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Testing the Effects of Tire Pressure Monitoring System Minimum Activation Pressure on the Handling and Rollover Resistance of a 15-Passenger Van

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16. Abstract

The objective of this study was to measure the effects of modifying tire inflation pressure on the handling and rollover resistance of one 15-passenger van (a 2003 Ford E-350). In addition to those specified on the vehicle identification placard, four other front/rear tire inflation pressure combinations were used. Multiple loading configurations were used: Nominal Load, 5-Occupant, 10-Occupant, and Maximum Occupancy. Not all loading configurations were used for each test. The tests performed in this study were performed in three groups. Handling in the linear range, at or near maximum lateral acceleration, and dynamic rollover resistance at the various inflation pressure combinations were evaluated.

The linear range handling measures and maximum lateral accelerations seen in this study showed measurable changes due to variations in tire inflation pressure. However, these small changes are believed not to be of practical significance. This is, of course, good since a high sensitivity to tire inflation pressure changes could cause in-use problems.

The lateral stability of the Ford E-350 at Nominal Load was asymmetric. Spinouts occurred during every right-steer test performed at or near maximum lateral acceleration, for each of the five inflation pressure combinations used in this study. Left-steer tests also produced spinouts, however their occurrence was not repeatable; they only occurred during one of the three tests performed in each respective series.

Tire inflation pressure had a substantial effect on the lateral stability of the Ford E-350 in the Maximum Occupancy configuration. Of the five tire inflation pressure combinations evaluated the only one for which spinouts occurred at Maximum Occupancy was that specified on the vehicle's placard (55-psi front, 80-psi rear). While right-steer tests had more loss of lateral stability in the Nominal Load configuration, left-steer tests had the spinouts at Maximum Occupancy loading.

Decreasing the front and rear inflation pressures from that specified on the vehicle's placard to the 46-psi front, 60-psi rear adversely affected the vehicle's dynamic rollover resistance. This occurred because reducing tire inflation pressure reduces the vehicle roll stiffness thereby increasing the amount of roll that occurs.

The effects of changing tire inflation pressure on light truck handling and rollover resistance cannot be fully determined from the results of this study. Only one vehicle was evaluated. For this reason, use of this study's generalized results to predict the performance of other similar vehicles may not be appropriate.

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CONVERSION FACTORS

Approximate Conversions to Metric Measures					Approximate Conversions to English Measures				
Symbol	When You Know	Multiply by	To Find	Symbol	Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.04	inches	in
in	inches	2.54	centimeters	cm	cm	centimeters	0.39	inches	in
ft	feet	30.48	centimeters	cm	m	meters	3.3	feet	ft
mi	miles	1.61	kilometers	km	km	kilometers	0.62	miles	mi
		AREA					AREA		
in^2	square inches	6.45	square centimeters	cm^2	cm^2	square centimeters	0.16	square inches	in^2
ft^2	square feet	0.09	square meters	m^2	m^2	square meters	10.76	square feet	ft^2
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)					MASS (weight)		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.45	kilograms	kg	kg	kilograms	2.2	pounds	lb
		PRESSURE					PRESSURE		
psi	pounds per inch^2	0.07	bar	bar	bar	bar	14.50	pounds per inch^2	psi
psi	pounds per inch^2	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pounds per inch^2	psi
		VELOCITY					VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h	km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION					ACCELERATION		
ft/s^2	feet per second^2	0.30	meters per second^2	m/s^2	m/s^2	meters per second^2	3.28	feet per second^2	ft/s^2
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit	5/9[(Fahrenheit) - 32°C]	Celsius	°C	°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

DISCLAIMER

NOTE REGARDING COMPLIANCE WITH
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For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided for graphical images contained in this report to satisfy Section 508 of the Americans With Disabilities Act (ADA).

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W. Riley Garrott
Garrick J. Forkenbrock

EXECUTIVE SUMMARY

On April 29, 2003, the Alliance of Automobile Manufacturers (Alliance) petitioned NHTSA to change the Minimum Activation Pressures (MAP) of Tire Pressure Monitoring Systems (TPMS) for light truck tires [1]. Separately from the Alliance petition, on August 4, 2003, the National Transportation Safety Board (NTSB) issued Safety Recommendation H-03-17. This reads:

> *"In developing long-term performance requirements for tire pressure monitoring systems, adopt more stringent detection standards than 25 or 30 percent below manufacturer-recommended levels, since pressures at those levels can have an adverse effect on the handling of vehicles, such as 12- and 15-passenger vans."*

In its letter transmitting this safety recommendation to NHTSA, NTSB discusses two 15-passenger van rollover crashes. The NTSB has reason to believe that immediately prior to both of these crashes, all four of both vehicles' tires were inflated to approximately 60-psi. NTSB is concerned that these tire inflation pressures may have adversely affected the handling of these vehicles and helped cause the crashes.

As a consequence of the Alliance petition and NTSB Safety Recommendation H-03-17, NHTSA performed a small study of the effects of tire inflation pressure on 15-passenger van handling and rollover resistance. The results of this study are documented in this report. Although the Alliance has indicated to NHTSA that many other current-production light trucks (large pick-ups and sport utility vehicles) using load-range D or E tires face the same issues 15-passenger vans do ("insufficient spacing between the recommended inflation pressure and the MAP" [1]), an evaluation of these vehicles was not requested by NTSB, and was thus deemed to be outside of this study's necessarily narrow scope.

The objective of this study was to measure how the handling and dynamic rollover resistance of a contemporary 15-passenger van may be affected by tire inflation pressure. At the time of this study, only two vehicle manufacturers produced 15-passenger vans for sale in the United States: Ford Motor Company (the E-350) and General Motors (the Chevrolet Express and the GMC Savana). For this study, logistical constraints permitted an evaluation of only one such van--a 2003 Ford E-350. Although this was a 2003 model year vehicle, Ford has told NHTSA that no significant changes were made to the chassis, suspension, or tires for 2004. For this reason, the handling and rollover resistance of the 2003 and 2004 model year vans should be identical.

Tire inflation pressure was an independent variable for the tests performed in this study. In addition to those specified on the vehicle identification placard, four other front/rear tire inflation pressure combinations were used. The inflation pressures used in this study were:

- **Placard** – 55-psi front, 80-psi rear
- **Increased Front** – 80-psi front, 80-psi rear
- **Current MAP** – 46-psi front, 60-psi rear
- **Alliance MAP** – 38-psi front, 60-psi rear
- **NTSB Concern** – 60-psi front, 60-psi rear

The tests performed in this study were performed in three groups. Test Group 1 (TG1) was intended to evaluate handling in the linear range of lateral acceleration at a variety of inflation pressure combinations. Due to the low lateral acceleration targets, outriggers were not mounted on the test vehicle for these maneuvers. The TG1 maneuvers were:

1. Slowly Increasing Steer to ≈0.5 g lateral acceleration
2. Step Steer to 0.408g
3. Sinusoidal Steer at 0.2 Hz to 0.2g

The same measures of handling performance were determined from the TG1 data as were used by the Alliance in its petition. These were Linear Range Understeer Gradient, Lateral Acceleration Response Time, and Steering Work Sensitivity.

Test Group 2 (TG2) was used to evaluate handling at or near the vehicle's maximum lateral acceleration. The sole TG2 maneuver was the Slowly Increasing Steer. However, unlike that used in TG1, this maneuver used a maximum of 270 degrees of steering to achieve maximum maneuver severity. Due to the "limit" nature of this maneuver, outriggers were used during all TG2 tests to insure driver safety.

The dynamic rollover resistance of the test vehicle was evaluated in Test Group 3 (TG3) using the NHTSA Road Edge Recovery maneuver. Although different versions of this maneuver exist, the Road Edge Recovery test procedures used in this study were identical to those used by NHTSA to generate data required by its New Car Assessment Program (NCAP) dynamic rollover rating system. For driver safety, outriggers were used during all tests performed in TG3.

During each group of testing, the test vehicle was evaluated with two load configurations. In the case of the handling tests (TG1 and TG2), the load configurations were Nominal Load, consisting of the driver and plus instrumentation, and Maximum Occupancy, consisting of Nominal Load plus 13 water dummies, weighing approximately 175 lbs each, positioned at each seating position for which an adult passenger may be restrained with a seatbelt, with the exception of the front seats. In the case tests used to assess dynamic rollover resistance (TG3), 5- and 10-Occupant configurations were used. These configurations consisted of the Nominal Load plus three (5-Occupant load) or eight water dummies (10-Occupant load).

The effects of changing tire inflation pressure on light truck or even 15-passenger van handling cannot be fully determined from the results of this study. Only one vehicle was evaluated. Generalization of the results to other similar vehicles (i.e., those produced by DaimlerChrysler, General Motors, or other manufacturers) may not be correct.

The changes in the linear range handling measures due to changes in tire inflation pressure determined during the TG1 testing generally agreed with those found by the Alliance [1]. However, the changes seen over the tire inflation pressure range studied are not believed to be of practical significance. In other words, the linear range handling of the Ford E-350 was essentially unaffected by changes in tire inflation pressure. This is, of course, desirable since a high sensitivity to tire inflation pressure changes could cause in-use problems.

The maximum lateral accelerations measured during the TG2 testing generally showed only small changes due to changes in the tire inflation pressure. Load configuration had a more pronounced effect on maximum lateral acceleration than did tire inflation pressure. The small changes in maximum lateral acceleration imposed by the tire inflation pressures used in this study are not believed to be of practical significance.

The lateral stability of the Ford E-350 at Nominal Load was asymmetric. Spinouts occurred during every right-steer test, for each of the five inflation pressure combinations used in this study. Left-steer tests also produced spinouts, however their occurrence was not repeatable; they only occurred during one of the three tests performed in each respective series

The lateral stability of the Ford E-350 at Maximum Occupancy also showed some asymmetries, although not for all tire inflation pressure combinations as was the case in the Nominal Load configuration. Interestingly, while right-steer tests always induced lateral instability in the Nominal Load configuration, left-steer tests were the only ones that induced spinout at Maximum Occupancy loading.

Tire inflation pressure had a substantial effect on the lateral stability of the Ford E-350 in the Maximum Occupancy configuration. Of the five tire inflation pressure combinations evaluated, the only one for which spinouts occurred was the Placard condition (55-psi front, 80-psi rear).

Decreasing the front and rear inflation pressures from Placard (55-psi front, 80-psi rear) to the Current MAP (46-psi front, 60-psi rear) adversely affected the dynamic rollover resistance of the Ford E-350. Producing two-wheel lift during tests performed with 5- and 10-occupants required lower maneuver entrance speeds in the Current MAP condition than did those tests performed with Placard pressures.

The authors believe it likely that lowering the front tire pressures to those requested by the Alliance will reduce the Ford E-350's rollover resistance to a level lower than that observed during the Current MAP tests. That said, since the number of tests performed in TG3 were limited, the authors did not assess the magnitude of this anticipated reduction. Lowering the front tire inflation pressure will further reduce the vertical stiffness of the front tires. This should result in the magnitude of the vehicle's roll responses to the RER steering inputs being larger than those seen during Current MAP testing and further reduce the vehicle's rollover resistance. However, how much of the decrease in dynamic rollover resistance that was seen between the Placard and Current MAP tire inflation pressures is due to the decrease in the front tire inflation pressure versus how much is due to the decrease in the rear tire inflation pressure is not known. If the decrease in rollover resistance were primarily due to the decrease in rear inflation pressure, then a further reduction of the front inflation pressure to 8-psi lower than the Current MAP condition may not have a substantial effect.

In summary, the change proposed by the Alliance in the minimum activation pressure of the front tires of the Ford E-350 van from the 46-psi contained in the recently rescinded FMVSS 138 to the 38-psi does not result in changes of practical significance to the linear range handling characteristics of this vehicle. Both the maximum lateral acceleration and the lateral stability of this vehicle in a limit slowly increasing steer maneuver are likewise essentially unaffected. Data collected during this study suggest that reducing the minimum activation pressure from the

Current MAP (46-psi, 60-psi) to the Alliance MAP (38-psi, 60-psi), may slightly reduce the dynamic rollover resistance of the Ford E-350. However, since no Road Edge Recovery tests were performed with Alliance MAP pressures, the magnitude of this reduction cannot be quantified.

In their petition [1], the Alliance stated, “if the current FMVSS 138 MAPs remain unchanged, it will be necessary to increase the recommended tire inflation pressures.” Increasing the recommended front tire inflation pressures is expected to increase their vertical stiffness. This, in turn, is expected to increase the effective front roll stiffness of the vehicle, decrease the roll angles that occur during dynamic rollover testing, and improve the vehicle’s dynamic rollover resistance. While the resulting increase in dynamic rollover resistance is expected to be quite small, increasing the recommended front tire inflation pressures is expected to have a positive effect on vehicle rollover safety.

In Safety Recommendation H-03-17, the National Transportation Safety Board expressed concern about the possible adverse effect on handling of permitting 12- and 15- passenger vans to operate with tire inflation pressures up to 25 percent below placard. In the letter transmitting this safety recommendation to NHTSA, NTSB expressed concern as to whether adverse handling had contributed to two crashes that they investigated. The 15-passenger vans in both of these crashes had tire inflation pressures of approximately 60-psi for all four wheels. Based on the results of the current study, allowing the Ford E-350 van to operate with tire inflation pressures up to 25 percent below placard should not have a substantial adverse effect on its handling. The lower tire inflation pressures will not result in changes of practical significance to the linear range handling characteristics of this vehicle. Both the maximum achievable lateral acceleration and the lateral stability of this vehicle in a limit slowly increasing steer maneuver are likewise essentially unaffected.

The dynamic rollover resistance of the Ford E-350 is expected to be slightly reduced with lower inflation pressure in the vehicle’s tires, given the physical changes such a reduction can impose on the vehicle. However, as discussed above, the testing performed for this study was insufficient to conclusively demonstrate either the presence, or the magnitude, of this anticipated reduction.

1.0 INTRODUCTION

On April 29, 2003, the Alliance of Automobile Manufacturers (Alliance) petitioned NHTSA to change the Minimum Activation Pressures (MAP) of Tire Pressure Monitoring Systems (TPMS) for light truck tires [1]. Specifically, the Alliance requested that instead of MAPs being determined by the load range of the tire as specified in the recently rescinded FMVSS 138, MAPs be determined by the recommended inflation pressure (placard pressure). Table 1.1 shows the current MAPs and Table 1.2 the requested MAPs.

Table 1.1. Minimum Activation Pressures in the Recently Rescinded FMVSS 138.

Tire Load Range	Minimum Activation Pressure (psi)
C	29
D	38
E	46

Table 1.2. Alliance Requested Minimum Activation Pressures.

Placard Pressure (psi)	Minimum Activation Pressure (psi)
36 to 51	29
51 to 65	38
65 to 80	46

The Alliance is concerned that the MAPs contained in Table 1.1 will cause excessive nuisance TPMS warnings for certain light truck vehicles such as the Chevrolet/GMC Express/Savana 3500 vans, the Dodge Ram 2500 and 3500 pickup trucks, and the Ford Excursion (among other vehicles; a complete list is contained in Attachment 2 of [1]). These vehicles are equipped with the same load range D or E light truck tires on all wheels, yet the front tire inflation pressures are lower than those of the rear on their respective placards.

According to the Alliance petition [1], “TPMSs require that the recommended inflation pressure be 7 to 10 psi greater than the pressure at which the warning is required in order to allow for requisite compliance margins and avoidance of nuisance warnings.” The Alliance believes that the front placard pressures of these vehicles are not enough above the MAPs contained in Table 1.1 to prevent an excessive number of nuisance warnings from being generated by the TPMSs.

From the Alliance petition [1], “if the current FMVSS 138 MAPs remain unchanged, it will be necessary to increase the recommended tire inflation pressures.” (Note that it is also possible to install Load Range C or D tires on the front axle, however, the Alliance indicates that this would not be their preferred course of action.) Therefore, if this petition is granted, the vehicles front placard pressures are expected to remain unchanged. In this case, the vehicles could be driven with front tire inflation pressures as low as just above the MAPs contained in Table 1.2 without the TPMSs generating warnings.

Separately from the Alliance petition, on August 4, 2003, the National Transportation Safety Board (NTSB) issued Safety Recommendation H-03-17. This reads:

> *"In developing long-term performance requirements for tire pressure monitoring systems, adopt more stringent detection standards than 25 or 30 percent below manufacturer-recommended levels, since pressures at those levels can have an adverse effect on the handling of vehicles, such as 12- and 15-passenger vans."*

In its letter transmitting this safety recommendation to NHTSA, NTSB discusses two 15-passenger van rollover crashes, one near Henrietta, Texas and the other near Randleman, North Carolina. The NTSB has reason to believe that immediately prior to both of these crashes, all four of both vehicles' tires were inflated to approximately 60-psi. NTSB is concerned that these tire inflation pressures may have adversely affected the handling of these vehicles and helped cause the crashes.

As a consequence of the Alliance petition and NTSB Safety Recommendation H-03-17, NHTSA decided to initiate a small study of the effects of tire inflation pressure on 15-passenger van handling and dynamic rollover resistance. The results of this study are documented in this report.

2.0 OBJECTIVE

The objective of this study was to measure how the handling and dynamic rollover resistance of a contemporary 15-passenger van may be affected by tire inflation pressure. At the time of this study, only two vehicle manufacturers produced 15-passenger vans for sale in the United States: Ford Motor Company (the E-350) and General Motors (the Chevrolet Express and the GMC Savana). For this study, logistically constraints permitted an evaluation of only one such van--a 2003 Ford E-350. At the time of the initiation of this study, it was the only vehicle with load range "E" light truck tires that NHTSA's Vehicle Research and Test Center (VRTC) had available for testing. Obtaining another vehicle would have both delayed the study and increased its cost. Although this was a 2003 model year vehicle, Ford has told NHTSA that no significant changes were made to the chassis, suspension, or tires for 2004. For this reason, the handling and rollover resistance of the 2003 and 2004 model year vans should be identical.

Although both crashes of concern to NTSB involved Dodge 15-passenger vans, the Ford vehicle was used because, again, a Dodge van was not available for testing. Since DaimlerChrysler no longer produces the Dodge van, and NHTSA regulates new vehicles, it seemed counterproductive to try to obtain a Dodge van for this study.

The tests performed in this study were performed in three groups. Test Group 1 (TG1) was intended to evaluate handling in the linear range of lateral acceleration at a variety of inflation pressure combinations. Due to the low lateral acceleration targets, outriggers were not mounted on the test vehicle for these maneuvers. Test Group 2 (TG2) was used to evaluate handling at or near maximum lateral acceleration with the vehicle at the same inflation pressure combinations as during the TG1 tests. Test Group 3 (TG3) used two of the inflation pressure combinations used in TG1 and TG2, in conjunction with two load configurations, to determine what effect lower pressures may have on dynamic rollover propensity. For safety, outriggers were used for TG2 and TG3.

3.0 TEST CONDITIONS

3.1 Test Vehicle

One vehicle was used for the work described in this report, a 2003 Ford E-350 15-passenger van. The vehicle was purchased new from a local dealership. Depending on the severity of the test maneuvers used, the vehicle was evaluated with or without outriggers. Descriptive parameters of the test vehicle are provided in Table 3.1.

Table 3.1. Vehicle Specifications.

Description	GVWR (lbs)	Rear GAWR (lbs)	Miscellaneous Features	Wheelbase (inches)	Mean Track Width (inches)	Steering Ratio (deg/deg)
2003 Ford E-350 Super Duty	9100	6084	15-passenger seating; 5.4L V8; 4-spd auto; RWD	138.0	68.3	22.8

3.2 Tires

3.2.1 Description

All tires were new and of the same make, model, size, and DOT specification as those installed by the manufacturer as original equipment. Specifications of the tires used in this study are provided in Table 3.2. The tire replacement interval was a function of the kind of tests performed, and is described in detail in Section 3.2.5 of this report.

Table 3.2. Tire Specifications.

Size	Load Range	Load Index	Make	Model	Placard Inflation Pressure (psi)	
					Front	Rear
LT245/75R16	E	120-116	Goodyear	Wrangler HT	55	80

3.2.2 Inflation Pressure

Tire inflation pressure was an independent variable for the tests performed in this study. In addition to those specified on the vehicle identification placard, four other front/rear tire inflation pressure combinations were used. The inflation pressures used in this study are specified in Table 3.3. The rational for each of the four tire inflation pressure combinations studied is presented after this table.

Table 3.3. Tire Inflation Pressure Combinations Used For This Study.

Description	Inflation Pressure (psi)	
	Front	Rear
Placard	55	80
Increased Front	80	80
Alliance MAP	38	60
Current MAP	46	60
NTSB Concern	60	60

Placard – 55-psi front, 80-psi rear. These are the pressures recommended by the vehicle manufacturer on the placard.

Increased Front – 80-psi front, 80-psi rear. The Alliance petition indicated that their likely alternative to lowering the MAPS was to increase the front placard pressure. However, their testing indicated that such an increase would degrade handling. While only a small pressure increase (approximately 5-psi for most affected vehicles) would be necessary, a 25-psi tire pressure increase was used for this testing. This was for two reasons: (1) the effects of a 25-psi tire pressure increase should be easier to measure than the smaller effects of a 5-psi pressure increase, and (2) NHTSA is interested in the effects of having equal front and rear tire inflation pressures.

Current MAP – 46-psi front, 60-psi rear. The 46-psi front tire inflation pressure is the recently rescinded FMVSS 138 minimum activation pressure for load range E tires. The placard pressure for the rear tires of the Ford E-350 is 80-psi. The 60-psi rear tire inflation pressure is 25 percent below the rear placard pressure. This is the pressure at which the upcoming version of FMVSS 138 is expected to require the TPMS to warn the driver. Reducing the rear tire inflation pressures all the way down to the MAP level (46-psi) seemed overly severe since the driver will have been warned well before this pressure can be attained by the rear tires due to any condition except a rapid air out.

Alliance MAP – 38-psi front, 60-psi rear. The 38-psi front tire inflation pressure is the minimum activation pressure that the Alliance has suggested for the E-350's front tires, given its front placard pressure of 55-psi. Note that this is more than 25 percent below the front placard pressure (41.25-psi) and, therefore, the TPMS would warn the driver, for this particular vehicle, before the minimum activation pressure was reached. There are two reasons for testing at 38-psi instead of 41.25-psi: (1) it is the Alliance's suggested minimum activation pressure, and (2) 38-psi is farther from 46-psi than is 41.25-psi. Having a larger differential increases the chances of having measurable effects due to changes in tire inflation pressure.

NTSB Concern – 60-psi front, 60-psi rear. In their most recent recommendations to NHTSA, NTSB indicated that they were concerned about possible vehicle handling problems with tires inflated to these pressures.

3.2.3 Break-In Procedure

Prior to the beginning of each Slowly Increasing Steer (SIS), Step Steer (STEP), or Road Edge Recovery (RER) tests, the tires were "scrubbed in" to wear away mold sheen and to be brought up to operating temperature. The break-in / warm-up procedure used for the tests performed in this study was identical to that used for NHTSA's Dynamic Rollover NCAP Test Procedure [2]. No warm-up tests preceded Sinusoidal Steer (SINE) tests since they immediately followed the STEP tests. Detailed maneuver descriptions are provided in Chapter 4.

3.2.4 Mounting Technique

No lubricant was used when mounting tires to the rims used for testing. This was done to eliminate the possibility of tire lubricant contributing to debeading during SIS and RER tests.

3.2.5 Frequency of Changes

To minimize the effects of tire wear on vehicle response characteristics, multiple tire changes were utilized. The following guidelines were followed:

- One set of tires was used for all TG1 tests. The same tire set was used during tests performed with Nominal and Maximum Occupancy loads at each of the five inflation pressure combinations. These were tests performed in the linear range of lateral acceleration, and therefore tire wear was not significant.

- TG2 used one set of tires to perform the Placard and Current MAP testing, a second set to perform the Increased Front and Alliance MAP tests, and a third set to perform NTSB Concern testing.

- For each combination of tire inflation pressure and load configuration, TG3 used one set of tires for (1) one low-severity SIS test series, and (2) one RER test series. However, if two-wheel lift was observed during a RER test initiated with a maneuver entrance speed greater than 45 mph, a new set of tires was used to verify the vehicle/configuration was responsible for the occurrence of the wheel lift, and that it was not the result of tire wear.

3.2.6 Use of Inner Tubes

The occurrence of debeads can result in significant damage to the test surface. To reduce the likelihood of tire debeading, inner tubes designed for radial tires were installed prior to every TG2 and TG3 test. Inner tubes were appropriately sized for the test vehicle's tires. Inner tubes were not used for any TG1 test.

3.3 Load Configurations

During each group of testing, the test vehicle was evaluated with two load configurations. These configurations varied between the three groups of tests. For Test Group 1, the load configurations were as follows:

> **Nominal Load.** The Nominal Load consisted of the driver and instrumentation (including a steering machine). Instrumentation was installed on or near the front passenger seat. The total weight of this instrumentation was approximately that of an average person. Standard, original equipment, bumpers were mounted on the test vehicle. The vehicle was tested fully fuelled.
>
> **Maximum Occupancy.** In addition to the driver and instrumentation used in the Nominal Load configuration, Maximum Occupancy tests used 13 water dummies, weighing approximately 175 lbs each, positioned at each seating position for which an adult passenger may be restrained with a seatbelt, with the exception of the front seats (see Figure 3.1). Instrumentation (indicated as DAS in Figure 3.1) was installed on or near the front passenger seat. The total weight of this instrumentation was approximately that of an average person. Standard, original equipment, bumpers were mounted on the test vehicle. The vehicle was tested fully fuelled. The Maximum Occupancy configuration simulates a 15-passenger load.

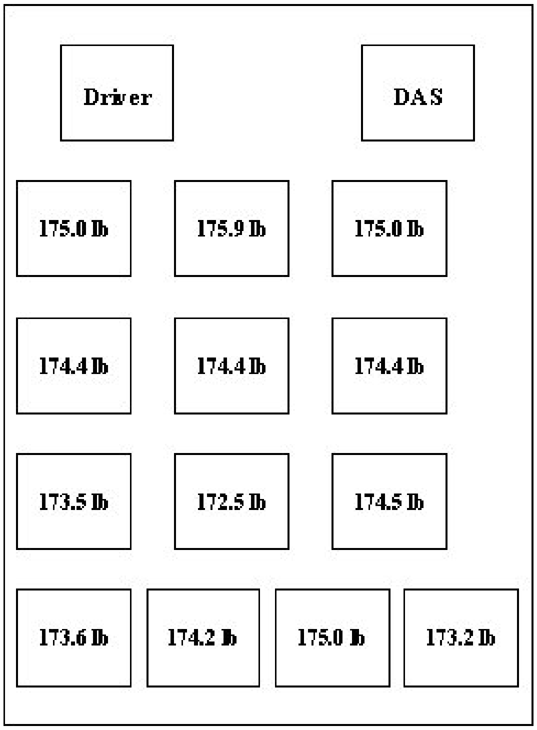

Figure 3.1. Water dummy weights used in the Maximum Occupancy load configuration.

For Test Group 2, both load configurations were modified by replacing the standard, original equipment, bumpers by NHTSA's "heavy-vehicle" titanium outriggers.

For Test Group 3, two different loading configurations were used. These were:

> **5-Occupant.** The Nominal Load configuration from Test Group 1 with the standard, original equipment, bumpers replaced by NHTSA's "heavy-duty" titanium outriggers plus 3 water dummies.
>
> **10-Occupant.** The Nominal Load configuration from Test Group 1 with the standard, original equipment, bumpers replaced by NHTSA's "heavy-duty" titanium outriggers plus 8 water dummies.

These loading configurations were used because other testing of this vehicle had found that these loading configurations were at the tip-up/no tip-up boundary for this vehicle.

