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TEST RESULTS: VEHICLE RESPONSES TO SIMULATED DRAG CAUSED BY FRONT TIRE TREAD DETACHMENT; THE EFFECT OF SCRUB RADIUS AND SPEED

Mark W Arndt
Transportation Safety Technologies, Inc.
Phoenix, Arizona, USA

Stephen M Arndt
Safety Engineering and Forensic Analysis
Phoenix, Arizona, USA

ABSTRACT

The effects of reduced kingpin offset distance at the ground (scrub radius) and speed were evaluated under controlled test conditions simulating front tire tread detachment drag. While driving in a straight line at target speeds of 50, 60, or 70 mph with the steering wheel locked, the drag of a tire tread detachment was simulated by applying the left front brake with a pneumatic actuator. The test vehicle was a 2001 dual rear wheel four-wheel-drive Ford F350 pickup truck with an 11,500 lb. GVWR. The scrub radius was tested at the OEM distance of 125 mm ($\Delta = 0$) and at reduced distances of 49 mm ($\Delta = -76$) and 11 mm ($\Delta = -114$). The average steady state responses at 70 mph with the OEM scrub radius were: steering torque = -24.5 in-lb; slip angle = -3.8 deg; lateral acceleration = -0.47 g; yaw rate = -8.9 deg/sec; lateral displacement after 0.75 seconds = 3.1 ft and lateral displacement after 1.5 seconds = 13.1 ft. At the OEM scrub radius, responses that increased linearly with speed included: slip angle (R^2=0.84); lateral acceleration (R^2=0.93); yaw rate (R^2=0.73) and lateral displacement (R^2=0.59 and R^2=0.87, respectively). At the OEM scrub radius, steer torque decreased linearly with speed (R^2=0.76) and longitudinal acceleration had no linear relationship with speed (R^2=0.09). At 60 mph and 70 mph for both scrub radius reductions, statistically significant decreases (CI ≥ 95%) occurred in average responses of steer torque, slip angle, lateral acceleration, yaw rate, and lateral displacement. At 50 mph, reducing the OEM scrub radius to 11 mm resulted in statistically significant decreases (CI ≥ 95%) in average responses of steer torque, lateral acceleration, yaw rate and lateral displacement. At 50 mph the average slip angle response decreased (CI=87%) when the OEM scrub radius was reduced to 11 mm.

INTRODUCTION

A tire tread detachment event is defined as when either part or all of a tire's tread separates (detaches) from the carcass of a tire. Sometimes tires with detaching or detached tread deflate. Tire tread detachment deflations vary in relation to the detachment time and duration. Some tire tread detachment disablements have been reported to immediately precede vehicle crashes. The effect of a tire tread detachment on vehicle handling depends on the wheel position where it occurs.

The effect of a tire tread detachment event on a vehicle driven at highway speed is often considered to be the result of two distinct stages that often overlap and can have confounding elements. The first stage that occurs is a disturbance caused while the tread is in the process of detaching from the carcass of the tire. The second stage involves changes in steering and handling characteristics resulting from the now disabled and/or disabling tire. Many injury-causing crashes that result from tire tread detachments happen when the failed tire is located at a rear wheel position. Research on the effects of rear tire tread detachment disablement have been widely reported over the last 20 years.

Disturbances in the first stage of a tire tread detachment disablement include noise, vibration, and pulling (the effect of drag) of the vehicle from its intended path in the absence of any steering input. The noise is caused by the separating tread flap flailing against vehicle components and the ground. The flailing tread also causes vibration due to an extreme unbalancing of the tire and the now irregular shape of the tire; the tire is rolling from an area where tread is still present to an area where the tread is missing. The vibration that occurs during a tread separation event leads to wheel hop which reduces the capacity of the tire to hold lateral forces. The flailing tread flap also causes an imbalance of tire forces resulting in the pulling of the vehicle out of its intended path. This paper addresses only the effects of drag caused by a tire disablement.

