Vehicle Handling with Tire Tread Separation

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Reprinted From: Vehicle Dynamics and Simulation 1999
(SP-1445)
ABSTRACT

Catastrophic and sudden tire tread separation is an event that drivers of motor vehicles may encounter and, in some instances, is implicated as the cause of motor vehicle crashes and related injury or property damage. In an effort to understand how tire tread separation affects vehicle handling, a series of tread separation handling test programs were conducted. In each tread separation test program a sport utility vehicle was instrumented and equipped with steel belted radial tires that were modified to emulate tread separation between the inner and outer steel belts. The test vehicle was then subjected to a variety of open and closed loop handling test maneuvers. This paper presents the data and analysis from these tests. The research demonstrates through controlled experiments that a tire tread separation has an effect on the vehicle’s fundamental handling characteristics. It also demonstrates that the effect depends on the position of the compromised tire on the vehicle.

INTRODUCTION

In order to better understand the effects of tire tread separation on a vehicle, a series of handling tests has been performed on vehicles with tires modified to emulate separation between the inner and outer tread belts. A methodology for creating a tire with a separated tread that is repeatable and uniform over multiple tests will be presented. A different methodology for generating a sudden and catastrophic failure was also used and will be presented.

Two different test programs were performed. In one, a tire was modified to emulate complete tread separation and mounted on the test vehicle. A series of steady state and transient limit performance test maneuvers were then performed.

In the second series, an actual catastrophic failure was generated. The failures were designed to occur while the vehicle was traveling in a straight line and the subsequent vehicle response was then measured. The tire preparation and test protocols for this series are significantly different than those in the first test series. For this reason, the tire failure simulation tests will be described and the results presented in separate sections.

The vehicle used in both test series was a sport utility vehicle equipped with instrumentation and added safety equipment to protect the driver. The modifications were made such that any effects on the mass and inertial properties of the test vehicle were minimal.

PREVIOUS RESEARCH

The subject of tires and their effect on automobile and truck performance is a topic that is extensively covered in the literature. This is expected since for reasonable speeds, and assuming no collisions with other vehicles and objects, the significant forces that affect the motion of the vehicle are transmitted through the tires. The literature on tire failure testing is small in comparison to that concerned with the effects of tires on performance and handling of vehicles.

In the Experimental Safety Vehicle work of 1974, Jacobson stated that many high-speed road cross over crashes might be attributable to tire failures. In the Jacobson test series a dramatic difference in vehicle behavior between front and rear tires was observed. In general, rear tire failures were more likely to result in loss of control [1].

In 1994, Metz, et. al. presented a series of simulations concerned with vehicle evasive maneuver capability with flat tires. The simulations predicted behavior similar to that presented in this work [2]. Blythe et. al. presented a series of vehicle handling tests in which a tire failure (blowout) was induced. Their tests indicated that the vehi-
cle pulls towards the damaged tire and that a rear blow-out results in a vehicle that exhibits oversteer tendencies [3].

Other works describe the importance of tire behavior on vehicle handling and stability. Allen, et. al. state that “Vehicle Handling Stability is dominated by tire force response characteristics.” Allen, et. al. further state that different front to rear tire saturation effects are the main cause of directional stability problems [4]. In his book, Wong mentions that oversteer is not desirable from a directional stability point of view [5]. Milliken and Milliken discuss tire failure briefly stating that a rear tire failure has a destabilizing effect on the vehicle [6]. In general the literature consistently states that a vehicle that oversteers, by design or circumstance, is highly undesirable.

TEST VEHICLES

In the test programs described, two nearly identical vehicles were used. Both were two-wheel drive Ford Bronco II's; one was a 1988 model year while the other was a 1989 model year. Prior to configuring the vehicles for testing, a complete mechanical inspection was performed by certified mechanics. The purpose of the inspections was to ensure that the drive train, suspension, frame and body were within original factory specification tolerance.

Prior to modifying the vehicles, the center of gravity in curb configuration was measured. This was also performed after test setup. The results of the “before” and “after” tests are presented in Table 1. Test vehicle setup consisted of installing instrumentation, data acquisition and driver protection equipment. In order to maintain vehicle center of gravity and inertial properties, most of the interior components were removed during setup. Each component that was removed was weighed and its center of gravity measured and recorded relative to the vehicle.