3.4 Vehicle Inertial Parameters

The inertial parameters of the test vehicle were measured on SEA's Vehicle Inertial Measurement Facility (VIMF) in five configurations: Baseline (vehicle at curb weight plus a driver), with the vehicle at Nominal Load both with and without outriggers, and with the vehicle at Maximum Occupancy both with and without outriggers. For each configuration, the vehicle was weighed, the location of its center of gravity (C.G.) measured, and its Static Stability Factor calculated (SSF). Additionally, the vehicle's roll, pitch, and yaw mass moments of inertia were measured. Table 3.4 presents the results of these measurements.

As Table 3.4 shows, the vehicle's center of gravity height essentially does not change between the Baseline and Nominal Load without outriggers configurations. The 0.06-inch increase present in Table 3.4 is within the measurement variability of the Vehicle Inertial Measurement Facility.

The 4.3-inch increase in C.G. height between the Baseline and Maximum Occupancy without outriggers configurations is substantial, giving the Maximum Occupancy vehicle a relatively low Static Stability Factor of 0.944. Going to the Maximum Occupancy without outriggers configuration also moves the vehicle's center of gravity location rearward by 15.5 inches and substantially increases the vehicles roll, pitch, and yaw mass moments of inertia.

3.5 Instrumentation

The test vehicle was instrumented with sensors, a data acquisition system, and a programmable steering machine. The instrumentation package was identical to that used during Phases VI and VII testing except no wheel lift sensors were used. Descriptions of this equipment, and how it was utilized, have been previously documented and are available in [2].

Table 3.4. 2003 Ford E-350 15-Passenger Van Weights, C.G. Locations, and Mass Moments of Inertia.

Configuration	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
Baseline (E-350 15-passenger van, 161 lb driver, fully fuelled)	6479.3	72.96	31.83	-0.54	1.073	6820	991	6969
Nominal Load w/o Outriggers (2 occupants) (E-350 15-passenger van, 161 lb driver, fully fuelled, instrumentation)	6611.2	72.39	31.92	-0.32	1.070	6852	989	6998
Maximum Occupancy w/o Outriggers (15 occupants) (E-350 15-passenger van, 161 lb driver, fully fuelled, instrumentation, 13 175 lb occupants)	8934.2	88.46	36.17	-1.57	0.944	9193	1122	9115
Nominal Load (2 occupants) (E-350 15-passenger van, 161 lb driver, fully fuelled, instrumentation, outriggers)	6817.2	72.62	31.46	-0.31	1.085	7538	1074	7718
Maximum Occupancy (15 occupants) (E-350 15-passenger van, 161 lb driver, fully fuelled, instrumentation, outriggers, 13 175 lb occupants)	9141.4	88.36	35.36	-1.15	0.966	9844	1224	9836

4.0 TEST MANEUVERS

4.1 Test Group 1

The tests performed in this study were performed in three groups. Test Group 1 (TG1) was intended to evaluate handling in the linear range of lateral acceleration at a variety of inflation pressure combinations. Due to the low lateral acceleration targets, outriggers were not mounted on the vehicle for these maneuvers. The TG1 maneuvers were:

1. Slowly Increasing Steer to ≈0.5g lateral acceleration (SIS)
2. Step Steer to 0.408g (STEP)
3. Sinusoidal Steer at 0.2 Hz to 0.2g (SINE)

Each maneuver was performed with Nominal and Maximum Occupancy loading. Each of the five inflation pressure combinations was used. The SIS and STEP maneuvers were each performed with three left turns followed by three right turns. A total of six SINE maneuvers were performed in each load condition, three beginning with steering to the left followed by three performed with an initial right steer. The TG1 test matrix is summarized in Table 4.1. More detailed descriptions of each maneuver are provided in Sections 4.4, 4.5, and 4.6.

Table 4.1. Test Group 1 Test Matrix.

Vehicle Loading	**Maneuver**	**Tire Inflation Condition**				
		Baseline	**Increased Front**	**Current MAP**	**Alliance MAP**	**NTSB**
Nominal Load	SIS	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R
	STEP	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R
	SINE	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)
Maximum Occupancy	SIS	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R
	STEP	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R
	SINE	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)	6 2-cycle tests (3L/3R)

4.2 Test Group 2

Test Group 2 (TG2) was used to evaluate handling at or near the vehicle's maximum lateral acceleration with the same inflation pressure combinations used during the TG1 tests. Due to the "limit" nature of these maneuvers, for safety, outriggers were used for TG2. TG2 used only one maneuver: the SIS. Unlike the SIS used in TG1, the TG2 SIS used much larger handwheel angles. The TG2 test matrix is summarized in Table 4.2. A more detailed description of the SIS maneuver is provided in Section 4.4.

Table 4.2. Test Group 2 Test Matrix.

Vehicle Loading	**Maneuver**	**Tire Inflation Condition**				
		Baseline	**Increased Front**	**Current MAP**	**Alliance MAP**	**NTSB**
Nominal Load	SIS	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R
Maximum Occupancy	SIS	3L/3R	3L/3R	3L/3R	3L/3R	3L/3R

4.3 Test Group 3

Test Group 3 (TG3) tests were performed to assess what effect decreased front and rear tire inflation pressure may have on the test vehicle's dynamic rollover propensity. This was determined by using NHTSA's Road Edge Recovery maneuver, two inflation conditions, and two load configurations. The load configurations used for TG3 were 5-Occupant and 10-Occupant. Note that these differ from those used for TG1 and TG2. The TG3 test matrix is provided in Table 4.3.

Table 4.3. Test Group 3 Test Matrix.

Vehicle Loading	**Maneuver**	**Tire Inflation Condition**	
		Placard	**Current MAP**
5-Occupant	RER	Default Procedure; Supplemental Procedures (if needed)	Default Procedure; Supplemental Procedures (if needed)
10-Occupant	RER	Default Procedure; Supplemental Procedures (if needed)	Default Procedure; Supplemental Procedures (if needed)

The two inflation pressures were Placard (55-psi front, 80-psi rear) and Current MAP (46-psi front, 60-psi rear), as these pressures are thought by the authors to be the most relevant[1] of those investigated in TG1 and TG2. The two load configurations were 5- and 10-Occupant. As part of another test program designed to look specifically at the dynamic rollover propensity of 15-

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[1] The Increased Front, Alliance MAP, and NTSB Concern conditions were used to examine the effects of manipulating inflation pressure from a set of values either specified by the manufacturer of the test vehicle (Placard) or by the Current FMVSS 138 standard (Current MAP). As such, these three conditions are more academic than the Placard and Current MAP conditions, offering less "real world" significance.

passenger vans, the Ford E-350 used in this study produced two-wheel lift during tests performed with 10- and 15-Occupant configurations. Two-wheel lift was also observed during a Default Procedure test (see Section 4.7.2) performed with 5-occupants, however subsequent tests performed with a new set of tires were unable to validate its occurrence. This is important not from a rating standpoint (i.e., determining the vehicles dynamic NCAP rating), but rather because it indicates the vehicle was near a threshold where two-wheel lift was possible but not necessarily certain.

4.4 Slowly Increasing Steer (SIS)

The SIS maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in SAE J266 [6]. NHTSA indicated its intent to use the SIS for this purpose in the October 2002 Notice of Proposed Rulemaking that was published in the Federal Register. As stated in that notice:

> "The Slowly Increasing Steer maneuver provides data to assess the amount of turning capability of a vehicle (the Maximum Attainable Lateral Acceleration) and whether the vehicle's handling degrades gracefully at the limit (did the vehicle plow or spin when the maximum achievable turn was attained). We performed this maneuver for every vehicle tested during Phases II, III, and IV of NHTSA Rollover Research. Based on our experience we believe that this maneuver can be performed with excellent objectivity and repeatability."

The intent of the SIS maneuver is not to simulate a "real-world" driving situation, but rather to function as a means of providing valuable insight into the terminal behavior of a vehicle being driven at the limit of lateral adhesion.

There is not general agreement with NHTSA's use of the SIS to characterize the lateral dynamics of each vehicle. While NHTSA has not received any written comments arguing against the use of the SIS maneuver for this purpose, one auto manufacturer verbally told NHTSA that they consider the SIS to be the wrong way to characterize a vehicle's limit lateral dynamics.

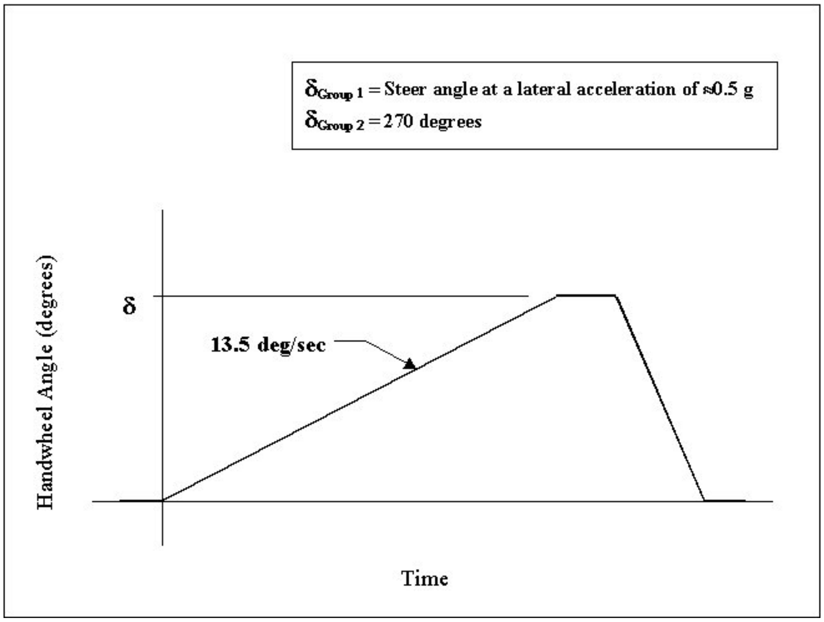

Figure 4.1. Slowly Increasing Steer (SIS) handwheel steering input description.

To begin the maneuver, the vehicle was driven in a straight line at 50 mph. The driver was instructed to maintain as constant a test speed as possible before, during, and after the steering inputs using smooth throttle modulation. For either test group, handwheel position was linearly increased at a rate of 13.5 degrees per second, as shown in Figure 4.1, briefly held constant, then returned to zero as a convenience to the driver. The steering ramp was slow enough that lateral acceleration performance in the linear range could be accurately evaluated. As a result, understeer gradient calculation was possible.

TG1 tests required the final magnitude of the steering ramp to be capable of producing a lateral acceleration of approximately 0.5g. Since TG2 tests were performed to determine maximum lateral acceleration, the total handwheel angle was increased to 270 degrees. The maneuver was performed to the left and to the right. Three repetitions of each test condition were performed.
In this study, the SIS maneuver was used to measure understeer gradient for two reasons. First, the maneuver is well suited for use with a programmable steering machine. Unlike a constant radius test, the SIS only requires the driver to modulate the throttle (rather than throttle and steering inputs). Since all steering is input by a machine, the data output from the SIS is generally very clean, with excellent test-to-test repeatability.

Second, the SIS maneuver provides the handwheel data required by the STEP, SINE, and RER maneuvers, as described in Sections 4.5, 4.6, and 4.7. This was accomplished by applying a first order polynomial best-fit line to the lateral acceleration data from 0.1 to 0.375g. NHTSA defines this as the linear range of the lateral acceleration response. Using the slope of the best-fit line, the average of handwheel positions at 0.2g (for the SINE maneuver) and 0.408g (for the STEP maneuver) was calculated using data from each of the six Slowly Increasing Steer tests performed for each vehicle.

4.5 Step Steer (STEP)

The STEP tests performed in this study are included in the "Step Input" section of ISO 7401 [5], however, they were only performed at a single lateral acceleration (the default value) and the steering inputs were automated.

To begin, the vehicle was driven in a straight line at the desired entrance speed of 50 mph. While maintaining a constant throttle position, the driver initiated a step steer to the handwheel average of 4 m/s^2 (0.408g), which was determined during the SIS maneuver. Following completion of the handwheel ramp, handwheel position was maintained for six seconds. As a convenience to the test driver, the handwheel was then returned to zero. STEP tests were performed in two directions, to the left and to the right, with a handwheel rate of 500 degrees per second. Figure 4.2 shows the handwheel steering angle during a STEP maneuver.

In this study, the output of the STEP maneuver was limited to Lateral Acceleration Response time. This was calculated by subtracting the reference time from the time when lateral acceleration first achieved 90 percent of its steady-state value. Reference time was defined as the instant handwheel position was at 50 percent of the total input, as shown in Figure 4.3.

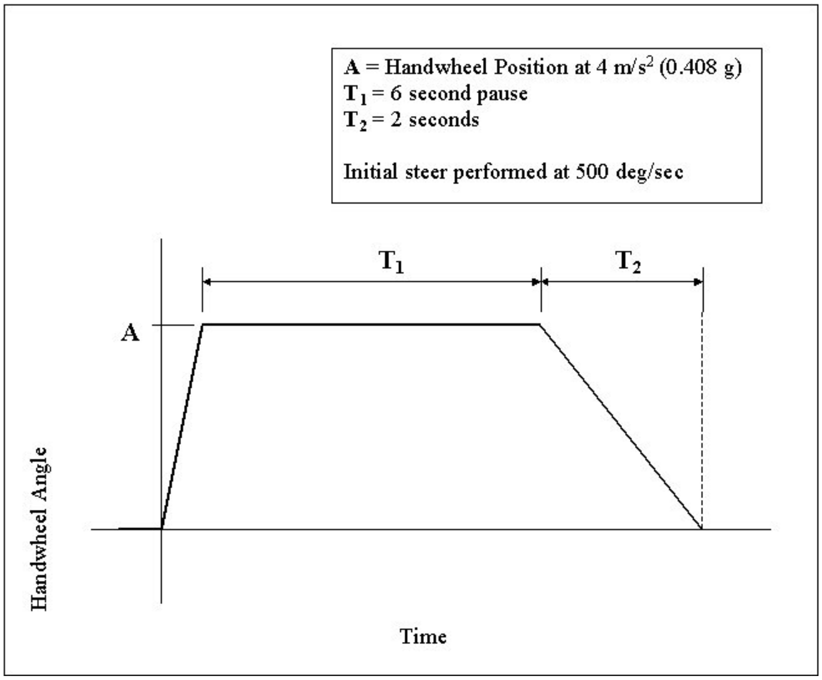

Figure 4.2. Step Steer (STEP) handwheel steering input description.

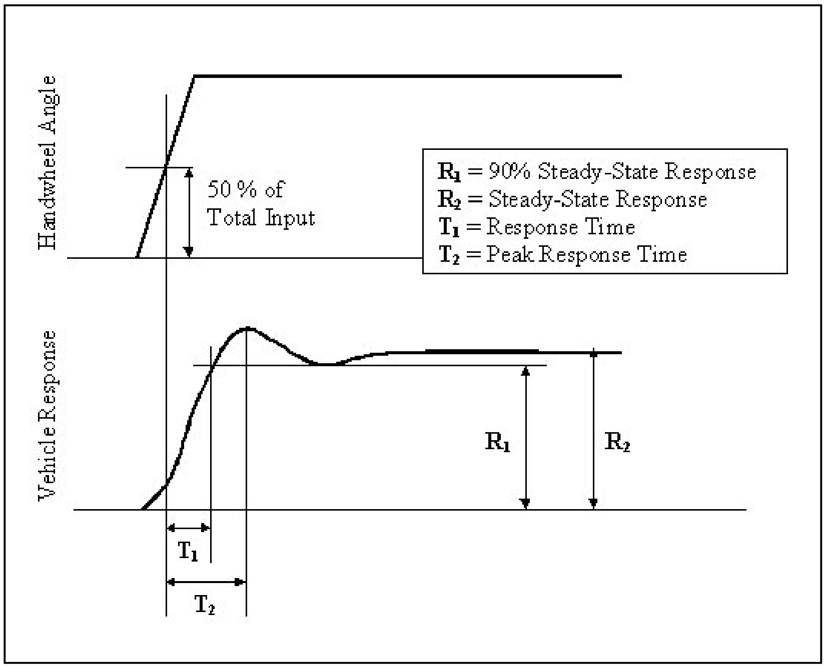

Figure 4.3. Response and peak response time specification. Traces are not drawn to scale.

4.6 Sinusoidal Steer (SINE)

The SINE tests were similar to those described in [6]. The principle difference was that those performed in this study used steering controller generated steering inputs while those in [6] used driver generated steering inputs.

To begin, the vehicle was driven in a straight line at the desired entrance speed of 50 mph. While maintaining a constant throttle position, the driver initiated a two-cycle, 0.2 Hz sinusoidal steer input. The handwheel magnitude was that capable of achieving a lateral acceleration of 0.2 g, which was determined during the SIS maneuver (described in Section 4.4). SINE tests were initiated with both directions of steer. Three tests began with an initial steer to the left, followed by three tests beginning with an initial right steer input. Figure 4.4 shows the handwheel steering angle during a SINE maneuver.

For this study, measures calculated from the output of the SINE maneuver were limited to Steering Work Sensitivity. The methods used to calculate this parameter are described in detail in [6].

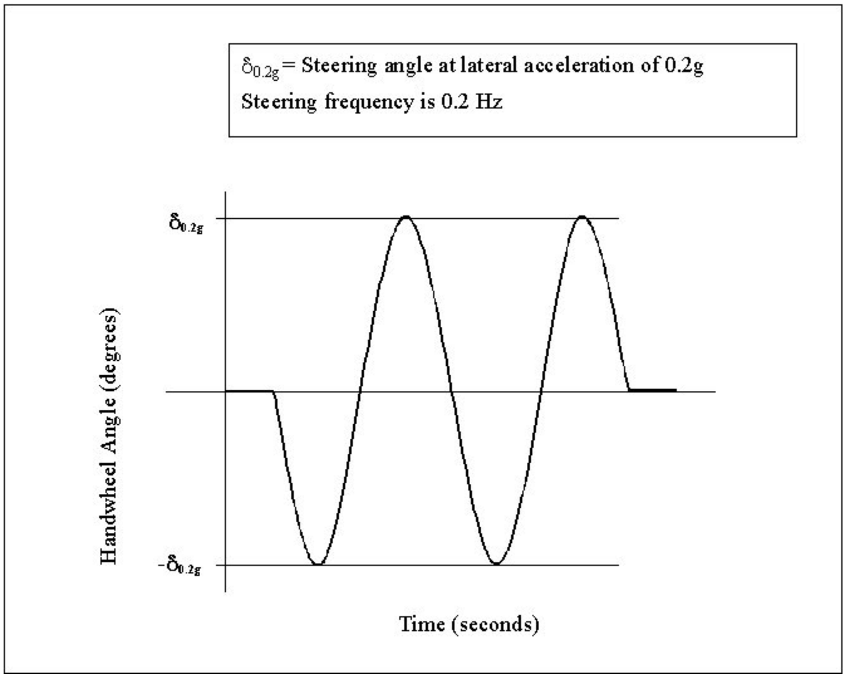

Figure 4.4. Sinusoidal steering (SINE) inputs used to evaluate Steering Work Sensitivity.

4.7 Road Edge Recovery (RER)

The handwheel inputs defining the RER maneuver approximate the steering a startled driver might use in an effort to regain lane position on a two-lane road after dropping two wheels off onto the shoulder. Of the nine Rollover Resistance maneuvers studied in the earlier Phase IV tests of the Agency Light Vehicle Rollover Research program [7], only the RER maneuver received "Excellent" ratings in each of the four maneuver evaluation factors (Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality). NHTSA considers the RER to be the best overall maneuver for evaluating dynamic rollover propensity. Phase IV testing has demonstrated the handwheel input rates and magnitudes of the RER are within the capabilities of an actual driver. RER tests performed in this study used procedures identical to those used to by NHTSA's NCAP dynamic rollover rating metric.

NHTSA's latest refinement of the RER test procedure (as contained in [8]) includes up to four components. For a given vehicle, each components each differ in two ways: the steering angle utilized and the range entrance speeds the maneuvers are begun at. The four components are:

1. Default Procedure
2. Supplemental Procedure 1
3. Supplemental Procedure 2
4. Supplemental Procedure 3

Note: Only the Default Procedure and Supplemental Procedure 1 components were required during the Ford E-350 tests discussed in this report. For the sake of brevity, detailed descriptions of Supplemental Procedures 2 and 3 have been omitted from this report. The entire RER test procedure, complete with detailed flowcharts outlining each component, is available in [8]. For these reasons, Section 4.7 presents the RER test procedure information relevant only to the Default Procedure and Supplemental Procedure 1 components.

4.7.1 Maneuver Overview

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, initiated the handwheel commands described in Figure 4.5 using a programmable steering machine. If a counterclockwise initial steer was input, the steering reversal following completion of the first handwheel ramp was to occur when the roll velocity of the vehicle was 1.5 degrees per second. If a clockwise initial steer was input, the steering reversal following completion of the first handwheel ramp occurred when the roll velocity of the vehicle was -1.5 degrees per second.

The handwheel rates of the initial steer and countersteer were 720 degrees per second for all test vehicles. Following completion of the countersteer, handwheel position was maintained for three seconds. As a convenience to the test driver, the handwheel was then returned to zero.

Each RER test series contained two sequences (with exceptions noted in the following sections): tests performed with left-right steering (first sequence), and tests performed with right-left steering (second sequence). The sequence of left-right tests always preceded those performed with right-left steering.

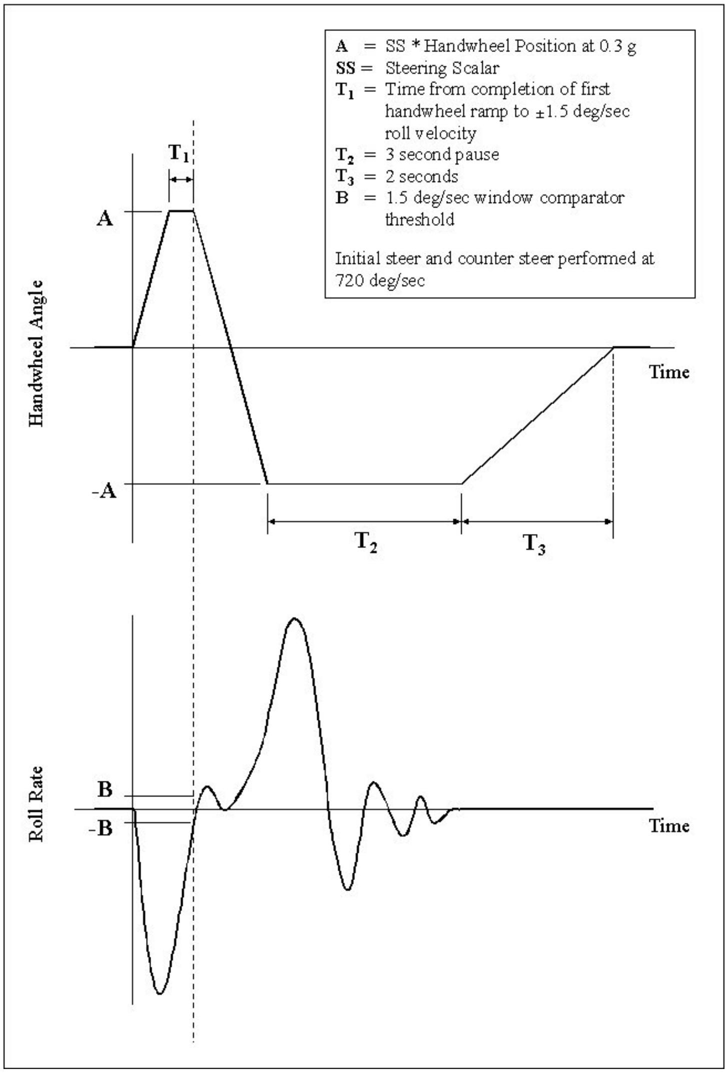

Figure 4.5. NHTSA Road Edge Recovery maneuver description.

4.7.2 Default Procedure

RER handwheel angles were calculated with lateral acceleration and handwheel angle data (δ) collected during a series of six SIS tests (a total of three left-steer and three-right steer tests are performed). For each SIS test, a linear regression line was fitted to the lateral acceleration data from 0.1 to 0.375 g. Using the slopes of these regression lines, the handwheel angles at 0.3 g were determined for each individual test ($\delta_{0.3\text{ g}}$). The six handwheel angles are then averaged to produce an overall value ($\delta_{0.3\text{ g, overall}}$).

$$\delta_{0.3\text{ g, overall}} = \left(\left| \delta_{0.3\text{ g, left (1)}} \right| + \left| \delta_{0.3\text{ g, left (2)}} \right| + \left| \delta_{0.3\text{ g, left (3)}} \right| + \delta_{0.3\text{ g, right (1)}} + \delta_{0.3\text{ g, right (2)}} + \delta_{0.3\text{ g, right (3)}} \right) / 6$$

The RER steering angles were calculated by multiplying $\delta_{0.3\text{ g. overall}}$ by a steering scalar (SS). The default steering scalar is 6.5.

$$\delta_{\text{RER (Default)}} = 6.5 \text{ x } \delta_{0.3\text{ g, overall}}$$

As explained in Section 3.2.5, most RER tests performed in this study began on the same tire set used for SIS tests performed with the same load configuration. The only exception was when two-wheel lift validation was required, as the process required use of a new tire set (further explained in Section 4.7.3).

4.7.2.1 Maneuver Entrance Speed

For the sake of driver safety, and as a final step in the tire scrub-in procedure, each Default Procedure sequence began with a Maneuver Entrance Speed (MES) equal to 35 mph. The MES was measured at the initiation of the first steering ramp, and was increased until a termination condition was satisfied. The order of MES for a sequence was, in mph: 35, 40, 45, 47.5, 50. For each test run, the actual MES was required to be within 1 mph of the target MES.

Note: NHTSA's experience with the RER maneuver indicates that an incremental increase in MES of 5 mph, up to 45 mph, minimizes tire wear without compromising test driver safety. However, when a MES greater than 45 mph is used, the severity of the responses produced with some vehicles can increase substantially from that observed at lesser entrance speeds. This is especially true if a vehicle has a propensity to oscillate in roll, and/or is able to produce two-wheel lift slightly less than NHTSA's threshold criterion of two inches. In some of these cases, the driver and/or experimenter may not be comfortable with a final 5 mph upwards increment in MES, and might, for the sake of driver safety, deviate from a test procedure that requires it. Generally speaking, such a deviation typically involves the experimenter's use of a more gradual 2.5 mph increase in MES.

To promote driver safety while also eliminating inconsistencies in the way RER maneuvers are performed, the test procedure used in this study (and during dynamic rollover tests used for NHTSA's NCAP rating metric, for that matter) *required* a MES increment equal to 2.5 mph be used above 45 mph if a test performed at 45 mph did not produce two-wheel lift, regardless of the vehicle being evaluated.

4.7.2.2 Outrigger Contact

If either outrigger contacts the pavement without two-wheel lift during a RER test run, the affected outrigger is raised 0.75 inches and the test is repeated at the same MES. If both safety outriggers contact the pavement without two-wheel lift, both outriggers are raised 0.75 inches and the test is repeated at the same MES.

4.7.2.3 Termination and Conclusion Conditions

A test sequence is terminated if the MES capable of producing two-wheel lift was observed and the MES is 45 mph or lower. If two-wheel lift is observed during a left-right sequence at 45 mph or lower, the [entire] series was terminated. If no two-wheel lift is observed during a left-right sequence, right-left tests were performed. If two-wheel lift was observed during a right-left sequence performed with a MES of 45 mph or lower, the test series was terminated.

If the MES capable of producing two-wheel lift during a left-right or right-left sequence was 47.5 mph or higher, a new set of tires was installed on the vehicle and the procedure described in Section 4.7.3 was implemented.

A test series was deemed complete if both test sequences within a given series were performed at the maximum maneuver entrance speed without two-wheel lift, rim-to-pavement contact, tire debeading, or outrigger-to-pavement contact. No two-wheel lift, rim-to-pavement contact, or tire debeading was observed during the tests performed in this study.

The flowchart presented in Figure A-1 describes the sequence of events for the Default Test Series.

