Analysis of Causes of an Unintended Rollover During a Tread Separation Event Test

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Abstract - A high speed multiple rollover crash occurred during a test program designed to evaluate the disturbances to a vehicle's straight ahead steady state path caused by a rear tire tread separation event. The tread separation that induced the crash was a partial tread separation event. The test run resulting in the rollover is documented by on-board test instrumentation and standard post-test crash investigation methods. Testing reported in previous papers documents a distribution of forces that cause an external disturbance to vehicles during tread separation events. These papers also document changes to vehicle steering characteristics following tread separation events. By themselves reported tread separation induced forces are insufficient to cause the initial vehicle motion in the rollover crash. Testing presented in this paper documents a change to vehicle handling stability due to tread separation induced rear wheel hop. Rear wheel hop and a special hop condition called tramp resulted in oversteer causing the vehicle to make an unintentional rapid turn. Characteristics of tread separation induced rear axle hop and tramp, including changes in vehicle handling, physical evidence left on the road, and the effects on vehicle motions are presented.

INTRODUCTION

On November 8, 2000 an unexpected rollover of a specially outfitted driver controlled test vehicle occurred. The test vehicle was a 1996 4-dr, 4X2 Ford Explorer. The vehicle was utilized in testing designed to evaluate the external disturbance that occurs in response to rear tire tread separation events. The right rear tire tread partially detached during the test.

The vehicle's right rear tire was prepared to produce tire tread detachment at highway speed. The method of experimentation involved accelerating the vehicle to a nominal speed of 75 mph (120 kph). The vehicle was then driven in a straight line at constant speed while the test tires tread detached. The test drivers were instructed to hold the hand wheel stationary during the tread separation event. This insured that only the vehicle's response was recorded eliminating any driver influence.

The test vehicle was equipped with safety equipment including: internal roll cage, 4-point racing harness, and outriggers. The test driver wore a neck brace and helmet. Onboard instrumentation was configured for a handling test and measured parameters included: longitudinal and lateral velocity, steering wheel (hand wheel) angle, roll, yaw, and pitch angle, roll rate, longitudinal, lateral, and vertical acceleration, LF and RF wheel angle and yaw rate. Testing occurred in a marked lane on a straight, flat 50 ft wide asphalt airport taxiway.

An initial report of the test run resulting in rollover describes the vehicle response without any analysis of the underlying cause(s) of the extreme path deviation experienced during the tread separation event [1].

PROBLEM

Prior to the recorded vehicle response in the test resulting in rollover, the general understanding of external disturbances that occur during a tread separation event was that the vehicle responds with noise, vibration and turning, or pulling, in the direction of the tire failure. The extent of turning, or pulling, that occurs is typically not sufficient to cause a trained and experienced test driver with pre-test knowledge of the impending tread separation event to loose control of the vehicle. The questions addressed by this paper include: (1) what was the cause of the extreme vehicle response resulting in rollover? And, what can be learned regarding the investigating, interpretation and analysis of incidents involving tread separation events?

METHOD

The tread separation event test run resulting in vehicle rollover prompted several new test programs to investigate specific consequences of tread separation events. These programs included: (1) characterization of the vehicle's handling utilizing standardized methods described in SAE J266 [2], including methods reported in prior papers [3]; (2) documenting a range of force response due to tread separation events on a trailer based test machine [4]; and (3), a program that investigated changes to the vehicle's handling due to vibrations induced by a tire's partial tread separation event [5]. An analysis of these tests results and comparison to the vehicle response in the test run resulting in rollover is presented.

DISCUSSION

Appendix A contains results from the test run resulting in vehicle rollover. It includes all of the data collected by the on-board test instrumentation from start of test to the end, a close-up look at all of the same data from the start of tire tread detachment to the start of the vehicle rollover, a diagram of tire marks and other vehicle physical evidence left on the test surface, photographs documenting tire marks left on the test track, and a chart summarizing key milestones from the test.

Handling Characterization

The results of circle turn testing on the Ford Explorer at curb weight plus driver and instrumentation is shown in Figure 1. This chart compares the vehicle response when equipped with four tires with tread attached versus the condition when the right rear tire has all of the tread and outer steel belt removed. Figure 1 also shows the response of the same vehicle with half the circumference of the right rear tire's tread and outer steel belt removed. All of the tires were inflated to the vehicle manufacture's recommended pressure. Figure 2 summarizes the calculated steer gradient from the circle turn test results. The steer gradient was calculated over the range of 0.05 G to 0.25 G.

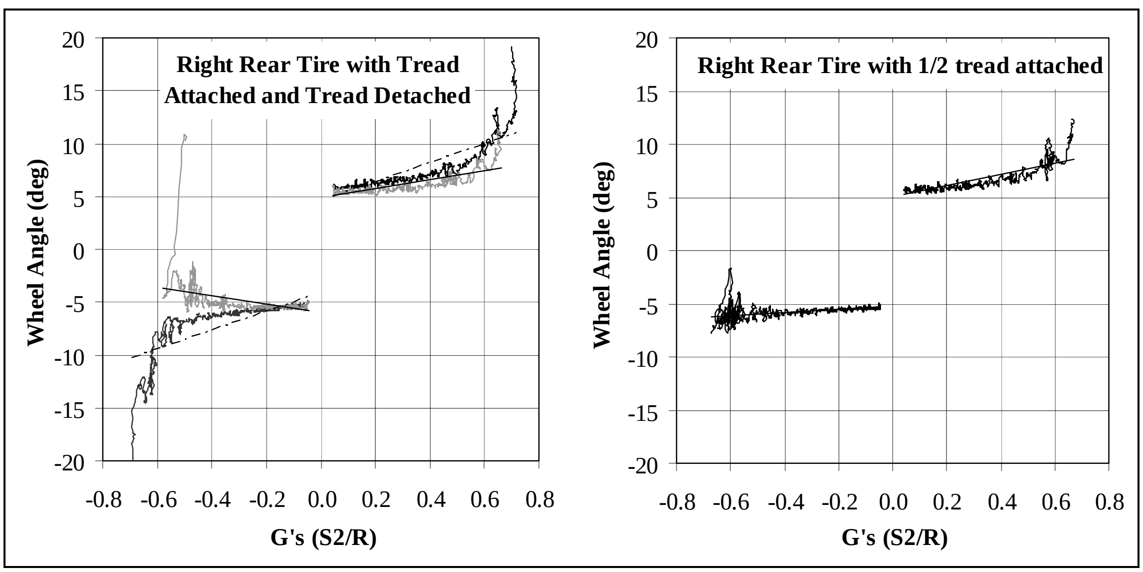


Figure 1. Steer characterizations, dark line in left graph is vehicle with unmodified tires

