

Comparing Dolly Rollover Testing to Steer-Induced Rollover Events for an Enhanced Understanding of Off-Road Rollover Dynamics

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ABSTRACT

The field of motor vehicle rollover research and testing has been one of multiple and varied approaches, dating back to at least the 1930's. The approach has been as simple as tipping a vehicle over at the top of a steep hill ([Wilson et al., 1972](#)), to as complex as releasing a vehicle from an elevated roll spit mounted to the rear of a moving tractor and trailer ([Cooper et al., 2001](#) and [Carter et al., 2002](#)). Between these extremes exists numerous other rollover initiation methods, including driving a vehicle into a ramp, sliding a vehicle sideways into soil or a curb-like obstruction, launching or releasing a vehicle from a dolly cart, and remotely steering a moving vehicle into an orientation that will produce a rollover event ([Cooper et al., 1990](#) and [Larson et al., 2000](#)). Each method has its own unique advantages and limitations, including degrees of initial and early condition repeatability, availability for robust dynamic documentation, and degree of applicability to rollover events in the field.

The method of releasing a vehicle from a dolly cart, also referred to as dolly rollover testing, has been used in the automotive industry for over 40 years, and its relevance to actual field rollover events has been debated for nearly as long. Debate has centered around the effect the initial conditions have on the subsequent rollover events. Specifically, whether these initial conditions alter the dynamics of the rolling vehicle in a way that is un-natural or beyond that which can occur in the real world. Until recently, however, there has not been a substantial or meaningful amount of data available to directly analyze and compare the

two environments, dolly rollover testing and real-world rollovers. Fortunately, the field of rollover experiments and analytical tools has progressed to the point where comprehensive data now exists with well documented steer-induced rollover demonstrations ([Asay et al., 2009](#) and [Asay et al., 2010](#)).

A substantial body of dolly rollover testing outside of the standard FMVSS 208 / SAE J2114 protocol is now available. Numerous dolly rollovers have been performed well above 30 mph, many between 35 and 45 mph, and some as high as 55 mph. These tests have also included those executed on dirt rollover surfaces. The body of steer-induced rollover tests has also expanded, and now includes numerous rollover events performed at various speeds, with specific classes of vehicles, and conducted off-road in the dirt adjacent to an actual highway. It is this subset of rollovers, events that occur off-road on dirt, at trip speeds above 30 mph that will be examined in detail in this study. The dolly rollover and steer-induced rollover tests that belong in this subset will be analyzed, and comparisons will be made between the two test methods, focusing on vehicle rollover dynamics. Specific dynamic parameters related to the development and progression of rollover events will be studied and related to the initial conditions of each test. These parameters include: rollover distance, number of rolls or quarter turns, average distance per roll, average translational deceleration, average roll rate, peak roll rate, and the development and progression of the roll rate history.

INTRODUCTION

When analyzing any testing method it is important to determine how representative the test method is to the actual event being studied. It is well understood that no rollover event in the field is likely to be initiated by the sudden deceleration of a large dolly cart holding a subject vehicle at a roll angle of 23 degrees. Theoretically, absent artificial forces or influences, once a test vehicle leaves the dolly, the only parameters influencing or controlling the dynamics of the vehicle are gravity, surface environment, and the laws of physics. The artificial influence would stop when the test vehicle separates from the dolly. The question that remains is then, what influence does rollover initiation on a dolly have on the subsequent rollover dynamics of a vehicle? In order for that question to be answered, a detailed examination and analysis of the rollover dynamics must be made to identify any influence and to what degree or magnitude it has an effect. This research endeavors to determine if the rollover dynamics during a dolly rollover test are any different than what can be reasonably expected from a rollover event in the field when the only influencing factors are the rollover surface environment, gravity, and the laws of physics.

The most obvious difference between a rollover event in the field and a dolly rollover test is that the field event is most often precipitated by a steering maneuver or other primary event that results in yaw velocity development. Other initiating events exist, such as abrupt surface elevation changes, impacts from other moving vehicles, or impacts with stationary objects.

