

Rollover Dynamics: An Exploration of the Fundamentals

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ABSTRACT

Research focusing on automotive rollovers has garnered a great deal of attention in recent years. Substantial effort has been directed toward the evaluation of rollover resistance. Issues related to crashworthiness, such as roof strength and restraint performance, have also received a great deal of attention. Much less research effort has been directed toward a more detailed study of the rollover dynamics from point-of-trip to point-of-rest.

The reconstruction of rollover crashes often requires a thorough examination of the events taking place between point-of-trip and point-of-rest. Increasing demands are placed on reconstructionists to provide greater levels of detail regarding the roll sequence. Examples include, but are not limited to, roll rates at the quarter-roll level, CG trajectory (horizontal and vertical), roll angle at impact, and ground contact velocity.

Often the detail that can be provided in a rollover reconstruction is limited by a lack of physical evidence. However, there are many cases where the physical evidence – both on the vehicle and the ground – allows for detailed re-positioning of the vehicle during the roll sequence. Using such a high level of detail would lead one to believe that the reconstruction of the rollover dynamics will be an accurate representation of the actual event. But, just how accurate will it be?

This paper seeks to examine the commonly used constant deceleration method of rollover reconstruction in light of detailed analyses of actual rollover tests. By comparing methods used in the field to detailed experimental observations this paper will provide an understanding of the accuracy and limitations of those methods. The underlying data that provide the

foundation for this article are derived from two high-speed soft-surface dolly rollover tests of sport utility vehicles.

INTRODUCTION

There can be no question that the study of automotive rollovers has garnered significant attention. Spending any amount of time examining the technical or public literature regarding automotive crashes will make it obvious that many people are concerned about rollover collisions.

Areas of investigation are diverse but have generally focused on rollover resistance and crashworthiness. Both topics are in and of themselves diverse with many investigative sub-specialties.

The importance of studies investigating rollover resistance and crashworthiness cannot be denied. However, from the standpoint of reconstructing an actual rollover in the field, these studies are of limited use.

An examination of the literature reveals a number of articles that cover the reconstruction of rollover events or provide data useful to the reconstructionist [1-13]. These articles variously describe the common methods for reconstructing a rollover crash and provide test-derived data useful for applying them.

If one parses these articles on rollover reconstruction to focus on that portion of the event between point-of-trip (POT) and point-of-rest (POR), one will find two areas of examination that receive much of the attention: 1) computing speed at trip and 2) scratch/abrasion pattern analysis. These are valuable areas of study/discussion, particularly, for the purposes of reconstructing the speed

at trip, determining the number of rolls, and sequencing ground contacts. However, reconstructing the rollover sequence between trip and rest oftentimes requires a greater level of detail and understanding than the speed at trip and number of rolls. The increasing demand for detail is partly due to the need to understand occupant dynamics at particular points during a roll sequence. Enhanced detail is also driven by reconstructionists who continue to advance the art and science of rollover reconstruction by stretching the limits of the available physical evidence.

One potential problem with the continued pursuit of greater detail relates to the accuracy and reliability of the fundamental methods that reconstructionists use. Typically a constant deceleration model is used to compute speed at trip based on the distance between POT and POR. Further, the time intervals between various positions along the roll path can be computed using the same model. With time intervals in hand the average roll rates between various positions and over the entire roll sequence can be computed.

Using this approach, the computations performed to reconstruct the dynamics of a rolling vehicle are straightforward, and from their simplicity comes the question that prompted this research: how accurately and reliably can the roll dynamics be reconstructed assuming the reconstruction analysis is based on a constant deceleration model?

The answer to this question does not appear to exist in the literature. In order to truly answer the question, the measured dynamics of actual rollover crashes would need to be compared to their reconstructed counterparts.

The purpose of this study lies in elucidating the accuracy and reliability of the constant deceleration model that is the fundamental method for reconstructing rollover crashes. This examination of accuracy and reliability will be accomplished through detailed dynamic analyses of two dolly rollover tests followed by comparison with vehicle dynamics defined using reconstruction techniques. It is hoped that the reader will gain a greater appreciation for the simplicity and power of the constant deceleration model. Further, it is hoped that the reader will gain a greater appreciation for the limitations associated with using a constant deceleration scheme.

METHODS

TEST SETUP

Two full-size sport utility vehicles (SUV) were used as test vehicles for this study. A summary of vehicle information is provided in Table 1. Both tests were conducted at the Exponent Test and Engineering Center in Phoenix, AZ. The details of each test can be found in Table 1.

Table 1 – Basic test information. Roll inertia values were obtained from Autostats.