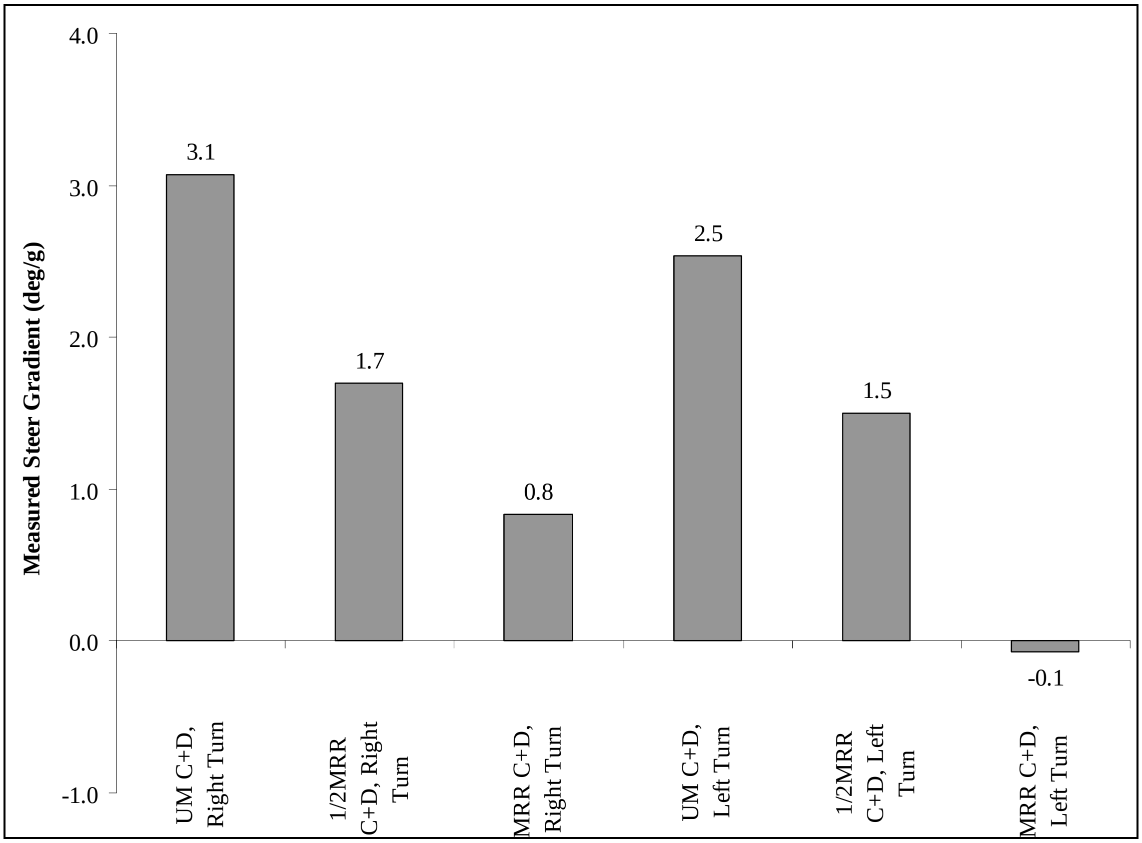


Figure 2. Calculated steer gradient for the angle of 0.05 G to 0.25 G

The circle turn testing is conducted on a circle of 100 ft (30.5 meter) radius. The peak speed attained during the circle turn testing was well below highway speed and the natural frequency of the rear suspension. The low speed in circle turn testing isolates the vehicle response in the half tread test condition to the response due to missing tread. The overall result supports a rule-of-thumb that there is a linear relationship between the percent missing tread and the percent steer gradient reduction due to the missing tread on an inflated tire. Removing half the circumference of a tire's tread and outer steel belt changes a vehicles steering, but for the lightly loaded Explorer tested at low speed the change does not cause an oversteer condition in the 0.05 G to 0.25 G linear range. Significant effects on vehicle handling, particularly in the linear range, due to the vibration produced during the half tread tests were likely not measured in low speed circle turn testing.

Tread Separation Force Response

Table 1 summarizes the results of tire trailer testing that measured the force response during a variety of tread separation events [4]. The first run listed in table 1 was a partial tread separation event that resulted in a peak longitudinal tow load of 938 lb (4172 N) and a peak resultant load of 1026 lb (4564 N). The forces measured by the test machine due to the tread separation event approach the maximum force that a tire can develop. These forces are limited by the tire-to-ground coefficient of friction. If a vehicle is driven in a straight line and one of the rear tires is braked without other changes to the vehicle or driver inputs, a turn or pulling of the vehicle toward the braked wheel will occur due to the imbalance of forces developed. However, the vehicle will not turn so rapidly that absent any other changes it can not be steered to reverse the imbalance induced turn or pulling.

Test #	Duration I, trigger to end, (sec)	Duration II, principal response, (sec)	Longitudinal		Lateral		Resultant Peak Tow Load (lb) zeroed
			Peak Tow Load (lb) zeroed	Impulse (lb*sec)	Peak Tow Load (lb) zeroed	Impulse (lb*sec)	
F	> 26.4	> 26.4	938	8913	416	3968	1026
H	2.2	1.0	327	202	152	75	361
I	2.6	1.5	737	480	412	265	844
J	13.4	12.2	1057	7984	472	3332	1151
K	*1.5	1.4	771	566	412	290	874
L	*1.2	1.2	639	427	362	249	733
M	*7.4	7.4	940	3730	419	1643	1029
N	4.7	1.4	564	571	291	269	635
	*Indicates those test that triggered early						

Table 1. Summary of force response during a variety of tested tread separation events.

Hop/Tramp Characterization

Vibrations due to a tire modified to simulate the vertical input produced by a partial tread separation in the live rear axle equipped Explorer were investigated [5]. This test program documented significant changes in vehicle steering and handling resulting from induced rear axle tramp. Measured changes are shown in table 2. During the test program a Ford Explorer was equipped with a modified right rear tire. The tire was modified by first shaving off most of the tread. Two sections of tire retread material which was equal to or less than ¼ of the circumference of the tire were then vulcanized to the tire at symmetrically opposite positions. The hopping of the test tire was only due to bumps in the tire and did not include the effect of tire imbalance.

Constant speed slowly increasing steering tests were utilized to measure changes in vehicle steering. The measured change in vehicle steer gradient due to axle tramp induced by a right rear tire partial tread separation ranged from 92-207 percent of the change in steer gradient due to removal of all of a tires rear tread and outer steel belt (complete tread separation). Vehicle skate was documented in straight line testing with the tramping rear live axle. The vehicle skate resulted in a yaw response requiring aggressive steering by the test driver. Oscillations in vehicle yaw and vehicle slip angle were induced in the low speed testing that would not have been controllable at highway speeds.

Test	Speed (mph)	Measure Speed (mph)	Tires	Steer Direction	Spinout	Max Steer (deg)	Raw Steer Gradient (deg/G)
B	20	18	unmodified	L	N	486	17.3
C	25	22	unmodified	L	N	510	17.4
D	30	28	unmodified	L	N	393	8.9
F	20	20	modified double 1/8	L	N	383	21.6
G	25	22	modified double 1/8	L	Y	335	14.8
H	30	27	modified double 1/8	L	Y	210	0.9
J	20	18	modified double 1/4	L	N	584	24.1
K	25	23	modified double 1/4	L	Y	336	11.7
L	30	28	modified double 1/4	L	Y	139	4.6
M	20	19	modified double 1/4	R	N	352	19.1
Q	25	23	modified double 1/4	R	N	193	10.5
R	30	29	modified double 1/4	R	N	556	3.9

Table 2. Summary of measured steer gradient during hop/tramp handling testing

Analysis

The pre-trip motion of the test run that resulted in rollover was analyzed through computer simulation beginning from the start of tread separation. This allowed a comparison between the actual test vehicle's measured performance and the response of the modeled vehicle to a tread separation event without axle tramp.

First, the test event was simulated using vehicle metrics from the test vehicle, tread separation forces from published testing, and steering inputs measured during the actual test. Tire property changes due to tread separation were modeled by decreasing the cornering stiffness of the separating tread tire in the simulation. Axle tramp was simulated by reducing the peak effective friction capacities of the rear tires until the path, slip angle, and yaw rate of the simulated vehicle matched those measured during the test.

The simulation was repeated to evaluate the response of the test vehicle to a tread separation in the absence of the effects of axle tramp. The tread separation drag forces, tire cornering stiffness, and driver steering from the first simulation were used but the friction capacities of the rear tires (previously reduced to simulate tramp) were left at their nominal settings. The results showed the vehicle's path curving toward the left, opposite the direction of travel in the actual test. This indicated that the driver's steering during the test was sufficient to overcome the vehicle's pull toward the right resulting from the tread separation forces but could not compensate for the rapid oversteer induced by axle tramp.

Cause of Test Vehicle Motion

During the test run that resulted in the rollover, the test vehicle was being driven in a straight line at 74 mph when the right rear tire partial tread separation event initiated. The right rear tire rotating with half of its tread attached induced a vibration in the rear axle which caused a hopping/tramp oscillation. A tramp oscillation of the rear axle occurs when one side of the axle moves upward as the other side moves downward.

The documented effect of the hop and rear axle tramp is a reduction in the vehicles steer gradient to a negative value when tramp oscillation amplitudes are greatest. Rear axle tramp can reduce the measured steer gradient in the Ford Explorer by two or more times the reduction attributed to complete removal of the tread and outer steel belt alone (complete tread separation). The steer gradient reduction can be four or more times the reduction attributed to removal of half the tread circumference and outer steel belt alone (partial tread separation) as documented in the 100 ft radius circle turn tests run at speeds where tramp mode oscillations were minimized.