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A portable, compact signal conditioning and data acquisition system that was assembled specifically for handling testing was installed making the test vehicle fully self contained. Table 2 is a list of the vehicle parameters recorded. All of the data was captured digitally at a sample rate of 100 Hz with a 10 Hz analog pre-filter.

The extra protection added for the driver consisted of a five point harness, a roll bar, window netting and a lightweight outrigger system. The outrigger design was reported in a previous paper concerning the effects of outrigger design on vehicle handling [6]. Figure 1 shows one of the test vehicles in test configuration.

TIRES

For all of the tests Firestone FR-480, size P205/75R15, tires were used. All of the tires used in the test programs were purchased new and throughout the test programs their condition, as well as that of the rims, was continually assessed with tire and/or rim replacements made as necessary. Tire pressure was set to the vehicles’ recommended value and maintained by checking it between each test run. The tire pressure in the separated tire was set 2 psi below the recommended value to account for the increase in volume that occurs when the tread detaches. Prior to beginning a test series at the beginning of the day or after a break, the tires were warmed up by driving for approximately twenty minutes. Modified tires were not subjected to the warmup procedure.

Table 1. Test Vehicle Weight, Before and After Setup

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Table 2b. Instrumentation Onboard ‘89 Bronco II

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<td>14</td>
<td>Left Rear Suspension Position</td>
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<td>Right Rear Suspension Position</td>
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Through many investigations of tire tread separation failures, it has been observed that typically the tread and outer tread belt separate from the tire and, in many cases, most or all of the tread detaches from the tire. For the first test program, tires were modified to emulate this total loss of the tread and outer belt.

The tires used in these test series have two steel belts under the tread. In order to create the modified tire, the tread was first removed using a sharpened putty knife lubricated with soap and water. This was accomplished by first cutting the base of the tread shoulder laterally around the perimeter of both sides of the tire. A cut was then made across the tread down to the first steel belt. Using locking pliers it was then possible to grab the loose end of tread piece and peel the tread off of the carcass by pulling and lightly cutting the interface between the tread and the carcass. The outer belt was removed by carefully cutting between the tread belts and pulling outer belt wires off of the carcass. At the end of this process the inner tread belt and carcass remained intact with most of the rubber between the inner and outer tread belt in place.

In addition to the instruments recording vehicle response data, video cameras captured vehicle behavior during each test run.

CIRCLE TURN TEST (UNDERSTEER)

The purpose of conducting circle turn tests was to determine the understeer/oversteer characteristics of the vehicle using a quasi-steady state maneuver. The maneuver consisted of driving the vehicle around a 61 m (200 ft.) diameter circle. The test was initiated with the vehicle at rest on a tangent line to the circle and the wheels pointed straight. The vehicle was then slowly accelerated and steered to stay on the 200-ft diameter circle. Slow acceleration continued until either the vehicle reached maximum speed due to drive wheel slip or it would no longer stay on the desired path. Typically a test run required 30 seconds to complete. Runs were conducted using both right and left turn maneuvers to determine any differences in vehicle behavior based on turn direction.

STEP STEER TEST (J-TURN)

This maneuver was performed by bringing the vehicle to speed, releasing the throttle, allowing the velocity to stabilize to the desired value, then rapidly applying a step steer input of the desired magnitude. Steer input was maintained until a steady state condition was attained or outrigger contact occurred. The step steer maneuvers were conducted for a single steer magnitude (180 degrees) and two speeds (11 and 16 m/s). The purpose of the test was to provide data concerning the transient response of the vehicle.

OBSTACLE AVOIDANCE

The obstacle avoidance test series was conducted using the course shown in Figure 2. The course was entered at a specified speed and the throttle released prior to entering the first gate. Throttle and brake were not applied in the course. Drivers were required to steer through a 2.66 m (12 ft) avoidance gate offset 1.33 m (6 ft) from the centerline of the entry lane, and then steer back to the 2.66 m (12 ft) wide exit lane. The avoidance gate was 18.3 m (60 ft) from the end of the entry lane and 18.3 m (60 ft) from the beginning of the exit lane. Cones were used to mark the course lanes and gate. Contact with the cones or failure to stay in the lanes constituted a failure.

