SAE International

2013-01-0776
Published 04/08/2013

doi:10.4271/2013-01-0776
saetransaf.saejournals.org

A Comparison of 25 High Speed Tire Disablements Involving Full and Partial Tread Separations

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ABSTRACT

Tire tread separation events, a category of tire disablements, can be sub-categorized into two main types of separations. These include full tread separations, in which the tread around the entire circumference of the tire separates from the tire carcass, and partial tread separations, in which a portion of the tread separates and the flap remains attached to the tire for an extended period of time. In either case, the tire can remain inflated or lose air. Relatively, there have been few partial tire tread separation tests presented in the literature compared to full tread separation tests. In this study, the results of 25 full and partial tire tread separation tests, conducted with a variety of vehicles at highway speeds, are reported. Cases in which the tire remains inflated and loses air pressure are both considered. The testing was performed on a straight section of road and primarily focused on rear tire disablements. The driver steering inputs required to keep the vehicle within its travel lane and the vehicle's dynamic response during the events were documented with video and data acquisition equipment. The results from the testing are presented and compared. It was found that the steering inputs required to keep the vehicle within its lane during a partial tread separation were similar in magnitude to those in the full separation testing. These results were also similar to the results of full separation testing documented by other researchers. In all cases, the vehicle was controlled within its lane with minor corrective steering. Figure 1 depicts video documentation and vehicle speed during one of the test runs.

CITATION: Beauchamp, G., Koch, D. and Thornton, D., "A Comparison of 25 High Speed Tire Disablements Involving Full and Partial Tread Separations," *SAE Int. J. Trans. Safety* 1(2):2013, doi:10.4271/2013-01-0776.

INTRODUCTION

Over the last several decades, there have been numerous tire disablement studies that have included various methods of tire testing. In general, those tests fall into one of three categories:

I. Tire tests performed on tire testing machines.

II. Vehicle tests with tires which had the tread previously removed, previously deflated tires, or modified "lumpy" tires.

III. Vehicle tests with tires prepared to facilitate tread separation or air loss at high speeds, driven by onboard drivers.

Figure 1. Example of Test Video

The current study focuses on the third category; tire disablements at highway speeds. Fifty-seven tire disablement tests, including tread separation or rapid air loss tests were reported in the previous literature dating back to 1987. In reviewing the testing discussed in the literature, several observations can be made. First, the majority of the testing focused on full tread separations. In all of the full tread separations, the driver controlled the vehicle with minor steering inputs. There are fewer partial tread separation tests reported in the literature than full separation tests. Of these, the majority of the tests were performed with a single make and model vehicle, a Ford Explorer with a solid rear axle. A table summarizing these tests appears in Appendix A followed by a discussion. For all the previous testing reported in Appendix A, the drivers made corrective steering inputs to keep the vehicle traveling a straight path or keep the vehicle in its lane of travel. Tests where the drivers were instructed to not steer, so that the vehicle's response alone could be recorded, were not included in Appendix A.

This study adds to the literature a number of partial separations across a wider selection of vehicles and also compares the results to full tread separation testing performed with the same vehicles. There do not appear to be any tests in the literature where a tread separation was accompanied by air loss. Testing that combined tread separation and air loss was included in this study.

TEST SITE

The test location in this study was a controlled access roadway that was regularly maintained and free of major defects. The asphalt roadway consisted of two opposing lanes of travel separated by a dashed yellow lane line. The roadway was bordered on either side by a downward sloping earthen shoulder. The length of the roadway was 2.1 miles and was relatively flat. The test surface had been resurfaced within the span of our testing. Figure 2 depicts the surface prior to resurfacing. Figure 3 depicts the testing site after the resurfacing. Weather conditions during each test day are summarized in Table 1.

Figure 2. Test Site Prior to Resurfacing

Figure 3. Test Site After Resurfacing

Table 1. Test Weather Conditions

	Temperature [°F]		Wind [mph]		Precipitation [in]
Test Date	High	Low	Speed (Direction)	Max Speed	
1/19/2012	59	32	8 (SE)	16	0.00
2/18/2012	35	12	7 (S)	12	0.00
3/21/2012	59	19	10 (W)	22	0.00
10/17/2012	57	35	18 (NW)	30	0.00
11/1/2012	69	41	8 (SSW)	13	0.00

TEST VEHICLES

Four vehicles from different manufacturers were used in the tread separation testing. These vehicles included two passenger cars, a Sport Utility Vehicle (SUV) and a minivan. All vehicles were retrofit with a roll cage, Summit racing seat and five-point safety harness. The vehicles tested were as follows:

Chevrolet Malibu

The four-door, 2004 model year Malibu LT was equipped with a 3.5-liter, 6-cylinder gasoline engine and a four-speed, front-wheel-drive automatic transmission. The Malibu has independent front and rear suspension. At the time of testing, the vehicle weighed approximately 3,270 pounds including instrumentation and driver, with a 64% front weight distribution. Prior to testing, the Malibu was inspected at a service center and was found to be in roadworthy condition. Figure 4 depicts the Malibu.

Figure 4. Test Chevrolet Malibu

Ford Expedition

The 2003 model year Expedition XLT was equipped with a 4.6-liter, 8-cylinder gasoline engine and a four-speed, rear-wheel-drive automatic transmission. The Expedition has independent front and rear suspension. At the time of testing, the vehicle weighed approximately 5,425 pounds including instrumentation and driver, with a 49% front weight distribution. Prior to testing, the Expedition was inspected at a service center and was found to be in roadworthy condition. Figure 5 depicts the Expedition on the day of the testing.

Figure 5. Test Ford Expedition

Dodge Caravan

The 2003 model year Caravan SE was equipped with a 3.3-liter, 6-cylinder gasoline engine and a four-speed, front-wheel-drive automatic transmission. The Caravan has independent front suspension and a live rear axle. At the time of testing the vehicle weighed approximately 4,026 pounds including instrumentation and driver, with a 59% front weight distribution. The Caravan was inspected and driven prior to testing and found to be in roadworthy condition. Figure 6 depicts the Caravan on the day of the testing.

Figure 6. Test Dodge Caravan

BMW 323i

The 1999 model year BMW was equipped with a 2.5-liter, 6-cylinder gasoline engine and a four-speed, rear-wheel-drive automatic transmission. The BMW has independent front and rear suspension. At the time of testing, the vehicle weighed approximately 3319 lbs including instrumentation and driver, with a 51% front weight distribution. The BMW tested was equipped with electronic stability control (ESC). Prior to testing, the BMW was inspected at a service center and was found to be in roadworthy condition. Figure 7 depicts the BMW on the day of the testing.

Figure 7. Test BMW 323i

TIRE PREPARATION

A variety of tires from different manufacturers were used in the testing. Tires were prepared to facilitate the tread and top belt separating, either fully or partially. First, a single cut was made across the tread of the tire along the belt bias. This cut went through top nylon cords, as depicted in figure 8. The shoulder on both sides of the tire was then cut around the entire circumference for full tread separations or around a portion, either 90 degrees or 180 degrees, for partial separations, as depicted in Figure 9. Cut depths into the shoulder were on the order of two inches, which initiated tread separations at highway speeds. For the Malibu, Expedition and Caravan tests, the tires were prepared to facilitate tread separation in the leading direction. In other words, the tread was cut so that the tread would peel off of the tire in the direction opposite of rotation, as depicted in Figure 10.

Figure 8. Example of bias cut across tread

Figure 9. Example circumferential shoulder cut

For the BMW, one tire was prepared for a full tread separation using the procedure discussed above. Several tires were prepared to partially separate in both the leading/peeling and the trailing/lifting direction. Figures 10 and 11 graphically depict the difference between leading and trailing separations. In Figures 10 and 11, the vehicle is traveling from left to right across the page, from position 1 to 3. In both Figures, the tread flap, which is in the process of separating, is indicated in red.

Figure 10. Leading/peeling separation

Figure 11. Trailing/lifting separation

Several tires were prepared to facilitate partial separation and air loss. In order to cause rapid air loss, detonation cord was placed on the inside of the tire across its width. The explosives were set so that they could be remotely detonated once the vehicle reached the desired test speed, or alternatively, to detonate after the tread separation had initiated. The amount of explosive chosen, determined through testing of stationary tires, was enough to deflate air rapidly without damaging the vehicle. Figure 12 depicts the detonation cord on the interior of one of the test tires. Figure 13 depicts a mounting bracket on the exterior of the rim that held the receiver in place. The trigger remote is depicted in Figure 14, affixed to the steering wheel of the test vehicle.

