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Comparison of Linear Variable Deceleration Rate Rollover Reconstruction to Steer-Induced Rollover Tests

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ABSTRACT

A variable deceleration rate approach to rollover crash reconstruction was proposed in 2009 by Rose and Beauchamp. A detailed description of Rose and Beauchamp's method was outlined in 2010. The method used a Linearly Variable Deceleration Rate (LVDR) as a function of roll distance. Improvements in responses as a function of time was demonstrated by Rose and Beauchamp using test data from two 208 dolly rollover tests; however, they noted that additional validation work using steering-induced rollover tests would be desirable. This paper provides additional validation of the LVDR model using the steer-induced rollover test data reported in 2011 by Stevens et al. The Over-The-Ground Speed (OGS) and recorded roll rate results from the five steer-induced rollover tests reported by Stevens' in 2011 were compared to reconstructed speed and roll rates as a function of time using the 2010 Rose and Beauchamp LVDR method. Using an appropriate range of average drag factors, the LVDR method produced agreement with the measured results of the Stevens rollover tests. Comparisons showed agreement with the predicted rollover duration, the shape of the roll rate curve and the maximum roll rate. Calculated roll rates were high if the calculated roll duration was low. Low roll durations were found associated with a Constant Drag Factors (CDF) method and the LVDR method utilizing high average drag factors. Greater roll rate uncertainty occurred in roll segments that have long airborne duration and/or high speed change. The LVDR method significantly improves prediction of speed and roll rate time history compared to a CDF method.

INTRODUCTION

It is common practice to reconstruct rollover speed at the point of rollover initiation using a Constant Drag Factor (CDF). The CDF approach has proven useful because roll phase distance can be determined from physical evidence and the length of the roll phase is often measured. Recently published studies reported that the CDF approach is not as good at predicting the roll duration or the speed and roll rate at discreet points (or times) when reconstructed along the roll path.

Carter's 2008 SAE paper provided an extended technical discussion on the physics at play during rollovers [1]. He observed that angular and translational velocities were constant during airborne phases. Carter also noted that a multiphase approach to reconstructing rollover crashes was suggested by his results and noted the appearance of a bi-linear relationship between roll rate and Over-The-Ground (OTG) distance. Carter demonstrated that results from 208 dolly rollovers on dirt produced OGS's that decreased, “in a non-linear fashion throughout the roll sequence.” Use of a CDF calculated from the recorded roll speed and roll distance was demonstrated to underestimate the roll duration.

In their 2009 SAE paper Rose and Beauchamp, “advance rollover crash reconstruction techniques beyond the assumption typically made that a rolling vehicle decelerates at a constant rate” [2]. Their approach was to identify two or three regions over a vehicle's roll distance, assign discrete deceleration rates to each region and equate the overall deceleration to average deceleration. Two examples from crash tests were examined. The authors noted, "Overall, each of the suggested variable deceleration rate profiles represented a significant improvement over using a constant deceleration rate."

Carter reinforced his published notation of a non-linear decrease in OGS during his 2010 Keynote Address before the Rollover Session of the 2010 SAE World Congress [3]. Carter presented results of refined video analysis from a Ford Expedition 208 dolly rollover on dirt demonstrating an exponential decay in OGS as a function of time.

A LVDR approach to rollover reconstruction in which the drag factor linearly decreases as a function of distance from first contact to the point of rest was presented in 2010 by Rose and Beauchamp [4]. Transforming from the displacement domain to time domain resulted in a decaying polynomial function. The approach was described as reducing error in reconstructed translational and angular velocity time histories. In their article the authors commented that the LVDR approach could benefit from more extensive validation.

In 2011 Stevens presented detailed OGS analysis of five instrumented steer-induced rollover tests [5]. The testing included detailed documentation of crash surface marking, vehicle damage, vehicle marking, and plots of recorded onboard instrumentation. Stevens demonstrated a consistent bi-linear response in OGS as a function of time and noted changes in the recorded roll rate responses corresponding to the transition time of deceleration rate. The bi-linear response could also be called a bi-constant drag factor where the first phase of the roll has a higher constant drag factor compared to the second phase. These findings motivate the development and validation of a reconstruction method that more closely models the duration and shape of speed versus time response. This paper uses five documented steer-induced rollovers presented by Stevens (5) in 2011 to further evaluate the validity of the Rose and Beauchamp LVDR approach.

METHOD

Linearly Variable Deceleration Rate (LVDR) rollover reconstructions of the speed and roll rate time histories were performed for the five rollover tests presented by Stevens [5]. The LVDR rollover reconstruction used the method outlined by Rose and Beauchamp in their 2010 article [4]. A linearly decreasing drag factor with respect to the distance from first post-trip ground contact to the point of rest was utilized.

The distance from first post-trip ground contact to the point of rest is defined as the rolling distance. The first airborne segment is the distance between the point of trip and the first post-trip ground contact. OGS is assumed constant during the first airborne segment. The roll phase distance is defined as the rolling distance plus the first airborne segment distance.