Multiple attempts to drive the course were made at varying speeds to increase the possibility of completion and document the required driver input for completion. Tests were conducted for two vehicle tire configurations: four unmodified tires and modified tire on the right rear. Runs were made at gradually increasing speeds until consistent failure to negotiate the course was observed. The left or right label refers to the initial turn direction of the test.
DISCUSSION - CIRCLE TURN TEST RESULTS

The circle turn maneuver was performed with four unmodified tires, 3 unmodified tires with a modified tire on the left rear and 3 unmodified tires with a modified tire on the left front. Turns were made both towards (left) and away (right) from the side with the modified tire.

Figure 3. Left Circle Turn Results

Analysis of the circle turn data was performed using the steering wheel angle and lateral acceleration data to plot the oversteer/understeer characteristics for the vehicle in each test configuration.

Figure 4. Right Circle Turn Results

The steering wheel angle data was first normalized by dividing by the steering box gear ratio of the Bronco II. Both data sets were then filtered using a 100 point moving average. The combined data set (steer angle v. lateral acceleration) was then curve fitted with a fifth order polynomial and plotted in Figures 3 and 4.

FOUR UNMODIFIED TIRES

The Bronco II equipped with four unmodified tires understeered throughout the circle turn test. In the limit, the front axle saturated prior to the rear and the vehicle “plowed out.” These observations were noted for both right and left circle turns. The maximum lateral acceleration achieved was approximately 0.74 g and 0.78 g for the right and left circle turns respectively. As can be seen in the Figures 3 and 4, the Bronco II understeer gradient increased as the maximum lateral acceleration was achieved.

MODIFIED TIRE AT LEFT REAR POSITION

When a modified tire was placed on the left rear wheel position and the circle turn was conducted to the right, the difference in behavior was dramatic. Figure 4 shows that the vehicle understeered slightly until a lateral acceleration of approximately 0.3 G was attained. The vehicle then began to oversteer at an increasing rate. The maximum lateral acceleration achieved during this test was approximately 0.6 G.

When the test was run to the left, the vehicle behaved similarly to the vehicle with four unmodified tires. The vehicle did not understeer as much, but was able to achieve a maximum lateral acceleration of 0.74 G which was only slightly less than the 0.78 G achieved with four unmodified tires. Vehicle understeer increased as the lateral acceleration increased. The test was terminated when the vehicle velocity could not be increased due to inside rear wheel spin. Neither vehicle was equipped with a limited slip type rear differential.

MODIFIED TIRE AT LEFT FRONT POSITION

A circle turn test to the right with the modified tire on the left front wheel position resulted in the Bronco II understeering substantially more when compared to the four unmodified tire configuration. The maximum lateral acceleration achieved during this test was approximately 0.55 G. This was a reduction in the lateral acceleration of approximately 0.19 G. The test was terminated when the front end of the vehicle began to plow out.

When the test was repeated to the left, the vehicle behaved similarly to the vehicle with four unmodified tires. The understeer was slightly greater than with four unmodified tires and the maximum lateral acceleration achieved was slightly less at approximately 0.72 G as compared to 0.78 G. For the Bronco II at the lateral acceleration limit, the inboard front wheel typically lifted off of the ground thus effectively eliminating the contribution of the modified tire. This test was terminated when the vehicle could no longer be driven on the circle due to front axle saturation.
DISCUSSION - STEP STEER TEST RESULTS

Step steer test runs were made with a steer (at steering wheel) input of 180 degrees and at speeds of 11 m/s (25 mph) and 16 m/s (35 mph). Runs were made in both left and right directions with three vehicle tire configurations: four unmodified tires, modified tire on the left front and modified tire on the left rear. Portions of the resulting data are presented in Figures 5 through 12. The data has been smoothed by running it through a nine sample wide moving average window. Each plot presents a single maneuver with data from each of the vehicle configurations overlaid for comparison.

