



Deceleration Rates of Vehicles with Disabled Tires

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Abstract

Tire disablement events can cause a drag force that slows a vehicle. In this study, the magnitude of the deceleration was measured for different phases of 29 high speed tire tread separation and air loss tests. These deceleration rates can assist in reconstructing the speed of a vehicle involved in an accident following a tire disablement.

Introduction

White published the results of coast down tests of several vehicles with intact tires. For the highest speed range reported, between 30 and 20 mph, the decelerations in drive predominantly ranged between 0.024 and 0.048 g [2]. Two vehicles were significantly higher. A Toyota Tundra in 4WD-LO decelerated at 0.086 g and the Nissan Altima decelerated at 0.1 g.

Cliff tested and reported several brake factors for various vehicle transmission gear choices. Also included are a rear wheel drive SUV and front wheel drive passenger car coasting with one flat front tire [3]. Cliff reported decelerations with flat front tires between 0.05 and 0.07g for speeds between 12 and 22 mph.

Gardner measured the coast down deceleration rate of a pickup and two passenger cars with one flat front tire [4]. The pickup truck decelerated from approximately 0.08 g at 50 mph, down to 0.06 g at 30 mph.

Robinette measured the coast down deceleration rate of four passenger cars and a pickup, all in drive, with either a front or rear deflated tire [5]. The vehicles were accelerated up to 30 mph then coasted. After 50 feet and 100 feet of coasting, the deceleration was recorded. For a front deflated tire, the vehicles decelerated at a rate of 0.03 to 0.07 g. For rear deflated tires, the vehicles decelerated at 0.02 to 0.04 g.

Tandy reported the longitudinal decelerations during two partial tread separation tests of Ford Explorers [6]. The longitudinal deceleration in both tests was on the order of 0.25 g while the tread was detaching. In both of these tests, the lateral deviation was large compared to other tread separation tests. Tandy attributed the larger path deviation to the relatively large longitudinal deceleration. In other tread separation testing performed by Tandy, the longitudinal deceleration and path deviation were described as being much less, although not specifically quantified.

This paper's authors previously reported the results of 25 high speed tire disablements [1]. The focus of that study were the effects of the tire disablement on the vehicle and the steering inputs required to maintain the vehicle's path. In this study, those 25 tests along with four previously unpublished tests are analyzed to determine the deceleration of the vehicle during the tests. It was found that each disablement event was made of one or more phases. In all, six different phases were identified. Decelerations during these phases are reported and discussed.

Vehicles

The vehicles tested were all 2-wheel drive models with automatic transmissions. [Table 1](#) provides a brief description of each vehicle. The vehicles were instrumented to document the vehicle behavior during tire disablements. The instrumentation included a VBox 20-Hz telemetry system that captured gross vehicle speeds and position. Steering wheel position, steering torque, and wheel speeds (in most tests) were also recorded. Three video cameras captured the driver, the test tire, and the test vehicle. Steering torque was measured via a torque cell installed in between the steering wheel and steering shaft. Steering position was measured by a string potentiometer affixed to the steering shaft. Wheel speeds were measured by custom built sensors. In the case of the Chevrolet Malibu the cars CAN data was captured for steering position and wheels speeds.

Table 1. Brief Description of Tested Vehicles.

Vehicle	EPA Classification	Driven Wheels	Average Test Weight ¹	Front Weight Distribution
 1999 BMW 323i	Compact	Rear	3319 lb	51%
 2004 Chevrolet Malibu	Midsized	Front	3267 lb	64%
 2003 Dodge Caravan	Minivan	Front	4026 lb	59%
 2003 Ford Expedition	Sport Utility Vehicle	Rear	5425 lb	49%

¹ Slight weight differences between test dates are given in the Appendix

Test Site

The private roadway used for testing was a 2 lane north/south service road that is approximately 2 miles long, straight, and has minor elevation changes. [Figure 1](#) is an image of the roadway taken facing northward. The roadway consisted of asphalt that had no signs of special surface treatment. Midway through the tests series, the roadway was resurfaced. The test site was surveyed using a laser total station in one hundred foot increments and key locations were recorded with a GPS locator. The grade of the road was measured and incorporated into the final deceleration values.



Figure 1. Photograph of Testing Roadway Taken Facing Northward.

Tires

All the tires tested were modified to produce partial or full tread belt detachments. Some tires were prepared to lose air rapidly during the tread detachment. The tires were cut along the bias of the tread and through the shoulder blocks around the circumference of the tire. The specific method of preparation was covered in detail within a previous publication [1]. [Figure 2](#) is an image of a tire prepared for testing.



Figure 2. Photograph of a Tire Prepared for Testing.

Tests

Of the 29 tests analyzed within this publication, 25 of the tests were previously published [1]. The effect of the tire disablement on the vehicle's path, as well as the steering inputs required to maintain the vehicle's path were the focus of the first publication. These previously published tests include partial and full tread belt separations and air loss events. Here, the vehicle's deceleration rates are analyzed and reported.

The four additional test were performed with the Chevrolet Malibu using the same methodology/location as the previous tests and span testing speeds from 58 to 69 miles per hour. Prior to the additional testing, the rear left quarter panel, which was damaged in previous testing, was repaired. All tires were prepared to produce full tread belt separations. These tests differed from the previous 25 as they were performed with the tires mounted on a side of the rear axle unknown to the driver. While the driver was absent, the tire was installed at a random location on the rear axle and covered with bags until the driver was in the vehicle. The bags were removed just before the test was conducted and the vehicle was driven down the very center of the roadway over the center lane line. In all four additional tests the vehicle's path was maintained with steering inputs less than 18 degrees.



Figure 3. Photograph of the Test Vehicle Prepared for Driver Entry.

In one test (8/20/15-M03), the tread belt wrapped around the axle and the wheel stopped rotating while the vehicle was at speed. This left an approximately 90 foot skid mark while the wheel was locked before the under layer was worn through and the tire rapidly lost air. This skid mark can be seen in [Figure 1](#). The tire resumed rolling after it aired out. [Figure 4](#) depicts the tread belt and vehicle at rest. [Figure 5](#) depicts the portion of under layer that was worn through.



Figure 4. Photograph of Axle Wrap Test at Rest.



Figure 5. Photograph of the Test Tire that Experienced Lockup.

Data Analysis

Previous to any of the disablement tests, coast down tests were performed with four intact tires. The vehicles were accelerated up to highway speed with the gear selector in “drive”, then the driver released the throttle and coasted. The deceleration during each test was calculated from the captured VBox vehicle velocity data. For this paper the specific data used from the VBox were wheel speeds, GPS position, time, and velocity.

Each tire disablement test can be broken down into one or more phases. For example, a full tread separation typically had two phases, beginning with the tread detaching, then followed by a coast down after the tread fully detached. The video, wheel speed data and vehicle velocity data were used to determine when each phase occurred. Within the collective 29 tests, six phases were identified for measurement of the deceleration rate. Portions of the tests in which the speed was under 50 mph or when the driver applied the brakes or throttle were excluded.

Identified Phases

During Tread Detachment

The beginning of this phase was identified by a difference between wheel speed and over the ground speed, and also by when a significant tread flap engages with the vehicle and/or roadway. This phase ends when the tread fully detaches from the tire.

During Tread Detachment - Deflated

The tread flap is detaching from the tire and the tire rapidly loses air simultaneously.

Axle Wrap / Wheel Lockup

The tread wraps around the axle and results in wheel lockup. This occurred in one test after the tread belt had fully detached from the tire.

Tread Detached Coast

The tread belt completely separates from the tire and the vehicle coasts down. The tire remains inflated during this phase.

Deflated Tire Coast

The tire is flat with the majority of its tread attached as the vehicle coasts down.

Deflated and Tread Detached Coast

The tread had fully detached from the tire and the tire became deflated prior to the vehicle coasting down.

Not all the phases occurred in every test, but each test included one or more of these phases. The [appendix](#) includes a summary of the test results and a description of which phases were included from each test. [Figure 6](#) depicts the disabled tire’s wheel speed and vehicle velocity data from Malibu test 08/20/15-M03 in which the wheel locked up. Three phases can be identified in [Figure 6](#), the During Tread Detachment Phase, Axle Wrap / Lockup phase, and the Deflated and Tread Detached Coast phase are labeled. As the disablement developed, there were small differences between the wheel speed and over the ground vehicle speed (before time zero in [Figures 6](#) and [7](#)). These differences are consistent with the noise and vibration that preceded each event. At time zero, the differences between wheel speed and over the ground vehicle speed became more pronounced as significant portions of the tire tread engaged with the vehicle. This decrease in wheel speed was identified as the start of the During Tread Detachment phase. This phase continued until the tread wrapped around the axle and the tire locked, as indicated when the wheel speed dropped to zero. The tire later deflated and began rolling again. The tire was deflated and without tread during this last phase. During the Deflated and Tread Detached Coast phase, the recorded wheel speed was slightly less than the vehicle over the ground speed. In this case, the wheel speed was generally a good indicator of the over the ground speed before the tire event and during the coast down, but underestimated the over the ground speed during the tire event.