The LVDR method used an average drag factor consistent with CDF analysis to calculate the speed at roll initiation, then imposed a plus 0.2 g starting drag factor and a minus 0.2 g ending drag factor. In other words, for the assumption of a 0.4 g average drag factor the method calculates speeds along the roll phase distance using 0.6 g at the start, linearly decreasing deceleration over the roll phase distance and ending with 0.2 g. Using stepwise calculations over constant distance increments the time per increment is determined and transformation to the time domain is completed. From reconstructed angular positions and distances a final calculation of segmental roll rates is performed.

Comparisons of the LVDS reconstructed speed versus time and roll rate versus time were made between the calculated OGS and recorded roll rate for all five steer-induced rollover tests. The comparisons were completed by using the calculated constant drag factor reported for each test and a low and high drag factor of 0.38 g and 0.5 g, respectively. The low and high drag factors represented the drag factor range from analysis presented in a 2011 ASME paper of 81 dolly rollover tests and 24 steer-induced rollover tests [6]. Consistent with the approach of Rose and Beauchamp the initial drag factor was assumed 0.2 g higher than the average[1].

Rose and Beauchamp provided an eight step method for performing a LVDR calculation [4]. The following initial steps were completed prior to starting the analysis:

1. The speed at the start of the rolling phase was calculated using an average (constant) drag factor.

2. The length of the first airborne segment distance was subtracted from the roll phase distance. This step yielded the rolling distance.

3. The effective constant deceleration was calculated for the rolling distance. This effective deceleration for the rolling distance was then utilized in the Rose and Beauchamp eight-step method. In other words, the calculated effective deceleration for the rolling distance was used where Rose and Beauchamp refer to average deceleration rates in their calculation.

Table 1 summarizes the average drag factors calculated for each test and contains the distance and duration of the first airborne phase of each test. The length of the first airborne phase is subtracted from the roll phase distance because

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[1] Rose and Beauchamp suggested an average range of 0.4 g to 0.6 g and corresponding initial drag factors of 0.6 g and 0.8 g. They reported: "using initial deceleration rates around 0.8 resulted in an excellent match with the OGS curves for the Expedition and Volvo dolly rollover tests. Considering this data, in this article [the 2010 article], we utilized average deceleration rates between 0.4 and 0.6g for both the constant and variable deceleration rate approaches and an initial deceleration rare between 0.6 and 0.8 for the variable deceleration rate approach" [4].

speed and roll rate remain constant in airborne phases. This refinement provides an improvement of the deceleration model.

Table 1. Summarizes the average drag factor calculated for each test and the effective constant drag factor over the roll distance. The length and time of the first airborne phase is listed.

Test No.	Average Drag Factor (g)		Length First Airborne Segment (ft)	Time First Airborne Segment (sec)
	Over Roll Phase Distance	Over Roll Distance		
R0	0.36	0.40	10.7	0.224
R1	0.42	0.46	22.4	0.264
R2	0.38	0.42	14.9	0.248
R3	0.33	0.38	11.1	0.250
R4	0.57	0.66	13.9	0.224

After calculating and plotting the speed versus time and roll rate versus time by the LVDR method, the calculated OGS and roll rate test data was overlaid for comparison. A SAE Class 60 filter was used for the test's data roll rate. Calculated roll rate results used roll angles derived from test results. The roll angle derived from test results was determined by integrating the roll rate recorded by test instruments and synchronizing ground marking to the roll angle record. The integrated roll angle results were in good agreement with video-recorded motions and the final rest conditions. Time zero was at the moment of the roll phase initiation (at the point of trip).

RESULTS

Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 in Appendix A compare test results of measured roll rate and calculated OGS presented in Stevens' 2011 paper to the LVDR derived speed and roll rate. Comparison results are labeled *Upper*, *Calc* (calculated) and *Lower* referring, respectively, to the upper drag factor of 0.5 g, the reported calculated constant drag factor (a quantity different for each test) and the lower drag factor of 0.38 g. For test R2 the calculated constant drag factor for the test was the same as the low constant drag factor, 0.38 g. Roll rate results from test R4 are not presented because roll rate was not collected due to an instrumentation problem. Table 2 summarizes the calculated and actual roll duration. The roll duration was defined to have ended when the vehicle first rolls to its final rest position. If the vehicle overshot the final rest position and then rocked back to final rest, the time representing the overshoot was neglected. Table 3 and Table 4 summarize the calculated and actual maximum roll rate and time of maximum roll rate, respectively. Actual roll rates are from recorded test data filtered to SAE class 60.

Table 2. Actual and calculated roll phase durations.