Figure 12. Detonation cord on the interior of the tire

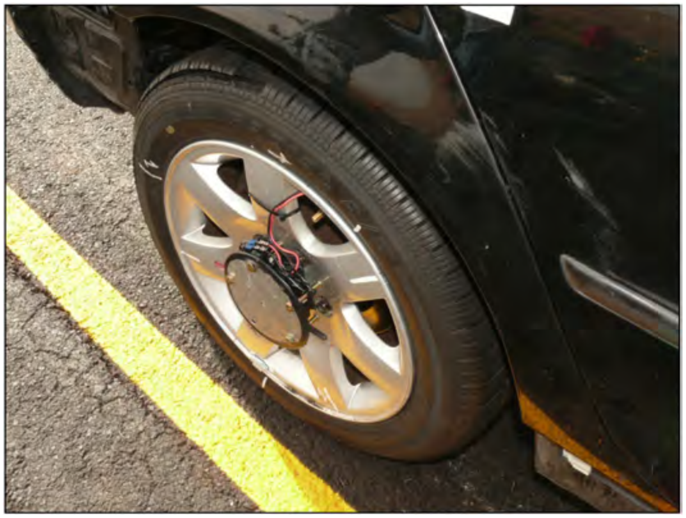

Figure 13. Plate securing the detonator

Figure 14. Remote detonating device

FULL SCALE TESTING

Instrumentation

The test vehicles were instrumented with data acquisition equipment from Racelogic. Specifically, the VBOX IISX + Slip, Pitch and Roll Angle recorded the vehicle's speed, as well as angular and translational position during the tests. A VBOX Inertial Measurement Unit (IMU) containing a three-axis accelerometer and yaw rate sensor was placed near the vehicle's center of gravity. In later tests, a second three-axis accelerometer was also placed near the vehicle's center of gravity and that data was logged with a National Interments 9234 Measurement System. The steering torque was recorded with a Futek torque sensor. When possible, the vehicle CAN Interface recorded wheel speeds and steering position from the vehicle's internal computer. Aftermarket sensors were utilized in some tests when the CAN interface was not supported. A minimum of three video cameras were utilized in each test. The first recorded the driver from inside the test vehicle at a rate of 29.97 frames per second. The second camera was affixed to a follow vehicle and recorded the motion of the test vehicle from that vantage point at a rate of 29.97 frames per second. A third camera was affixed to the outside of the test vehicle and recorded the subject tire at a rate of 120 frames per second.

Pretest

Prior to running any tire disablement tests, the vehicles were weighed and photographed. Slow speed runs were conducted to zero out the accelerometers. Torque and steering sensors were calibrated. A pre-disablement run with four unaltered tires was then conducted to confirm that the instrumentation and cameras were operational.

Test Protocol

A prepared tire was placed in the desired location. The vehicle was then accelerated up to the desired test speed. In several runs, the tread began to separate from the tire before the desired test speed was reached. During the BMW testing, some of the events were initiated by remotely detonating explosives within the tires once the desired test speed was achieved. When the tire disablement began, the driver removed his foot from the accelerator, did not apply the brakes, and correctively steered the vehicle to keep it within its lane of travel. The test drivers were aware that the tire disablement would occur. The driving was performed by Gray Beauchamp and Stephen Fenton from Kineticorp, LLC.

TESTING RESULTS

Initially, all the vehicles responded similarly during all of tread separation events. There was a buildup in vibration and noise as the tread began to separate. When the tread began to peel off, the noise and vibration increased in intensity. As the flap of tread interacted with the ground and parts of the vehicle, it created a longitudinal force at that wheel that pulled the vehicle slightly towards the side of the vehicle with the separating tire. The tire flap caused significant damage to the vehicle in many cases. In order to maintain lane position, the driver steered slightly in the opposite direction. For example, during a tread separation of the left rear tire, the vehicle pulled slightly to the left and the driver steered slightly to the right to remain within the lane. In the case of air loss, the flat tire again created a slight pull towards that side of the vehicle. These initial trends were true in all cases, regardless of whether the event involved a rear or front tire, was a partial or full tread separation or whether the tire did, or did not, retain air. The steering torque required to keep the vehicles in their lanes was small, and slightly greater than what is required to maintain lane position with four new tires. The torques during the disablement events were significantly less that the torques recorded when the driver turned the vehicle around at the end of the test road.

Prior to analyzing any of the recorded data, the three video clips from each run were synced with one another, and then synced to the instrumentation data. A visual signal captured by all three cameras was used for syncing. A screen capture from one of the test runs, showing all three camera perspectives, was depicted earlier in Figure 1. In many tests, the visual signal for the cameras corresponded to the beginning of the VBOX data. Through analysis of the high speed video, the initial movement of the vehicle in the video was confirmed to be the initial movement of the vehicle in the VBOX data. The beginning of the disablement event was then identified as time zero for each run. The beginning of the event was defined as the first time a tread flap of significant size was visible in the video. This time in the video corresponded to a drop in wheel speed and the beginning of lateral movement of vehicle.

A summary of data collected during the each run is summarized in Appendix B. In Appendix B, the weight of the vehicle is the test weight including the driver. The speed column indicates the speed of the vehicle when the tread separation began. The duration column is the time from the initiation of the event until tread detached from the tire. In some partial tests, the tread flap remained attached until the vehicle came to rest. In other cases, a 180 degree flap detached and the remaining tread remained on the tire. The maximum lateral deviation is the lateral movement towards the side of the vehicle with the disablement as a result of the event. Lateral vehicle movement between 3 and 27 inches resulted during the testing. In each event, the driver was required to steer to remain in the lane. The maximum steer angle indicates the driver's maximum initial steer away from the side with the disablement. As shown, the driver steered between 6 and 32 degrees. Appendices C, D, E, F, G, H depict graphical results for each run.

Chevrolet Malibu

Nine successful tests were conducted on January 19, 2012 and February 18, 2012. A successful test was defined as one where highway speed was achieved prior to separation, the instrumentation successfully recorded the event, and a substantial flap separated from the tire. Not all of the runs were successful. On January 19, 2012, all tests runs were full separations at the rear left location, at speeds between 60 and 66 mph. On February 18, 2012, the tests included two full tread separations (M02, M06) and three partial separations (M05, M07, M08), all at the rear left tire at speeds between 70 and 80 mph. All tread separations were in the leading direction. The full separations lasted between 1.1 and 5.7 seconds. In one of the partial tests, the entire tread came off of the tire after 6.4 seconds (M07). In the other two partial tests, the tread flap remained attached until the end of the test (M05, M08). The vehicle remained in its lane with steering inputs under 32 degrees. The maximum lateral deviation was 24 inches, and occurred during a full separation. In the full tread separation tests, two steering inputs were required to keep the vehicle in its lane. As the tread was coming off the tire, the driver steered to the right. When the tread released, the driver steered to the left. In other tests, the tread flap remained attached until the vehicle came to rest. In these tests, steering in one direction, to the right, kept the vehicle in its lane. The test results are summarized in the table of Appendix B. Appendix C and D include plots from the Malibu tests.

Ford Expedition

Seven successful tests were conducted on March 21, 2012 and October 17, 2012. These included four full tread separations (E01, E02, E03, E04), three at the rear left tire and one at the front left tire. Three partial tread separations at the rear left tire were also conducted (E05, E06, E07). All tread separations were in the leading direction. Test speeds ranged between 50 - 78 mph. In all runs, the vehicle remained in its lane with steering inputs under 28 degrees. The full separations lasted between approximately 0.5 seconds and 2 seconds. In all three partial tests, the tread flap detached, leaving half of the tread on the tire. The flap detachment occurred between 1.75 and 7.5 seconds of the initiation of the event. The maximum lateral deviation, 27 inches, and maximum steering input, 28 degrees, occurred during test E01, a full separation. In test E01, the tire lost air in the early stages of the detachment. The air loss was not expected during this test. The tread then came fully off of the tire approximately one second later. In this test, the effects of the air loss dominated and a drag force remained at the rear left tire until the vehicle came to a controlled rest. Steering in a single direction, to the right, was required to keep the vehicle in its lane, similar to Malibu partial tests M05 and M08. For all other Expedition tests, the driver made an additional steering input, either when the full tread or flap detached from the tire. The front tread separation was similar to the rear tread separations, consistent with the findings of other researchers.12 The Expedition test results are summarized in the table of Appendix B. Appendices E and F include plots from the Expedition tests.

Dodge Caravan

Four successful tests were conducted on October 17, 2012. These included two full tread separations and two partial separation tests at the rear right tire. All tread separations were in the leading direction. Test speeds ranged between 54 - 75 mph. In all runs, the vehicle remained in its lane with steering inputs under 25 degrees. The full separations (C01, C02) were approximately one second in duration. In both partial tests (C03, C04), tread around the entire circumference detached approximately six seconds after the initiation of the event. The maximum lateral deviation of 27 inches and maximum steering of 25 degrees occurred during test C04, a partial separation test. High speed video of both tires was synced and reviewed. The rear tire on the opposite side of the separation remained on the ground during the tests. In all tests, the driver reversed steering direction when the tread released. The test results are summarized in the table of Appendix B. Appendix G includes plots from the Caravan tests.