Test Number	1	2
Date	10/19/2005	7/17/2006
Exponent Test #	PH09825	PH10303
Vehicle Year	1998	2004
Vehicle Make	Ford	Volvo
Vehicle Model	Expedition	XC90
Drivetrain	5.4 L V8 4X4	2.5L I5 4X4
Launch Speed	69.5 kph (43.2 mph)	69 kph (42.9 mph)
Test Weight	29509 N (6634 lbf)	22298 N (5013 lbf)
Roll Inertia	1143 N-m-sec ² (843 lb-ft-sec ²)	1009 N-m-sec ² (744 lb-ft-sec ²)

Both vehicles were accelerated to the desired test speed on a dolly similar to that specified in FMVSS 208 and SAE J2114. The dolly supported each vehicle at a roll angle of 23 degrees (Figure 1). The leading side tire sidewalls rested against 10.2 cm (4 inch) tall steel retaining plates 22.9 cm (9 inches) above the crash rail surface. In these tests the leading side was the driver's side. After reaching the desired test speed the dolly was rapidly decelerated over a distance of 5 to 6 feet.

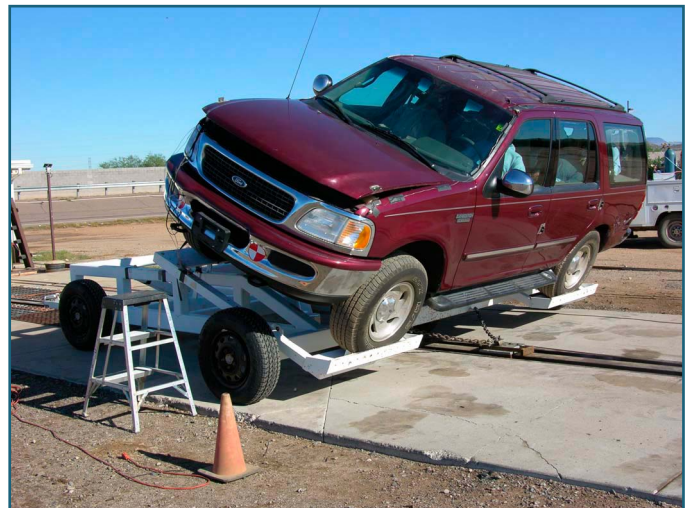


Figure 1: Photograph showing the Expedition used in Test 1 positioned on the rollover dolly pre-test. This photograph shows the hood of the vehicle open to facilitate pre-test preparations. Before the test was conducted the hood was closed.

The rollover surface was desert soil that was lightly compacted after placement on the concrete crash rail. The final depth of the desert soil was approximately 6-inches. The appearance of the test surface is depicted in Figure 2.

Vehicle preparation involved draining all fluids and ballasting to the as-received curb weight with the appropriate fore/aft distribution. Each vehicle was equipped with tires and wheels as recommended by the manufacturer.



Figure 2: Photograph depicting a typical test surface. In the foreground the ends of the “snubber” tubes are visible. The snubber tubes approximate the stopping point for the portion of the dolly under the left-side tires.

Anthropomorphic Test Devices (ATDs) were utilized in both tests. The ATDs were added after the vehicles were ballasted. Six ATDs were positioned inside the Expedition, at each of the outboard seating positions. Four ATDs were positioned inside the XC90 at each of the outboard seating positions. Detailed studies of the occupant kinematics during these tests have been previously published [14].

In these tests, any tempered side glass adjacent to a seating position was removed and replaced with laminated glass. Additionally, the doors were bolted shut to isolate the performance of the door glass. A discussion of the performance of laminated glass in these tests has been previously published [15]

As part of the documentation of each test, real-time and high-speed video and film cameras were used. Two pairs of ground-level real-time and high-speed cameras were placed at off-board positions on either side of the rollover path and panned during the event. Additionally, a fixed ground-level high-speed camera was positioned at the downstream end of the dirt rollover surface looking upstream at the rolling vehicle. High-speed cameras recorded the event at a rate of 250 frames per second.

Onboard data acquisition was used to sample roll and yaw rates. A sensor package capable of measuring roll and yaw rates was mounted to the floorpan along the longitudinal centerline at the approximate vertical projection of the center of gravity. The signals from the onboard instrumentation were sampled and filtered according to the specifications in the SAE J211 recommended practice.

POST-TEST DOCUMENTATION

Following each test the entire test surface was digitally mapped to document physical evidence deposited during the test. The mapping was performed with a Laser Total Station (Leica Geosystems, St. Gallen, Switzerland) and a Vulcan Digital Measurement device (ArcSecond, Inc., Dulles, Virginia).

Ground-level photographs of the test surface evidence were taken to correlate with the digital mapping. Additionally, photographs of the test surface were taken from a mobile high-lift platform.

Still photographs were taken of each vehicle before and after testing. The post-test photographs included detailed documentation of vehicle damage and abrasion patterns.

