THE IMPORTANCE OF DYNAMIC TESTING IN DETERMINING THE YAW STABILITY OF VEHICLES

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ABSTRACT

The fundamental understeer/oversteer signature of a vehicle has historically been evaluated through steady state circular skid pad testing done according to one of the four methodologies outlined in SAE J266. These tests evaluate a vehicle's fundamental handling behavior but are insufficient to fully establish its yaw stability and control characteristics and performance envelope. Transient testing of the vehicle is also necessary because vehicles are not operated under steady state conditions. This becomes of greatest importance in an emergency situation where a driver must respond quickly.

For good handling and control, it is necessary for a vehicle to understeer in circular skid pad testing. Additionally, the vehicle must not become yaw-unstable in a J-turn.

In the present work, full-scale handling tests were conducted on a 15-passenger van configured in a variety of loading and design conditions. The test results showed substantial differences in vehicle performance when comparing steady state tests (constant radius tests per SAE J266) and transient tests (J-turns). The tests revealed some undesirable handling characteristics during the transient maneuvers that were not uncovered by steady state tests alone. Design changes were tested and found to substantially improve the vehicle's dynamic handling characteristics.

INTRODUCTION

Vehicle handling has a long-established relationship to motor vehicle safety. A vehicle that is not stable in yaw up to its limit of performance is more likely to lose control. This can potentially lead to any number of accident scenarios including rollover, impact with fixed objects, impact with other motor vehicles, and impact with pedestrians. Traditional measures of vehicle handling are based on a combination of subjective driving evaluations along with some objective steady state testing. SAE J266 "Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks"[1] is often used.

Subjective evaluation will typically result in a number of test drivers providing their personal feedback to the designer. Subjective vehicle handling evaluations often use ill-defined terminology. Some common terms include crisp, sluggish, on-center-feel, firm, and soft. Terms such as these lack objective definition and do not properly compare vehicles for a range of vehicle utility, vehicle class, and vehicle operator demographic. An objective description of vehicle handling based upon subjective driver evaluations is not possible.

Steady state testing does provide an objective analysis of the vehicle's directional control. However, steady state test results cannot always predict how a vehicle will behave in a transient environment similar to that encountered in the real world. This is critically important when a vehicle's response to an emergency requires an evasive steer. Under these circumstances, the driver needs the vehicle to behave in a predictable and stable manner.

Modern vehicles, with rare exception, meet steady state measures of handling performance under normal conditions. For good handling, as judged by steady state testing, it is desirable that the understeer gradient of the vehicle be as follows:

1. Linear and positive at low lateral acceleration levels
2. Increasing in magnitude (or at worst, constant and positive) at high lateral acceleration levels.

For the population of motor vehicles in use today the objectively determined steady state handling characteristics vary widely within an acceptable range of values. However, when a rapid steering is input (such as when an evasive maneuver is required) the handling characteristics described by steady state tests and subjective driving evaluations are insufficient to completely determine if a vehicle will respond in a stable and predictable way. This paper demonstrates the need for additional transient maneuver testing by reporting on the results of both steady state and transient tests of vehicles that fill very different positions in the spectrum of vehicle utility.

TEST DESCRIPTION

Test Methodology

Two different test procedures were performed during the vehicle evaluation testing reported in this paper:

1. Constant radius tests
2. Step steer (J-turn) tests.

Constant Radius Tests

This test is designed to measure the steady state understeer and/or oversteer characteristics of the vehicle. The tests were conducted per SAE J266, Method 1, on a closed asphalt skid pad around a 100 ft (30.5 m) radius circle.

The continuous test procedure was used requiring that the vehicle begin at a stop and slowly accelerate around the prescribed circle at less than 1 mph/sec (.05 g) until reaching the maximum speed attainable. The procedure required that the vehicle be driven around the circle within 1.6 ft (0.5 m) of either side of the perimeter.

Step steer (J-turn) tests

Step steer testing was performed to evaluate the transient response of each test vehicle. The target speed for each test was 45 mph (72.4 kph) with a target step input to the steering wheel of 180°. The test driver accelerated the vehicle as quickly as possible to the target test speed. After a steady state condition at the target speed was reached, the driver released the throttle and steered the vehicle to the designated steering angle as rapidly as possible. The steering wheel angle was held fixed until the vehicle came to rest or for a minimum of five seconds. The speed and steering wheel angle were chosen to insure that the driver could easily provide the necessary steer angle in one continuous motion and to insure that the tires would saturate.