The mechanism of vehicle pulling in response to a disabled tire has historically been related to longitudinal forces at its contact with the road. In 1968 Kondo noted increased rolling resistance in deflated tires [1]. Similarly, Anderson in 1975 reported increased rolling resistance for flat truck tires. For the condition of a flat tire Anderson calculated a net resulting aligning torque and handwheel torque based upon a truck's king pin offset (scrub radius) at the ground. He then tested alternative wheel designs that reduced scrub radius to zero. Anderson measured handwheel torque and tie rod load in the deflation experiments and documented by indirect measurements longitudinal force at the disabled tire [2]. In 1979 while modeling post blowout controllability of a truck, Bernard and Shapley used a drag force of 30 percent of the static normal load on a front tire and calculated the road wheel angle and associated slip angle required to hold a non-curving path [3].

Direct measurements of forces during tire disablements were made by Gardner in 1998 when he pulled vehicles rigged to sustain a rear tire tread detachment. In Gardner's tests the rear tires did not deflate and maximum drag forces measured with a load cell were between 153.1 lb. to 318.5 lb [4]. In 2003 Daws reported the average longitudinal force of tires rigged to have a tread detachment during flat track machine testing to be 1,570 lb. [5]; the tires were subject to a 1,500 lb. vertical load suggesting that the longitudinal forces that occur in tread detachments can be equal to 100 percent of normal load. In 2004, Arndt et al. measured a distribution of forces and durations associated with tires experiencing a rigged tread detachment event during testing with a special trailer. Arndt's trailer testing recorded longitudinal tire tread detachment forces in the range of 181 lb. to 576 lb. for event durations of 1.0 second to 12.2 seconds respectively [6]; the normal load of the subject test tire was measured statically to be 1,319 lb.

In 2007 Tandy et. al. simulated the longitudinal forces of a rear tire tread detachment by conducting Isolated Brake Testing (IBT). This was done by applying the brake at only the right rear wheel of an SUV. It was conducted to study the vehicle response to the longitudinal force from a tire tread detachment. The reported longitudinal force was 1,250 lb. [7]. Tire disablement testing using the IBT method is based upon decades of published works which initially related disabled tires to causing longitudinal drag forces and later directly measured a distribution of disabled tire induced longitudinal forces and force durations.

Arndt conducted an IBT simulating the longitudinal force from a front tire tread detachment event in 2009 [8]. The brake was applied at the left front wheel of a 2003 Ford F250, 4WD, diesel pickup truck which was reported to have a scrub radius of 5.05 in. (128.3 mm) [9]. This test demonstrated that a significantly greater path deviation (pulling) occurred during the left front wheel IBT when compared to an equivalent left rear wheel IBT [8].

PROBLEM

Anecdotal evidence resulting from numerous crash investigations conducted by the authors of this paper over the last 20 years has suggested that certain pickup trucks are overrepresented in the front tire tread detachment crashes that do occur. A number of design features and tire disablement conditions appeared to be common in the trucks that crashed. The list included:

- 3/4 and 1-ton chassis,
- Four-wheel drive,
- Hotchkiss front suspension,
- Large positive scrub radius,
- Diesel engine,
- Hydroboost power steering/brake assist, and
- Either partial tread detachment or long duration complete tread detachment.

It is hypothesized that the large positive scrub radius might be a significant factor in these loss of control crashes. The present study was designed to measure differences in vehicle pulling responses with changes in scrub radius and speed.

METHOD

The subject test vehicle was a 2001 Ford F350 Superduty Crewcab with 4-wheel drive and dual rear wheels (DRW) (Figure 1). The truck was equipped with a 7.3 liter diesel engine, 4 speed automatic transmission and a hydroboost power steering/brake assist system. The GVWR was 11,500 lb. (5,216 kg) and the wheel base was 172.4 in. (4,379 mm). The specified tires and wheels were LT235/85R16E on 16X6 alloy wheels. The specified tires/wheels were used at the DRW locations. To facilitate testing at the reduced scrub radii, LT265/60R20 tires mounted on 20X8 alloy wheels were used at the front wheel positions. Different width spacers were used to effect scrub radius changes. The larger rims were necessary to provide clearance between the rim and the brake, steering, and suspension components located at the end of the front axle when the scrub radius was reduced. The larger front rim and tire assembly was 24 lb. heavier than the OEM configuration.

Figure 1. 2001 Ford F350 Superduty Crewcab with 4-Wheel Drive and Dual Rear Wheels (DRW).