RIGHT STEP STEER

As expected the right turn maneuvers resulted in the most dramatic difference between the three configurations. In the right steer series the steer input was away from the modified tire resulting in lateral load transfer onto the modified tire. The steer input and longitudinal velocity plots demonstrated that the three runs presented occurred at approximately the same initial speed and that the steer inputs were nearly identical. Once the maneuver began, the longitudinal velocity of the modified rear tire configuration dropped off rapidly due to the resulting high slip angle. At 11 m/s the unmodified tires and front modified configurations behaved similarly. At 16 m/s the unmodified tires configuration slowed more rapidly than the front modified configuration.

The difference between the tire configurations was best demonstrated in the lateral velocity and slip angle plots. The modified rear tire configuration spun out at both speeds. The discontinuity in the plot is due to the vehicle exceeding the maximum slip angle allowed by the sensor (approximately 40 degrees). At 16 m/s the slip angle of the four unmodified tires configuration was more than twice that of the modified front tire configuration while at 11 m/s the slip angle response was quite similar. At both speeds the four unmodified tires and front modified configurations demonstrated stable understeer responses to the steer input. At both speeds the modified rear tire configuration demonstrated an unstable response.

The heading and yaw rate data followed the same trend with the yaw rate, and naturally, the heading change being significantly greater for the rear modified condition. At both speeds the heading change and yaw rate were greater for the four unmodified tires configuration than for the modified front tire configuration indicating greater understeer for the modified front tire configuration.

The lateral acceleration results showed the four unmodified tires configuration to generate higher values than the modified front tire configuration. The modified rear tire configuration showed a higher value than the four unmodified tires configuration in the 11 m/s run and approximately the same value in the 16 m/s run. The anomalies observed in the results for the modified rear tire configuration data were caused by the high yaw rate generated in the maneuver.

LEFT STEP STEER

Comparison of the left to right data was more interesting than comparison of the different configurations in the left step steer runs. Again the steer input and longitudinal velocity data shows the initial conditions of the individual runs to be approximately the same. The first significant observation was that all of the configurations demonstrated a stable understeer response at both speeds.

At 11 m/s all three configurations had similar responses. The four unmodified tires and modified rear tire configurations were almost identical for the parameters measured. The modified left front configuration displayed lower heading change, yaw rate and lateral acceleration responses than the other two configurations.

At 16 m/s the modified rear tire configuration differs from the four unmodified tires and modified front tire configurations. The lateral velocity and slip angle responses were greater. The heading change and yaw rate were similar to those of the four unmodified tires configuration. The modified front tire configuration displayed less heading change.

RESULTS - OBSTACLE AVOIDANCE TEST

Due to the oscillatory nature of the steer input required to negotiate the test course, vehicle response was similarly oscillatory in nature. In general an initial three-peak curve of steering input was necessary to complete the obstacle avoidance course. Overshoot during the recovery after entering the return lane resulted in additional steering peaks. Most of the measured vehicle parameters had a similar oscillatory nature that differed between the different tire configurations. By measuring the magnitude of the vehicle response peaks, a family of graphs has been produced. Graphs for the steer input versus initial speed and the vehicle responses of yaw angle and yaw rate versus initial speed are shown in Figures 13 through 15.

The graphs have points labeled as "modified tires outside or inside." The use of the term outside or inside refers to the location of the modified rear tire in the first turn of the maneuver. A test with the "modified tire outside" refers to a course with the obstacle to the left.

While the early response peaks were similar for all test conditions, a failure to negotiate the obstacle avoidance course often resulted in a higher magnitude of vehicle responses. In general the population of vehicle responses was different depending on the rear tire condition.
DISCUSSION - OBSTACLE AVOIDANCE TEST

While obstacle avoidance tests are by nature subjective they also yield objective data. The test method depends on the driver’s input. The simple pass/fail criteria which has been applied to a vehicle as a result of obstacle avoidance testing is not appropriate given the sensitivity of the test method to driver skill and driver learning during testing.

Pass/fail in the negotiation of the obstacle avoidance course is an objective indicator for comparing test results when measuring driver control and vehicle response. The obstacle avoidance course could be completed at higher speed with unmodified tires. Without a modified tire, the course could not be successfully negotiated above 16 m/s (35 mph). Successful completion of the obstacle avoidance course could not be accomplished for the condition of a modified tire on the inside rear above 13.4 m/s (30 mph).