4.7.3 Supplemental Procedure 1

Following the tire scrub-in procedure mentioned in Section 3.2.3, tests were performed with handwheel angles equal to $\delta_{\text{RER (Default)}}$, as explained in Section 4.7.2. The steering combination (i.e., either left-right or right-left) that produced two-wheel lift in the Default Test Series was used. The first test was performed at a MES of 35 mph to ensure any mold sheen remaining from the tire break-in procedure had been removed from the tires. The second test was performed at the MES at which two-wheel lift had been previously observed (i.e., with the previous tire set). If two-wheel lift was produced during the test performed with handwheel angles equal to $\delta_{\text{RER (Default)}}$, the tip-up observed in the Default Procedure was validated (considered a vehicle-dependent phenomenon, not the result of tire wear), and the test series deemed complete. If two-wheel lift was not produced and the MES is 47.5 mph, the MES was increased to 50 mph. If two-wheel lift was produced during the test performed with MES equal to 50 mph, the tip-up observed in the Default Procedure was also deemed valid, and the test concluded.

4.7.4 Summary of Road Edge Recovery Handwheel Angles

A summary of the RER handwheel angles used in this study is presented in Table 4.4. Additionally, Table 4.4 presents the overall range of dwell times observed during tests performed with each vehicle and load configuration. As previously indicated in Figure 4.5, dwell time is defined as the time from completion of the first steering ramp to the initiation of the steering reversal.

Table 4.4. Road Edge Recovery Handwheel Angles and Dwell Times.

Load Configuration	Placard (55-psi front, 80-psi rear)			Current MAP (46-psi front, 60-psi rear)		
	Steering Scalar	Handwheel Angle (degrees)	Dwell Time Range (ms)	Steering Scalar	Handwheel Angle (degrees)	Dwell Time Range (ms)
5-Occupant	6.5	364	105 - 160	6.5	393	55 - 85
	5.5	TNP		5.5	TNP	
10-Occupant	6.5	373	165 - 185	6.5	401	120 - 150
	5.5	TNP		5.5	TNP	

Note: TNP = Test Not Performed. Vehicle did not require the use of steering calculated with a steering scalar of 5.5.

5.0 TEST GROUP 1 RESULTS

5.1 Measured Data

The same measures of handling performance used by the Alliance in [1] were determined from the TG1 data. These are Linear Range Understeer Gradient, Lateral Acceleration Response Time, and Steering Work Sensitivity. Table 5.1 summarizes these performance measures for the Nominal Load vehicle at each of the five tire inflation pressure combinations. Table 5.2 shows these performance measures for the Maximum Occupancy vehicle.

Table 5.1. Test Group 1 Nominal Load Performance Summary.

Front / Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)			Lateral Acceleration Response Time (ms)			Steering Work Sensitivity (g^2/100 N-m)	
	Left	Right	Overall	Left	Right	Overall	Overall	Median
55 / 80	2.51 (0.14)	2.35 (0.200)	2.41 (0.18)	650 (59)	653 (43)	652 (45)	7.5 (3.3)	7.5
80 / 80	4.03 (0.15)	2.94 (0.14)	3.49 (0.61)	588 (23)	587 (10)	588 (16)	8.1 (2.7)	8.0
38 / 60	3.58 (0.16)	2.77 (0.19)	3.18 (0.47)	517 (35)	490 (41)	503 (37)	5.1 (1.8)	4.8
46 / 60	3.44 (0.26)	2.96 (0.20)	3.20 (0.34)	499 (28)	525 (18)	510 (26)	7.2 (2.7)	7.5
60 / 60	3.91 (0.10)	3.21 (0.22)	3.56 (0.41)	562 (33)	482 (15)	522 (50)	8.5 (5.2)	6.5

Note: Standard deviations are presented in parentheses.

Note that Table 5.2 contains three rows labeled 38 / 60 (RERUN), 46 / 60 (RERUN), and 60 / 60 (RERUN). When data from this testing was first examined, there were concerns about some of the measured Lateral Acceleration Response Times for the Maximum Occupancy vehicle with rear tires inflated to 60-psi. Therefore, this retesting was performed. The Understeer Gradient was also re-measured for the 60-psi front / 60-psi rear Maximum Occupancy vehicle. While some differences were seen in the retest data, these differences are not large enough to confirm the doubts about the original data. Therefore, data from both the original tests and the retests were used in the analyses that follow.

Table 5.2. Test Group 1 Maximum Occupancy Performance Summary.

Front / Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)			Lateral Acceleration Response Time (ms)			Steering Work Sensitivity (g^2/100 N-m)	
	Left	Right	Overall	Left	Right	Overall	Overall	Median
55 / 80	3.84 (0.30)	3.26 (0.179)	3.55 (0.39)	499 (19)	610 (28)	536 (61)	6.2 (3.1)	4.9
80 / 80	4.75 (0.21)	3.32 (0.219)	4.04 (0.79)	512 (10)	535 (13)	523 (17)	9.8 (7.7)	5.9
38 / 60	4.18 (0.09)	2.76 (0.154)	3.47 (0.78)	503 (8)	508 (10)	506 (9)	5.7 (4.4)	3.6
38 / 60 (RERUN)	Re-test not performed			442 (8)	473 (18)	458 (21)	Re-test not performed	
46 / 60	4.73 (0.09)	3.0 (0.31)	3.86 (0.97)	500 (25)	535 (17)	518 (27)	5.2 (2.9)	4.2
46 / 60 (RERUN)	Re-test not performed			493 (6)	533 (3)	513 (22)	Re-test not performed	
60 / 60	4.39 (0.24)	3.03 (0.36)	3.61 (0.78)	517 (35)	477 (20)	497 (34)	4.8 (3.2)	4.5
60 / 60 (RERUN)	3.84 (0.17)	3.10 (0.05)	3.47 (0.42)	450 (18)	488 (21)	469 (27)	Re-test not performed	

Note: Standard deviations are shown in parentheses.

Analyzing Table 5.1, at Nominal Load, the Ford E-350 had the least overall linear range understeer with the tires inflated to Placard (55-psi front, 80-psi rear) pressures (2.41 deg/g). It had the most overall linear range understeer with the tires inflated to the NTSB Concern (60-psi front, 60-psi rear) pressures (3.56 deg/g). As was determined by NHTSA during the Office of Defects Investigation's analysis of the Bridgestone/Firestone petition to initiate a safety defect investigation regarding the handling and control characteristics of Ford Explorer [9], all of the Nominal Load linear range understeer gradients were within the range of understeer gradients commonly seen in the vehicle fleet.

At Nominal Load, the vehicle had the quickest overall lateral acceleration response time with the tires inflated to the Alliance MAP (38-psi front, 60-psi rear) pressures (503 ms). It had the slowest response time with the tires inflated to the Placard (55-psi front, 80-psi rear) pressures (652 ms). The vehicle had the highest steering work sensitivity with the tires inflated to the NTSB Concern (60-psi front, 60-psi rear) pressures (8.5 g^2/hn-m). It had the lowest steering work sensitivity with the tires inflated to the Alliance MAP (38-psi front, 60-psi rear) pressures (5.1 g^2/hn-m).

Analyzing Table 5.2, at Maximum Occupancy, the Ford E-350 had the least overall linear range understeer with the tires inflated to the Alliance MAP (38-psi front, 60-psi rear) pressures (3.47 deg/g). It had the most overall linear range understeer with the tires inflated to the Increased Front (80-psi front, 80-psi rear) pressures (4.04 deg/g). Once again, all of the Maximum Occupancy linear range understeer gradients were within the range of understeer gradients commonly seen in the vehicle fleet.

At Maximum Occupancy, this vehicle had the quickest overall lateral acceleration response time with the tires inflated to the Alliance MAP (38-psi front, 60-psi rear) pressures (458 ms). It had the slowest response time with the tires inflated to the Placard (55-psi front, 80-psi rear) pressures (536 ms). This vehicle had the highest steering work sensitivity with the tires inflated to the Increased Front (80-psi front, 80-psi rear) pressures (9.8 g^2/hn-m). It had the lowest steering work sensitivity with the tires inflated to the NTSB Concern (60-psi front, 60-psi rear) pressures (4.8 g^2/hn-m).

5.2 Statistical Analysis

As shown in Tables 5.1 and 5.2, for much of the TG1 data, the standard deviations in the response measures were of a comparable magnitude to the differences that were seen between the different tire inflation conditions. To determine which differences were likely real versus those potentially attributable to measurement noise, the TG1 data was statistically analyzed using SAS. Due to the unequal number of front tire inflation pressures tested for the two rear tire inflation pressures, the data was analyzed in two groups. Group A was data collected with a rear tire inflation pressure of 80-psi. Group B was data collected with a rear pressure of 60-psi.

Proc GLM (General Liner Model) was used to analyze both groups of data. Three independent variables, direction of steer (Right, Left), vehicle loading (Nominal Load, Maximum Occupancy), and front tire inflation pressure (55-psi and 80-psi for Group A, 38-psi, 46-psi, and 60-psi for Group B) were used for each group. Direction of steer was not used as an independent variable for the Steering Work Sensitivity response measure because the test used to measure Steering Work Sensitivity includes steering to both the left and the right.

The results of these analyses are summarized in Tables 5.3 through 5.8. In these tables, differences are considered to be statistically significant if there is less than a 5 percent chance of them occurring due to random happenstance. They are “Nearly” statistically significant if there is a 5 to 10 percent chance of them occurring due to random happenstance.

Table 5.3 shows the effect of direction of steer on Linear Range Understeer Gradient and Lateral Acceleration Response Time. This vehicle has significantly more linear range understeer when steered to the left than when steered to the right. It also had a shorter Lateral Acceleration Response Time when steered to the left, although this difference was only statistically significant for a rear tire inflation pressure of 80-psi.

When the authors drove this vehicle, they could not detect differences between steering the vehicle to the left and to the right. Therefore, while these differences are statistically significant, they are thought not to be of practical significance.

Table 5.3. Effect of Direction of Steer on Linear Range Understeer Gradient and Lateral Acceleration Response Time.

Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)				Lateral Acceleration Response Time (ms)			
	Average Left Steer	Average Right Steer	Statistically Significant Difference?	Pr>F	Average Left Steer	Average Right Steer	Statistically Significant Difference?	Pr>F
80	3.98	3.06	Yes	<0.0001	557	604	Yes	0.0413
60	4.01	2.98	Yes	<0.0001	498	501	No	0.6430

Table 5.4 shows the effect of vehicle loading on Linear Range Understeer Gradient, Lateral Acceleration Response Time, and Steering Work Sensitivity. The Ford E-350 had significantly more linear range understeer when loaded to Maximum Occupancy than at Nominal Load. It also had a shorter Lateral Acceleration Response Time at Maximum Occupancy, although this difference was only nearly statistically significant for a rear tire inflation pressure of 60-psi. For a rear tire inflation pressure of 60-psi, the vehicle had a lower Steering Work Sensitivity when loaded to Maximum Occupancy than at Nominal Load. For a rear tire inflation pressure of 80-psi, Steering Work Sensitivity was not significantly affected by vehicle loading.

Tables 5.5 through 5.8 focus on the main topic of this report, the effect of tire pressure on selected vehicle handling metrics.

Table 5.5 shows that for a rear tire inflation pressure of 80-psi, the Linear Range Understeer Gradient of the Ford E-350 increased with increasing front tire inflation pressure. The same trend is seen in the 60-psi rear tire inflation data; however, the differences 60-psi differences were not statistically significant. Since the 60-psi trend agreed with the 80-psi trend, the differences seen are probably real and not merely experimental measurement noise.

When the vehicle was evaluated with the Alliance MAP tire inflation pressures (38-psi front, 60-psi rear) it had less Linear Range Understeer Gradient than it did with the Current MAP inflation pressures (46-psi front, 60-psi rear). However, the difference between the two configuration's Linear Range Understeer Gradient was small (a delta of 0.21 degrees/g). Going from the Current MAP inflation pressures to the Alliance MAP inflation pressures had less effect on Linear Range Understeer Gradient than does reversing the direction of steering (average delta of 0.98 degrees/g) or changing the vehicle from Nominal Load to Maximum Occupancy (average delta of 0.56 degrees/g). As stated earlier, when the authors of this report drove this vehicle, they could not detect differences between steering the vehicle to the left and to the right. Therefore, the far smaller effect on Linear Range Understeer Gradient of changing from the Current MAP inflation pressures to the Alliance MAP inflation pressures is thought not to be of practical significance.

Table 5.4. Effect of Vehicle Loading on Linear Range Understeer Gradient,
Lateral Acceleration Response Time, and Steering Work Sensitivity.

Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)				Lateral Acceleration Response Time (ms)				Steering Work Sensitivity (g^2/100 N-m)			
	Average at Nominal Load	Average at Maximum Occupancy	Statistically Significant Difference?	Pr>F	Average at Nominal Load	Average at Maximum Occupancy	Statistically Significant Difference?	Pr>F	Average at Nominal Load	Average at Maximum Occupancy	Statistically Significant Difference?	Pr>F
80	3.00	3.83	Yes	0.0003	624	530	Yes	<0.0001	7.78	7.77	No	0.9935
60	3.31	3.60	Yes	0.0074	512	493	Nearly	0.0666	6.95	5.24	Yes	0.0321

Table 5.5. Effect of Front Tire Inflation Pressure on Linear Range Understeer Gradient,
Lateral Acceleration Response Time, and Steering Work Sensitivity with a Rear Tire Inflation Pressure of 80-psi.

Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)				Lateral Acceleration Response Time (ms)				Steering Work Sensitivity (g^2/100 N-m)			
	Average at 55-psi	Average at 80-psi	Statistically Significant Difference?	Pr>F	Average at 55-psi	Average at 80-psi	Statistically Significant Difference?	Pr>F	Average at 55-psi	Average at 80-psi	Statistically Significant Difference?	Pr>F
80	3.03	3.80	Yes	<0.0001	602	555	Yes	0.0142	6.88	8.95	Nearly	0.0874

Table 5.6. Effect of Front Tire Inflation Pressure on Linear Range Understeer Gradient with a Rear Tire Inflation Pressure of 60-psi.

Rear Inflation Pressure (psi)	Linear Range Understeer Gradient (deg/g)				
	Average at 38-psi	Average at 46-psi	Average at 60-psi	Statistically Significant Difference?	Pr>F
60	3.32	3.53	3.55	No	0.2163

Table 5.7. Effect of Front Tire Inflation Pressure on Lateral Acceleration Response Time with a Rear Tire Inflation Pressure of 60-psi.

Rear Inflation Pressure (psi)	Lateral Acceleration Response Time (ms)				
	Average at 38-psi	Average at 46-psi	Average at 60-psi	Statistically Significant Difference?	Pr>F
60	489	513	496	Nearly	0.0854

Table 5.8. Effect of Front Tire Inflation Pressure on Steering Work Sensitivity with a Rear Tire Inflation Pressure of 60-psi.

Rear Inflation Pressure (psi)	Steering Work Sensitivity (g^2/100 N-m)				
	Average at 38-psi	Average at 46-psi	Average at 60-psi	Statistically Significant Difference?	Pr>F
60	5.39	6.28	6.93	No	0.2972

When evaluated with the NTSB Concern tire inflation pressures (60-psi front, 60-psi rear), the Ford E-350 had almost the same Linear Range Understeer Gradient as it did with the Current MAP inflation pressures (46-psi front, 60-psi rear). There was nothing in the measured Linear Range Understeer Gradient at the NTSB Concern inflation pressures that indicates a potential handling problem.

Table 5.5 shows that for a rear tire inflation pressure of 80-psi, the vehicle's Lateral Acceleration Response Time decreased with increasing front tire inflation pressure. This change was statistically significant. The same trend was seen in the 60-psi rear tire inflation data when going from a front pressure of 46- to 60-psi, while the opposite trend was seen as the front pressure changed from 38- to 46-psi. Although SAS indicated that the Lateral Acceleration Response Time differences in the 60-psi rear tire inflation data were nearly statistically significant, this trend reversal and the small magnitude of the differences (approximately 5 percent of the measured values) make it likely that these differences are not real and merely experimental measurement noise.

Therefore, the Alliance MAP tire inflation pressures (38-psi front, 60-psi rear), the Current MAP inflation pressure (46-psi front, 60-psi rear), and the NTSB Concern tire inflation pressure (60-psi front, 60-psi rear) all have approximately the same Lateral Acceleration Response time. This was quicker than that of the Placard tire inflation pressures (55-psi front, 80-psi rear). There was nothing in these Lateral Acceleration Response Times that indicates a possible handling problem for any of the three 60-psi rear tire inflation pressure configurations.

Table 5.5 shows that for a rear tire inflation pressure of 80-psi, the vehicle's Steering Work Sensitivity increases with increasing front tire inflation pressure. The change was nearly statistically significant. The same trend was seen in the 60-psi rear tire inflation data but this time the differences were not statistically significant. Since the 60-psi trend agreed with the 80-psi trend, the differences seen are probably real and not merely experimental measurement noise. Taking both the 60- and 80-psi rear tire inflation pressures together, the Steering Work Sensitivity increased with increasing front tire inflation pressure. This was reasonable since one would expect Steering Work Sensitivity to depend far more upon front tire inflation pressure than upon rear tire inflation pressure.

At 5.39 g^2/100 N-m, the Alliance MAP tire inflation pressures (38-psi front, 60-psi rear) had the lowest Steering Work Sensitivity of any of the tire inflation pressure configurations studied. In [10], Jaksch of Volvo determined that there was an optimum value for Steering Work Sensitivity. This optimum value has been subjectively determined to be in the range of 2.5 to 3.5 g^2/100 N-m. All of the Steering Work Sensitivities measured for the Ford E-350 are well above this optimum value. Being the lowest, the Alliance MAP inflation pressures Steering Work Sensitivity was the closest to the optimum value, and therefore presumably the best, of any of the tire inflation pressure configurations studied. According to the Alliance petition [1], the vehicle will feel more-and-more "darty" as the front tire inflation pressure is increased.

In summary, the linear range handling measures determined during the TG1 testing show only small changes due to changes in the tire inflation pressure over the range studied. The small changes seen are believed not to be of practical significance. In other words, the linear range handling of the Ford E-350 is essentially unaffected by changes in tire inflation pressure. This is, of course, good since a high sensitivity to tire inflation pressure changes could cause in-use problems.

6.0 TEST GROUP 2 RESULTS

For the purposes of TG2, SIS tests were used to evaluate handling at or near the maximum lateral acceleration. The vehicle was evaluated with the same inflation pressure combinations used during TG1. This chapter discusses two aspects of vehicle handling: the maximum lateral acceleration and lateral stability at the limit of adhesion.

6.1 Maximum Lateral Acceleration

Table 6.1 summarizes the maximum lateral accelerations observed during TG2 at each of the five tire inflation pressure combinations. Both Nominal Load and Maximum Occupancy results are provided.

Table 6.1. Test Group 2 Maximum Lateral Acceleration Summary.

Front / Rear Inflation Pressure (psi)	Nominal Load (g)			Maximum Occupancy (g)		
	Left	Right	Overall	Left	Right	Overall
55 / 80	0.77 (0.014)	0.76 (0.025)	0.76 (0.020)	0.75 (0.001)	0.70 (0.012)	0.72 (0.025)
80 / 80	0.75 (0.007)	0.77 (0.031)	0.76 (0.021)	0.74 (0.019)	0.71 (0.016)	0.72 (0.020)
38 / 60	0.76 (0.015)	0.78 (0.029)	0.77 (0.023)	0.76 (0.026)	0.67 (0.028)	0.72 (0.054)
46 / 60	0.81 (0.007)	0.81 (0.033)	0.81 (0.021)	0.71 (0.012)	0.72 (0.012)	0.72 (0.012)
60 / 60	0.75 (0.021)	0.76 (0.032)	0.75 (0.024)	0.74 (0.011)	0.66 (0.028)	0.70 (0.046)

Note: Standard deviations are presented in parentheses. All tests were performed with outriggers.

6.1.1 Effects of Loading

Generally speaking, the maximum lateral accelerations of the Ford E-350 were greater in the Nominal Load configuration. The only exception to this trend was when left-steer tests were performed with the Alliance MAPs. For this condition, the maximum lateral accelerations were the same for both load configurations. There was good consistency for the maximum lateral accelerations in the Nominal Load configuration compared to the values observed during Maximum Occupancy tests. In every Nominal Load configuration, the averages of the left-steer tests were within 0.02g of the comparable right steer tests. Results were much more asymmetric when the vehicle was loaded to Maximum Occupancy. Average left- and right-steer maximum lateral accelerations differed by as little as 0.01g with the Current MAPs to as much as 0.09g with the Alliance MAPs.

The standard deviations seen in the various inflation/load combinations were all quite low. In the Nominal Load configuration, the maximum lateral acceleration standard were less than 4.3 percent of their respective mean values, regardless of direction of steer. Maximum Occupancy standard deviations differed by no more than 4.2 percent of the mean values.

6.1.2 Effects of Inflation Pressure

At Nominal Load, the overall maximum lateral accelerations were very similar, ranging from 0.75g with NTSB Concern pressures, to 0.81g with the Current MAPs. With the exception of the Current MAP results, all overall values were within 0.02g. The maximum lateral accelerations achieved with the Current MAPs were 0.04 to 0.06g greater than any other value observed during Nominal Load testing. The authors are unsure as to why this phenomenon occurred.

When loaded to Maximum Occupancy, the overall maximum lateral accelerations ranged from 0.70 to 0.72g. In fact, an overall value of 0.72g was observed for four of the five inflation pressure combinations. As was the case for the Nominal Load configuration, tests performed with the NTSB Concern pressures produced the lowest overall maximum lateral accelerations in the Maximum Occupancy configuration.

Table 6.2 summarizes the steering angles required to reach maximum lateral acceleration ($\delta_{AY,max}$). These data help quantify how able the vehicle was able to respond to increasing steering angles as a function of tire inflation pressure (i.e., the steering required to saturate the vehicle's lateral road holding capacity). When considering these data, perusal through Appendix Figures A-3 through A-22 may be useful. These figures present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during each TG2 SIS maneuver performed in this study.

Experimental noise present in the region of maximum lateral acceleration can introduce disparity in the values of $\delta_{AY,max}$, as explained in NHTSA's Phase IV Technical Report [7], For this reason, the $\delta_{AY,max}$ ranges for some test conditions are greater than others. Also, numerous spinouts or near spinouts occurred during TG2 testing (this is discussed later in Section 6.2). Since spinouts increase peak lateral acceleration variability, they also increase $\delta_{AY,max}$ disparity.

The data presented in Table 6.2 do not provide a clear indication of whether the various combinations of tire inflation pressure investigated in this study influence $\delta_{AY,max}$. For example, consider the overall average $\delta_{AY,max}$ values of the Placard and Increased Front (80-psi front, 80-psi rear) conditions. In the Nominal Load configuration, the vehicle generally required more steering to reach maximum lateral acceleration when the tires were inflated to Placard pressures than it did when the Increased Front pressures were used (228 versus 196 degrees). Conversely, when the vehicle was evaluated in the Maximum Occupancy configuration, less steering was required to reach maximum lateral acceleration when the tires were inflated to Placard pressures than it did when the Increase Front pressures were used (159 versus 231 degrees). To further confuse matters, a somewhat different trend was seen when the Alliance MAP, Current MAP, and NTSB Concern data were considered. For both load configurations, more steering was required to reach maximum lateral acceleration when the front inflation pressure was increased from 38- to 46-psi. However, when the front pressure was increased from 46- to 60-psi, less steering was required. In fact, the overall $\delta_{AY,max}$ values of the NTSB Concern were lower than the Current MAP and Alliance MAP for both load configurations.

Table 6.2. Steering Angles Required to Reach Maximum Lateral Acceleration.

Front / Rear Inflation Pressure (psi)	Nominal Load (deg)			Maximum Occupancy (deg)		
	Left Range	Right Range	Overall Average	Left Range	Right Range	Overall Average
55 / 80	206 - 245	234 - 242	228 (17.6)	130 - 136	142 - 268	159 (53.9)
80 / 80	175 - 180	174 - 265	196 (35.4)	195 - 210	258 - 267	231 (36.6)
38 / 60	165 - 178	227 - 268	212 (45.2)	146 - 164	146 - 153	152 (6.4)
46 / 60	193 - 206	243 - 268	228 (32.5)	162 - 231	251 - 261	232 (36.6)
60 / 60	171 - 177	186 - 198	183 (11.1)	133 - 147	130 - 148	138 (7.8)

Note: Standard deviations are presented in parentheses. All tests were performed with outriggers.

In agreement with the TG1 findings of the linear range handling tests, the maximum lateral accelerations measured during the TG2 testing generally show only small changes due to changes in the tire inflation pressure. With the possible exception of the results of tests performed with the Current MAPs in the Nominal Load configuration, the small changes seen are believed not to be of practical significance.

The authors cannot explain the apparent inconsistency of how inflation pressure influences the amount of steering required to reach maximum lateral acceleration. Factors such as the experimental noise present in the region of maximum lateral acceleration and peak lateral acceleration variability due to the spinouts may be have confounded the results.

6.2 Lateral Stability

As discussed in Chapter 5, the maneuvers performed in TG1 showed that changes in tire inflation pressure (over the range studied) resulted in only small changes in vehicle responses that are thought not to be of practical significance. Similarly, tire pressure changes generally had little effect on the maximum achievable lateral acceleration for a particular load configuration. However, changes in inflation pressure did have an important effect on the lateral stability of the test vehicle. Since the responses of the vehicle were strongly dependent on loading, this section discusses each load configuration separately.

In this section, the authors define "spinout" or "limit oversteer" as a loss of directional stability resulting in the rapid yaw rotation of the vehicle. They are characterized by increasing yaw rates that exceed 30 degrees/second.

6.2.1 Nominal Load

The lateral stability of the vehicle with Nominal Load was highly asymmetric. Spinouts occurred during every right-steer test, for each of the five inflation pressure combinations used in this study. Left-steer tests also produced spinouts, however their occurrence was more anomalous than repeatable; they only occurred during one of the three tests performed in each respective series[2].

When left steering was used in the Nominal Load configuration, increasing the steering angle generally resulted in a gradual increase in yaw rate until the vehicle eventually reached a quasi steady state cornering condition. As can be inferred by the fact that different steering angles were required to reach maximum laterally acceleration (recall Table 6.3), the times required for the vehicle to achieve steady state differed. Although the yaw rate typically stabilized 12 to 15 seconds after the maneuvers were initiated, there were two exceptions to this trend. The first test performed in the Current MAP condition and the third test performed in the Increased Front condition both produced spinouts that began just before completion of the SIS steering ramp, approximately 16 to 18 seconds after the maneuver began. Appendix Figures A-3, A-5, A-7, A-9, and A-11 present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during left-steer tests performed in the Nominal Load configuration.

Right-steer tests performed with the five inflation pressure conditions can be grouped into two categories: (1) pressure combinations that allowed yaw rate to build to the point of spinout, and (2) pressure combinations that allowed yaw rate to build, temporarily stabilize, and then increase to produce spinout. The first category was comprised of the Placard, the first of the three Increased Front tests, the Alliance MAP, and the Current MAP conditions. The second category includes two Increased Front tests and the NTSB Concern conditions. Appendix Figures A-4, A-6, A-8, A-10, and A-12 present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during right-steer tests performed in the Nominal Load configuration.

The behavior of the vehicle during the tests included in the first category is self-explanatory, although some differences in the amount of time between initiation of the maneuver and the

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[2] Recall that a SIS test series was comprised of three left-steer tests followed by three right-steer tests.

beginning of the spinouts were apparent. Spinouts that occurred when the tires were at the Placard and Increased Front pressures started earlier in the maneuver (approximately 12 to15 seconds after the maneuver began) than the spinouts observed in the Alliance MAP and Current MAP conditions (approximately 17 to18 seconds after the maneuver began, very near the time of completion of the SIS steering ramp).

