

The True Definition and Measurement of Oversteer and Understeer

Donald F. Tandy, Jason Colborn, Jung C. Bae, and Clay Coleman
Tandy Engineering & Associates Inc.

Robert Pascarella
Ford Motor Company

ABSTRACT

The concept of vehicle understeer and oversteer has been well studied and equations, test methods, and test results have been published for many decades. This concept has a specific definition in the steady-state driving range as opposed to quantification in highly transient limit handling events. There have been specific test procedures developed and employed by automotive engineers for decades on how to quantify understeer. These include the constant radius method, the constant steering wheel angle/variable speed method, the constant speed/variable radius method, and the constant speed/variable steer method. These methods are very good for calculating the understeer gradient but care must be taken in interpreting the result at the limits of tire traction since lateral tire forces can be reduced on a drive axle when significant throttle is applied.

This paper focusses on the mainstream definition of understeer and oversteer and how that objective metric should be measured on a motor vehicle and where care should be taken in interpreting results. A proposed "Transient Oversteer metric" was also evaluated and was found to not have mainstream acceptance and was very dependent on driver inputs and not vehicle handling characteristics. In fact, the results could not be repeated.

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INTRODUCTION

The concept of vehicle understeer and oversteer has its roots in the early studies of vehicle handling which, in fact, stemmed from the study of airplane dynamics and control. It is interesting to some on race Sunday to hear race car drivers, who rarely if ever, measure understeer or oversteer in an objective sense report subjective feelings of vehicle cornering using words such as "push" or "loose." Understeer is an objective metric that quantifies a specific handling quality of a vehicle at a given loading condition. In simplistic terms, an understeer vehicle requires more steering input into the turn if the speed of the vehicle is gently increased on a constant radius path. Conversely, an oversteer vehicle requires the driver to reduce the magnitude of steering as speed, and therefore lateral acceleration, is increased.

The National Highway Traffic Safety Administration (NHTSA) has performed extensive testing using a constant speed, variable steering understeer test they called the Slowly Increasing Steer Test (SIS) on a host of different vehicles. When these tests were used on some heavy vehicles with large cargo carrying capacities, it was found that these vehicles could spin out in the high lateral acceleration range. In 2004, the NHTSA published a report documenting testing they performed on two fifteen passenger vans [1]. One maneuver they used to characterize the vehicles was a slowing increasing steer test (SIS).

When the vehicles were approaching their limits in some of the tests, roll oscillations and spinout were reported. The authors attributed this behavior to an oversteer characteristic.

Recently, Renfroe [2] published a paper describing a metric he referred to as "transient oversteer" where yaw rate is compared to a parameter called "Ackermann yaw rate." It is important to note here that Ackermann has a specific definition. It is the steer angle required at low speed for the vehicle to track a circle [3]. Ackermann has no mainstream definition in high speed maneuvers and it is not related to yaw rate. Notable conclusions from this paper include that a yaw rate overshoot in a transient maneuver is an instability in the vehicle and that the transient oversteer metric could be only weakly correlated to test speed or maneuver type, even though tests were only reported at 35 and 40 miles per hour and only two turn and one turn limit maneuver experiments were run.

The mainstream definitions of understeer and oversteer have always been isolated to a vehicle in a steady turn [ref 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. The accepted test protocols used by vehicle manufacturers worldwide to measure understeer and oversteer behavior have also mandated steady state cornering with very gradual changes in steering or speed, depending on what method is being employed. ISO 4138 [14] and SAE recommended practice J206 [15] highlight

several methods to measure understeer and how to calculate the understeer gradient. General Motors Corporation also described a method they employ in an SAE paper published in 1984 [16].

This paper focuses on the definition of understeer and whether it has any definition in a transient maneuver. Scientific testing was also performed in order to evaluate the different methods of evaluating the understeer of various vehicles including a fifteen passenger van. The data from these tests are compared and discussed.

DISCUSSION

This paper will be segmented into three sections. The first deals with the true scientific concepts of understeer and oversteer and industry accepted tests are presented. The second section investigates some findings related to oversteer and understeer by the NHTSA. The last section covers the theories put forth by Renfroe in [2] on a proposed "Transient Oversteer Metric."