The test vehicle yawed clockwise due to the unbalanced forces developed by the partial tire tread separation during the test run which resulted in the rollover, Axle tramp significantly contributed to the vehicle's substantial oversteer characteristics resulting in a rapid and uncontrolled turn of the test vehicle.

Tire mark Analysis

Photographs taken at the test crash site of the tire marks document skipping that is characteristic of wheel hop and axle tramp in the Ford Explorer (Appendix A, photographs 1-3). Hop or tramp induced roadway marking are probably not always observed or documented in real world crashes. Photographs 3 and 4 (Appendix A) show the left rear tire marks as initially skipping and then translating to a wavy tire mark. The same skipping tire marks are documented in measurements and are shown in Appendix A, diagram 3. The tire marks prior to significant vehicle turning are characteristic of wheel hop and axle tramp. Body roll of the sprung mass and weight transfer occurs as the vehicle begins to respond to turning motion. The effect of body roll and weight transfer is a reduction in axle tramp due to asymmetric loading of the vehicle suspension. Diminished axle tramping is visible in the photographs as the vehicle progresses in its turning motion. In Appendix A, photograph 5 no tramp motion is visible in the vehicle tire marks because of diminished vehicle speed, slip angle, reduced tire rpm and asymmetric loading of the vehicle suspension.

Illustration of Hop/Tramp Effects

Figure 3 is a chart that schematically explains the measured changes to the vehicle steer gradient caused by the individual elements present during a rear tire partial tread separation event that occurs at highway speeds. The chart represents an event where ½ of the tread comes off. The resulting reduction in steer gradient caused by detaching half of the tread and outer steel belt is approximately half of the steer gradient reduction due to a complete tread separation. The effect due to axle tramp is approximately four (4) times greater and the net steer gradient reduction is shown as the sum of the two.

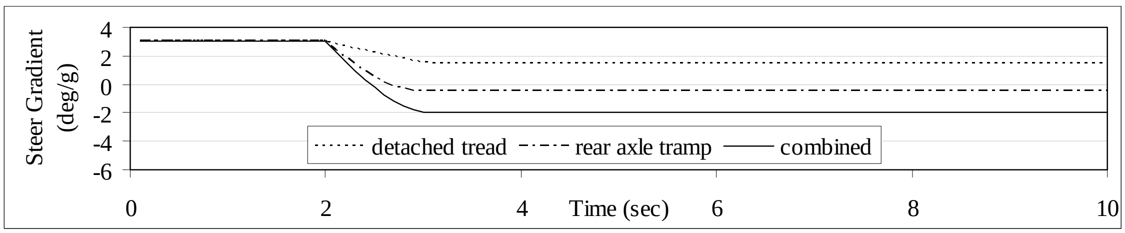


Figure 3. Rear tire partial tread separation event with axle tramp

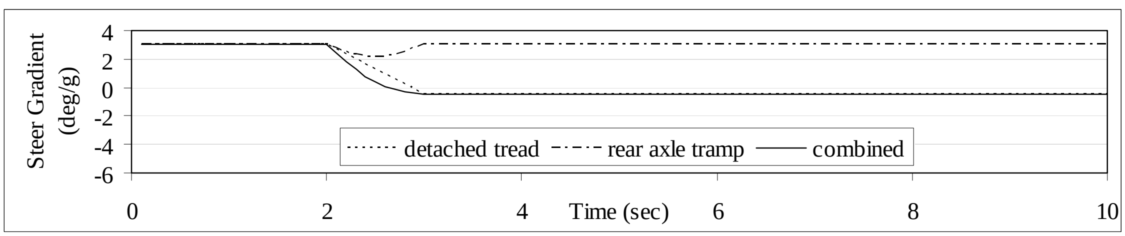


Figure 4. Rear tire fast complete tread separation event with transient axle tramp

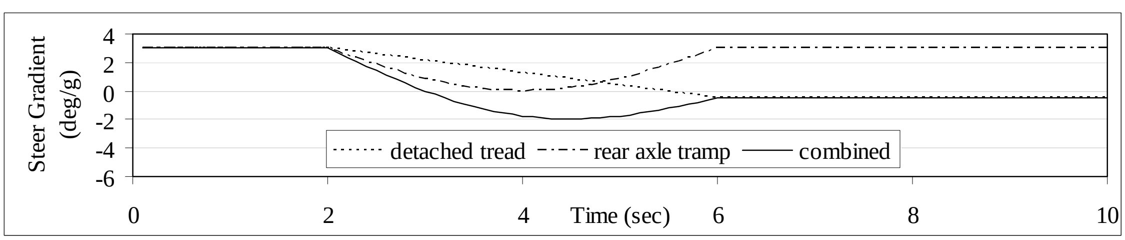


Figure 5. Rear tire long complete tread separation event with transient axle tramp

A transient axle tramp may occur in vehicles with live axles during the course of a complete tread separation event. This occurs during the portion of the event when part of the tread remains attached to the tire. The effect of the transient axle tramp will primarily be dependant upon the event duration. It may also depend upon the nature of the tread detachment. Rapid tread separation events that progressively increase the degree of tread detachment may be less prone to induce significant axle tramp oscillations. Tread separation events in which the detachment occurs haltingly or at a relatively slow rate could induce significant transient wheel hop and axle tramp oscillations.

Figure 4 is a chart illustrating the reduction in steer gradient caused by the relative contributions of axle tramp vibration and tread detachment during a short duration rear tire complete tread separation event. The peak reduction in steer gradient occurs at the conclusion of tread detachment. Rapid tread separation events often produce a single large piece of tread that approximates the tire's circumference. This type of short complete tread separation event would be unlikely to induce significant changes in the steer gradient and therefore vehicle path due to wheel hop and axle tramp.

Figure 5 is a chart illustrating the reduction in steer gradient caused by the relative contributions of wheel hop and axle tramp vibration and tread detachment in a medium or long duration rear tire complete tread separation event the peak reduction in steer gradient exceeds the final reduction and occurs before the conclusion of the tread detachment. The peak understeer gradient reduction occurs when forces generated by the detaching tread are inducing an unsteered turn of the vehicle.

The vehicle at the conclusion of a complete tread separation has changed to oversteer when the tread separated tire is on the outside of a turn regardless of whether it is a short or long duration tread separation event. Other detrimental changes to the vehicle's steering have also occurred including: a reduced range of linear steer response, a non-symmetrical left versus right steer response, a reduction in limit lateral acceleration magnitude, and oversteer at the limit in both left and right turns.

CONCLUSION

An unintended rollover of a test vehicle was caused by a right rear tire with a partially detached tread that induced rear wheel hop and axle tramp. The rear wheel hop and axle tramp negatively changed the handling characteristics of the vehicle, reducing its steer gradient, causing vehicle skate, and producing an oversteer condition. Negative changes to the vehicle handling due to rear axle tramp exceed changes to the vehicle attributed to removal of the tread and outer steel belt alone. The change in vehicle heading caused by a tread separation with axle tramp is significantly greater than the heading change resulting from the absence of tread alone. The reduced tire to ground contact for an axle experiencing hop and/or tramp increases the hazard posed by a separating tire.

During a tread separation at highway speeds, tire to ground contact is reduced as a result of wheel hop and, on live axles, axle tramp. For partial tread separation events, the steer gradient change due to wheel hop and axle tramp is greatest when axle tramp oscillations are near peak amplitude. The steer gradient change is a transient phenomenon of variable magnitude for complete tire tread separation events. A distinct skipping tire mark may be observed on the roadway from a tire experiencing a tread separation as a result of wheel hop, tire asymmetries and tread slap. A skipping tire mark may also be observed on the side opposite the tread separating tire when axle tramp occurs. Hop or tramp induced roadway markings may be indicative of their occurrence, but the absence of roadway marking should not be interpreted to mean that hop or tramp did not occur.

REFERENCES

1 Arndt, Stephen M. and Arndt, Mark W., The Influence of a Rear Tire Tread Separation on a Vehicle Stability and Control, ESV 2001 paper No. 258, June 2001.

