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DRAG FACTORS FROM ROLLOVER CRASH TESTING FOR CRASH RECONSTRUCTIONS

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ABSTRACT
A study of numerous published rollover tests was conducted by reexamination of the original works, analysis of their data, and centralized compilation of their results. Instances were identified where the original reported results for trip speed were in error, requiring revision because the analysis technique employed extrapolation versus integration and lacked correction for offset errors that develop by placing the Global Positioning System (GPS) antenna away from the vehicle Center of Gravity (CG). An analysis was performed demonstrating revised results. In total, 81 dolly rollover crash tests, 24 naturally occurring rollover crash tests, and 102 reconstructed rollovers were identified. Of the 24 naturally occurring tests, 18 were steer-induced rollover tests. Distributions of the rollover drag factors are presented. The range of drag factors for all examined dolly rollovers was 0.38 g to 0.50 g with the upper and lower 15 percent statistically trimmed. The average drag factor for dolly rollovers was 0.44 g (standard deviation = 0.064) with a reported minimum of 0.31 g and a reported maximum of 0.61 g. After revisions, the range of drag factors for the set of naturally occurring rollovers was 0.39 g to 0.50 g with the upper and lower 15 percent statistically trimmed. The average drag factor for naturally occurring rollovers was 0.44 g (standard deviation = 0.063) with a reported minimum of 0.33 g and a reported maximum of 0.57 g. These results provide a more probable range of the drag factor for use in accident reconstruction compared to the often repeated assertion that rollover drag factors range between 0.4 g and 0.65 g.

INTRODUCTION
The study of rollover crashes in phases, including the dynamics phase, tripping phase and rollover phase, was at least as old as the often-cited study published by Hight, Siegel, and Nahum at the 1972 Stapp Car Crash Conference (1). Though not stated as clearly as present day enunciations, Hight and his coauthors clearly described and discussed rollover injury causation as a sequence of events that start with vehicle dynamics followed by tripping and rollover phases. Phases of rollover causation were later discussed by Orlowski and coauthors in their 1989 SAE paper, "Reconstruction of Rollover Collisions (2)." Orlowski included discussion on pre-trip tire marks, tripping and the airborne phase.

A clear description of the phases of a rollover sequence was provided by Martinez and Schlueter in their 1996 "Primer" on rollover reconstruction (3) in which they describe a pre-trip phase, trip phase and post-trip phase. In 2000 Meyers and coauthors (4) describe three rollover phases, adopting and refining Martinez's definition for the start of the tripping phase, and stated: "Rollovers are generally considered in three distinct stages. The pre-trip phase; the trip phase; and the post-trip or rollover phase. (sp) The pre-trip phase is typically considered to begin at loss of vehicle control and end at the point where wheel lift occurs. The trip phase covers the portion of the accident wherein the trailing wheels lift, or leave the surface of the roadway and the vehicle begins to rollover. The rollover phase, then, can be considered to be the rolling or tumbling portion of the accident before the vehicle comes to rest."

Roll Phase
Historically, rollover phase experiments utilized a dolly rollover method described in the SAE J2114 recommended practice (5), commonly referred to as the "208 rollover dolly." Over time, numerous means of examining the rollover phase for crash reconstruction have been performed, including Reconstruction Analysis (pre video recorder); Reconstruction Analysis (video recorded); Dolly rollover test (on asphalt); Dolly rollover test (on dirt); Curb and Soil Induced Rollover test; Modified dolly rollover test; NHTSA's Rollover Test Device (RTD); Controlled

Rollover Impact System (CRIS) tests and steering controller tests (natural rollover tests).

The roll phase begins at the point of leading tire lift or four wheel lift. In crash reconstruction this beginning point was assumed to be the end of tire marking and was described in 1989 by Orlowski: "The beginning of the airborne rollover trajectory and path can be defined as that point along the path at which the vehicle center of gravity is over the tire or wheel contact with the ground surface. Thus, any rotation of the vehicle beyond this point will result in a rollover, as opposed to the vehicle returning (falling back) onto its wheels. This point is approximately at the ending of the tire marks. The beginning of the tripping process will occur earlier (2)." The rollover phase ends at the vehicle point of rest.

Hight, Siegel, and Nahum (1) performed reconstruction analysis consistent with available knowledge and methods inuse prior to their 1972 paper. The often-cited 0.4 to 0.65 g drag factor range originates from figure 4 of this source. In the words of the authors, "Sixty percent of the vehicles that rolled on approximately level ground decelerated between the range of 0.40-0.65 g". Without knowledge of average roll phase drag factors, Hight, Siegal, and Nahum performed speed reconstructions on approximately 70% of 139 rollover crashes studied in Southern California over 5 years prior to 1972. Ninety of the study's rollovers were single vehicle crashes. Hight, Siegel, and Nahum's description of their paper's figure 4 - its development, basis and interpretation - is often absent from citation of the drag factor range in follow-up publications. It was clear from Hight, Siegel, and Nahum's figure 4 that numerous rollovers on level ground were reconstructed to have occurred at values of deceleration in excess of 0.65 g and numerous were reconstructed to have occurred below 0.4 g.

Calculation of speed at the beginning of the roll phase, or speed at trip, commonly utilizes an average drag factor over the roll distance. Drag factors calculated from the launch point in 41 dolly rollover crash tests where the launch speed and rollover distance were measured were reported by Orlowski in 1989 (2). Orlowski stated, "The average deceleration for these crash tests was 0.42 g. with a range of 0.36 g to 0.61 g."

In 2010, Yeak provided a summary of numerous rollover tests (6), including 51 208 Dolly rollover tests (many of the 208 Dolly rollover tests were previously reported by Orlowski), ten RTD tests with more than 2 quarter rolls, seven RTD tests with 2 quarter rolls or less, three steering controller tests, eight zero degree, curb trip 208 Dolly rollover tests, two curb tests, and two soil tests. Yeak's summary provided a range for the rollover drag factor considering all of the data in her report, including the Hight (1) reconstruction results. The range of vehicle deceleration was 0.32 g to 0.65 g with an overall average deceleration of 0.44 g.