Mainstream Tests for Evaluating Understeer and Oversteer

Society of Automotive Engineers J266

SAE Standards J266 [15] prescribes four different test methods for determining understeer:

- Constant Radius
- Constant Steering Wheel Angle / Variable Speed
- Constant Speed / Variable Radius
- Constant Speed / Variable Steer

Constant Radius

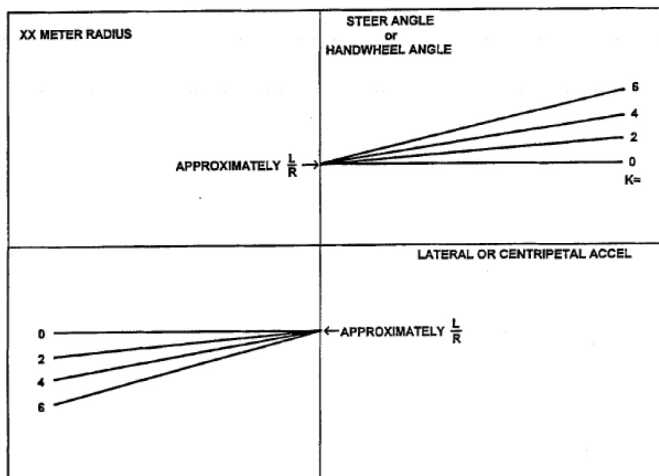


FIGURE D1—CONSTANT RADIUS TEST

Figure 1. Diagram from SAE J266 of steering wheel angle versus lateral acceleration.

This is a closed loop test where the vehicle is driven in a constant radius turn. First, the radius is driven at the slowest speed possible to determine the Ackermann steering angle. Speed is increased in small

increments and the vehicle is held in equilibrium to determine the required steering angle at each speed (and thus lateral acceleration) driven. Speed is increased until the vehicle is no longer able to maintain the radius. The data is typically presented in an X-Y graph with steering wheel angle on the vertical axis and calculated lateral acceleration (speed x speed / radius) on the horizontal axis (see Figure 1 which is taken from SAE J266).

Constant Steer Angle Test

The constant steer angle test is an open loop test where the vehicle is driven at various speeds using a fixed steering angle. First, the vehicle is driven at very slow speed to determine Ackermann steering radius for the selected steering angle. Then vehicle is driven at increasing speeds steady state until the maximum lateral acceleration level of the vehicle is reached. The radius of turn at each speed is compared to the Ackermann radius to determine understeer. Typical data presentation are the two graphs in Figure 2 which is reprinted from SAE J266.

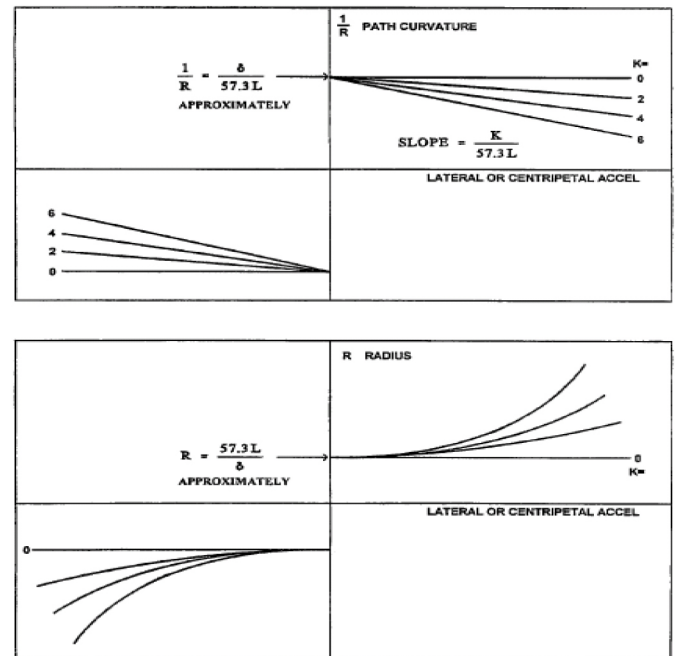


FIGURE D2—CONSTANT STEER ANGLE TEST

Figure 2. Data charts for the constant steer angle test as shown in SAE J266.

Constant Speed Variable Radius

This closed loop test is performed at many discrete radii at a constant speed. The vehicle is driven onto the circle in a steady straight line, then turned onto the circle. The portions of the test where the vehicle is at equilibrium are used to calculate the understeer gradient. The data is typically presented in a X-Y graph with steering wheel angle on the vertical axis and calculated lateral acceleration (speed x speed / radius) on the horizontal axis (see Figure 3 which is taken from SAE J266).

