THE INFLUENCE OF A REAR TIRE TREAD SEPARATION ON A VEHICLE'S STABILITY AND CONTROL

Stephen M. Arndt
Safety Engineering And Forensic Analysis, Inc.
Mark W. Arndt
Transportation Safety Technologies, Inc.
United States
Paper Number 258

ABSTRACT

A series of open loop tests was conducted on three vehicles instrumented per SAE J266 to determine the effect of a rear tire tread separation on the vehicles' behavior. The vehicles tested were a 1989 Ford Bronco II, a 1996 Ford Explorer, and a 1993 Ford Taurus. The tests were categorized as tread separation event tests and tread-separated tests. The tread separation event tests were designed to determine how the vehicle responds as the tread is separating from the tire carcass at speeds ranging from 58-119 km/h (36-74 mph). Tires were prepared in a manner that would initiate either a complete or partial separation of the tread. The vehicle was driven on a straight path with the steering wheel held fixed as the tread came off. The tread-separated tests were run on vehicles where the tread was removed from one of the rear tires. The maneuvers conducted were circle turns per SAE J266 (constant radius and constant steer) and step steer turns. These tests were run to evaluate the steady state and dynamic oversteer/understeer characteristics of the vehicles.

The results of the tread separation event tests demonstrate that the vehicle's response is dependent on speed, duration, and the nature of the separation event. The vehicle responds by pulling to the side of the tread-separating tire. The longer the tread takes to come off, the greater the vehicle response. Once the tread had separated, the vehicle's response to the event ceased. Partial tread separations result in a significant vehicle response due to the continuous duration of the event. Higher speeds result in a greater vehicle response. The tread-separated tests show that the vehicles oversteer when the tread-separated tire is on the outside of the steering maneuver resulting in vehicle spinout. The vehicles transition to a steady state oversteer behavior at lateral acceleration levels of approximately 0.2 g.

INTRODUCTION

The reporting in the news media of consumer problems, including crashes, caused by catastrophic tire failures [tread separation events] has been increasing. The reports indicate that the vehicles are extremely difficult to control and that crashes are occurring in increasing numbers. Investigations of crashes and experimental testing have shown that the control problems clearly appear to be related to the response of the vehicle as a result of the catastrophic tire failure.

STATEMENT OF THE PROBLEM

Tire tread separation is a class of tire disablement that has not received attention over the years. This class of tire disablement typically has been lumped into the larger group of tire disablements labeled as flat tires and blowouts even though loss of air may not occur during a tire tread separation event. There is very little statistical data specifically about tire tread separations. Consequently, minimal testing has occurred to evaluate the effects of a tire tread separation on a vehicle's response, stability, and handling characteristics.

Some data that has been published recently represents "Closed Loop" tests evaluating whether a driver who has knowledge of the impending tread separation can control the vehicle. [1,2] This type of data is subjective in nature. "Open Loop" tests (such as those presented in this paper) remove the driver's influence from the outcome allowing an objective analysis of the result. Data from a series of open loop tests conducted on a Bronco II has recently been published providing an objective view of a vehicle's behavior during and after a tread separation event. [3]

Additional data, like that developed for the Bronco II, which spans across classes of vehicles is necessary to better understand the potential hazards associated with a tire tread separation event on all vehicles.

HYPOTHESIS

It had been shown through previously published work that a Bronco II (small Sport Utility Vehicle) would respond to a tread separation event by deviating from its original heading toward the side of the tread-separated tire. It was hypothesized that the heading change was a result of the tire tread interaction with the wheel well and surrounding structure. This was thought to create drag at this wheel position which in turn would generate a yaw moment that produced the heading change. The duration or time that it takes the tread to completely separate from the carcass of the tire was also believed to influence the heading angle change due to the magnitude of the impulse resulting from the drag. It was further hypothesized that these basic physics were present on all vehicles that experienced a tire tread separation.

SCOPE OF RESEARCH

A series of "Open Loop" tests was conducted to evaluate the behavior of two classes of vehicles while the tire's tread was separating (Tread Separation Event Tests) and after the tire tread had separated (Tread-Separated Tests). The types of tests performed were consistent with test protocols previously used to evaluate a Ford Bronco II. The new data developed could be directly compared to the previous results.

Tread Separation Event Tests

These tests were conducted to evaluate the vehicle's response as the tread was coming off the carcass of the tire and interacting with the wheel well, surrounding structure, and roadway surface.

The simulated tread separation event was designed to occur with a rear tire prepared to separate under controlled test conditions. The test driver was aware of the impending tire tread separation event and the possible consequences of the event. The driver was instructed to hold the steering wheel at a fixed angle prior to, during, and after the separation event.

The vehicle's response was documented by measuring changes in the vehicle's behavior through instrumentation and videographic footage that were recorded on computer and videotape, respectively. These test results were contrasted to a "control" vehicle's behavior when equipped with four normal tires.

Tread-Separated Tests

Tests were conducted to evaluate the vehicle's handling characteristics once the tire's tread had been completely removed from the carcass of the tire.

The separated tire handling experiments documented the response of the test vehicle when an inflated tire with a completely separated tread is present on the rear of the vehicle. The experiments are designed to measure steady state and transient responses during controlled and generally accepted vehicle-handling maneuvers which included constant radius turns, constant steer turns, and step steer turns. The behavior was contrasted with a "control" vehicle's behavior when equipped with four normal tires.

Test Vehicle/Tire Selection

Two vehicles were selected for testing based on their representation across two broad categories of vehicle classes. The two classes were a full-size front wheel drive four-door sedan and a midsize four-door SUV. The vehicles selected for testing were a 1993 Ford Taurus (VIN: 1FACP52U4PG225700) and a 1996 Ford Explorer (VIN: 1FMDU32P1TUD55494). Both of these vehicles were number one in sales for the classes of car and SUV respectively during the model year tested. Additionally, these two vehicles have remained at the top or very near the top in sales for the ten-year period beginning in 1991 through the present. Table 1 shows the sales ranking for these two vehicles over this time period. [4]

Table 1.
Sales Rank by Number of Vehicles Sold in the U.S.