Some of the earliest articles which discussed dolly rollover testing addressed the test methodology and its applicability to rollovers that had been investigated in the field ([Orlowski et al., 1985](#) and [1989](#)). Much of the early research utilizing the dolly rollover procedure was designed to replicate severe rollover events associated with serious injuries. Subsequent rollover articles, addressing a variety of rollover research issues, and often utilizing various other rollover initiation techniques, have provided further critique of the rollover dynamics of a vehicle launched from the rollover dolly ([Cooperrider et al., 1990](#), [Cooper et al., 2001](#), and [Carter et al., 2002](#)). Researchers have also attempted to compile the available knowledge about various rollover testing methodologies and discuss those methods in the context of field relevance and frequency ([Parenteau et al., 2003](#) and [Patel et al., 2004](#)). Limited studies have also been performed attempting to compare the results of forensic reconstructions of field rollover events and the results obtained from dolly rollover testing ([Jones et al., 2000](#) and [Altman et al., 2002](#)). A common shortcoming with all of the above referenced studies and articles, is the complete lack of available, comprehensive, real-time data from field rollover events. Additionally, these studies all relied upon data from hard surface dolly rollover events, preformed at speeds near or below 30 mph.

Steer-induced rollover testing is a relatively modern method of initiating a rollover event. Until recently, only a handful of such tests had been performed and had their results published in a peer-reviewed setting. As the name suggests, a steering input, or set of steering inputs, induces a set of dynamic conditions that results in the vehicle tipping and subsequently rolling. The vehicle responds freely (or naturally) without being inhibited. In fact, the entire vehicle is left to respond to the roadway and off-road surfaces, as well as the steering inputs at the steering wheel, exactly as it would if a human driver were controlling it. The driver is simply replaced with an automated steering controller. The vehicle is towed up to a selected speed, released, and freely reacts and moves as the environment and steering inputs dictate. Therefore, when a rollover is achieved, the dynamic conditions at the time of trip or overturn are solely the result of the dynamic steering inputs and the vehicle's reaction to them. It is the opinion of the authors that these steer-induced rollover tests are representative of how many rollover events happen in the real world, and that they capture the conditions that occur during natural rollover events.

Eight dolly rollover tests and seven steer-induced rollover tests were selected for additional analysis in this research. All 15 subject test vehicles fell within the sport-utility vehicle (SUV) or multi-purpose vehicle (MPV) classification. The rollover portions of each test occurred on dirt surfaces. All but one test has been previously presented in earlier publications addressing related rollover dynamics and component performance issues ([Luepke et al., 2007](#), [Luepke et al., 2008](#), [Carter et al., 2008](#), [Henry et al., 2009](#), [Asay et al., 2009](#), [Croteau et al., 2010](#), and [Asay et al., 2010](#)).

METHODS

A detailed description of the methodology and procedures involved in steer-induced rollover testing can be found in the previous research by [Asay et al. \(2009 and 2010\)](#). Seven rollover tests were selected from this body of research, and will be referenced by the identification (ID) nomenclature of SI1 through SI7 (as in Steer-Induced Test 1, etc.). Eight dolly rollover tests were also selected, and will be referenced by the identification nomenclature of DR1 through DR8 (as in Dolly Rollover Test 1, etc.).

In addition to detailed information about test procedures, the methods and extent of pre- and post-test documentation has also been thoroughly described and presented in previous publications ([Luepke et al., 2008](#), [Asay et al., 2009](#), and [Asay et al., 2010](#)).

A comprehensive comparison of dirt dolly rollover testing and off-road steer-induced rollovers was performed by examining the significant variables and parameters associated with vehicle rollover dynamics. One of the primary initial condition variables, trip velocity (for steer-induced tests), or

release velocity (for dolly rollover tests), was compared to the result parameters of number of rolls completed and rollover distance. By analyzing the entire body of 15 rollovers together for initial velocity and result parameter correlation, outlying events, as well as overall trends, could be identified. An additional method of rollover comparison was performed by analyzing relationships between result parameters. For example, if dolly rollovers artificially influence rollover dynamics in a way that results in more rolls for a given rollover distance, the data should clearly reflect such an effect when compared to steer-induced rollovers.