The brake system was modified to apply the left front brake In the IBTs that were conducted. The truck's brake pedal was actuated by a floor mounted pneumatic cylinder. An auxiliary hydraulic pump was mounted in the bed of the truck to supplement the hydroboost power steering system. The hydroboost system operates both the brake and steering assist, but prioritizes brake assist when simultaneous demands are made of both systems. Adding the auxiliary hydraulic pump insured that any limitations of the hydroboost were eliminated.

The truck was instrumented to measure speed, slip angle, steering torque, brake pedal force, power steering fluid flow rate, power steering fluid pressure, hydroboost fluid pressure, tri-axis acceleration, and roll/pitch/yaw rates. The path of the truck during the test was measured with a GPS using a VBox instrument. The truck weight was measured to be 8,676 lb. (3,935 kg) for the test. The truck was fitted with an AB Dynamics steering robot for locking the steering wheel at zero degrees during each IBT run. The test was documented with interior and exterior video. The interior video only picked up the interior of the truck and did not provide a view out the front window.

Most tests were conducted with the transfer case selector in the 2WD position. Tests were conducted at the OEM scrub radius and at scrub radii reduced by 3.0 in (76 mm) and 4.5 in (114 mm). Speeds varied between 40 mph and 70 mph. A four-test series at 60 mph and a single test at 70-mph were conducted with the transfer case selector in the 4WD position while the vehicle was configured with the OEM scrub radius (Δ=0).

The test plan included conducting three IBT runs for each scrub radius configuration at highway speeds of 60 mph and 70 mph. The brake pedal actuation force was set to 25 lbs. This produced a longitudinal deceleration at highway speeds of approximately -0.17 g or 58 percent of the normal force of the left front tire/wheel.

The test protocol required that the test driver accelerate the truck up to the target speed and into a straight ahead driving alignment prior to reaching the start gate. The cruise control was set when the truck achieved the target speed prior to reaching the start gate. The test was initiated at the start gate. At test initiation, the steering was locked and data acquisition began at time equals 0.0 seconds. Brake pedal force application began at 0.5 seconds. The brake controller was designed to apply a step input in less than 0.3 seconds with a steady state force of ± 1 lbs. Only the left front brake was applied during the test with a steady state dwell of 3.0 seconds. The brake pedal force was released no later than 3.5 seconds after the start (time = 0.0 seconds) of each IBT. At the end of each test the driver would regain control and bring the truck to a stop.

RESULTS

The first three tests presented in Table 1 were conducted in part to familiarize the test driver with the IBT setup and test method. Initial testing started at 40 mph and was increased by 10 mph increments. After two tests, the brake dwell time was increased from 2.0 seconds to 3.0 seconds. A series of at least three tests were conducted at 50 mph, 60 mph, and 70 mph at the OEM scrub radius (Δ=0 mm). Four additional tests were conducted at 60 mph and one at 70 mph with the 4WD engaged. A series of three tests were conducted at 60 mph and 70 mph at the other scrub radii (Δ=-76 mm and Δ=-114 mm).

The steady state responses of the truck's hand wheel torque, slip angle, longitudinal acceleration, lateral acceleration, and yaw rate were averaged over the period from 1.5 seconds to 3.0 seconds (for the first two tests, run 3 and run 4, the responses were averaged over the period from 1.0 to 2.3 seconds). The lateral deviation at 0.75 seconds and 1.50 seconds after the beginning of brake application are presented to assess the effect that the scrub radius had on the magnitude of the vehicle's path deviation. Results are provided in Table 1, located at the end of the paper, for all successful IBT tests.

The truck yawed left during each IBT run even though the steering wheel was locked at the zero degree straight ahead driving position. Typical response data is provided in Figure 2, located at the end of the paper, which shows the results for Test No. 9 as a function of time. This test was conducted at 70-mph and the vehicle was configured with the OEM scrub radius (Δ=0). Both upper and lower charts of Figure 2 show the input parameters of speed and brake pedal force. The upper chart shows the vehicle's slip angle, steering torque, and yaw rate while the lower chart shows the longitudinal and lateral accelerations.

Figure 3 shows the trucks path during Test No. 9. The path is marked at 0.5 seconds, which corresponds to the start of left front brake application and at 2.0 seconds (1.5 seconds after the brake application began).