Model Year	Taurus Sales Rank	Explorer Sales Rank
1991	2	1*
1992	1	1
1993	1	1
1994	1	1
1995	1	1
1996	1	1
1997	3	1
1998	3	1
1999	3	1
2000	3	1

* Data tabulated for Explorer/Bronco II during 1991

The tires evaluated were Original Equipment Manufacturers make, model, and size for each of the respective vehicles. The tires tested on the Explorer were Firestone ATX P235/75R15SL on 15 X 7.0 J rims. Two different tires were evaluated on the Taurus. These were the OEM tires that came on a 1993 Ford Taurus and its replacement (next generation) tire that was the OEM tire on later model years. The OEM tire that came on the 1993 Taurus was a General Ameri Tech ST P205/65R15 on 15 X 6 rims, and the replacement tire was a General Ameri G4S P205/65R15 on 15 X 6 rims.

Used General Ameritech ST tires were evaluated because they were no longer manufactured at the time the tests were conducted and could not be purchased new. All other tires tested were purchased new from a tire dealership.

Information about the Bronco II and its tires can be found in reference 3.

The Test vehicles utilized in the recent work are shown in Figures 1 and 2.

Vehicle Preparation

The test vehicles were prepared with the goal of minimizing any changes to the weight of the vehicle. Instrumentation and safety equipment were mounted as close to the center of gravity as possible. In some cases, original equipment was removed to compensate for the weight of items that were added. All modifications and test vehicle weights were documented.

Figure 1. 1993 Ford Taurus.

Figure 2. 1996 Ford Explorer.

<u>Instrumentation:</u> The following instrumentation was added to both test vehicles:

- Tri-axial accelerometer (three channels)
- Longitudinal/Lateral velocity sensor (Datron) (two channels)
- Gyro Pack (pitch/yaw/roll position and roll rate) (four channels)
- Steering wheel angle (one channel)
- Right & Left front wheel angles (two channels)

<u>Safety Equipment:</u> The following safety equipment was added to the SUV: 4-point restraint, roll cage, and outriggers.

In addition to adding instrumentation and safety equipment, the following inspections and procedures were performed on each test vehicle:

<u>Frame Inspection:</u> This was done to insure that the test vehicles had no prior collision damage and that the frame was within manufacturer's original specifications.

<u>Tune-up:</u> Work included replacing spark plugs and spark plug wires as necessary, checking all of the fluids and flushing/replacing where necessary, and a complete safety inspection including brakes.

<u>Front and Rear Alignment:</u> This included an inspection of the front and rear suspension to insure that all components were OEM. It also included the replacement of all four shocks, and replacement of any worn bushings.

<u>Tire Modification:</u> The tires utilized during the tread separation event tests were cut in a manner that would result in the tread separating at a target speed in excess of 89 km/h (55 mph). This was accomplished by cutting the tire between the steel belts from both the inboard and outboard tread block a specified distance across the tread and over a specified percentage of the circumference (Figure 3).

Figure 3. Tire Prep for Tread Separation Simulation.

The width and length of the cut was varied based on the desired tread separation failure mode (complete or partial separation, inboard or outboard failure direction). The tire tread was then scored at an angle that matched the direction of the outer steel belt. The depth of the scoring was only to the level of the outer steel belt. A one-inch initiation cut through the tread and outer steel belt was then made on the leading edge of the scoring. The cut between the two steel belts was made completely across the width of the tire underneath the scored area.

TEST METHODOLOGY

The methodology used is consistent with the procedures developed in prior experimental test programs as reported in published manuscripts, SAE papers 1999-01-0499 and 1999-01-0120.

Tread Separation Event Tests

The experiment was conducted by preparing one of the rear tires on the subject vehicle to experience a simulated tire tread separation while the vehicle was being operated on a straight**,** flat asphalt surface at highway speeds. The steering wheel was held in a fixed position during the separation event. The steering was held fixed as long as possible during and after the separation event with countersteer input only to keep the vehicle from leaving the paved test surface.

Tread-Separated Tire Tests

<u>Steady State Behavior:</u> This experiment is designed to measure the understeer or oversteer characteristics of the vehicle. The test was conducted per SAE J266, Method 1 (Constant Radius Test) and Method 2 (Constant Steering Wheel Angle Test). The Constant Radius Test was performed on a 30 m radius circle. The continuous test procedure was employed. This requires that the vehicle begin from a stop and slowly accelerate at less than 1.5 km/h/sec to the maximum speed attainable. The driver must steer the vehicle on the 30 m radius circle plus or minus 0.5 m.

The constant steer angle test method requires that the driver hold a fixed steering wheel angle and accelerate the vehicle from a stop up to the maximum speed attainable. The test was run at a steering wheel angle that produces approximately a 20 m radius turn at low speed.

Tests were run with the test vehicle equipped with four good tires (in a control condition) and with a tread-separated tire on a rear wheel position. Tests were run in both directions for both the constant radius test and the constant steer test (with a tire at the outboard and inboard rear).

<u>Transient Behavior:</u> Step steer (J-turn) tests were performed to evaluate the transient response of the test vehicle. The tests were run at speeds of 40, 56, and 72 km/h with step input to the steering wheel of 180 degrees. The test vehicle was accelerated to the test speed, the throttle was modulated to hold the test speed at steady state, upon passing the start gate the throttle was disengaged, and the steer input was rapidly applied (>500 degrees/sec). The steering wheel angle was held fixed until the vehicle reached a steady state condition for a minimum of 5 seconds. Tests were run with the test vehicle equipped with four good tires (in a control condition) and with a tread-separated tire on a rear wheel position. Tests were run in both directions (with a tire at the outboard and inboard rear).