To further compare the two rollover test methods, an examination of the measured data and calculated results was necessary. Comparing the average distance per roll revolution provides an additional method of determining whether or not dolly rollover conditions results in artificially more rolls, and therefore, generally higher roll rates. The average translational deceleration rates were also calculated and compared, which would tend to highlight more subtle rollover surface effects between test methodologies and environment locations. Total time durations were measured and compared across result parameters such as roll distance and number of rolls. Additionally, the development and progression of roll rates, including average and peak values, were analyzed and compared between rollover methods. A detailed examination was performed to analyze the development of the roll velocity during the early stages of each event, and also to compare the progression and change in roll velocity as the events continue to rest.

Extensive analysis of the early stages of the dolly rollover tests was conducted in order to understand what influence the dolly cart has on the early dynamics of a tested vehicle.

In order to establish a common baseline for detailed comparisons between dolly rollover and steer-induced rollover events, an initial vehicle orientation was chosen. The orientation selected as a baseline was when the steer-induced vehicle was at a 23 degree roll angle. This orientation was the most practical selection because dolly-tested vehicles rest at this angle atop the dolly during the roll out and vehicle release stages of the testing. Also, and perhaps most importantly, very little roll angle change was observed during these tests from the 23 degree roll orientation on the dolly and the initial contact with the dirt rollover surface. The selection of this common baseline was determined to be appropriate since it is reasonably close to the orientation of the steer-induced vehicles as they approach trip.

Once a common baseline condition was established, peer rollovers could then be studied across a consistent and synchronous time history. By studying the time histories in parallel, their respective rollover dynamics could be analyzed and compared. The selected peer rollover events were divided into two groups, A and B, relative to the body of rollovers

within this research. Group A contained 3 rollovers, each between 3 ½ and 4 rolls, at initiation velocities of 41 to 43 mph. Group B also contained 3 rollovers, each between 7 and 8 ½ rolls, at initiation velocities of 51 to 66 mph. The time history images for Group A captured the events between the baseline 23 degree orientation and near the ½ roll orientation. Excessive dust along the roll path prevented a clear view for portions of the SI4 rollover beyond the ½ roll orientation. The time history images for Group B captured the events between the baseline 23 degree orientation and the end of the second roll. These respective time histories were selected in order to analyze the early stages of the rollover, where the effects of initial conditions and rollover initiation methods would be most obvious.

Group A consisted of 1 steer-induced test, SI4, and two dolly rollover tests, DR3 and DR4. All three rollovers were conducted and documented with onboard roll rate data acquisition, as well as ground based or support-vehicle-mounted high speed video cameras. Group B consisted of 2 steer-induced tests, SI5 and SI7, and one dolly rollover test, DR8. SI5 was conducted and documented with onboard roll rate data acquisition, as well as ground based and support-vehicle-mounted high speed video cameras. SI7 also was conducted and documented with ground based and support-vehicle-mounted high speed video cameras, however the onboard roll rate data acquisition was interrupted during the event and was supplemented with a calculated roll rate history. The supplemental roll rate history for SI7 was calculated with a frame-by-frame analysis of the high speed videos. DR7 was conducted and documented with ground based high speed film cameras and no onboard roll rate data acquisition. A roll rate history was calculated for DR8 based upon a frame-by-frame analysis of a rear-facing high speed film camera found to be operating at the indicated speed of 500 frames per second. The calculated roll rate histories for both SI7 and DR8 were based upon segment average roll rates between ¼ roll orientations.

All high speed video footage for the steer-induced rollover events was recorded at 300 frames per second; therefore, each frame is separated by 0.003 seconds. Some dolly rollover events were recorded at 250 frames per second, while others were recorded at 500 frames per second, and therefore each frame is separated by either 0.004 seconds or 0.002 seconds. Due to this discrepancy between frame rates, not every captured frame within the figures that contain labeled filmstrips of rollover images is taken from the exact time indicated. When a common time frame was not available between the two peer events, a nearby frame was chosen at the next available time frame. The discrepancy between the labeled time and the actual time for the dolly rollover test in a given column could be as small as 0.000 seconds (a common time with the steer-induced test) or as large as 0.002 seconds.