TEST ANALYSIS

The process of analyzing these rollover tests began with a frame-by-frame study of the video footage. Through this process, the orientation of the vehicle was broken down into quarter rolls and linked to the roll rate measurements captured by the onboard instrumentation. Subsequently, the test footage and onboard data were correlated to the physical evidence documented on the desert soil test surface.

Linking the test footage and onboard data to the physical evidence was an iterative process. To begin, the onboard data and video footage were synced by a trigger system that flashed a number of lights when the dolly engaged with the snubbers and began decelerating. At the same moment the lights flashed a trigger signal was sent to the onboard instrumentation indicating time-zero. The lights, which were visible in the video footage, provided the mechanism for synchronizing the onboard instrumentation and the offboard cameras. The video footage for Test 1 was offset from time-zero by 0.804 seconds. The video footage for Test 2 was offset from time-zero by 0.780 seconds.

Once the data and video were synced, several quarter-roll positions associated with distinct ground contacts were defined. Each quarter roll position was then specified temporally using both the test footage and the onboard instrumentation data. Additional quarter-roll positions were placed along the path where the video footage, physical evidence, and previously established quarter-roll positions allowed. Unfortunately, the physical evidence on the ground and the video footage did not allow for the specification of every quarter-roll position.

Once all possible quarter-roll positions were established, the path of the center-of-gravity (CG) was traced. The rollover sequence was then broken down by the Over-The-Ground (OTG) CG-to-CG distance between adjacent quarter-roll positions along the CG path. Since

the quarter-roll positions were already linked to time through the instrumentation data and video footage, it was then possible to relate travel distance between positions to the time interval between positions.

A spline was applied to the distance versus time data providing a smooth and continuous relationship that was amenable to differentiation. The spline was applied in Mathcad 14 (Parametric Technology Corp., Needham, MA) using the Ispline interpolation routine. The Ispline routine in Mathcad is a cubic spline that is linear at the endpoints.

Temporal differentiation of the spline fit of distance versus time produced the OTG speed for the vehicle CG as a function of time. An additional differentiation with respect to time provided the OTG deceleration of the vehicle CG.

Roll angle data was generated in two ways. One method relied on the temporal integration of the roll rate data from the onboard instrumentation. The other method was based on frame-by-frame analysis of the test footage that related quarter-roll positions to time. The analysis of the test footage yielded a piecewise approximation to roll angle versus time rather than the essentially instantaneous roll angle produced by integrating the roll rate data.

Next, the translational and rotational kinetic energies were computed. Translational kinetic energy was calculated using the OTG speed and the mass of the vehicle as defined by the test weight including ATDs. The rotational kinetic energy was computed using the roll rate data and the roll moment of inertia obtained from Autostats (4N6XPRT Systems, La Mesa, CA). The roll inertia for the Expedition was confirmed using the NHTSA Inertia Database [16], which did not have data for the XC90. Finally, the total kinetic energy was computed by simply adding the translational and rotational values for each time point.

RECONSTRUCTION ANALYSIS

Once the “measured” results were established, each test was approached in a manner akin to the reconstruction of a real-world crash. To start, a constant deceleration model (Equation 1) was used to obtain OTG speeds at each CG location working upstream from point-of-rest (POR) to the point of first ground contact by the inside tires. The deceleration values ranged from 0.4g to 0.6 g, consistent with the typical range applied to the reconstruction of rollover collisions.

After establishing the OTG speeds at each quarter-roll position the time intervals between positions were established with the definition of average acceleration shown in Equation 2.

With the time intervals established the average roll rates between adjacent quarter roll positions were computed. The average roll rate was computed simply by dividing

the roll angle between adjacent quarter roll positions by the time interval between those positions.

$$V_i^2 - V_f^2 = 2 \cdot a \cdot S \quad (1)$$

$$a = \frac{\Delta V}{\Delta t} \quad (2)$$

As a final step, speed and roll rate were related to time. For the purposes of this paper, time-zero for the reconstructed speeds and roll rates was defined at the first ground contact in each test. It was necessary to either start the clock at first ground contact or stop the clock at point-of-rest because the sum of the time intervals computed using the definition of average acceleration did not necessarily equal the measured event duration from first ground contact to POR. This inequality was particularly noticeable when the vehicle reached its eventual POR but continued rocking or shifting for some additional amount of time. Moreover, it appeared reasonable to set time-zero at the first ground contact since that was where the roll sequence essentially began.

RESULTS

Mapping the test surface digitally following each test provided a detailed visualization of the evidence deposited by the test vehicles. This sort of digital mapping is very similar to the type of mapping that a reconstructionist would perform in the field. The surface maps for each test can be found in Appendix A.