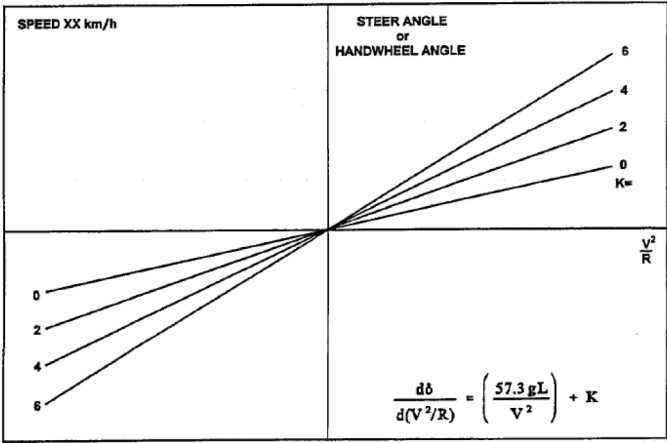


FIGURE D3—CONSTANT SPEED, VARIABLE RADIUS TEST

Figure 3. Data plot shown in SAE J266 for the constant speed, variable radius test.

Constant Speed Variable Steer Angle

This open loop test is driven at a constant speed for several seconds in a straight line, then for several seconds more after a selected steering input is made. The portions of this test where the vehicle is in equilibrium are used to determine understeer gradient. Figure 4 is a graph taken from SAE J266.

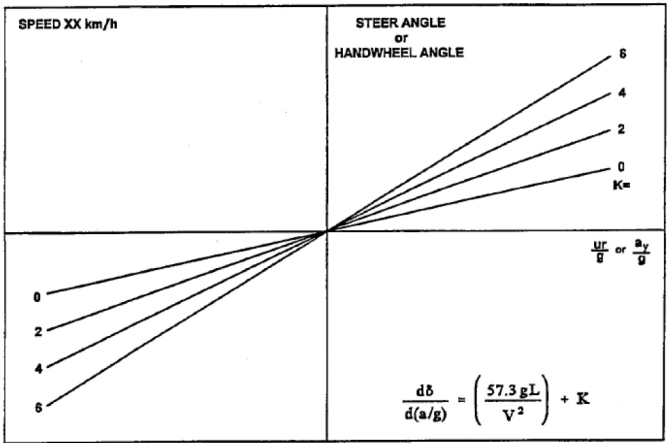
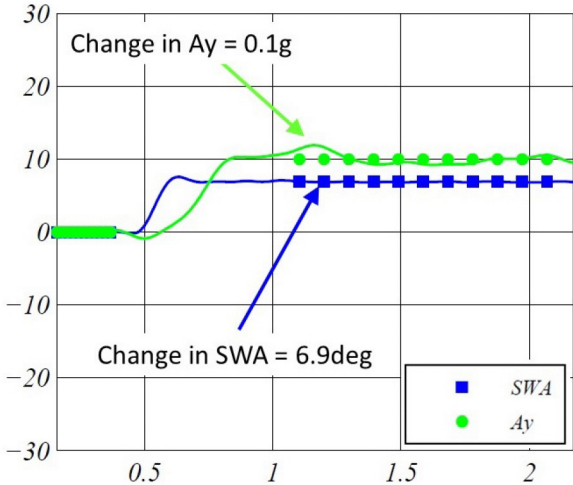


FIGURE D4—CONSTANT SPEED, VARIABLE STEER TEST

Figure 4. Example data chart shown in SAE J266 for the constant speed, variable steer test.

International Organization for Standardization ISO

ISO 4138 [14] describes an open loop steady state method for computing vehicle characteristics at steady state, including understeer gradient. The document describes the same methods put forth by SAE J266 but only highlights in detail the constant radius method. ISO uses the same protocol as SAE J266 so it is not repeated here.



Steering Sensitivity @ 63.5mph = 1.45 g/100degSWA
Understeer Gradient = 2.65 deg/g

Figure 5. Example of actual vehicle test data in a GM low g step steer tests with steering sensitivity and understeer gradient calculated.

General Motors Corporation Procedure Described in SAE 840561

The method for measuring understeer described in “Typical Vehicle Parameters for Dynamics Studies Revised for the 1980's” which was authored by the Engineering and Manufacturing staff at General Motors employs a 0.15 g turn at 100 kph [16]. Although this test involves a step-type steering input, the transient portion of the test is disregarded. Instead, the steady-state straight and cornering portions of the test are used separately to find the steering sensitivity. Understeer gradient at 0.15 g can then be calculated from steering sensitivity. Figure 5 shows an example of the calculated steering sensitivity and then understeer from a single run. It is however recommended to repeat the test for multiple runs and then average the values for the metrics.