RESULTS

General information as well as initial conditions and result parameters for all 15 rollover tests are summarized in [Table 1](#). The tests are listed from top to bottom in order of increasing trip/release velocity. Weight information is the as-tested condition, including any camera and data acquisition equipment, as well as anthropomorphic test devices (ATDs) when applicable.

Table 1. General test information.

ID	VEHICLE	WEIGHT (lbf)	VELOCITY (mph)	NUMBER OF ROLLS	ROLL DISTANCE (feet)
SI1	1998 Ford Expedition	5681	34	1 ½	53
SI2	2002 Ford Explorer	4811	35	2	79
SI3	1984 AMC Eagle	3583	36	3	82
DR1	1986 Chevrolet Suburban	4942	37	3 ¾	87
SI4	1994 Nissan Pathfinder	4221	41	3 ¾	114
DR2	1987 Jeep G. Wagoneer	4905	41	3 ¾	105
DR3	1997 Ford Aerostar	4757	42	3 ½	95
DR4	1998 Ford Expedition	6634	43	4	113
DR5	2004 Volvo XC90	5013	43	4 ¾	112
DR6	2003 Subaru Forester	3545	43	5 ¾	138
DR7	2003 Subaru Forester	3545	44	5 ½	129
SI5	1991 Isuzu Rodeo	4266	51	7	185
DR8	1989 Chevrolet Blazer	4063	55	8	204
SI6	1996 Oldsmobile Bravada	4440	63	10 ½	267
SI7	1991 Mitsubishi Montero	4140	66	8 ½	243

A graphical analysis of initial conditions and result parameters for potential relationships as well as test method differences was performed. [Figures 1](#), [2](#), and [3](#) illustrate this analysis.

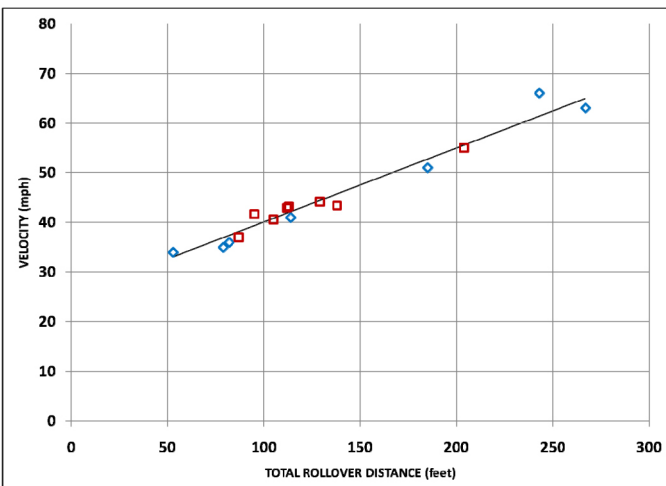


Figure 1. Initial rollover velocity v total rollover distance with linear regression. Red squares are dolly rollover tests and blue diamonds are steer-induced rollover tests.

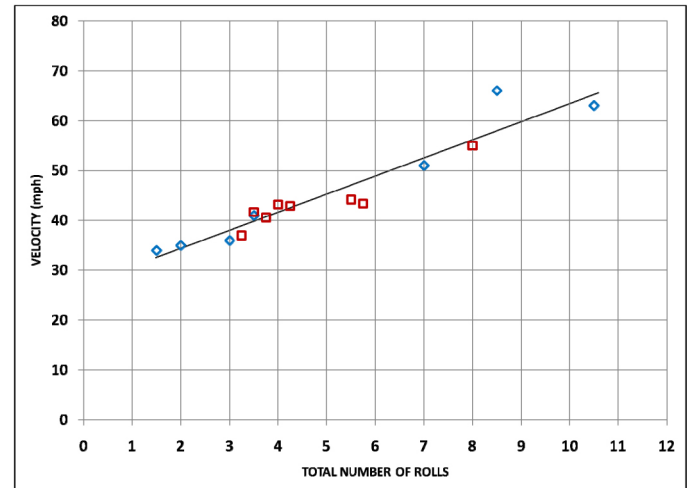


Figure 2. Initial rollover velocity v total number of rolls with linear regression. Red squares are dolly rollover tests and blue diamonds are steer-induced rollover tests.