In 2008 Luepke and coauthors reported on five dolly rollover tests conducted over dirt (7). These tests used the 208 rollover dolly. Luepke reported the roll distance and associated drag factor from the launch point (0.50 g to 0.58 g, 0.53 g average) and from the point of first ground contact (0.50 g to 0.61 g, 0.55 g average). In a follow-up paper Carter and coauthors analyzed the first two of Luepke's rollovers (8) and reported the drag factor from the point of first ground contact (0.55 g for both tests) and from the end of the tire marks where the test vehicle became airborne (0.48 g and 0.53 g). Results of two additional dolly rollovers on dirt were reported by Croteau in 2010 (9). Luepke in 2011 (10) reported the results of one new dolly rollover test on dirt. Drag factors for the eight dolly rollovers in Luepke's 2011 paper were reported in the range of 0.46 g to 0.61 g.

Carter's 2008 paper (8) provided an extended technical discussion on the physics at play during rollovers. He observed that angular and translational velocities were constant during the airborne phases. Carter also showed that a multiphase approach to reconstructing rollover crashes was suggested by his results. A variable deceleration rate approach to rollover reconstruction in which the drag factor linearly decreases from first contact to the point of rest was presented in 2009 by Rose and Beauchamp (11). The approach was described as reducing error in reconstructed translational and angular velocity time histories.

Prior Publication of Natural Rollover Tests

Natural rollovers are described in the literature as steering controller tests by Yaek (6), steer-induced rollover tests by Larson (12), Wilson (13) and Stevens (14), and tests on an actual highway by Asay and Woolley (15, 16). Though its stated aim was to present tools for recreating rollover crashes, Larson's 2000 SAE paper (12) demonstrated the feasibility of a naturally occurring rollover test as a research tool for evaluating, validating and developing methods for the reconstruction of rollover crashes. In 2007 Wilson, Gilbert and Godrick (13) presented results of two staged crashes in which steering alone induced rollovers on a ground based grid. Post-test analyses of the videotaped rollovers yielded calculated rollover deceleration rates and scale drawings depicting vehicle motions and surface marks.

Asay and Woolley published the first of two papers in 2009 that described a method for testing on an actual highway (15). The method used a large truck to tow an instrumented vehicle with a programmable steering controller on a two lane highway. The towed vehicle was released from the truck and then steered in a manner that resulted in a loss of control condition leading to an off highway path and rollover. Severe limitations in the speed measuring device required lengthy speed extrapolation or integration from the time each vehicle left the paved road surface to the time that it started to rollover. The authors reported a single speed at the start of rollover with no discussion of probable error. Despite its limitations, this 2009 paper represented a breakthrough in full scale rollover testing with a thoughtful attempt at vehicle control, instrumentation, and documentation of the loss of control phase, tripping phase and rollover phase. The resulting post-test road and vehicle markings were carefully documented for presentation.

Asay and Woolley's second paper published in 2010 (16) reported the results of six rollover tests of sport utility vehicles (SUV) on an actual highway. A significant improvement in test instrumentation and test control was demonstrated. Interpretation of the instrumented vehicle's recorded response was presented. Three of the tests required extrapolation or interpolation of the recorded speed to determine the speed at the start of the rollover phase, and there is no discussion of the need to correct the GPS-generated recorded speed due to mounting the GPS antenna away from the vehicle CG.

Stevens and coauthors presented five steer-induced rollover tests in 2011 (14). Tests were conducted on a variety of surfaces, and rollovers were initiated both on road and off road. Stevens provided a detailed discussion of the recorded and observed vehicle responses at the initiation of the rollover phase. A formula for correcting the GPS measured speed was derived and validated. Natural steer-induced rollover test results presented by Stevens and coauthors in 2011 corroborated Carter's 2008 suggestion (8) of a multiphase approach by documenting a bilinear roll phase deceleration characteristic. The average drag factor was reported from .033 g to 0.57 g with a mean of .041 g. A bilinear roll phase deceleration characteristic was identified with initial drag factors ranging from 0.51 g to .071 g and final drag factor ranging from 0.21 g to 0.42 g.

ROLLOVER RECONSTRUCTION: THE HIGHT STUDY

An often-quoted source of rollover drag factor is the 1972 study, "Injury Mechanism In Rollover Collisions" by Hight, Siegel and Nahum (1). Comments in subsequent publications cite Hight's summary and conclusion, "A vehicle's deceleration during rollover is 0.40 - 0.65 g," but neglect the basis and context. In fact, Hight's study presents drag factors in a range of 0.04 g to 1.20 g for all 102 plotted results from rollover crashes that supported estimates of speed, including downhill rollovers and rollovers with vertical drops. For rollovers on flat ground the reconstructed range was 0.21 g to 0.83 g.

The basis for the Hight study was rollover collisions that occurred in Southern California during the five years prior to its publication (1966 to 1971). The study included 139 vehicles that rolled of which ninety were single-vehicle-only rollover collisions. In making what Hight described as an "estimate" of the rollover speed, various factors were included such as other road users' statements, highway geometry, braking and centrifugal skid marks, critical cornering speeds, etc. The estimated rollover speed was obtained for about 70% of the cases. In the other cases, there was insufficient physical evidence available to estimate speed with a reasonable degree of certainty.

After its description of method, Hight's study then states:

> "*Sixty percent of the vehicles that rolled on approximately level ground decelerated between the range of 0.40-0.65 g, as indicated in Fig. 4 [Figure 1 in this paper] by the diagonal lines. The vehicle that was upset and slid on its side generally traveled farther than the vehicle that was broadsliding, tripped, and sustained multiple impacts to its side, roof, and wheels.*"
>
> "*The letter D in Fig. 4 denotes a vehicle that rolled down a decline. The distance traveled before these vehicles came to rest was large, with reference to the speed at which they left the highway, and the deceleration was low.*"
>
> "*The vehicles that dropped vertically before they impacted the generally level ground were denoted by the letter V. These vehicles after impact usually slid less and the deceleration was greater.*"

