

Rollover Testing on an Actual Highway

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ABSTRACT

Three full-size sedans were towed to highway speeds along a section of a remote rural highway. Upon release, an automated steering controller steered the vehicles through a series of maneuvers intended to result in rollover. Repeated attempts to roll each vehicle were made until rollover resulted. Non-rollover attempts produced cornering tire marks by the out-of-control vehicle. Out of numerous runs, 3 rollover and 2 non-rollover tests were selected for documentation and analysis. One additional steer-induced rollover test is presented that was conducted along a simulated road section at a closed test-track facility. All six tests presented are instrumented *real-world* type tests that were later reconstructed based upon the data obtained from on-board instrumentation, videotape, survey measurements, and still photographs obtained of each respective test. The test data presented within the paper includes the various phases associated with vehicle rollovers: loss-of-control, trip, and rolling phases. A more complete presentation of data for each of the six respective tests can be found in the appendix.

INTRODUCTION

Rollover accidents are known to be unique, violent crash events. Unlike vehicle-to-vehicle or vehicle-to-fixed object collisions, rollovers are not entirely reproducible by a single test event. This is because a rollover accident consists of not just one, but a sequence of several unique events, each altering subsequent events.

The basic sequence for a typical rollover can be described in three basic phases: loss-of-control, tripping, and rolling or tumbling.

The vehicle path initially deviates from the normal alignment with the roadway. This loss of driver control (loss-of-control) over the vehicle occurs over a period of time and distance during which cornering tire marks from one or more tires are often produced.

The loss of control continues with a series of out of control maneuvers that leads to a tripping process resulting in vehicle rollover. Leading side tire marks are made as the vehicle overturns.

At the end of the tripping phase, the vehicle overturns and tumbles to rest completing the rollover accident. During this rolling phase, the vehicle is subjected to multiple collisions as it interacts with the surface, each of which alters the motion and subsequent events.

These three phases, or aspects, of a typical rollover have been the subject of numerous studies, all of which address each phase of the rollover sequence separately:

LOSS-OF-CONTROL— Loss-of-control and vehicle handling studies provide important information for application in reconstructing rollover accidents. These are generally conducted on a skid pad under a controlled environment, often with outriggers attached to the test vehicle. Vehicle tip-up conditions and critical cornering data result. An overview of rollover crash safety, including field crash statistics, pre-roll, and rollover dynamics test procedures and dummy responses has been compiled by Viano and Parenteau together with a bibliography of pertinent literature [Viano 2004]. These authors analyzed real-world rollover crashes from NASS-CDS 1995-1999 database to determine the precipitating events leading to rollovers.

They concluded that the vast majority of rollovers (90%) involve the vehicle departing the road with two thirds of those vehicles having all four wheels off the road [Viano 2003]. Larson also addressed vehicle loss-of-control involving an initial off-roadway excursion followed by a return to the roadway based upon the NASS data and measurement of vehicle response [Larson 2008].

TRIPPING– A variety of trip mechanisms leading to vehicle rollover have been observed and studied. Among these are sliding through soil or sod, fall-over, impacting curbs or obstacles, and dropping off embankments [Cooperrider 1990], [Viano 2004]. The majority of these trip condition studies involve sliding a vehicle sideways into a curb or in soil (for example) after release from a tow and guidance system along a test track.

ROLLOVER– Rollover motion and landing impacts of vehicles are often studied after release of a test vehicle from a dolly. Eight lateral dolly rollover tests were conducted on 1983 Chevrolet Malibus at a nominal speed of 51.5 km/h (32 mph): four with standard production roofs and four with reinforced roll cages [Orlowski 1985]. Typical deceleration rates, roll distances and vehicle damage patterns were quantified and described [Orlowski 1989]. Specific predefined landings in a rollover sequence can also be analyzed by dropping a moving and rotating vehicle onto a surface. The Controlled Rollover Impact System (CRIS) test apparatus has been previously applied to this area of research and testing [Cooper 2001, Moffat 2003]. Additional rollover testing has also been conducted for the purpose of occupant ejection reduction [O'Brien-Mitchell 2007]. The occupant containment characteristics of automotive laminated safety glass in side window applications were evaluated through full-scale, full-vehicle dolly rollover tests [Luepke 2007]. Additionally, there have been a few actual accidents that have been captured on videotape. Two *real-world* rollover crashes with occupant ejections were later reconstructed by analyzing the video footage along with aerial images of the crash sites [Funk 2008].