Comparison of the Calculated Understeer Gradient for Different Methods for Several Vehicles

Table 1. Comparison of understeer gradients on four different vehicles

	J266 Circle Test	GM Step Steer	Variable Steer Constant Speed
Mid-size Size SUV	3.1	3.1	3.3
Full Size Pickup Truck	1.6	1.6	1.5
Mid-size Passenger Car	3.0	2.9	2.6
Full Size SUV	2.4	2.3	2.7
Minivan	3.7	3.6	3.6

In order to compare numeric values for the linear understeer gradient provided by different methods, four vehicles were tested using three understeer test procedures. The procedures selected were the constant radius method, the GM low g step steer procedure, and the variable steer, constant speed test. The four vehicles included a mid-size utility vehicle (see Figure 6), a full size pickup truck (see Figure 7), a mid-size front-wheel-drive passenger car (see Figure 8), a full-size utility vehicle (see Figure 9).

9), and a minivan (see Figure 10). The data shows that all methods provide understeer gradient levels well within one degree per g of one another. Therefore, these procedures are all reliable methods for obtaining the numeric value of linear range understeer.



Figure 6. 2003 Mid-size rear wheel drive SUV



Figure 7. Full size rear wheel drive pickup truck



Figure 8. Mid-size front wheel drive passenger car



Figure 9. Full size four wheel drive SUV



Figure 10. Front wheel drive minivan.

An Analysis of the Slowly Increasing Steer Test and Its Application at the Limit of Tire Traction

Slowly Increasing Steer Testing conducted by the NHTSA

In 2004, the NHTSA had conducted testing utilizing the Slowly Increasing Steer (SIS) protocol on two fifteen passenger vans [1]. This maneuver is basically a constant speed, variable steer understeer test where the steering wheel angle is ramped up in a linear fashion. Testing was conducted at two loading conditions: Nominal Load (i.e. two occupants) and Maximum Occupancy (i.e. fifteen occupants). Per that report; 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."

Even though the slowly increasing steer test does not simulate a "real-world" driving situation, the maneuver is generally accepted as an effective procedure to evaluate the understeer gradient and steering sensitivity of a vehicle in the linear range. There is however not a general agreement on the use of SIS to the limit of adhesion to quantify the lateral dynamics of every vehicle.

The protocol the NHTSA employed for the slowly increasing steer test was to drive the test vehicle in a straight line at fifty miles per hour. The driver must attempt to maintain this speed during and briefly after the steering is input using smooth throttle modulation. At time zero, hand wheel position, usually with the assistance of a steering controller, was linearly increased from zero to 270 degrees at a rate of 13.5 degrees per second. When the NHTSA was developing the test, they used lighter weight vehicles and therefore were able to maintain speed throughout the maneuver. Figure 11 shows data for a Mercedes ML320 that was tested by the NHTSA in 2002.

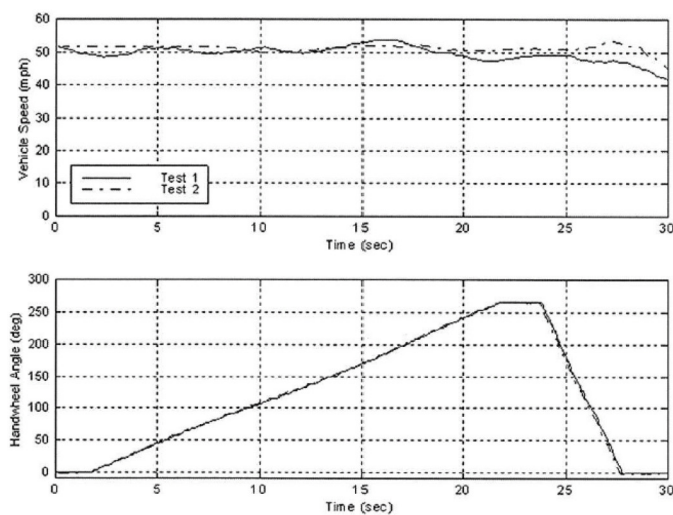


Figure 11. Velocity and hand wheel angle versus time for two slowly increasing steer tests on a Mercedes ML320.

However, in 2004 the NHTSA employed this test on fifteen passenger vans which were much heavier than the vehicles it previously evaluated. As observed in the testing of the van fully loaded and at the nominal load, speed was not able to be maintained by the driver (see Figure 12 for the nominal load test run).

