

Rollover Crash Tests on Dirt: An Examination of Rollover Dynamics

Peter A. Luepke

P. Luepke Consulting

Jarrold W. Carter

Origin Engineering

Kevin C. Henry and Geoff J. Germane

Germane Engineering

James W. Smith

Exponent

Copyright © 2008 SAE International

ABSTRACT

Most rollover literature is statistical in nature, focuses on reconstructed field data and experiences, or utilizes a very broad pool of dissimilar test data. When test data is presented, nearly all of it involves hard surface rollover tests performed at speeds near 30 mph, with a mix of passenger cars, sport utility vehicles and minivans.

Five full-scale dolly rollover tests on dirt of production sport utility vehicles (SUV) and multi-purpose vehicles (MPV) were performed with similar input parameters. The similarities included Federal Motor Vehicle Safety Standard (FMVSS) 208 rollover dolly initiated events, level dirt rollover surfaces, and initiation speeds over 40 mph. All tests were recorded with multiple high-speed and real-time cameras. Additionally, some of the tests included detailed documentation of the rollover surface and the resulting evidence and debris patterns, as well as onboard angular rate sensing instrumentation. Typical dynamic parameters such as roll distance, number of rolls, average deceleration rates, and angular roll rates are compared and discussed. Parameters rarely commented upon before are analyzed and discussed, such as the time duration and nature of individual ground contacts and airborne segments, the vehicle orientation changes experienced during those segments, and the dynamic effects of various ground contact orientations.

INTRODUCTION

Previous studies and literature have addressed dynamic parameters involved in rollover reconstructions. Historically, when such research includes testing data, it has a dominant focus on hard surface events, and at speeds closer to 30 mph (Orlowski, et al. 1989). While such data have been extremely valuable, it excludes the environment that many real-world rollover events experience: highway speed on off-road surfaces. Other research has explored soil-tripped rollovers, but primarily the dynamics before and during trip and overturn (Cooperrider, et al. 1990 and 1998). To date, there are no published full-scale tests that address the SUV/MPV dirt rollover environment and examine in detail the vehicle dynamics of the post-trip portions of such events.

Soft-surface rollover tests performed at higher speeds would be useful for analyzing the potentially unique dynamics present when vehicles encounter such an environment. In particular, the results of these off-road SUV/MPV rollovers can be examined relative to the body of lower speed, on-road passenger car rollover research.

The objective of this study is to analyze a group of rollover events performed in a substantially similar environment with extensive documentation, allowing a more precise approach to their analysis. This analysis included a detailed look at both typical rollover reconstruction parameters like rollover distances, deceleration values, and number of rolls, as well as secondary, or more detailed parameters like center of gravity, roll angle, and roll rate.

issues and ground contact versus airborne segment orientations and affects.

METHODS

Four full-size sport utility vehicles and one multi-purpose vehicle were used as test vehicles for this study. A summary of vehicle and test information is provided in Table 1. It has been previously commented upon that such higher profile vehicles may have unique rollover dynamics when compared to shorter (height) passenger car sedans and coupes (Orlowski, et al. 1989). Pre-test photographs of each vehicle are included in Figure 2.

All vehicles were accelerated and transported to the rollover surface via a dolly cart. The cart used is as defined for FMVSS 208 dolly rollover compliance testing. The test vehicle sits upon the dolly with its tires resting on contact plates angled 23 degrees from horizontal. The leading side tire sidewalls rest against 4 inch tall steel plates 9 inches above the crash rail surface. In the case of these dirt rollover tests, the crash rail surface is used for the acceleration of the dolly/test vehicle combination. Four of the five tests had rollover initiation speeds between 40 and 44 mph. Test 4 was conducted at 55 mph.

Upon rapid deceleration of the dolly cart, the test vehicle is allowed to move and rotate toward the leading side, off of the stopped dolly, and onto the dirt rollover surface. The rollover surface was comprised of desert soil, lightly compacted after placement on the concrete crash rail, and measuring approximately 6 inches deep. Figure 1 depicts the appearance of this surface prior to one of the tests. All tests except Test 5 included this dirt surface from the point of first ground contact to rest position of the vehicles. Test 5 incorporated a bare concrete space of approximately 30 feet from the area of dolly deceleration forward to the dirt surface.

All fluids were drained from the vehicles, which were ballasted to as-received curb weight and fore/aft distribution. The vehicles were equipped with tires and wheels recommended by the vehicle manufacturers. Anthropomorphic Test Devices (ATD) were utilized in each of the tests. Each ATD was added after the vehicles were ballasted. Six ATDs were positioned inside of the Expedition, four ATDs inside of the XC90 and Aerostar, one ATD inside of the S10 Blazer, and two ATDs inside of the Grand Wagoneer. A detailed study of the occupant kinematics during Tests 1 and 2, the Expedition and XC90, has been previously published (Luepke, et al. 2007).