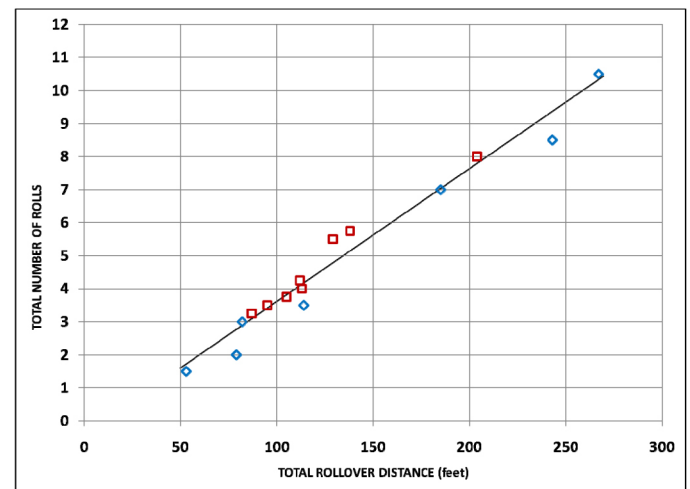


Figure 3. Total number of rolls v total rollover distance with linear regression. Red squares are dolly rollover tests and blue diamonds are steer-induced rollover tests.

[Figures 1](#), [2](#), [3](#) provided an opportunity to graphically analyze all 15 dirt rollovers together. By plotting initial velocities against gross results for these rollover events, any outlying results can be visually distinguished. Conversely, if general uniformity exists across test methods, as well as across the range of initial velocities, it should be visually evident also. Indeed, as one views the result parameters of roll distance and number of rolls, it is evident that as those results increase, the corresponding initial velocities generally increase as well. This analysis also shows that dolly rollover initiation does not result in any significant deviation from this trend. In fact, the single rollover event that displays any significant deviation is the 8 ½ roll steer-induced rollover at 66 mph.

Since the initial velocities of the steer-induced rollover tests were sometimes determined through methods of calculation, as opposed to direct measurement, an analysis independent of this variable also seemed appropriate. Plotting roll distance against total number of rolls provided another method of determining any artificial influence a dolly may have on the subsequent rollover dynamics. Such an influence would most obviously manifest as a much greater number of rolls for a given roll distance. Analysis of [Figure 3](#) shows no evidence of such an influence. The greatest differences noted amongst similar roll distances were on the order of ½ roll.

As an initial level of comparison, the analysis of roll distance and total rolls for the 15 rollover events provided a significant degree of confidence in the similarity of vehicle rollover dynamics between test methods. No artificial influence on subsequent rollover dynamics through rollover dolly initiation was discernable in this data. A secondary level of comparison was conducted, with a deeper level of rollover dynamics analysis. A summary of these rollover dynamic parameters is presented in [Tables 2](#) and [3](#).

Rollover time duration was calculated by examining the high speed camera coverage and the roll rate data when available. Events began when the roll orientation reached 23 degrees or the dolly launched vehicle made initial ground contact, and the event ended when forward roll movement reached its end. Negative roll motion backwards to rest was ignored. For a driver's side leading rollover, the total time duration only considered the driver's side leading roll motion. Therefore, and as an example, any motion and time duration that was part of a vehicle rolling backwards from a 3/8 roll orientation back down to a ¼ roll orientation at rest was not considered. Also, any bouncing or jostling about a whole or half-roll position was neglected.

Table 2. Average deceleration and distance per roll information.

ID	ROLL DISTANCE (feet)	AVERAGE DECELERATION	AVERAGE DISTANCE PER ROLL (feet)
SI1	53	0.74 g	35
SI2	79	0.52 g	40
SI3	82	0.54 g	27
DR1	87	0.53 g	27
DR3	95	0.61 g	27
DR2	105	0.52 g	28
DR4	112	0.55 g	26
DR5	113	0.55 g	28
SI4	114	0.50 g	33
DR7	129	0.51 g	23
DR6	138	0.46 g	24
SI5	185	0.46 g	26
DR8	204	0.50 g	26
SI7	243	0.60 g	29
SI6	267	0.50 g	25

Table 3. Total time duration and roll rate information.