BMW 323i

Five successful tests were conducted on November 1, 2012. These included a full tread separation, blowout tests, a partial separation, and a partial separation with blowout, all at the rear right position. The blowouts were created using cord explosives placed inside the tire spanning its tread width as discussed earlier. Test speeds ranged between 70 and 81 mph. The full separation lasted 1.6 seconds. Test B03 and B04 were prepared with explosives and pre-cut, such that the driver could accelerate to speed and detonate the explosives, causing a blowout and initiating the tread separation. In B06, the tire was prepared to facilitate a trailing direction partial separation, in which the tread lifted off of the tire in the direction of tire rotation, and also prepared for blowout. In test B06, the driver accelerated to speed until the tire tread began to separate, and then detonated the explosives. In test B07, the tire was prepared to separate partially in the trailing direction. No air loss occurred in test B07. In all runs, the vehicle remained in its lane with steering inputs under 21 degrees. The maximum lateral deviation was 21 inches, and occurred during a blowout. Tests involving blowout required steering in one direction. When the tire remained inflated, successive steering was required when the flap or full tread released. Partial separations in the trailing direction produced minor vehicle lateral motion and the driver kept the vehicle within the lane with steering inputs under 10 degrees. The test results are summarized in the table of Appendix B. Appendix H includes plots from the BMW tests.

DISCUSSION

Roadway Physical Evidence

Following each run, the physical evidence deposited on the roadway was documented. During each test, a single tire mark was deposited by the separating tire. The marks were irregular and non-continuous, consistent with the tread flap striking the ground. When the tread released from the tire, the tire mark ceased. IF the tread flap remained attached, the tire mark continued until the vehicle speed reduced considerably. When air loss occurred, the tire mark was noticeably different. Specifically, the mark was still irregular, but more continuous than when the tire retained air pressure. When air loss occurred, the edges of the tire mark were darker, as a result of point loading from the rim. Figure 15 depicts a tire mark from a full tread separation test. As depicted, the tire mark ends, corresponding to the release of the tread. The tread can be seen in Figure 15, beyond the tire mark. However, the end location of the tread didn't necessarily correspond to the location the tread released from the tire. In several tests, the tread became entangled with the vehicle and was carried a significant distance down the roadway before being deposited. Figure 16 is the mark from a partial tread separation test. The tread remained attached throughout this test and the mark continues until near the vehicle rest position. In Figure 17, the tire lost air during a full separation event. The mark in this case continued beyond the tread flap, as depicted, due to the lack of air pressure.

Figure 15. Tire mark from a full tread separation test

Figure 16. Tire mark from a partial tread separation

Figure 17. Tire mark from a full tread separation with air loss

Vehicle Physical Evidence

The damage to the vehicle was documented after each test. Running multiple tread separation events with a single vehicle produced significant vehicle damage, primarily in the rear quarter panel area. The damage was repaired periodically using bailing wire to retain the basic shape of the rear quarter panel. In the Malibu, the rear quarter panel was eventually destroyed completely, so a quarter panel was fabricated from steel sheeting. This modified structure was torn from the vehicle in the final test. Figure 18 depicts the final condition of the Malibu. No identifiable differences in vehicle dynamics were noted for different pretest vehicle conditions. In some tests, the damage to the vehicle as a result of that test was minor, limited to light scuffing. In others, the structure was damaged significantly. However, vehicle movement and subsequent driver steering was minor in all cases. Damage to the vehicle from the tread engagement was not an accurate indicator of vehicle controllability.

Figure 18. Damage to Malibu test vehicle

The number of tire slap marks on the vehicle was not a good indicator of duration, lane deviation or required steering input. For example, consider the first Caravan test and first Expedition test. Both disablements were under one second in duration and in both cases the vehicle was kept within its lane with minor steering inputs. Both vehicles exhibited damage to the rear taillights. The Expedition exterior was essentially clean of slap marks after the first test, as depicted in Figure 19. By contrast, the Caravan had extensive slap marks on its exterior, extending from the rear of the vehicle to the sliding door, as depicted in Figure 20. The rear bumper cover and rear tailgate were also dented significantly.

Figure 19. Ford Expedition following test E01

Figure 20. Ford Expedition following test C01

In test C04, a partial separation with the Dodge Caravan, a portion of the tread became lodged in the axle assembly and the parking brake cable was damaged significantly. The wheel speed sensor was also damaged during this test. Figures 21 and 22 depict the tread and parking brake cable, respectively, following the test. The specific effect of the parking brake interaction is unclear. In any case, the vehicle was kept within its lane with steering inputs less than 25 degrees.

Figure 21. Tread lodged following test C04

Figure 22. Damage to parking brake cable following test C04

Tire Physical Evidence

In the full separation tests for the Malibu, Expedition, and Dodge, the tread came off of the tire in one piece. During the BMW full separation test, the tread broke into several pieces. Whether the tread came off in one piece or several pieces, the vehicle was kept in its lane with minor steering adjustments. Multiple pieces of tread were not a good indicator of either the duration of the event or controllability. Figure 23 depicts a tire following a full separation. Note that no tread remains on the shoulders of the tire. Tires that were prepared to partially separate varied in their final condition after the tests. For the Malibu testing, the flap remained attached to the tire for the duration of two of the tests. The ends of the flap were frayed and damaged extensively, as depicted in Figure 24. In other partial tests, the tread eventually came off the tire around its entire circumference, but portions of the shoulder tread remained attached, as depicted in Figure 25. In other partial tests, the flap detached but 180 degrees of tread remained firmly attached, as depicted in Figure 26. When portions of tread remained on the tire, there was noticeable vibration until the vehicle came to rest. Although the vehicle tracked straight with little or no steering, the driver was aware that there was a problem with the tire following the separation through the vibrational feedback as the vehicle traveled to rest.

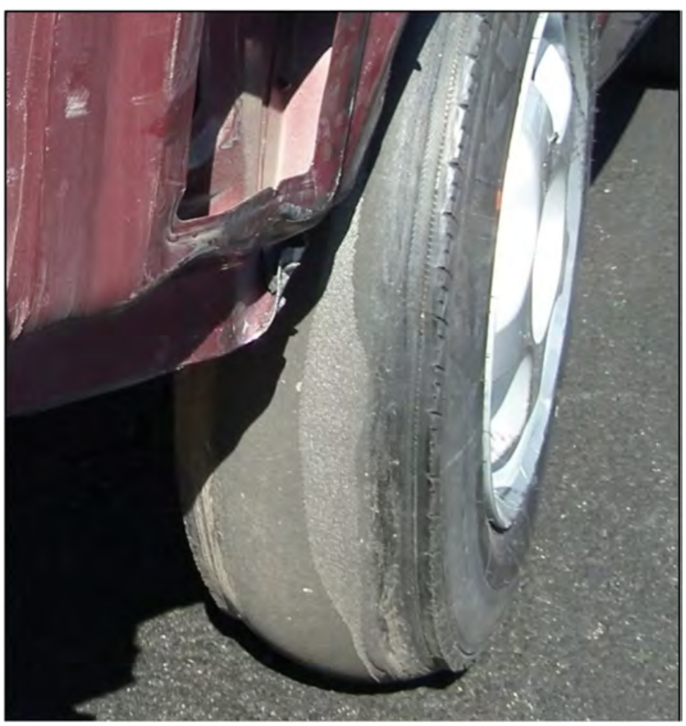

Figure 23. Tire following a full tread separation test

Figure 24. Tire following a partial tread separation test where the tread flap remained attached

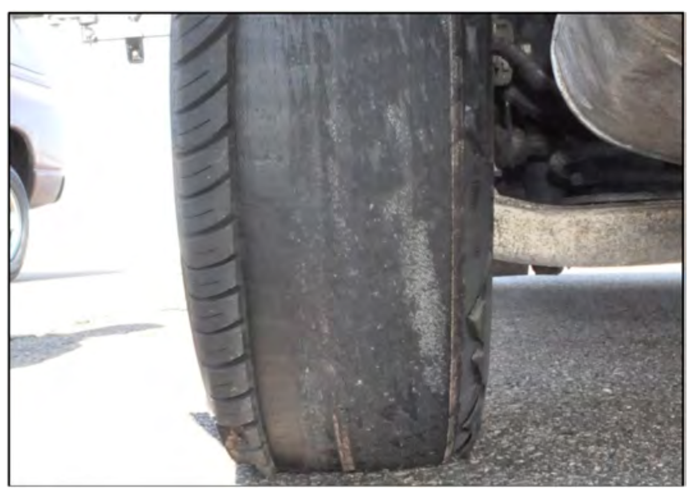

Figure 25. The tire following a partial tread separation test where the tread detached around the entire circumference, but some shoulder tread remained attached

Figure 26. The tire following a partial tread separation test where the tread flap detached leaving 180 degrees of tread remaining on the tire

During the Expedition test E01, the tire was prepared to facilitate full tread separation. During the early stages of the separation, the tire lost air rapidly. The tire split across the width of the tire and on both sidewalls. Figure 27 depicts the tire from test E01.