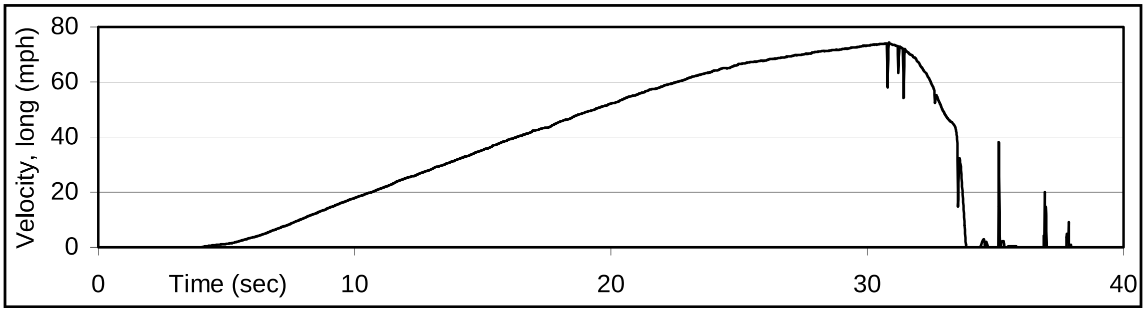
2 SAE Surface Vehicle Recommended Practice, Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks, SAE J266.

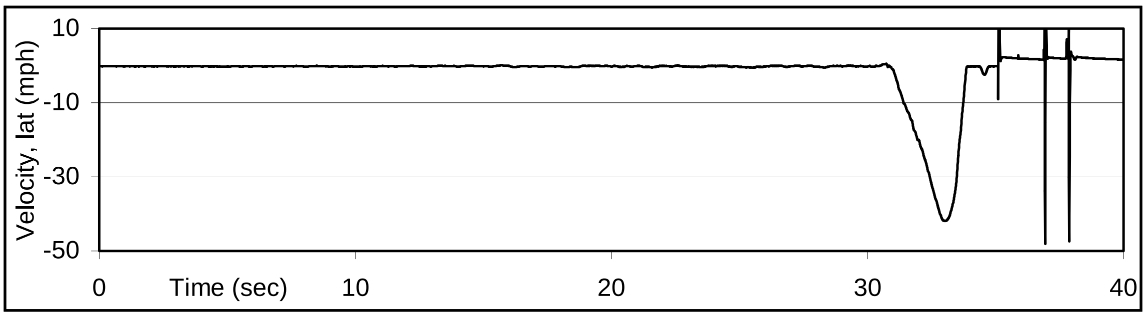
3 Dickerson, Charlie, Arndt, Mark W. and Arndt, Stephen M., Vehicle Handling with Tire Tread Separation, SAE Paper No. 1999-01-0450, 1999.

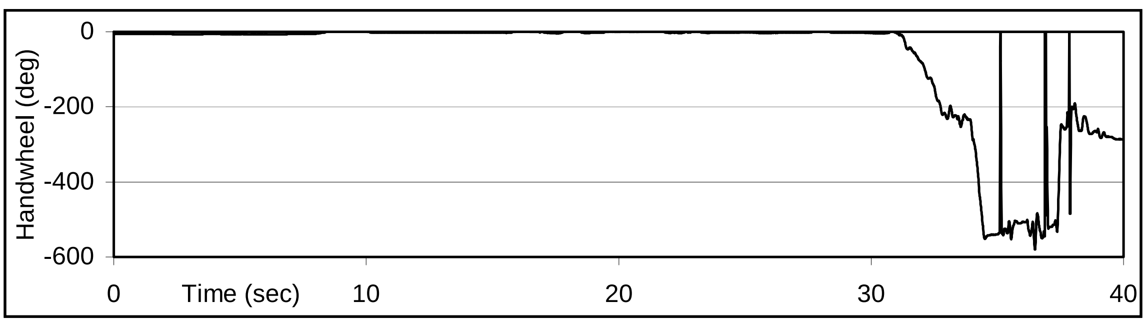
4 Arndt, Mark W., Rosenfield, Michael J., Arndt, Stephen M., and Stevens, Don C., Force Response During Tire Tread Detachment Event, SAE Paper 2004-01-1075, SAE International Congress, March 2004.

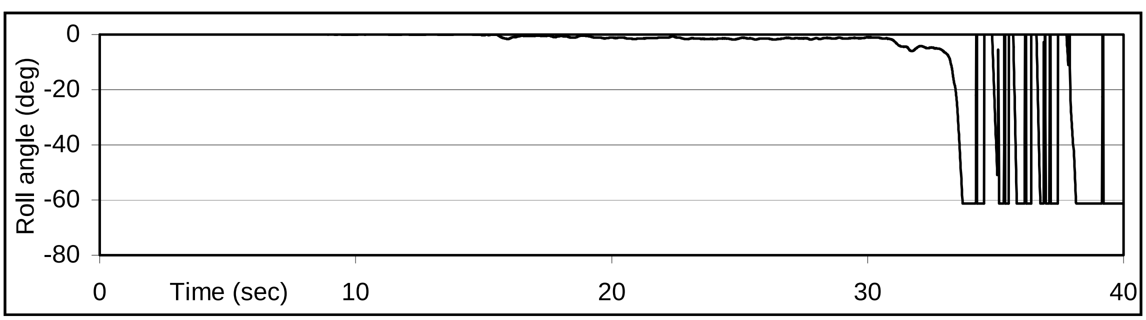
5 Arndt, Mark W., Rosenfield, Michael J. and Arndt, Stephen M., Measurement of Changes to Vehicle Handling Due To Tread Separation Induced Axle Tramp, SAE Paper 2006-01-1680 SAE International Congress, April 2006.