Figure 4, located at the end of the paper, provides six plots of the recorded response parameters versus test speed for all runs where the truck was configured with the OEM scrub radius (Δ=0) and was in 2WD. The coefficient of determination, R^2, is

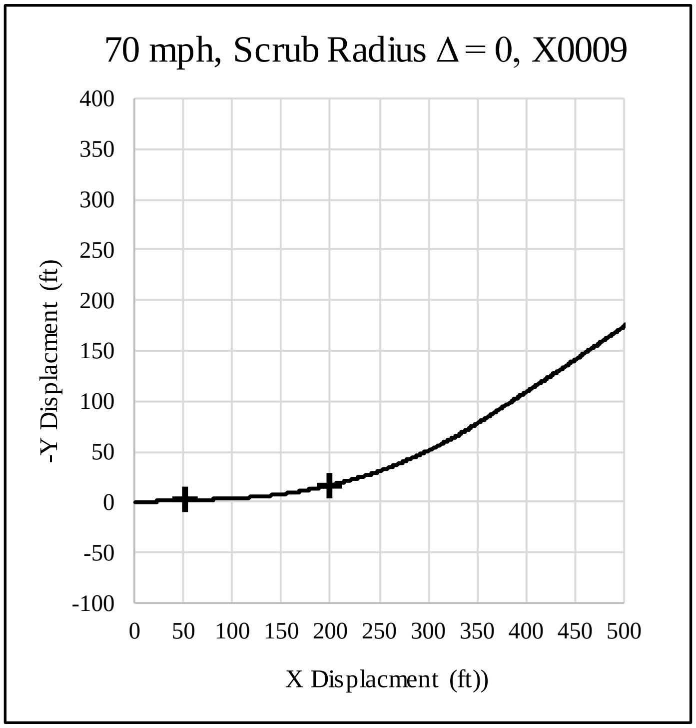

Figure 3. Test 9 X-Y displacement, 70 mph target speed and OEM scrub radius (Δ=0).

provided for each plot. These plots show response parameters that have a linear relationship to speed. Longitudinal acceleration was the same at all speeds and scrub radius so the plot was not provided.

The averaged results with confidence intervals where significant differences were calculated for each speed and scrub radius combination are presented in Table 2.

DISCUSSION

The results of this vehicle handling test series demonstrate that the scrub radius has a significant effect on the response of the test vehicle when drag forces consistent with that produced during a tire tread detachment event are applied to the left front wheel position. The severity of the response is directly affected by vehicle speed and the correlation can be expressed as linear.

The controlled vehicle handling tests used a steering robot to firmly hold the steering wheel throughout the test maneuver to resist the steering torque and prevent the steering wheel from turning. While the measured steering torques would not jerk the steering wheel out of the hands of a driver focused on preventing its motion, it could easily slip within the grip of a relaxed driver. An unsuspecting driver under real world highway conditions would likely not successfully prevent the steering wheel from turning. Any additional turning of the steering wheel resulting from the steering torque would add to the lateral displacement of the vehicle. Greater lateral displacement lowers the probability that drivers successfully return to their original intended travel path.

The slip angle never achieves a value that would suggest that the vehicle was out of control and would not respond to a steering input. While not the topic of this paper, it should be noted that any vehicle that experiences a tire tread detachment at a front wheel position will exhibit an increase in understeer. The result of increased understeer is that a greater than normal steering input will be required to redirect the vehicle back to the driver's intended travel path. The lateral acceleration approached 0.5 G when the test vehicle was configured with the OEM scrub radius (Δ=0) and was in 2WD. This is significantly above the comfort level of a typical driver that is steering their vehicle at highway speeds.

The average lateral displacement of the truck after 1.5 seconds of brake application when traveling at 70mph was 13.3 ft at the OEM scrub radius (Δ=0), 6.3 ft at a scrub radius of 49 mm (Δ=-76), and 5.0 ft at a scrub radius of 11 mm (Δ=-114). The test vehicle in the OEM scrub radius configuration produces a lateral path deviation that is more than double the magnitude of that produced by either of the other two reduced scrub radii configurations. These differences in the lateral displacement may provide some explanation as to why certain trucks appear overrepresented in crashes resulting from front tire tread detachment events. It would be reasonable to consider that the lateral displacement from this test series might be reproduced on the highway under real world conditions surrounding a tire tread detachment event. The 1.5 second time marker after brake application used for measuring the lateral displacement in the test data is typical perception/reaction time used for comparison purposes. The duration of a tread detachment event can exceed 1.5 seconds.