The vehicle position layouts that provide the basis for the bulk of the analysis conducted in this article can be found in Appendix B. Reviewing these layouts reveals a significant difference in the number of defined positions that can be established by correlating physical evidence on the ground, video footage, and onboard instrumentation. In Test 2 the vehicle spent significantly more time in the air and made fewer distinct ground contacts that could be mapped to a quarter roll position adequately. Adding more positions to Test 2 would require a photogrammetric analysis of the test footage, which is beyond the scope of this study.

The results of the analyses conducted for this article provide a high level of detail regarding the subject tests. Table 2 is a general summary of the test data and highlights the kind of valuable data commonly used by reconstructionists.

The results that are the basis for this article can be broken down into two categories: “measured” and “reconstructed.” For clarity, the term “measured” does not necessarily mean that all of the data presented were actually measured. However, the implication is that the “measured” results attain greater fidelity because they are based on video coverage and onboard instrumentation,

and physical evidence. The “reconstructed” results, on the other hand, rely on the methods typically used in reconstruction to generate the vehicle dynamics, and therefore, are not expected to have the same level of fidelity.

Table 2: General test results. Note that the distance rolled is taken from the first ground contact to point-of-rest along the path traced by the center-of-gravity. The deceleration provided is computed assuming a constant deceleration over the distance rolled.

Test Number	1	2
Launch Speed	69.5 kph (43.2 mph)	69.0 kph (42.9 mph)
Distance Rolled	34.4 m (113 ft)	34.0 m (111.5 ft)
Number of Rolls	4	4 1/4
Deceleration	0.55g	0.55g
Peak Roll Rate	636 deg/sec	631 deg/sec
Average Roll Rate	339 deg/sec	317 deg/sec

MEASURED RESULTS

The “measured” results fundamentally rely on the relationship between distance traveled and time (Figure 3 and Figure 4). This relationship starts at first ground contact by the onside (left-side) tires and ends at the POR. The nonlinear nature of the distance histories for these tests is readily apparent in the plots. Recall, that these traces were created by fitting a spline through the discrete points established by the CG-to-CG distances of adjacent quarter-roll positions.

Careful examination of the distance histories reveals that in Test 1 the vehicle rolled past its POR by a small amount and then rolled back before coming to rest. A similar occurrence was noted in Test 2, however, the camera coverage made it difficult to assess just how far beyond POR the vehicle rolled before settling. Since, the onboard instrumentation could not be relied on for establishing the maximum roll angle (see results for roll angle as a function of distance below) the settling phase of the vehicle in Test 2 could not be incorporated into the analysis. Therefore, the distance history for Test 2 ended when the vehicle reached its POR.

Differentiation of the distance histories produced the OTG speed histories (Figure 5 and Figure 6). There is a clear non-linear trend in the speed histories for both tests. Both traces show the speed of the vehicle generally decreasing over time, with areas where the trace flattens out. In the areas where the speed flattens out, the vehicle is essentially airborne. This is consistent with the expectation that once the vehicle leaves the ground it is in a ballistic trajectory mode and the OTG speed should remain constant, neglecting air resistance.

Triangular markers are shown in the speed history plots. These markers denote the time index for specific

quarter-roll positions that were defined as discussed above. These markers correspond in time to the circles shown in the distance histories (Figure 3 and Figure 4) excluding additional markers that incorporate settling at the end of Test 1.

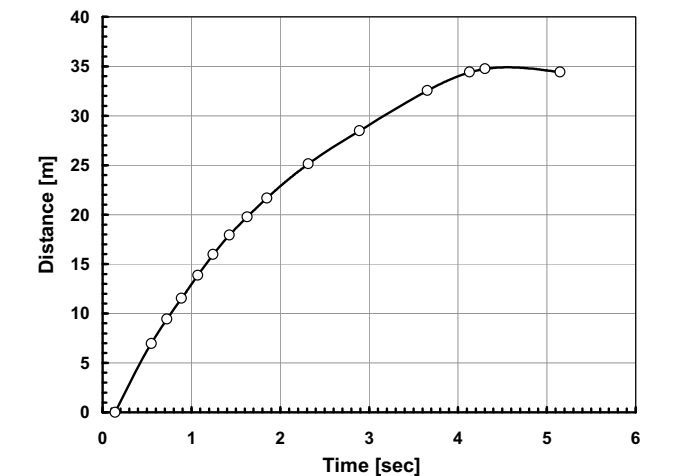


Figure 3:Time history of the distance traveled by the CG during Test 1. The circles represent the discrete points through which the spline was fit.