The literature cited above is a small fraction of what is available as a basis for reconstructing rollover accidents. Additional sources have been included in the references section. It should be noted that missing from the body of rollover research are instrumented rollover accidents that cover all three phases of a rollover accident and occur in the highway environment.

OBJECTIVE

While there exists a sizable body of rollover related research to assist the analyst, there are no published studies for steering induced rollovers on an actual highway. For this reason, the objective of this research was to attempt to collect information covering the three phases of a rollover accident from instrumented test

vehicles that had lost control at highway speeds while on a remote section of public highway or in a simulated highway environment.

METHODS

RURAL HIGHWAY TESTING–

GENERAL TEST PROCEDURE– A number of instrumented vehicles were towed to highway speed, released, and then steered by an automated steering controller into a series of steer reversals which resulted in a loss-of-control condition for each test vehicle. No attempt was made to match specific accident conditions; rather, these runs produced test cases that were both videotaped and documented with on-board instrumentation. Subsequently, five of these test cases were additionally surveyed and photographed. The test data is presented with respect to the phases leading to rollovers: Loss-of-Control phase, Trip phase, and Rollover phase. Typical reconstruction parameters associated with cornering data, trip conditions, and rollover data are reported and discussed where applicable.

Five of the six tests presented are associated with testing along a section of remote rural highway located in the west desert of Utah. A straight section of rural public highway was located that was remote, well maintained, and was two lanes wide (one in each direction). Each shoulder of the highway had been graded for drainage. The shoulders consisted of dirt and gravel and were without any edge discontinuities at the asphalt interface. Beyond the graded dirt side slope was open desert with natural berms, desert grass, and sage brush, (Figure 1).



Figure 1. A two-lane well maintained remote rural public highway utilized for rollover testing.

The vehicles tested were towed to highway speed by means of the Massive Moving Barrier (MMB) test vehicle before being released (Woolley et al 2000), (Figure 2). The MMB, or tow vehicle, is a 1986 International W-900 ten-wheeled tractor that was modified for moving barrier testing and was utilized as an effective tow vehicle for these tests. The MMB as a tow vehicle provided sufficient power and stability for towing each of the test vehicles. The weight of the MMB tow vehicle at the time of testing was approximately 43,000 lbs. A tow hitch was designed and fitted to the back of the tow vehicle that utilized the air powered fifth wheel to actuate an air cylinder for a convenient release of the vehicle being towed, (Figure 3). This allowed the tow vehicle driver to release the test vehicle at a pre-determined location along the highway. A chase vehicle was utilized for each of the tests for safety and traffic control.



Figure 2. Rollover test configuration of tow vehicle (MMB) and vehicle used for tests #4 and #5.



Figure 3. Release tow hitch mechanism attached to rear of tow vehicle (MMB).

Three full-size sedans of different years and makes were selected for testing because they were readily available.

One vehicle, the 1994 Buick Skylark, had the windshield removed and the roof was damaged in another non-associated test prior to being used for this series of rollover testing. (This damage did not have any significant affect on the rollover testing conducted with the Skylark). Prior to each test, the test vehicle went through a thorough preparation that included the following:

- Mounting in the vehicle the appropriate instrumentation and data acquisition system. (Accelerometer pack, speed sensor, and three string pots).
- Installation of the independent programmable steering controller to the steering wheel assembly and the air cylinder over the brake pedal.
- Removal of the battery and select fluids from the vehicle (gasoline, radiator, engine oil, and washer fluid). The remaining brake and transmission fluids were filled to their recommended levels.
- Adjustment and alignment of the wheels and tires for appropriate tracking of the vehicle. The manufacturer recommended tires and tire pressures were used for each test (unless otherwise noted).
- Windows and mirrors were painted various bright colors for easier identification of glass deposits after breaking in a rollover.

When the test vehicle was released and separated from the tow vehicle, an independent programmable automated steering controller (equipped in each vehicle) would activate and drive the test vehicle through a pre-programmed sequence of turns. This device was designed and manufactured by Wilderness Design located in Orem, Utah. The controller electronically actuated solenoid valves that allowed pressurized air to drive both a motor attached to the steering wheel and a cylinder that would apply the brake pedal of the test vehicle. Since the focus of these tests was on steering-induced rollovers without braking, the brake was only applied at the end of the event as a safety precaution.

Table 1. Steering input for the programmable controller used for Test #1.