Test Vehicles

This paper presents the results for testing of a front wheel drive 4-door sedan with a front weight-bias and a rear wheel drive 15-passenger van with a rear weight-bias. The van was tested in its baseline configuration with a Single Rear Wheel (SRW) axle and the same vehicle was tested again after being modified to use a Dual Rear Wheel (DRW) axle.

The two base vehicles tested were a 1993 Ford Taurus GL sedan (Figure 1) and a 1996 Ford E-350 Club Wagon XL 15-passenger van (Figure 2). The Taurus was equipped with a 3.0 liter V6 engine and P205/65R15 tires. The E-350 was equipped with a 5.8 liter V8 engine and LT245/75R16 load range E tires in the SRW configuration and LT225/75R16 load range D tires in the DRW configuration.

The Taurus was loaded to its curb weight plus the weight of the driver for all tests. Both the SRW and DRW vans were tested in their curb-plus-driver configurations, and the tests were repeated with the vehicles in a fully loaded configuration for which 14 water dummies weighing approximately 175 lb. each were added.

Figure 1. 1993 Ford Taurus GL.

Figure 2. 1996 Ford Club Wagon XL.

Test Instrumentation

The vehicles were each equipped with a set of instruments to record the test inputs and the vehicle response. As a minimum, one of each of the following instruments was used:

Datron velocity sensor

Used to measure longitudinal and lateral speed, this instrument was mounted at the center of the rear bumper on the Taurus test vehicle and at the center of the front bumper in tests of the E-350.

String potentiometer

Used to measure steering wheel angle, this instrument was mounted within the engine compartment adjacent to the steering shaft. The string was extended and wrapped around the steering shaft such that turning the steering wheel produced either an extension or contraction depending on direction that the steering wheel was turned. The potentiometer was calibrated to each vehicle, providing a known relationship between the steering wheel angle and the extension of the string.

Triaxial accelerometer

Used to measure longitudinal, lateral, and vertical accelerations, this instrument was mounted on the floor of each vehicle at the centerline near the longitudinal center of gravity.

Additional on-board equipment included a laptop computer for data acquisition and a tripod with a video camera mounted just behind the driver's right shoulder. The video camera was set up to record the steering wheel movement as well as the view through the front windshield.

Test Location/Surface

All tests were conducted on the skid pad at Firebird International Raceway in Chandler, Arizona. The skid pad consists of a flat level asphalt surface of approximately 590 by 460 ft.

Data Analysis

Constant Radius Tests

The constant radius test data were analyzed by plotting the lateral acceleration (A_y) versus the steering wheel angle divided by the steering gearbox ratio (δ). This plot is used to determine if the vehicle is understeer or oversteer at any given lateral acceleration. A generic plot is shown in Figure 3. A positive slope at a given lateral acceleration indicates understeer. A slope of zero indicates neutral steer. A negative slope indicates oversteer. It is obviously undesirable for a vehicle to exhibit oversteer.

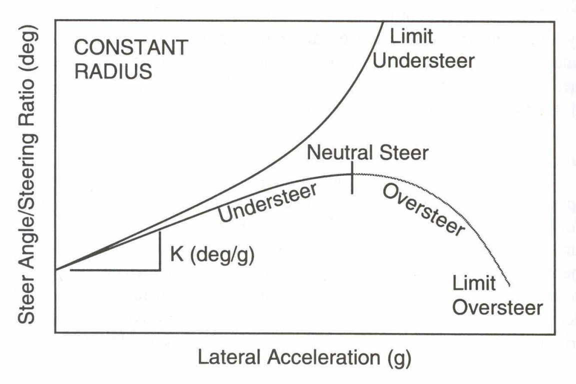

Figure 3. Generic understeer gradient.

A plot of the actual test data fitted with a least squares fifth order polynomial was used to separately analyze each of the constant radius tests. Such a plot for a right turn constant radius test of the SRW E-350 is shown in Figure 4.