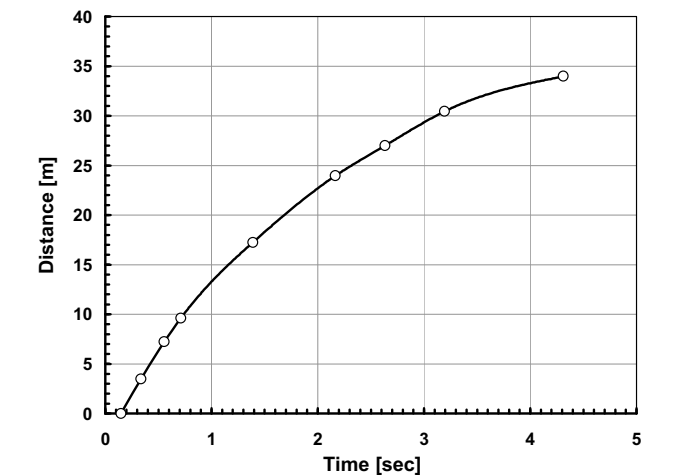


Figure 4: Time history of the distance traveled by the CG during Test 2. The circles represent the discrete points through which the spline was fit.

It is important to note that there are segments, particularly in Test 2, where the vehicle rolls anywhere from a half revolution to a complete revolution without leaving enough evidence to define quarter-roll positions in-between. It is in the areas where quarter-roll positions are lacking that the analysis loses definition in terms of computing OTG speed and acceleration.

Temporal differentiation of the OTG speed histories produced OTG acceleration histories (Figure 7 and Figure 8). The acceleration histories clearly show that the vehicles are decelerating during the duration of the rollover sequence. Further, they demonstrate a significant degree of non-linearity. The observed non-linearities are largely related to the state of the vehicle during the sequence: in contact with the ground vs. airborne.

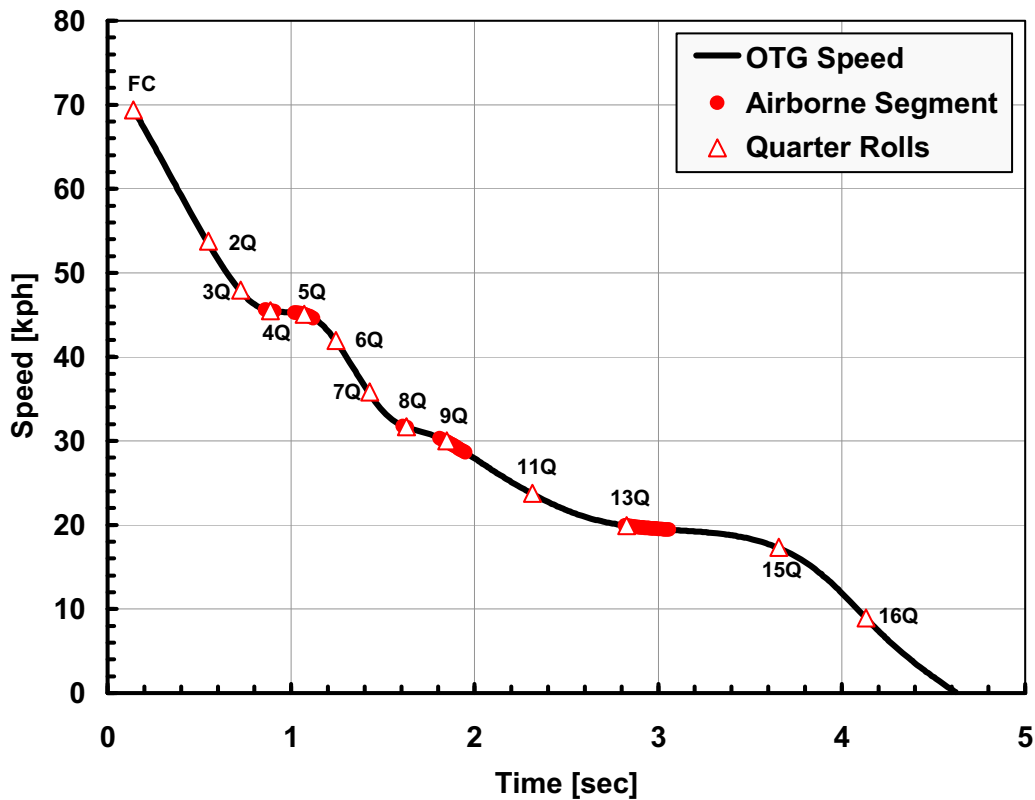


Figure 5: Time history of OTG speed for Test 1. The filled circles represent airborne segments. The open triangles represent defined roll positions. The label FC represents the first contact with the ground after launch. The labels #Q represent quarter rolls (e.g. 6Q is 6 quarter rolls or 1-1/2 rolls).