Since driver input improved as an obvious result of repeated attempts at the obstacle avoidance course, a point of comparison was derived in comparing only the successful runs. Overall, the data indicated that a more deliberate input for the first two steer inputs and a greater magnitude for the third steer input were necessary to complete the obstacle avoidance course when the modified tire configuration was compared to the unmodified tires configuration. This result is illustrated in the family of three graphs in Figure 13. The higher third peak steer magnitude for the modified inside tire test was consistent with the driver’s expectation of vehicle oversteer during the second turning maneuver.

The vehicle yaw angle behavior is shown in Figure 14. For the first two peaks, the modified tire vehicle yaw angle was higher in magnitude that for the vehicle with four unmodified tires. The first peak graph demonstrates that for a “passing” run with the modified tire on the inside, the vehicle was within the population of response for unmodified tires. If the modified tire was on the outside of the initial turn, a significantly higher yaw angle was observed. This result was consistent with the unstable oversteer condition which existed with the modified rear tire on the outside of a turning maneuver.

The family of graphs showing peak yaw rate response more clearly demonstrates the generally higher magnitude of vehicle response that occurs with the modified tire on the rear. Similar to yaw angle, the first peak yaw rate response plot shows the maneuver with the modified inside tire within the population of unmodified tire results. In general the higher magnitude of yaw rate peak response is more pronounced than that observed for yaw angle.

Driver response to a vehicle’s behavior during obstacle avoidance testing provides an opportunity to compare the necessary driver input for successful completion of the test course. Failed test results show the greatly varied response of the vehicle and driver. The oversteer condition which exists when modified tires are attached at the rear is objectively demonstrated in the plots shown in figures 13 through 15. Overall different driver response was necessary in the presence of the modified tire. Different steer input magnitudes and greater vehicle responses were necessary to maintain control of the vehicle.

TIRE FAILURE SIMULATION

TEST VEHICLE – In this test series, the 1989 two-wheel drive Ford Bronco II was used. It was prepared in exactly the same way as the test series described above. In addition to the instruments already onboard, a video camera was mounted internally with two microphones to capture the sounds of the tire failure. A pink noise generator and audio noise power level meter were used to calibrate the sound recording. The steering shaft between the hand wheel and the steering box was also instrumented to measure torque.

TIRE PREPARATION – The tires were prepared somewhat similarly to the total separation tires with the exception that the tread was not removed. The tire was carefully cut in from the edge of the base of the tread shoulder between the two outer steel belts. This cut went around the entire perimeter of the tire but not all of the way across the tread block. Cuts were made going inward from both tread shoulders leaving a narrow patch of rubber at the center of the tread block bonding the inner belt to the outer belt around the perimeter of the tire. The tread was also scored parallel to the outer belt filaments over its entire width in one place. It should be noted that this process evolved over several test runs as changes were made to create a tread separation failure in a predictable time and place.

TEST PROTOCOL – The modified tire was mounted on the right rear wheel position. The test was run on the taxiway of a local airport. This provided a long area for acceleration and adequate lateral space for vehicle motion. The test driver was instructed to accelerate to the desired test speed and maintain as room allowed. When the tread separation occurred, the test driver held the steering wheel constant and did not respond until it was necessary so as to avoid leaving the taxiway.

TEST RESULTS – Three successful runs were made. Success was defined as a run in which the tread separation was sudden and the majority, if not all, of the tread detached and electronic data was captured. Data from these runs are presented in Figures 16 through 18. Speed, steering wheel angle, and longitudinal and lateral acceleration are presented.

Overall, the separation resulted in a loud banging noise as the loose tread battered the fender and inner wheel well. Accompanying the noise was damage to the right rear quarter panel and tailpipe. The driver reported that the noise was very loud. In all cases the tire carcass remained inflated after the separation was complete. In
the cases where complete tread detachment occurred, once the noise stopped, there was not any feedback to the driver to indicate that there was a problem with the vehicle.

In the three runs presented, the test driver did not input any steering until it was necessary to do so to remain on the track.