Time	Description
0.00 sec	Release from hitch
0.50 sec	Delay, dwell
1.00 sec	Turn hard right
2.00 sec	Turn back hard left
3.00 sec	Turn back hard right and hold
8.00 sec	Apply Brakes

The basic steer input sequence used by the controller for these high-speed, highway test runs was developed by prior research and testing of the controller at much lower speeds. As an example, the steer input used for Test #1 is presented in Table 1 and is based upon the relative duration of each event. For example, after release, the steering wheel was held straight for 0.50 seconds before turning hard right. Once the limit switch was met for the magnitude of the right turn, the steering wheel was held for 1.0 seconds before turning back hard to the left. Additional time transpires as the controller transitions between the events. The actual steering input was measured for each test and can be found along with the other test specific notes in the Appendix.

Testing occurred on six different days over four different months: April, May, June, and July. The reason testing occurred over several different months was two-fold: first because of the logistics associated with preparing each test vehicle and second there was an attempt to conduct the tests at a time when the moisture content of the ground was higher (in order to reduce the amount of dust resulting from off-road excursions by the test vehicle). Hence, testing was scheduled, when possible, following periods of measurable precipitation to minimize the dust associated with the test vehicles going off-road.

GENERAL TEST DOCUMENTATION– Each of the vehicles tested was equipped with an on-board high speed digital data acquisition system (DataBRICK GMH Engineering, Orem, Utah). Upon release the DataBRICK collected and stored data for a tri-axial 10g accelerometer, a non-contact Doppler velocity sensor, and three 20 inch string pots (Table 2). Roll rate sensors were not utilized for this series of tests. Two of the string pot sensors used on the front suspension assisted in determining when the suspension of the vehicle was in compression or flexion throughout the different phases of the test.

Table 2. Instrumentation used for highway rollover tests.

Serial #	Device	Location
90103	DataBRICK Data Acquisition	RR Floor Pan
024	10 G Tri-Axial Accelerometer	Vehicle CG
GMH	Non-Contact Radar Speed Sensor	Rear Trunk
33030181	Unimeasure 20" LX-PA String Pot	Steering Wheel
33030182	Unimeasure 20" LX-PA String Pot	LF Suspension
33020265	Unimeasure 20" LX-PA String Pot	RF Suspension

The target release speed for each test was 75 mph. The 10-wheeled tow vehicle pulled the test vehicle to the pre-appointed area of release along the highway and maintained 75 mph until release. (The speedometer of the tow truck had been previously calibrated using a speed trap over a wide range of speeds and found to be

accurate to within a mile an hour.) For safety purposes and to prevent damage to the instrumentation, the speed trap was not used along the highway, instead the non-contact speed sensor attached to the data acquisition system recorded the velocity, but had to be scaled to match the actual velocity of both the tow and test vehicles at release.

Several video cameras were also used to document each test, from various vantage points. The video formats used to document the events were either Hi-8 or Mini-DV (video was captured at 1/30th of a second or 33 ms). Only one test, Test #1, does not have any video of the test. Additionally, each test was documented both before and after with digital photographs. Three dimensional survey measurements were also taken after the tests to document tire marks, gouges, wheel landings, scrapes, furrows in the soil, debris, and vehicle rest positions.

Three different four-door sedans were used in a total of five tests along this section of rural highway. The three vehicles used for these highway tests are shown in their pretest condition in Figure 4. Three vehicles were used in five tests because two of the vehicles did not roll over on prior attempts and were re-tested. Two of the vehicles re-tested before rolling were the 1996 Buick Skylark and the 1987 Ford Taurus.



Figure 4a. Highway Tests #1, #2 - 1996 Buick Skylark.



Figure 4b. Highway Test #3 – 1984 AMC Eagle.

Closed Test-Track–



Figure 5. Simulated highway, closed test-track test configuration.

TEST PROCEDURE– The sixth test presented was conducted at Exponent, Inc. in Phoenix, Arizona at their closed test-track facility. A single lane of asphalt was constructed along with a dirt graded right side shoulder (simulating a highway and shoulder) that transitioned to the large flat skid pad as depicted in Figure 5. The soil section along the asphalt was 12 feet in width and 4 inches deep extending the length of the single asphalt lane. The asphalt lane was 12 feet in width and was straight and flat.