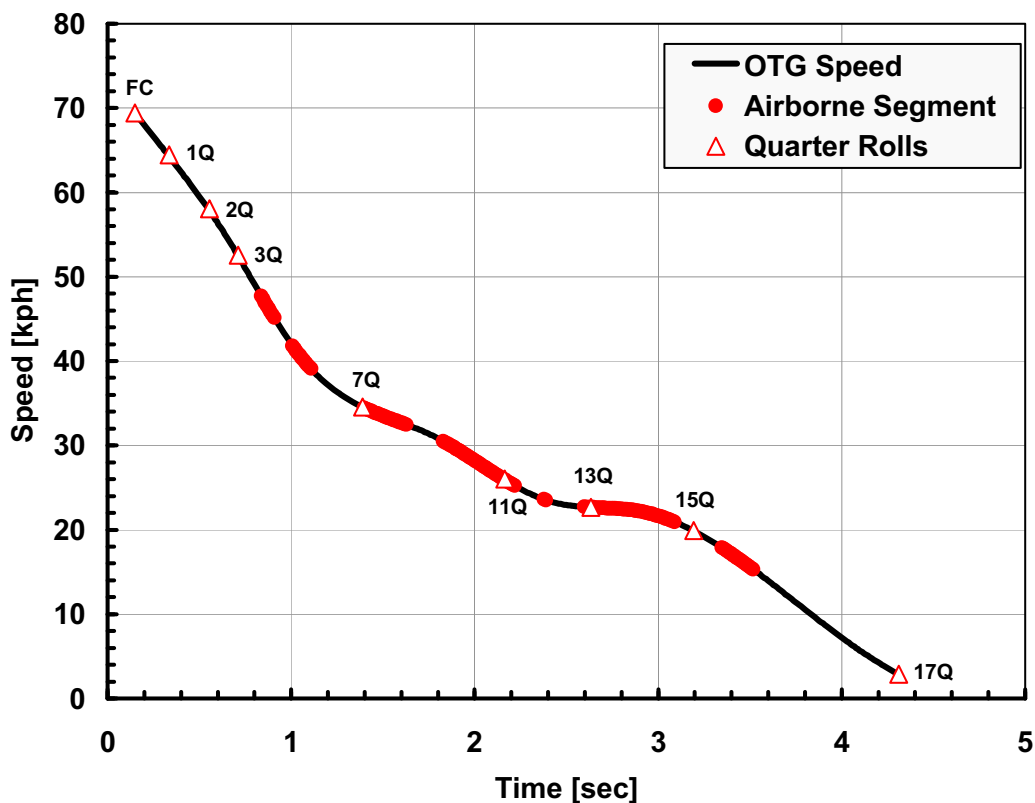


Figure 6: Time history of OTG speed for Test 2. The filled circles represent airborne segments. The open triangles represent defined roll positions. The label FC represents the first contact with the ground after launch. The labels #Q represent quarter rolls (e.g. 6Q is 6 quarter rolls or 1-1/2 rolls).