In the case of the second category, the yaw rate of two Increased Front tests and each of the three NTSB Concern tests increased in a manner nearly identical to that observed during the previously mentioned tests, but rather than building to the instance of spinout, the yaw rate settled approximately 13 to14 seconds after the maneuver began. However, after remaining stable for approximately 4 to5 seconds, yaw rate then increased until the vehicle ultimately spun out.

Table 6.3 presents an overall lateral stability summary for the tests performed in the Nominal Load configuration. In this table, the term "limit understeer" describes a test for which the vehicle did not spinout. The term "limit oversteer" describes a test for which spinout was observed.

Table 6.3. Test Group 2 Lateral Stability Summary (Nominal Load).

Front / Rear Inflation Pressure (psi)	Left	Right
55 / 80	Limit understeer	• **Limit oversteer** • Severe rear axle hop was produced as the vehicle approached its maximum lateral acceleration, and continued until the vehicle spun out
80 / 80	• Limit understeer observed for two of the three tests performed • **Limit oversteer** observed for one of the three tests performed (during the final test of the series)	• **Limit oversteer** • Two of the three tests produced rear axle hop as the vehicle spun out
38 / 60	Limit understeer	• **Limit oversteer** • Rear axle hop was produced as the vehicle spun out
46 / 60	• Limit understeer observed for two of the three tests performed • **Limit oversteer** observed for one of the three tests performed (during the first test of the series)	**Limit oversteer**
60 / 60	Limit understeer	• **Limit oversteer** • Rear axle hop was produced as the vehicle spun out

Note: Although it is unclear as to whether it had a significant effect on the lateral stability of the vehicle, rear axle hop was observed during most right-steer tests performed in the Nominal Load configuration. The hop occurred as the vehicle approached maximum lateral acceleration, and continued until the vehicle ultimately spun out. No axle hop was detected during left-steer tests. No axle hop was observed during any test performed at Maximum Occupancy.

6.2.2 Maximum Occupancy

The lateral stability of the vehicle in the Maximum Occupancy configuration also was asymmetric. However, in terms of lateral stability, the vehicle's behavior was generally much better than that observed during tests performed at Nominal Load[3]. Interestingly, while right-steer tests always induced lateral instability in the Nominal Load configuration, left-steer tests seemed to be more severe with Maximum Occupancy loading.

The only tire inflation pressure combination that resulted in spinouts was Placard. When tested at these inflation pressures and left steering, increasing the steering angle resulted in a gradual increase in yaw rate until the vehicle began to spinout approximately 8 to 9 seconds after the maneuver began; earlier in the maneuver than any spinout seen in the Nominal Load configuration. Every left-steer test performed at these tire pressures produced a spinout. An example is presented in Figure 6.1. This figure shows a sequence of six frames taken from a video of the vehicle during a left-steer test performed at Placard inflation pressures and Maximum Occupancy loading. Appendix Figure A-13 shows the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during left-steer tests performed in the Maximum Occupancy configuration at Placard tire inflation pressures.

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[3] As measured with the Slowly Increasing Steer maneuver. The authors stress that the SIS is just one maneuver capable of assessing a lateral stability. It is only comprised of a gradual increase in steering angle, in one direction per test, and is much less severe that a maneuver that endeavors to measure transient responses (e.g., a Road Edge Recovery or Lane Change). For this reason, the SIS results presented in this study should be interpreted as an indicator of the Ford E-350's handling tendencies, not an absolute quantification of the vehicle's overall handling characteristics.

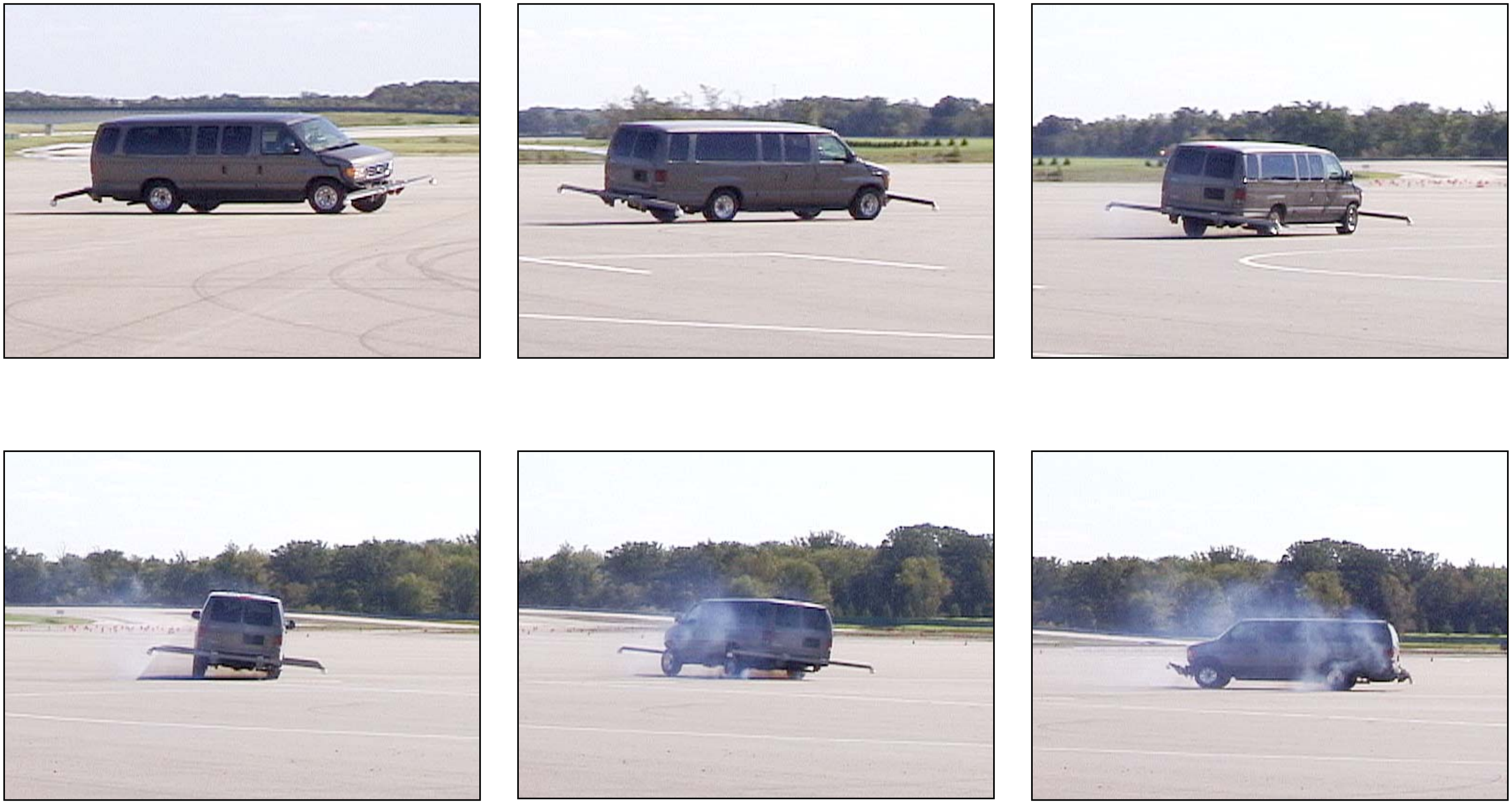

Figure 6.1. One of three "spin-outs" observed during 2003 Ford E-350 Slowly Increasing Steer tests performed with left steering, Placard tire inflation pressures (55-psi front / 80-psi rear), and Maximum Occupancy loading.

Increasing the front tire pressure from Placard to Increased Front reduced the vehicle's propensity to spinout (none occurred). The first left-steer test of the series produced a peak yaw rate greater than most of the other peaks observed in the Maximum Occupancy configuration. Until 17 to 18 seconds after maneuver start, the yaw rates of each left-steer, Increased Front tests performed at Maximum Occupancy increased as a function of steering angle. However, rather than achieving steady state, the yaw rates decayed after their respective peak values had been achieved. The yaw rates diminished until the SIS steering ramp was complete. Appendix Figure A-15 shows vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during left-steer tests performed in the Maximum Occupancy configuration with Increased Front inflation pressures.

Lowering the inflation pressures to the Alliance MAP or Current MAP produced the most benign left-steer responses to the SIS maneuver at Maximum Occupancy. In the case of the Alliance MAP tests, increasing the steering angle resulted in a gradual increase in yaw rate until the vehicle eventually reached a quasi-steady state cornering condition. Yaw rates typically settled 11 to 13 seconds after maneuvers initiation. Inflating the front tires to the Current MAP pressures produced similar results, but rather than reaching steady state, the yaw rates produced during each of these tests continued to build gradually throughout the duration of the maneuver. Appendix Figures A-17 and A-19 present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during left-steer tests performed in the Maximum Occupancy configuration with Alliance MAP and Current MAP inflation pressures, respectively.

For two of the three left-steer tests, increasing the front tires to those specified in the NTSB Concern condition produced yaw responses similar to those observed in the Increased Front condition, however the peak yaw rates occurred earlier in the maneuver. In this sense, the left-steer NTSB Concern tests have some characteristics of the left-steer Placard tests (those producing spinouts). Comparison of NTSB Concern and Placard pressure video data revealed that the vehicle began to spin midway through the maneuver in the NTSB Concern condition, but unlike the tests performed in the Placard condition, the vehicle was able to regain its lateral stability and complete each test without actually spinning out. Interestingly, the third of the three tests performed in the left-steer NTSB Concern condition produced a yaw response nearly identical to those observed during Alliance MAP testing—the most benign of the left-steer tests performed at Maximum Occupancy. For this test, increasing the steering angle resulted in a gradual increase in yaw rate until the vehicle eventually reached a quasi steady state corning condition where yaw rates settled 11 to 13 seconds after the maneuver was initiated. In other words, left-steer tests performed with the NTSB Concern inflation pressures produced yaw responses ranging from laterally stable to near spinout.

Note: Although the vehicle did not spinout during any left-steer test performed with the NTSB Concern inflation pressures at Maximum Occupancy, two tests did produce left-front wheel lift. The magnitude of the wheel lift was small (one inch or less), but was most apparent during the third test—the same test that produced the most consistent yaw response for that inflation pressure/load configuration. Of all the TG2 tests performed in this study, the authors only observed wheel lift in this condition.

No occurrences of rear axle hop were observed during any left-steer tests performed at Maximum Occupancy. Appendix Figures A-13, A-15, A-17, A-19, and A-21 present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during right-steer tests performed in the Maximum Occupancy configuration.

Right-steer tests performed at Maximum Occupancy exhibited very similar behavior to the left-steer tests performed in the Nominal configuration. When Placard, Alliance MAP, and NTSB Concern inflations were used, increasing the steering angle generally resulted in a gradual increase in yaw rate until the vehicle eventually reached a quasi-steady state corning condition. Yaw rates typically settled 12 to 15 seconds after maneuver initiation. Tests performed with Increased Front and Current MAP had similar responses, but rather than reaching steady state, the yaw rates produced during each of these tests continued to build gradually throughout the duration of the maneuver. No spinouts or occurrences of rear axle hop were observed during right-steer tests performed at Maximum Occupancy. Appendix Figures A-14, A-16, A-18, A-20, and A-22 present the vehicle speed, handwheel angle, yaw rate, and lateral accelerations observed during right-steer tests performed in the Maximum Occupancy configuration.

Table 6.4 presents an overall lateral stability summary for the tests performed in the Maximum Occupancy configuration. In agreement with the language used for Table 6.4, the term “limit understeer” describes a test for which the vehicle did not spinout. The term “limit oversteer” describes a test for which spinout was observed.

Table 6.4. Test Group 2 Lateral Stability Summary (Maximum Occupancy).

Front / Rear Inflation Pressure (psi)	Left	Right
55 / 80	• **Limit oversteer** • Lateral stability was the lowest of any inflation pressure / load configuration evaluated in this study	Limit understeer
80 / 80	• Limit understeer • First of the three tests produced a peak yaw rate greater than most of the other peaks observed in the Maximum Occupancy configuration	Limit understeer
38 / 60	Limit understeer	Limit understeer
46 / 60	Limit understeer	Limit understeer
60 / 60	• Limit understeer • First of the three tests produced a peak yaw rate greater than many of the other peaks observed in the Maximum Occupancy configuration • Two of the three tests produced some roll oscillation and minor left front wheel lift	Limit understeer

7.0 TEST GROUP 3 RESULTS

TG3 was performed to assess what effect the combination of decreased front and rear inflation pressure might have on the Ford E-350's dynamic rollover propensity. This was determined using the RER maneuver, two inflation conditions, and two load configurations.

Although the amount of data is limited, there is a clear indication the lower tire pressures adversely affected the Ford E-350's dynamic rollover resistance. In the 5-Occupant configuration, the vehicle did not produce two-wheel lift during any left-right RER performed with Placard inflation, regardless of maneuver entrance speed. This was not the case when the pressures were lowered to those of the Current MAP condition, where a test initiated at 49.5 mph produced substantial two-wheel lift, as shown in Figure 7.1. Since two-wheel lift was produced during this test, no right-left steer tests were performed.

Comparison of tests performed with 10-occupants and the two inflation conditions produced similar results. In this configuration, with Placard tire inflation pressures; two-wheel lift occurred during a test initiated at 44.6 mph. When the pressures were lowered to those of the Current MAP condition, the maneuver entrance speed required to produce two-wheel lift dropped to 39.5 mph, one speed increment lower than that required by the Placard condition. Table 7.1 compares the maneuver entrance speeds for which two-wheel lift was observed during TG3 testing.

Table 7.1. Maneuver Entrance Speeds For Which Two-Wheel Lift Was Observed During Road Edge Recovery Testing.

Load Configuration	**Placard (55-psi front, 80-psi rear)**		**Current MAP (46-psi front, 60-psi rear)**	
	Left-Right Steering	**Right-Left Steering**	**Left-Right Steering**	**Right-Left Steering**
5-Occupants	--	--[1]	49.5 mph	TNP
10-Occupants	44.6 mph	TNP	39.5 mph	TNP

Note: TNP = Test Not Performed

[1] Two-wheel lift was observed during a left-right test performed at 49.5 mph during "Default Procedure" testing, however it was not confirmed with a "Supplemental Procedure 1" test performed at 49.6 mph. For this reason, the first occurrence of two-wheel lift was deemed to be the result of tire wear.

Why did reducing the tire inflation pressures from Placard to those specified by the Current MAP condition increase the Ford E-350's rollover propensity? Study of appendix Figures A-23 through A-29 indicate that tire inflation pressures in the Current MAP condition reduced the vehicle's ability to adequately suppress (i.e., dampen) maneuver-induced body roll responses. Of the RER tests presented in appendix, Figures A-26, A-28, and A-29 are of particular interest.

Figure 7.1. Two-wheel lift produced during a 5-occupant, left-right Road Edge Recovery maneuver initiated at 49.5 mph with a 2003 Ford E-350. Tires were inflated to the Current MAP pressures (46-psi front, 60-psi rear).

Figure A-26 compares two left-right RER tests initiated at approximately 50 mph. These tests were performed with Placard and Current MAP pressures, with a 5-occupant load. Although the vehicle speeds[4] and yaw responses of the two tests were nearly identical, substantial differences in the roll responses were observed. These differences were apparent almost immediately, as shown by comparison of the roll angles produced by the two initial steer inputs. The peak initial steer roll angle produced during the Placard test was 5.6 degrees, versus the 7.2-degree peak seen during the Current MAP test (29 percent greater). Interestingly, the lateral acceleration responses of each test (to the initial steer) were equal. Given the equivalence of the yaw and lateral acceleration responses, the data indicate that while the lateral adhesion generated with the two inflation pressure combinations was the same, the decrease in inflation pressure reduced the tires' effective vertical stiffness (manifested by increased the sidewall deformation). It is believed this deformation was responsible for the difference in body roll angle.

Differences in the roll responses of the Ford E-350 were much more apparent after completion of the RER steering reversals. In the example presented in Figure A-26, both tests produced post-reversal roll oscillations. Although the magnitude of these oscillations diminished over time in the Placard condition, lowering the inflation pressures to those of the Current MAP resulted in oscillations that increased in a near-exponential manner until substantial two-wheel was ultimately produced.

The tests presented in Figure A-28 were performed with a 10-occupant load, rather than the 5-Occupant configuration used for the tests shown in Figure A-26. As seen in Figure A-26, the different inflation pressure combinations produced nearly the same yaw rate and lateral acceleration responses from the initiation of the maneuver through the completion of the steering reversals. Greater post initial steer roll angles continued to occur for the lower tire inflation pressure condition. However, the post steering reversal roll responses presented in Figure A-28 differ from those seen previously in Figure A-26. Although the test performed with the Current MAP pressures still produced two-wheel lift while the test performed with the Placard pressures did not, the roll oscillations did not build until after tip-up had already occurred. In other words, when tested with the Current MAP pressures and a 10-occupant load, the overshoot of vehicle's roll angle response produced two-wheel lift during the first post-reversal roll oscillation. Only after the vehicle had returned all four wheels to the test surface did the roll oscillations begin to build in the negatively-damped manner seen in Figure A-26.

Up to the occurrence of the two-wheel lift, the Placard and Current MAP tests presented in Figure A-29 show many of the same trends seen in Figures A-26 and A-28, including very similar vehicle speeds[5], lateral accelerations, and yaw rates. However, the different roll angle magnitudes produced during these tests help to quantify how much more severe this maneuver becomes when the tires were inflated to the lower pressures of the Current MAP condition. Using similar steering inputs (Current MAP: 401 degrees, Placard: 373 degrees), identical maneuver entrance speeds (44.6 mph), and the same load configuration (10 occupants), the peak

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[4] Due to an instrumentation malfunction, the vehicle speeds presented in the first pane of Figure A-26 are not accurate shortly after *t* = 4 seconds.

[5] Due to an instrumentation malfunction, the Current MAP vehicle speeds presented in the first pane of Figure A-29 are not accurate from shortly before *t* = 4 seconds throughout the remainder of the test.

roll angle produced during the Current MAP test was approximately 14.6 degrees greater than that observed during the Placard test.

TG3 tests were performed at two load configurations (5- and 10-Occupant) and two inflation pressure conditions (Placard and Current MAP). Results from these tests indicate that lowering the inflation pressures of the front and rear tires from those specified on the vehicle's identification placard substantially lowered the Ford E-350's rollover resistance.

Since the number of tests performed in TG3 were limited, the authors cannot definitively state that lowering the front tire pressures to those requested by the Alliance will necessarily lower the rollover resistance of the Ford E-350 beyond that observed during the Current MAP tests. That said, it is known that reducing inflation pressure lowers the vertical stiffness of a tire (the tire becomes more compliant). For this reason, the vehicle's roll responses with Alliance MAP pressures (i.e., to RER steering inputs) are expected to be larger than comparable tests performed with Current MAP pressures. The authors believe larger roll responses generally equate to reduced rollover resistance.

8.0 CONCLUSIONS

The effects of changing tire inflation pressure on light truck or even 15-passenger van handling cannot be fully determined from the results of this study. Only one vehicle was evaluated. Generalization of the results to other similar vehicles (i.e., those produced by Daimler-Chrysler, General Motors, or other manufacturers) may not be correct.

Changes in the linear range handling measures due to changes in tire inflation pressure generally agreed with those found by the Alliance [1]. However, the changes seen over the range of pressures studied are not believed to be of practical significance. In other words, the linear range handling of the Ford E-350 is essentially unaffected by changes in tire inflation pressures used in this study. This is, of course, desirable since a high sensitivity to tire inflation pressure changes could cause in-use problems.

The changes in maximum lateral acceleration due to changes in inflation pressure were generally small. At Nominal Load, the overall maximum lateral accelerations achieved by the Ford E-350 ranged from 0.75g with NTSB Concern pressures (60-psi front, 60-psi rear), to 0.81g with the Current MAPs (46-psi front, 60-psi rear). When loaded to Maximum Occupancy, the overall maximum lateral accelerations ranged from 0.70 to 0.72g. Load configuration had a more pronounced effect on maximum lateral acceleration than did tire inflation pressure. The small changes in maximum lateral acceleration due to changes in the tire inflation pressures used in this study are not believed to be of practical significance.

The lateral stability of the vehicle at Nominal Load was asymmetric. Spinouts occurred during every right-steer test, for each of the five inflation pressure combinations used in this study. Left-steer tests also produced spinouts, however their occurrence was not repeatable; they only occurred during one of the three tests performed in each respective series

The lateral stability of the Ford E-350 at Maximum Occupancy also showed some asymmetries, although not for all tire inflation pressure combinations as was the case in the Nominal Load configuration. Interestingly, while right-steer tests always induced lateral instability in the Nominal Load configuration, left-steer tests were the only ones that induced spinout at Maximum Occupancy loading.

Tire inflation pressure had a substantial effect on the lateral stability of the Ford E-350 in the Maximum Occupancy configuration. Of the five tire inflation pressure combinations evaluated, the only one for which spinouts occurred was the Placard condition (55-psi front, 80-psi rear).

Decreasing the front and rear inflation pressures from Placard (55-psi front, 80-psi rear) to the Current MAP (46-psi front, 60-psi rear) adversely affected the vehicle’s dynamic rollover resistance. Producing two-wheel lift during tests performed with 5- and 10-occupants required lower maneuver entrance speeds in the Current MAP condition than did those tests performed with Placard pressures.

Since the number of tests performed in TG3 were limited, the authors cannot definitively state that lowering the front tire pressures to those requested by the Alliance will necessarily lower the rollover resistance of the Ford E-350 beyond that observed during the Current MAP tests. That said, it is known that reducing inflation pressure lowers the vertical stiffness of a tire (the tire becomes more compliant). For this reason, the vehicle's roll responses with Alliance MAP pressures (i.e., to RER steering inputs) are expected to be larger than comparable tests performed with Current MAP pressures. The authors believe larger roll responses generally equate to reduced rollover resistance.

8.1 Summary of Effects of Changing Minimum Activation Pressures

Changing the minimum activation pressure of the front tires of the Ford E-350 van from the 46-psi contained in the recently rescinded FMVSS 138 to the 38-psi suggested by the Alliance does not result in changes of practical significance to the linear range handling characteristics of this vehicle. Both the maximum achievable lateral acceleration and the lateral stability of this vehicle in a limit slowly increasing steer maneuver were likewise essentially unaffected.

The dynamic rollover resistance of the Ford E-350 van is expected to be slightly reduced by reducing the minimum activation pressure of this vehicle's front tires. The expected reduction in dynamic rollover resistance should be small. As discussed above, the testing performed for this study was unable to conclusively demonstrate either the presence, or the magnitude, of this reduction. However, based on the physics of the vehicle, the authors believe that some reduction can be expected.

Data collected during this study suggest that reducing the minimum activation pressure from the Current MAP (46-psi, 60-psi) to the Alliance MAP (38-psi, 60-psi), may slightly reduce the dynamic rollover resistance of the Ford E-350. However, since no Road Edge Recovery tests were performed with Alliance MAP pressures, the magnitude of this reduction cannot be quantified.

In their petition [1], the Alliance stated, "if the current FMVSS 138 MAPs remain unchanged, it will be necessary to increase the recommended tire inflation pressures." Increasing the recommended front tire inflation pressures is expected to increase their vertical stiffness. This, in turn, is expected to increase the effective front roll stiffness of the vehicle, decrease the roll angles that occur during dynamic rollover testing, and improve the vehicle's dynamic rollover resistance. While the resulting increase in dynamic rollover resistance is expected to be quite small, increasing the recommended front tire inflation pressures is expected to have a positive effect on vehicle rollover safety.

8.2 Summary of Results About NTSB Recommendation H-03-17

In Safety Recommendation H-03-17, the National Transportation Safety Board expressed concern about the possible adverse effect on handling of permitting 12- and 15- passenger vans to operate with tire inflation pressures up to 25 percent below placard. (At 25 percent below placard, the tire pressure monitoring system would warn drivers to inflate their tires.) In the letter transmitting this safety recommendation to NHTSA, NTSB expressed concern as to whether adverse handling had contributed to two crashes that they investigated. The 15-passenger vans in both of these crashes had tire inflation pressures of approximately 60-psi for all four wheels.

Based on the results of the current study, allowing the Ford E-350 van to operate with tire inflation pressures up to 25 percent below placard should not have a substantial adverse effect on its handling. That said, such under inflation may cause tire endurance problems. The lower tire inflation pressures did not result in changes of practical significance to the linear range handling characteristics of this vehicle. Both the maximum achievable lateral acceleration and the lateral stability of this vehicle in a limit SIS maneuver were likewise essentially unaffected.

Similarly, having the Ford E-350 van operate with 60-psi inflation pressures for all four tires should not have a substantial adverse effect on its handling. The testing performed for the current study found no changes of practical significance to the linear range handling characteristics of this vehicle. Both the maximum achievable lateral acceleration and the lateral stability of this vehicle in a limit slowly increasing steer maneuver were likewise essentially unaffected.

The effect on dynamic rollover resistance of operating the Ford E-350 van with 60-psi inflation pressures for all four tires was not determined during the current study. Increasing the vehicle’s front tires from 55- to 60-psi should increase the vehicle’s effective roll stiffness, an effect expected to improve rollover resistance. However, such an increase could be offset by lowering the vehicle’s rear tires from 80- to 60-psi, a change that is expected to reduce the vehicle’s effective roll stiffness and degrade rollover resistance. The balance between these two effects is not known. However, the net change in the vehicle’s dynamic rollover resistance is expected to be quite small.

9.0 REFERENCES

1. Alliance of Automobile Manufacturers, “Petition for Rulemaking – Tire Pressure Monitoring Systems; Controls and Displays; Final Rule; 49CFR Parts 571 and 590 Docket No. NHTSA-2000-8572 (67 Fed. Reg. 38704; June 5, 2002),” Document No. 265 in NHTSA Docket No. NHTSA-2000-8572.

2. Forkenbrock, Garrick J., O’Harra, Brian C., Elsasser, Devin, “An Experimental Evaluation of 26 Light Vehicles Using Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover and a Discussion of NHTSA’s Refined Test Procedures – Phases VI and VII of NHTSA’s Light Vehicle Rollover Research Program,” NHTSA Technical Report, DOT HS 809 547, October 2003.

3. SAE J266, Surface Vehicle Recommended Practice, “Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks,” 1996.

4. Federal Register, Vol. 67, No. 194, October 7, 2002.

5. ISO 3888:1988(E), “Road Vehicles – Lateral Transient Response Test Methods.”

6. Norman, Kenneth D., “Objective Evaluation of On-Center Handling Performance”, SAE Technical Paper 840069, 1984.

7. Forkenbrock, Garrick J., Garrott, W. Riley, Heitz, Mark, O’Harra, Brian C., “A Comprehensive Experimental Examination of Test Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover – Phase IV of NHTSA’s Light Vehicle Rollover Research Program,” NHTSA Technical Report, DOT HS 809 513, October 2002.

8. Federal Resister, Vol. 68, No. 198, October 14, 2003.

9. National Highway Traffic Safety Administration, “Analysis of a Request for a Defect Investigation Submitted by Bridgestone/Firestone, Inc.”, February 4, 2002.

10. Jaksch, Friedrich O., “Driver-Vehicle Interaction with Respect to Steering Controllability”, SAE Technical Paper 790740, 1979.