The vehicle depicted in Figure 6 was towed to speed by means of the crash-rail vehicle tow system. At the appropriate point, the vehicle was released and an automated steering controller steered the vehicle with a pre-programmed steering input. The steer input used was unique to this test and was obtained from test pad steering maneuvers previously performed. The test vehicle turned to the right and entered the graded dirt side slope, it then turned back to the left and experienced the end of the tripping phase as it re-entered the asphalt surface where it tumbled and rolled across the large flat skid pad to rest.



Figure 6. 1991 Ford Escort used in the simulated highway closed test-track test.



Figure 4c. Highway Tests #4, #5 - 1987 Ford Taurus.

Table 3 is a summary of all six tests and the respective test vehicles and test specific parameters.

Table 3. General test parameters.

Test #	Vehicle Year, Make, Model	Vehicle Color	Release Speed (mph)	Steer Input Right/Left
Highway				
1	1996 Buick Skylark	Blue	75	R/L/R
2	1996 Buick Skylark	Blue	75	L/R/L
3	1984 AMC Eagle	White	75	L/R/L
4	1987 Ford Taurus	Red	75	L/R/L
5	1987 Ford Taurus	Red	75	L/R/L
Test Track				
6	1991 Ford Escort	Blue	75.7	R/L

Details associated with each specific test are summarized in the Appendix. These include test-to-test differences and any variations from the standard methodology described herein. Changes to the steering input, where applicable, are noted in the Appendix.

TEST DOCUMENTATION– The vehicle tested was equipped with an on-board data acquisition system. Upon release, the system stored data for a tri-axial accelerometer, two-axis velocity sensor, steering wheel angle, steering wheel torque, and height sensors along the left and right frame rails. The target speed at release was 75 mph and was measured at release by the calibrated tow motor. The test was documented with photographs before and after the test. Three dimensional survey measurements were also taken to document tire marks, gouges, rim prints, wheel landings, debris, and the vehicle rest position. Two real-time video cameras were used to document the test, one panning and one mounted on-board the vehicle.

RESULTS

Out of the tests conducted, six are presented. All but the first test were documented by one or more video cameras. The other four tests (#2, #3, #4, and #5) were videotaped from the tow vehicle with either a fixed camera or a panning camera. Test #6 had both an overhead panning camera and an on-board camera facing out through the front windshield. A compilation of various arbitrary frames captured from the five tests videotaped is presented in Figure 7.

Examination of the videos documenting the tests that resulted in rollover revealed several instances of the test vehicle experiencing an entire non-contact roll, a non-wheel contact, or a non-roof contact.

The primary purpose for conducting this testing was to quantify and explore the nature of rollovers in all three phases, specifically, the loss-of-control phase, tripping phase, and rollover phase. Rather than discussing each test individually, the remainder of the results section contains a summary of all the tests with respect to the data obtained for those three phases.

LOSS-OF-CONTROL PHASE– Roughly 16 tests were conducted that were unsuccessful at rolling the test vehicle. Initially, the unsuccessful attempts were considered to be failed non-rollover tests and were discarded. However, a two of these non-rollover tests together with the three successful rollovers provide several documented high-speed, out-of-control events in the loss-of-control phase. For this analysis, the loss-of-control phase is defined as the period just after release, when the test vehicle is still at high velocity, and before it begins to trip into a rollover. It may or may not contain

multiple turns depending upon the motion of the vehicle through the course of the test. In this phase numerous tire marks were made on the asphalt prior to leaving the highway by at least four out of the six out-of-control vehicles (Tests #1, #3, #4, and #5). For all of the tests, the motion and trajectory of the test vehicle was measured and photographed.

The four tests that left sufficient cornering marks were evaluated to determine whether critical cornering had been achieved. This determination was made by comparing the measured speed values (V_m) to several points where the critical cornering formula (Equation 1) was applied. The critical cornering velocity (V_{cc}) was calculated at various positions along the test vehicle's trajectory (diagrams of each test are provided in the Appendix). Numerous electronic templates were positioned along measured cornering marks in arbitrarily spaced positions. An arc was drawn through three adjacent templates in order to determine the approximate radius. This process was performed for those templates positioned along the highway where cornering marks were present and the speed sensor data was valid.



Figure 7. Various video frames captured from five of the six tests documented.