ID	NUMBER OF ROLLS	TIME (seconds)	AVERAGE ROLL RATE (degrees/second)	PEAK ROLL RATE (degrees/second)
SI1	1 ½	3.7	135	295
SI2	2	2.7	248	379
SI3	3	unk	241	361
DR1	3 ¼	unk	unk	unk
DR3	3 ½	4.49	270	569
SI4	3 ½	3.35	376	677
DR2	3 ¾	4.90	261	587
DR4	4	4.16	340	636
DR5	4 ¼	4.96	317	631
DR7	5 ½	5.7	unk	700
DR6	5 ¾	5.7	unk	700
SI5	7	5.97	410	765
DR8	8	6.75	550	849
SI7	8 ½	9.32	503	844
SI6	10 ¼	8.9	595	900

Analyzing the camera coverage of the dolly rollover tests resulted in a clear understanding that very little roll orientation change takes place during vehicle launch. Following dolly contact with the dolly snubbers, the dolly is rapidly decelerated, and the vehicle is free to continue moving forward. The sidewalls on the leading side tires of the vehicle rest against 4 inch tall flanges on the dolly, and these tires have, theoretically, an opportunity to develop a force against the flanges following the onset of dolly deceleration. During the dolly rollover tests that are a part of this research, the leading side tires experienced significant lateral flexion of the sidewalls during their interaction with the dolly flanges. The energies associated with these higher velocity tests appeared to have overwhelmed the side stiffness of the vehicle tires, resulting in remarkably little change in the orientation of each vehicle between dolly snub and the initial ground contact.

An additional factor affecting the majority of these tests is the decrease in the elevation change between the dolly platform and the rollover surface. Compacted dirt was applied at a depth of at least 6 inches across the crash rail surface immediately in front of the dolly snubbers, resulting in an elevation difference between the leading side tires (when on the dolly) and the dirt rollover surface of at most 3 inches. The rollover surface immediately in front of the snubber tubes during test DR2 was the concrete crash rail, and the dolly was raised during tests DR6 and DR7 such that the dirt rollover surface was 9 inches below the leading side tires. [Figure 4](#) depicts the orientation of 3 dolly rolled vehicles at three different times during the process of vehicle launch: the initiation of dolly deceleration (dolly snub), halfway to initial ground contact, and initial ground contact. The time durations from dolly snub to initial ground contact for DR3, DR4, and DR8 were 0.120 sec., 0.136 sec., and 0.160 sec., respectively.



Figure 4. High speed video/film images between dolly snub and initial ground contact.

In addition to visually examining the roll orientation of the dolly tested vehicles, the roll rate histories during the stages of dolly snub, vehicle release, and initial ground contact were studied. A bi-modal roll rate developed and became evident when the early time histories of the roll rates were plotted. The roll rate increases as the vehicle is launched from the dolly and becomes airborne, but increases much more rapidly as the vehicle engages the dirt rollover surface with its leading side tires and wheels. The roll rate histories during these two stages for DR3 and DR4 are shown in [Figure 5](#). The general slope of each stage is indicated with red lines. Note that on these graphs time 0.00 seconds coincides with the initiation of dolly snub, and that initial ground contact occurs at 0.120 seconds (DR3) and 0.136 seconds (DR4). This ground contact transitions from the initial contact of the outer tire surface to deeper furrowing and penetration into the dirt. Video and roll rate history analysis both indicate that the duration of this transition was approximately 40 to 50 milliseconds. Note in [Figure 5](#) that the roll rate increases to between 100 and 150 degrees/second in the first approximately 175 milliseconds, and increases to approximately 400 degrees/second in the next 100 milliseconds.

The single dynamic component that was most obviously missing from the dolly rollover events was yaw orientation and yaw rate. Analysis of the steer-induced rollovers revealed that while their yaw orientations were most often less than 90 degrees at the time of trip and rollover, each steer-induced event transitioned to near 90 degrees yaw by the time of $\frac{1}{2}$ roll.