TEST RESULTS

Tread Separation Event Testing

All three test vehicles (including the Ford Bronco II from previous work) demonstrated a similar behavior in response to the tire tread separation event. The vehicles would experience a deviation in path to the side of the vehicle on which the tread was separating. Both the Bronco II and Explorer were evaluated with the tread separation event occurring on the right rear of the vehicle. Both of these vehicles had path deviations to the right as the tread was coming off. The Taurus was evaluated with a left rear tread separation event and experienced a path deviation to the left.

<u>Duration of the Tread Separation Event:</u> Data from the Taurus and Explorer Tread Separation Event tests has been provided in Figures 4-8 and Figures 9-13 respectively. The four Taurus tests shown in the figures represent short, long, and partial (continuous) tread separation events at highway speeds in excess of 103-km/h and a partial tread separation event at a much lower speed (LS Partial) of 58 km/h. The two Explorer tests shown represent a short and a partial tread separation event at highway speeds in excess of 118 km/h. All of the data has been time adjusted so that the tread separation event occurs at 0.0 seconds on the plots.

It was found that the time that it takes the tread to separate from the carcass of the tire directly impacted the path deviation of the test vehicle. The duration of the tread separation event was defined by the time the tread began to peel away from the carcass of the tire until it was no longer attached to the carcass of the tire. This is observed in acceleration data (Figures 7 & 12) as a sudden increase in data trace amplitude. Once the tread had completely separated, the date trace would smooth out. This was physically felt and heard by the test driver. Additionally, once the tread had separated, the vehicle's response to the event ceased.

The effect of the separation duration was most dramatically illustrated when comparing complete separations to partial separations. A partial separation is defined as one where part of the tread peels off the carcass of the tire and the remainder stays affixed. The majority of the partial separations experienced during the test series resulted in 50 percent of the tire tread separating and 50 percent remaining attached.

In general, all three evaluated vehicles demonstrated a similar relationship between event duration and path deviation. When the duration of the event was quick, the path deviation was small. When the duration of the event was long, the path deviation became much more dramatic. Partial (continuous) separation produced the most significant vehicle disturbances. The range of vehicle responses is a continuum from minor responses resulting from quick separations to critically destabilizing responses resulting from partial separations.

Speed Effects During a Tread Separation Event: The magnitude of the vehicle's path deviation increased as the speed of the vehicle at the time of the tread separation increased. This can best be seen in Figures 4-8 by comparing the two partial separation events. The speeds of the two events were 58 km/h and 105 km/h. There was no measurable path deviation during the low speed partial separation. The path deviation during the high-speed partial separation was the greatest in magnitude for all of the Taurus test runs.

Several low speed complete tread separations occurred during the course of the Taurus test series. The general trend of greater path deviation with greater speed held true for both complete and partial separations.

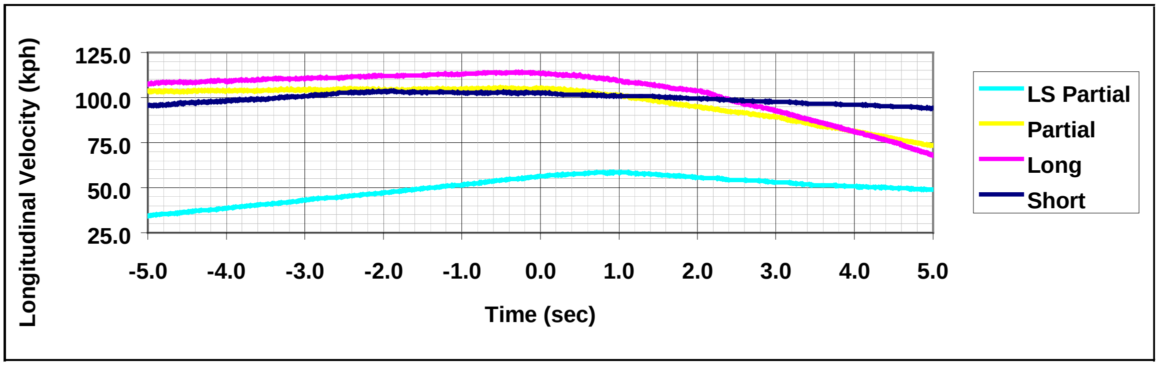

Figure 4. 1993 Ford Taurus Tread Separation Event Test, Longitudinal Velocity.

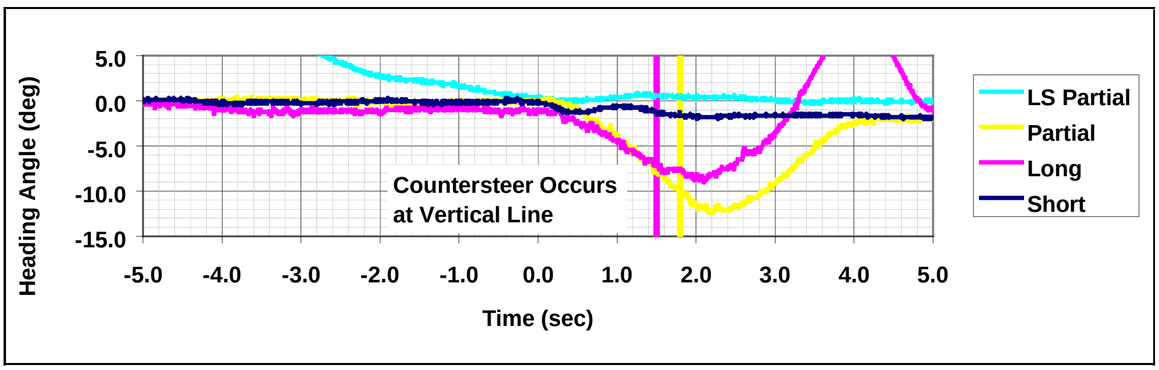

Figure 5. 1993 Ford Taurus Tread Separation Event Test, Heading Angle.