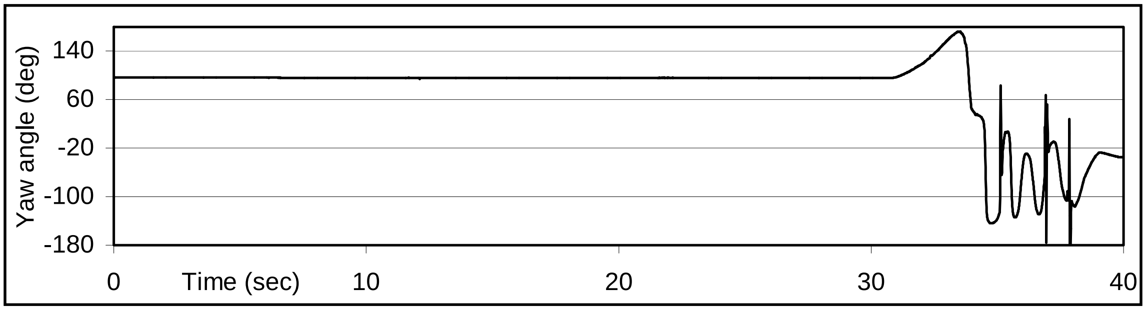
APPENDIX A, Test Data – Start to End







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Time (sec)
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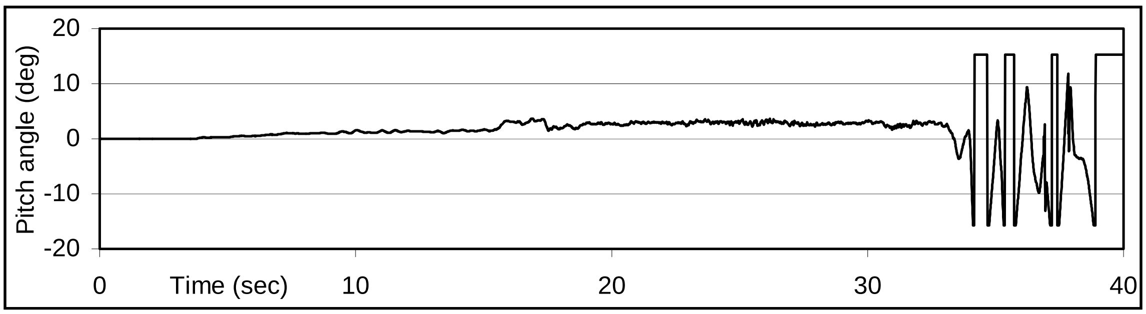
20
30
40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-20
0
Time (sec)
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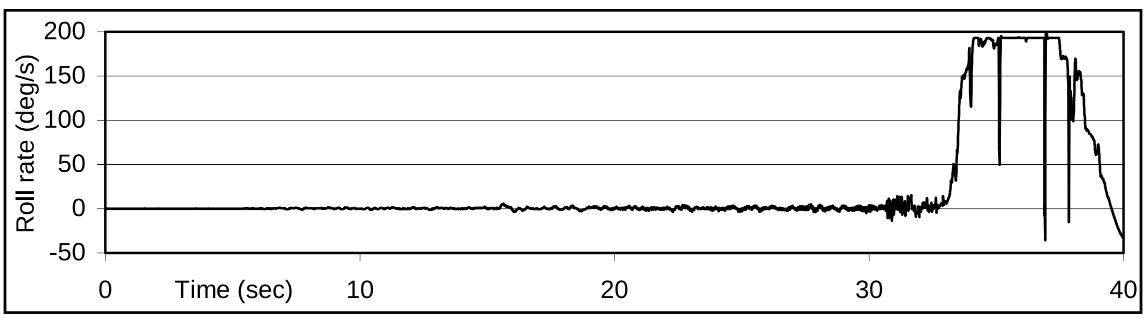
20
30
40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-50
0
Time (sec)
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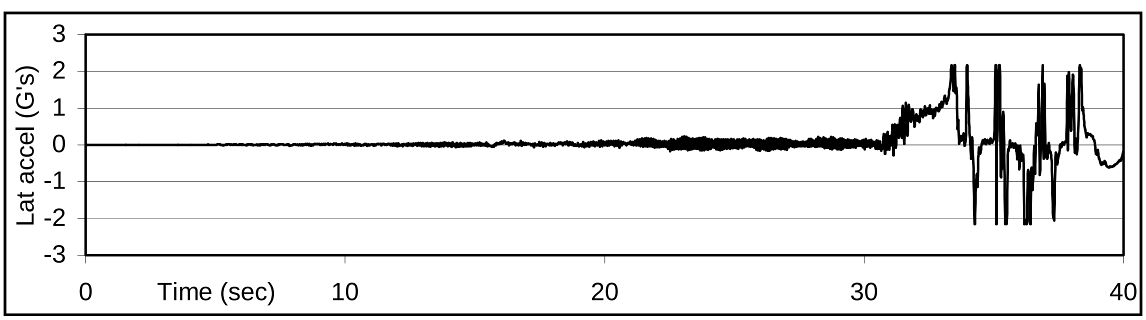
20
30
40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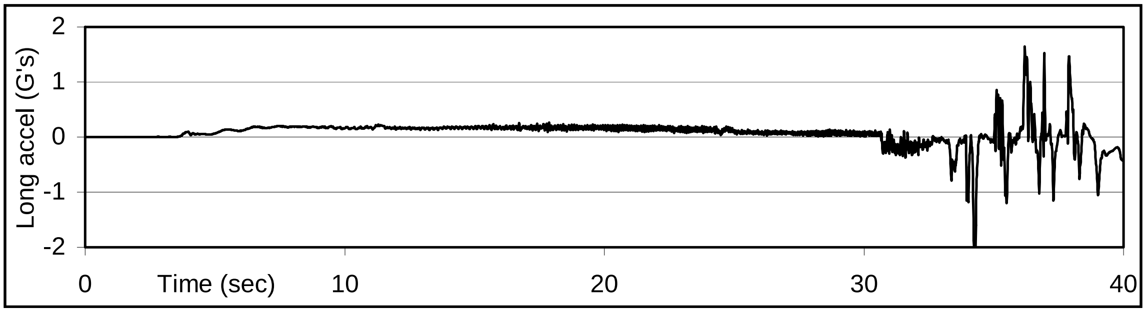
-2
-3
0
Time (sec)
10
20
30
40


Long accel (G's)
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-2
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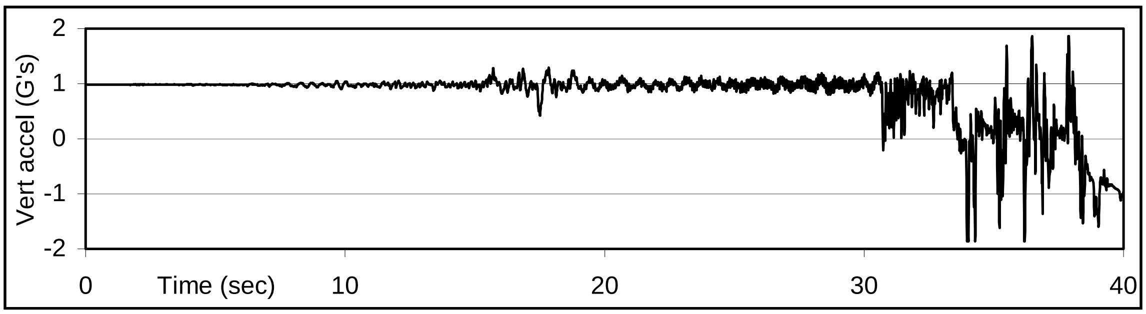
Time (sec)
10
20
30
40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0
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0
Time (sec)
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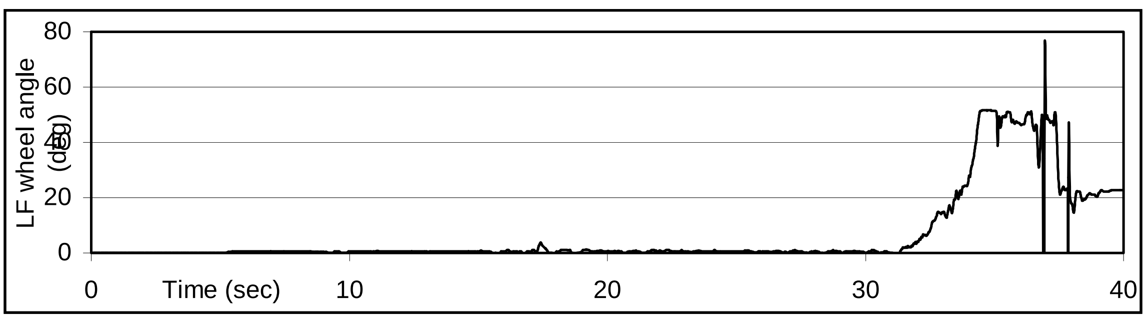
20
30
40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40
20
0
0
Time (sec)
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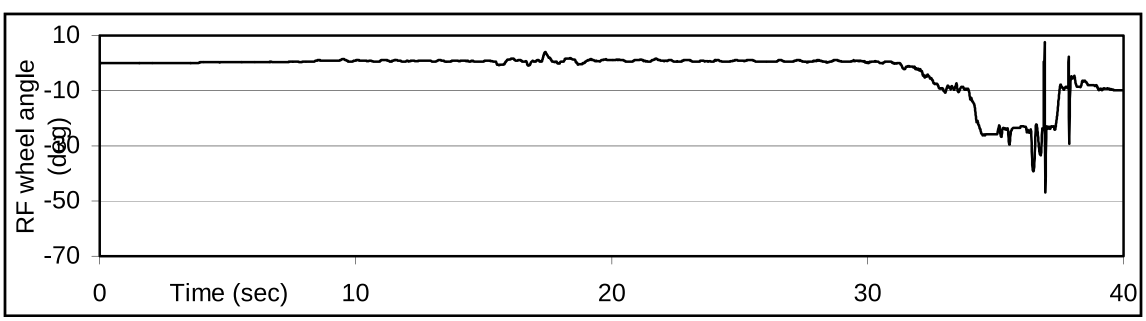
20
30
40