Test No.	Roll Phase Duration (sec)			
	From Assumed Drag Factor			Actual
	Calc	Upper	Lower	
R0	4.99	3.94	4.79	5.05
R1	7.16	6.34	7.71	7.58
R2	5.65	4.65	5.65	5.31
R3	4.92	3.64	4.41	3.70
R4	3.53	3.84	4.65	3.58

Table 3. Actual and calculated maximum roll rates. Actual roll rates from data filtered to SAE class 60.

Test No.	Maximum Roll Rate (deg/sec)			
	From Assumed Drag Factor			Actual
	Calc	Upper	Lower	
R0	179	238	189	417
R1	861	964	804	757
R2	542	632	542	734
R3	492	616	531	580
R4	455	419	348	n/a

Table 4. Actual and calculated time of maximum roll rates. Actual time from data filtered to SAE class 60.

Test No.	Time of Maximum Roll rate (sec)			
	From Assumed Drag Factor			Actual
	Calc	Upper	Lower	
R0	4.16	3.31	4.00	2.18
R1	2.43	2.20	2.58	1.84
R2	0.87	0.76	0.87	1.69
R3	0.62	0.50	0.57	0.71
R4	1.44	1.55	1.82	n/a

DISCUSSION

The explicit inclusion of the first airborne segment in the development of speed and roll rate with respect to displacement and time was a refinement in modeling of the roll phase. Prior modeling had described varied deceleration over the rolling distance; but, during the first segment of a rollover, assuming it is an airborne segment, OGS is constant. Based upon five tests presented by Stevens [5] the length of a steering-induced rollover's first airborne segment increases with trip speed, but on average was 0.242 seconds (standard deviation = 0.018 seconds). All of the reconstructions assumed flat surfaces. Adjustments to the applied deceleration rates may be needed when significant elevation changes occur between trip and rest.

While a CDF predicts the speed at trip in a rollover, a varying drag factor provided a more accurate description of the vehicle's motions with respect to time. Deceleration in the Stevens' tests was reported to change over the rolling distance and linearly varying drag factor along the path of a reconstructed rollover was noted to improve agreement with the roll duration. When a test's reported CDF was used as the average deceleration to derive LVDR roll duration, deviation from the actual roll duration averaged ± 9.5 %. When test R3 was excluded, because a large change in OGS occurred in the last segment of the test, deviation from the actual roll duration averaged ± 3.6 %. Additionally, when test R3 was excluded, the high and low drag factor deviated from the actual roll duration on average ± 11.9 % and ± 12.5 %, respectively.

With the exception of R0 the shape of calculated roll rate versus time curves categorically followed the actual response. The similarities included that, following a constant roll rate in the first airborne segment, the roll rate increased then decreased following a triangular shape and the base of the increasing leg of the triangle was shorter than the base of the decreasing leg. Roll rate measurements from test R4 were not available because of instrument problems.

In test R0 the tested minivan slid on its roof during the first roll, slowing the roll rate to zero while still translating at 31 ft/s, before resuming rolling in line with the triangular characteristic. The calculated roll rates for R0 predicted the drop in roll rate in the first roll, but did not describe the extent of decrease. The lowest calculated roll rates in R0 for the calculated (*Calc*), *Upper* and *Lower* drag factors were 130 deg/s, 155 deg/s and 134 deg/s, respectively. The measured roll rate decreased to essentially zero at 1.093 seconds. The maximum roll rate in test R0 was also under predicted. The highest calculated roll rates in R0 for the calculated (calc), upper and lower drag factors were 179 deg/s, 238 deg/s and 189 deg/s, respectively; the measured roll rate increased to a maximum of 417 deg/s at 2.181 seconds.

Calculated roll rates in R1 over predicted and identified a delayed time of maximum roll rate. Roll rates in R1 were over predicted for the calculated (*Calc*), *Upper* and *Lower* drag factors by 14%, 27% and 6%, respectively. The times of maximum roll rate in R1 were delayed for the calculated (*Calc*), *Upper* and *Lower* drag factors by 0.595 sec, 0.365 sec and 0.745 sec, respectively. A large change in OGS at approximately 2 seconds coincided with the deviation in the predicted versus actual roll rate.

For R2 and R3 the calculated roll rate based upon the calculated (*Calc*) drag factor followed the measured roll rate. The quality of the predicted curves was made possible because of the large number of known ground impacts and accurate corresponding roll orientations.

In test R2 the roll rate spike event at 1.694 seconds was approximately 100 ms long and aligned with a large change in the OGS. If the spike event at 1.694 seconds was excluded the predicted maximum roll rates in R1 were 9% low for the calculated (*Calc*) drag factor and 7% high for the upper drag factors. The low drag factor was equal to the calculated (*Calc*) drag factor for test R2. In test R3 sufficient alignment with ground marking and accurate roll orientation successfully predicted a second roll rate increase and local maximum at approximately 2 seconds.