DISCUSSION - TEST RESULTS

Plots for Run A show that an external disturbance to the vehicle caused by the tire separation occurred at approximately 7.5 seconds. The vehicle speed was approximately 24.6 m/s (55 mph) and the test driver held the wheel steady until approximately 10.5 seconds. The separation resulted in a spike in the yaw rate data and a heading deviation to the right. Over a period of about 3 seconds a small tire separation induced heading change took place.

The longitudinal acceleration shows an instantaneous deceleration. Later in the run this increases as the driver releases the throttle then applies brakes. Between 10.5 and 14 seconds, the test driver inputs a steering pulse with a maximum amplitude of approximately 20 degrees to realign the vehicle with the test track.

Plots for Run B show similar results. An external disturbance to the vehicle caused by the tire separation occurred at approximately 11 seconds. The test driver responded with steer input to counteract the separation induced clockwise yaw at about 13 seconds. During this 2 second time between external disturbance and driver input, the vehicle turned clockwise approximately 7 degrees. During this time a 0.1 g deceleration was recorded as well as a 5 deg/sec yaw rate. The separation occurred at about 20.1 m/s (45 mph).

Plots for Run C show external disturbance at approximately 10.5 seconds. Corresponding to the disturbance is a peak in the lateral acceleration of 0.2 g's consistent with a right turn. An increase in the yaw rate is observed beginning at approximately 10 seconds with a corresponding heading change. The test driver began to respond with opposite steer between 12.5 and 13 seconds. Overall a 6 degree heading change was recorded with a non-driver induced 3 degree heading deviation at the beginning of the tire failure induced disturbance.

Overall review of the steering shaft torque data revealed that little, if any, torque was fed back to the driver during the separation event. Phasing of the torque data relative to the steering wheel angle data supported this. Since this vehicle was equipped with power steering, this was to be expected.

CONCLUSIONS

Two test programs were run to quantify the effects of tire tread separation on the handling characteristics of a sport utility vehicle. In the first program a tire was modified by removing the tread and outer belt with the intended purpose of creating a tire that had suffered a complete tread detachment. This modified tire was mounted on the test vehicle and a series of handling tests performed. From these tests some conclusions can be expressed.

If the separated tire was on the back of the vehicle and the vehicle was turned away from the tire, the vehicle exhibited dramatic oversteer characteristics and was unstable.

If the separated tire was on the back of the vehicle and the vehicle was turned towards the tire, the vehicle exhibited less understeer generally stable. Overall the behavior was asymmetric.

In avoidance situations, the vehicle required greater steer inputs and produced significantly different vehicle responses if the modified tire was on the rear axle.

If the separated tire was on the front of the vehicle, then the vehicle exhibited increased understeer. This effect was more pronounced if the vehicle was turned away from the modified tire than if it was turned towards the modified tire.

In the second test program a tire was modified such that it would suffer a catastrophic tread detachment while the test vehicle was being driven in a straight line at highway speeds. In these tests the modified tire was mounted on the right rear.

When the separation occurred, the vehicle pulled in the direction towards the modified tire.

Beyond the induced motion, the driver heard a loud noise as the tire pieces contacted the inner wheel well and fender.

If total separation occurred, after the separation was complete, there was not any feedback to the driver to suggest that there was a problem with the tire.

The work presented has been performed using a sport utility vehicle with a relatively narrow track width and high center of gravity as compared to a typical sedan. This resulted in significant lateral load transfer and played a role in the magnitude of the asymmetry of the results and the magnitude of the difference in the handling characteristics for different modified tire locations.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the ultimate test team: Dave Clark, Ambrose Hubbard, Gary McDowell, Greg Mowry, and their intrepid leader Pete Baray. Without their hard work and ingenuity none of the handling tests would have been successful.
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Figure 5. 11 m/s Left Step Steer Data
Figure 6. 11 m/s Step Steer Data
Figure 7. 11 m/s Right Step Steer Data
Figure 8. 11 m/s Right Step Steer Data
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Figure 16. Time Failure Simulation, Run A
Figure 17. Time Failure Simulation, Run B
Figure 18. Time Failure Simulation, Run C