RF wheel angle (deg)
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-30
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-70
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Time (sec)
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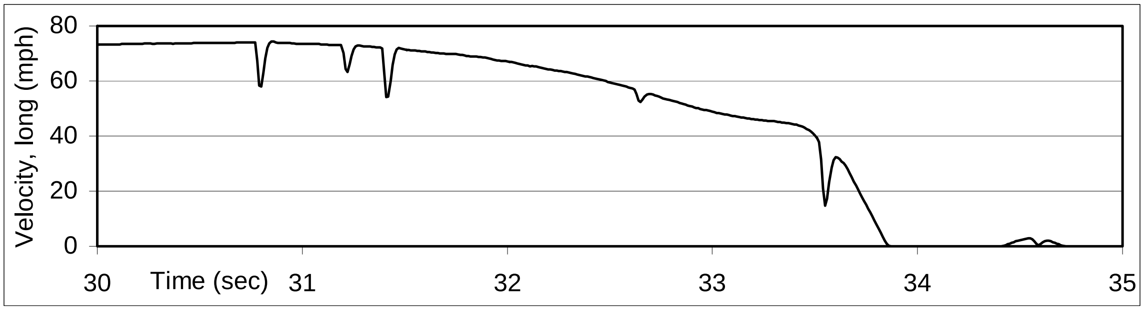
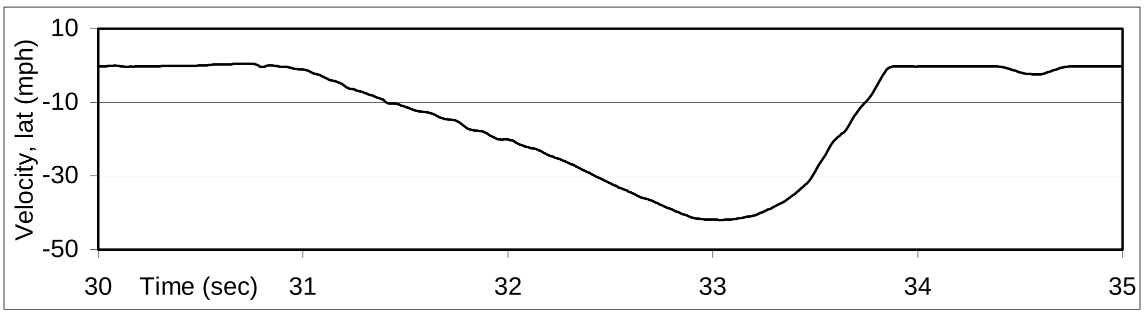
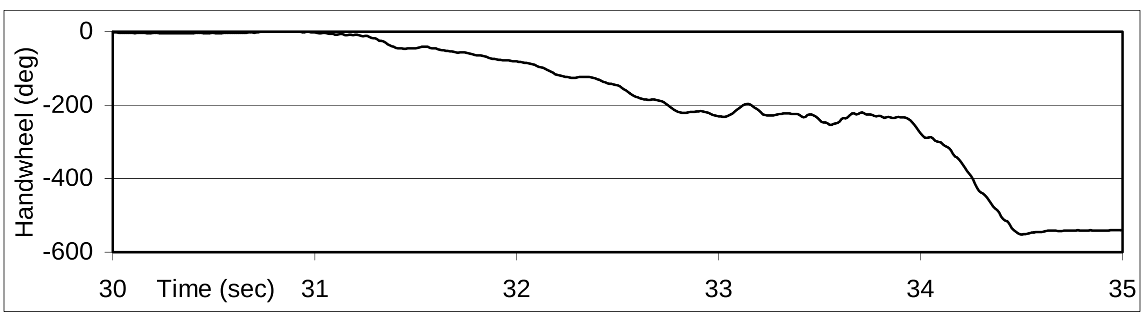
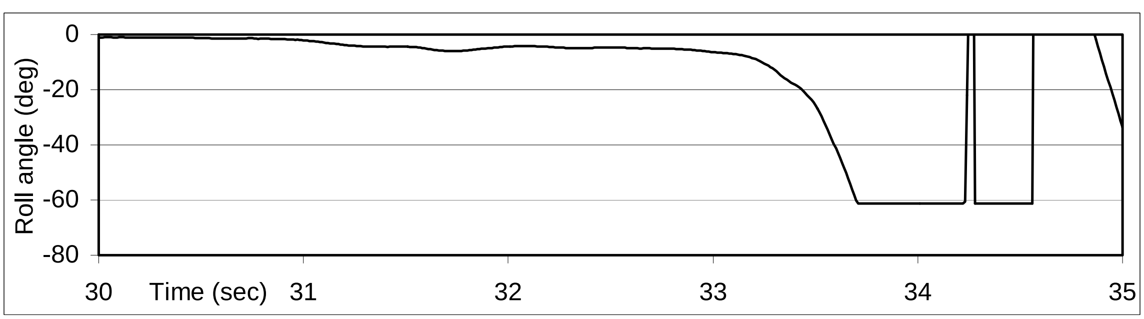
20
30
40

Test Data – Start of Tread Detachment to Rollover










Yaw angle (deg)
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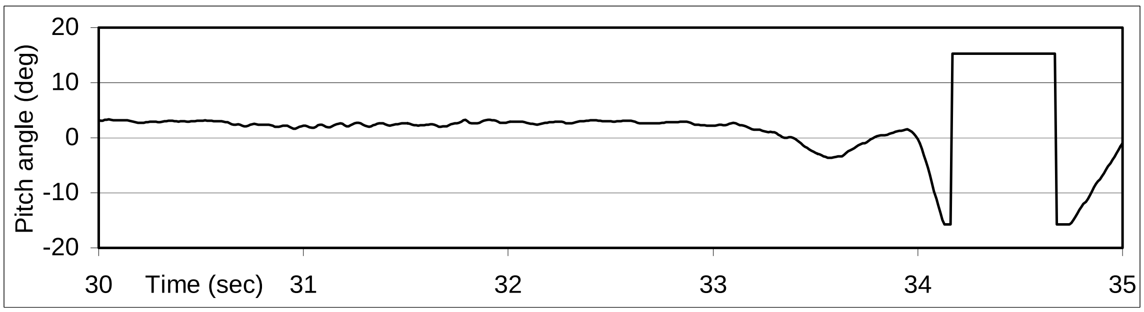
130
110
90
30
Time (sec)
31
32
33
34
35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Time (sec)
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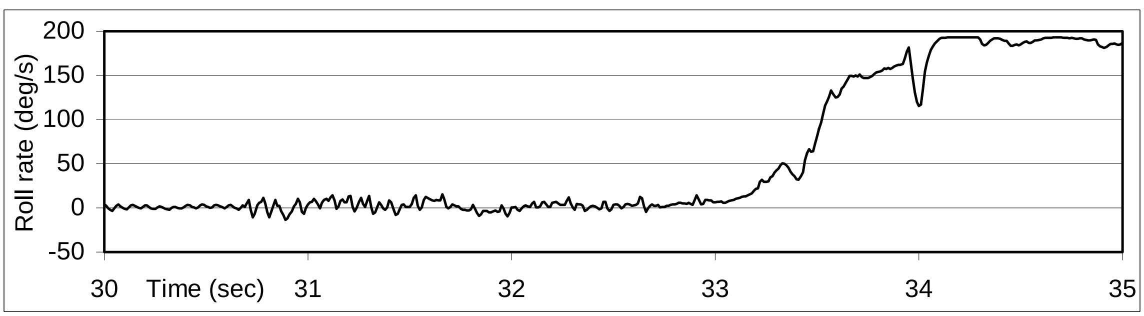
34
35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Time (sec)
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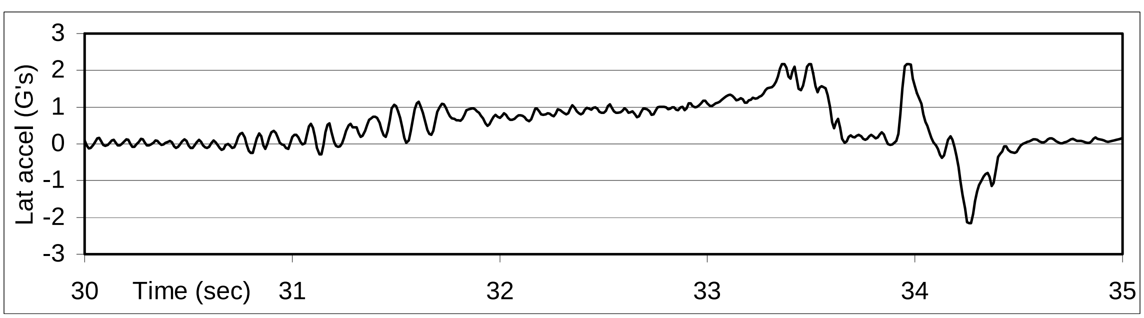
32
33
34
35