Comparisons relied upon well documented tests with conditions and data that do not typically exist in actual reconstruction situations[2]. For example, the roll angle at each point of contact along a test vehicle's roll path was documented by video coverage and derived by integrating the measured roll rate. The precision of roll angles at ground contact along a test vehicle's roll path would not be expected in a typical reconstruction. To explore the effect of uncertainty in reconstructed roll angles with respect to position an analysis using test R2's results was performed in which the reconstructed roll angle for a given position was rounded to the nearest 1/8 roll angle (45 degrees).

The effect from rounding to the nearest 1/8 roll angle is illustrated in Figure 6 for test R2 using the reported constant drag factor as the average drag factor in LVDR predicted roll rate. It seems intuitive that the coarser the reconstructed analysis the more potential exists for variation. With rounding to the nearest 1/8 roll angle Figure 6 demonstrates increased variation from measured results in the first 1-1/2 seconds. After the first 1-1/2 seconds, rounding to the nearest 1/8 roll angle predicted correlation with the measured roll rate. Further research is warranted in exploring effects of roll angle uncertainty in a LVDR reconstruction.

The accuracy of the roll rate prediction is also affected by the number of reconstructed roll positions. The effect of a reduced number of roll positions is illustrated for R0 [Appendix A, Figure 1] where the predicted roll rate versus time was substantially different from the measured roll rate. In general, anomalies in the predicted roll rate also corresponded to high changes in OGS, long airborne segments, or long segments of uncertain angular orientation.

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[2] Documentation of ground markings from the rollover tests were made within minutes of test completion. The vehicle and motion pictures of the rollover were reviewed during measurement. The crash site was controlled so that vehicles and foot traffic did not destroy or obfuscate ground markings. Analysis of each test applied multiple sets of high quality controlled data including: documentation of the vehicle immediate following the crash; aforementioned scene control, measurement and photographic documentation; multiple synchronized videoed perspectives; synchronized high speed video and synchronized test data. These data and conditions do not exist in real reconstruction situations [5].

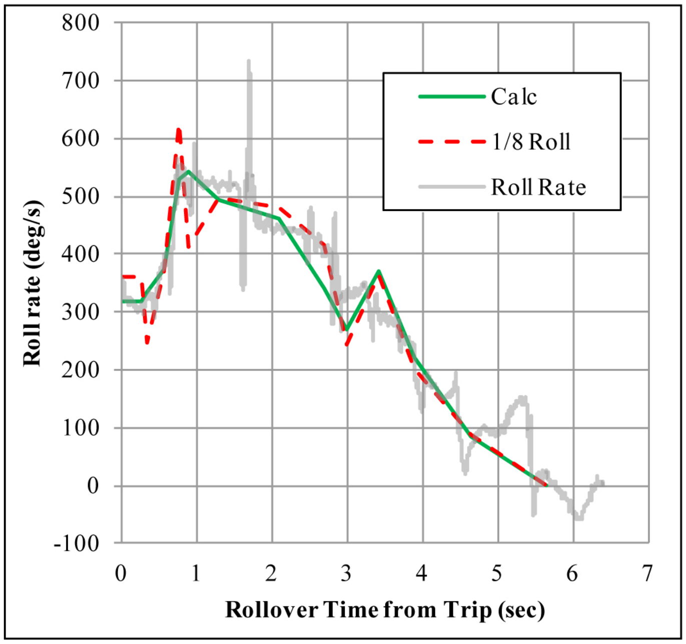

Figure 6. Roll rate versus time for LVDR comparing roll angle from test R2 to roll angle rounded to nearest 1/8 (45 degree).

To illustrate the improved description of roll motions from the LVDR method compared to the CDF method, predicted roll speeds and roll rates were calculated using the results of test R2. In this comparison responses were plotted using 0.38 g and 0.50 g with the CDF method and a 0.38 g average (± 0.20 g) with the LVDR method. Figure 7 illustrates the under prediction of roll duration and corresponding over prediction of roll rate magnitude associated with a CDF method. The best predictions of roll rate magnitude are associated with accurate predictions of roll duration. It was also noted that offsets in the time of predicted maximum roll rate occurred with the LVDR method. The time of maximum roll rate offsets are shown in Table 4 and for the Stevens tests appear to be associated with the time of reported change in drag factor and/or larger changes in OGS.

A key factor in predicting the roll rate time history is choosing a deceleration model that properly predicts the total rollover duration. A model that tends to underestimate the rollover duration (typical of a constant deceleration method and high average deceleration in a LVDR method) will overestimate the roll rate. Conversely, a model that overestimates the rollover duration will underestimate roll rates.