The measured lateral displacement was lower when the 4WD was engaged during the IBTs yet the vehicle response was generally more violent. This can be seen in the larger slip angle, lateral acceleration, and yaw rate data for these tests. The average lateral acceleration of 0.68 G measured during the 70-mph test suggests the tires were at or near their saturation level. The lower lateral displacements measured with the 4WD engaged versus the 2WD does not by itself imply that a real-world driver would have an easier time regaining their intended travel path. This is because of the significantly increased slip

Table 2. Averaged results with confidence interval for statistical significant differences. (Control condition: 2WD with Δ0 mm offset)

Δ offset (mm)	Drive Train	Target Speed (mph)	Steering Torque (in-lb)	Slip Angle (deg)	Y Accel (G)	Yaw Rate (deg/s)	Y after 0.75 seconds (ft)	Y after 1.50 seconds (ft)
0	2WD	50.0	-29.8	-1.6	-0.21	-5.8	2.1	8.0
-114	2WD	50.0	-16.8 (CI 99%)	-1.0	-0.11 (CI 98%)	-2.9 (CI 95%)	1.1	3.8 (CI 96%)
0	2WD	60.0	-28.9	-3.3	-0.40	-9.1	2.2	9.9
0	4WD	60.0	-26.8 (CI 96%)	-4.4	-0.48	-10.8	0.9 (CI 95%)	7.8
-76	2WD	60.0	-22.5 (CI 95%)	-1.5 (CI 97%)	-0.21 (CI 99%)	-4.2 (CI 99%)	2.1	7.3
-114	2WD	60.0	-8.7 (CI 97%)	-1.2 (CI 95%)	-0.14 (CI 98%)	-3.1 (CI 99%)[1]	0.8 (CI 95%)	4.0 (CI 95%)
0	2WD	70.0	-24.5	-3.8	-0.48	-9.0	3.2	13.3
0	4WD	70.0	-14.4 (CI 99%)	-7.7 (CI 99%)	-0.68 (CI 99%)	-16.0 (CI 99%)	1.3 (CI 98%)	8.8 (CI 98%)
-76	2WD	70.0	-17.0 (CI 97%)	-1.7 (CI 99%)	-0.24 (CI 99%)	-4.2 (CI 99%)	1.4 (CI 96%)	6.3 (CI 98%)
-114	2WD	70.0	-6.4 (CI 99%)	-1.1 (CI 99%)	-0.14 (CI 99%)	-2.7 (CI 99%)	1.3 (CI 98%)[1]	5.0 (CI 98%)[1]

(1) CI for comparison to 0 Δ offset. Comparison to -76 Δ offset was not significant.

angle and yaw rate. Only one test was made at 70 mph with the 4WD engaged. An in-field decision was made to terminate the other two 70 mph tests because of concern for driver safety. The test speed was dropped to 60 mph for the remainder of the 4WD IBTs here.

CONCLUSIONS

- The scrub radius has a significant effect on a vehicle's response to a drag force consistent with that produced during a tire tread detachment event when applied to a front wheel position.
- The magnitude of the measured response was related to the speed at which the vehicle was traveling and the relationship can be expressed as linear.
- Having the 4WD engaged during IBTs produced greater vehicle response in slip angle, yaw rate and lateral acceleration when compared to the 2WD configuration.
- Crash investigators should consider the scrub radius as a possible contributor when assessing the cause of a loss of control crash involving a front tire tread detachment event.
- Crash investigators should consider 4WD engagement as a possible contributor when assessing the cause of a loss of control crash involving a front tire tread detachment event.