Figure 27. Tire following a full tread separation with unintended air loss

During the BMW tests, the tires were prepared in a variety of ways, and the post-test tire condition varied as well. Figure 28 depicts the tire following test B06, a trailing partial separation test with air loss. In test B04, the tire was prepared to blowout, initiating a partial separation in the leading direction. More explosives than were required were utilized in this test, resulting in severe tire damage. The outer tread belt did not separate from the tire. Rather, a large hole was blown through the tire, creating a large flap of both belt layers. Figure 29 depicts the tire from test B04. Figure 30 depicts the tire following test B07, a partial separation in the trailing direction. Approximately 90 degrees of tread detached during this test and the tire remained inflated.

Figure 28. Tire following a trailing partial separation with air loss

Figure 29. Tire following a blowout

Figure 30. Tire following a partial separation in the trailing direction

Disablement Types

The largest difference between the full and partial tread separation events were the number of steering inputs that were required by the driver. For example, during a left rear full tread separation, the vehicle pulled slightly to the left while the tread was coming off. In response, the driver steered slightly to the right. This right steering input was held, maintaining a straight vehicle path until the flap released from the tire. When the tire tread released, the effective braking force at that wheel ceased, and the vehicle began to move slightly back to the right. The driver then steered slightly to the left. Thus, in a full tread separation event, two minor steering inputs were required to keep the vehicle in its lane. During a partial tread separation at the rear left tire, the vehicle again pulled slightly to the left, similar to the full separation. Similarly, the driver steered to the right to remain in the lane. In some of the partial tests, the tread eventually did come off or some of the tread came off and some remained on the tire. These tests were similar to full tread separation events except there was a longer delay between the first and second steer inputs. In the partial tests in which the tread flap remained attached until the vehicle came to rest, only one steer input was required. This was also the case if the tire lost air, regardless of how much of the tread came off the tire.

Event Duration

In this test series, the tread separations lasted between approximately 0.5 and 48 seconds (or until the vehicle came to a controlled stop). Duration of the event was not a good indicator of lateral deviation or required steering. For example, the smallest lateral deviation of 2 inches occurred in run number 02/18/12-M05, a rear partial separation in which the tread never detached from the tire. In all cases, as the tread began to separate, the driver steered slightly to keep the vehicle in its lane. If the event took longer, the driver was typically required to hold the steering input longer.

Vehicle Differences

All vehicles in all tests were kept within their lane of travel with steering inputs less than 32 degrees. There were differences between tests, and different vehicle/disablement combinations yielded different lane deviations and required steering inputs. However, no substantial differences among vehicles were identified in this test series.

CONCLUSIONS

1. In each tread separation test, noticeable noise and vibration occurred before the vehicle began to move laterally.

2. During each tire disablement, a drag force was created at the location of the modified tire. This force had the effect of pulling the vehicle slightly towards the side of the disablement.

3. In response to the vehicle pull, the test drivers steered away from the side with the disabled tire.

4. If the tire lost air during the test, the drag force remained at that tire until the vehicle came to rest, which required the driver to maintain one steering input away from the side with the disablement.

5. If the tread separated partially and the tread flap remained connected to the tire, the drag force remained at that tire until the vehicle came to rest, which required the driver to maintain one steering input away from the side with the disablement.

6. During full tread separations, the driver initially steered away from the side with the disablement. Once the tread detached from the tire, the drag force ceased, and the driver was required to steer slightly back towards the side with the disablement. Partial separations in which the tread flap eventually detached were similar to the full tread separation tests except the initial steering input was held for a longer time.

7. There were no substantial differences identified between the test vehicles in terms of lateral deviation or required steering inputs. Included in the test set were several vehicle classes with a variety of drivetrains and suspensions.

8. Evidence deposited on the vehicle, such as the number of tire slap marks or damage, was not a reliable indicator of required steering or lateral deviation.

9. The duration of the tread separation event was not a reliable indicator of lateral deviation. Longer events typically required the drivers to hold steering inputs for a longer duration.

10. Partial and full tread separations were conducted at highway speeds with vehicles that had both solid axles and independent rear suspensions. For all vehicles and all disablement types, vehicles were all kept within their lanes with steering corrections less than 32 degrees.

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ACKNOWLEDGMENTS

The Authors would like to thank Stephen Fenton and Will Bortles from Kineticorp for their assistance during the testing and helpful comments. Also, the authors thank William Neale, Toby Terpstra and Eric Thomas from Kineticorp for their assistance with graphics and video production. The inclusion of several air loss cases requiring explosives would not have been possible without the assistance of James Milligan and Chris Rink of FX West. Testing in this study was funded by Kineticorp, Cooper Tire & Rubber Company, and Pep Boys.

APPENDIX

APPENDIX A - Summary of Testing in the Literature

Year	Author	Vehicle	Location	Speed (mph)	Steering (deg)	Disablement
1987	Gardner	1985 Ford Pickup	RL	55	10	Blowout
		1981 Chevrolet Van	RR	55	54	
		1983 Ford Wagon	RL	55	56	
1998*	Gardner	1994 Ford Explorer 1996 Toyota Camry Station Wagon 1993 Chevrolet Pick-up	RL RL RR	53.4	12.5	Full Separation
				57.2	16.16	
				54.1	12.31	
				58.3	22.81	
				59.6	40.07	
				60.4	22.52	
				60.4	33.92	
				58	42.81	
				57.9	40.5	
1999	Fay	1993 Ford Taurus GL SR5	RL	71+	Little to No Steering	Full Separation
			FL	65		
			FR	50-55		
			RR	65		
			RL	70-75		
			FL	60-65		
			FR	67		
			RR	70		
			FL	70		
			FR	50		
			RR	65		
			FL	70		
1999**	Klein	1989 Nissan Pathfinder	RR	55	~15	Full Separation
			RR	55	~15	Full Separation
		1982 Chevrolet Pickup	-	50-60	~15	Full Separation
2007	Durisek	1999 Ford Explorer 4x4	RR	60	19	Full Separation
			RR	56	20	
2007	Tandy	1999 Ford Explorer 4x4	RR	67	22	Full Separation
			RR	60	20	
			RR	77	23	Distressed Full Separation
2007	Tandy	Ford Explorer	RR	70	90	Partial Tread Separation
			RR	~70	small corrections	
2011	Tandy	1999 Ford Ranger 4x2	RR	69	15	Full Tread Separation
		2000 Ford Windstar	RR	70	3	
		1992 Ford Explorer 4x2 2dr	FR	57	5	
			RR	72	12	
		1994 Ford Explorer 4x4 2dr	RR	72	17	
		1998 Ford Explorer 4x4 4dr	RR	70	17	
		1999 Isuzu Rodeo 4x2 4dr	FR	70	20	
			RR	68	20	
		1997 Ford Explorer 4x2 4dr	RR	73	13	
			FR	73	24	
		2001 Ford Expedition 4x2 4dr	RR	73	6	
		2000 Ford Excursion 4x4 4dr	RR	70	21	
			FR	75	26	
		2002 Ford Excursion 4x2 4dr	RR	71	17	
		1997 Land Rover Discovery 4x4 4dr	RR	65	18	
		2000 Ford Ranger 4x2	RR	69	19	
		1996 Ford Ranger 4x4	FR	70	38	
			RR	68	15	
		2002 Nissan Pathfinder 4x2 4dr	RR	73	12	
		2003 Ford Expedition 4x2 4dr	RR	61	9	
			FR	66	12	
		2000 Ford F-150 4x2 2dr	RL	68	22	
		1999 Ford Explorer 4x4 4dr	RR	57	8	

*** The authors do not specify which vehicle was used for each test. Steering angles measured "peak to peak"**
**** The authors do not report steer angles . A plot from Gardner is shown and Klein's results are said to corroborate that work.**

In 1987, Gardner [1] reported the results of three rear tire blowout tests. The vehicles tested were a 1985 Ford pick-up, 1981 Chevrolet van and 1983 Ford Club Wagon. The maximum steering inputs for each vehicle were documented for blowouts occurring at 55 mph. The maximum steering angles for the Ford pick-up, Chevrolet van and Ford Club Wagon were 10 degrees, 54 degrees and 56 degrees, respectively. The mechanism used to cause the blowout was not discussed.