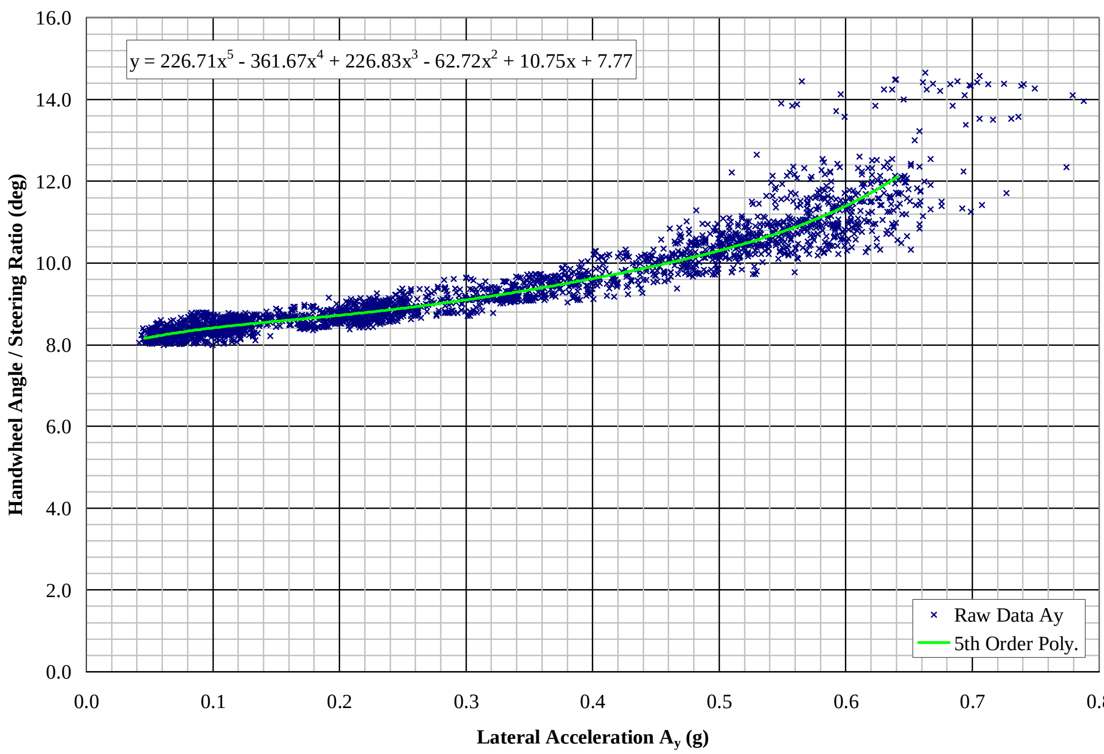

Figure 4. Constant Radius Test Results: SRW E-350 in Curb-Plus-Driver Configuration.

The polynomial equation describing the data was differentiated ($d\delta/dA_y$) to arrive at an equation for its slope. The slope of the polynomial equation is the understeer gradient. The understeer gradient can be calculated at each value of lateral acceleration of interest from the equation for the slope. If there was an inflection in the curve, the maximum or minimum could also be derived. This is particularly useful to determine the steady state lateral acceleration level at which a vehicle transitions from understeer to oversteer. Neither the Taurus nor the E-350 vans experienced a transition from understeer to oversteer during the constant radius tests described in this paper.

Transient Step Steer Test

The data were analyzed by plotting the measured quantities of interest vs. time. The data presented in the paper include the two key input parameters of speed and steering wheel angle and the response parameter of slip angle. The two input parameters were compared between each test vehicle to insure that all vehicles were given the same input conditions.

The slip angle data were analyzed to answer the question: Did the vehicle respond by achieving a steady state body slip angle which diminished over time as the vehicle bled off speed? This kind of response provides predictability for the driver and maximizes the opportunity to maintain vehicle control. A vehicle response resulting in an increasing slip angle could ultimately lead to vehicle loss of control if the slip angle became too large.

DISCUSSION OF RESULTS

Steady State Tests – Constant Radius Turns

All three test vehicles exhibited a positive understeer gradient throughout the entire range of lateral acceleration up through tire saturation. The trends in the results were the same for tests performed to the right and to the left. The data from the right turn constant radius tests are presented in Figure 5.