For each of the four tests, there was only one area identified where the application of the critical cornering formula was similar to the measured speed. Tire marks before and after this area were not associated with critical cornering. The arc drawn through the templates in this area provided the radius (R) for the critical cornering speed (V_{cc}) calculated from the formula in Equation 1. The uncertainty associated with the measured speed values (V_m) was approximately +/- 1.0 mph. The critical cornering formula relates the surface friction and turning radius to the velocity.

$$V_{cc} \leq \sqrt{\mu R g} \quad (1)$$

The radius (R) that was used for the critical cornering velocity calculation (V_{cc}) is reported in Table 4. Friction of the highway, μ , was measured in the same direction the tests were conducted by means of a vehicle instrumented with a Vericom™ performance measurement device owned and operated by the Utah Highway Patrol. The friction value used for the critical cornering calculations on the highway was 0.795.

For comparison purposes, an equivalent critical cornering friction (μ equiv) was solved for and reported in Table 4, that was based upon the measured speed and the radius estimated for the critical cornering. For test #2, the critical cornering analysis was not applied (NA) due to the lack of cornering tire marks made by the test vehicle before it left the asphalt surface of the highway. Critical cornering was not applied (NA) to Test #6 due to discrepancies associated with the measurements of the tire marks on the paved asphalt portion.

Table 4 is a summary of the results of the comparison between the measured speed and the calculated speed from the critical cornering analysis performed for the loss-of-control phase for four of the six tests. The acceleration data reported (A_y) is uncorrected for gravity and is in vehicle coordinates with X positive to the front, Y positive to the passenger side, and Z positive to the roof (LH coordinate system). All of the data has been filtered according to the SAE standards for post-processing data using a 60 Hz CFC filter.

Table 4. Analysis results of the loss-of-control phase for each test

Test #	Peak A _y (g's)	V _m (mph)	Radius (ft)	V _{cc} (mph)	μ Equiv
Highway $\mu=0.795$					
1	1.02	73	435	71.9	0.819
2	NA	NA	NA	NA	NA
3	0.89	73	439	72.2	0.812
4	0.98	72	445	72.7	0.779
5	0.97	72	432	71.7	0.802
Test Track					
6	NA	NA	NA	NA	NA

TRIPPING PHASE– Four of the six tests documented and reported resulted in a successful rollover event (Test #2, #3, #5, and #6). For these four tests several of the parameters with respect to the tripping phase are reported in Table 5. The tripping phase is defined as that portion of the sequence where the lateral forces slowing the vehicle are sufficient to initiate lifting of the trailing side tires through the end of the phase when the entire vehicle lifts-off from the ground. In all four of these tests this event occurred off-road in the soil. The peak uncorrected lateral acceleration (A_y) is reported for the respective leading side of the vehicle at trip. The measured vehicle acceleration has been appropriately filtered but not adjusted for gravitation effects (as noted on the graphs in the Appendix). The heading of the vehicle is reported based upon the placement of a vehicle template on the surveyed measurements within a CAD file.

The speed at trip was not measured directly because the speed sensor utilized dropped-out after the test vehicle went off the pavement and started to rotate-up and roll. For this reason, the velocity at trip (V_{trip}) was determined, for each of the vehicles that rolled, by two methods, a time-distance extrapolation method and a two-dimensional integration of the X and Y accelerations obtained from the tri-axial accelerometer.

TRIP VELOCITY EXTRAPOLATION– The time-distance extrapolation to determine the velocity at trip was performed by correlating videotape, event timing (reported by the instrumentation), and the diagram drawn from the survey measurements with respect to time and position. Based upon this correlation, two positions were identified: one at the end of the tripping phase, the other was back on the road surface, before the speed sensor dropped-out. These two positions are identified on the graphs in the Appendix as the position of Trip and as the Reference Point. The speed at the reference point was defined by the speed sensor, before it dropped-out (V_{rp}). The difference between both points in time and distance was then determined (ΔT , ΔX). Finally, based upon Newton's laws of motion, and average acceleration, two equations were derived (Equations 2 and 3) that solved for the unknown velocity at trip (V_{trip}) and the average deceleration or drag factor between the two points.

$$\bar{f} = 2(V_{rp} - \frac{\Delta X}{\Delta T}) / g\Delta T \quad (2)$$

$$V_{trip} = V_{rp} - \bar{f}g\Delta T \quad (3)$$

The data used for the extrapolation of the velocity at trip is presented in Table 5. There was no roll (NR) data for Tests #1 and #4. In the case of Test #5 a mound of dirt was impacted while the vehicle was in the tripping phase, damaging the passenger side rocker panel.

Therefore the trip velocity extrapolation was conducted in two steps, before and after the impact, with an approximated 10 mph delta-V at impact.