[Figure 7](#) depicts vehicle velocity and wheel speed from test 08/20/15-M02, a full tread separation test in which two phases were identified. The During Tread Detachment phase and the Tread Detached Coast phase are labeled. The tire remained inflated during this test. Small differences in wheel speed and vehicle speed are visible prior to time zero, again consistent with the noise and vibration that preceded vehicle motion. Significant portions of tread began to contact the vehicle and road at time zero, causing a drop in wheel speed. When the tread fully detached from the tire, the wheel speed became steady,

but recorded a value less than the vehicle speed. In this case, the recorded wheel speed underestimated the vehicle over the ground speed during the tread detachment and subsequent coast down.

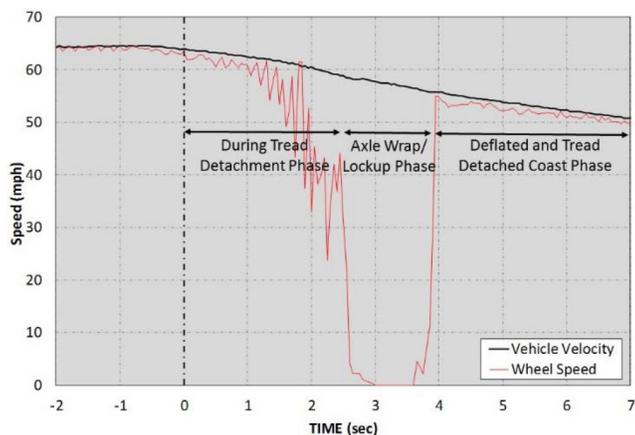


Figure 6. Plot of Wheel and Vehicle Speeds from Test 08/20/15-M03 (Full Tread Separation, Axle Wrap and Wheel Lock, Deflation).

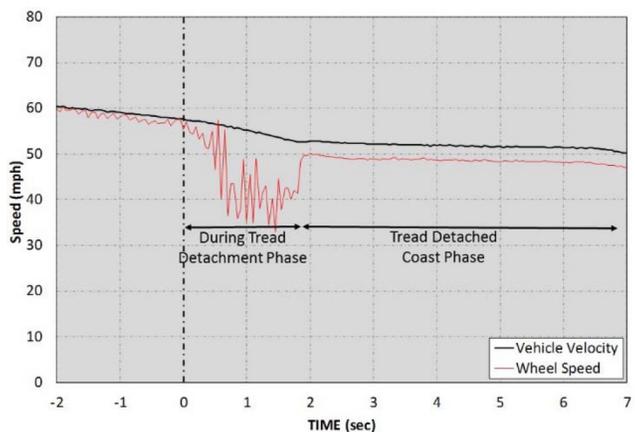


Figure 7. Plot of Wheel and Vehicle Speeds from Test 08/20/15-M02 (Full Tread Separation).

In most cases, the phases could be identified in the vehicle velocity and wheel speed data and confirmed through the video. In some cases, wheel speed data could not be obtained and phases were identified through video analysis. All decelerations were calculated during times when the vehicle was traveling between 78 and 50 mph. All calculated decelerations include effects of aerodynamic drag and were adjusted for grade of the road. The deceleration for each phase was calculated from change in velocity divided by change in time.

Significant and variable changes in wheel speed were a good indicator of when the tread and outer belt began to significantly detach from the tire. Also, tire events created a discrepancy between wheel speed and vehicle over the ground speed. Many modern Event Data Recorders (EDR) record vehicle speed from wheel speed measurements or by measuring the speed of the transmission output shaft. It is possible that the accuracy of the speed reported by the EDR could be effected during and following a tire event. In these tests the wheel speed generally under-reported the over the ground speed during the tire event. In some cases, it may be possible to

determine when a tire event occurred based on the vehicle speed data in the Crash Data Retrieval (CDR) report if that speed uses measured wheel speed or transmission output shaft speed. Consider Figure 8, a CDR report that captured data during a full tread separation and subsequent vehicle rollover. In this case, the vehicle was proceeding in its lane when a rear tire experienced a full tread separation. The CDR reported a steady speed of approximately 70 mph, then an abrupt speed reduction at approximately -6.0 seconds (labeled A in Figure 8) before any brake application. This reduction in reported speed is consistent with a reduction in wheel speed during the tire disablement event.

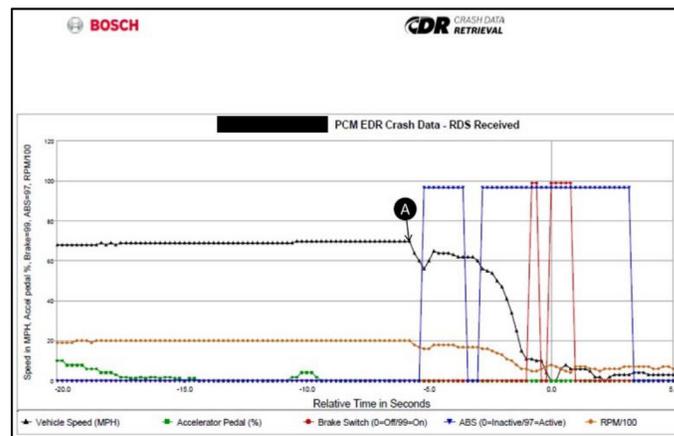


Figure 8. Plot From CDR Report in Which Vehicle Experienced a Full Tread Separation.

Results

The decelerations are categorized in Table 2 and 3 according to the vehicle's EPA classification and deceleration phase. Table 2 contains the average values. The number contained within the parenthesis represents the sample population in that category. Table 3 reports the range of decelerations. The Appendix contains a summary of all the tests. Vehicle and wheel speeds (when recorded) are also included in the appendix.

Table 2. Results of Tire Disablement Deceleration Testing - Averages.

	During Disablement Event				Coast Down Disabled Tire		
	Coast Down	During Tread Detachment	During Tread Detachment-Deflated	Axle Wrap/ Wheel lock	Tread Detached	Deflated Tire	Deflated & Tread Detached
Compact	0.06 (1)	0.11 (2)	0.12 (3)			0.09 (2)	
Midsized	0.03 (1)	0.13 (10)		0.11 (1)	0.04 (6)		0.09 (1)
Minivan	0.05 (1)	0.09 (4)			0.06 (3)		
SUV	0.04 (1)	0.09 (3)	0.16 (1)		0.06 (5)		0.11 (1)

Table 3. Results of Tire Disablement Deceleration Testing - Ranges.

	During Disablement Event				Coast Down Disabled Tire		
	Coast Down	During Tread Detachment	During Tread Detachment-Deflated	Axle Wrap/ Wheel lock	Tread Detached	Deflated Tire	Deflated & Tread Detached
Compact	0.06	0.10 - 0.12	0.09 - 0.15			0.09	
Midsized	0.03	0.11 - 0.16		0.11	0.03 - 0.06		0.09
Minivan	0.05	0.08 - 0.09			0.05 - 0.07		
SUV	0.04	0.07 - 0.12	0.16		0.05 - 0.07		0.11

Conclusions

The following conclusions were reached in conducting this study:

- Different types of tire disablements result in different vehicle decelerations.
- A single tire disablement may be made of several phases, and each phase may result in a range of different deceleration rates.
- Wheel speed data was found to be the best indicator of the different tire disablement phases.
- Before the tire events, the wheel speed and vehicle over the ground speed were generally consistent with one another. However, during and following a tire disablement, the wheel speed was typically less than the over the ground speed. These differences may affect the accuracy of EDR or speedometer reported speed during a tire event if they rely on wheel speed or transmission output shaft speed.
- In a real world crash, if an EDR records vehicle speed using wheel speed or transmission output shaft speed, it may be possible to identify the time of the tire event using the reported vehicle speed in the CDR report.
- The minor steering correction required to maintain the vehicle's heading for the 4 new tests were similar to the other previously reported tests. This includes the test 08/20/15-M03, where the tread wrapped and fully locked the wheel.
- This study reported deceleration rates and weight distributions of the test vehicles. In order to generalize these findings to other vehicles, the location of the subject disabled tire and the subject vehicle's weight distribution should be considered.