APPENDIX

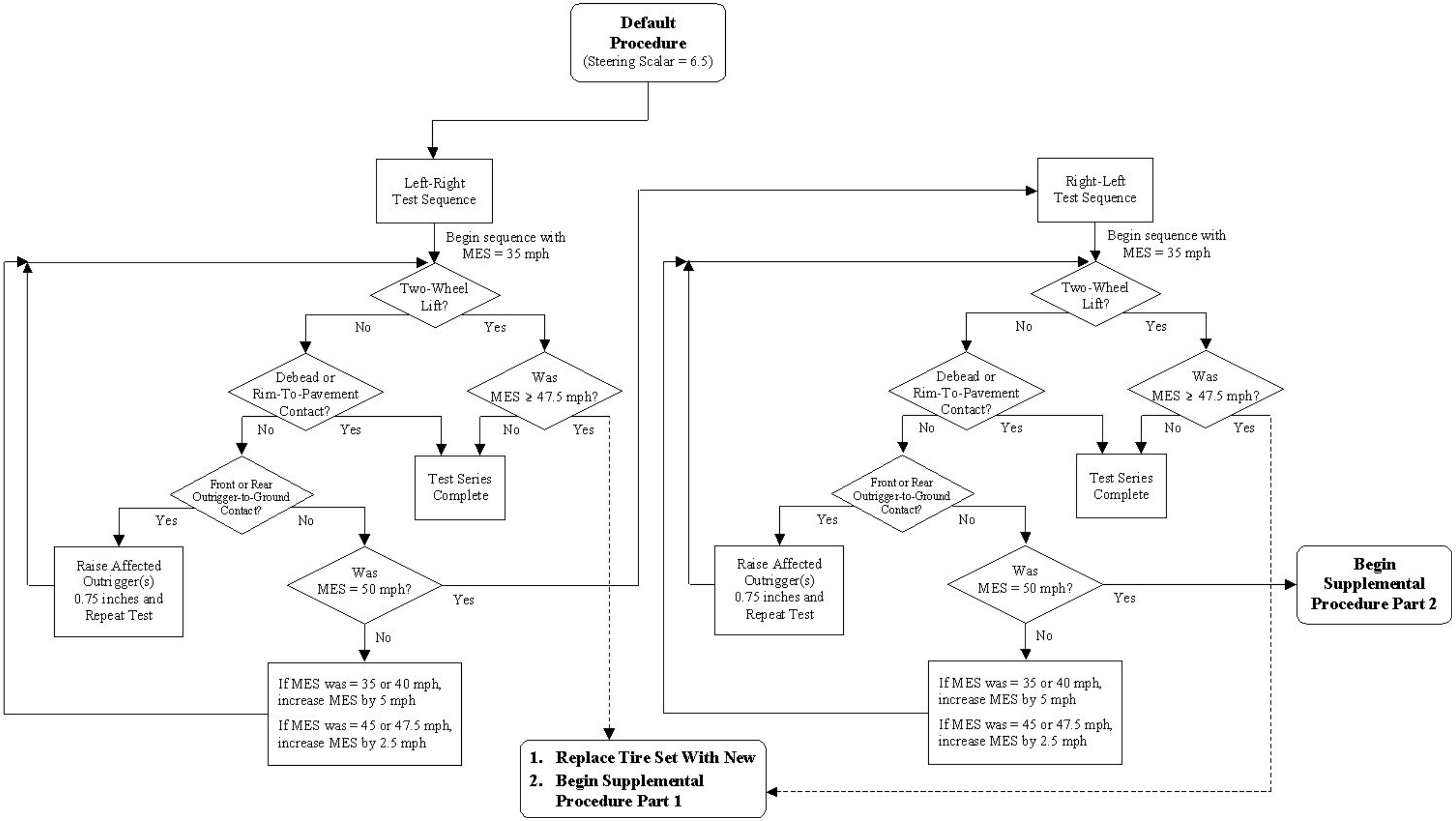

Figure A-1. Road Edge Recovery Default Test Procedure.

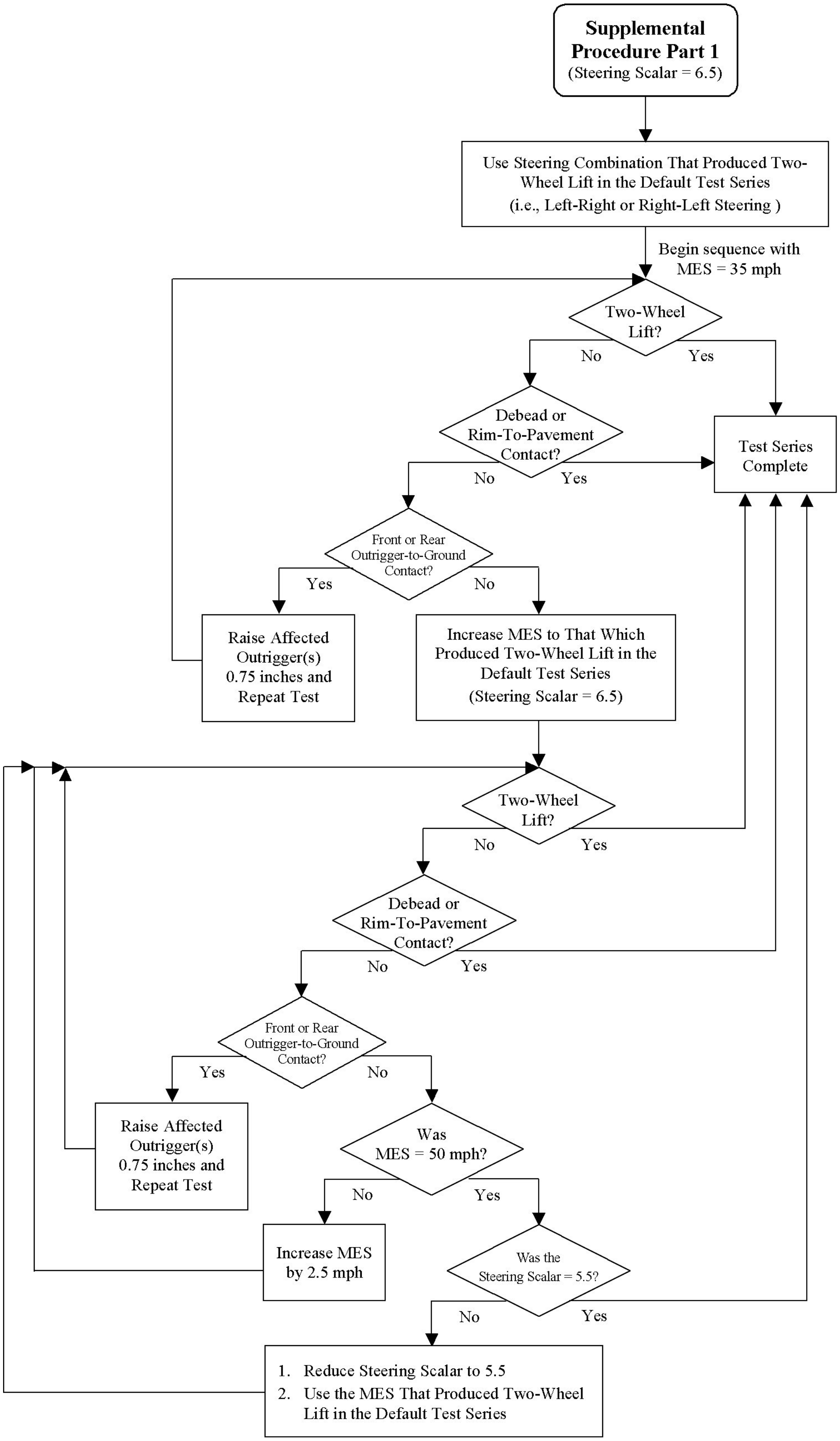

Figure A-2. Road Edge Recovery Supplemental Procedure 1.

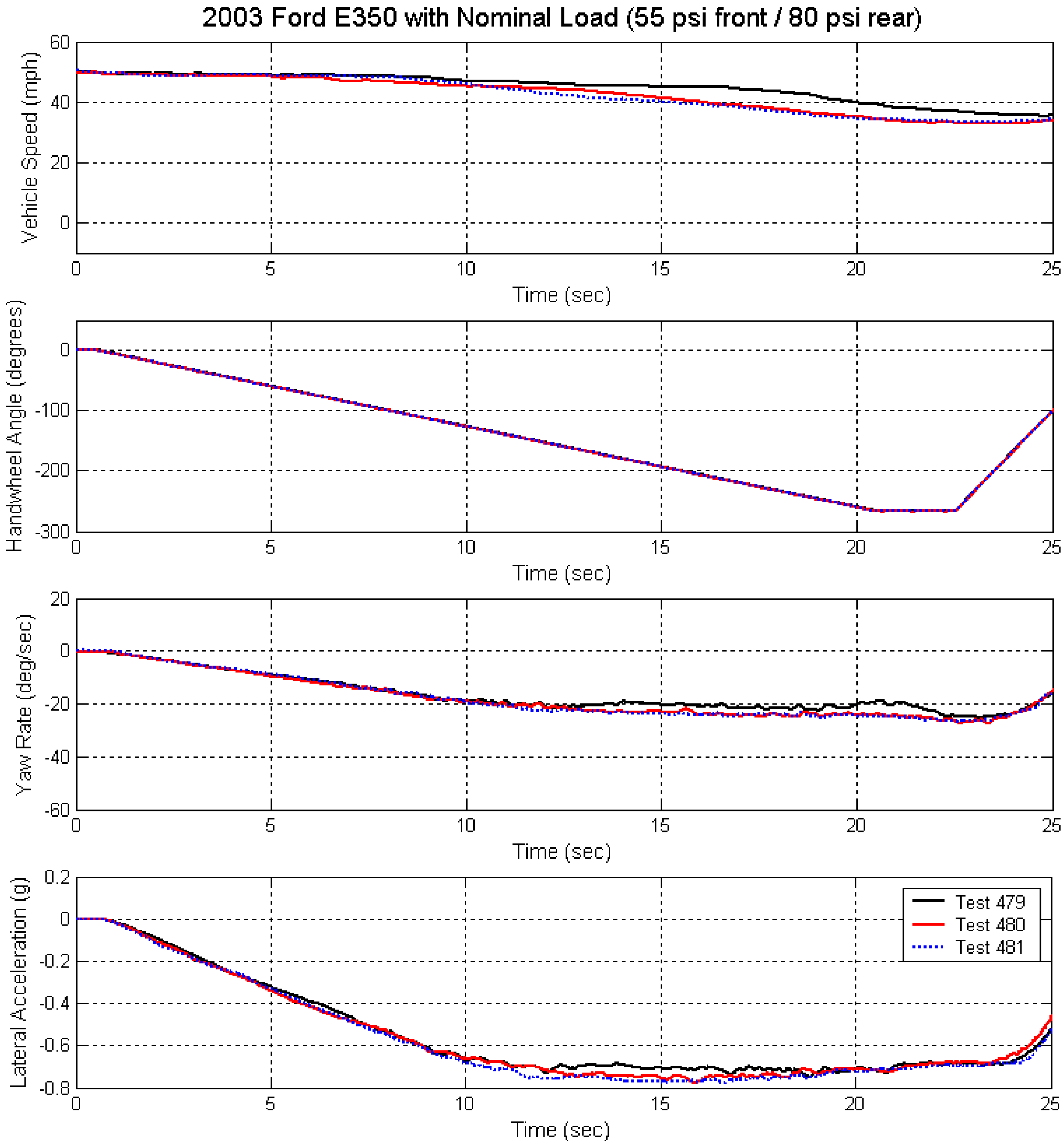

Figure A-3. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Placard inflation pressures and Nominal loading (left steer).

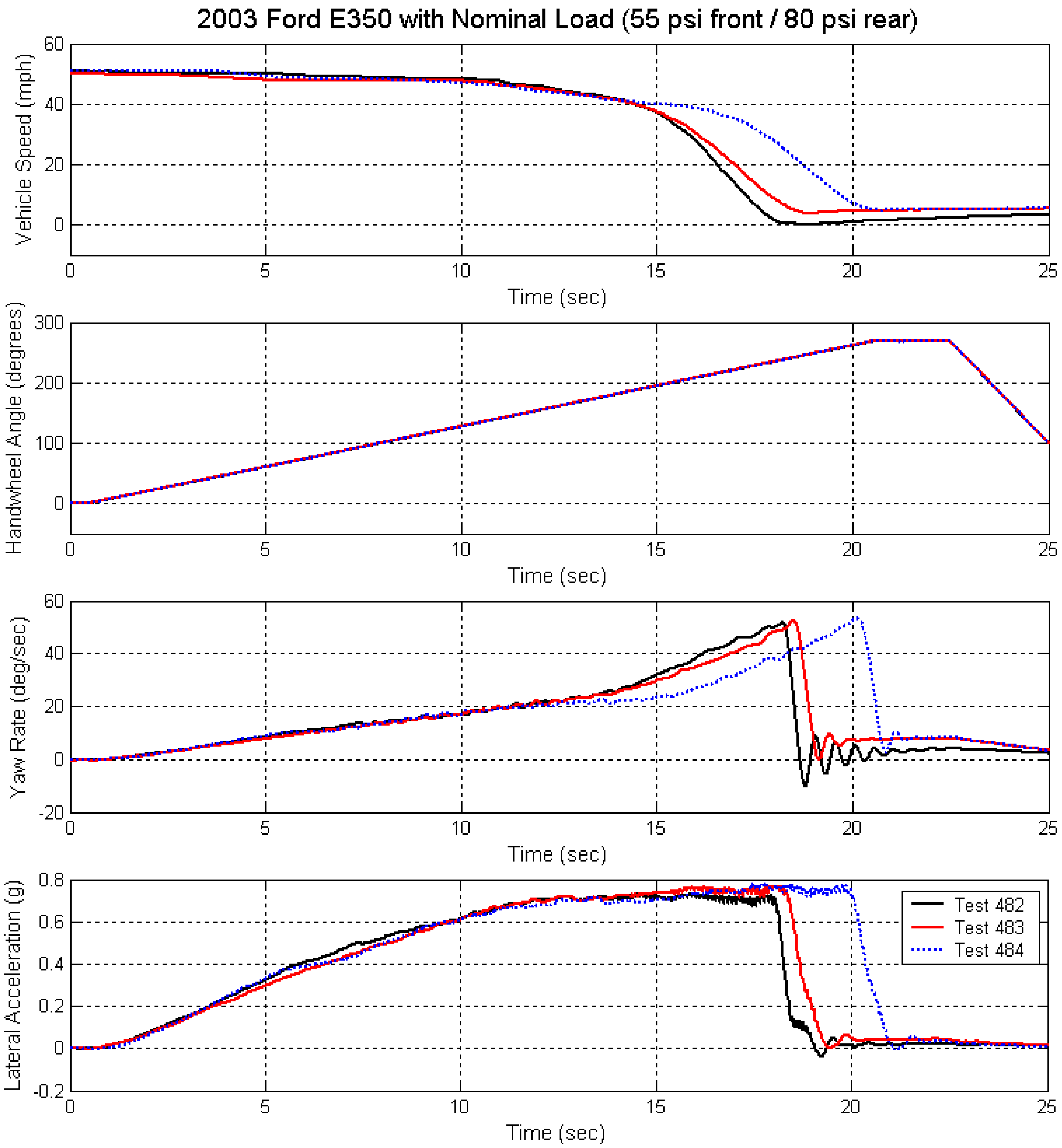

Figure A-4. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Placard inflation pressures and Nominal loading (right steer).

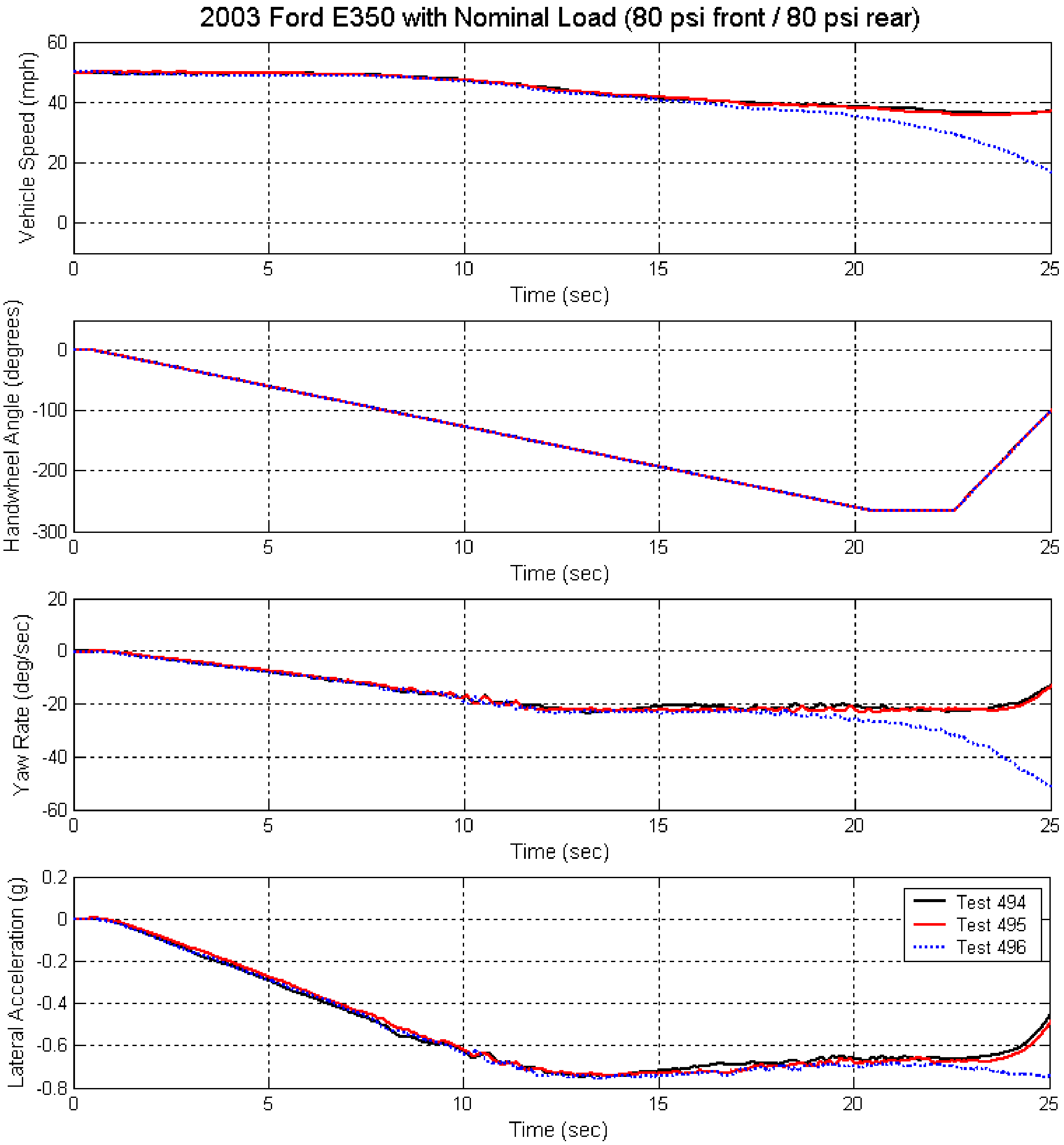

Figure A-5. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Increased Front inflation pressures and Nominal loading (left steer).

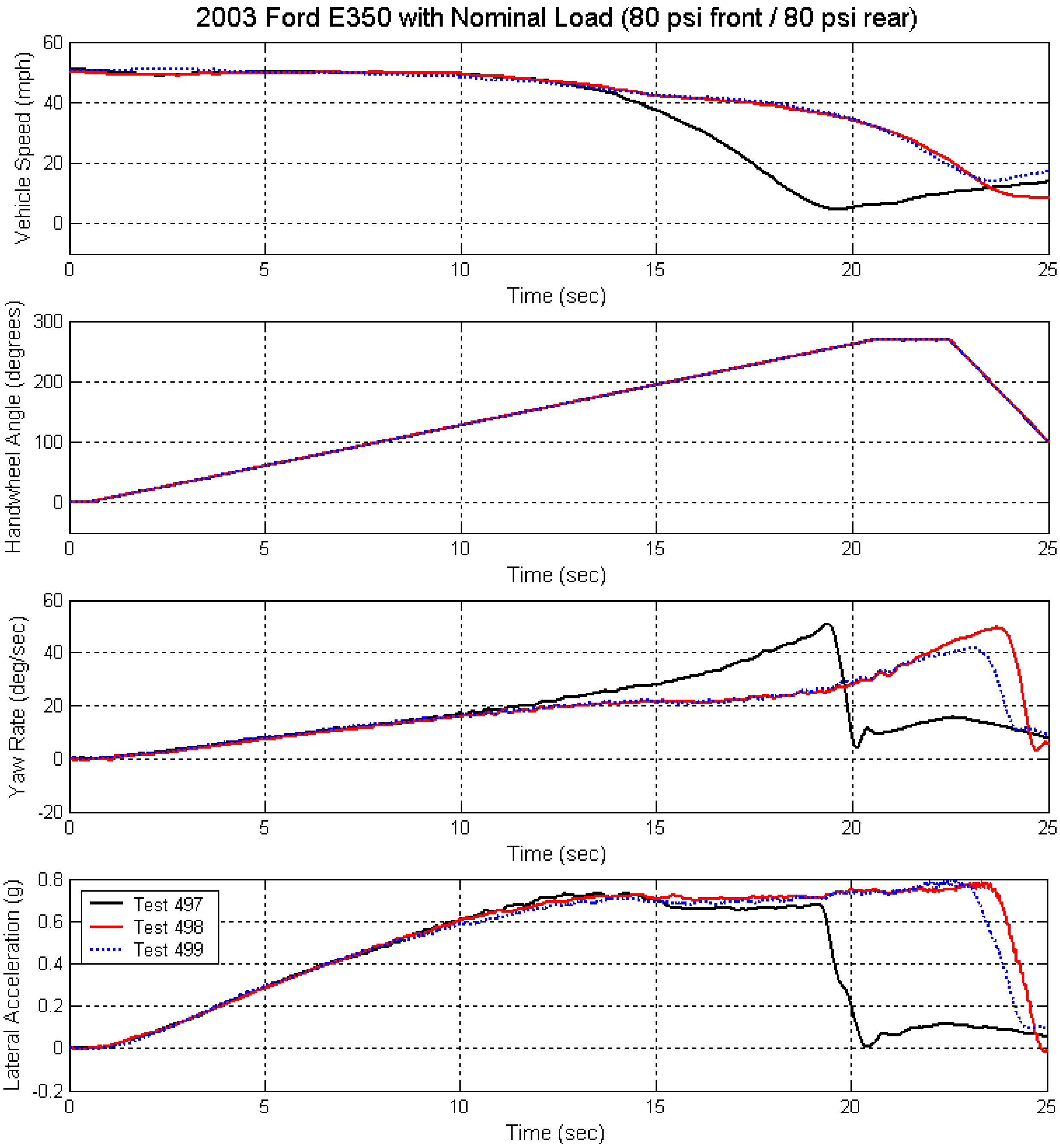

Figure A-6. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Increased Front inflation pressures and Nominal loading (right steer).

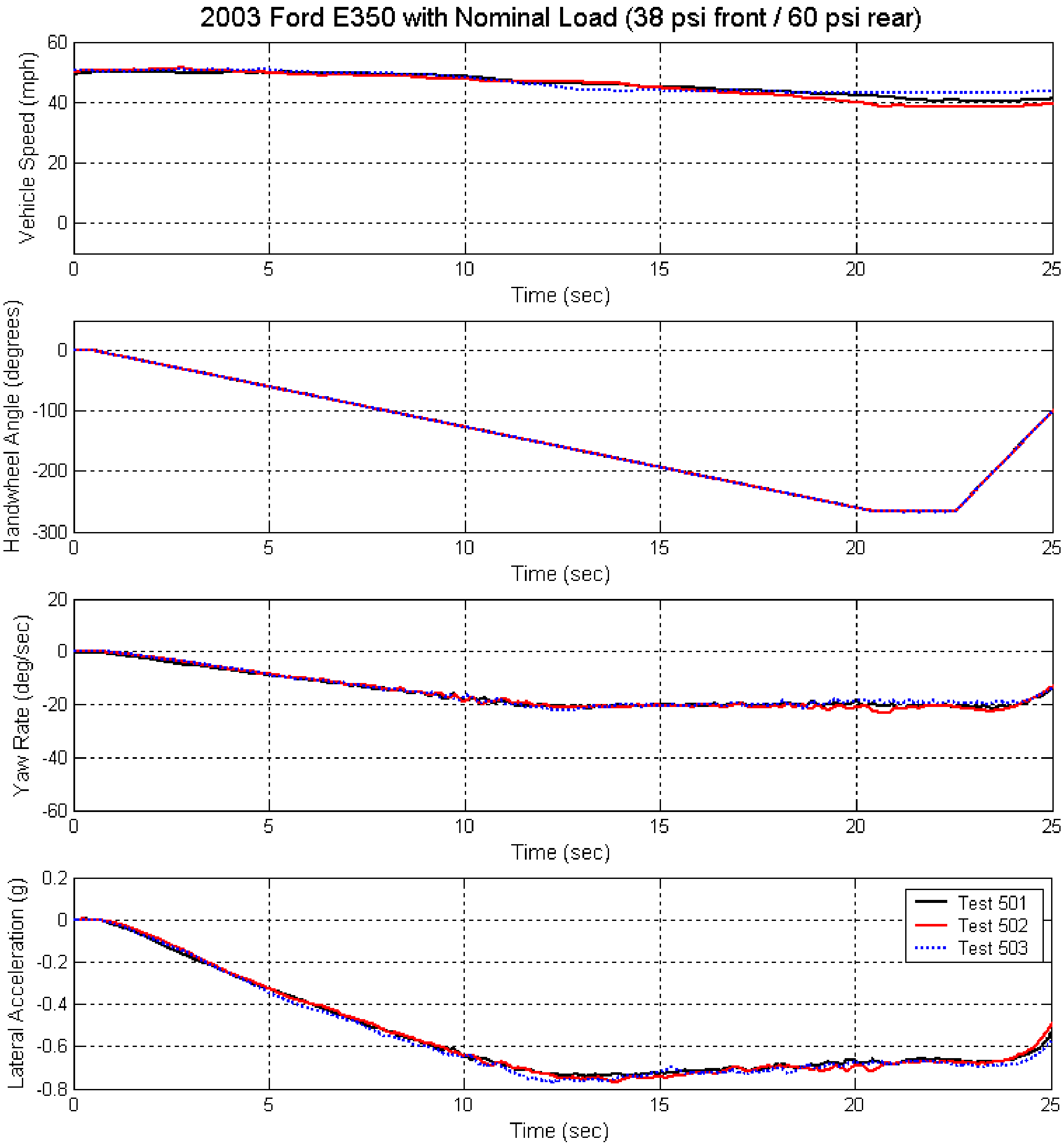

Figure A-7. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Alliance MAP inflation pressures and Nominal loading (left steer).