At the point where the speed begins to drop off, the driver is applying significant throttle in an effort to maintain speed but speed drops off quickly. As this is taking place the yaw rate begins to climb, ultimately resulting in the vehicle "spinning out" (see Figure 13).

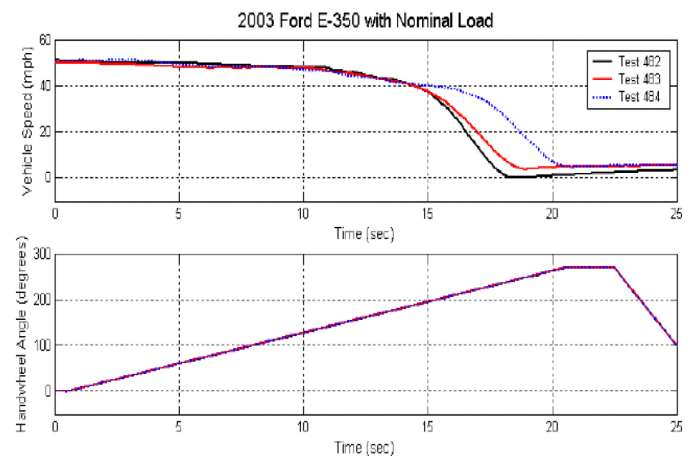


Figure 12. Velocity and hand wheel angle versus time for three slowly increasing steer tests to the right on a Ford E-350 fifteen passenger van.

When the slowly increasing steer test was conducted with a steering input to the left, a different response was observed in that the yaw rate plateaus and a spinout does not occur (see Figure 14). With this vehicle, an application of throttle creates a torque through the drivetrain which acts to increase the normal force on the left rear tire and decrease the load on the right rear tire. In a right turn, this acts as an increase in the rear load transfer distribution but in left turns, the opposite is true. This affect can account for some of the asymmetry in this limit maneuver with heavy throttle application.

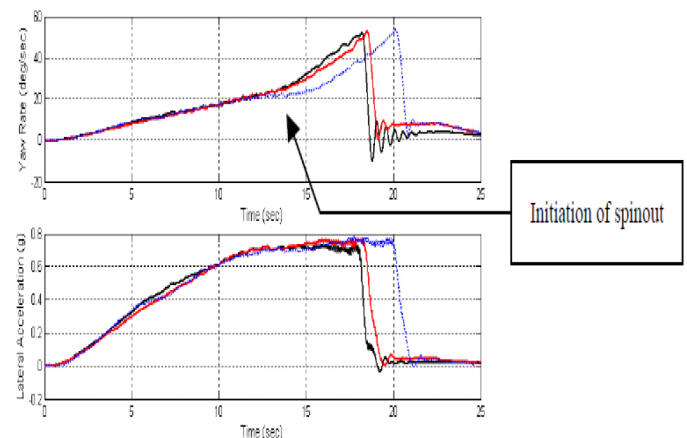


Figure 13. Slowly Increasing Steer test data showing point of spinout initiation.

Unlike the lighter vehicles tested, the heavy fifteen passenger vans require a significant amount of longitudinal tire force to keep the vehicle at speed at the limit when large steer angles are being used. However, as the driver demands more and more longitudinal tire force, the amount of available tire lateral force is reduced (see Figure 15 for the concept of the friction ellipse). This reduction in lateral tire force sets up an unbalance of forces and a spinout response can develop.

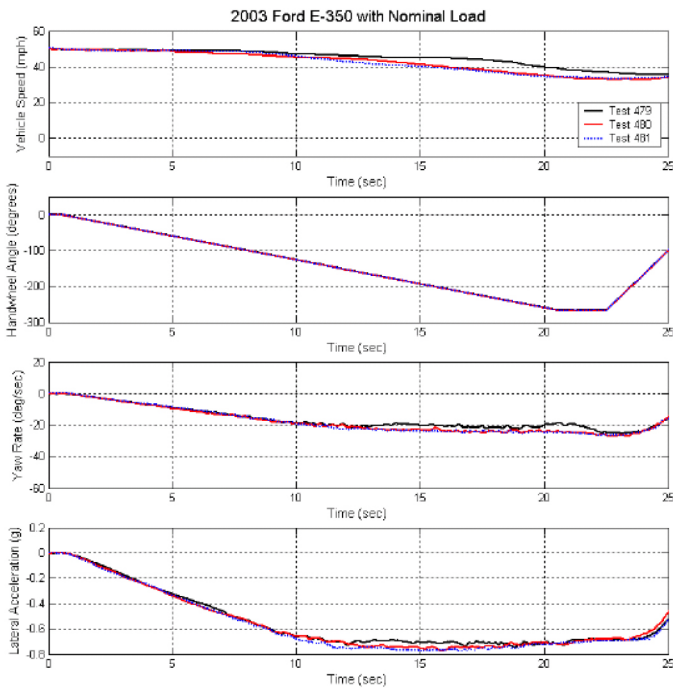


Figure 14. Vehicle input and response time histories for three slowly increasing steer tests to the left on a Ford E-350 fifteen passenger van at nominal load.