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APPENDIX

Vehicle	Drive	Weight	Run Number ¹	Speed ² (mph)	Tire Preparation ³	Prepared Tire Location	Phases Included	
 2004 Chevrolet Malibu	FWD	3286 lb	01/19/12-M02	61	Full	RL	TEST NOT USED - Throttle Application	
			01/19/12-M03	64	Full	RL	During Tread Detachment	
			01/19/12-M04	66	Full	RL	During Tread Detachment, Tread Detached Coast	
		01/19/12-M06	60	Full	RL	TEST NOT USED - Throttle Application		
		02/18/12-M02	78	Full	RL	During Tread Detachment, Tread Detached Coast		
		02/18/12-M05	73	180 deg Partial	*	RL	During Tread Detachment	
	3263 lb	02/18/12-M06	70	Full	RL	TEST NOT USED - Throttle Application		
		02/18/12-M07	76	90 deg Partial	RL	During Tread Detachment, Tread Detached Coast		
		02/18/12-M08	80	180 deg Partial	*	RL	During Tread Detachment	
		08/20/15-M01	66	Full	RR	During Tread Detachment, Tread Detached Coast		
		08/20/15-M02	58	Full	RL	During Tread Detachment, Tread Detached Coast		
		08/20/15-M03	64	Full / Blowout	RL	During Tread Detachment, Axle Wrap / Wheel Lockup, Deflated and Tread Detached Coast		
 2003 Ford Expedition	RWD	5421 lb	03/21/12-E01	71	Full / Blowout	RL	During Tread Detachment, During Tread Detachment - Deflated, Deflated & Tread Detached Coast	
			03/21/12-E02	71	Full	RL	Tread Detached Coast	
			03/21/12-E03	77	Full	FL	Tread Detached Coast	
			03/21/12-E04	78	Full	RL	During Tread Detachment, Tread Detached Coast	
	5428 lb	10/17/12-E05	50	180 deg Partial	**	RL	NOT USED - Below 50 mph	
		10/17/12-E06	65	180 deg Partial	**	RL	During Tread Detachment, Tread Detached Coast	
		10/17/12-E07	73	180 deg Partial	**	RL	During Tread Detachment, Tread Detached Coast	
 2003 Dodge Caravan	FWD	4026 lb	10/17/12-C01	64	Full	RR	During Tread Detachment, Tread Detached Coast	
			10/17/12-C02	75	Full	RR	During Tread Detachment, Tread Detached Coast	
			10/17/12-C03	54	180 deg Partial	RR	During Tread Detachment	
			10/17/12-C04	62	180 deg Partial	RR	During Tread Detachment, Tread Detached Coast	
 1999 BMW 323i	RWD	3319 lb	11/01/12-B01	70	Full	RR	During Tread Detachment	
			11/01/12-B03	77	Blowout	RR	During Tread Detachment - Deflated, Deflated Tire Coast	
			11/01/12-B04	76	Blowout	RR	During Tread Detachment - Deflated	
			11/01/12-B06	72	60 deg Trailing Partial Blowout	**	RR	During Tread Detachment - Deflated, Deflated Tire Coast
			11/01/12-B07	81	90 deg Trailing Partial	**	RR	During Tread Detachment

¹ Calibration runs, low speed disablements and runs in which the instrumentation malfunctioned are not included.

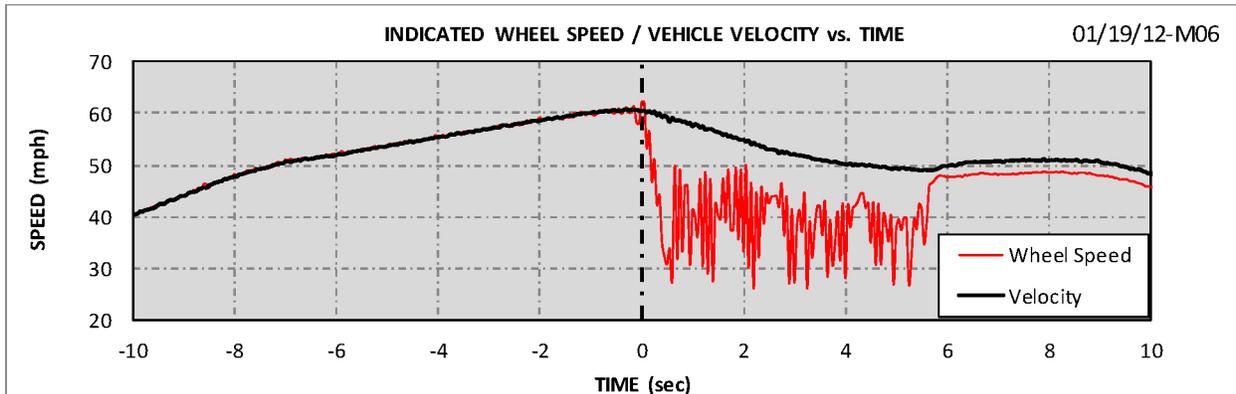
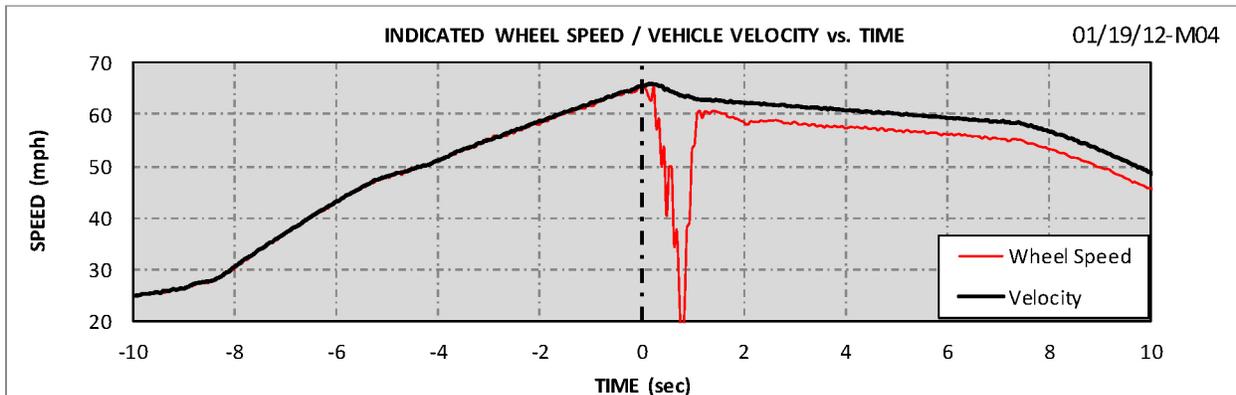
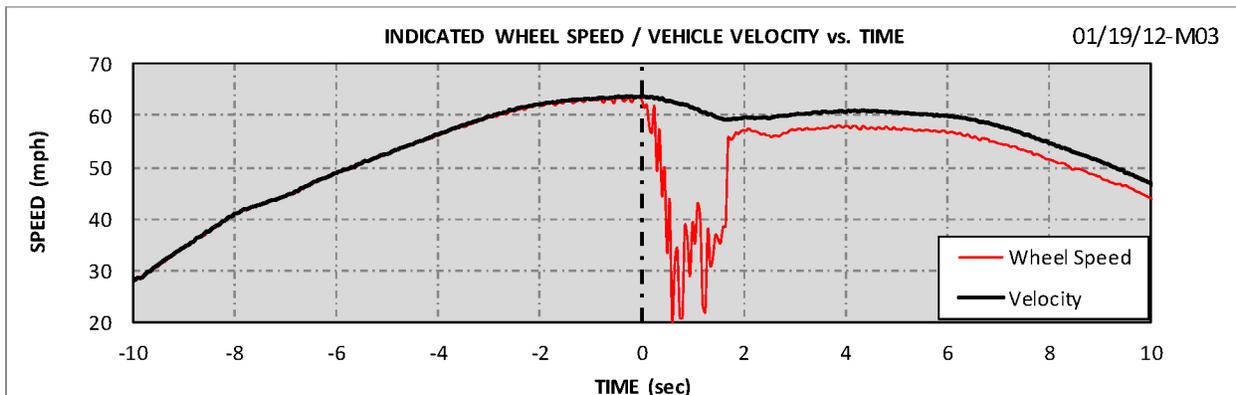
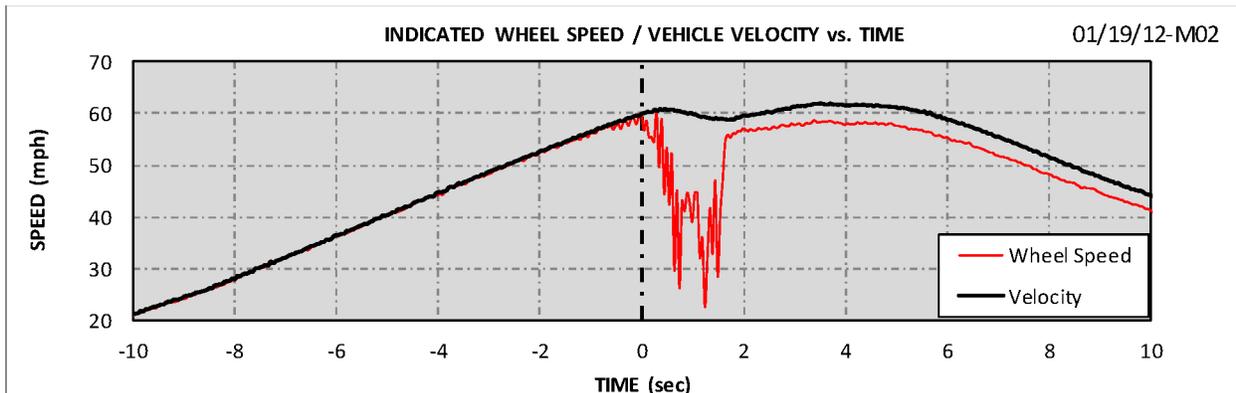
² Speed when tire disablement began.