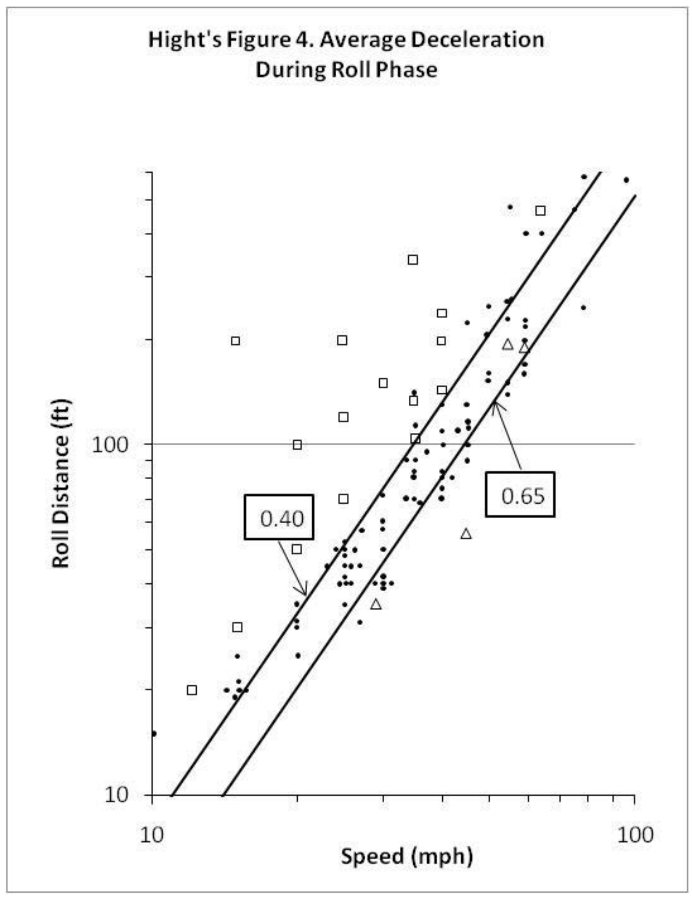

Figure 1. Hight's Figure 4 was reproduced by digitizing the original. D, representing downhill roll, was replaced with boxes. V, representing vertical drop before landing on flat ground, was replaced with triangles. Level ground incidents were depicted with a point.

Hight's description of his Figure 4 (Figure 1 in this paper[1]) - its development, basis and interpretation - is often absent from citation of the drag factor range in follow-up publications. The chart and Hight's own words affirm that the middle 60 percent of his rollover crashes on level ground decelerated at reconstructed drag factors between 0.4 g and 0.65 g. Hight's figure 4 demonstrates that numerous rollovers on level ground were reconstructed to have occurred at levels of deceleration in excess of 0.65 g and numerous occurred below 0.4 g. The Hight, Segal and Naham study made a significant historical contribution to the science of rollover analysis, but no experimental program has documented rollover deceleration at the 0.65 g level without unusual circumstances; and the Hight study was based on reconstruction techniques without experimental input from the 1960's. It is past time to discontinue use of the study's drag factor range as a basis for substantiating modern experimental results or methods and as a basis for the range of roll-phase drag factors applied to rollover accident reconstruction.

IS A DOLLY ROLLOVER A ROLLOVER?

Much has been written regarding the analysis of dolly rollover test results as they relate to the reconstruction of the rolling phase of rollover crashes. Dolly rollover tests are typically conducted as described in FMVSS 208 (17) and SAE J2114 (5). The dolly rollover test method launches a vehicle sideways (90 degree heading) at an initial roll angle of 23 degrees with the leading tires resting against a 4-inch bar 9 inches above the test surface.

In roll phase reconstructions it is common to identify several key points along a vehicle's rolling path including the end of the tire marks (represents the trip point or roll initiation point), points of vehicle to ground contact (preferably to include an identification of the point of first contact), debris fields, and the point of rest. Some of these key points along the roll path of a natural rollover do not relate well to what has historically been presented from the analysis of dolly rollover tests. Orlowski's presentation of dolly rollover results (2, 18) related roll distance from the point of launch from the dolly to the point of rest and calculated effective drag during the roll phase for the same distance. Lupke (7) and Carter (8) presented results with a time zero at the point of first wheel contact following launch.

In his first "Malibu" paper[1], published in 1985 and titled, "Rollover Crash Tests - The Influence of Roof Strength on Injury Mechanics" (18) Orlowski described the typical process of the Malibu vehicle moving off the dolly:

> "*Test:6 was typical of all tests in that the vehicle began to roll as it left the dolly. A slight tripping force was generated between the dolly and the tires of the vehicle such that a roll velocity of approximately 75 deg/s, and a slight decrease in translational velocity were incurred as the vehicle became airborne leaving the dolly". "..., the vehicle was airborne until it struck the ground on its right side wheels at a roll angle of approximately 40 degrees. Immediately prior to the wheels striking the ground the vehicle was translating at approximately 13.8 m/s (45 ft/s) and rotating at a comparatively low rate of 75 deg/s. Consequently, this first ground impact involved a lengthy sliding contact adding significant rotational velocity at the expense of translational velocity. During this first ground impact, the roll velocity increased to 310 deg/s, and the translational velocity decreased to 12 m/s (39 ft/s).*"

It is in Orlowski's description (18) of the start of a dolly rollover where the differences between a dolly rollover and a natural rollover are rooted.

The first ground contact in a natural rollover is typically on the roof. This is in distinct contrast to a 208 dolly rollover test in which the vehicle's first ground contact after launch occurs when the leading tires drop to the test surface. After the tires have slid some distance along the surface, the vehicle develops a sufficient roll angle and roll rate to overturn the vehicle. It is this moment, at the start of overturn when the contact of the leading tires ends, that is comparable to the trip point in a natural rollover. Unfortunately, the vehicle's position and speed at the end of the leading tire contact in a dolly rollover test is not measured or documented.

Typical differences between the point of first contact in a dolly rollover and the point of first contact in a natural rollover include (1) first contact with the leading tires in a dolly rollover compared typically to the roof in a natural rollover; (2) the roll rate at first contact (with the tires) is low in a dolly rollover, reported as typically 75 deg/sec in the Malibu series, compared to up to 400 deg/sec in a natural rollover; and (3) a dolly rollover is perpendicular to the direction of travel and most natural rollovers occur at a slip angle other than 90 degrees. The implications of the differences in first contact conditions are that, in a dolly rollover, the tripping and rolling phases are combined while the analysis of a natural rollover begins at the trip point.

During the tripping phase of a natural rollover, the vehicle rolls laterally about a line between the leading tires causing the CG to rise from its nominal height to a position over the leading tires. From this point, the CG continues to rise (often including the time that the leading tires lose contact with the ground) until gravity overcomes the vertical component of the CG velocity. It is this phenomenon that results in the airborne phase between the trip point and the first ground impact. In contrast, the roll rate of a vehicle at the point of release in a dolly test is very low

[1] Malibu refers to the model of vehicle used in successive papers that presented experimental results of dolly rollovers of Chevrolet Malibu sedans with the parameters of production vs. rigid roof and with and without a restrained front seat occupant (18, 19).

and the path of the CG at release is parallel to the ground. As the vehicle drops to the test surface, the CG necessarily develops a downward component of velocity before the leading tires contact the ground. As a result of the dissimilar CG trajectories at the trip point and dissimilar vehicle structures involved in the first ground contact, there are substantial differences in the conditions and forces experienced during the first roll when comparing natural and dolly rollovers,.