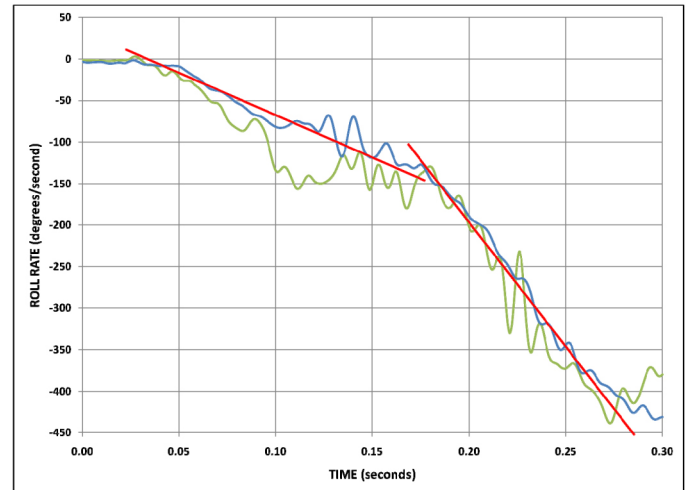


Figure 5. Roll rate histories following dolly snub for DR3 and DR4.

PEER ROLLOVER EVENTS

The selected peer rollover events were analyzed using a common initial condition methodology. This involved moving time-zero to be coincident with the selected initial condition of a 23 degree roll angle. For dolly rollover events, time-zero is coincident with the initial ground contact of the leading side tires. For the steer-induced events, time-zero is coincident with a 23 degree roll orientation during the tripping phase of those tests. Analyzing the stages of dolly snub, vehicle release, and the initial airborne phase of the dolly rollover tests resulted in a determination that at the time of initial ground contact, very little change occurred from the initial 23 degree roll angle. The 23 degree roll orientation of the steer-induced vehicles was found to be very close, within 0.050 and 0.130 seconds for SI4 and SI5, to the time that trip was approximated. This methodology provided the most accurate means of establishing a common baseline for comparing two different test methods, while capturing the unique nature of each method during the early stages of a rollover. Therefore, from this point forward in this research, wherever a time of 0.000 seconds is noted on a graph or adjacent to a frame-captured image, it is indicative of the initial ground contact during a dolly rollover, or the time of 23 degrees roll during a steer-induced rollover.

GROUP A

The steer-induced rollover of a 1994 Nissan Pathfinder (SI4) resulted in $3\frac{1}{2}$ rolls from a velocity at rollover initiation of 41 mph. The most obvious peer rollover event from the body of dolly rollover tests was a 42 mph, $3\frac{1}{2}$ roll dolly rollover of a 1997 Ford Aerostar (DR3). The second rollover chosen as a peer for SI4 was the dolly rollover of a 1998 Ford Expedition (DR4) at 43 mph, resulting in 4 rolls. Beyond the similarities between initial velocities and total number of rolls, the total

rollover distances were separated by only 19 feet. The average distance per roll for SI4 was 33 feet, and the average distance per roll for DR3 and DR4 were 27 feet and 26 feet, respectively. While not a selected peer event, it should be noted that a 3 roll, 36 mph steer-induced rollover (SI3) covered a total distance of 82 feet and averaged 27 feet per roll. The rollovers in Group A had average decelerations between 0.50 g and 0.55 g. These parameters, while indicative of rollover dynamics, are more directly evidence of overall result similarities.

A better representation and comparison of rollover dynamics within the duration of the rollover events involved an analysis of vehicle orientation across discreet timesteps and an examination of the roll rate histories. Figure 6 contains the roll rate histories for SI4 and DR3. These two rollover events begin with very similar roll velocities, and their roll velocities progressed at nearly parallel rates for more than 100 milliseconds. Each rollover lasted between approximately 3.5 and 4.5 seconds, and reached peak rollover velocities near or before 1 second. SI4 was between the 1 roll and 1 ½ roll orientation at the time of peak roll rates, and DR3 was between the 1 roll and 1 ¼ roll orientation at the time of peak roll rate. The steer-induced rollover experienced a peak roll rate more than 100 degrees/second higher than the dolly rollover. Following the progressions to peak roll rates, both rollovers experienced near-parallel declining roll rate histories for the subsequent 1 second.