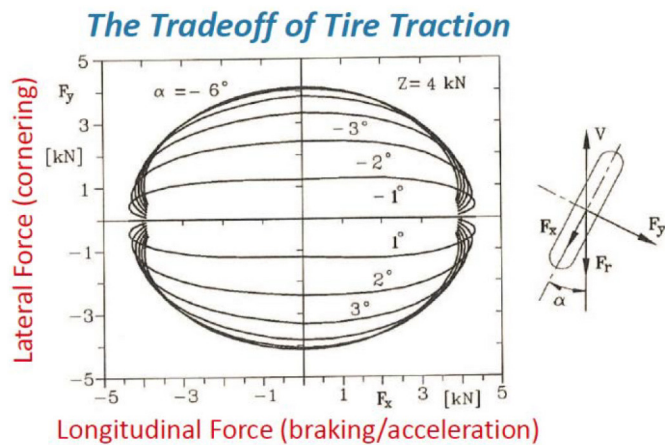


Figure 15. The friction ellipse which highlights the concept that a tire can only provide so much force (modified version of Figure 2.40 in [10]).

Evaluation of Different Understeer Test Methods on a Fifteen Passenger Van

Since the Ford E-350 fifteen passenger van spun out in the NHTSA slowly increasing steer maneuver in one direction, tests were performed using several other understeer test methods (constant radius and constant steer, variable speed) as well as a repeat of the slowly increasing steer test. A 2003 model year E-350 was instrumented and loaded to the nominal condition. In these tests, the vehicle understeered to the limit and did not experience a spin out response. Figure 16 shows the steering angle versus lateral acceleration plot for the reproduction of the fifty mile per hour slowly increasing steer test and Figure 17 shows the vehicle input and responses. Figure 18 shows the steering angle versus lateral acceleration plot for the two hundred foot constant radius understeer

test and Figure 19 shows the vehicle input and responses during the maneuver. The understeer plot for the constant steer, variable speed test is shown in Figure 20 with the time history data in Figure 21.

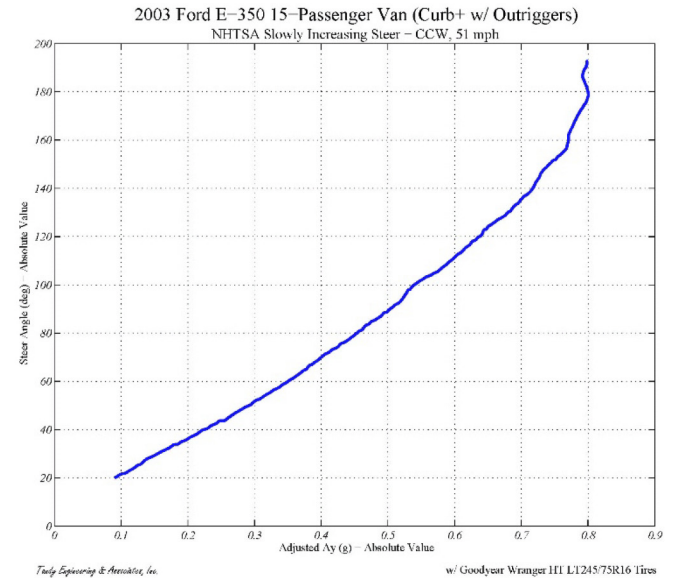


Figure 16. Steering wheel angle versus adjusted lateral acceleration plot for a 50 mile per hour slowly increasing steer test on a 2003 Ford E-350 van.