A manifested dissimilarity at the start of dolly rollovers on dirt was demonstrated by Luepke in 2011 (10) in his several comparisons to steer-induced rollovers. Although Luepke concluded that the peak roll rates were similar[2], early in the tests the roll rate increased more rapidly in dolly rollovers on soil. This may be due to the falling of the vehicle from the elevated dolly into dirt, producing high overturning forces from wheel-to-soil furrowing, inducing a greater tripping effect and associated rise in roll rate.

RESULTS

Drag Factors From Dolly Rollover

Eighty-one (81) dolly rollover crashes were reexamined and reanalyzed to calculate the average drag factor. Tests were from the sources described in Annex A. A listing of the tests is included in Annex B.

The tests include dolly rollovers that typically follow the method described in FMVSS 208. Exceptions to this method include:

1. DOT HS-800 615 (23) in which many of the tests used a 2.5-inch bar instead of the standard 4-inch bar and were launched at 10.25 inches and 10.5 inches above the test surface.
2. SAE 2002-01-0693 (24) in which small trucks were launched at zero degrees into a curb instead of 23 degrees onto flat ground.
3. SAE 2008-01-0156 (7) for which four vehicles were launched on to 6 inches of dirt, reducing the height above the test surface to 3 inches, and one vehicle was launch onto a section of concrete before rolling onto a 6-inch dirt surface
4. SAE 2010- 01-0515 (9) in which two of the vehicles were launched from a height 9 inches above a compacted dirt surface.

The Subaru Forester dolly rollover test on concrete from SAE 2010-01-1112 presented by Croteau (9) involved two complete rolls followed by 40 feet of tracking or rollout on its wheels to a point of rest. The drag factor was calculated over the roll distance only using the speed at launch and speed at start of rollout as reported in the paper.

The range of calculated drag factors from launch point to point of rest was 0.31 g to 0.61 g for all dolly rollover tests. The average drag factor was 0.44 g (SD 0.064). Trimming the results and using the middle 70 percent yields an average of 0.44 g and a range of 0.38 g to 0.50 g. The distribution of the results is shown in Figure 2. This distribution shows that there is a lower probability that the drag factor will occur on the high side of the range when running a dolly rollover test.

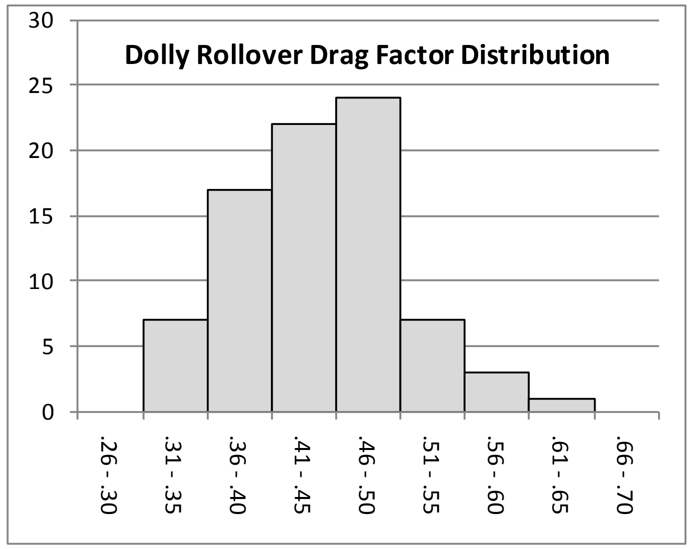

Figure 2. Dolly Rollover Drag Factor Distribution.

Seven dolly rollover tests were conducted such that the test vehicle rolled entirely on a dirt surface. Two of the six involved a 9-inch drop to the dirt, while the other five involved a 3-inch drop. All of the dolly rollovers on dirt involved SUVs with the exception of one test which involved a minivan. The minivan test resulted in a 0.58 g drag factor. The SUV dolly rollover tests on dirt produced drag factors ranging from 0.46 g to 0.54 g with an average of 0.50 g. There are no reported dolly rollover tests of passenger cars on dirt, therefore conclusions about the relative differences between passenger cars and SUV's on dirt are not possible. The drag factor range for the seven dolly rollovers on dirt was within the range of the drag factors for the other 74 reported dolly rollover tests on pavement. Therefore, conclusions regarding differences in drag factors between rollovers on dirt and on pavement are currently unsupported.

Ten SUV dolly rollovers with an initial roll angle of 23 degrees were identified. Table 1 lists the drag factors for these tests in ascending order. Six of these SUV dolly rollover tests were conducted on dirt and three were on pavement. The remaining test involved dual surfaces, with a 1987 Jeep Wagoneer that was launched onto 30 feet of concrete before it rolled onto dirt. The three tests on pavement included two tests conducted at the

[2] Lupke's charts of roll rate from different tests show use of an obviously different filter or method for determining roll rate. Assertions regarding similarity of peak response should be considered in light of this difference.

lowest test speed (30 mph) and one test of a Subaru Forester that stopped rolling after 160 ft and tracked on its wheels to its point of rest. These factors make the populations of SUV dirt rollovers and SUV pavement rollovers so different that drawing significant conclusions about the relative drag factors is not appropriate.

Vehicle	Speed at Launch (mph)	Roll Distance (ft)	Drag Factor (g)	Surface
94 Ford Explorer	30.0	88.7	0.34	concrete
03 Subaru Forester	42.3	160.0	0.37	concrete
93 Ford Explorer	30.0	78.8	0.38	concrete
03 Subaru Forester	43.4	138.0	0.46	dirt
89 Chevrolet S10	55.3	216.0	0.47	dirt
87 Jeep Wagoneer	40.6	110.0	0.50	concrete to dirt
03 Subaru Forester	44.2	129.0	0.51	dirt
98 Ford Expedition	43.2	120.0	0.52	dirt
86 Chevy Suburban	37.0	87.0	0.53	dirt
04 Volvo XC90	42.9	115.0	0.54	dirt

Table 1. SUV Dolly Rollovers Listed by Increasing Drag Factor.

A review of Table 1 shows that the drag factors for SUV dolly rollovers on dirt were higher than those on pavement and the drag factor from the dual-surface test (0.50 g) was in the middle of the reported range for tests on soil (0.46 g to 0.54 g). Overall, the range of drag factors for SUV rollovers on dirt and on pavement (0.34 g to 0.54 g) is within the range of drag factors for other vehicles on pavement ((0.31 g to 0.61 g). Thus, no significant conclusions can be drawn from the body of test data regarding differences in drag factors between rollovers of SUV's and passenger cars.