Lat accel (G's)
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Time (sec)
31
32
33
34
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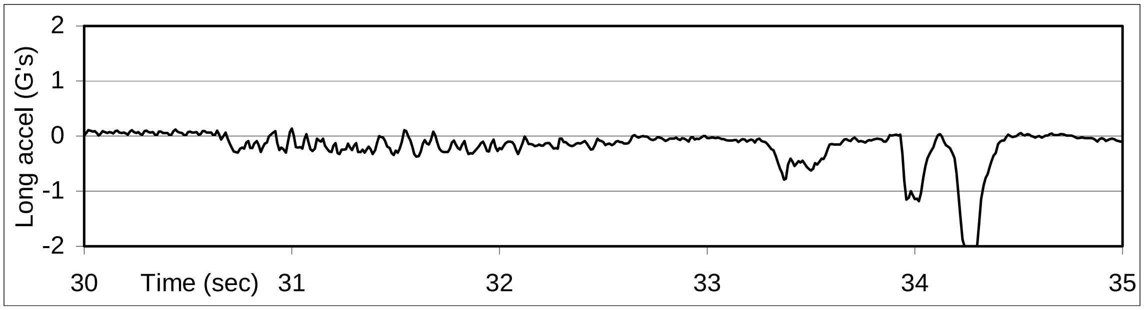

Long accel (G's)
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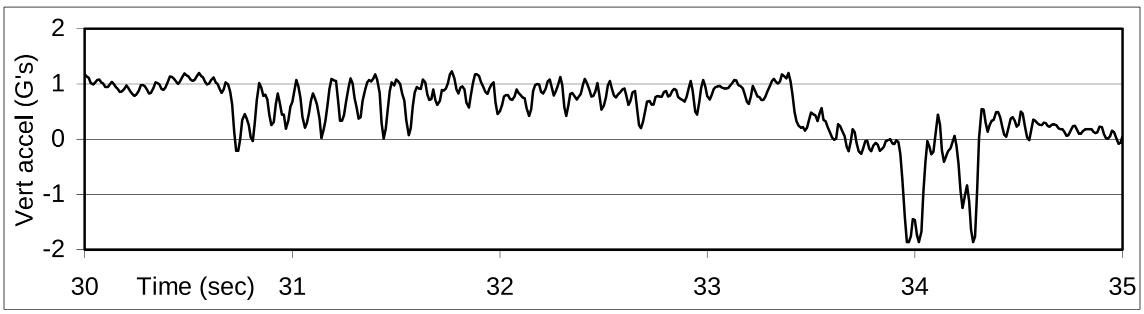
1
0
-1
-2
30
Time (sec)
31
32
33
34
35



Vert accel (G's)
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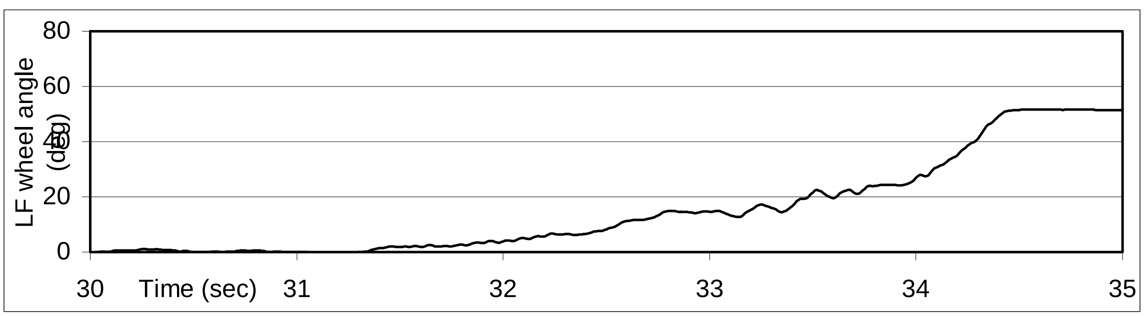
1
0
-1
-2
30
Time (sec)
31
32
33
34
35



LF wheel angle (deg)
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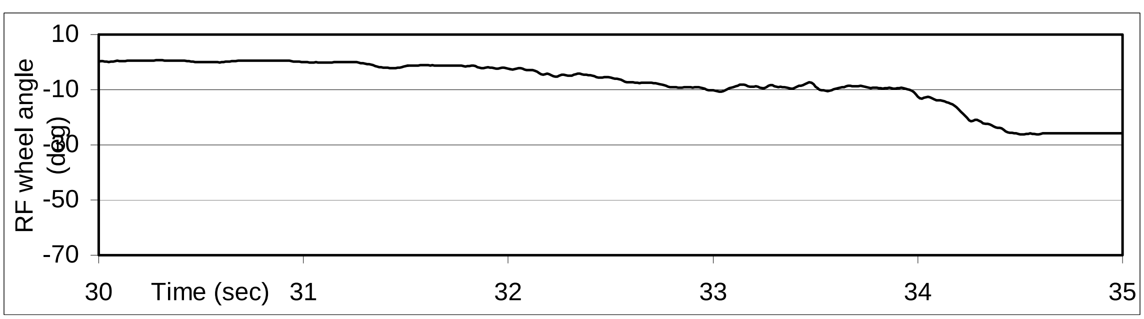
60
40
20
0
30
Time (sec)
31
32
33
34
35