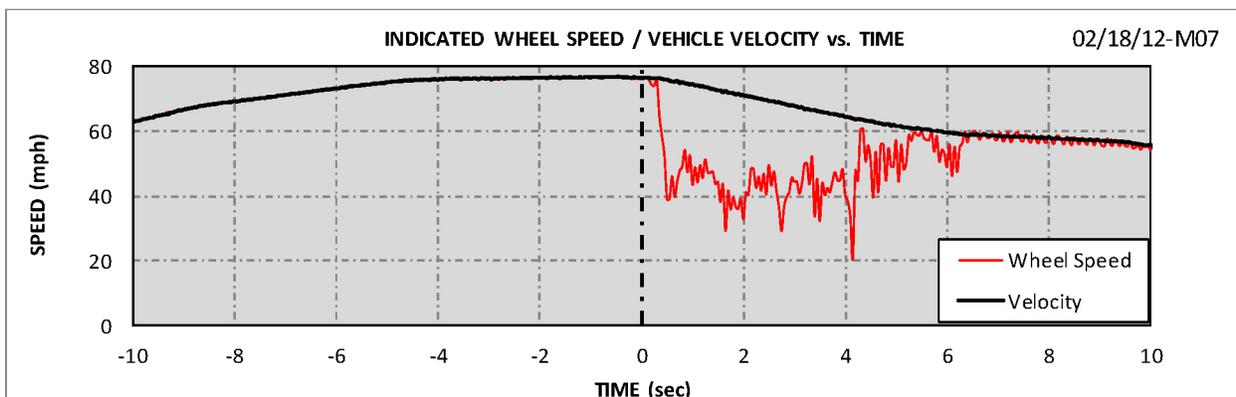
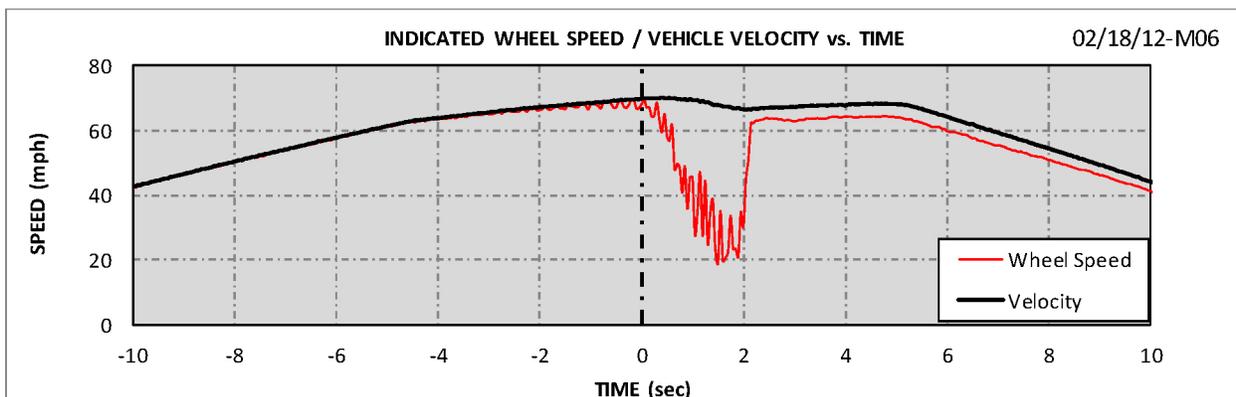
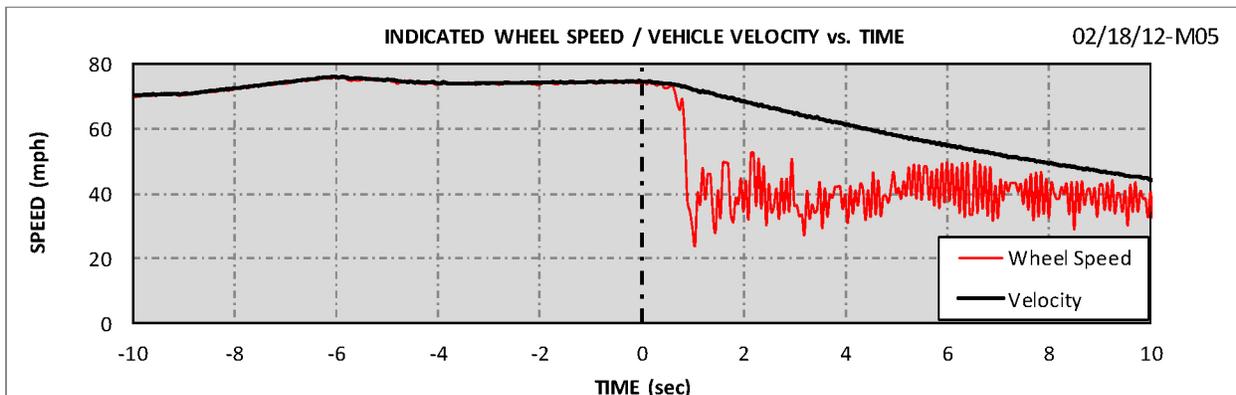
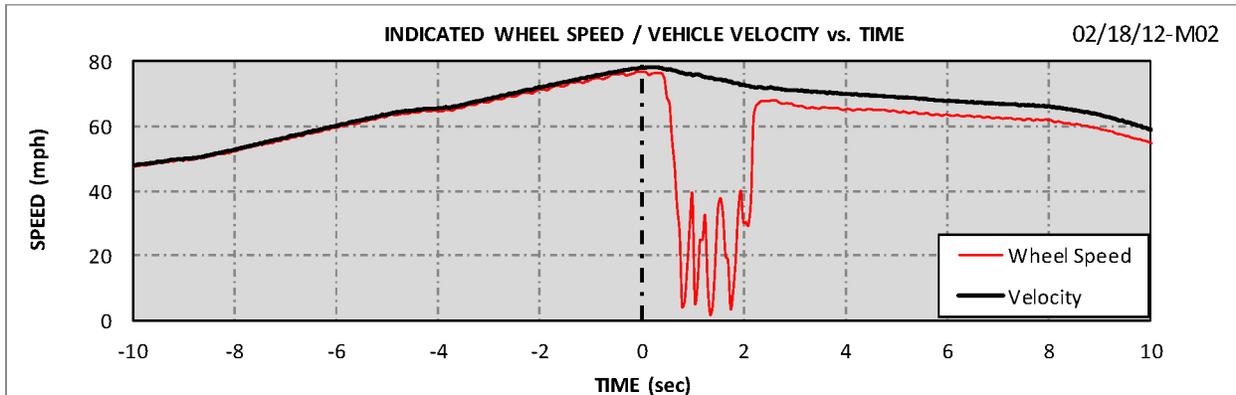
³ All tread separations are leading unless otherwise indicated. For partials, the flap size is indicated in degrees.