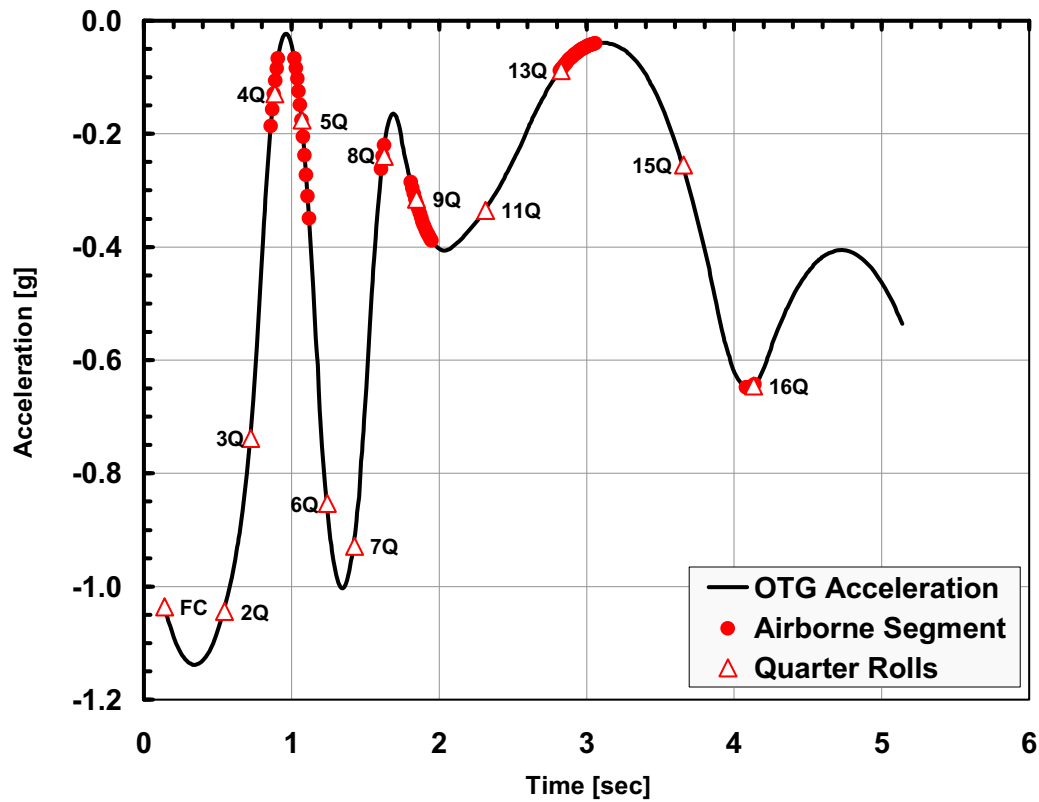


Figure 7: Time history of acceleration for Test 1. Negative acceleration indicates the vehicle is decelerating during the sequence. Airborne segments are shown with red filled circles. Quarter roll positions are shown as red open triangles.

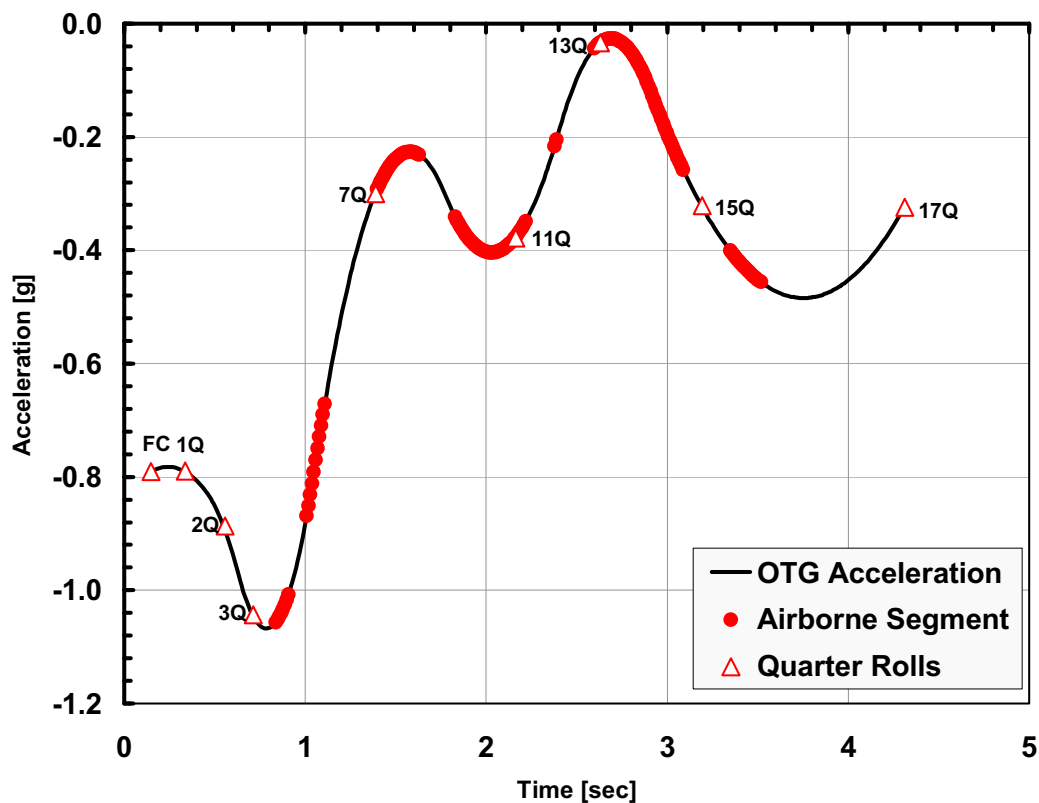


Figure 8: Time history of acceleration for Test 2. Negative acceleration indicates the vehicle is decelerating during the sequence. Airborne phases are shown along the time axis.

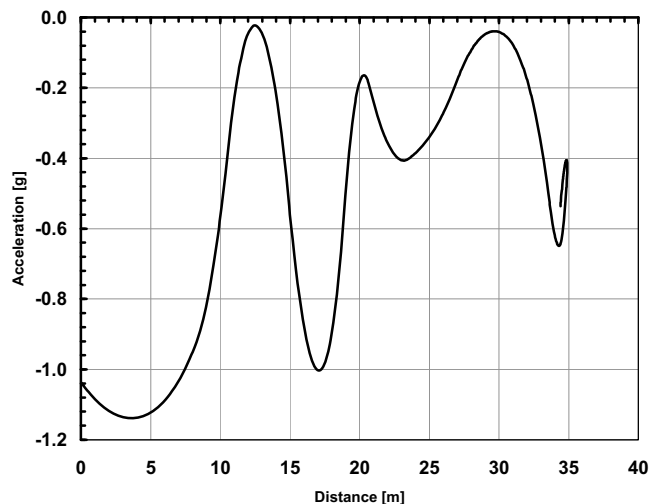


Figure 9: Acceleration as a function of distance for Test 1. Negative acceleration indicates the vehicle is decelerating during the sequence.