Roll Phase Drag Factors From Actual Highway Rollovers

In 2009 and 2010 Asay and Woolley published two papers with results of 10 rollover crash tests conducted on an actual highway (15, 16). The first four tests (2009) utilized passenger cars and the last six (2010) were conducted with SUV's. All of the tests were conducted by towing the vehicle up to speed on a straight section of highway, releasing it, and then steering it with an automatic steer controller to induce rollover. The trip speed of the vehicles was determined by the authors through calculation and/or direct measurement by roof-mounted GPS.

Using the data provided in the two Asay and Woolley papers along with a simplification of the analysis methods described by Stevens (14), the trip speeds were re-calculated for eight of the ten tests. The reasons for reevaluating each test vehicle's trip speed and subsequent rollover drag factor are described below.

Two tests in the 2009 paper and one test in the 2010 paper used the extrapolation method to calculate the trip speed (15). In the two 2009 tests that used extrapolation, the vehicles moved 196.6 ft and 178.9 ft over a time of 2.28 s and 2.23 s, respectively. During this time, the test vehicles moved from a known reference point while essentially tracking on the road to sliding sideways off road at lateral deceleration rates sufficient to overturn the vehicles. The extrapolation technique assumes that the deceleration measured at the reference point remains constant over this entire time and distance while the vehicle experiences a significant change in slip angle and ground surface interaction due to the change in road surface and potential furrowing of the tires and wheels. These factors raise questions about the accuracy of the extrapolation approach.

Given that the test vehicles were equipped with instrumentation-grade accelerometers to measure the accelerations of the vehicle CG[3], the speed at the start of the rollover can be more accurately determined by integrating the actual measured accelerations of the vehicle instead of assuming a constant deceleration rate from the start of the test through the trip point.

The authors reported a trip speed by both methods for each test. All 2009 tests using the integration method yielded lower trip speeds compared to speeds derived from extrapolation. The reported integration method trip speed is used in this paper's analysis.

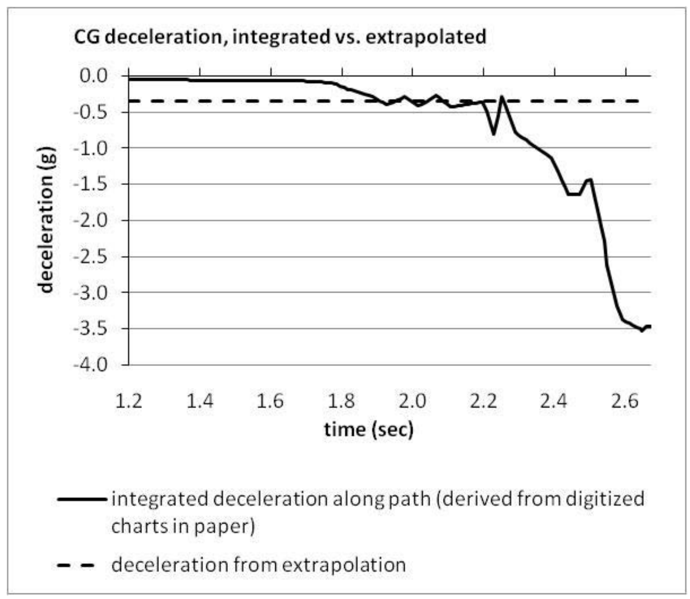

Figure 3. Calculated resultant deceleration along the vehicles path in test 1 from the Asay and Woolley 2010 paper derived from digitizing charts contained in the paper versus the constant acceleration embodied in the extrapolation method.

A VBox III GPS speed sensor was utilized during the tests reported in the 2010 paper. However, the VBox failed to record

[3] The tests only measure the X and Y vehicle accelerations at the CG. Trip velocity was calculated by integrating the measured vehicle accelerations from the reference point through the trip point in two dimensional planer space along the vehicle path. Path direction relative to the vehicle heading was determined from a vehicle template positioned on a scale diagram.

Vehicle	Reference	Test No.	Published trip speed (mph)	Reevaluated trip speed (mph)	Roll distance (ft)	Published Drag factor	Reevaluated Drag factor
96 Buick Skylark	SAE2009-01-1544	test 2	45.6	41.6	122.4	0.57	0.47
84 AMC Eagle	SAE2009-01-1544	test 3	36.4	34.6	82.2	0.54	0.49
87 Ford Taurus	SAE2009-01-1544	test 5	27.1	n/a	62.5	0.39	n/a
91 Ford Escort	SAE2009-01-1544	test 6	51.6	n/a	173.6	0.51	n/a
96 Oldsmobile Bravada	SAE2010-01-0521	test 1	63.4	57.2	266.6	0.50	0.41
91 Isuzu Rodeo	SAE2010-01-0521	test 2	50.7	44.4	185.3	0.46	0.36
94 Nissan Pathfinder	SAE2010-01-0521	test 4	41.3	36.7	114.1	0.50	0.39
02 Ford Explorer	SAE2010-01-0521	test 6	35.2	32.4	78.6	0.53	0.45
98 Ford Expedition	SAE2010-01-0521	test 7	34.0	28.7	52.5	0.74	0.52
91 Montero	SAE2010-01-0521	test 8	66.1	61.0	242.6	0.60	0.51

Table 2. Summary of the original and reevaluated results from the Asay and Woolley tests.

during Test 1 and the authors reverted to the extrapolation method outlined in the 2009 paper to calculate the trip speed. No results were presented for the trip speed based on the integration method. The extrapolation, as presented in the 2010 paper, was carried forward from a known reference point assuming a constant deceleration for 1.47 seconds. During this time, the vehicle moved from generally tracking on the road to having a 42.3 degree slip angle at the point of trip off road (the distance traveled was not explicitly provided in the paper). The measured peak acceleration as reported in the paper during the extrapolated phase of the crash was 4.28 g's. An illustration of the differences in the deceleration profiles utilized in the extrapolation method, which assumes constant deceleration, versus the integration method, which uses the resultant x and y measured decelerations is shown in Figure 3.