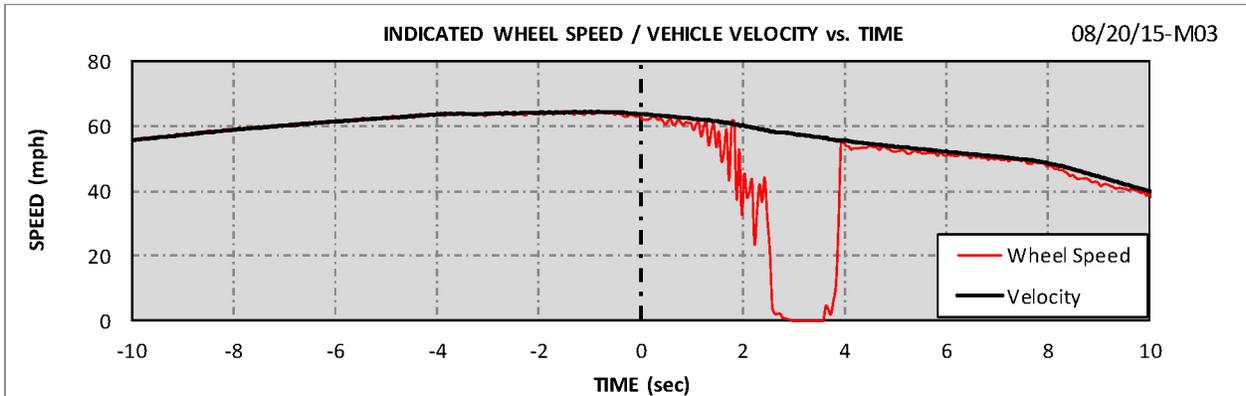
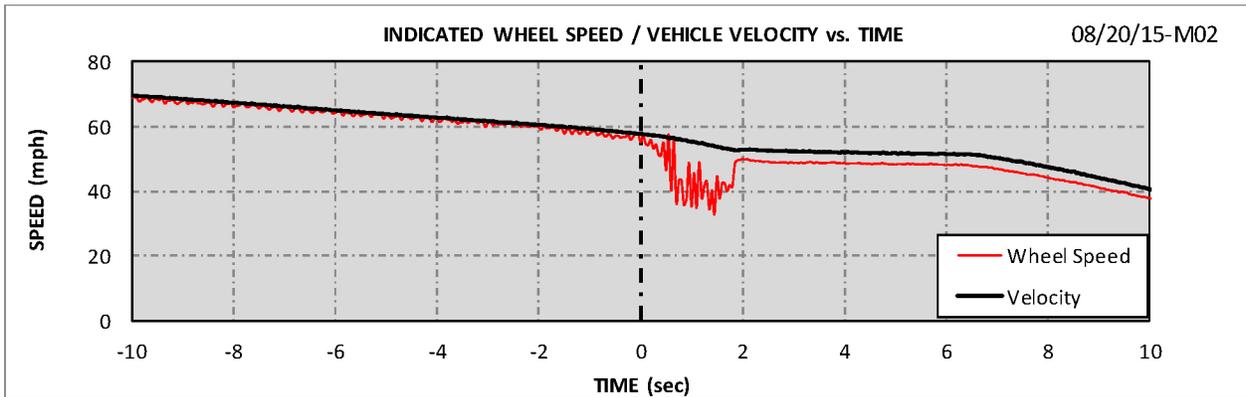
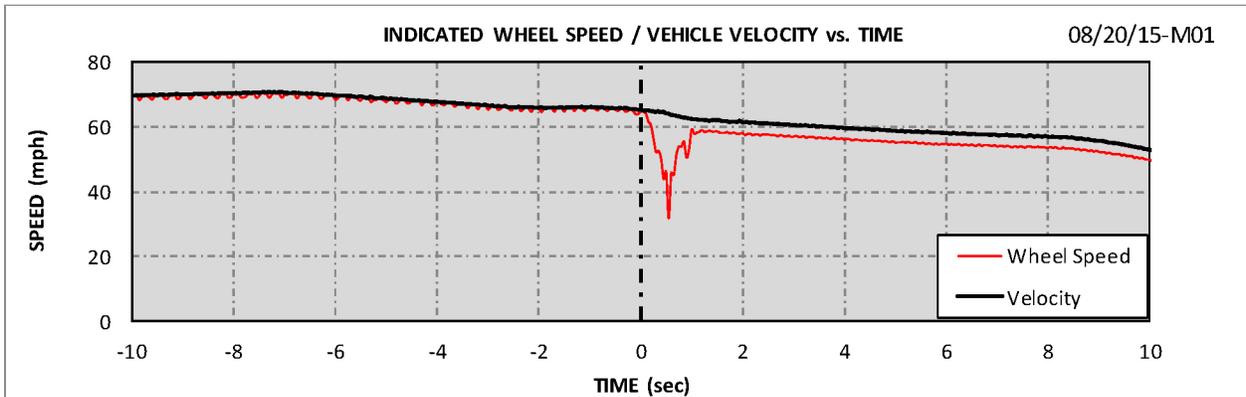
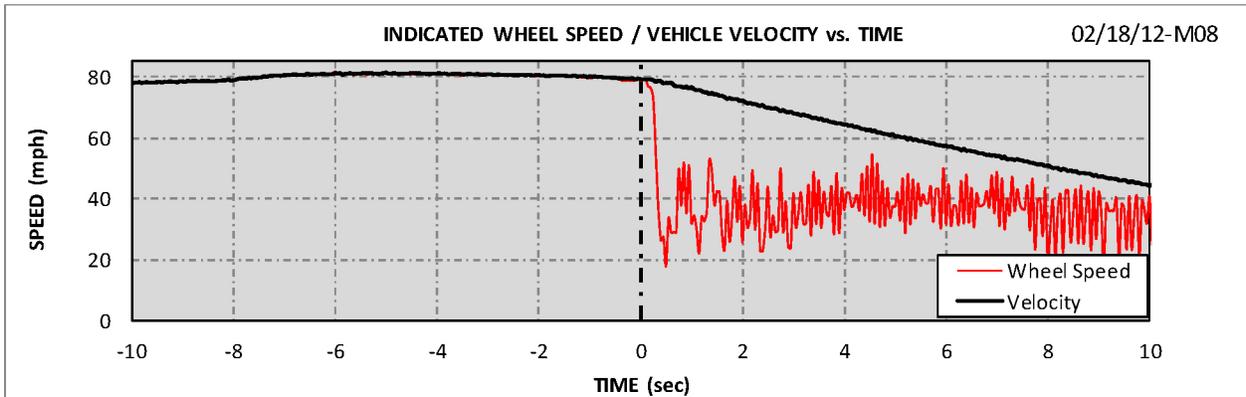
* Flap remained attached until the end of the test