Table 5. Parameters used for the extrapolation process to obtain the trip velocity.

Test #	Vrp (mph)	DeltaX (ft)	DeltaT (sec)	Extrapolated	
				Drag (g's)	V-ext (mph)
Highway					
1	NR	NR	NR	NR	NR
2	72.0	196.6	2.28	0.53	45.6
3	73.0	178.9	2.23	0.75	36.4
4	NR	NR	NR	NR	NR
5	72.0	185.6	2.13	0.54	
	36.8	25.6	0.55	0.84	27.3*
* Two step calculation					
Test Track					
6	71.0	120.6	1.33	0.63	52.6

TRIP VELOCITY INTEGRATION– Trip velocity was also estimated by integrating the measured vehicle acceleration from the reference point (identified in the extrapolation process) through the point of trip. The integration calculation was performed in two dimensional planar space along the vehicle path, Equation (4).

$$V_{trip} = V_{Ref} + \int_{ref}^{trip} A_{path} dt \quad (4)$$

Because the same two points used in the velocity extrapolation were used for the integration, the interval and the starting speed were identical to those used in the speed extrapolation, Table 5. Acceleration used in the integration was the component in the direction of vehicle motion, as defined by Equations 5 and 6. In these equations c_x and c_y are the vehicle accelerations in the longitudinal and lateral directions with positive directions forward and toward the passenger side, respectively. Vehicle heading, ψ , was found from the electronic vehicle templates positioned on the scene diagram as defined by the measured tire marks. Path direction, α , was taken as the angle between the vehicle positions as they changed for this interval in the electronic CAD diagram (counterclockwise angle positive).

$$\begin{aligned} A_x &= c_x \cos(\psi) - (-c_y) \sin(\psi) \\ A_y &= c_x \sin(\psi) + (-c_y) \cos(\psi) \end{aligned} \quad (5)$$

$$A_{path} = A_x \cos(\alpha) + A_y \sin(\alpha)$$

Table 6. Parameters used for the integration of the acceleration to obtain the velocity at trip.

Test #	Vrp (mph)	DeltaT (sec)	Integrated	
			DeltaX (ft)	V-int (mph)
Highway				
1	NR	NR	NR	NR
2	72.0	2.28	208.30	41.6
3	73.0	2.23	185.70	34.6
4	NR	NR	NR	NR
5	72.0	2.63	230.70	27.1
Test Track				
6	71.0	1.33	121.40	51.6

Both methods of calculating the trip velocity yielded reasonable estimates. However, it was determined that two speeds would be used from one method and two from the other (based on small differences in the test events and in the ability to define the two points for the interval). The trip velocity obtained by the extrapolation process was used for Tests #2 and #3 due to the high degree of confidence in the data across the interval evaluated. The results of integrating the X and Y accelerations were more reliable for Tests #5 and #6 than those obtained by the extrapolation method. For those tests the trip velocity obtained from the integration process was selected for the speed at trip. The uncertainty in the trip velocity is illustrated by the differences in the two methods. Additional parameters summarizing the results of the tripping phase are found in Table 7.

Table 7. Result summary of tripping phase analysis.

Test #	Leading Side	Peak Ay at Trip (g's)	Trip Slip Angle (deg)	Vtrip (mph)
Highway				
1	NR	NR	NR	NR
2	Driver	2.53	48	45.6
3	Passenger	-3.94	118	36.4
4	NR	NR	NR	NR
5	Passenger	-4.01	101	27.1
Test Track				
6	Passenger	-2.50	55	51.6

ROLLING PHASE– The same four tests reported in the tripping phase were also analyzed for the rolling phase (Tests #2, #3, #5, and #6). For these four tests the rolling phase parameters are presented in Table 8. The rolling phase is defined by the motion of the vehicle that consists of the rolling and tumbling of the vehicle from overturn (end of tripping phase) to rest.

It was previously mentioned that the roll rate was not directly measured for the tests conducted along the highway (Tests #2, #3, and #5). Based upon the event timing and distance analysis performed to estimate the speed at trip, the roll rate for these three tests was calculated. A detailed analysis of the cumulative rotation angle and the event timing for each test was then

performed. A central difference method was utilized to approximate the derivative of angular position and time.