REFERENCES

1. Kondo, M., Nagaishi, T., Seki, K., Takeda, T., "Dynamical Behaviors of a Car When One Tire is Punctured Simulatively," XII FISITA, Barcelona, Spain, May 19-25, 1968.
2. Anderson, R. L., et al., "Control of Commercial Vehicle Accidents Caused by Front Tire Failures," Prepared for the US DOT, August 1975, p. 3-8.
3. Bernard, J. E. and Shapley, C. G., "The Effect of Vehicle Design on Post Blowout Controllability," SAE Truck Meeting, Ft. Wayne. IN, November 5-8, 1979, p. 3.
4. Gardner, J., "The Role of Tread/Belt Detachment in Accident Causation," ITEC 1998, p. 7.
5. Daws, J. W., "Force Characteristics of Tire Tread Delamination," Presentation at the 2003 Meeting of the Tire Society, p. 8.
6. Arndt, M. W., et al., "Force Response During Tire Tread Detachment Event," published at the SAE 2004 World Congress, Detroit, Michigan, 2004 (Addendum made July 2007).
7. Tandy, D. F., et al., "An Analysis of Yaw Inducing Drag Forces Imparted During Tire Tread Belt Detachments," SAE 2007 World Congress, Detroit, Michigan, April 16-19, 2007, SAE Paper No. 2007-01-0836, p. 4.
8. http://www.transport-safety.com/blog/random/new-test-results-a-breakthrough-in-understanding-front-tire-failure-crashes/, 2009.
9. Office of Defect Investigation Resume, Investigation: EA00-017, July 29, 2009, p. 12.

Table 1. Summary results for all IBT tests. (Test 27, 28 and 30 were not used because of invalid brake force).

Test no.	Δ offset	Drive Train	Target Speed	speed	Steering Torque	Slip Angle	X Accel	Y Accel	Yaw Rate	Y after 0.75 seconds	Y after 1.50 seconds
	(mm)		(mph)	(mph)	(in-lb)	(deg)	(G)	(G)	(deg/s)	(ft)	(ft)
3	0	2WD	40	37.0	-31.5	-1.2	-0.13	-0.14	-4.5	1.4	5.4
4	0	2WD	50	44.9	-29.4	-1.3	-0.15	-0.19	-5.1	2.3	8.0
5	0	2WD	50	50.3	-30.3	-1.9	-0.15	-0.24	-6.4	2.0	8.1
19	-114	2WD	50	50.4	-16.8	-1.0	-0.17	-0.11	-2.9	1.1	3.8
6	0	2WD	60	58.1	-29.0	-2.7	-0.18	-0.37	-8.4	2.4	10.5
12	0	2WD	60	58.5	-28.2	-4.0	-0.11	-0.45	-10.2	1.5	8.1
18	0	2WD	60	58.6	-29.6	-3.2	-0.18	-0.38	-8.6	2.6	11.0
26	-76	2WD	60	60.8	-19.6	-1.6	-0.16	-0.24	-5.0	2.0	7.6
29	-76	2WD	60	58.6	-22.1	-1.5	-0.16	-0.20	-4.1	2.2	7.1
30	-76	2WD	60	58.8	-25.9	-1.4	-0.16	-0.19	-3.4	n/a	n/a
20	-114	2WD	60	59.5	-6.5	-1.4	-0.18	-0.15	-3.3	0.8	4.2
21	-114	2WD	60	59.7	-11.6	-1.1	-0.16	-0.13	-2.9	0.6	3.3
22	-114	2WD	60	59.6	-8.0	-1.1	-0.19	-0.14	-3.2	1.0	4.4
14	0	4WD	60	60.1	-26.0	-5.1	-0.22	-0.54	-12.2	0.7	7.8
15	0	4WD	60	59.9	-27.3	-4.3	-0.17	-0.46	-10.4	1.2	8.5
16	0	4WD	60	59.8	-26.9	-4.0	-0.18	-0.46	-10.4	0.8	7.6
17	0	4WD	60	60.0	-27.0	-4.2	-0.18	-0.47	-10.1	0.8	7.4
7	0	2WD	70	70.7	-22.8	-3.8	-0.12	-0.48	-9.1	3.2	12.9
8	0	2WD	70	70.8	-24.4	-3.9	-0.20	-0.49	-9.0	2.6	12.2
9	0	2WD	70	71.2	-26.3	-3.8	-0.16	-0.48	-8.9	3.7	14.8
32	-76	2WD	70	68.0	-17.0	-1.7	-0.19	-0.26	-4.2	1.0	5.1
33	-76	2WD	70	68.0	-14.8	-1.7	-0.19	-0.24	-4.3	1.9	7.6
34	-76	2WD	70	67.5	-19.2	-1.6	-0.18	-0.22	-4.1	1.4	6.1
23	-114	2WD	70	67.9	-7.6	-1.2	-0.20	-0.14	-2.7	1.0	4.2
24	-114	2WD	70	68.5	-6.2	-0.9	-0.18	-0.13	-2.5	1.5	5.4
25	-114	2WD	70	68.2	-5.6	-1.1	-0.19	-0.15	-2.8	1.5	5.5
13	0	4WD	70	68.0	-14.4	-7.7	-0.19	-0.68	-16.0	1.3	8.8