In 1998, Gardner [2] conducted tread separation testing with a 1994 Ford Explorer, 1996 Toyota Camry station wagon, and 1993 Chevrolet pick-up. The steering wheel torque and steering angle to maintain control of the vehicle during the rear tire tread separation events were recorded. Based on the time associated with the events, they are presumed to be full separations, although this was not specifically reported. No air loss was reported for any of the tests. Disablements were reported to occur between 53.4 and 60.4 mph. Steering wheel angles between 12.31 and 42.81 degrees were executed by the test drivers. It is unclear which vehicle was used for each reported result. The author concluded that forces developed during a tread/belt detachment are well within the range of a driver's ability to control a vehicle. Steering torques during tread separation events were described to be comparable to lane change maneuvers.

In 1999, Dickerson [3] conducted full tread separation testing using a 1989 Ford Bronco II. The vehicle was accelerated to the desired test speed with a modified tire in the rear right location. When the tread separated, the driver held the steering constant and did not respond until it was necessary to keep the vehicle on the track. The response of the vehicle was documented. Three runs are reported. In all runs, the modified tire maintained air pressure and the tread fully detached from the tire. The authors reported a loud banging noise while the tread was detaching. After the tread had separated from the tire, the authors reported that there was no feedback to the driver that there was a problem with the tire. During the event, the vehicle pulled towards the side of the modified tire.

In 1999, Fay [4] conducted nine tread separation tests with a 1993 Ford Taurus sedan. A modified tire that had been cut to facilitate a full tread separation was placed at various tire locations. The test vehicle was accelerated to speed, and a tread separation event ensued. Separations occurred at speeds between 50 and 75 mph. The driver was instructed to hold the steering wheel steady and maintain the vehicle's previous path. Some of the separations occurred on straight stretches of the track, others on curves. During the tread separation, a loud noise was noted that terminated after the tread fully detached from the tire. The authors reported that little or no corrective steering was needed to maintain the vehicle's path. No specific steering inputs were reported. There was no report of any of the tires losing air pressure during any of the tests. In all tests, torque at the steering wheel was reported to be less than what was required during a parallel parking maneuver.

In 1999, Klein [5] reported the results of full tread separation testing with a 1989 Nissan Pathfinder and 1982 Chevrolet pick-up. Tires were cut to facilitate full tread separations at speeds between 50 and 60 mph. The author noted that vibration and noise increased for up to 10 seconds preceding the detachments. In all runs, the vehicle was brought to a controlled stop. No tire air loss was reported in any of the tests. No specific steering inputs were given, however, the inputs were qualitatively described as being on the order of a lane change, and consistent with the results of Gardner's 1998 paper [2].

In 2001, Arndt [6] conducted full and partial tread separations with a 1993 Ford Taurus and 1996 Ford Explorer. Rear tires were cut to fully or partially separate at speeds from 30 mph to in excess of 73 mph. Vehicle acceleration, velocity, yaw, pitch, roll, and steering angle were monitored. During the testing, the drivers were instructed to hold the steering wheel at a constant angle before, during and after the tread separation event. No air loss was reported in any of the tests. The authors reported that the amount of lateral path deviation was influenced by the vehicle speed and duration of the tread separation. Specifically, longer tread separations at higher speeds resulted in larger lateral path deviation. In the case of the partial tread separation testing, the driver was able to redirect the Taurus with steering. During the Explorer testing, the driver was not able to redirect the vehicle, and it subsequently spun out and rolled over. In a later paper [7], the authors analyzed the cause of the unintended rollover. It was noted that, by themselves, forces during a tread separation are insufficient to cause the motion that preceded the rollover in their test. It was concluded that a special wheel hop condition known as axle tramp, when one side of the axle moves upward while the other side moves downward and vice versa, was responsible for the vehicle's rapid turn. It was stated that axle tramp may occur in solid axle vehicles. Negative changes to the vehicle handling due to axle tramp were said to exceed changes to the vehicle from removing the tread alone.

In 2007, Tandy [8] examined two partial tread separation tests that involved large lateral deviation, both involving Ford Explorers with solid rear axles. Case #1, also known as 2030 G, was a test run by Arndt that terminated in the vehicle rolling over (discussed above). According to Tandy, the run before 2030 G (2030 D) was run under the same conditions but the vehicle did not deviate its path. Case #2 was a partial tread separation of the right rear tire run by Carr Engineering, also known as test R10. The tire had been cut to stage a 180 degree partial tread separation. The Explorer was accelerated up to 70 mph, and during the tread separation, the vehicle was pulled to the right into the adjacent lane. The driver retained control over the vehicle with relatively large steering inputs, approximately 70 degrees to the left initially followed by a counter steer of approximately 90 degrees to the right. A previous test run under the same conditions, test R08, was kept within its lane with minor steering corrections. The authors concluded that the vehicles were not in pure axle tramp mode. Further, the authors analyzed the longitudinal acceleration in each test and concluded that the deviation was due to a large longitudinal deceleration force created by the tire detachment and not due to axle vibration. The exact mechanism for these two tread separations is stated as not clear, however, it was stated that the drag force and yaw response are independent of vehicle type and suspension type.

In 2007, Durisek [9] conducted two full tread separation tests with a 1999 Ford Explorer. The rear right tire in each test was cut to facilitate tread separations at highway speeds. The authors noted noise and vibration early in the test runs that increased in intensity preceding the separation events. Separations occurred at speeds of 56 and 60 mph and in each case, the vehicle remained in its travel lane with steering inputs less than 25 degrees. No air loss was reported in any of the tests. The tread separation did not force the vehicle out of the driver's control.

In 2007, Tandy [10] compared full tread separation tests using circumferentially cut tires to a test using a distressed tire. The circumferentially cut tires were cut to facilitate tread separation at highway speeds (2 of these tests were also included in Durisek's 2007 paper of which Tandy was co-author). A cut tire was placed at the rear right position of a 1999 Ford Explorer and the vehicle was accelerated to highway speeds and driven until the tread detached. The driver steered to keep the vehicle in its lane. The pre-cut tires separated at speeds between 60 and 67 mph. The cut tires were tested at an inflation pressure of either 15 or 26 psi. The authors also prepared a tire to separate by the process of distressing. The distressed tire underwent several procedures aimed to breakdown the tire material and allow the tire tread to detach without any preparatory cuts. The procedure is explained in detail by the authors. The distressed tire was placed at the rear right position of a 1999 Ford Explorer and the vehicle was accelerated to highway speeds and driven until the tread detached. The distressed tire was inflated to 15 PSI. The vehicle was accelerated to highway speed and was driven around a track for over four hours before the tread detached from the tire. Over the four hours, noise and vibration steadily increased until the tread separated at a speed of 77 mph. In all tests, the vehicle pulled slightly towards the side with the modified tire and the vehicle was kept within its travel lane with steering inputs less than 25 degrees. None of the vehicles were forced out of the driver's control. In all cases, the tread separated from the tire in approximately 1-2 seconds. No tire air loss was reported. The vehicle responses were similar for distressed and circumferentially cut and distressed tires and across the range of tire inflation pressures. The authors concluded that circumferentially cutting tires is an appropriate method for staging a tread separation event.

In 2011, Tandy [12] reported the results of full tread separations of seventeen different vehicles. The tests included a minivan, and SUV's and Pick-ups of various sizes. Tires were cut to facilitate full tread separations. Prepared tires were placed in rear and front locations. The vehicles were accelerated to highway speeds and tread separations occurred between 57 and 73 mph. The separations were reported to last 1 - 2 seconds, during which the vehicle was pulled slightly towards the side of the disablement. The steering inputs required to keep the vehicle within its lane of travel were recorded. For rear separations, steer inputs ranged from 3 - 21 degrees. These were slightly less than front tire separations, which ranged between 5 - 38 degrees. The authors noted no considerable differences between vehicle types, drive type, suspension type, or tire size (all tires tested were within the manufacture's range).