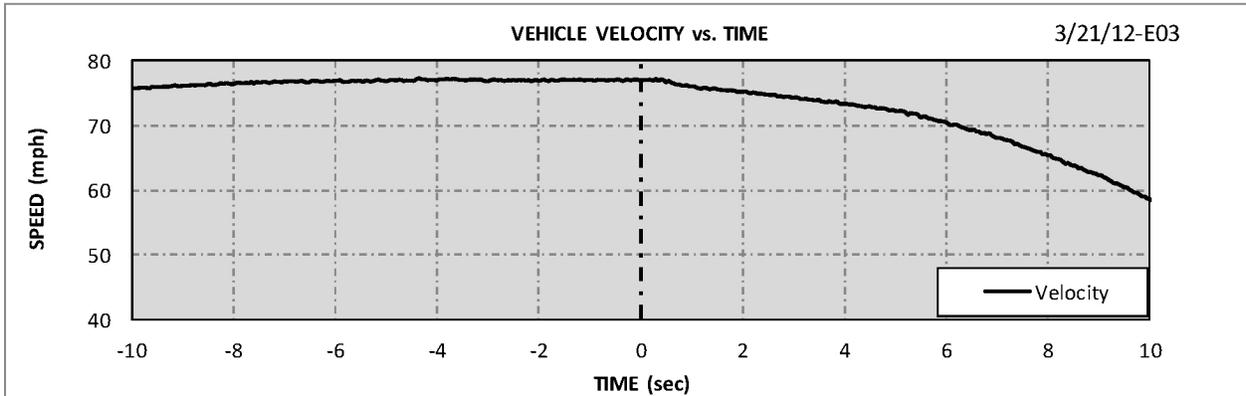
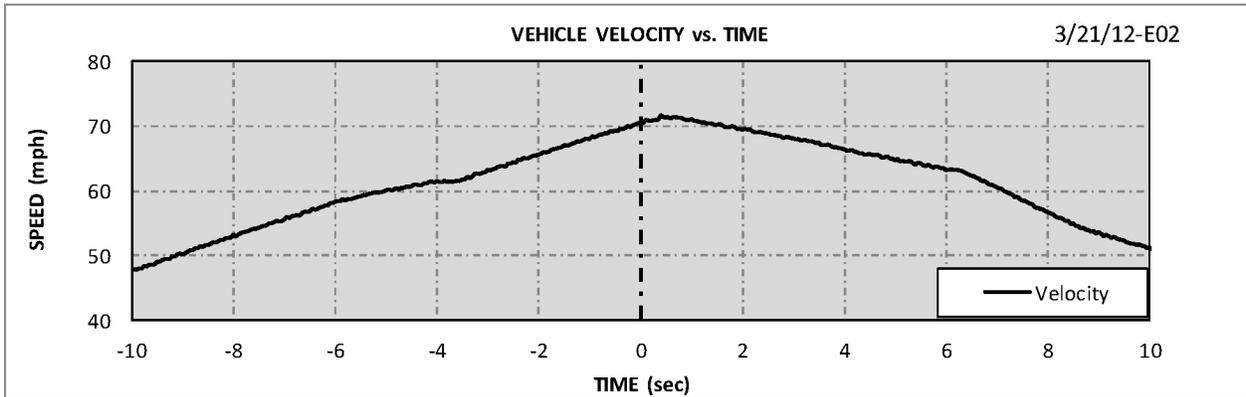
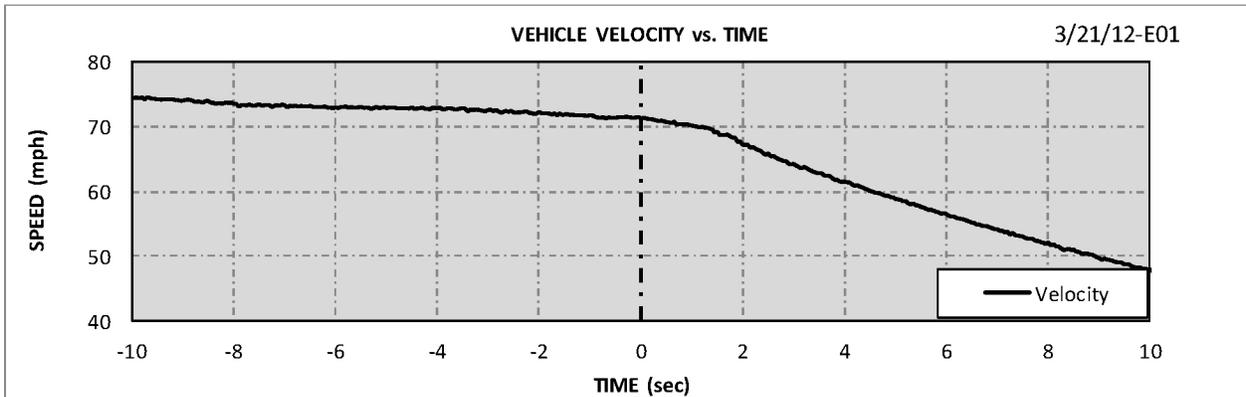
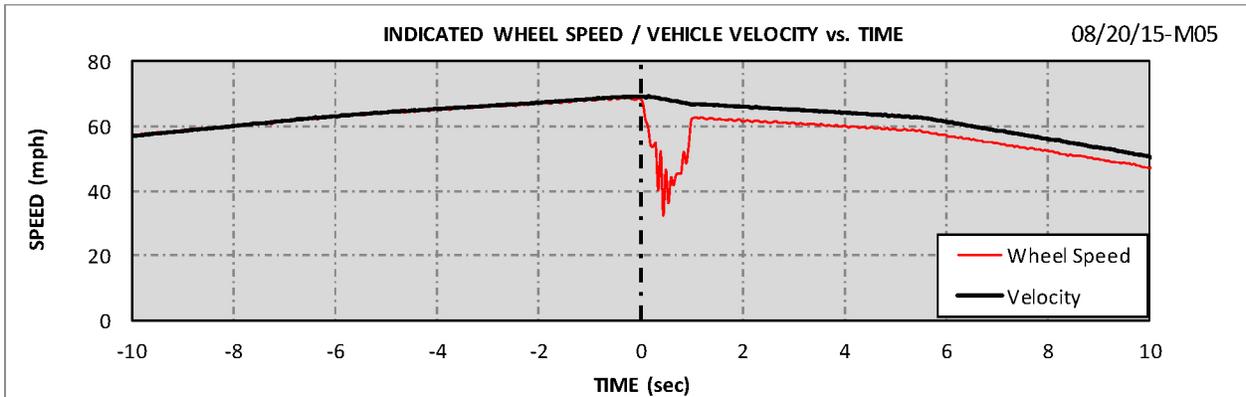
** Flap detached from tire

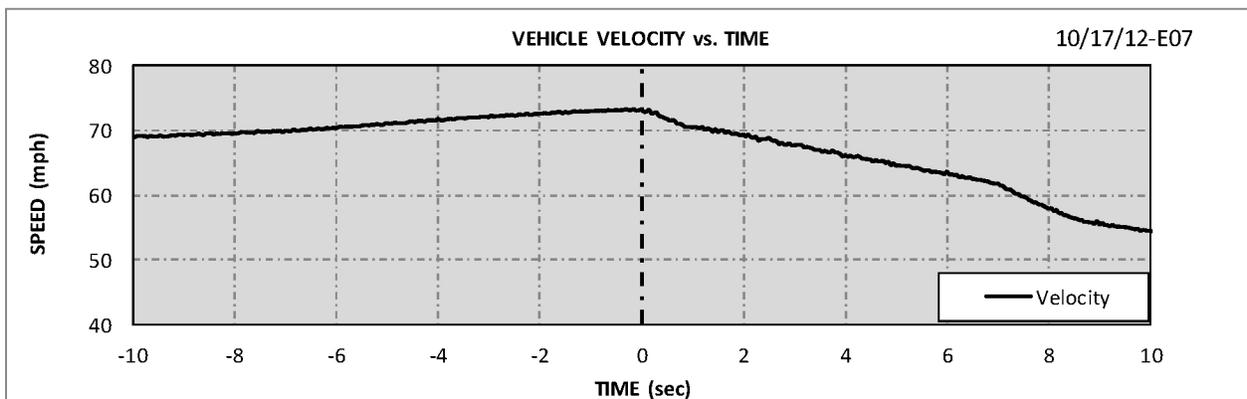
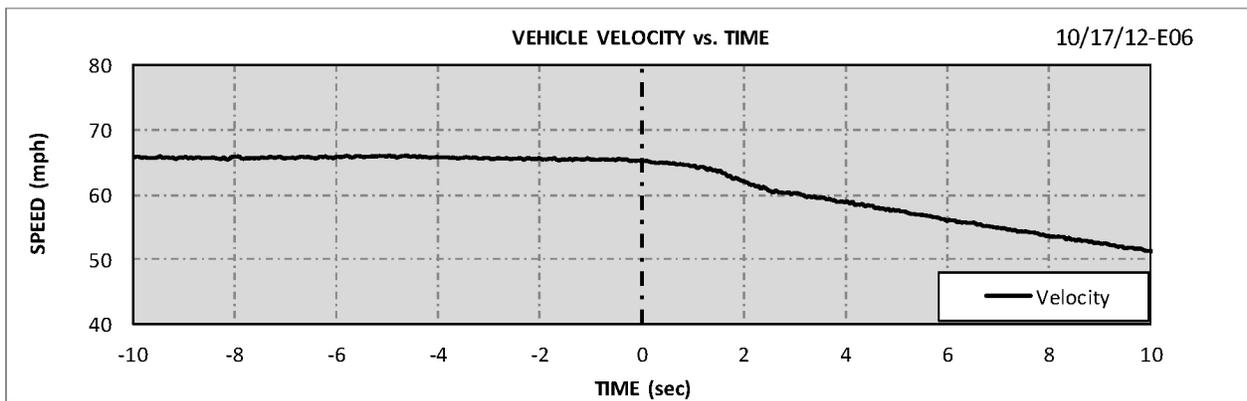
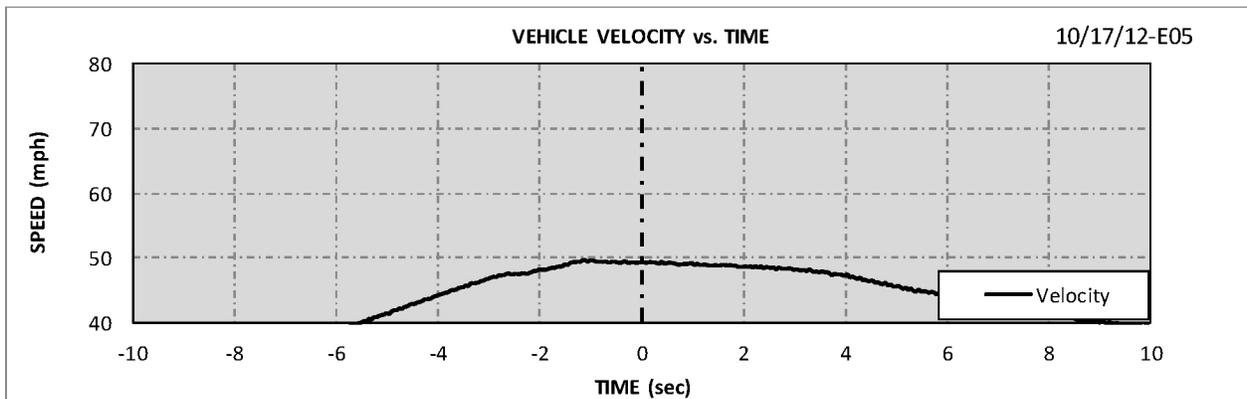
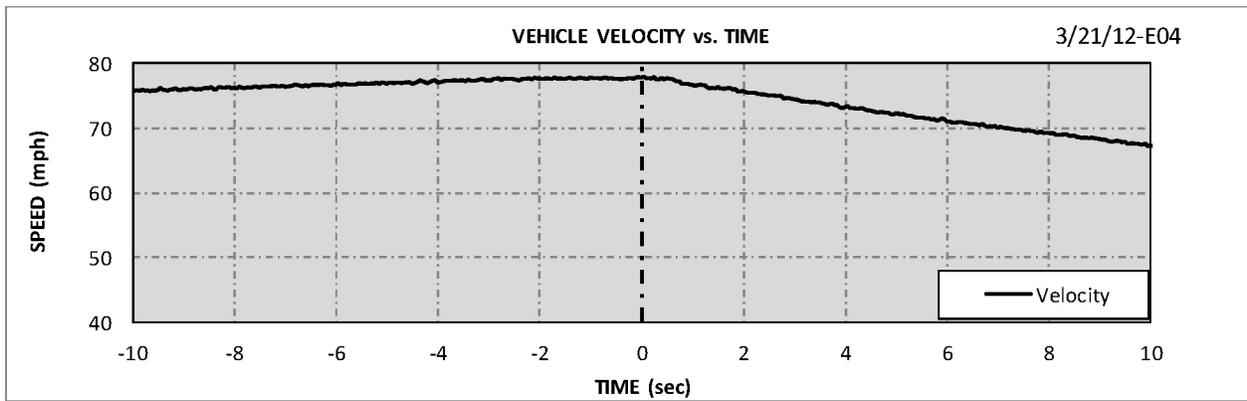
Over the ground vehicle speed and wheel speed for the disabled tire plots appear below. Wheel speeds were not measured for the Expedition tests. Wheel speed data for Minivan test 10/17/12-C01 contained interference from opposite side sensor. During minivan test 10/17/12-C04, the wheel speed sensor was damaged during the test.