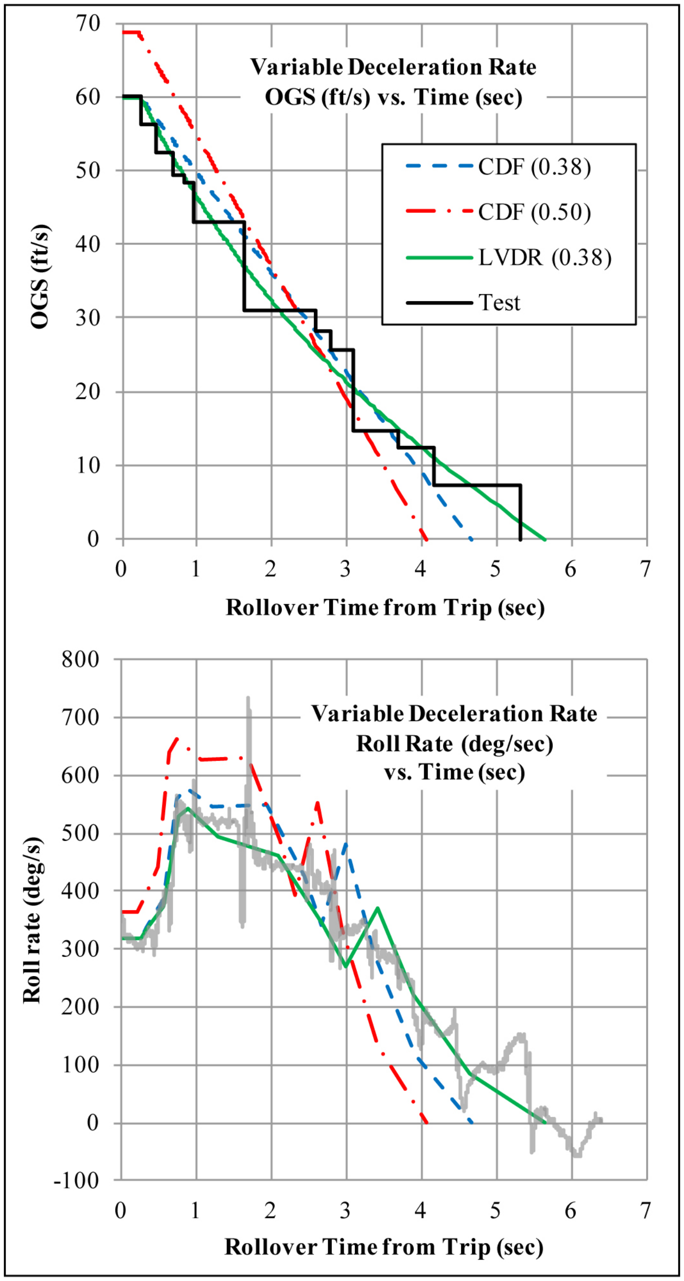

Figure 7. Under prediction of R2 roll duration and over prediction of R2 roll rate magnitude associated with CDF method.

One of the shortcomings of the LVDR approach in modeling the Stevens roll tests was that it assumed a constant rate of decreasing deceleration with the average deceleration at the midpoint of the rollover distance. The Stevens rollover testing consistently showed that the maximum roll rate and an associated drop in deceleration rate occur in the first half of the rollover distance. The effect of using the LVDR in modeling the Stevens test was to delay the predicted time of the maximum roll rate. A bi-constant deceleration approach, like that reported for the Stevens roll testing, with a change in deceleration rate at the point in the rollover when the OGS versus time curve changes slope, may more closely predict the time of the maximum roll rate. In the interest of improving an analyst's ability to predict the time and magnitude of maximum roll rate and more accurately describe the speed and roll rate time histories it would be useful to develop a reconstruction model using a bi-constant deceleration. It may be possible to use published steer-induced rollover test results (Stevens [5], Asay [7]) as a basis for developing and validating a bi-constant rollover reconstruction method.

CONCLUSION

Using an appropriate range of average drag factors, the LVDR method produced agreement with the measured results of the Stevens rollover tests. The LVDR method significantly improves prediction of roll rates compared to a CDF method because it better predicts the duration of a rollover and speed versus time. Comparisons between LVDR predicted responses and the Stevens test results with numerous ground contacts and accurate roll orientation showed agreement in calculated rollover duration, shape of the roll rate curve and maximum roll rate. LVDR analysis predicted low roll duration and higher roll rate magnitude when the assumed average drag factor was too high. A greater roll rate uncertainty in roll segments that have long airborne duration and/or high speed changes was observed; uncertainty by these mechanisms would occur regardless of the deceleration model.

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DEFINITIONS

CDF
Constant Drag factor.

First Airborne Segment Distance
The distance between the point of trip and the first post-trip ground contact.

LVDR
Linear Variable Deceleration Rate.

OGS
Over-The-Ground Speed.

Rolling Distance
The distance from first post-trip ground contact to the point of rest.

Roll Phase Distance
Rolling distance plus the first airborne segment distance.