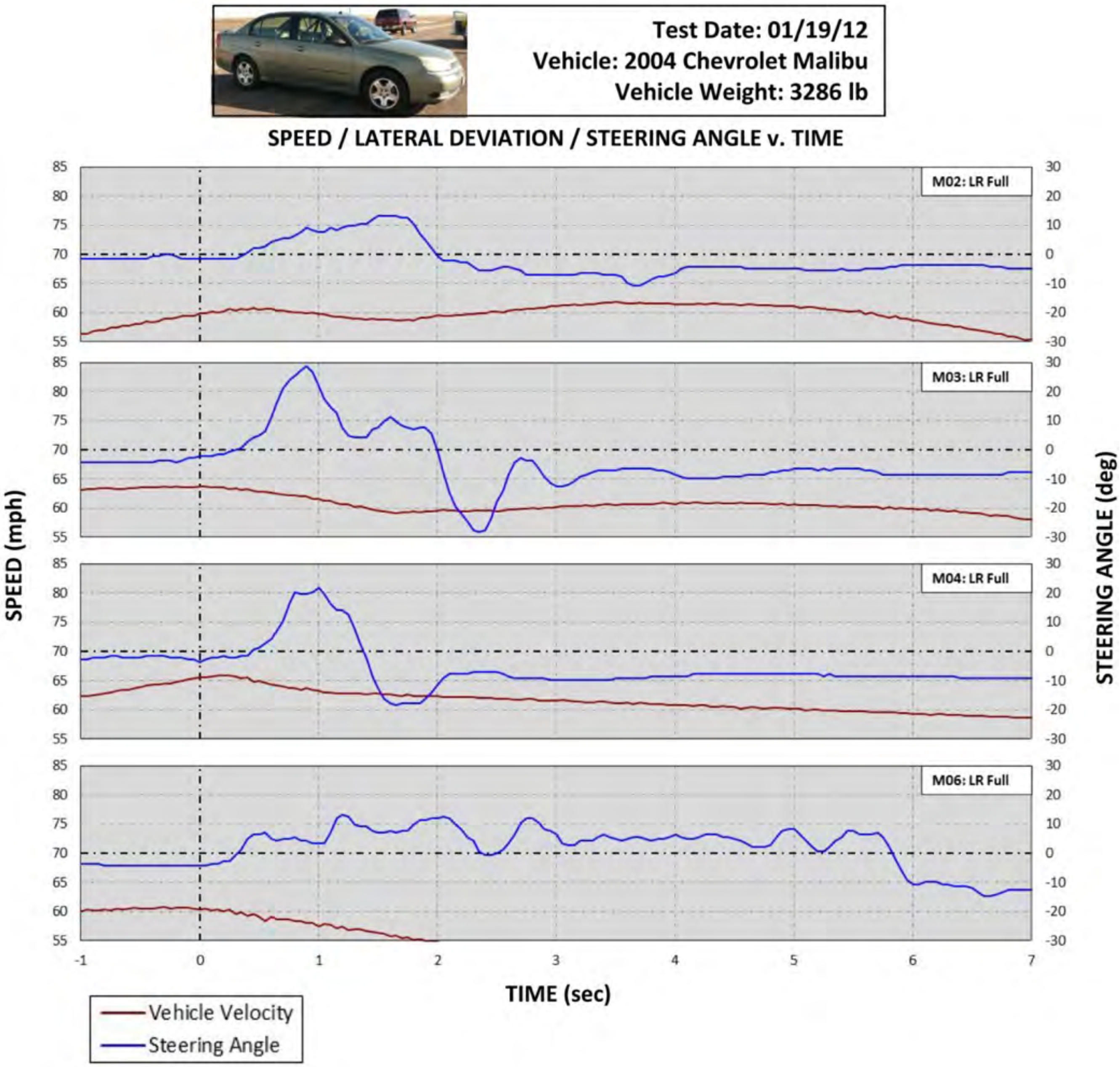
APPENDIX B - Summary of Test Results

Vehicle	Drive	Suspension	Weight	Run Number[1]	Speed[2] (mph)	Tire Preparation[3]	Prepared Tire Location	Duration[4] (sec)	Steering[5] (deg)	Lateral Deviation[6] (in)
 2004 Chevrolet Malibu	FWD	Independent	3286 lb	01/19/12-M02	61	Full	RL	1.5	15	19
				01/19/12-M03	64	Full	RL	1.6	32	19
				01/19/12-M04	66	Full	RL	1.1	18	12
				01/19/12-M06	60	Full	RL	5.7	17	18
			3252 lb	02/18/12-M02	78	Full	RL	2.4	15	24
				02/18/12-M05	73	180 deg Partial	RL	48 *	17	2
				02/18/12-M06	70	Full	RL	2.2	23	13
				02/18/12-M07	76	90 deg Partial	RL	6.4	19	7
				02/18/12-M08	80	180 deg Partial	RL	28 *	20	23
 2003 Ford Expedition	RWD	Independent	5421 lb	03/21/12-E01	71	Full / Blowout	RL	1.1	28	27
				03/21/12-E02	71	Full	RL	0.5	9	7
				03/21/12-E03	77	Full	FL	0.5	20	3
				03/21/12-E04	78	Full	RL	2.1	19	9
			5428 lb	10/17/12-E05	50	180 deg Partial	RL	7.5 **	6	10
				10/17/12-E06	65	180 deg Partial	RL	3 **	20	24
				10/17/12-E07	73	180 deg Partial	RL	1.75 **	20	20
 2003 Dodge Caravan	FWD	Solid Rear Axle / Leaf Spring	4026 lb	10/17/12-C01	64	Full	RR	1	20	6
				10/17/12-C02	75	Full	RR	0.8	12	10
				10/17/12-C03	54	180 deg Partial	RR	5.5	18	15
				10/17/12-C04	62	180 deg Partial	RR	6.5	25	27
 1999 BMW 323i	RWD	Independent	3319 lb	11/01/12-B01	70	Full	RR	1.6	21	9
				11/01/12-B03	77	Blowout	RR	-	10	7
				11/01/12-B04	76	Blowout	RR	-	19	21
				11/01/12-B06	72	60 deg Trailing Partial Blowout	RR	1.6 **	10	7
				11/01/12-B07	81	90 deg Trailing Partial	RR	1.3 **	9	5

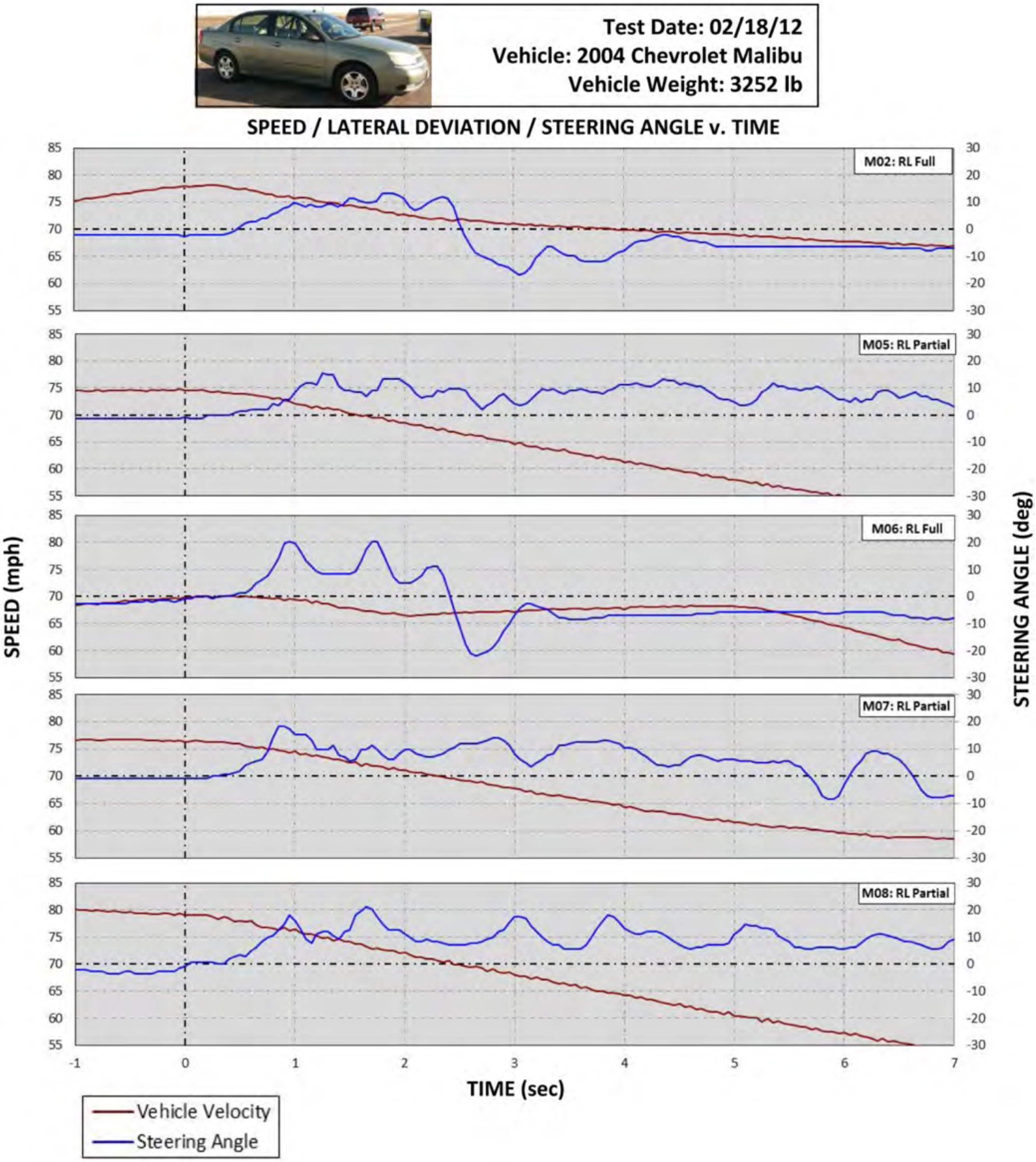
[1] Calibration runs, low speed disablements and runs in which the instrumentation malfunctioned are not included.
[2] Speed when tire disablement began.
[3] All tread separations are leading unless otherwise indicated. For partials, the flap size is indicated in degrees.
[4] Beginning when large tread flap was visible, ending when tread or tread flap released from tire.
[5] Steering required to oppose the pull created by the disablement.
[6] Deviation towards the side of the vehicle with the tire disablement.