The data indicate that the SRW E-350 has a greater understeer gradient than the Taurus throughout most of the lateral acceleration range when comparing both vehicles in the curb-plus-driver load configuration.

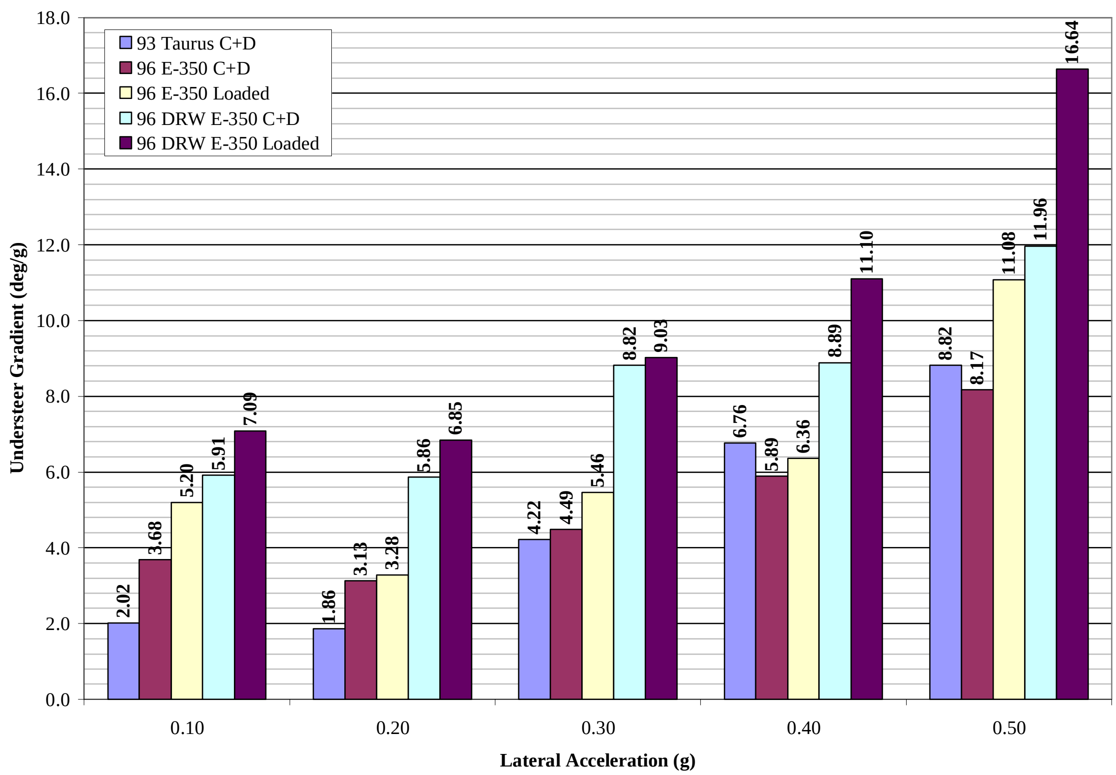

Figure 5. Understeer Gradient Data from Constant Radius Testing

The data further indicate that the SRW E-350 has a greater understeer gradient when fully loaded than when in the curb-plus-driver configuration. This second finding, while counterintuitive, is likely a result of the vehicle's suspension design.

The DRW E-350 exhibited the largest understeer gradient of the three vehicles tested. This vehicle's understeer gradient was greater in the fully loaded configuration than in the curb-plus-driver configuration. This is the same trend observed in comparing the test results for the two loading configurations of the SRW E-350.

Using the steady state constant radius test as the sole criteria for yaw stability would indicate that the DRW E-350 is the most stable vehicle (i.e., it has the largest understeer gradient), followed by the SRW E-350, and lastly, the Taurus. The transient test maneuver is necessary to find out if this result will hold true in more realistic, non-steady state steering.