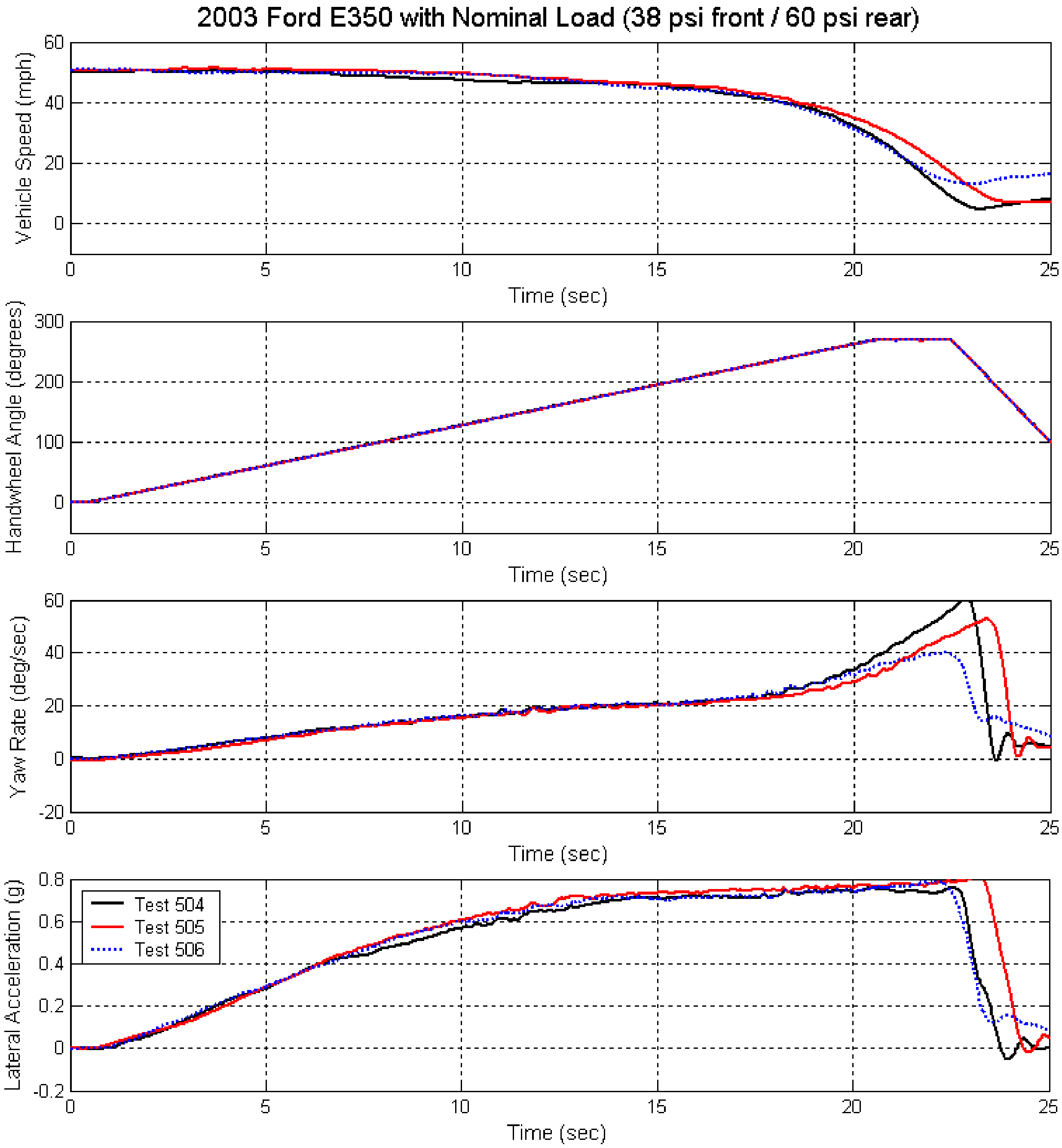

Figure A-8. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Alliance MAP inflation pressures and Nominal loading (right steer).

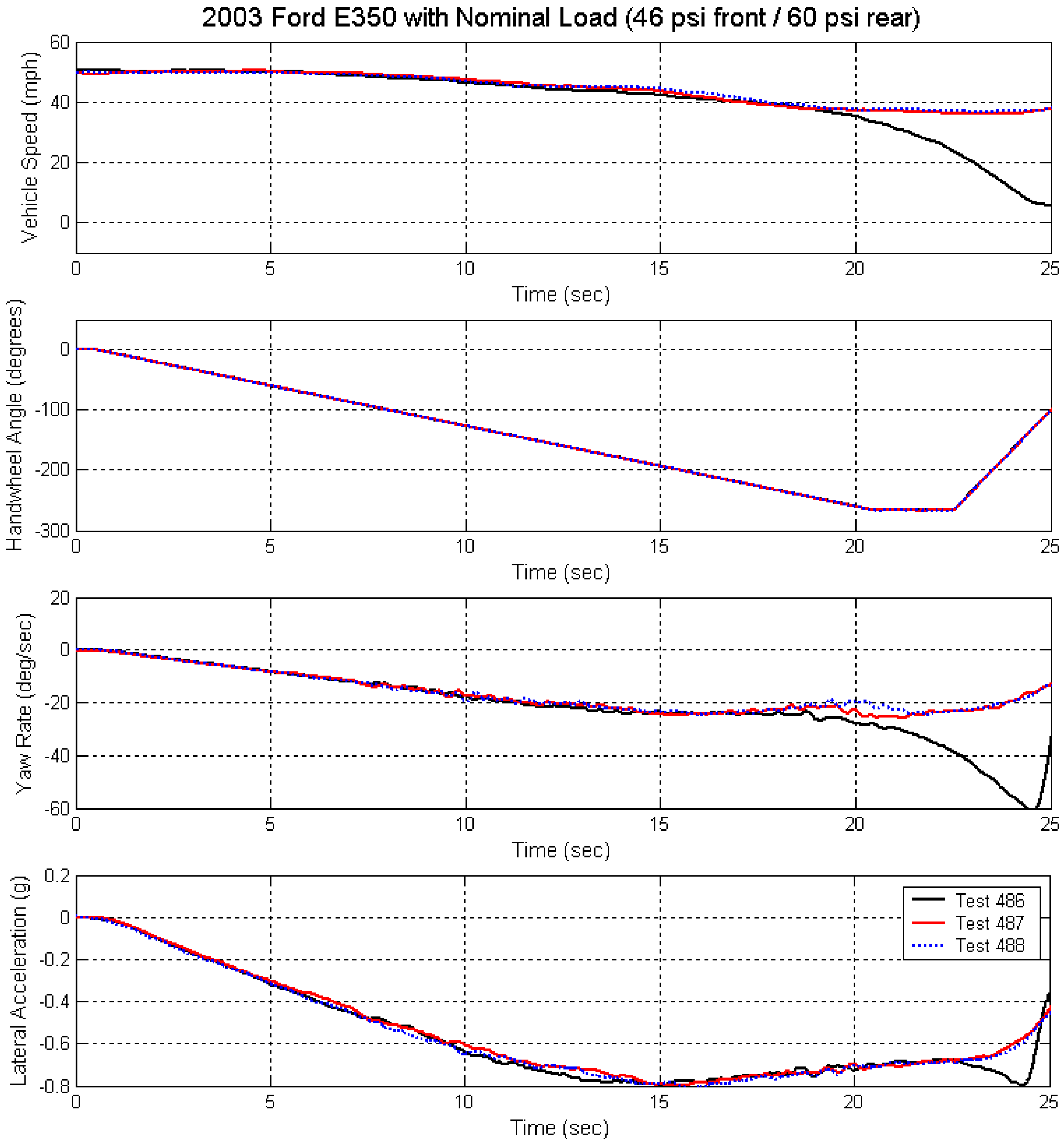

Figure A-9. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Current MAP inflation pressures and Nominal loading (left steer).

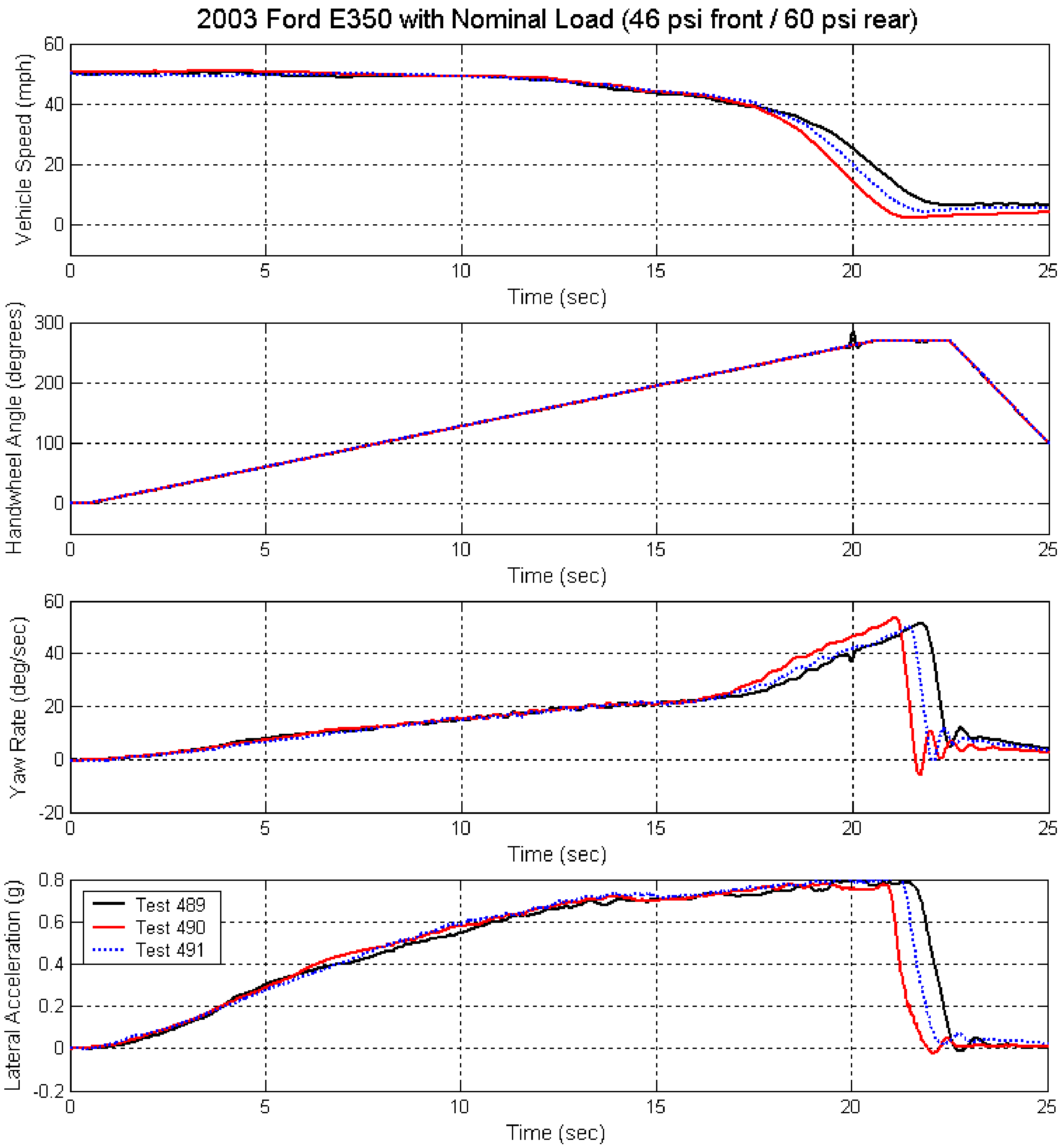

Figure A-10. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Current MAP inflation pressures and Nominal loading (right steer).

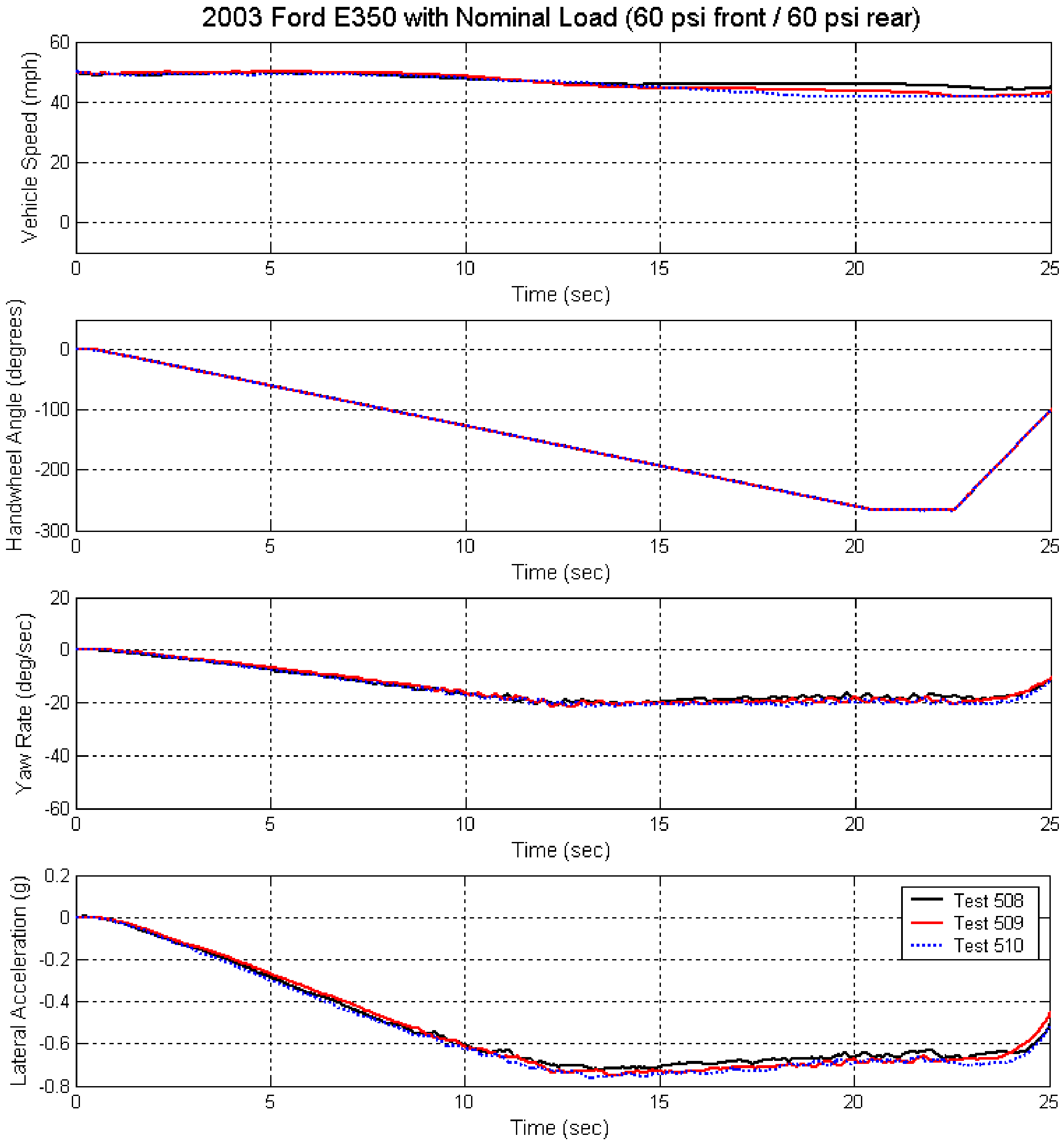

Figure A-11. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with NTSB Concern inflation pressures and Nominal loading (left steer).

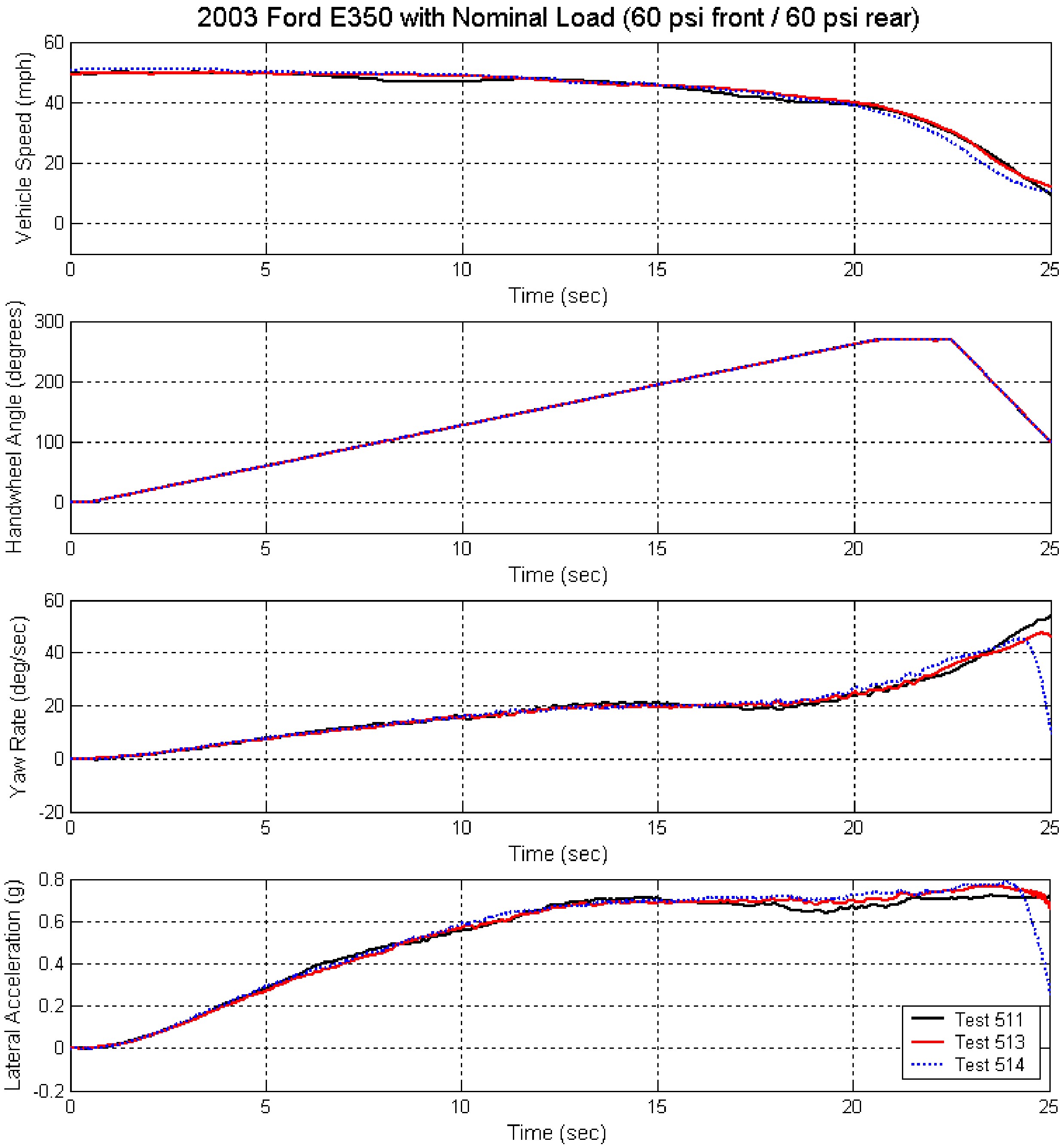

Figure A-12. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with NTSB Concern inflation pressures and Nominal loading (right steer).

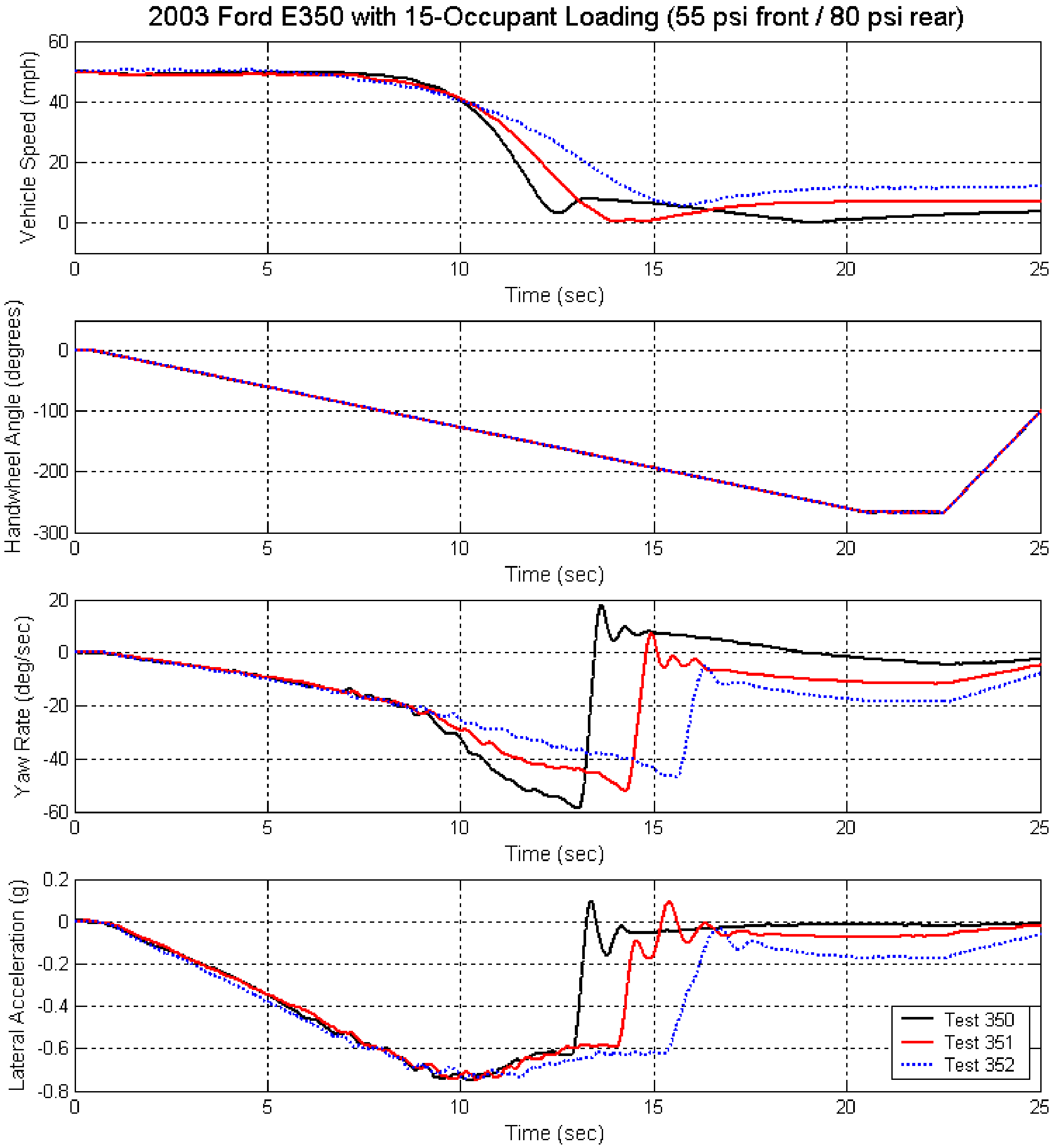

Figure A-13. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Placard inflation pressures and Maximum Occupancy loading (left steer).

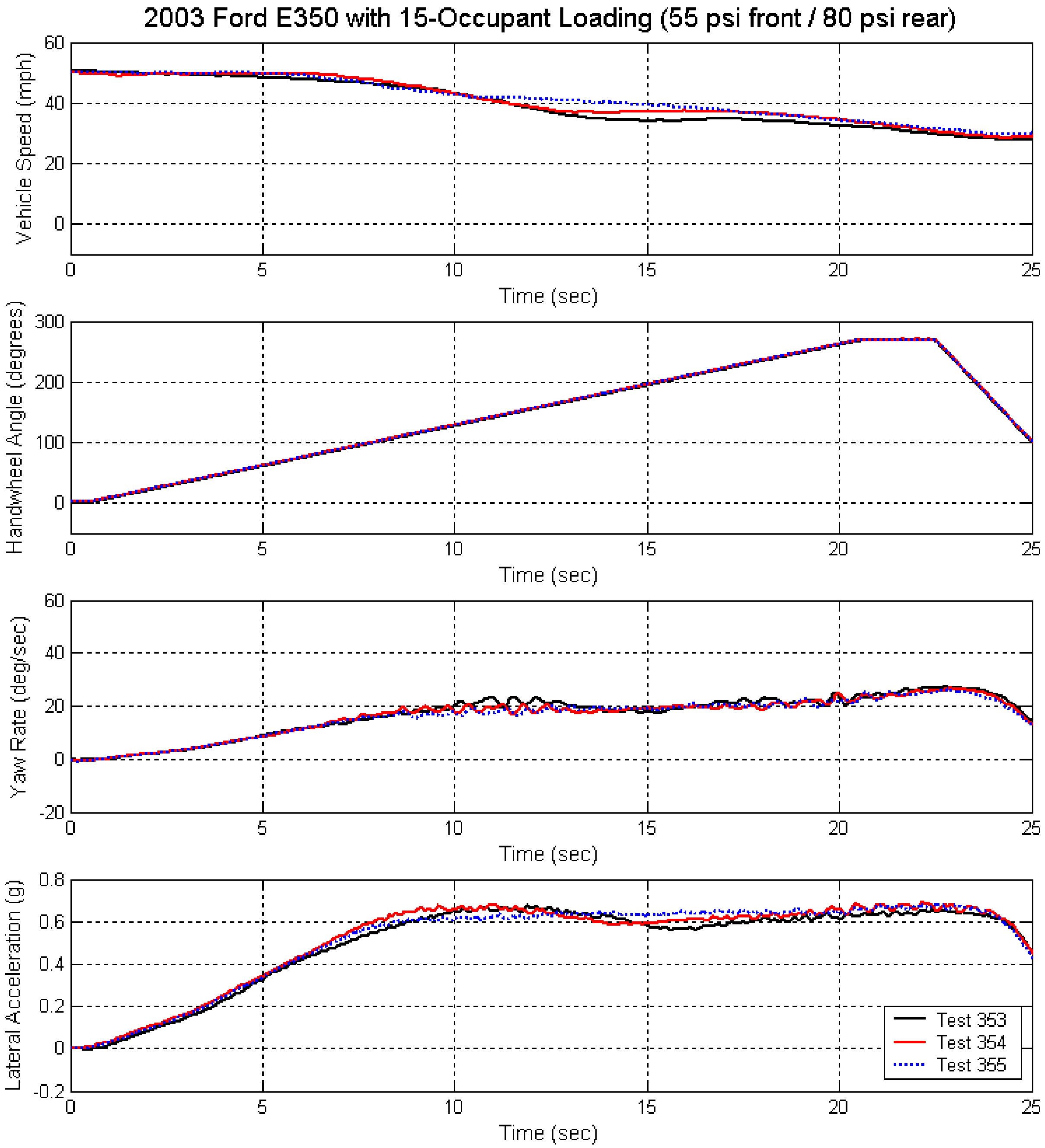

Figure A-14. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Placard inflation pressures and Maximum Occupancy loading (right steer).

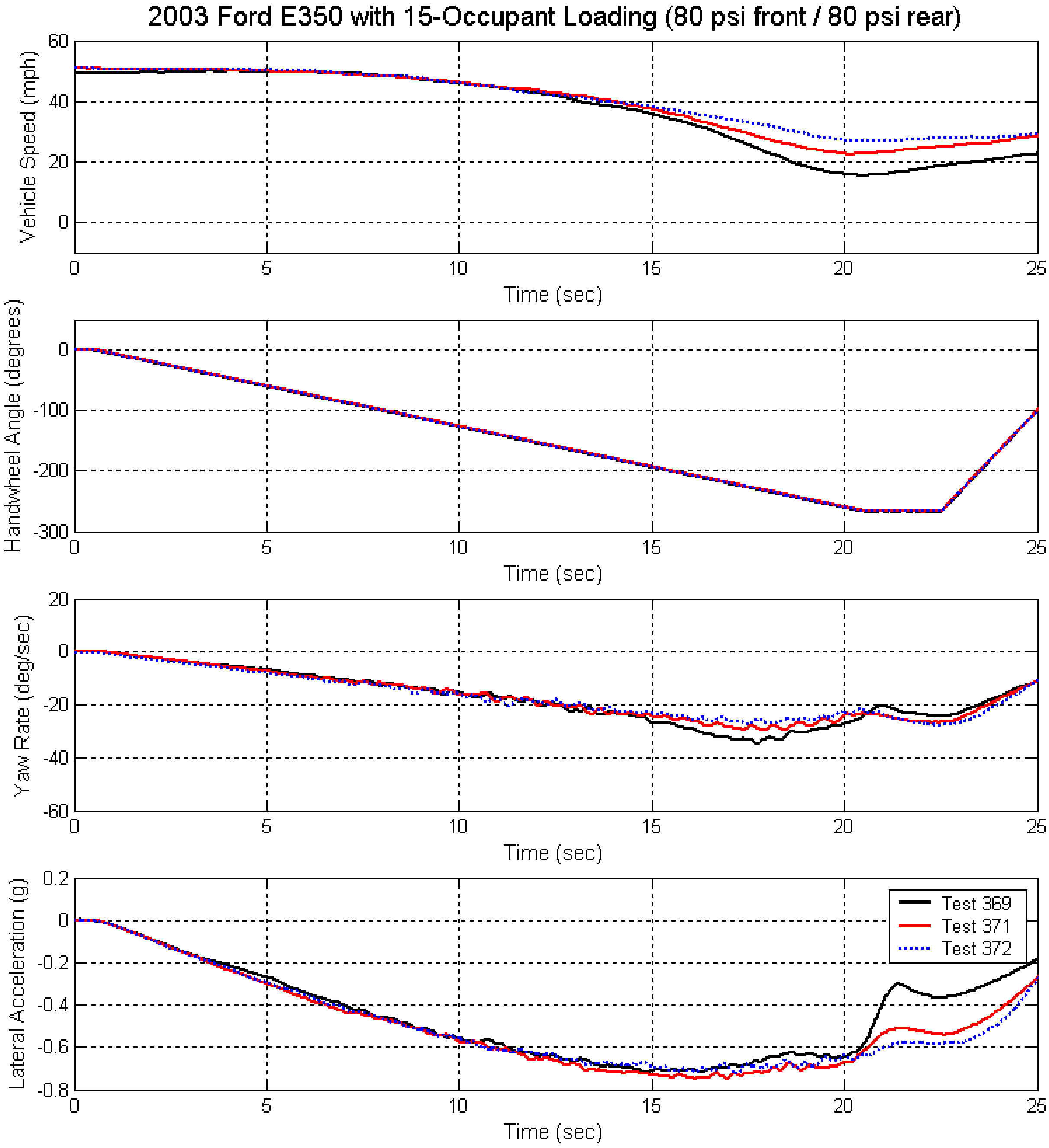

Figure A-15. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Increased Front inflation pressures and Maximum Occupancy loading (left steer).