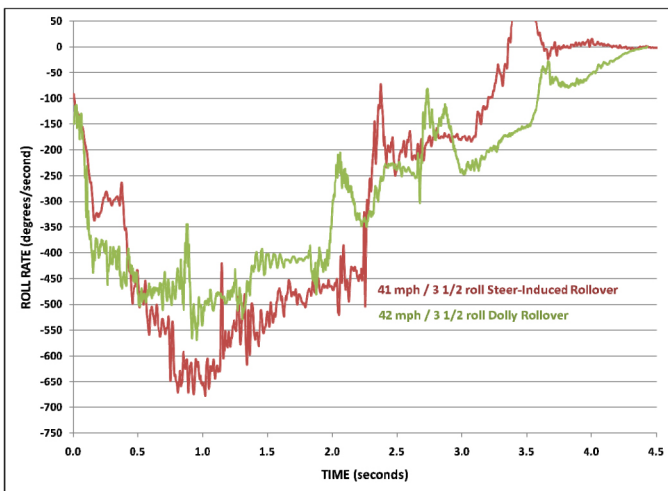


Figure 6. Roll rate histories for SI4 and DR3.

Examination of the respective roll orientations between the initial 23 degree roll angle and slightly before the ½ roll position revealed striking similarities between SI4 and DR3. High speed video and film frame captures every 33 milliseconds are illustrated in Figure 7 within the Appendix. The two vehicles reached the ¼ roll orientation at nearly identical time durations, and considering the increasing dust

conditions of SI4, appeared as though they would reach the ½ roll orientation at similar times as well.

[Figure 7 - See Appendix]

The early stages of the roll rate history for SI4 and DR3 are more clearly examined in Figure 8. Each event begins at a roll rate near 100 to 150 degrees per second and followed a relatively collinear path for nearly 90 milliseconds. The roll rate histories then deviate slightly, with DR3 reaching rates approximately 100 degrees per second higher for the next 250 milliseconds. Each roll rate experiences the same leveling-off following the initial ramp up at the beginning of the events. By 0.600 seconds the roll rate of SI4 has climbed above the roll rate of DR3, and remains so generally until beyond 2 seconds for both events.

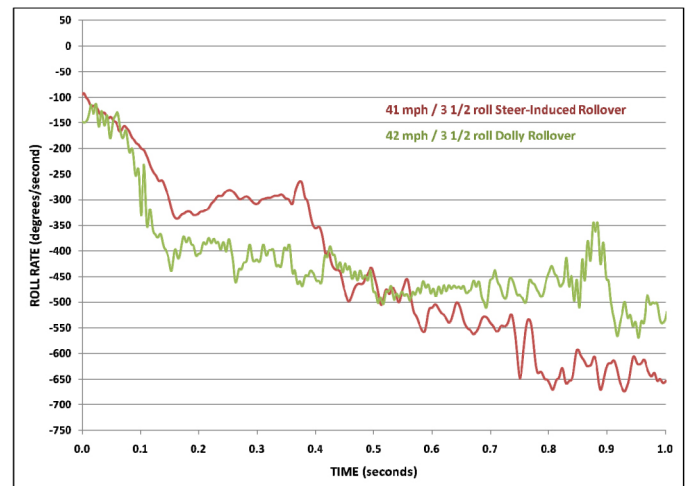


Figure 8. Roll rate histories for the 1 second following 23 degree roll/ground contact for SI4 and DR3.

Figure 9 contains the roll rate histories for SI4 and DR4. These two rollover events began with even greater similarity in roll velocities, and their roll velocities progressed at nearly parallel rates, if not collinear rates, for nearly 200 milliseconds. Each rollover lasted between approximately 3.5 and 4 seconds, and reached peak rollover velocities before 1 second. DR4 was near the approximate ¾ roll orientation at the time of peak roll rate. The steer-induced rollover experienced a peak roll rate of approximately 40 degrees/second higher than the dolly rollover. Figure 10 in the Appendix illustrates the high speed video frame captures of SI4 and DR4. Figure 11 illustrates additional similarities in the early roll rate histories of SI4 and DR4.