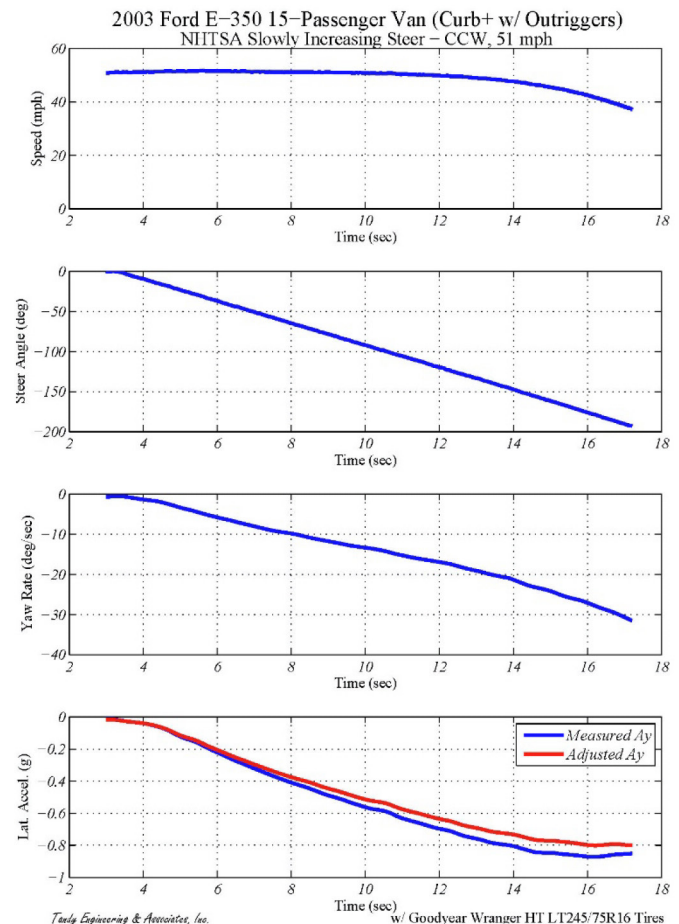


Figure 17. Vehicle input and output responses for a 50 mile per hour slowly increasing steer test on a 2003 Ford E-350 van.

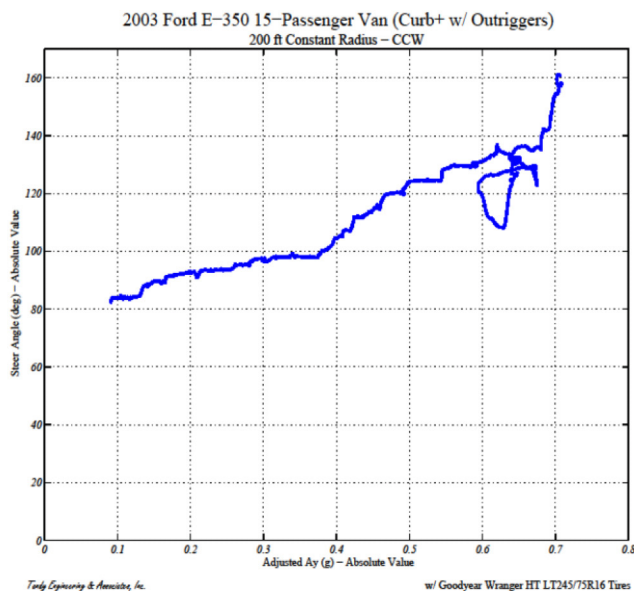


Figure 18. Steering wheel angle versus adjusted lateral acceleration plot for a 200 foot constant radius understeer test on a 2003 Ford E-350 van.