On each acceleration trace, segments where the vehicle was airborne have been clearly specified. When the vehicles were in contact with the ground, particularly in the early stages of the sequence, the decelerations were relatively large – on the order 1g or more. When the vehicle becomes airborne the decelerations would be expected to drop to zero assuming the vehicle behaves according to basic ballistics theory. And, as shown in the time histories, particularly for the Expedition, they do approach zero in general. However, in segments where quarter-roll information is lacking, the behavior is not as expected. This unexpected behavior is particularly noticeable toward the end of the Expedition test and in several places during the XC-90 test.

Another way of looking at the acceleration history during a test is to relate it to the distance traveled during the sequence (Figure 9 and Figure 10). During the first half of both tests the decelerations are peaking at over 1g. As each vehicle moves toward the end of the sequence the peaks tend to stay below 0.5g, except for the end of Test 1. At the end of Test 1, the Expedition dug in hard with the onside (left-side) wheels to produce a spike of 0.65 g, bringing the event to a halt.

The roll rate time histories were developed by sampling a roll rate transducer during each test (Figure 11 and Figure 12). These plots demonstrate that the peak roll rate was developed relatively early in the sequence. In both tests the peak roll rate was experienced in less than a second after the first ground contact. In both tests the peak roll rates are consistent in magnitude at slightly more than 630 deg/sec.

Once the peak roll rate is reached the roll rate appears to drop off in a relatively linear fashion for both tests. At the end of test 1 the Expedition's roll rate demonstrates a sudden drop. This is related to the hard final contact where the onside (left-side) wheels dug into the test surface. The XC-90, on the other hand did not

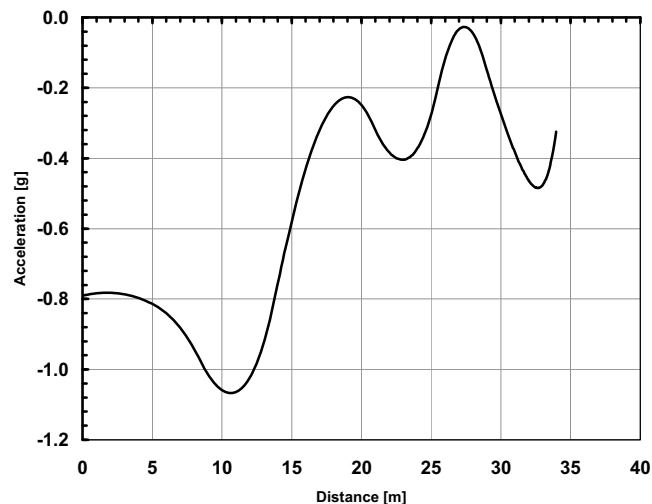


Figure 10: Acceleration as a function of distance for Test 2. Negative acceleration indicates the vehicle is decelerating during the sequence.

experience the same type of ground contact at the end of the event and, by all appearances, maintained a nearly linear reduction in roll rate until it came to rest.

An examination of both roll rate histories does demonstrate a common characteristic. Both histories demonstrate a triangular pattern. The leg of the triangle leading up to the peak is steep and is followed by a much shallower leg after the peak has been reached.

Note that in Test 2, the roll rate transducer experienced dropouts and noise spikes. These dropouts and spikes in the data correlate to times when hard impacts occurred between the vehicle and the test surface.

When the roll rate data is related to distance traveled the triangular pattern is still present although somewhat less distinct (Figure 13 and Figure 14). Test 2, in particular, appears less triangular on the leg following the peak. However, this loss of triangular character may be more closely related to the noisy signal and dropouts evident in the data trace (Figure 12).

The relationship of roll angle to distance demonstrates what appears to be a bi-linear relationship to distance (Figure 15 and Figure 16). The shallower slope occurs prior to the peak roll rate. Once the peak roll rate has passed, the slope increases noticeably and remains essentially constant until the end of the sequence.

The roll angle traces shown in Figure 17 and Figure 18 were generated by combining video analysis and instrumentation data analysis. Early in the sequence the roll angle values from the video analysis agreed well with those produced by integrating the roll rate data from the onboard instrumentation. Continued close agreement was found for Test 1 (Figure 17); however, Test 2 showed progressive separation between video analysis and integration (Figure 18).