during the contact with the curbs depend on many factors that are difficult to determine or model. This and the precision required in selecting the test conditions make the tests 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 to lock the shoulder belt mechanisms, the shoulder belt will provide minimum restraint.

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 provided 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. They also raised many other questions, suggesting that future comprehensive testing and simulation studies are needed.

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APPENDIX A
DATA FILTERING IN TRC TESTS

In all the rollover tests conducted at TRC, the data were filtered using a 1650 Hz analog filter, then digitally sampled at 1000 samples/second. This sampling rate was chosen to accommodate the relatively long time span of the rollover tests. The filtering method is questionable, because the sampling rate is lower than the filtering frequency. To investigate the validity of the data filtered using this method, three methods of filtering were used by TRC with the data from a representative rollover test, the 16 November 1989, Nissan Pick-Up Truck Rollover (D15):

A. 1650 Hz analog filter, 1000 samples/second
B. 1650 Hz analog filter, 8000 samples/second
C. 300 Hz analog filter, 1500 samples/second

Method A is the process used in all of the TRC rollover tests described in this test report. Method B is the SAE J211 standard for impact tests. Because of the high sampling rate required, this method cannot be used with TRC's data collection system over the time span of the rollover tests. Therefore, only the data within the interval of 1.2 to 2.2 seconds was analyzed using Method B. Method C is an alternative method that has a good sampling-rate-to-filtering frequency ratio and will allow data to be collected over the entire rollover event.

The HIC values for this test using each of the three filtering methods are listed in Table A-1. Method B data have a time shift of approximately 0.015 seconds relative to the other two sets of data that is not due to the filtering methods. This can be seen in the HIC time intervals. This comes from the difficulty in precisely indexing the analog tape to a point other than zero time for the start of the data analyzed using Method B. It should also be noted that each of the three sets of digital data was read independently by TRC from the analog tape. Thus, the Method A data do not constitute a subset of the Method B data.

Table A-1. HIC Values For Test D15

Filtering Method	**HIC**	**Time Interval (seconds)**
A	1049.3	1.369 - 1.388
B	1026	1.384 - 1.402
C	1000	1.370 - 1.389

After taking into account these differences, two types of analysis were used to compare the three sets of data. First, the plots of all three sets of data were compared visually and the numerical values of minima and maxima were compared. The second type of analysis was used on several selected channels from all three data sets. The signal was integrated and the results of two successive integrations on corresponding channels were compared. Irrelevant spikes in the data would have no effect on the integrated curves, while meaningful spikes would change the shape of the integrated curves. Comparison of the integrated curves obtained from the different filtering methods showed no significant differences.

Overall, all three data sets compare very well. The Method C data curves are a little smoother, with less signal noise, than the Method B data curves, as expected. No significant signal information appears to be lost by analog filtering at 300 Hz. In visually analyzing very noisy signals, for instance the vehicle center of gravity accelerations, the 300 Hz filtered data actually represents the meaningful signal shape better.

Method C has also been used to filter the data from five other tests (D16, D18, D19, P1, and P2) in which the analog tapes were still available. HIC values for these tests, using filtering Method C and the original Method A, are listed in Table A-2. Again, there is a time shift of approximately 0.023 seconds in the P1 test data, as can be seen in the HIC time interval. In general, all five sets of data filtered by Method C compare well with the data filtered by Method A.

Table A-2. HIC Values Using Filtering Methods

Test #	Method C		Method A	
	HIC	Time Interval (sec)	HIC	Time Interval (sec)
D16	676	1.349 - 1.361	774.3	1.348 - 1.360
D18	3144	0.989 - 0.995	3014.8	0.987 - 0.992
D19	872	1.451 - 1.476	937.5	1.451 - 1.476
P1	1331	0.269 - 0.272	1328.3	0.292 - 0.294
P2	425	0.119 - 0.147	425.5	0.119 - 0.147

Based on the results of these comparisons, the Method A filtered data from all the rollover tests reasonably characterize the rollover results. Also, Method C appears to be an acceptable alternative for filtering the data for rollover tests with the limitations of TRC's data collection system. It uses a proper sampling-rate-to-filtering frequency ratio, allows data to be collected over the entire rollover test event, and provides signal information from rollover tests comparable to that for the standard Method B.