For Test #6, conducted at the closed test track, the roll rate was directly measured by a roll rate sensor, but the rates the sensor experienced exceeded the 200 deg/s full-scale range for a period of nearly 4 seconds (beginning at or near trip T=3.3-7.3 sec). The same event timing and distance analysis that was performed on Tests #2, #3, and #5 was performed on Test #6. Additionally, the calculated roll rate data for Test #6 was compared to the data reported from the roll rate sensor. Based on the calculated data, the peak roll rate was found to be approximately 720 deg/s. A comparison between the measured and calculated roll rates is made in Figure 8. The calculated roll rate (whole rolls in red and fractions of a roll in yellow) was added to the graph of the measured roll rate for Test #6.

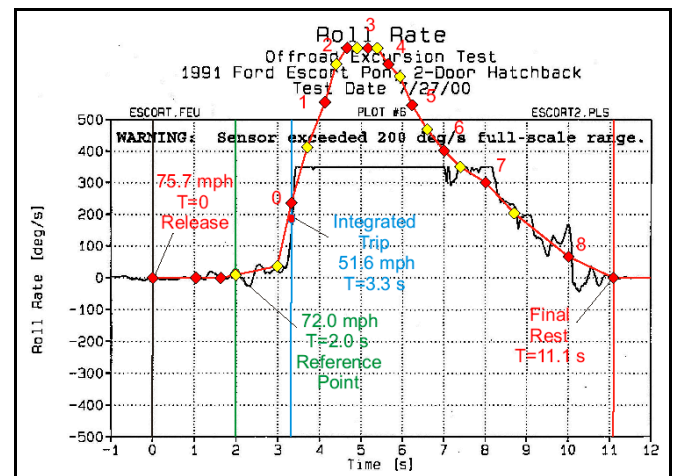


Figure 8. Test #6 calculated roll rate data compared with roll rate sensor data.

The roll rates determined for the three tests conducted on the highway in addition to the one conducted at the closed test track are presented in Figure 9.

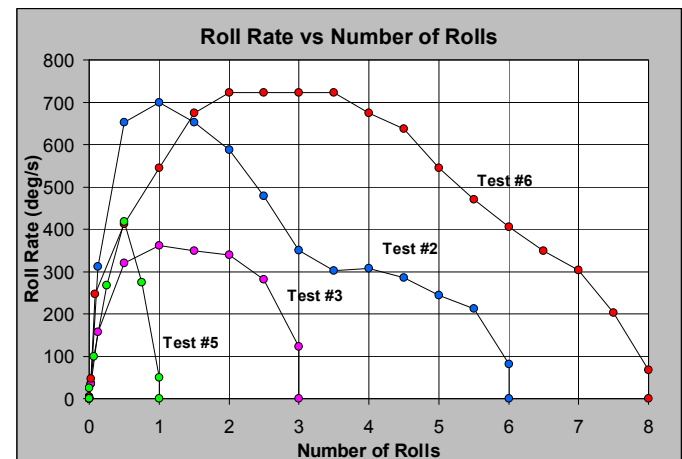


Figure 9. Calculated roll rates for tests #2, #3, #5, and #6.

Two rolling phase distances are presented in Table 8. The first is the distance from end of trip to rest and the second is from first landing contact to rest. (It should be noted that this first contact is not the same as initial touchdown in a dolly rollover test). The second is a parameter that is presented mainly for reconstruction purposes. The average drag factor was calculated based upon the trip velocity (V_{trip}) and the respective distance to rest (S) (Equation 4).

$$\bar{f} = \frac{V_{trip}^2}{2gS} \quad (7)$$

Two average drag factors are presented, the first is based upon the trip to rest measurement and the second, in parentheses, is based upon the first landing contact to rest.

Table 8. Results of rolling phase analysis.

Test #	Roll Distance Trip to Rest (ft)	1st Landing to Rest (ft)	Rolls #	Vtrip (mph)	Ave Drag Factor (g's)
Highway					
1	NR	NR	NR	NR	NR
2	122.4	106.3	6	45.6	.568 (.654)
3	82.2	63.3	3	36.4	.539 (.700)
4	NR	NR	NR	NR	NR
5	62.5	54.2	1	27.1	.393 (.453)
Test Track					
6	173.6	149.3	8	51.6	.513 (.596)

The drag factors calculated from trip to rest ranged from 0.39 g's to 0.57 g's. The deceleration values determined for the first landing contact to rest ranged from 0.45 g's to 0.70 g's. These rolling phase parameters when plotted together with the trip velocity are depicted in Figure 10.