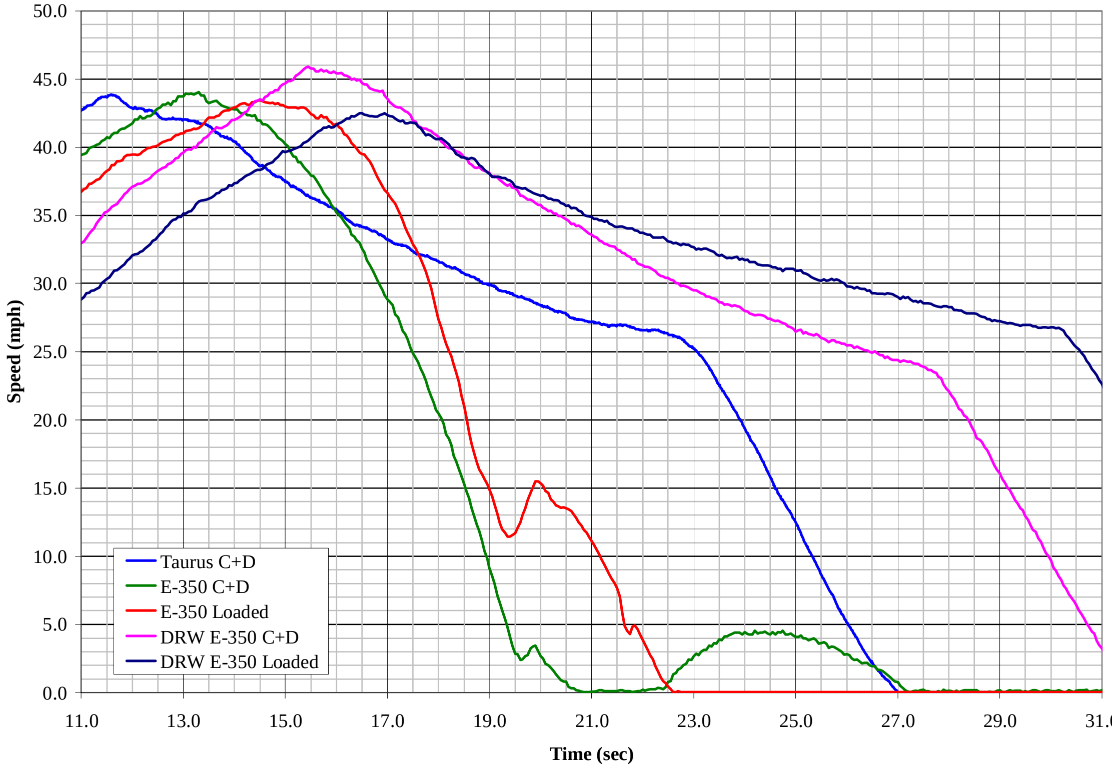

Figure 6. Test speed input for right step steer maneuvers

Transient Tests – Step Steer Turns

Figure 6 shows the test speed for each run. The target speed was 45 mph (72.4 kph). The data illustrate that the target speed was achieved within plus 0.3 mph (0.5 kph) and minus 3.0 mph (4.8 kph) at the time that the steering input was made for all runs. Four of the runs were within 1 mph (1.6 kph) of each other while the DRW E-350 in the curb-plus-driver configuration was at a slightly higher input speed, just above the target speed.

Figure 7 shows the steering wheel angle (SWA) input for each of the five runs. The target SWA was 180°. Analysis of these data indicates that the input for all of the five tests was within plus 1.0° and minus 9.0° for the duration of interest. Some of the runs experienced a brief SWA overshoot of 20° or less as the step steer approached the target value. The steering wheel angle was held for a minimum of five seconds. Two of the runs which resulted in vehicle spinout had a greater variance in the SWA as the violence of the spinout made it more difficult to hold the SWA constant.

The body slip angle was analyzed as the vehicle response to the input parameters discussed above. These data are presented in Figure 8. The body slip angle is calculated from the arctangent of the lateral velocity divided by the longitudinal velocity. These velocities were measured by the Datron sensor.

An initial peak is observed during the first second following steering wheel input in all of the plotted slip angle data. This peak is in the positive direction for the E-350 and in the negative direction for the Taurus. This peak is the result of the mounting location of the Datron velocity sensor. The mounting of the Datron instrument on the vehicle bumper introduces a small error based on its distance from the rotational center of the vehicle. When the instrument is mounted on the front bumper, the error will be in the positive direction for right-hand turns.