APPENDIX

APPENDIX A

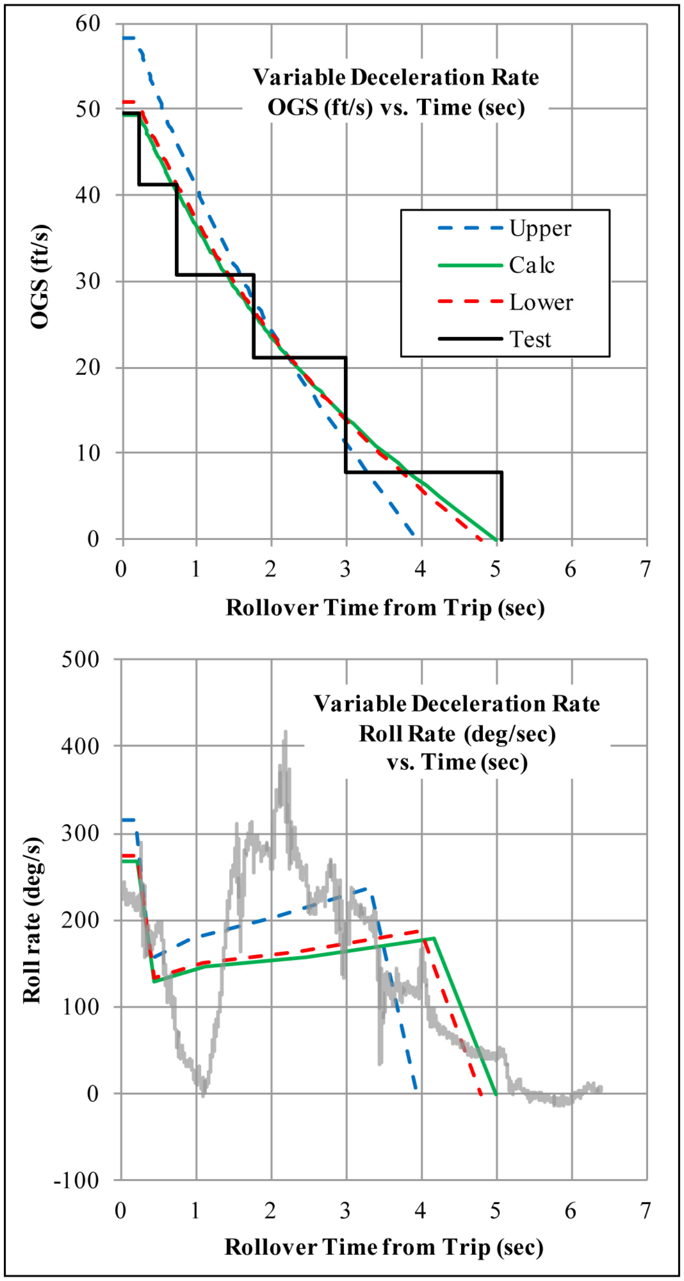

Figure 1. Speed and roll rate versus time for variable deceleration rate model compared to test Roll 0 (R0).