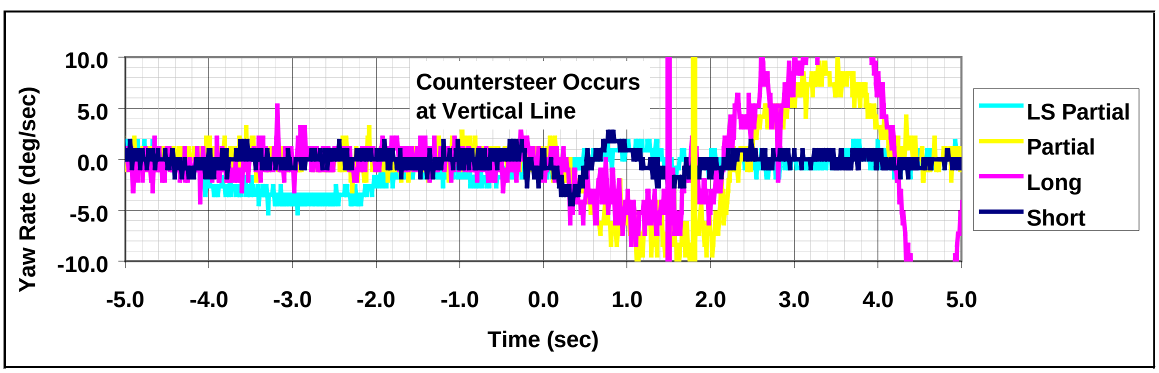

Figure 6. 1993 Ford Taurus Tread Separation Event Test, Yaw Rate.

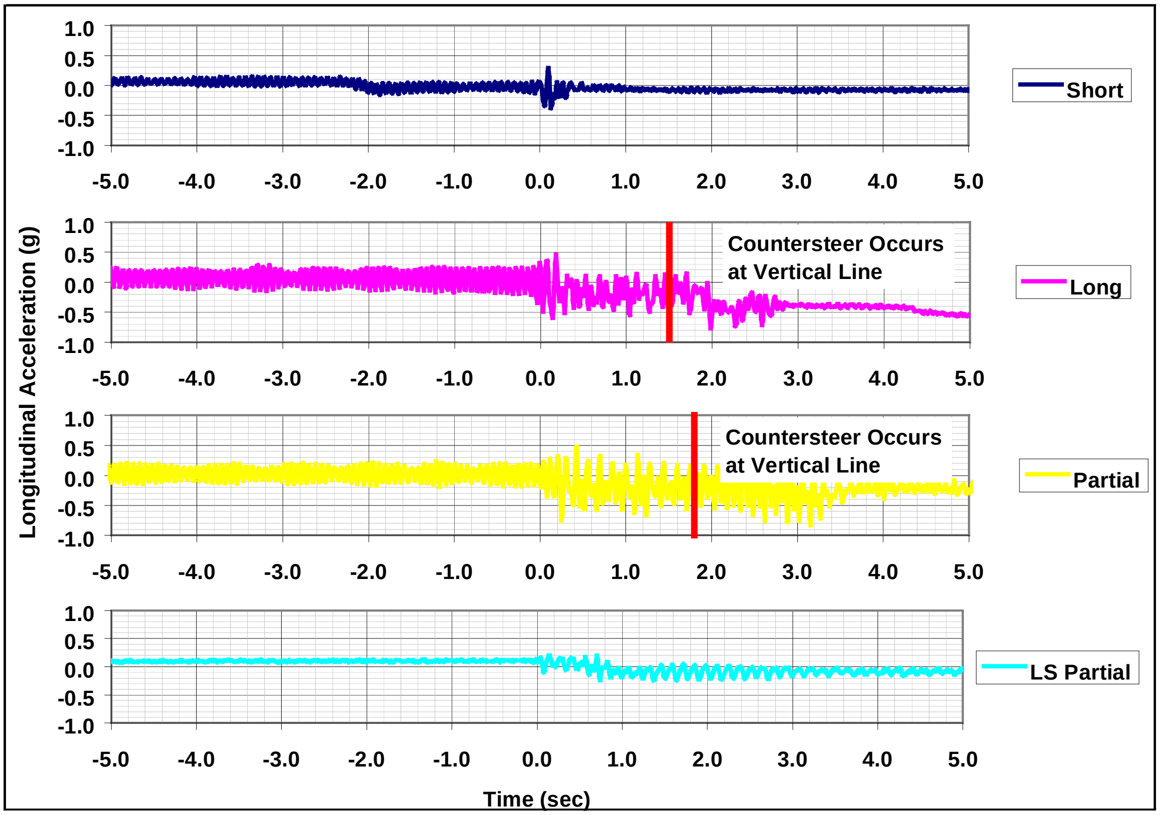

Figure 7. 1993 Ford Taurus Tread Separation Event Test, Longitudinal Acceleration.