Vehicles used in Tests 1 through 4 had onboard cameras and brackets installed that required some interior trim components and seat position hardware to be removed. Other tests, such as 1 and 2, required that tempered side glass be removed and replaced with laminated glass and that the doors be bolted shut to isolate the performance of the door glass. Additionally, test specific parameters required that the right side

sliding door and rear hatch be removed from the Aerostar in Test 3.

Table 1. General test information.

Test Number	1	2	3	4	5
Date	10/19/2005	7/17/2006	1/5/2006	1/10/1995	12/8/2005
Vehicle Year	1998	2004	1997	1989	1987
Vehicle Make	Ford	Volvo	Ford	Chevrolet	Jeep
Vehicle Model	Expedition	XC90	Aerostar	S10 Blazer	Grand Wagoneer
Drivetrain	5.4 L V8 4X4	2.5L I5 4X4	4.0L V6 4X4	4.3L V6 4X4	5.9L V8 4X4
Weight (lbf)	6634	5013	4757	4063	4905
Speed (mph)	43.2	42.9	41.7	55.3	40.6
Leading Side	Driver	Driver	Passenger	Driver	Driver



Figure 1. Dirt rollover surface.

As part of the documentation of each test, real-time and high-speed video and film cameras were used. These cameras were typically placed at off-board positions along each side of the rollover path, with some panning through the event. Additionally, some tests utilized a camera positioned downstream and looking back at the rolling vehicle. Nearly all of the high-speed cameras recorded the event at a rate of 250 frames per second. Still photographs were taken of each vehicle before and after each test. For Tests 1, 2, and 3, the post test photographs included detailed documentation of vehicle damage and abrasion patterns. Additionally, photographs were taken of the rollover scene surface following each test. The most detailed post test scene photography was performed for Tests 1, 2, and 3.

The Test 1, 2, 3, and 5 vehicles were equipped with onboard data collection equipment for sampling roll and yaw rate. The roll and yaw rate sensor package was mounted inside the vehicles on the roll axis, the longitudinal centerline, and the approximate vertical



Figure 2. Test vehicles.

projection of the center of gravity. Test 4 did not have onboard instrumentation installed inside the vehicle. The results of Test 4 are presented here as they pertain to primary parameters such as rollover distance, number of rolls, and average deceleration rate. Figure 2 contains pre-test photographs of each vehicle.

Following Tests 1 and 2 the entirety of the test surface was digitally mapped to document ground impact marks from vehicle body panels/structural features, as well as wheels and tires. The mapping also accounted for debris fields, separated vehicle components, window glass, ejected ATD locations, and the rest positions of the vehicles. The mapping was performed with a Leica Laser Total Station and an Arc Second Vulcan Digital Measurement Device. Additionally, aerial photographs of each rollover surface were taken from a movable aerial platform following Tests 1, 2, and 3.

Tests 1 and 2 were documented more extensively than the other tests included in this study. This included the number, locations, and quality of the video and film coverage, and also the level of post test rollover scene documentation, from both a photographic and digital measurement perspective. Test 3 had video and film coverage that was equally extensive, but lacked the digital measurement component of the scene evidence. The remaining tests included in this study, Tests 4 and 5, were sufficiently documented to allow the capture of dynamic parameters important to the analysis and comparisons discussed.

Examination of each test involved recording the overall distances traveled in the rollover portion of each event and the total number of rolls completed by each vehicle. Additionally, some tests involved the documentation of discrete segment distances in the form of scene evidence. The process of analyzing these rollover tests also involved a frame-by-frame study of multiple high-speed cameras. With more thorough documentation, this process was more completely executed for Tests 1 and 2. A detailed description of this analysis for Tests 1 and 2, along with an additional examination of rollover dynamics, is presented in Carter, et al., 2008. Dynamic angular rate data was collected for Tests 1, 2, 3 and 5. This data could be matched with the position and orientation data gleaned from the time-synced high-speed camera coverage.

An analysis of the individual segments that comprise a rollover event, the separate ground contact and airborne phases, was conducted. By careful examination of multiple camera views, a timeline could be established that captured exactly when a ground contact phase began and ended, and when an airborne phase began and ended. Not only were those beginning and ending times noted, but the vehicle orientations at and through those points in time were studied. By reviewing details such as which vehicle structures were involved in given phases of a ground contact segment, characterizations of the rollovers could be studied. This intensive approach usefully broke down each test into the

individual dynamic events that comprise the entire rollover. Particular attention was devoted to which vehicle structures are involved in long and short duration ground contacts, and by comparison, what structural contacts precede long and short duration airborne phases.