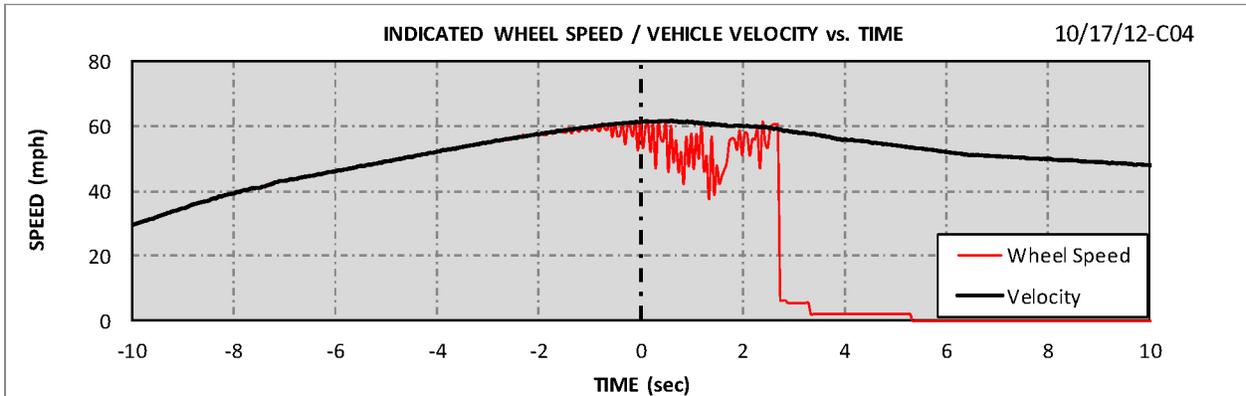
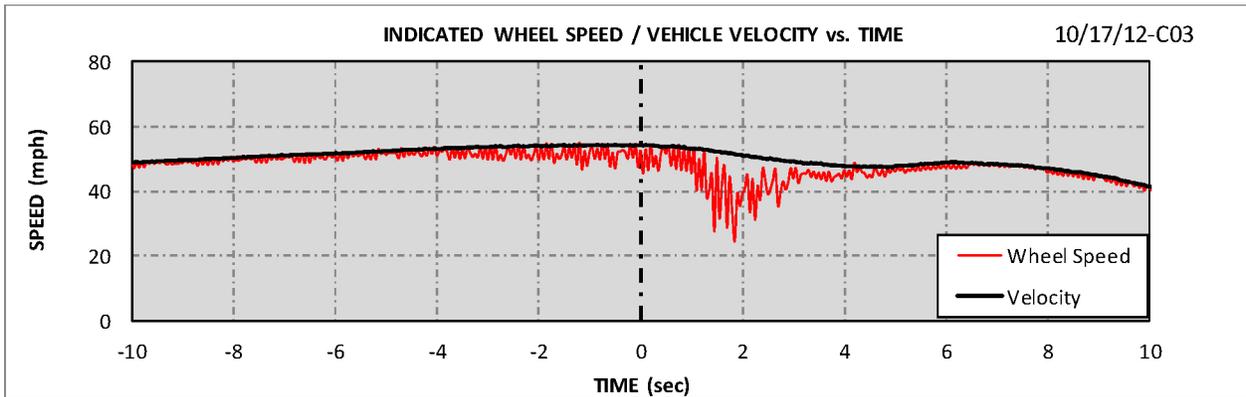
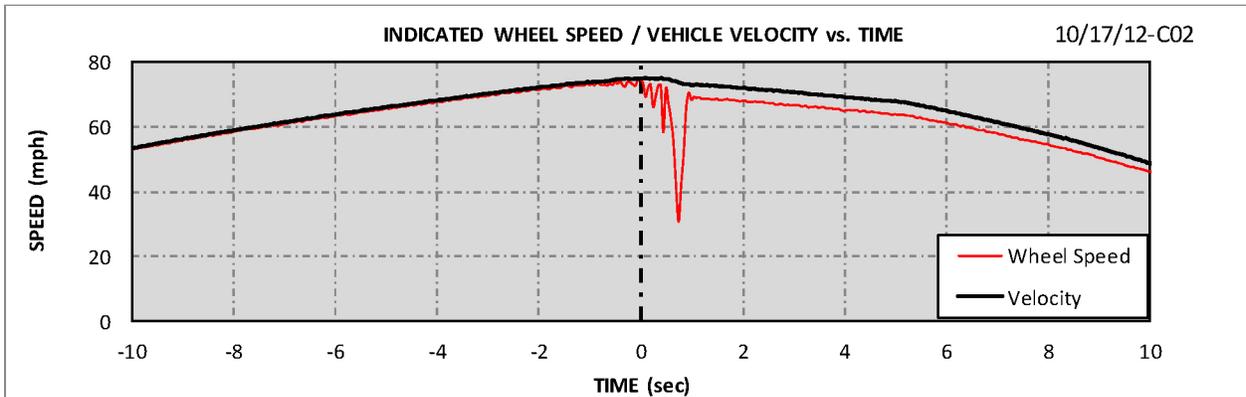
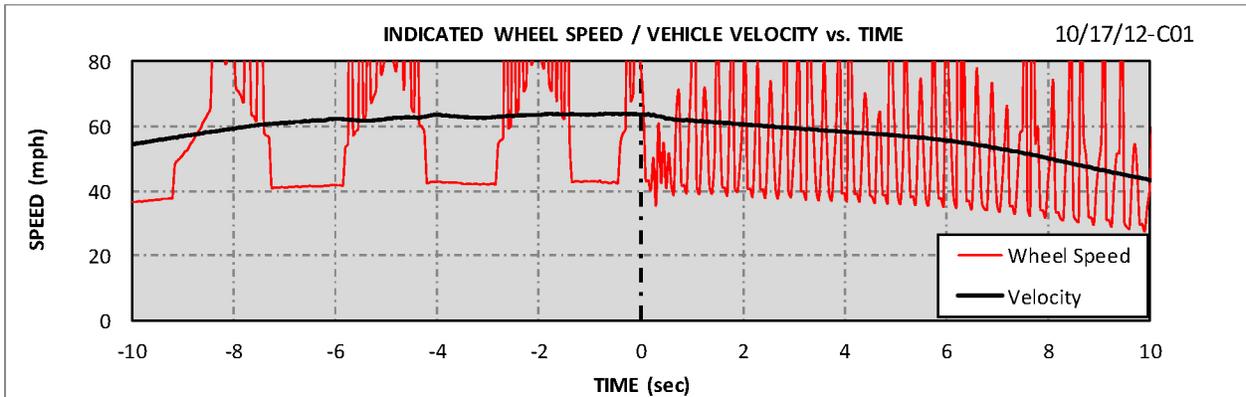