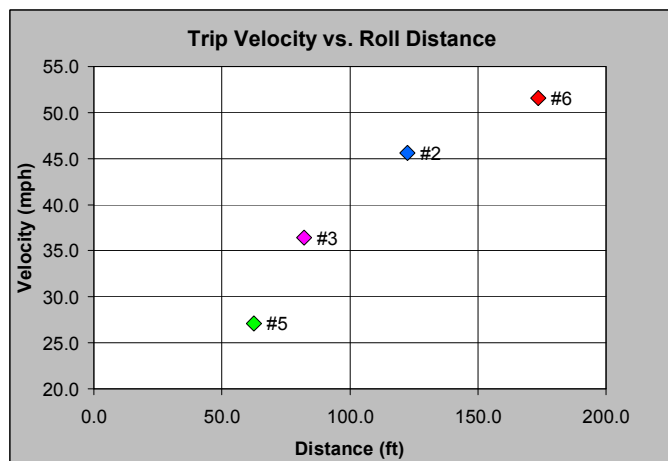


Figure 10a. Trip velocity compared to roll distance.

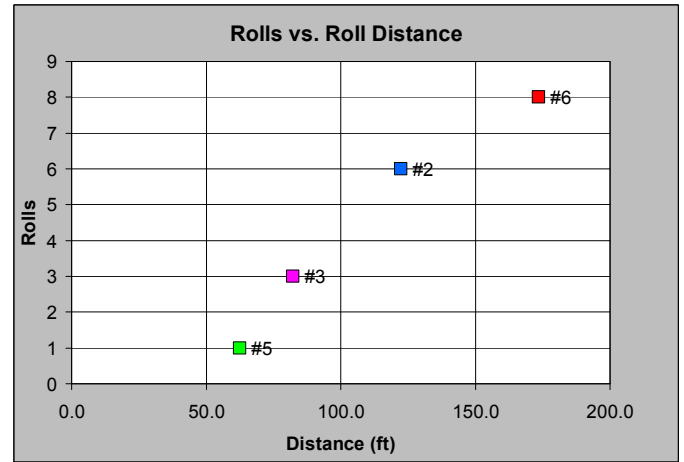


Figure 10b. Number of rolls compared to roll distance.

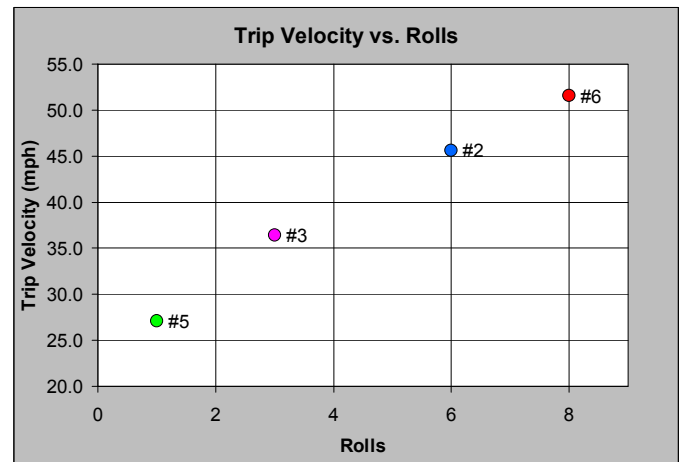


Figure 10c. Trip velocity compared number of rolls.

Additionally, the rectangular perimeter of each test vehicle was calculated based upon published overall width (OAW) and overall height (OAH). Another useful parameter used in reconstructing rollover accidents is the average rolling circumference. This value is defined as the roll distance (from trip to rest) divided by the number of rolls. Both of these parameters along with the maximum roll circumference (which was the trip to first wheel landing) and the minimum roll circumference experienced in the roll sequence are reported in Table 9.

Table 9. Additional rolling vehicle reconstruction parameters.

Test #	Published Specs OAW (in)	Published Specs OAH (in)	Vehicle Perimeter (ft)	Ave Roll Circ. (ft)	Max Roll Circ. (ft)	Min Roll Circ. (ft) (location)
Highway						
1	NR	NR	NR	NR	NR	NR
2	67.6	53.6	20.20	20.40	25.7	17.5 (Roll 5-6)
3	72.3	54.6	21.15	27.40	39.9	20.8 (Roll 1-2)
4	NR	NR	NR	NR	NR	NR
5	70.8	54.3	20.85	62.50	62.5	62.5 (Roll 0-1)
Test Track						
6	66.7	52.5	19.67	21.70	39.7	17.2 (Roll 7-8)