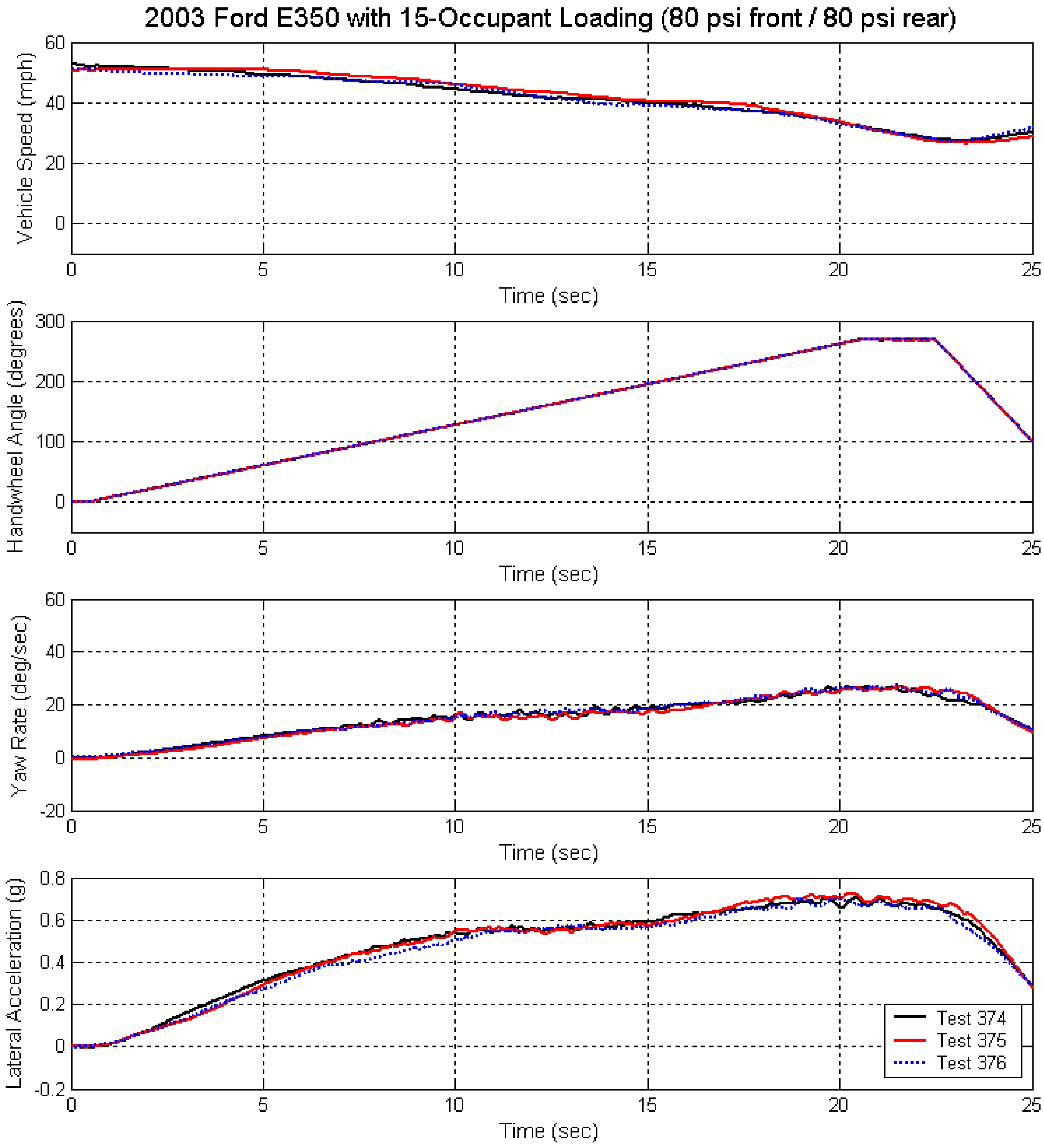

Figure A-16. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Increased Front inflation pressures and Maximum Occupancy loading (right steer).

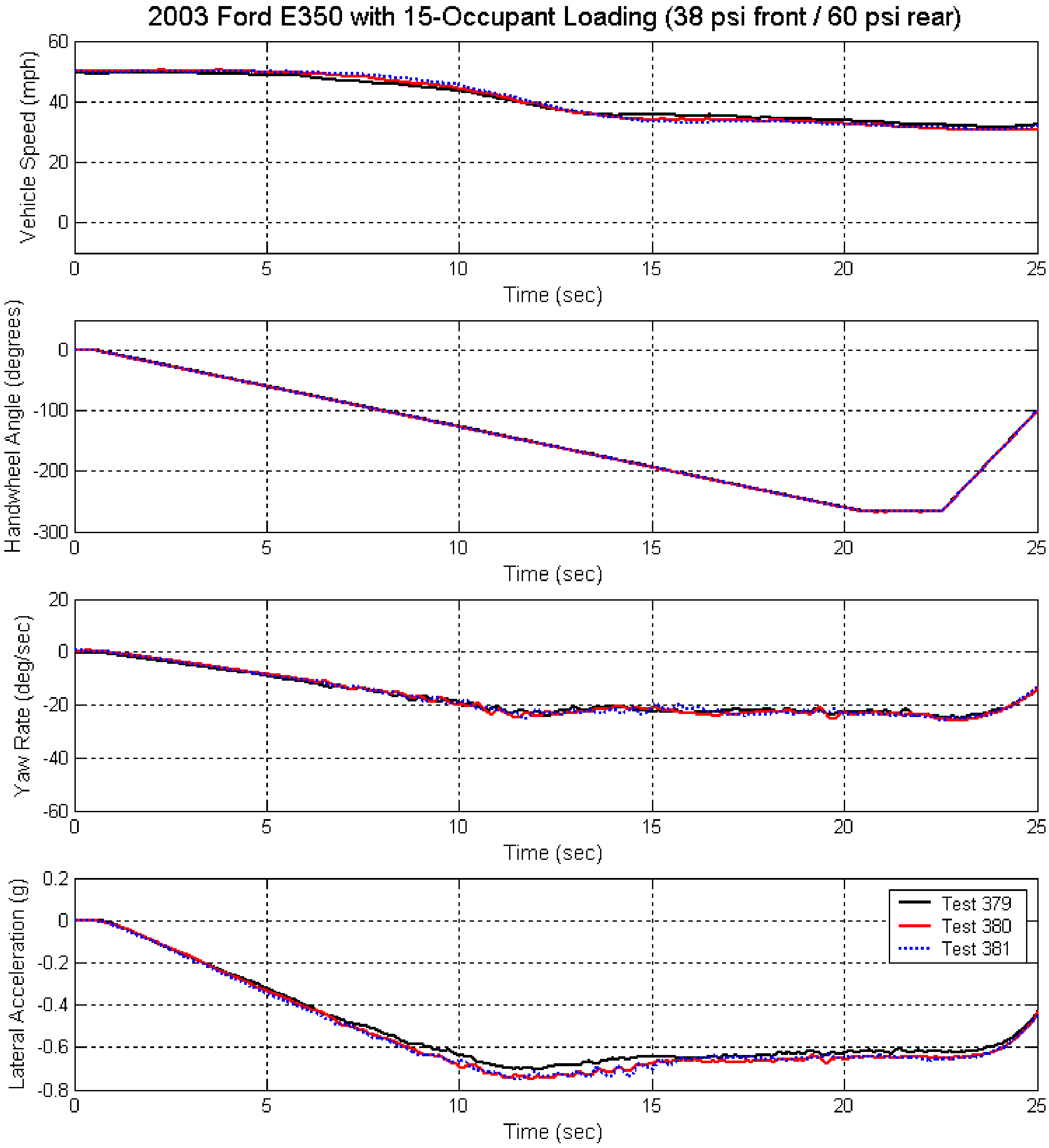

Figure A-17. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Alliance MAP inflation pressures and Maximum Occupancy loading (left steer).

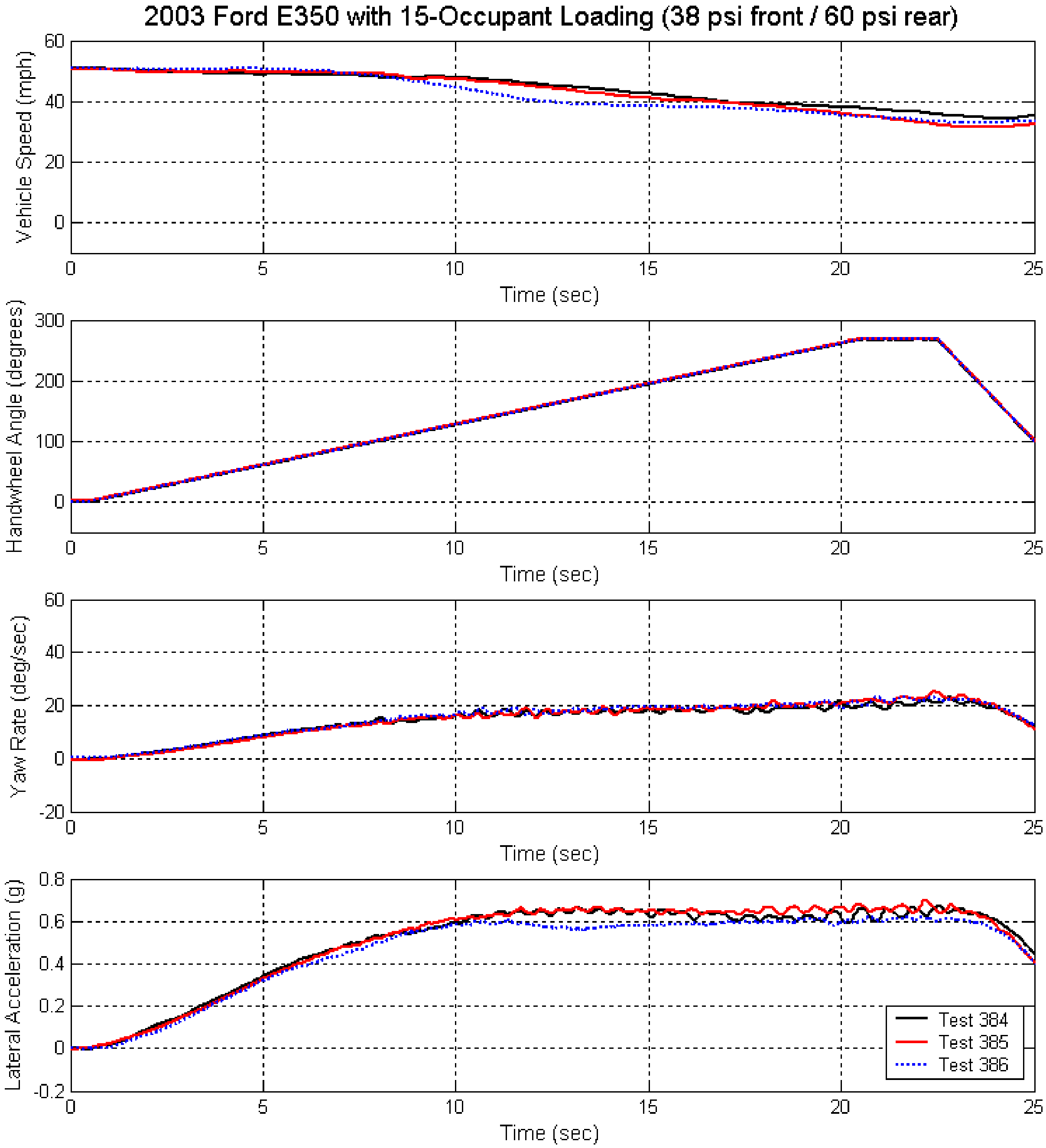

Figure A-18. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Alliance MAP inflation pressures and Maximum Occupancy loading (right steer).

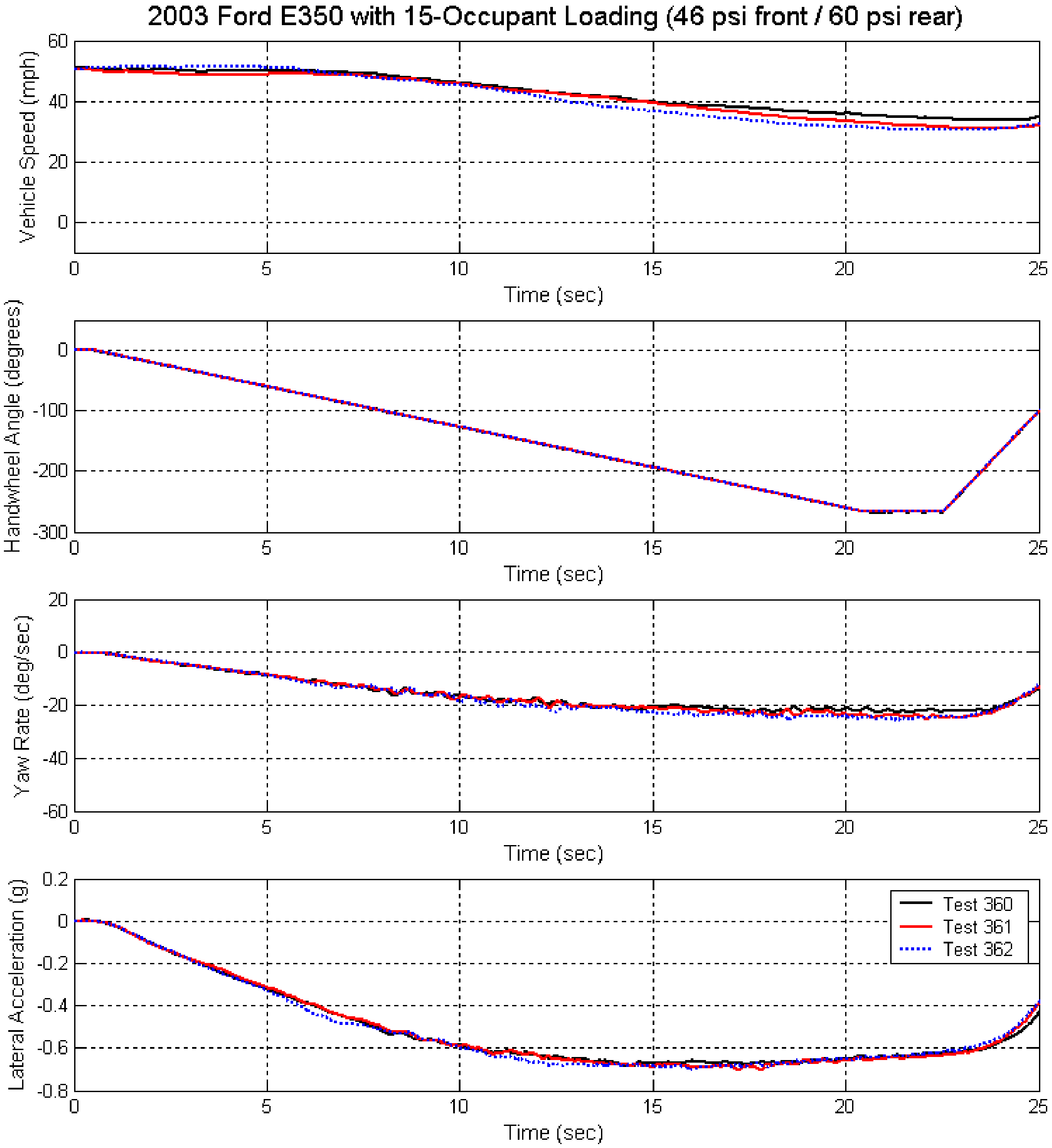

Figure A-19. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Current MAP inflation pressures and Maximum Occupancy loading (left steer).

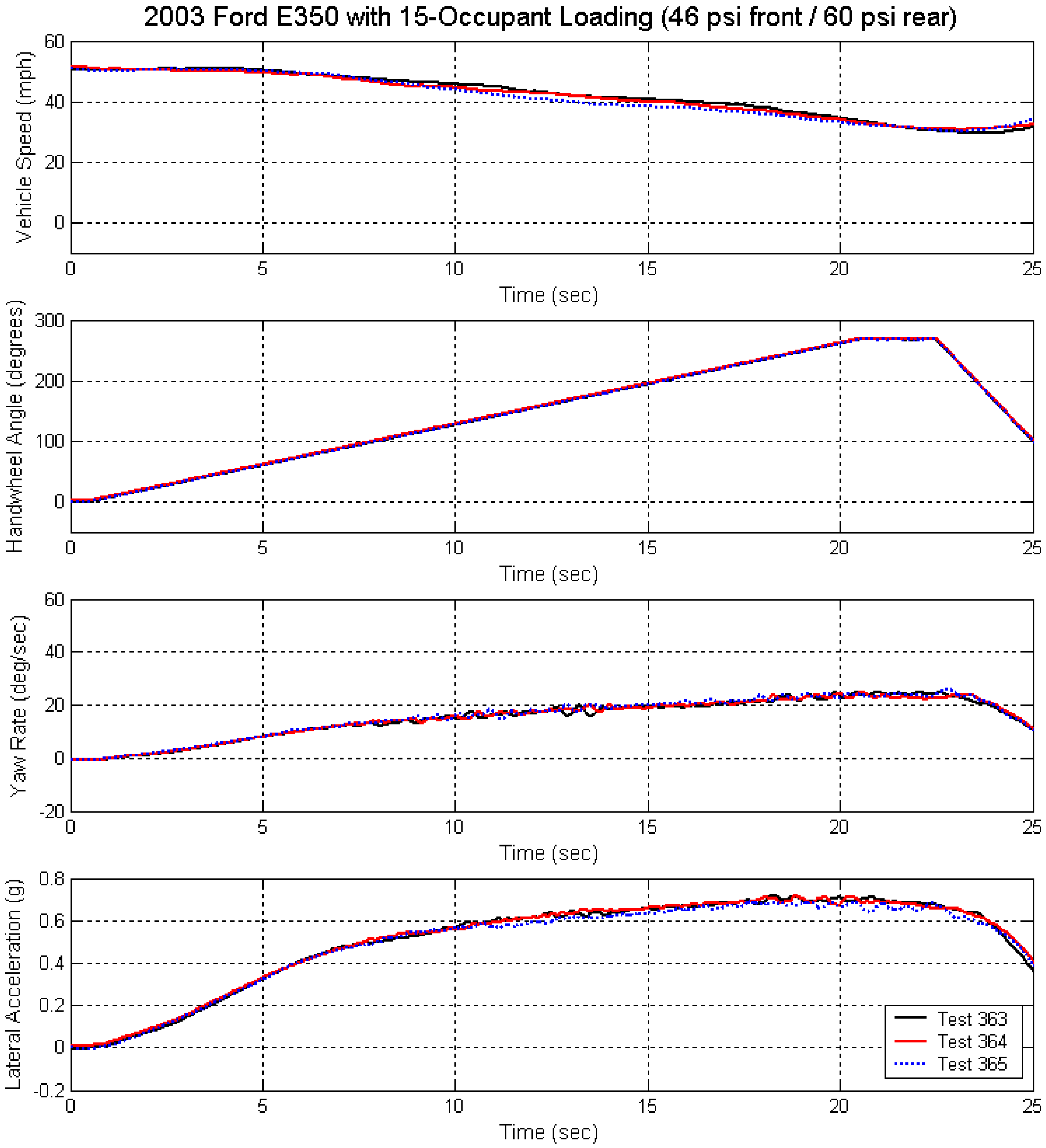

Figure A-20. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with Current MAP inflation pressures and Maximum Occupancy loading (right steer).

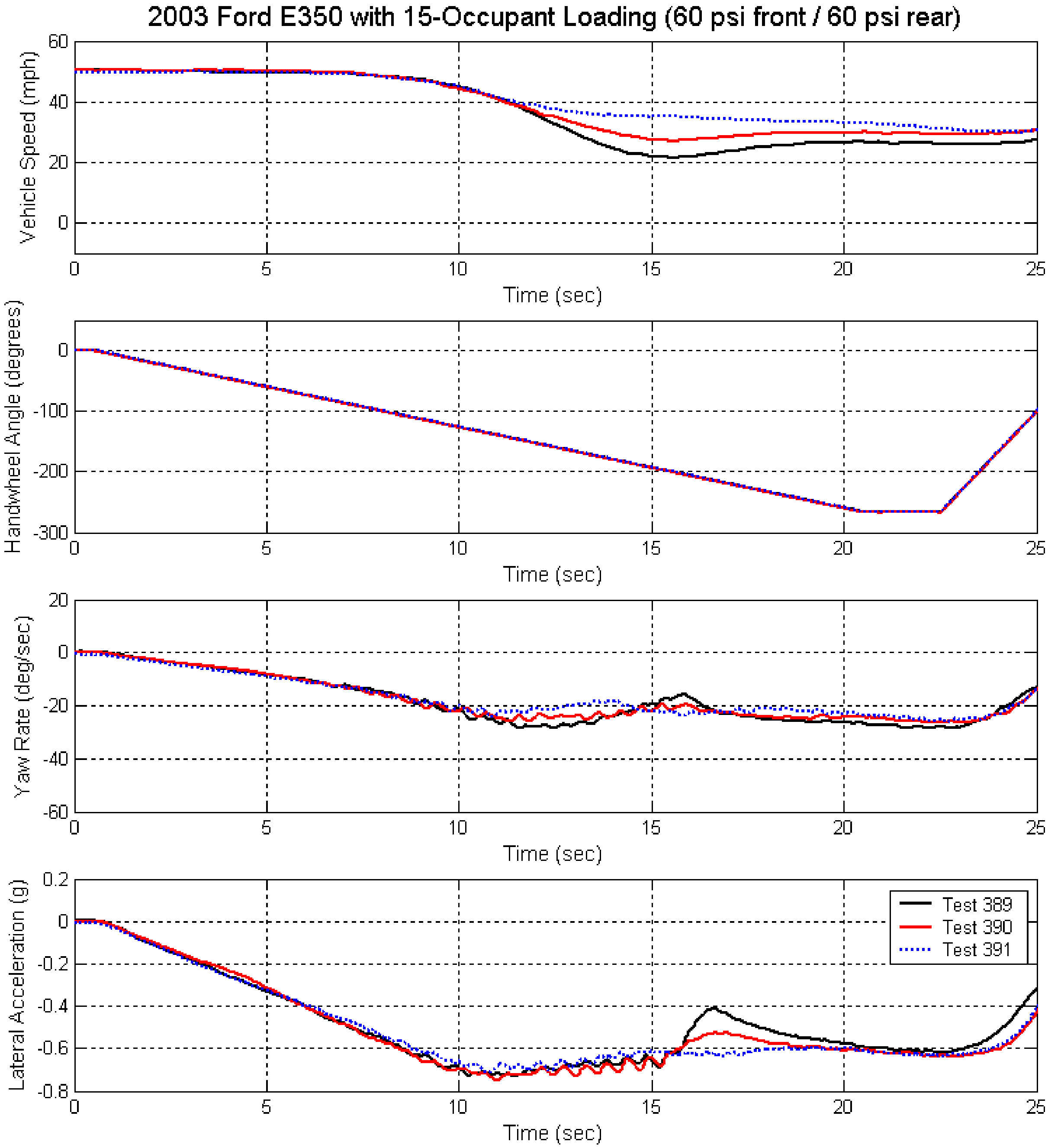

Figure A-21. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with NTSB Concern inflation pressures and Maximum Occupancy loading (left steer).

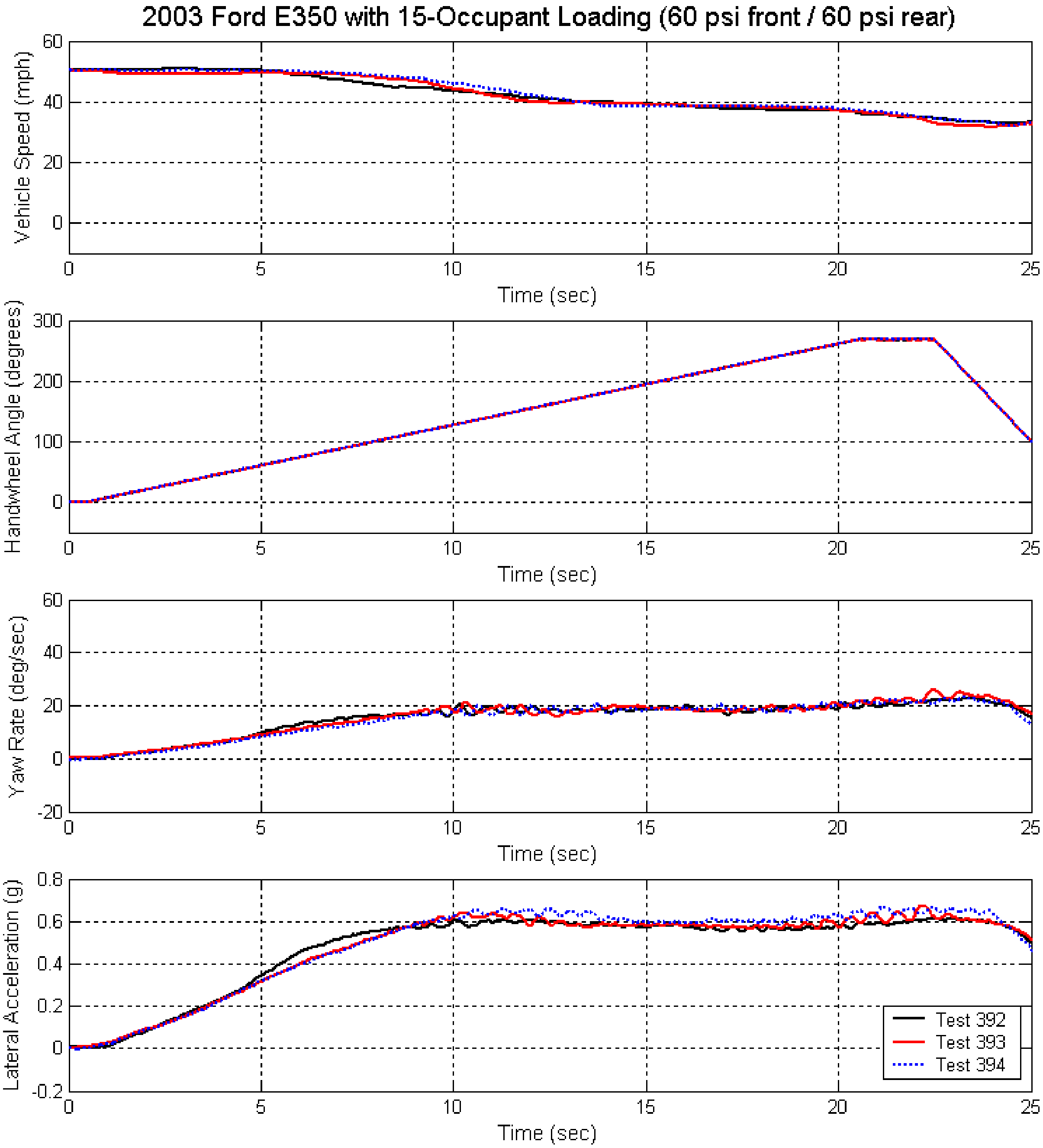

Figure A-22. Vehicle speeds, handwheel angles, yaw rates, and lateral accelerations observed during three Slowly Increasing Steer tests performed with NTSB Concern inflation pressures and Maximum Occupancy loading (right steer).