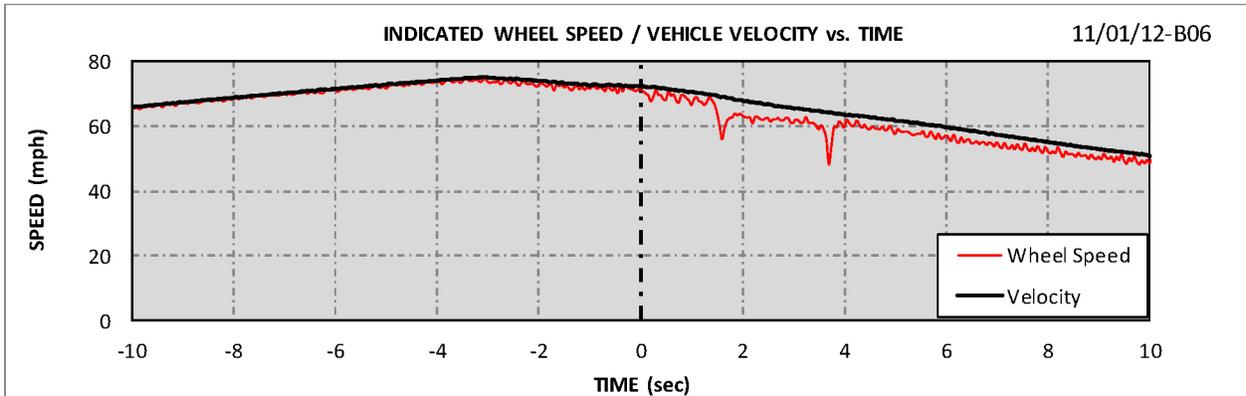
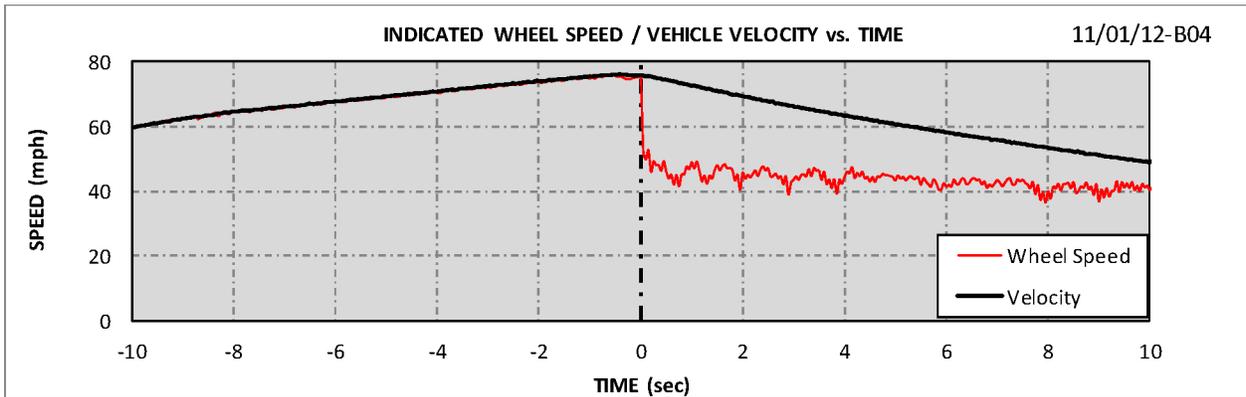
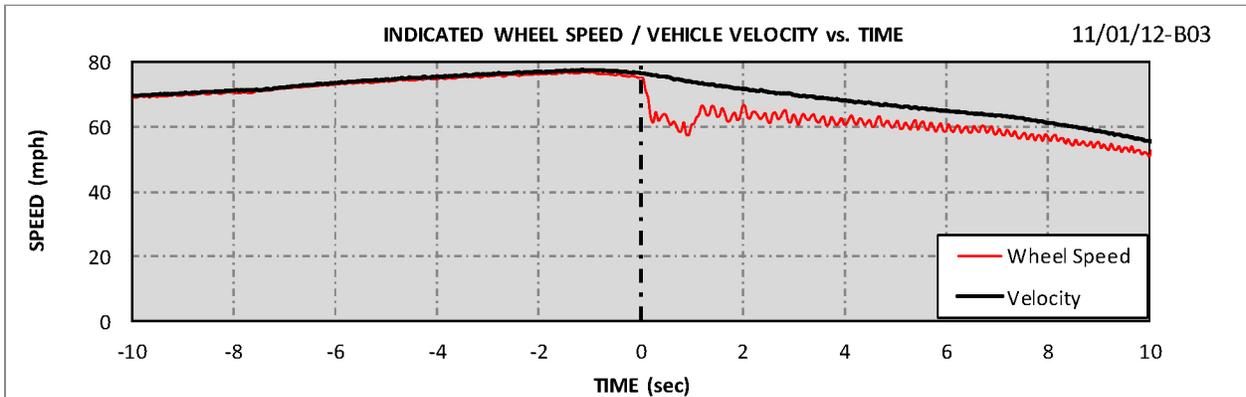
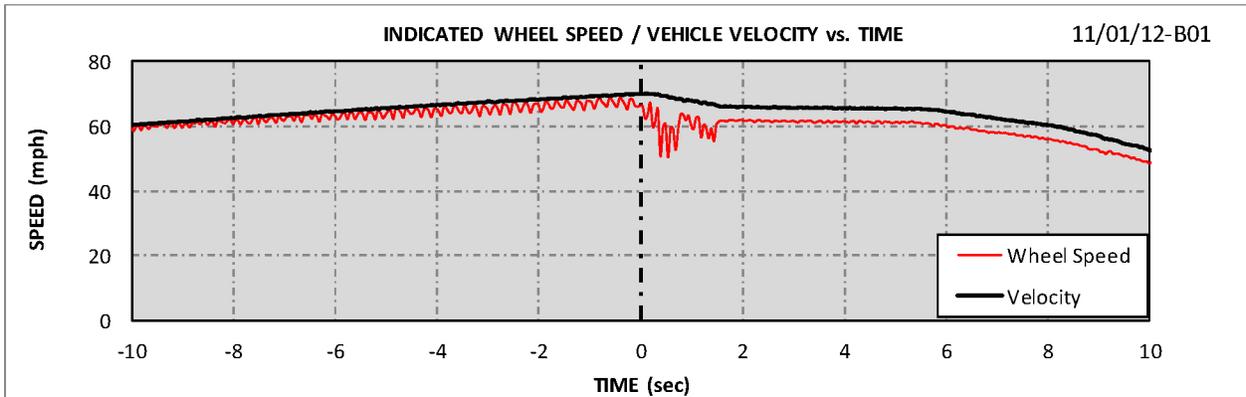


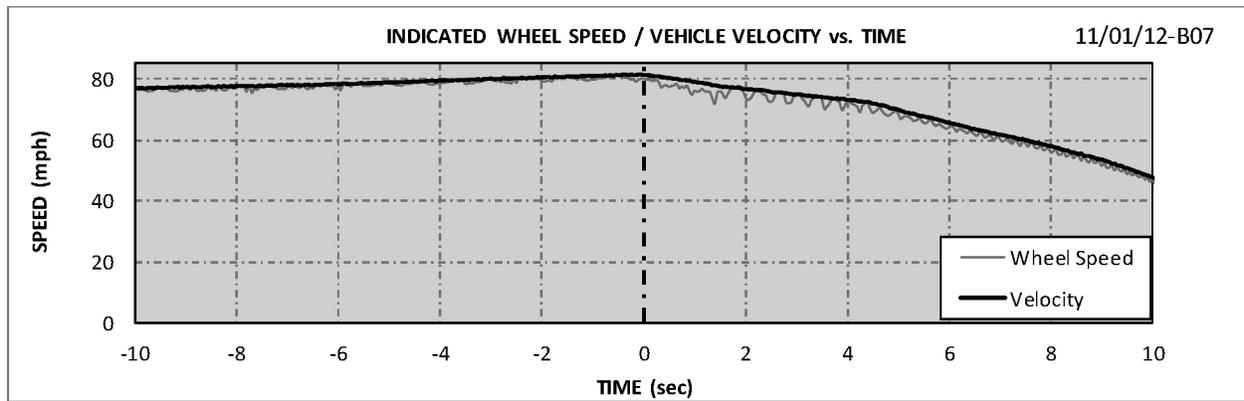












The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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