By digitizing the lateral and longitudinal acceleration from the data presented in the 2010 paper, measuring slip angles from the scene diagram, and using the integration method described in the 2009 paper, a trip velocity was calculated. A further check of the trip speed was completed utilizing a method outlined by Stevens (14) that evaluates the speed of the vehicle during the first airborne phase (from trip to first landing). The trip speed can be calculated from the published distance of the first airborne phase and the duration for this phase as determined from the published acceleration and roll rate data. The trip speeds calculated using these two different methods were consistent with each other and lower than the trip speed published in the 2010 paper. A limitation to the integration analysis presented is that it was accomplished by integrating a digitization of the data plots presented in the 2010 paper. This analysis also neglects the effects of roll angle and z-axis acceleration on the result. An integration of the actual recorded data which takes into account both roll angle and z-axis acceleration may prove to provide the most accurate calculation of the trip speed for Test 1.

A correction of the VBOX III measured speed was made for all of the remaining tests reported in the 2010 paper, with the exception of Test 7. The correction was based on a method outlined by Stevens (14) simplified to accommodate the limited data published in the paper. The data necessary to apply the correction includes the slip angle, roll angle, and roll rate at trip. Necessary geometric characteristics of the test vehicle are the distance from the leading edge of the tires to both the vehicle CG and the GPS sensor. The slip angle at trip was published, and the roll rate was extracted from the published roll rate plot. A roll angle at trip of 60 degrees was used in the correction of each test's trip speed since the roll angle at trip was not presented. Integration of the recorded and properly-filtered roll rate data may be the best method to obtain the roll angle. Ideally a calculation of the trip speed should use a strict application of the method outlined by Stevens, correcting the VBOX III measured speed at the roll angle of 45 degrees and integrating the 3D accelerations from that position to the point of trip.

A close look at the published acceleration and rotation plots for test 7 of the 2010 paper revealed a trip point 0.31 seconds later than presented. At the point of trip the leading tires lift from the ground and a vehicle enters its first airborne phase. During airborne phases the roll rate is nearly constant. Asay and Woolley identified this phenomenon (16). Carter (8) noted that the decelerations would be expected to drop to zero when the vehicle becomes airborne according to basic ballistics theory. The point of trip published in the paper was brought into question because all three directions of acceleration have significant and changing response at the identified time of trip. Additionally, the roll rate is noted to become constant and the accelerations appear to drop to near-zero about 0.31 seconds later than the time identified in the paper as the trip point. A GPS speed was extracted from the published velocity plot at the time-shifted trip speed and corrected for slip angle, roll rate and roll angle.

The result of trip speed reevaluation was a reduction in roll phase drag factors. The averaged roll phase drag factors, as published in the two papers, was 0.53 g (min = 0.39 g, max = 0.74 g) and the averaged recalculated drag factors was 0.45 g (min = 0.36 g, max = 0.52 g). Table 2 summarizes the original and reconsidered results.

Naturally Occurring Rollover Testing

In total, 24 naturally occurring rollover tests were reviewed and analyzed. The tests include steer-induced rollovers on asphalt and dirt and tests in which the vehicle was towed sideways into a tripping mechanism. Tests were from the sources described in Annex A and listed in Annex B.

Analysis of the naturally occurring rollover test population excluded the two rollovers induced by a curb trip presented by Cooperider (26) and the rollover of the 1997 Toyota 4Runner presented by Gilbert in his 2007 Collision article (31). The curb trip rollovers from SAE 900366 were excluded because the mechanism of roll initiation was different than all of the other rollovers. The reported curb trip drag factors were 0.32 g and were the lowest of any drag factors from a non-dolly rollover test. Gilbert's Toyota 4Runner test was excluded because, during the rollover, the vehicle landed on its wheels and tracked or rolled out before restarting its rollover. The reported drag factor in the Toyota 4Runner test was 0.34 g.

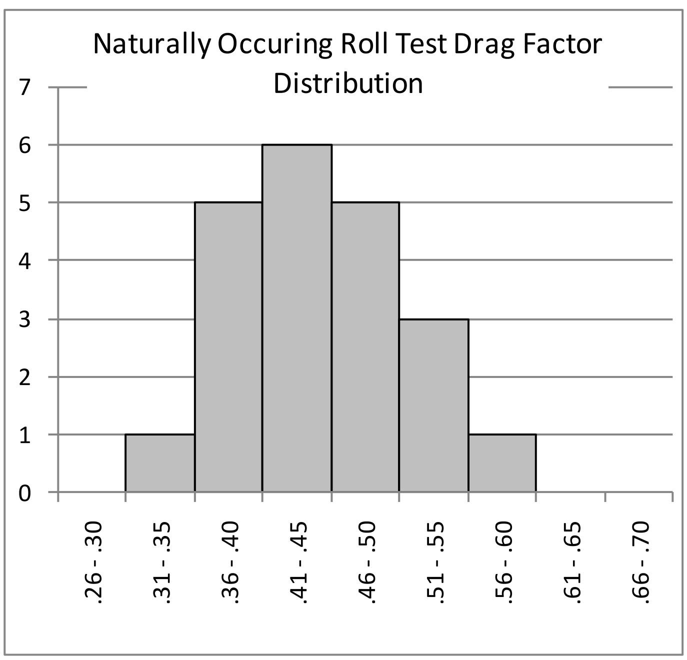

Figure 4. Drag factor distribution from naturally occurring rollover tests including the reevaluated results of Asay and Woolley (15, 16)

The calculated average roll phase drag factor for the population of naturally occurring rollover tests including the reevaluated results from the Asay and Woolley tests was 0.44 g (min = 0.33 g; max = 0.57 g). Trimming the upper and lower 15%, the average roll phase drag factor was 0.44 g (min = 0.39 g; max = 0.50 g). Drag factor distribution from these tests is shown in Figure 4.

The calculated average roll phase drag factor for the population of naturally occurring rollover tests, when taking the Asay and Wooley results as originally published, was 0.48 g (min = 0.33 g; max = 0.74 g). Trimming the upper and lower 15%, the average roll phase drag factor was 0.48 (min = 0.39; max = 0.54).

CONCLUSION

- Dolly rollover tests reported between 1972 and 2011 involving a wide population of vehicles suggests that the appropriate drag factor range for use in rollover reconstruction, excluding special circumstance, is 0.38 to 0.50. The finding is from the calculated results of 81 dolly rollover crash tests statistically trimmed to exclude the upper and lower 15 percent.
- Reevaluation of roll phase analysis published in two papers reporting results of rollover tests on an actual highway found lowered average roll phase drag factors. The average roll phase drag factor as published in the papers was 0.53 g (min = 0.39, max = 0.74) and the average reevaluated drag factor was 0.45 g (min = 0.36, max = 0.52) Reevaluation of these tests is categorically correct, but should be finalized by analysis of the original tests data.
- Natural rollover tests suggest that the appropriate drag factor range for use in rollover reconstruction, excluding special circumstances, is 0.39 to 0.50. The finding is from the calculated results of 21 naturally occurring rollover crash tests statistically trimmed to exclude the upper and lower 15 percent.
- These results provide a more probable range of the drag factor for use in accident reconstruction compared to the often repeated assertion that rollover drag factors range between 0.4 g and 0.65 g.