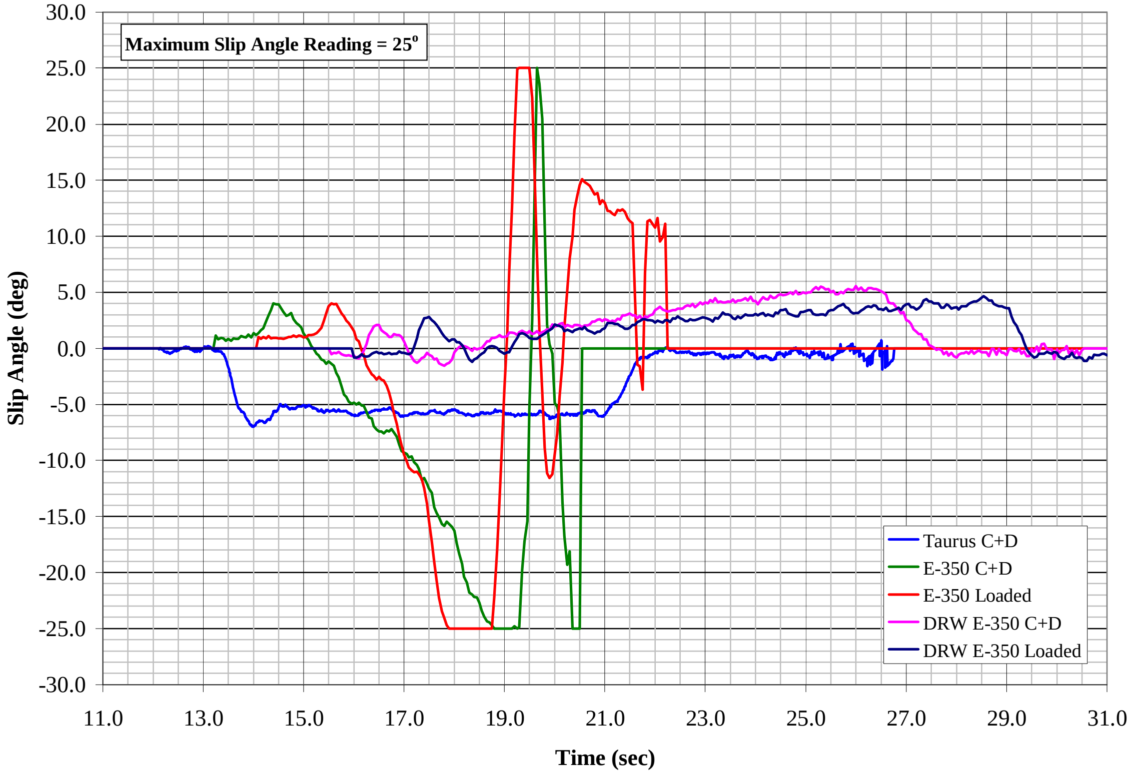

Figure 7. Steering wheel angle input for right step steer maneuvers.