RF wheel angle (deg)
10
-10
-30
-50
-70
30
Time (sec)
31
32
33
34
35

Diagram of Tire Marks and Other Vehicle Marking

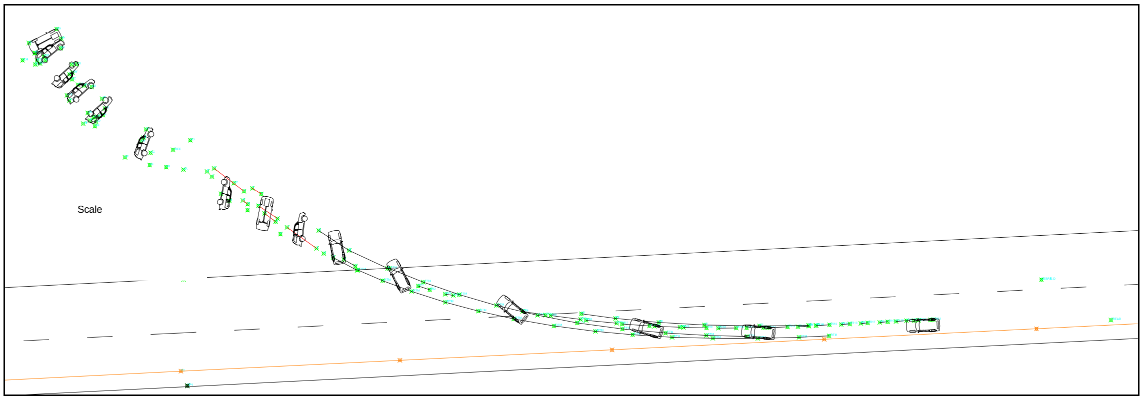


Diagram 1. Overall scene

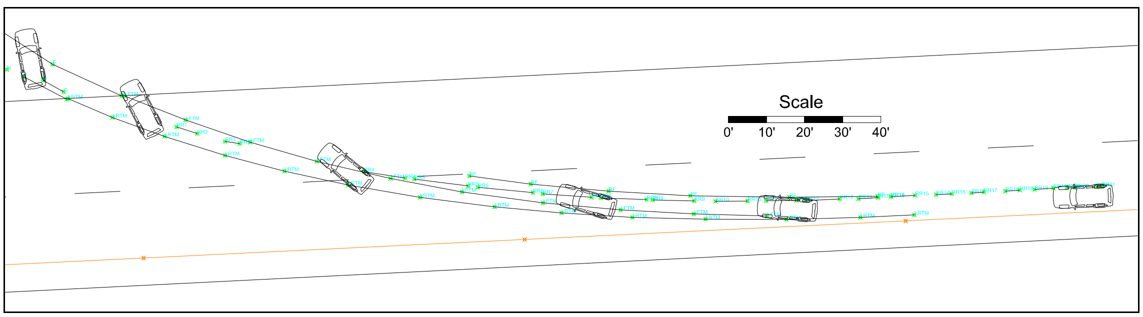


Diagram 2. Pre rollover

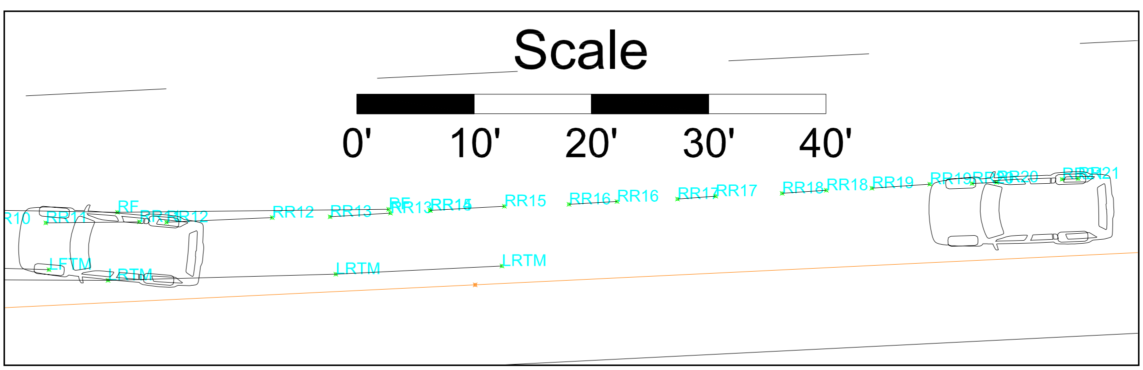


Diagram 3. Axle tramp induced tire marking

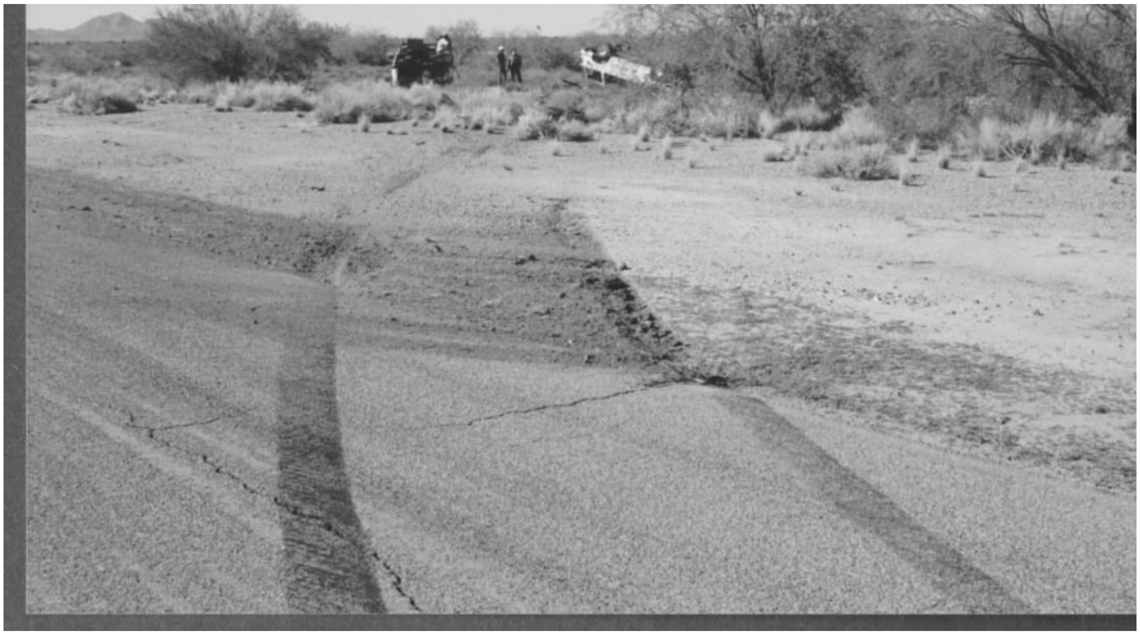
Photographs of Tire Marks

Photograph 1. Start of hopping right rear tire marks

Photograph 2. Hopping rear tire marks

Photograph 3. Hopping rear tire marks

Photograph 4. Hopping/wavy rear tire marks



Photograph 5. Left tire marks, hopping not present

Photograph 6. Tire at point of rest

Test Milestones

Milestone	Time (sec)	Zeroed Time (sec)	Speed (mph)	Steering Wheel Angle (deg)	Long Velocity (mph)	Lateral Velocity (mph)	Slip Angle (deg)	Roll Rate (deg/sec)	Roll Angle (deg)	Yaw Rate (deg/sec)	Yaw Angle (deg)	Pitch Angle (deg)	Long Accel. (g)	Lateral Accel. (g)	Vertical Accel. (g)
Event Start	0.00	-30.65	0.04	-4.09	0.04	0.00	-4.66	-0.01	-0.01	0.00	0.90	-0.01	0.00	0.00	0.00
Speed Reaches 10 mph	7.82	-22.83	10.02	-4.44	10.02	0.11	0.63	0.49	0.05	-0.88	0.02	0.95	0.20	0.01	-0.01
Speed Reaches 20 mph	10.61	-20.04	20.04	-0.59	20.04	0.02	0.06	0.49	-0.10	0.00	0.37	1.10	0.17	0.00	-0.02
Speed Reaches 30 mph	13.43	-17.22	30.00	-0.24	30.00	0.07	0.14	0.59	-0.31	0.00	0.37	1.02	0.17	0.00	-0.01
Speed Reaches 40 mph	16.26	-14.39	40.02	2.21	40.02	-0.21	-0.30	-0.01	-1.14	0.88	0.20	2.93	0.18	0.04	-0.03
Speed Reaches 50 mph	19.30	-11.35	50.03	-0.59	50.03	0.09	0.10	2.52	-1.38	-0.88	0.02	2.66	0.18	0.00	-0.01
Speed Reaches 60 mph	22.52	-8.13	60.04	-0.94	60.04	0.10	0.09	2.72	-1.35	-0.88	0.20	2.89	0.16	0.01	-0.02
Speed Reaches 70 mph	27.31	-3.34	70.01	-0.24	70.01	0.05	0.04	0.39	-1.71	0.00	0.02	2.83	0.08	0.03	-0.01
Tread Separation Event Initiation	30.65	0.00	74.05	-1.64	74.05	0.50	0.39	-0.82	-1.83	-0.88	-0.16	2.43	0.06	0.01	0.01
Counter Steer by Driver Exceeds 5 degrees	31.07	0.42	73.72	-5.13	73.68	-2.34	-1.82	5.55	-2.94	10.62	2.50	2.23	-0.11	0.02	-0.38
One Second Event Duration	31.65	1.00	72.05	-50.92	70.79	-13.46	-10.76	8.38	-6.05	21.24	14.35	2.19	-0.21	0.44	-0.26
Body Slip Angle Exceeds 15 degrees	31.91	1.26	71.38	-75.39	68.87	-18.78	-15.25	-3.86	-5.24	23.89	20.37	3.24	-0.19	0.64	-0.23
Roll Angle Starts Increasing Continuously (leaves pavement)	32.80	2.15	66.64	-217.29	54.09	-38.94	-35.75	3.63	-5.45	43.36	52.93	2.83	-0.10	0.83	-0.31
Counter Steer Reaches 220 degrees	32.82	2.17	66.67	-220.09	53.76	-39.43	-36.26	5.65	-5.54	44.24	53.62	2.83	-0.10	0.83	-0.30
Outrigger Contact	33.33	2.68	59.42	-221.13	46.23	-37.33	-38.92	50.58	-14.98	34.51	73.46	0.33	-0.08	1.09	-0.29
Roll Angle Exceeds 45 degrees	33.62	2.97	N/A	-233.37	N/A	N/A	N/A	135.28	-45.03	-17.70	72.40	-3.37	-0.34	1.17	-0.74
Explorer Comes to Rest (3-1/2 to 4-1/2 rolls)	39.00	8.35	0.00	-259.93	0.00	0.00	0.00	0.00	N/A	0.00	N/A	N/A	0.00	0.00	-1.00

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