The angular roll rates measured were examined in relation to the observed dynamics of the vehicles. Roll rate is often a key parameter needed to thoroughly characterize the interior environment for an occupant. Given the relatively complex nature of rollover events, the approach typically involves estimating an average rollover rate across the entire rollover path. While that may be useful and even accurate, such an average number cannot capture the potential maximum values. By capturing the actual roll rate data, the peak and sustained values could be compared to the overall averages.

RESULTS

When reviewing the overall results of each test it is important to keep in mind how some of the primary parameters are measured and reported. Table 2 contains some of the general test result data. It has been customary, when measuring and reporting the rollover distance from a dolly rollover test, to establish the zero point at the dolly launch point. For the sake of consistency, and drawing from the authors' experience performing dolly rollover tests, the very end of the snubber tubes is considered the dolly launch point for each of the tests studied here. The center of gravity of the test vehicle is usually very close to this point when the launch movement off of the dolly is clearly noticeable. In Table 2, this length measurement is noted as Distance (dlp), where dlp stands for dolly launch point. In an effort to more closely replicate how reconstructionists measure evidence in the field, a second distance was measured for the tests. This distance has a zero point at the location of first visible contact on the rollover surface. Such a location has more in common with field practices of measuring rollover distances from the end of tire or furrow marks, i.e., the overturn location. In addition, extensive film and video analysis shows that the test vehicles lose very little speed, indeed less than a few tenths of a mile-per-hour, between dolly launch point and the first point of ground contact. The result of these two definitions of the zero point is reported as two different drag factors in Table 2; (td) indicating the average deceleration from the point of first touch-down on the dirt surface, and (dlp), indicating average deceleration from the dolly launch point.

The average decelerations, or drag factors, for all five tests, from the dolly launch point, were at the upper end of the range of previously reported rollover drag factors. Comparing these five dolly rollover tests, with drag factors between 0.50 and 0.58, with previously reported dolly rollover tests, with drag factors between 0.38 and 0.63 (Orlowski et al., 1989), there appears to be a degree of upper level bias evident in these dirt rollovers.

The mean value, or average, of the previous dolly rollover research is 0.43, and this value is commonly used in the reconstruction community for calculating the initial speed at trip of real-world rollover events. The tests analyzed in this research of dirt rollovers have a mean deceleration value of 0.53.

Table 2. General test result data.

Test Number	1	2	3	4	5
Vehicle Make	Ford	Volvo	Ford	Chevrolet	Jeep
Vehicle Model	Expedition	XC90	Aerostar	S10 Blazer	Grand Wagoneer
Distance (dolly-launch-point) (feet)	120	115	100	NR	110
Distance (touch-down) (feet)	113	112	95	204	105
Complete Rolls	4	4 1/4	3 1/2	8	3 3/4
Drag Factor (dlp)	0.52g	0.53g	0.58g	N/A	0.50g
Drag Factor (td)	0.55g	0.55g	0.61g	0.50g	0.52g
Peak Roll Rate (deg./sec.)	636	631	569	NR	724 (587)
Mean Roll Rate (deg./sec.)	339	317	270	N/A	261

Note: The secondary value for Test 5 Peak Roll Rate neglects the shortest duration spikes in the data.

Figures 3, 4 and 5 illustrate some of the results of this testing as a group. An interesting relationship appears to exist between the number of rolls completed and the distance traveled. Plotting these data for the five tests results in a nearly linear relationship, and is illustrated in Figure 5.

Roll rate, and the relationship that mean or average values have to the actual real-time measurement of this parameter over the life of the rollover event, was examined. In each of the five tests, the mean value of the measured roll rate data was substantially less than the peak values. These differences are reported in Table 2.

While a difference between mean and peak values of nearly any dynamic parameter, including roll rate, is not unusual or unexpected, the extent of difference demonstrated in these tests is significant. In all five tests, the peak roll rate was nearly twice the mean. For example, the measured peak roll rate for Test 1 was 636 degrees/sec while the mean value of the measured roll rate was 339 degrees/sec. Figures 6, 7, 8, and 9 are graphs of the actual measured angular roll rate data from four of the studied tests.

It is important to note that the mean values reported for these tests are the result of averaging measured values. As a reconstructionist, the benefit of measured data is not available, but estimations of average roll rates are frequently performed. The practice typically involves using average drag factor estimates to calculate both an initial speed of the rollover and also an overturn time duration estimate. Combined with knowledge about the