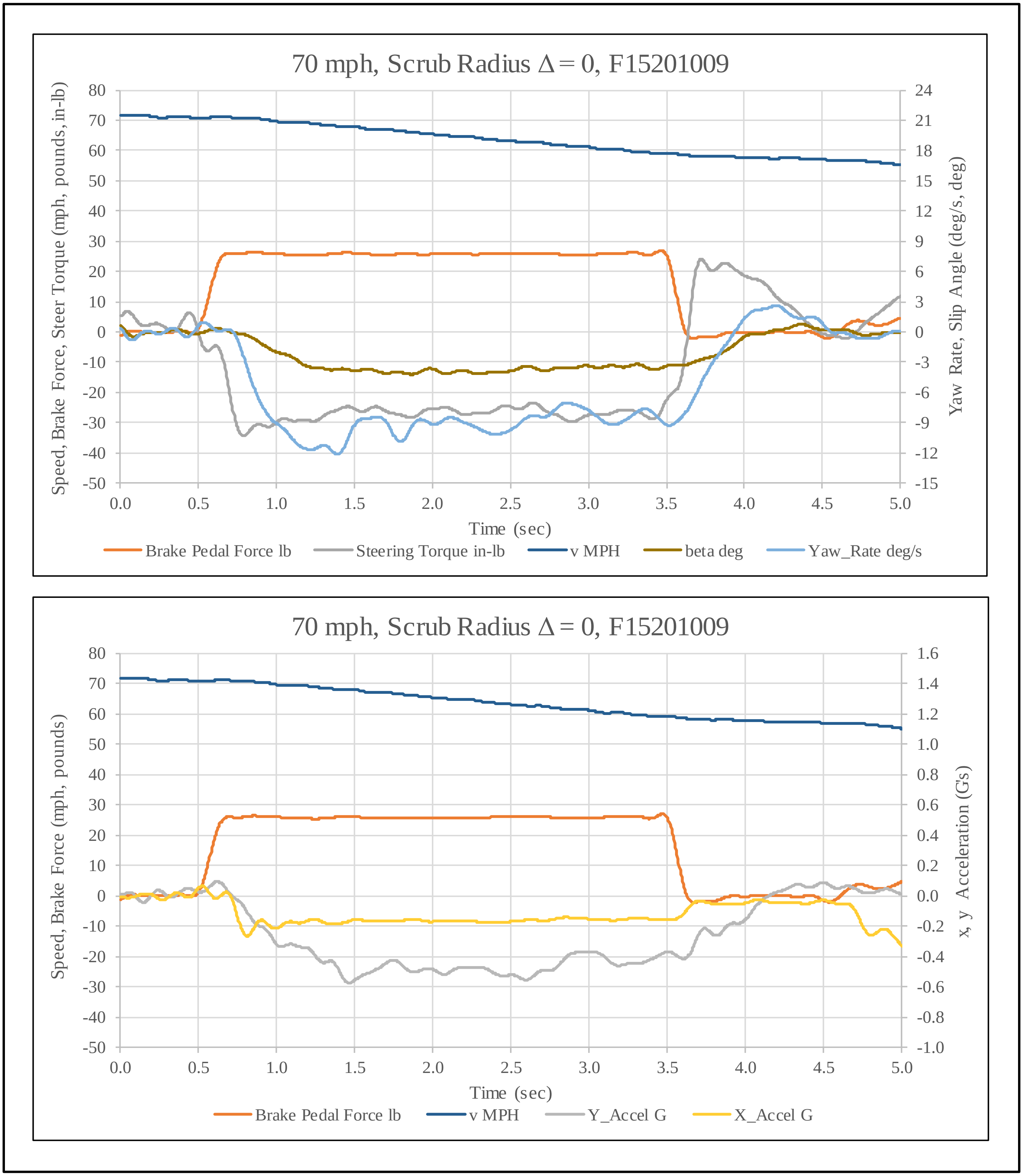

Figure 2. Test 9 measured results, 70 mph target speed and OEM scrub radius (Δ = 0).