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ANNEX A

SOURCE AND DESCRIPTION OF TESTS

DOLLY ROLLOVER TESTS

- SAE 720495 (20), four dolly rollovers reported by General Motor at a nominal speed of 30 mph, roll distance digitized from a chart;
- DOT HS-805 648 (21), twenty-six tests digitized from a chart;
- DOT HS-801 776 (22), twelve tests with results described in the body of the report. Eleven of the tests were also plotted on the chart described above in DOT HS-805 648;
- DOT HS-800 615 (23), ten tests with results described in the body of the report;
- SAE 2002-01-0693 (24), eight tests launched at zero degrees into a curb instead of 23 degrees onto flat ground;
- SAE 2002-01-0694 (25), one 55 mph dolly rollover of a Ford 15-passenger Van;
- SAE 2008-01-0156 (7), five tests conducted on dirt. One of the tests launched the vehicle onto a 30 foot concrete surface before it rolled into dirt;
- SAE 851734 (18) and SAE 902314 (19), sixteen tests associated with Malibu I and II;
- SAE 890857(8), one new test. In addition to presentation of prior results this paper presents a single new test of an unknown vehicle at 50 mph;
- SAE 900366 (26), one test of a 1981 Dodge Challenger;
- SAE 931976 (27), one test of a Chevrolet Sprint;
- NHTSA v2514 (28) and NHTSA v2553 (29), two tests of Ford Explorers.
- SAE 2010-01-0515 (9), three test of a Subaru Forester. Two on dirt, one on concrete;
- SAE 2011-01-1112 (10), one test of a Chevrolet Suburban on dirt.
- DOT HS-803-463 (30), one test of a 1977 Electra-Van 500.

NATURAL ROLLOVER TESTS

- SAE 2009-01-1544 and SAE 2010-01-0521, Ten steer-induced rollover tests on an actual highway reported by Asay and Woolley (15, 16) with reevaluated trip speeds;
- SAE 900366, Four tests by Cooperider (26) in which the vehicle was released sideways into either soil or a curb;
- Collision Magazine, V2, I1, One test of a steer-induced rollover by Wilson (13);
- Collision Magazine, V2, I2, One test of a steer-induced rollover by Gilbert (31);
- SAE 2000-01-1641, One test of a steer-induced rollover by Larson (12);
- SAE 931976, One test described as a furrow rollover (27);
- SAE 2008-01-1486, One result from a rollover recorded on video (32) and
- SAE 2011-01-1114, five steer-induced rollover tests by Stevens (14).

ANNEX B

LIST OF DOLLY ROLLOVER TESTS

Vehicle Type	Vehicle Model	Model Year	Speed (mph)	Distance (ft)	Drag Factor (g)	Dirt Surface (Y/N)
pass	71 Vega	1971	30.0	95.7	0.31	N
pass	71 Vega	1971	30.0	93.3	0.32	N
pass	71 Vega	1971	30.0	90.9	0.33	N
pass	71 Vega	1971	30.0	90.6	0.33	N
pass	83 Chevrolet Malibu	1983	32.0	102.0	0.34	N
SUV	94 Ford Explorer	1994	30.0	88.7	0.34	N
pass	83 Chevrolet Malibu	1983	32.0	97.1	0.35	N
pass	71-72 Vega	1971	30.0	82.8	0.36	N
pass	69 Oldsmobile 98	1969	30.3	84.0	0.37	N
van	68 Ford Club Wagon (Van)	1968	28.9	76.0	0.37	N
SUV	03 Subaru Forester	2003	42.3	160.0	0.37	N
pass	83 Chevrolet Malibu	1983	28.0	69.9	0.37	N
van	68 Volkswagon Microbus	1968	29.2	76.0	0.38	N
pass	71 Vega	1971	29.9	79.0	0.38	N
SUV	93 Ford Explorer	1993	30.0	78.8	0.38	N
pass	83 Chevrolet Malibu	1983	31.8	87.9	0.38	N
pass	83 Chevrolet Malibu	1983	32.5	89.9	0.39	N
unknown	Unknown	unknown	50.0	212.0	0.39	unk
pass	68 Oldsmobile 98	1968	30.0	76.0	0.40	N
pass	68 Oldsmobile 98	1968	30.2	77.0	0.40	N
van	77 Electra-Van	1977	29.6	73.0	0.40	N
pass	59 Plymouth	1959	30.0	74.9	0.40	N
pass	70 Plymouth	1970	30.0	74.9	0.40	N
pass	59 Ford	1958	30.0	74.8	0.40	N
pass	83 Chevrolet Malibu	1983	32.0	84.0	0.41	N
pass	70 Chrysler Newport	1970	30.0	73.0	0.41	N
pass	83 Chevrolet Malibu	1983	32.0	83.0	0.41	N
pass	83 Chevrolet Malibu	1983	32.0	83.0	0.41	N
PU	68 Ford Pickup	1968	29.6	70.0	0.42	N
pass	68 Oldsmobile	1968	30.0	71.8	0.42	N
pass	71 Vega	1971	30.2	72.0	0.42	N
SUV	01 Nissan Pathfinders	2001	30.3	72.2	0.42	N
SUV	01 Nissan Pathfinders	2001	30.3	72.2	0.42	N
pass	70 Plymouth	1970	30.0	70.8	0.42	N
pass	71-72 Vega	1971	30.0	70.8	0.43	N
pass	69 Oldsmobile 98	1969	29.7	69.0	0.43	N