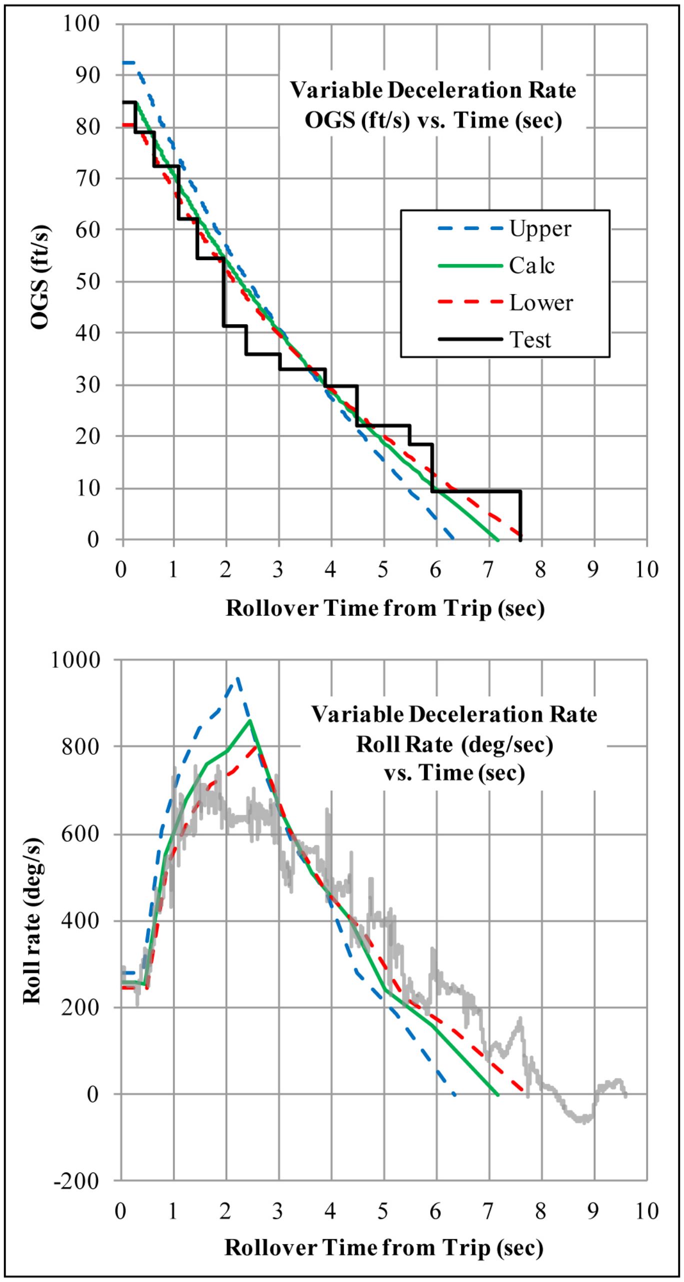

Figure 2. Speed and roll rate versus time for variable deceleration rate model compared to test Roll 1 (R1).

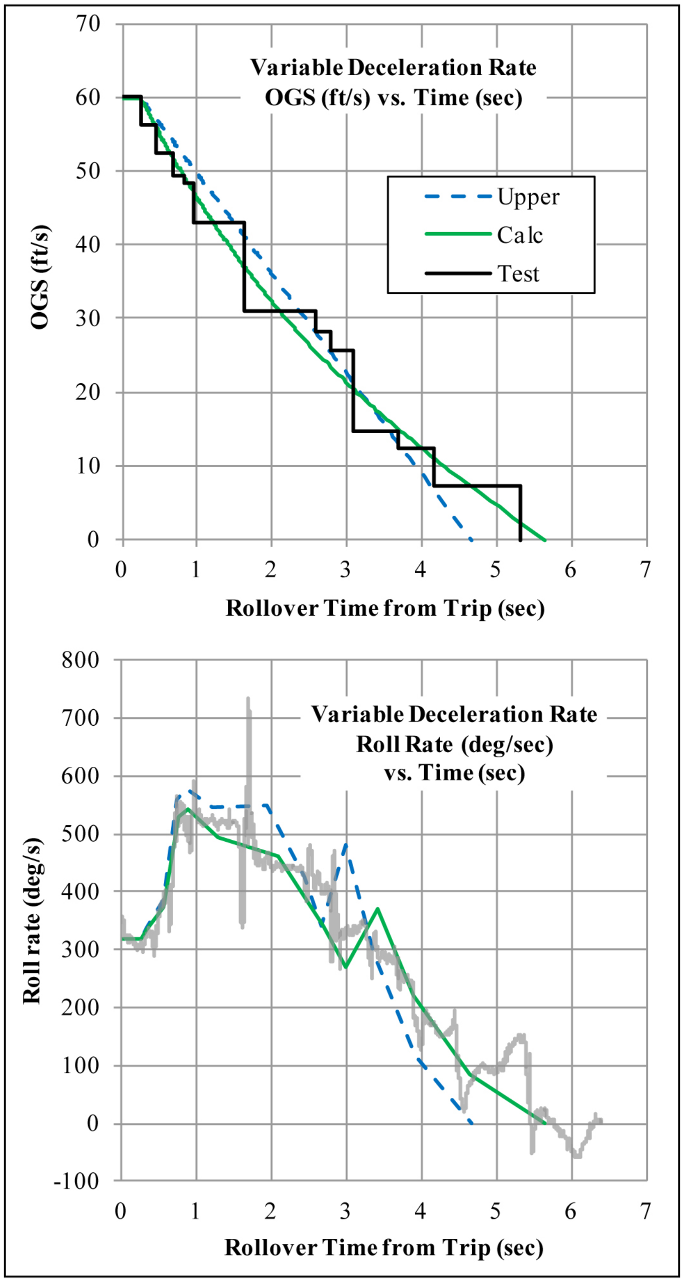

Figure 3. Speed and roll rate versus time for variable deceleration rate model compared to test Roll 2 (R2).