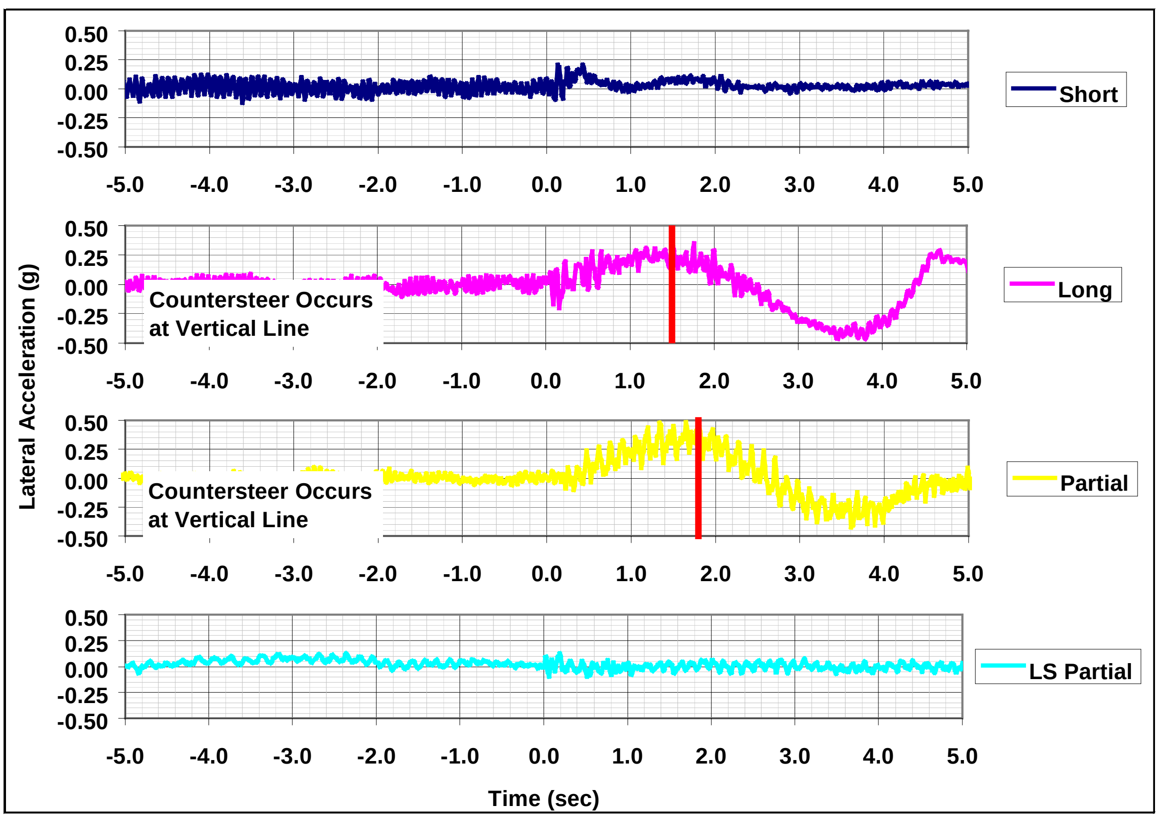

Figure 8. 1993 Ford Taurus Tread Separation Event Test, Lateral Acceleration.

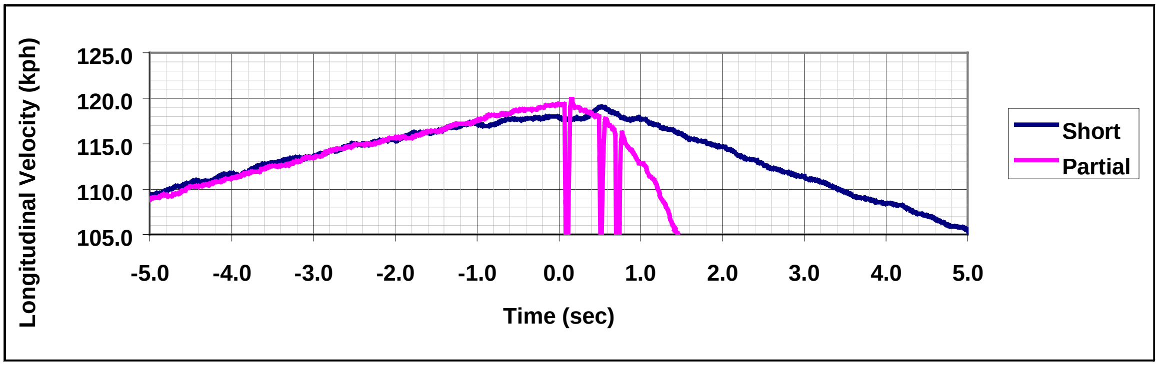

Figure 9. 1996 Ford Explorer Tread Separation Event Test, Longitudinal Velocity.

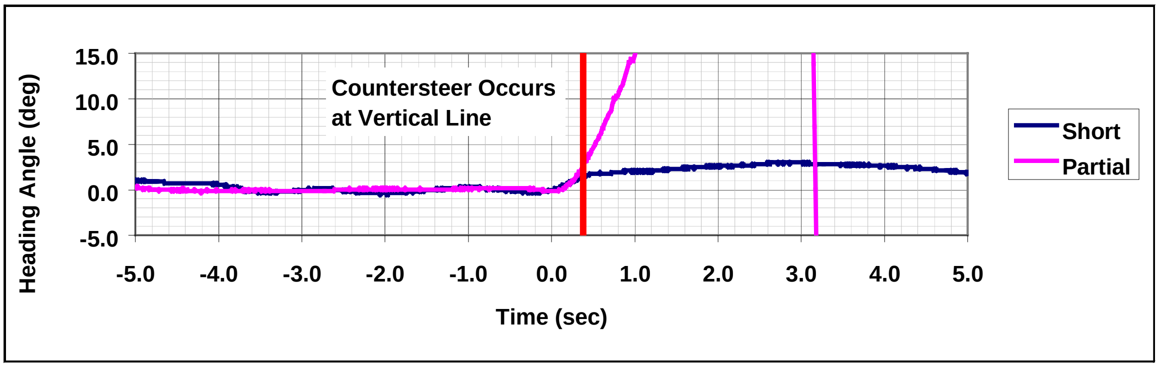

Figure 10. 1996 Ford Explorer Tread Separation Event Test, Heading Angle.

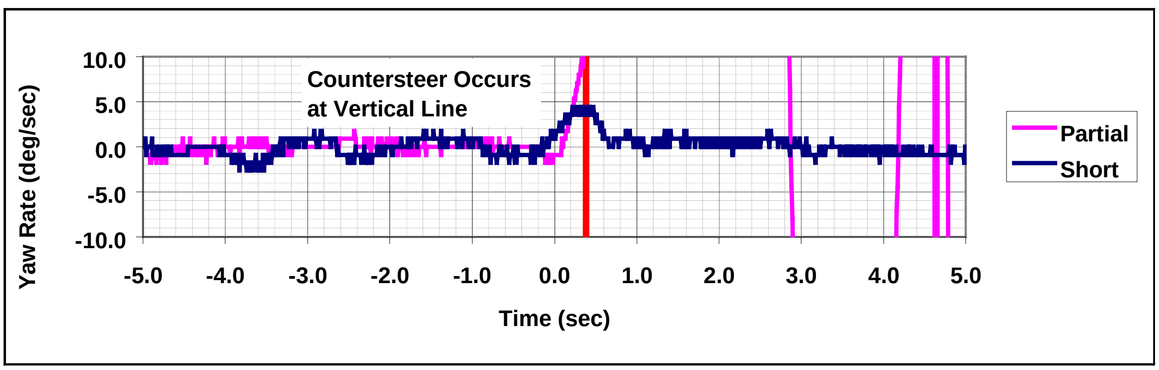

Figure 11. 1996 Ford Explorer Tread Separation Event Test, Yaw Rate.