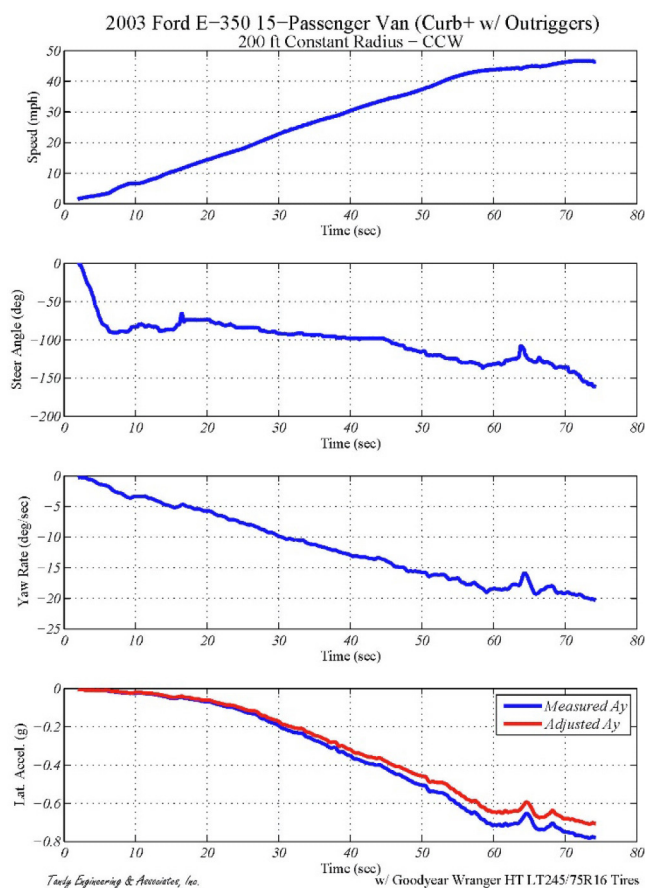


Figure 19. Vehicle input and output responses for a 200 foot constant radius understeer test on a 2003 Ford E-350 van.

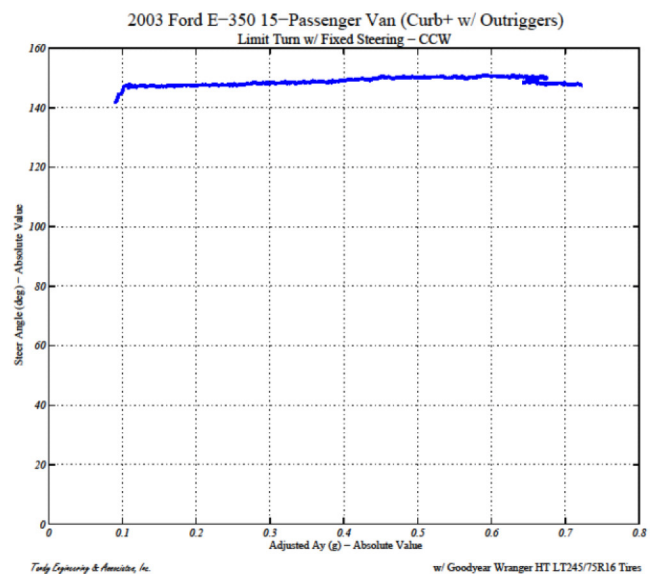


Figure 20. Steering wheel angle versus adjusted lateral acceleration plot for a constant steer / variable speed understeer test on a 2003 Ford E-350 van.

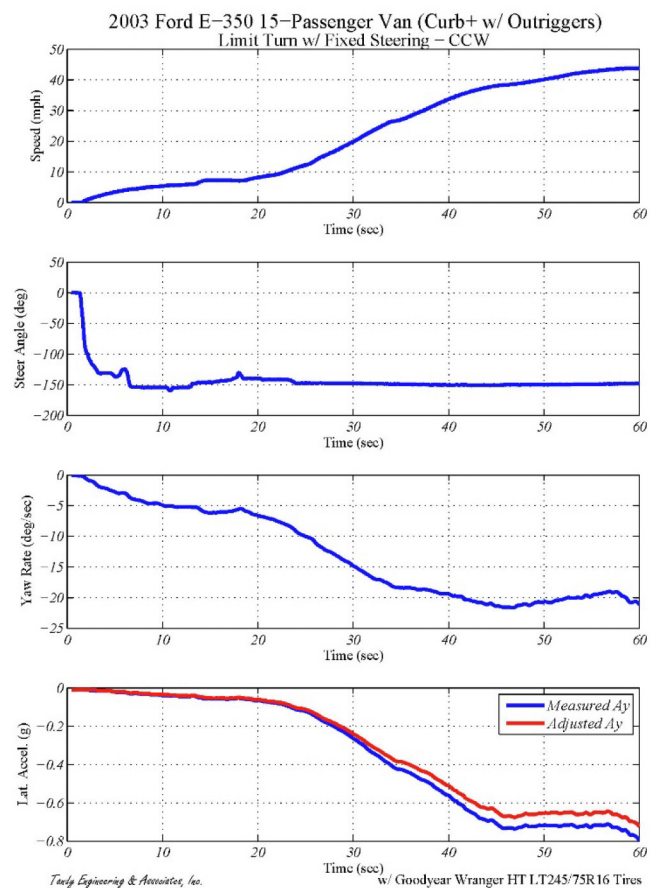


Figure 21. Vehicle input and output responses for a constant steer / variable speed understeer test on a 2003 Ford E-350 van.

As seen in the figures above the vehicle response at the limit of adhesion in the NHTSA SIS as compared to the constant radius and fixed steering events is quite different. In the constant radius and fixed steering evaluations, the vehicle does not "spin" as in the case for the NHTSA SIS in the left turn direction.