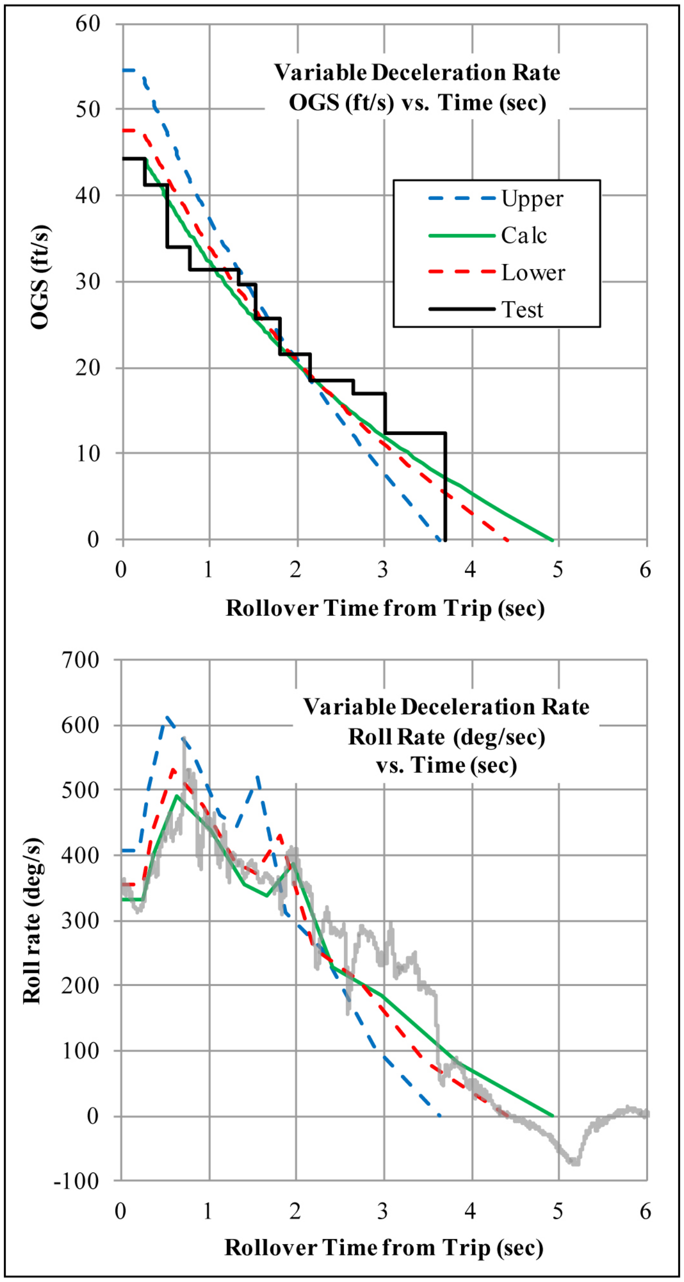

Figure 4. Speed and roll rate versus time for variable deceleration rate model compared to test Roll 3 (R3).

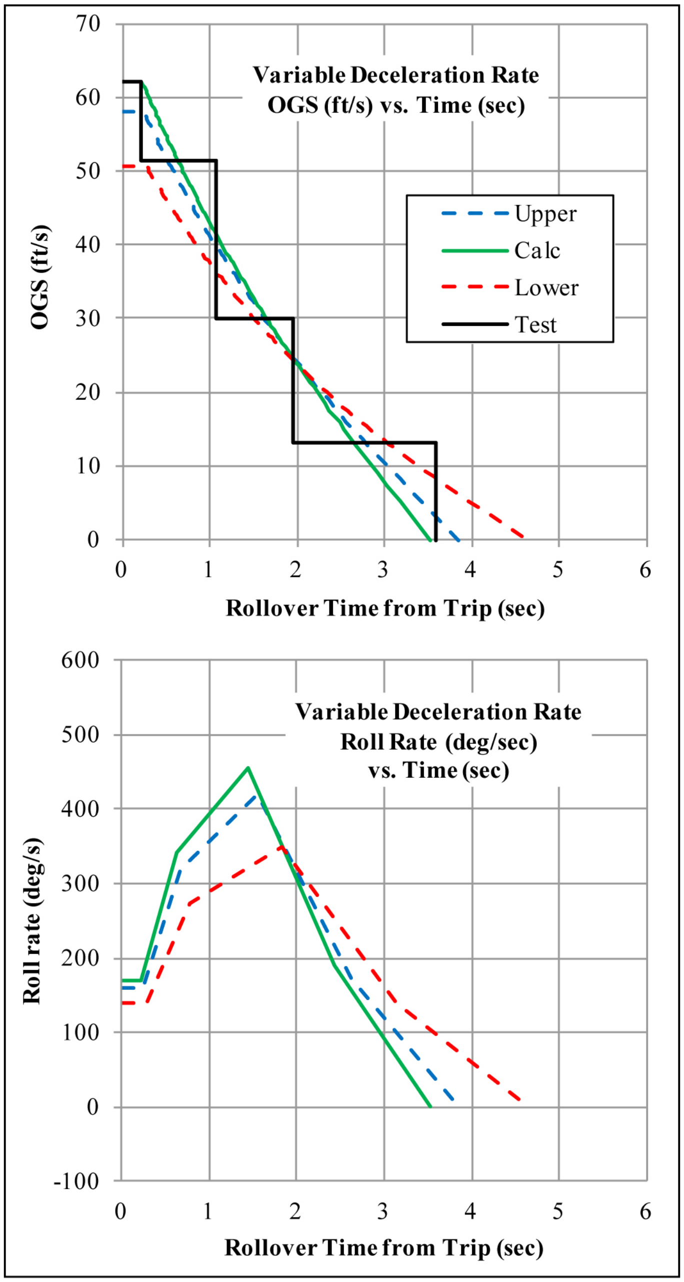

Figure 5. Speed and roll rate versus time for variable deceleration rate model compared to test Roll 4 (R4).

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