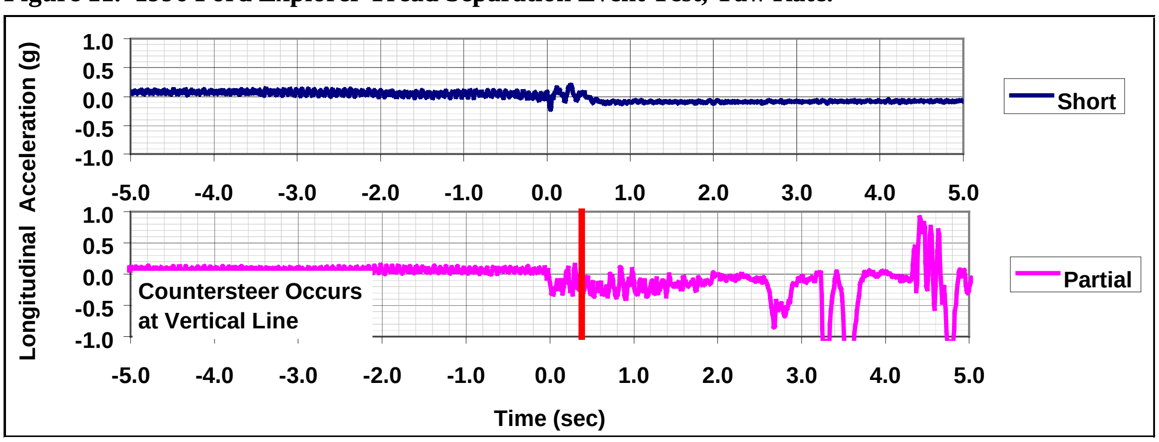

Figure 12. 1996 Ford Explorer Tread Separation Event Test, Longitudinal Acceleration.

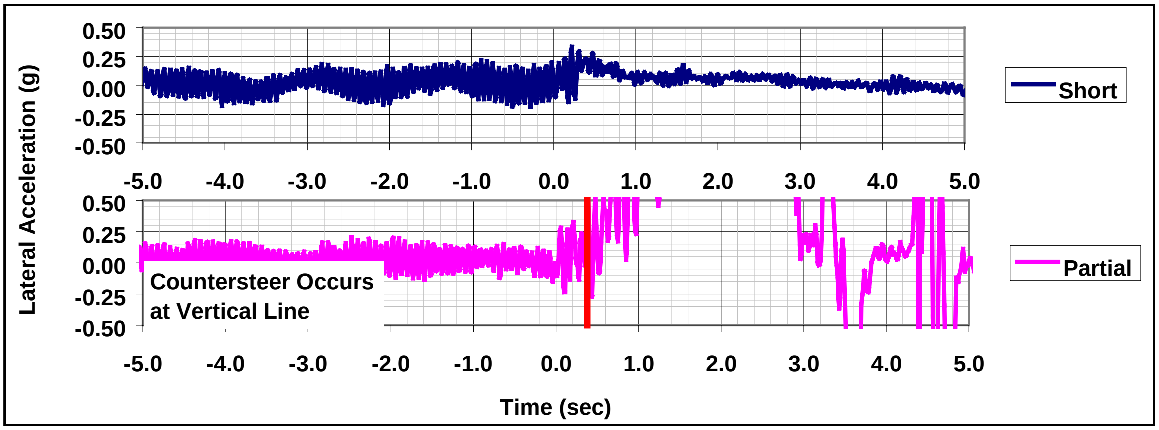

Figure 13. 1996 Ford Explorer Tread Separation Event Test, Lateral Acceleration.

Vehicle Class Differences: The primary difference between the classes of vehicles was the magnitude of the response. This is demonstrated by comparing the response of the Taurus to that of the Explorer during partial separations. Both vehicles experienced a significant path deviation. The test driver could redirect the Taurus heading down the road with a countersteer. The test driver could not redirect the Explorer with a countersteer. The result was that the Explorer left the paved test surface and tripped and rolled coming to rest approximately 175 ft away (Figure 14).

The loss of control during the Explorer test was unexpected. It suggests that there is more than just drag that is responsible for the change in vehicle path during a tread separation event. Drag alone could not have redirected the Explorer to the extent demonstrated during this test.

Tread-Separated Tire Tests

This type of testing has not yet been completed on the Explorer due to the rollover that occurred during the tread separation event tests. This section will report the results of the Taurus testing and contrast it with the work previously completed on the Bronco II.

Circle Turn Tests: An oversteer/understeer gradient plot is shown in Figure 15 documenting the results of the constant radius turn tests. The two curves illustrate the behavior of the Taurus with four good tires and with a tread-separated tire located at the outboard rear of the cornering maneuver. The Taurus has a typical understeer characteristic with four good tires. The vehicle behaves as an oversteering vehicle when a tread-separated tire is on the outside rear corner of the vehicle.

Figure 15 demonstrates the transition of the Taurus to an oversteer regime at a lateral acceleration of approximately 0.2g with a tread-separated tire at the outboard rear. This finding closely matches data previously reported for the Bronco II in Reference 3. The single major difference between the Bronco II results and the Taurus results was that the Bronco II would spin out at the end of the constant radius test with a tread-separated tire at the outboard rear wheel position. The Taurus was very difficult to control at the end of the runs but did not spin out. This is likely due to the front wheel drive of the Taurus.