* Flap remained attached until the end of the test
** Flap detached from tire

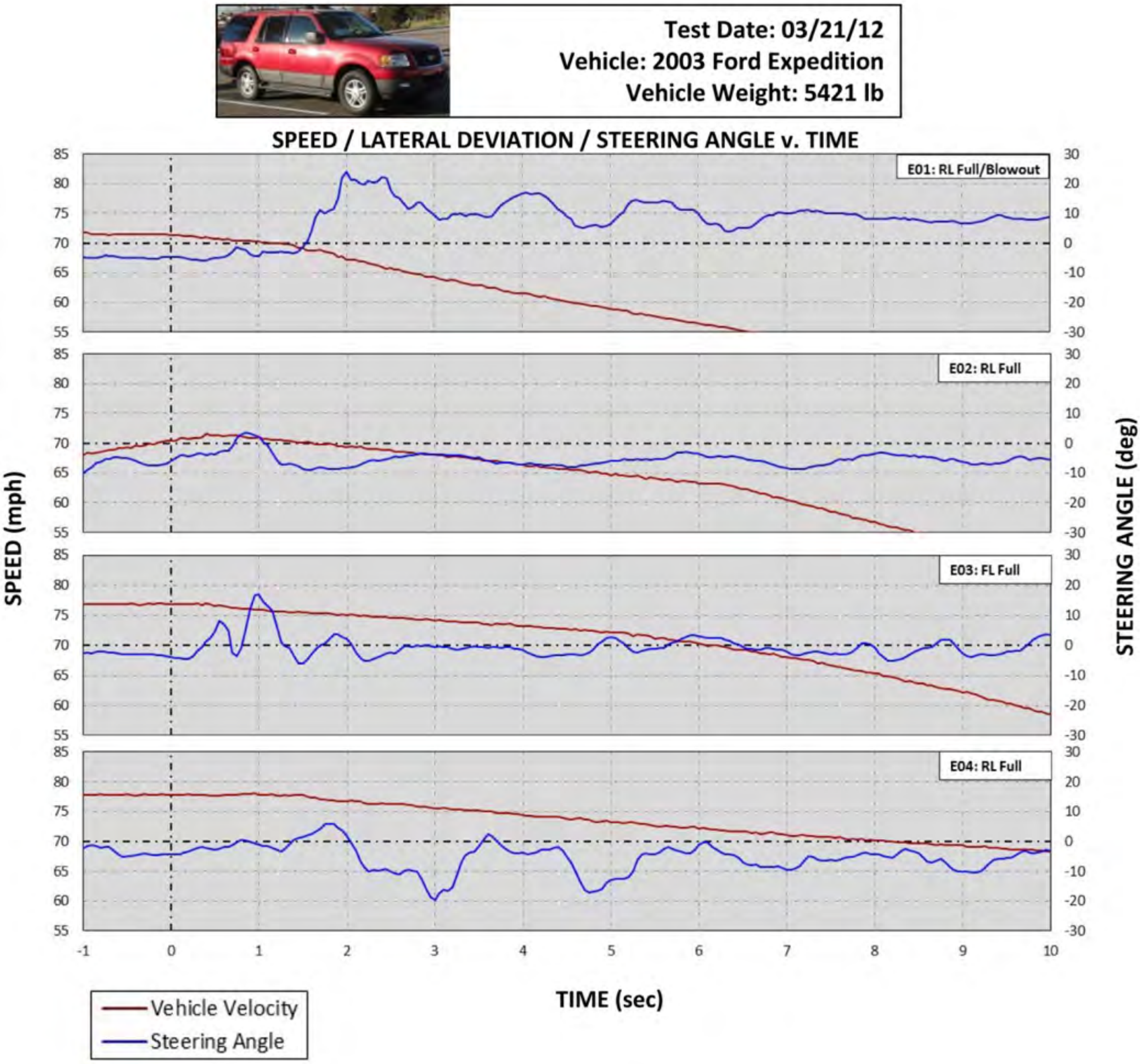
APPENDIX C


Test Date: 01/19/12
Vehicle: 2004 Chevrolet Malibu
Vehicle Weight: 3286 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
M02: LR Full
M03: LR Full
M04: LR Full
M06: LR Full
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle

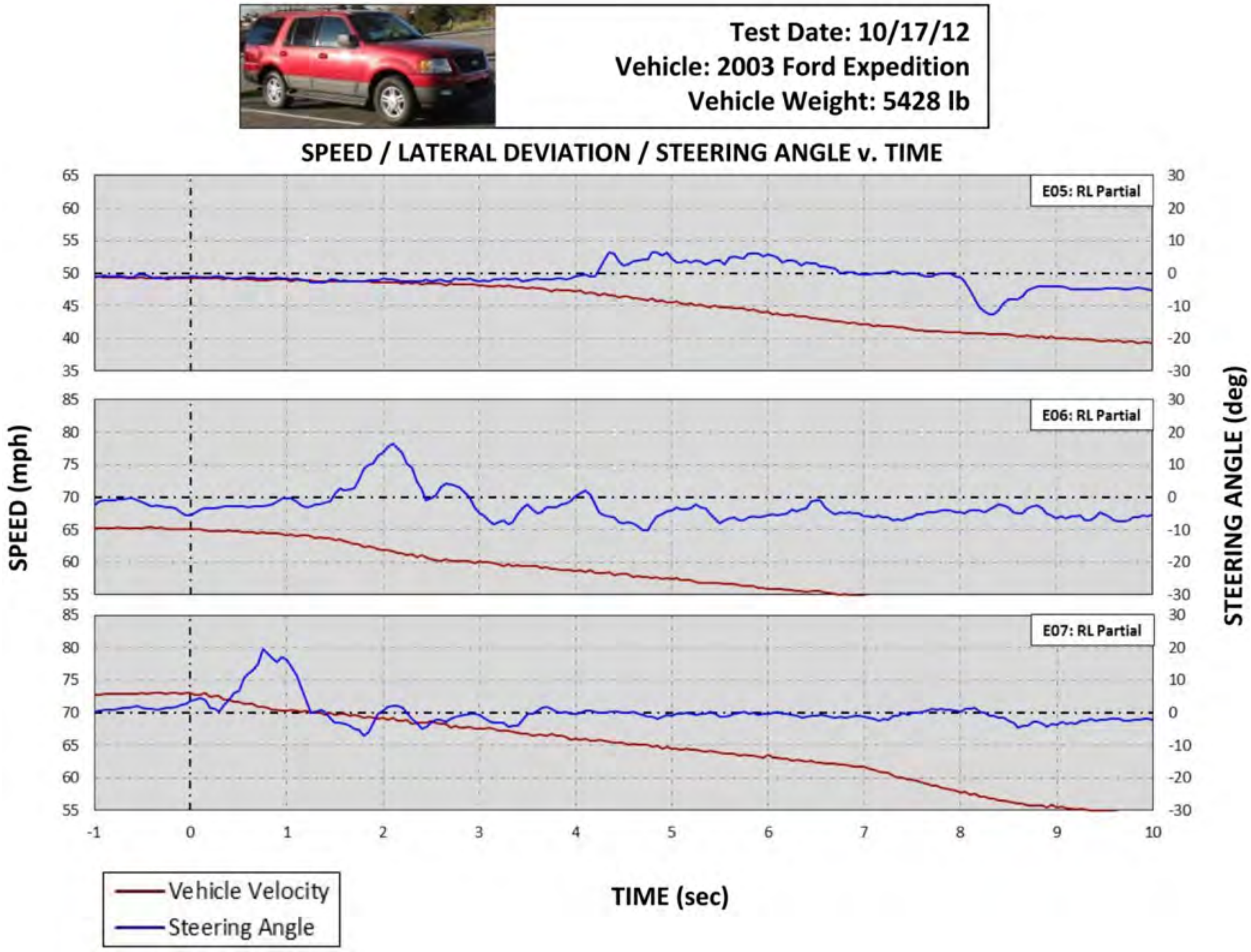
APPENDIX D


Test Date: 02/18/12
Vehicle: 2004 Chevrolet Malibu
Vehicle Weight: 3252 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
M02: RL Full
M05: RL Partial
M06: RL Full
M07: RL Partial
M08: RL Partial
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle

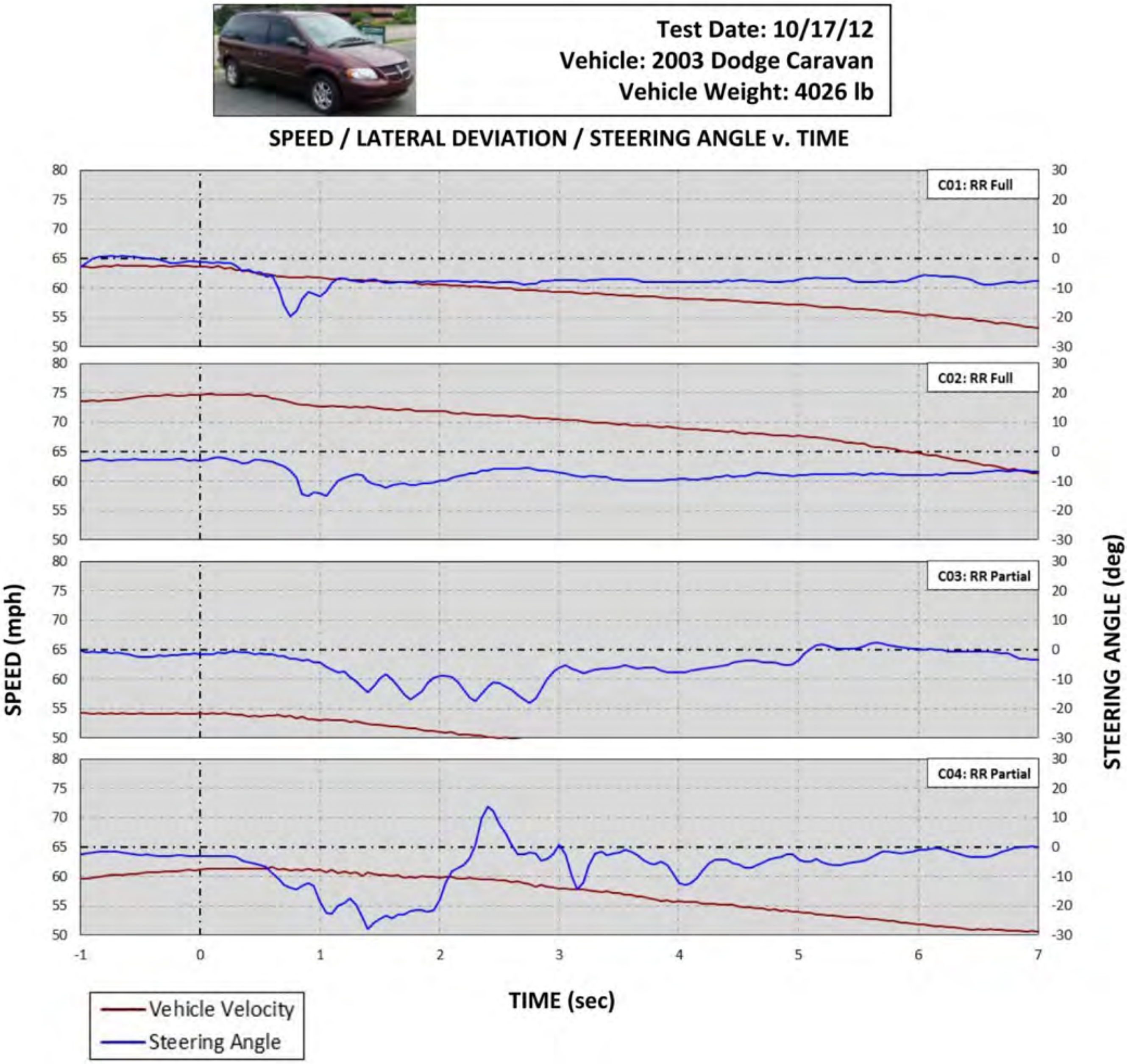
APPENDIX E


Test Date: 03/21/12
Vehicle: 2003 Ford Expedition
Vehicle Weight: 5421 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
E01: RL Full/Blowout
E02: RL Full
E03: FL Full
E04: RL Full
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle

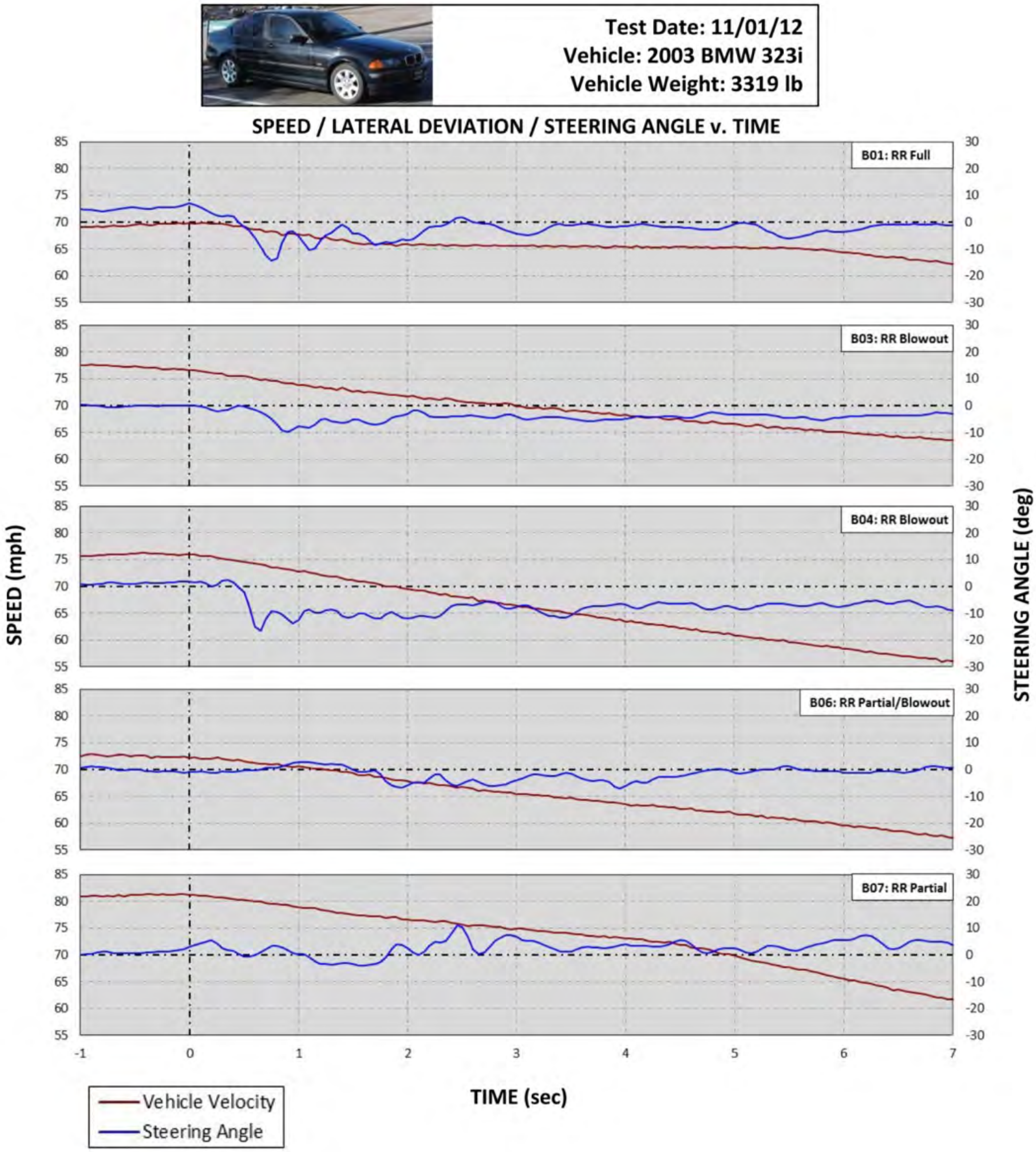
APPENDIX F


Test Date: 10/17/12
Vehicle: 2003 Ford Expedition
Vehicle Weight: 5428 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
E05: RL Partial
E06: RL Partial
E07: RL Partial
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle

APPENDIX G


Test Date: 10/17/12
Vehicle: 2003 Dodge Caravan
Vehicle Weight: 4026 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
C01: RR Full
C02: RR Full
C03: RR Partial
C04: RR Partial
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle

APPENDIX H


Test Date: 11/01/12
Vehicle: 2003 BMW 323i
Vehicle Weight: 3319 lb
SPEED / LATERAL DEVIATION / STEERING ANGLE v. TIME
B01: RR Full
B03: RR Blowout
B04: RR Blowout
B06: RR Partial/Blowout
B07: RR Partial
SPEED (mph)
STEERING ANGLE (deg)
TIME (sec)
Vehicle Velocity
Steering Angle