Vehicle Type	Vehicle Model	Model Year	Speed (mph)	Distance (ft)	Drag Factor (g)	Dirt Surface (Y/N)
pass	83 Chevrolet Malibu	1983	32.0	80.1	0.43	N
pass	83 Chevrolet Malibu	1983	33.6	87.9	0.43	N
pass	68 Volkswagon Sedan	1968	31.2	76.0	0.43	N
pass	83 Chevrolet Malibu	1983	32.0	78.7	0.43	N
pass	69 Oldsmobile 98	1969	30.2	70.0	0.44	N
pass	81 Dodge Challenger	1981	30.2	70.0	0.44	N
pass	69 Chrysler Newport	1969	29.4	66.0	0.44	N
pass	70 Ford 4-dr	1970	29.5	65.0	0.45	N
SUV	01 Nissan Pathfinders	2001	29.7	65.6	0.45	N
pass	68 Volkswagon Sedan	1968	31.2	72.0	0.45	N
SUV	03 Subaru Forester	2003	43.4	138.0	0.46	Y
pass	69 Oldsmobile 98	1969	29.8	65.0	0.46	N
pass	83 Chevrolet Malibu	1983	31.9	74.1	0.46	N
pass	86 Chevrolet Sprint	1986	40.0	116.0	0.46	N
pass	83 Chevrolet Malibu	1983	32.0	74.1	0.46	N
pass	83 Chevrolet Malibu	1983	31.9	73.8	0.46	N
pass	58 Ford	1958	30.0	64.9	0.46	N
pass	59 Plymouth	1959	30.0	64.9	0.46	N
SUV	01 Nissan Pathfinders	2001	31.1	68.9	0.47	N
pass	70 Ford 4-dr	1970	29.6	62.0	0.47	N
SUV	89 Chevrolet S10	1989	55.3	216.0	0.47	Y
SUV	01 Nissan Pathfinders	2001	30.5	65.6	0.47	N
pass	70 Oldsmobile 98	1970	29.2	60.0	0.48	N
pass	70 Oldsmobile 98	1970	30.0	63.0	0.48	N
pass	69 Oldsmobile 98	1969	28.8	58.0	0.48	N
SUV	01 Nissan Pathfinders	2001	30.6	65.6	0.48	N
van	Ford 15-passenger Van	unknown	55.3	212.0	0.48	N
SUV	87 Jeep Wagoneer	1987	40.6	110.0	0.50	conc/dirt
pass	68 Oldsmobile 98	1968	29.5	58.0	0.50	N
pass	59 Ford	1959	30.0	59.9	0.50	N
pass	59 Ford	1959	30.0	59.9	0.50	N
pass	59 Plymouth	1959	30.0	59.9	0.50	N
pass	70 Plymouth	1970	30.0	59.9	0.50	N
pass	71-72 Vega	1971	30.0	59.9	0.50	N
SUV	03 Subaru Forester	2003	44.2	129.0	0.51	Y
SUV	98 Ford Expedition	1998	43.2	120.0	0.52	Y
SUV	86 Chevy Suburban	1986	37.0	87.0	0.53	Y
pass	83 Chevrolet Malibu	1983	32.0	65.0	0.53	N
pass	83 Chevrolet Malibu	1983	32.4	65.9	0.53	N
SUV	04 Volvo XC90	2004	42.9	115.0	0.54	Y
SUV	01 Nissan Pathfinders	2001	30.4	57.4	0.54	N
SUV	01 Nissan Pathfinders	2001	30.1	54.1	0.56	N
van	97 Ford Aerostar	1997	41.7	100.0	0.58	Y
pass	70 Plymouth	1970	30.0	49.9	0.60	N
PU	68 Ford Pickup	1968	29.0	46.0	0.61	N

LIST OF NATURAL ROLLOVER TESTS

	Paper Speed (mph)	Trip Speed (mph, corrected)	trip to rest distance (ft)	drag factor (g)	Surface	
81 Dodge Challenger	n/a		n/a	0.32	unk	drag factor from body of paper
79 Datsun B210	n/a		n/a	0.32	unk	drag factor from body of paper
97 Toyota 4Runner	n/a		n/a	0.34	asphalt	reported in body of article
97 Ford Explorer 4WD	30.2		92.4	0.33	dirt	
91 Isuzu Rodeo	50.7	44.4	185.3	0.36	dirt	speed in chart is corrected for RR, body of paper reports speed 50.7 mph
89 Ford Aerostar	33.8		104.5	0.37	concrete	
02 Explorer Sport RWD	41.0		146.7	0.38	asph_dirt	
87 Ford Taurus	27.1		62.5	0.39	dirt	
94 Nissan Pathfinder	41.3	36.7	114.1	0.39	dirt	last .5 roll on asphalt, speed in chart is corrected for RR, body of paper reports speed 41.3 mph
91 Ford Explorer	n/a		164.0	0.41	asph_dirt	reported in body of article
96 Oldsmobile Bravada	63.4	57.2	266.6	0.41	dirt	last 1.5 rolls on asphalt, speed in chart from first airborne phase OTG speed (data from paper and first RR dwell time), body of paper reports speed 63.4 mph from extrapolation
85 Toyota 4WD	57.0		260.0	0.42	asphalt	calculation of speed at four wheel lift preformed by dividing the longitudinal velocity by the cosine of the slip angle yields a speed of approximately 57 mph
01 Chevrolet Blazer	57.9		264.7	0.42	asph_dirt	
03 Ford Explorer Sport	54.0		250.0	0.43	asph_dirt	grade adjusted drag factor in body of paper; roll speed 54 mph, distance 250 ft.
02 Ford Explorer	35.2	32.4	78.6	0.45	dirt	speed in chart is corrected for RR, body of paper reports speed 35.2 mph
79 Datsun B210			24.0	0.47	dirt	slid into soil, speed at start of roll not given, drag factor from body of paper
96 Buick Skylark	45.6	41.6	122.4	0.47	dirt	speed in chart is integration result, paper uses speed from extrapolation, 45.6 mph
81 Dodge Challenger			42.0	0.48	dirt	slid into soil, speed at start of roll not given, drag factor from body of paper
84 AMC Eagle	36.4	34.6	82.2	0.49	dirt	speed in chart is integration result, paper uses speed from extrapolation, 36.4 mph
unknown	25.0		42.0	0.50	dirt	described as furrow rollover
91 Ford Escort	51.6		173.6	0.51	asphalt	

	Paper Speed (mph)	Trip Speed (mph, corrected)	trip to rest distance (ft)	drag factor (g, corrected)	Surface	
91 Montero	66.1	61.0	242.6	0.51	asph_dirt	roll 5 - 8 on asphalt, speed in chart is corrected for RR, body of paper reports speed 66.1 mph
98 Ford Expedition	34.0	28.7	52.5	0.52	dirt	speed in chart had corrected trip time and is corrected for RR, body of paper reports speed 34.0 mph
95 Nissan Pathfinder	42.3		105.2	0.57	dirt	