Figure 14. Explorer at Rest Following Rollover.

A plot of the slip angle versus velocity is provided as Figure 16 for the constant steer circle turn test. This data clearly shows the dramatically different behavior of the Taurus with four good tires when compared to the same vehicle with a tread-separated tire located at the outboard rear position. The vehicle with four good tires continues to track around the turn up to the point of maximum lateral acceleration. The vehicle with a tread-separated tire at the outboard rear position records a different response across the entire range of speed and spins out at a velocity 40 percent lower than the maximum achieved with four good tires.

Step Steer (J-Turn) Tests: Tests were conducted at speeds of 40, 56, and 72 km/h. The general behavior of the vehicle at all three test speeds was similar. Data is presented for the 56 km/h tests in Figures 17-19. The data shows the vehicle response with four good tires and with a tread-separated tire at the outboard rear of the cornering maneuver. All tests were run with a steering input of 180 degrees. The data is presented with a time adjustment so that the steering input occurs at time equals 0.0 seconds.

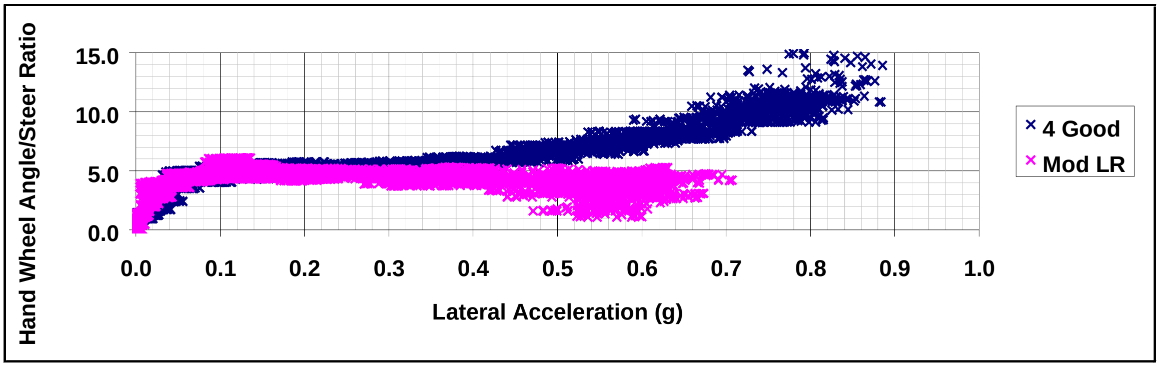

Figure 15. 1993 Ford Taurus Right Constant Radius Circle Turn, Understeer/Oversteer Gradient.

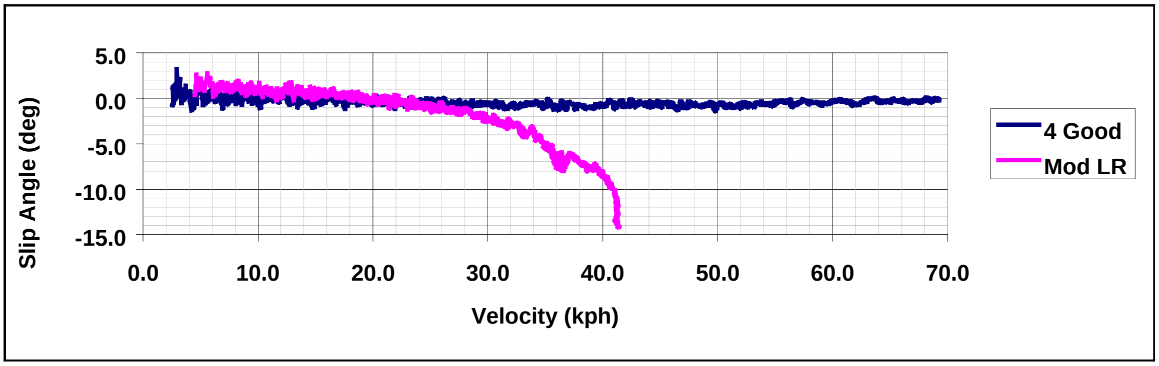

Figure 16. 1993 Ford Taurus Right Constant Steer Circle Turn, Slip Angle.

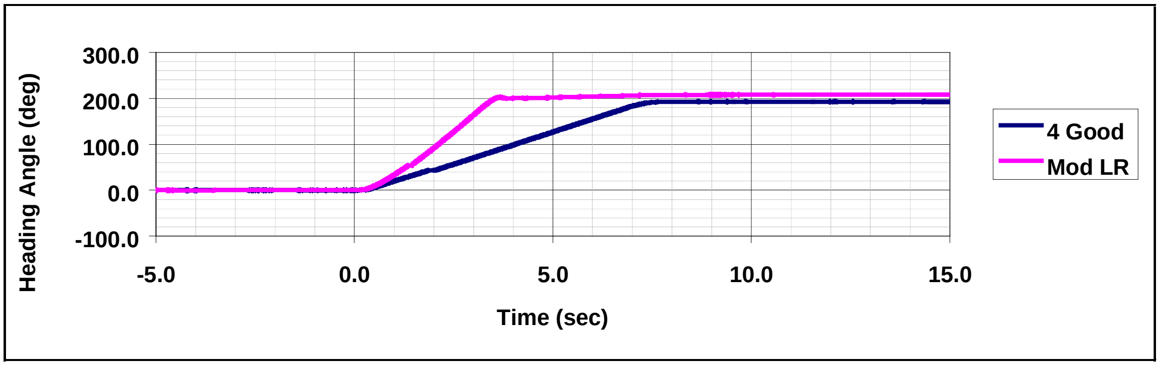

Figure 17. 1993 Ford Taurus 56 km/h Right Step Steer, Heading Angle.