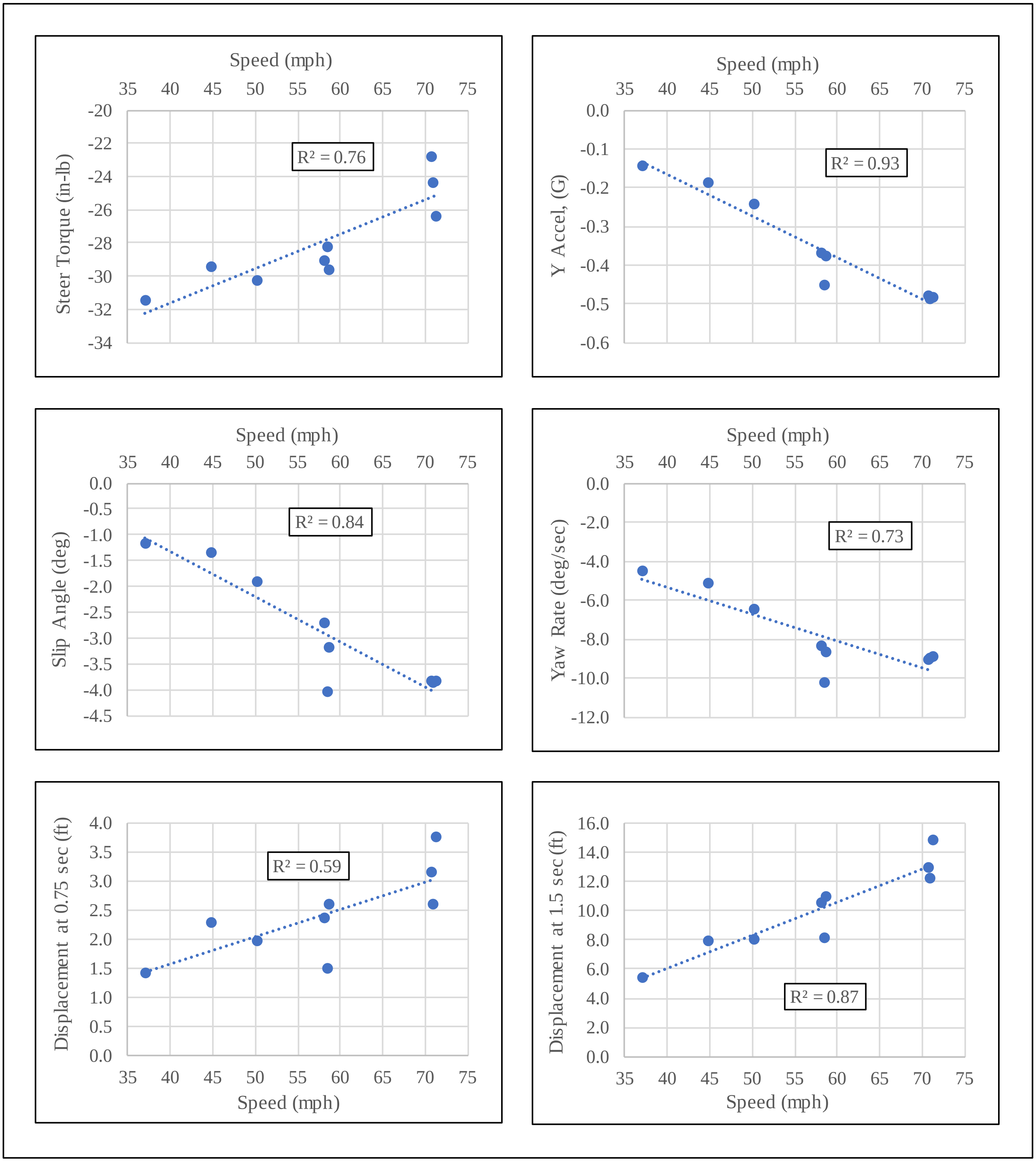

Figure 4. 2WD, Zero offset (Δ = -114), Responses vs Speed.