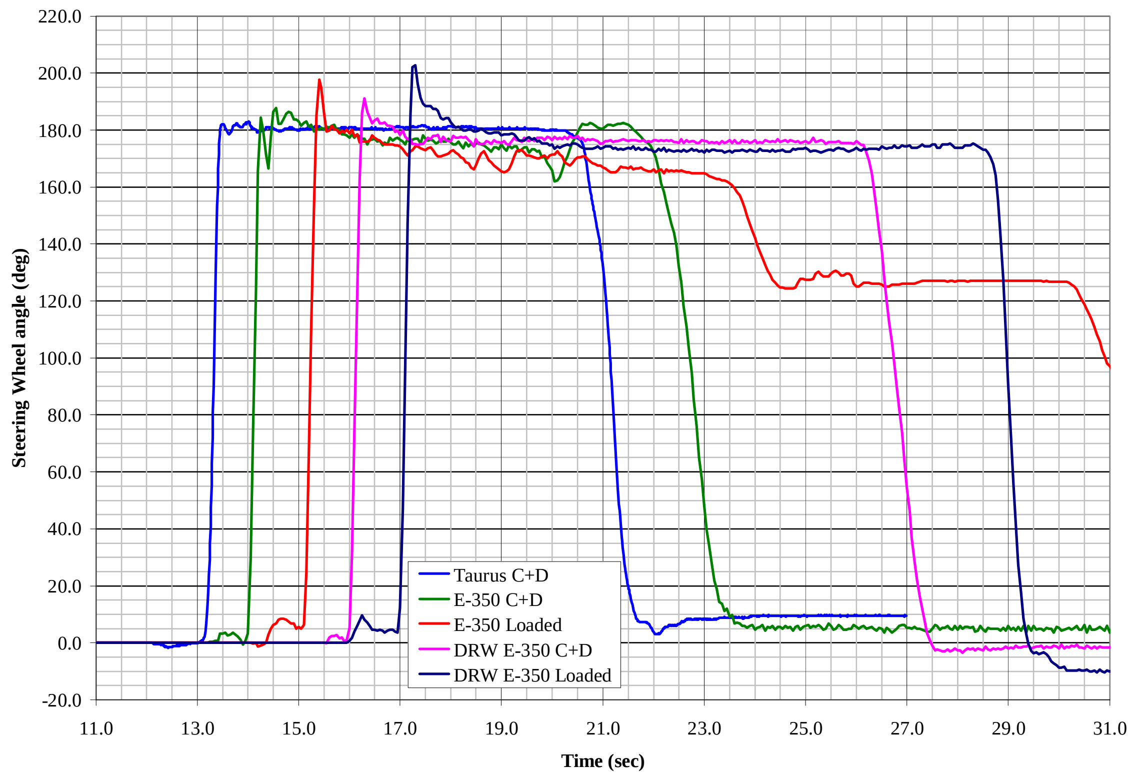

Figure 8. Slip angle response for right step steer maneuvers

This was the case for all of the E-350 tests. When the instrument is mounted on the rear bumper, the error will be in the negative direction for right-hand turns. This was the case for the Taurus tests.

Analysis of the slip angle data indicates that the Taurus and the DRW E-350 van maintain a vehicle slip angle of less than 5° throughout the duration of the maneuver. The test vehicles were observed to track throughout these maneuvers. The SRW E-350 van obtains measured body slip angles in excess of 25° in both the curb-plus-driver and loaded configurations. Examination of the video indicates that the test vehicle becomes yaw-unstable and spins out during these two runs. The spinout is evident in the slip angle data of Figure 8 as a sudden sign change which is a result of the vehicle experiencing a directional change in the lateral velocity

The SRW E-350 in the loaded configuration exceeds a 25° slip angle in approximately 2.8 seconds. The SRW E-350 in the curb-plus-driver configuration exceeds a 25° slip angle in approximately 4.8 seconds. While both results indicate that this vehicle has an undesirable response to the transient step steer maneuver, the response of the loaded van is worse. This result is opposite that demonstrated by the steady state constant radius tests in which the vehicle's handling appeared to improve when fully loaded compared to its handling in the curb-plus-driver loading configuration.

FINDINGS AND CONCLUSIONS

An unstable response to steady state or transient test maneuvers is undesirable. A vehicle that exhibits an unstable response to either type of test will be much more difficult (and perhaps even impossible) for a driver to control when faced with an emergency that requires an evasive steer maneuver. This can lead to a loss of control which in many instances results in a rollover event or other collision.

Steady state constant radius tests showed that the DRW E-350 had the greatest understeer gradient followed by the SRW E-350 and then the Taurus. Under transient testing, the Taurus and DRW E-350 exhibited a stable response to the step steer maneuvers, but the SRW E-350 experienced loss of control and spinout in both loading configurations. This result is much different than that predicted by the steady state analysis.

While suspension design can overcome some of the steady state yaw stability problems that are inherent in a vehicle with an aft weight-bias, there is no guarantee that this will resolve potential yaw stability problems during transient maneuvers. The SRW E-350 had an unstable response during the transient step steer tests which was not detected during the steady state testing. Further, the steady state tests alone would have suggested that the yaw stability of this vehicle improves with loading. This was proved to be incorrect by the transient test results.

It is critical to evaluate vehicles in both steady state and transient test maneuvers. The opposing results of constant radius tests and step steer tests performed on the SRW E-350 demonstrate that transient test maneuvers must be part of a vehicle's overall evaluation for directional stability.

REFERENCES

SAE J266, "Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks," SAE Surface Vehicle Recommended Practice, 1996.

Gillespie, T.D., "Fundamentals of Vehicle Dynamics," Published by Society of Automotive Engineers, Warrendale, PA, 1992.