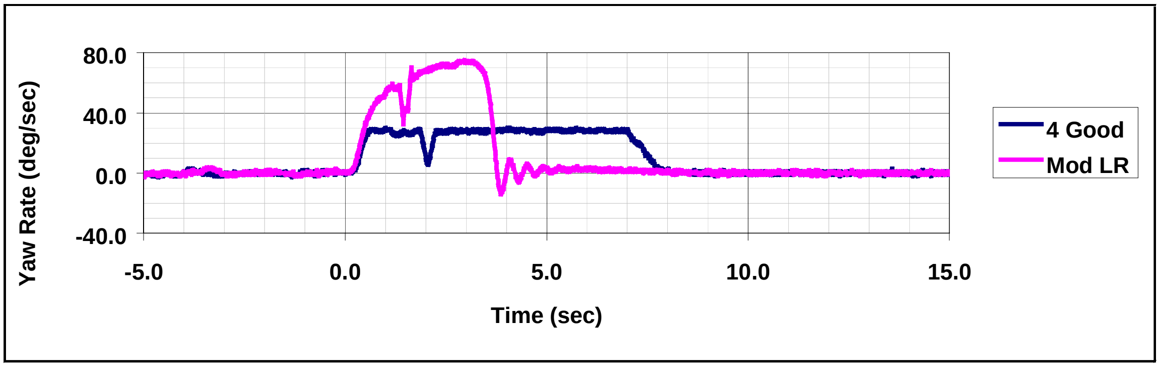

Figure 18. 1993 Ford Taurus 56 km/h Right Step Steer, Yaw Rate.

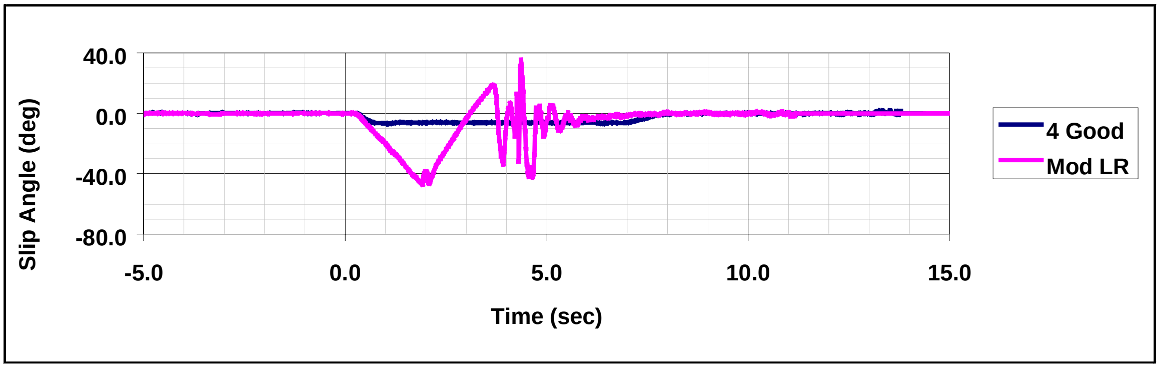

Figure 19. 1993 Ford Taurus 56 km/h Right Step Steer.

The vehicle with four good tires tracked around the turn at all three test speeds. Maximum lateral acceleration was achieved for both the 56 and 72 km/h runs.

The Taurus spun out at all three test speeds when a tread-separated tire was placed at the outboard rear wheel position. Large slip angles were developed and the vehicle achieved maximum lateral accelerations at all three test speeds.

The results for the Bronco II and the Taurus were very similar. Both vehicles exhibited distinctly different behavior when a tread-separated tire was located at an outboard rear wheel position when compared to their performance with four good tires.

CONCLUSIONS

Three different vehicles ranging from a front wheel drive passenger car to a short wheelbase, high CG SUV were tested to evaluate their response to a tire tread separation. All three had a similar response. Each vehicle changed its path toward the side of the separating tire as a result of a rear tread separation event.

The magnitude of the response in a rear tread separation is dependent on the speed of the vehicle and the duration of the event. Higher speeds and longer duration events produce greater magnitudes of vehicle path deviations. Partial tread separations produce a continuous response from the vehicle.

While the three vehicles tested generally respond similarly, the degree of their responses differs. A partial tread separation on an Explorer at highway speed can produce a result that even a skilled, knowledgeable driver cannot control. The Taurus did not exhibit this extreme response.

While drag created by the separating tread plays a role in the vehicle's path deviation, there are additional lateral forces input to the vehicle as a result of the interaction of the separating tire with the ground. These forces can be large enough to cause loss of control regardless of driver response.

The Bronco II and the Taurus each transitioned from an understeer to an oversteer vehicle with a tread-separated tire at the outboard rear of a cornering maneuver. This occurs at approximately 0.2 g of lateral acceleration. The basic behavior of the vehicle is distinctly different with a separated rear tire than when it is equipped with four good tires. The oversteer condition is most pronounced (vehicle spins out) during dynamic maneuvers such as a J-turn.

The combination of 1) a tread separation event resulting in a vehicle path deviation with 2) the fundamentally changed vehicle behavior when the tread comes off of a rear wheel produces a significant handling problem for the driver. This combination can cause loss of control.

The tests presented here demonstrate that a vehicle can have a significant, destabilizing response to a tire tread separation event even when the driver's behavior is restricted to holding the steering steady ("open loop"). These results imply that, in a collision involving a tire tread separation, it is a significant over-simplification to implicate driver behavior as the sole cause of a vehicle's loss of control. Like all crashes, those involving tread separation events should be studied considering the crash vehicle, the environment, and the driver during both the pre-crash and post-crash phases.

REFERENCES

1. Klein, Black, *Anatomy of Accidents Following Tire Disablements*, SAE Paper No. 1999-01-0446
2. Fay, et. Al., *Drag and Steering Effects from Tire Tread Belt Separation and Loss*, SAE Paper No. 1999-01-0447
3. Dickerson, Arndt, Arndt, *Vehicle Handling with Tire Tread Separation,* SAE Paper No. 1999-01-0450
4. 1992 through 2001 Automotive News Market Data Book