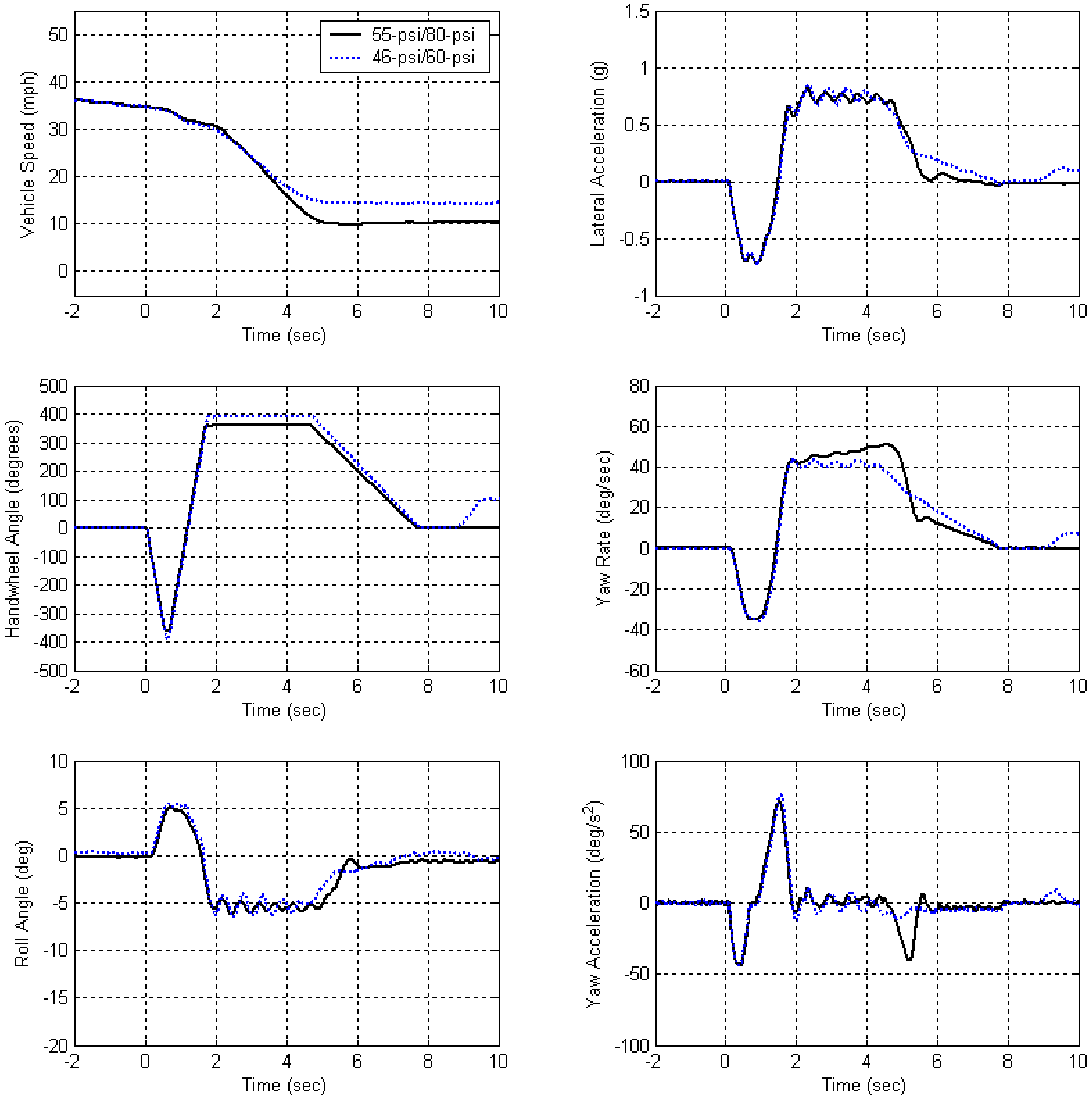

Figure A-23. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 5-occupant load. Tests were initiated at 35 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

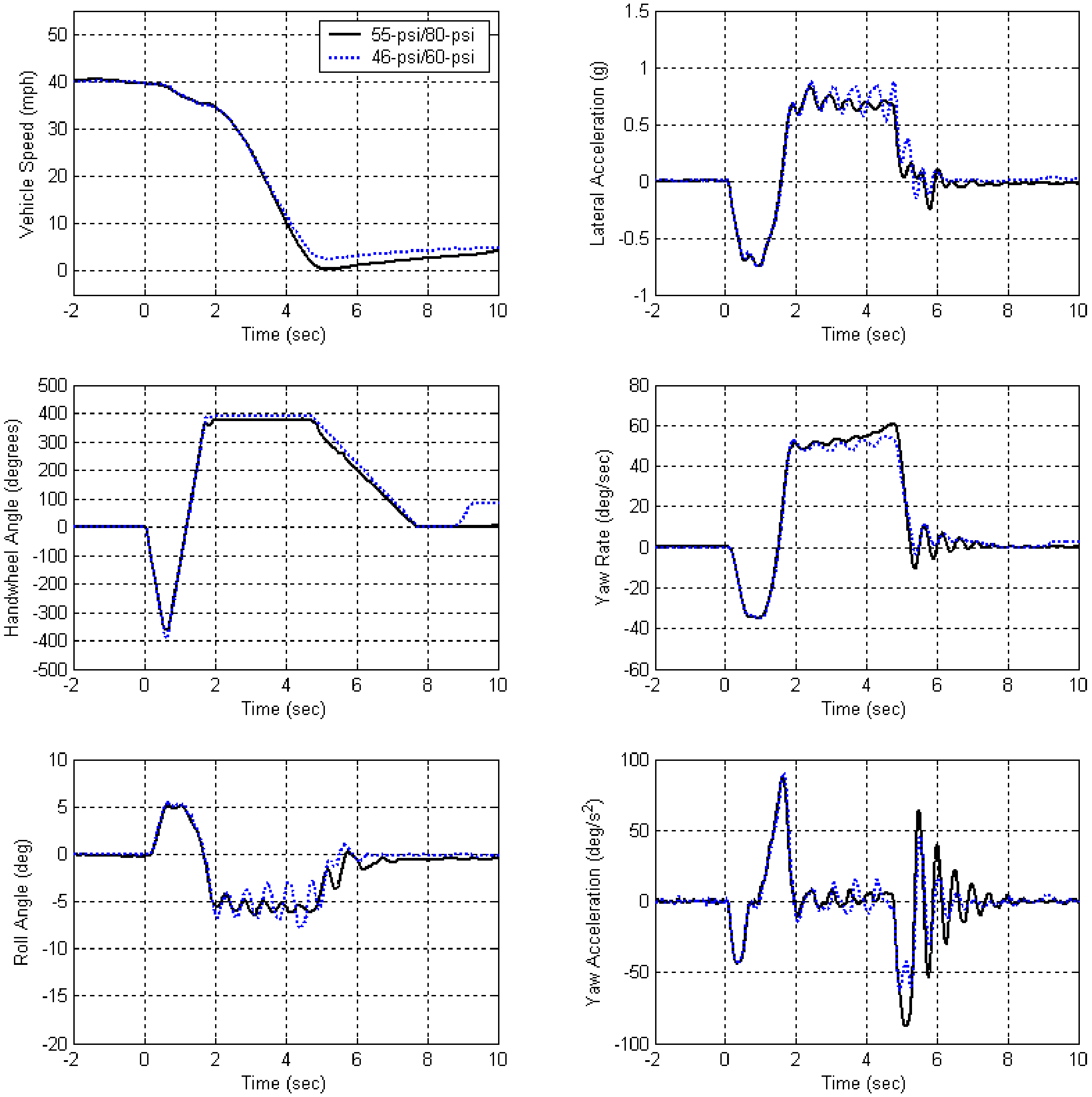

Figure A-24. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 5-occupant load. Tests were initiated at 40 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

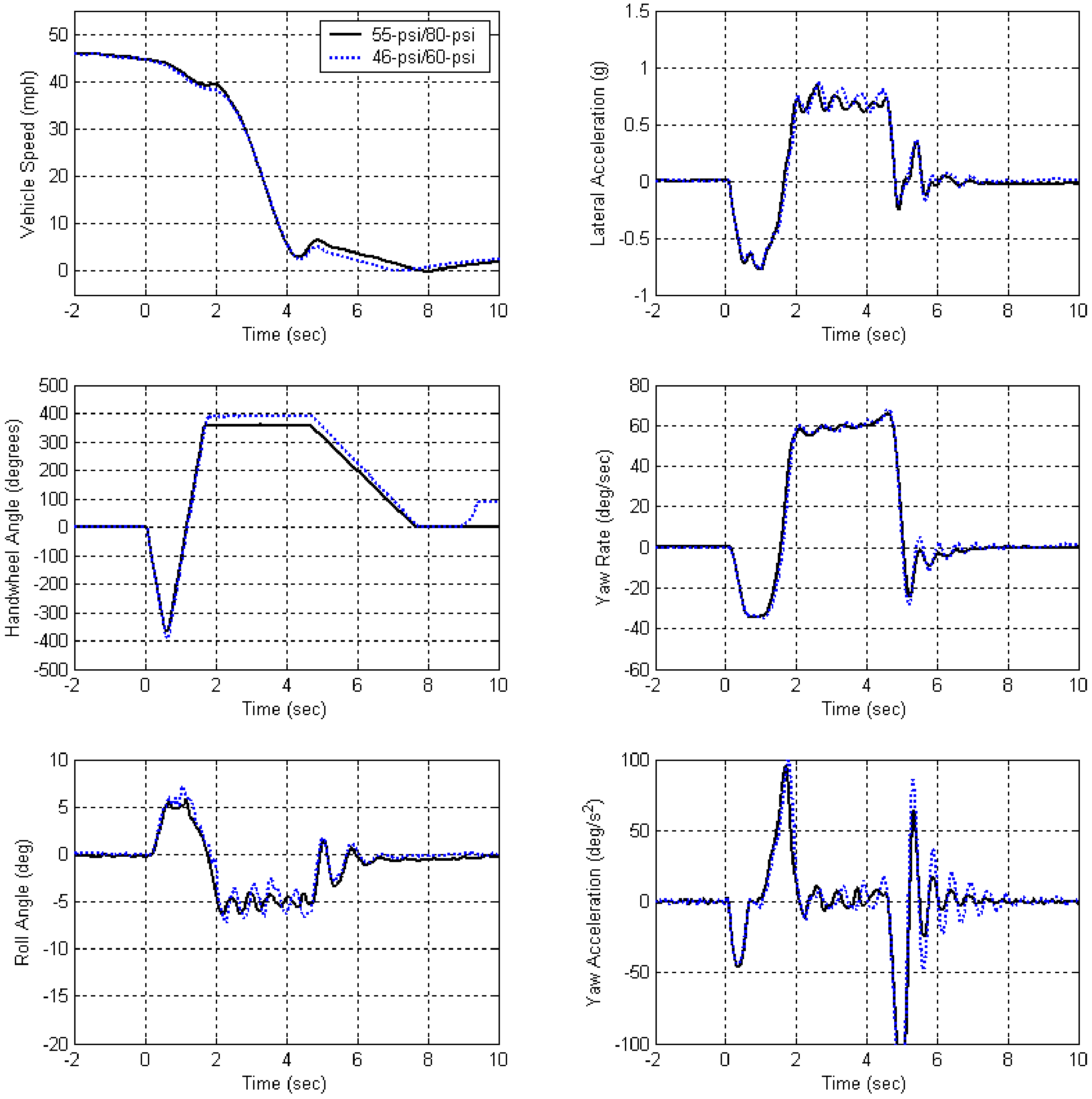

Figure A-25. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 5-occupant load. Tests were initiated at 45 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

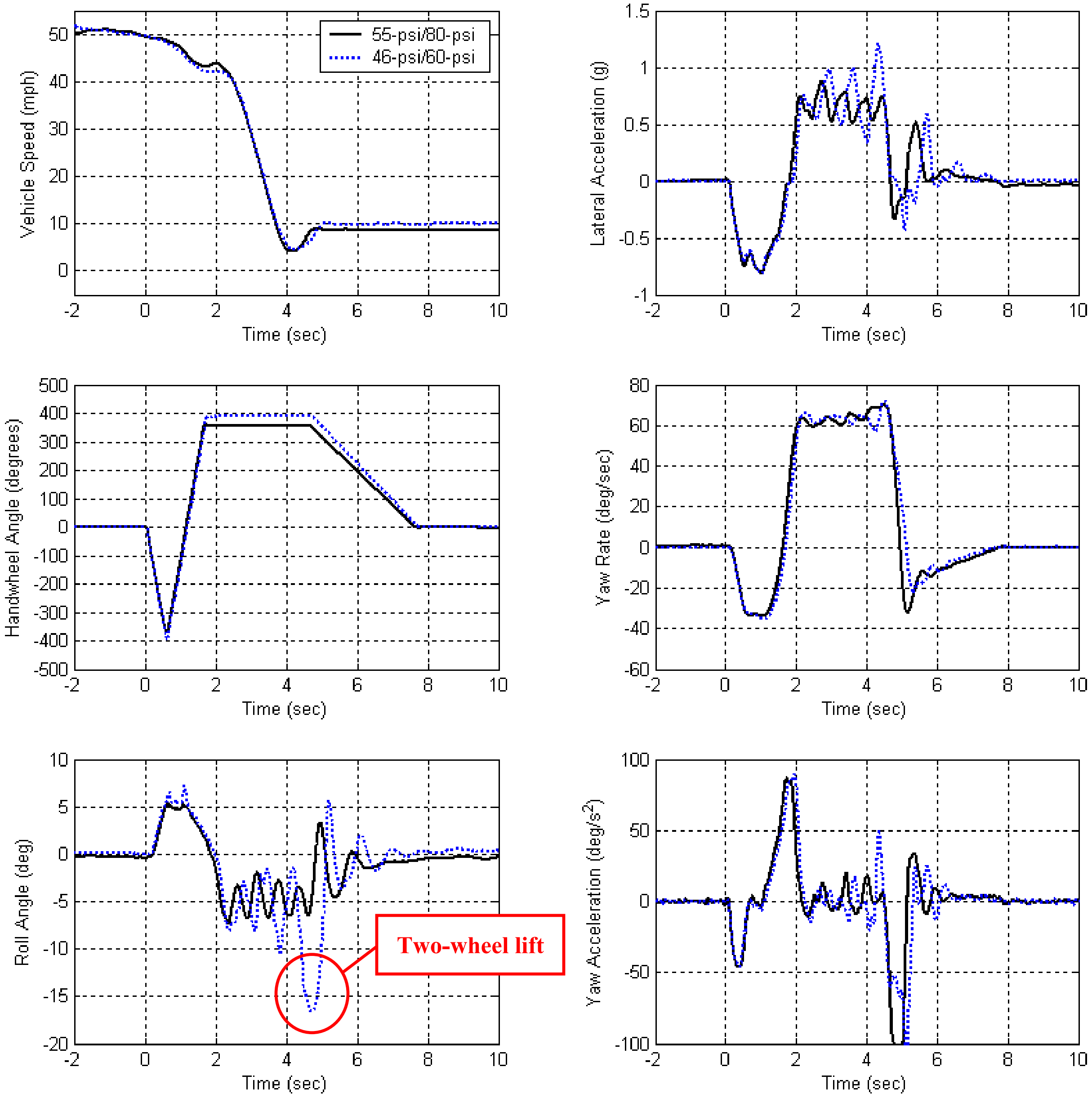

Figure A-26. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 5-occupant load. Tests were initiated at 50 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

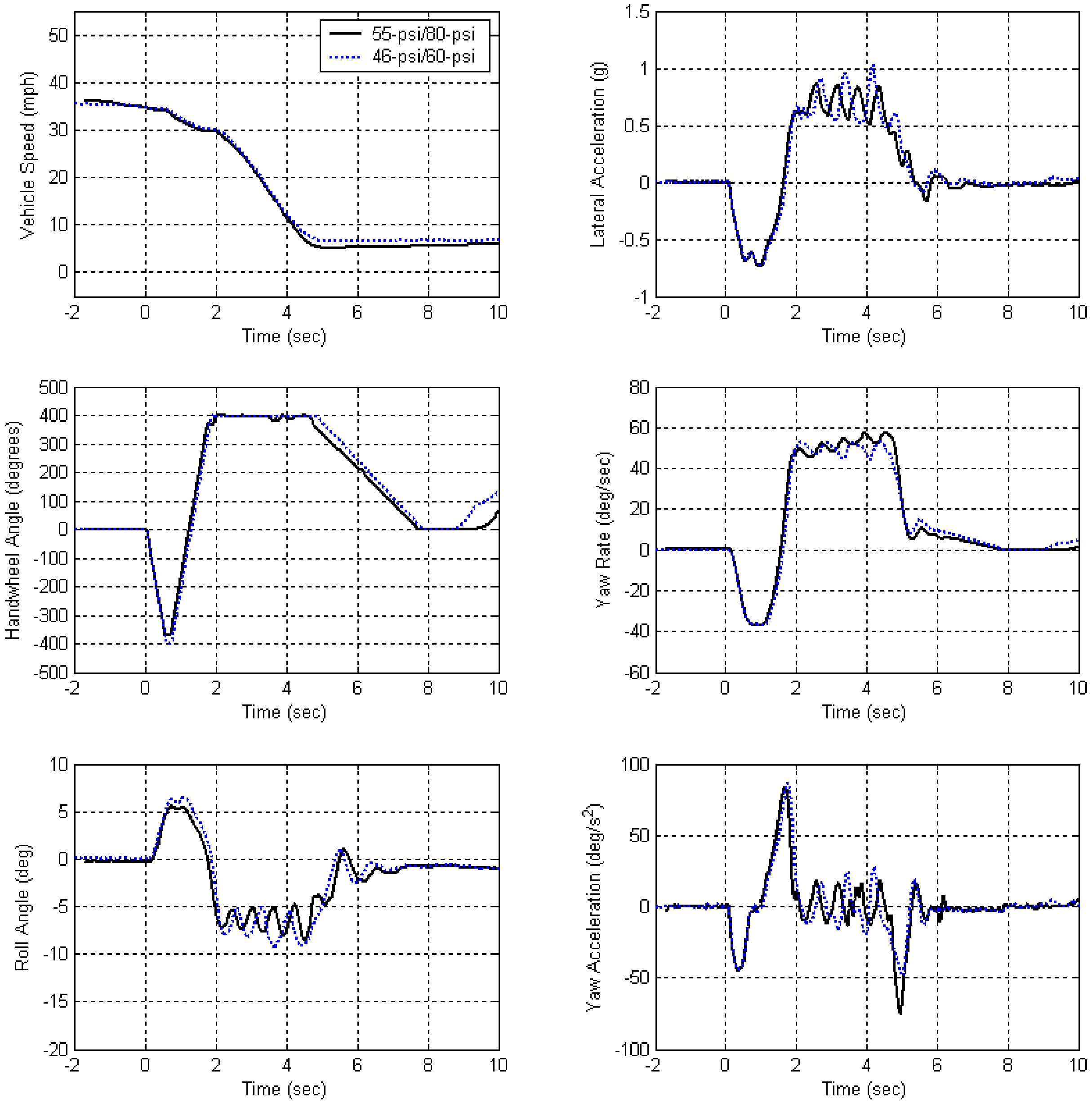

Figure A-27. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a <u>10-occupant</u> load. Tests were initiated at <u>35 mph</u>, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

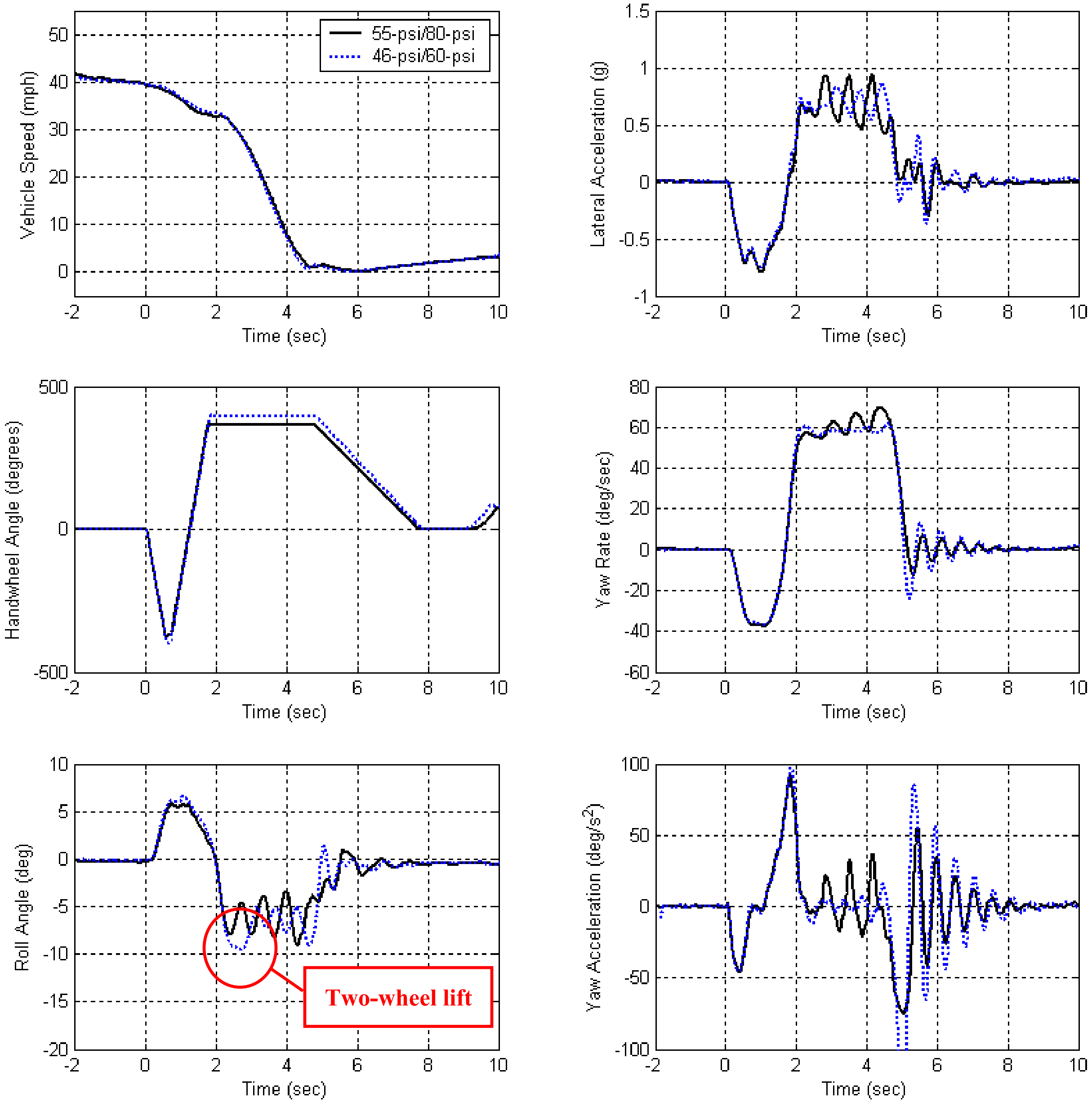

Figure A-28. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 10-occupant load. Tests were initiated at 40 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.

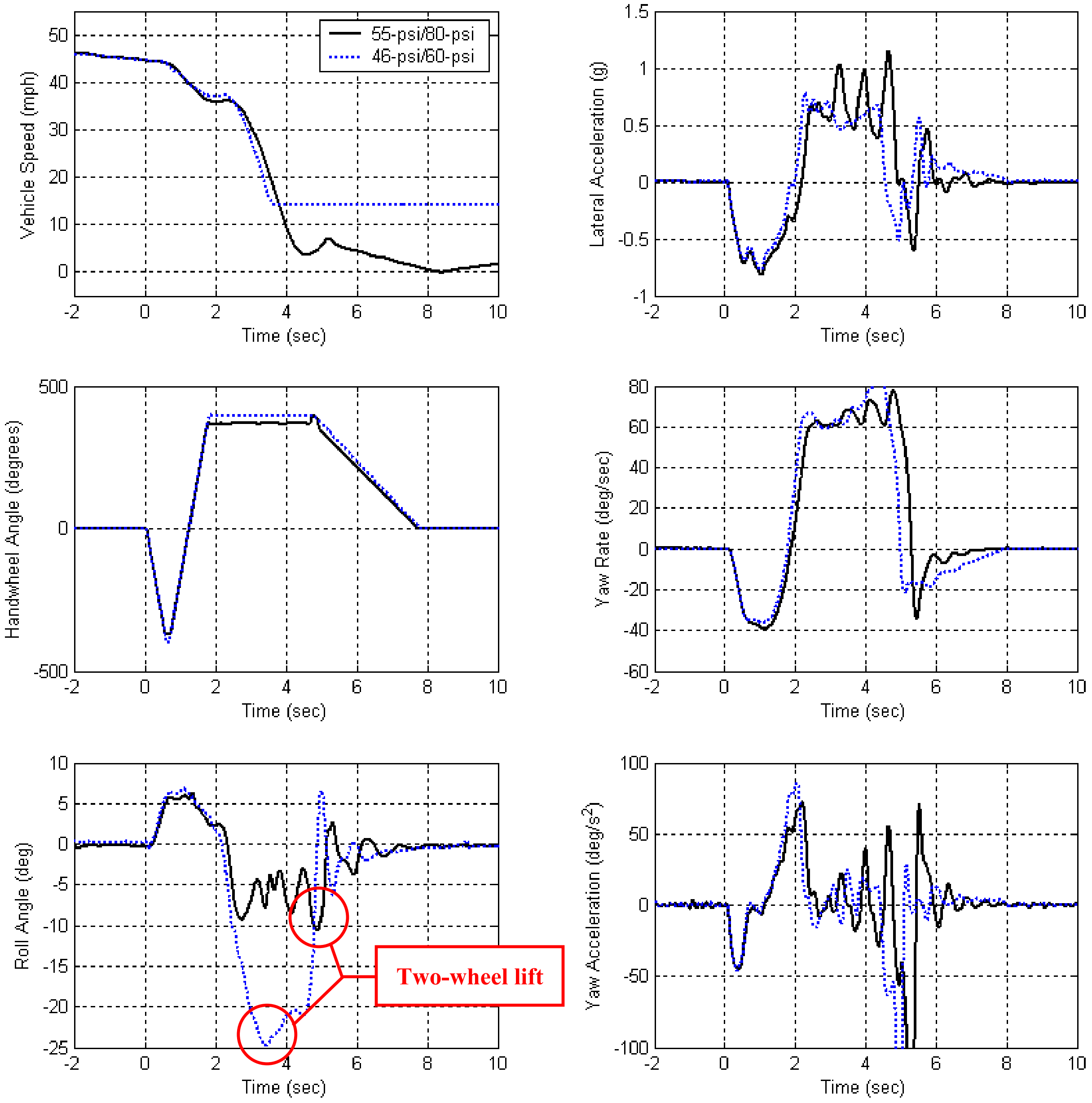

Figure A-29. Vehicle speeds, handwheel angles, roll and yaw rates, and lateral and roll accelerations observed during two Road Edge Recovery tests performed with a 10-occupant load. Tests were initiated at 45 mph, and were performed with the tires inflated to Placard and Current MAP inflation pressures.