QUANTITIVE MEASURE OF TRANSIENT OVERSTEER OF ROAD VEHICLES

David A. Renfroe
Paul T. Semones
Alex Roberts
Engineering Institute, LLC.
United States
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ABSTRACT

When discussing oversteer of a vehicle, reference is made to results of the SAE J266 circle test or gradually increasing steer test. However, these tests demonstrate the vehicle's characteristics at a quasi-static condition and do not consider the dynamic effects of the moment of inertia of the vehicle or of the wheelbase and tire characteristics during yaw accelerations occurring in transient maneuvers. Frequently, there are discussions of the transitional effects on oversteering of the vehicle and reference may be made to the radius of gyration squared versus the product of the front and rear distances from the axles to the CG. This particular relationship, however, assumes that the tire lateral capabilities on the front and the rear are the same. This paper will discuss the comparison of the "Ackermann yaw rate" versus the measured yaw rate in transient steer maneuvers such as the step steer. The Ackermann yaw rate will be the yaw rate developed if the vehicle were to track exactly along the direction that the wheels are pointing. If this theoretical yaw rate is compared to the measured yaw rate, a vehicle's transitional handling characteristics can be quantified. An example where there has been considerable discussion is with the 15-passenger van. Loss of control of these vans, attributed to oversteer when attempting an accident avoidance maneuver, has been discussed extensively by government and private groups. That oversteer occurs even though these vans exhibit understeering characteristics when tested with the J266 protocol up to a transition to oversteer at the vehicle's lateral adhesion limit. The technique described here allows the transitional oversteer characteristic of any vehicle to be quantified. This will help to explain and quantify the characteristic causing loss of control of these vans and other similar vehicles.

INTRODUCTION

Recent discussion concerning 15-passenger vans states that these vehicles are oversteer at higher lateral accelerations [NHTSA, 2004]. However, testing of a 15-passenger van, using the SAE J266 circle test, illustrates that these vehicles are definitely understeer up to the limit of lateral acceleration where they transition to oversteer (see *Figure 1*).

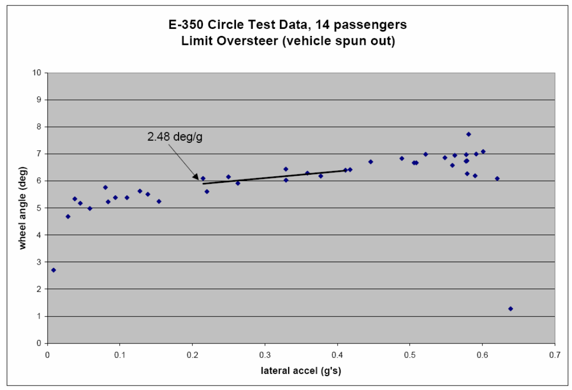

Figure 1. Steer angle versus lateral acceleration for Ford E-350.

Nevertheless, it continues to be asserted that these vehicles are oversteer, and in defense of this claim, driving a fully loaded van certainly feels unstable and there is a tendency to wander on some models. The reason that a 15-passenger van does not oversteer in this quasi-static circle test is that the moment of inertia of the cargo box is not affecting handling during that maneuver, since there is very little or no angular acceleration during the maneuver. Even though the center of gravity moves rearward as the load of the van increases, the force on the rear tires also increases which will increase their lateral load handling capacity. Also, with the large rear overhang, as the load moves beyond the rear axle the front axle actually begins to unload. This would tend to cause the front end to drift out in the circle test, causing classic understeer.

However, during the transitional phase of a turn, the vehicle has a yaw acceleration. Once the yaw rate approaches the Ackermann yaw rate as defined by the steering angle, velocity, and wheel base (see *Equation 1*), the angular inertia of the vehicle tends to cause the vehicle to overshoot the Ackermann yaw rate. This overshoot is what is felt by the driver and is in fact an instability.

In an attempt to quantify this instability as a form of oversteer, measured yaw rate will be compared to an ideal yaw rate or "Ackermann yaw rate." The Ackermann yaw rate (AYR) is the theoretical ideal. This would be the yaw rate that would occur with no lateral slip in the tire. The AYR would be strictly a function of the wheel base (W), steering angle (A), and velocity (V).

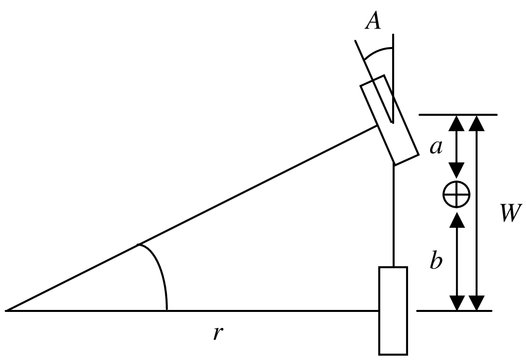

Figure 2. The bicycle model in a constant radius turn.

The resulting function would be:

$$AYR = \frac{V \cdot \tan(A)}{W} \qquad (1.)$$

The actual (i.e., measured) yaw rate can then be compared to this AYR to quantify the transitional oversteer or understeer of the vehicle by observing the undershoot or overshoot of the measured yaw rate to the AYR. Since most maneuvers are conducted with a dropped throttle resulting in a decreasing velocity during the maneuver, the AYR can be calculated and plotted over time with respect to the measured velocity of the vehicle. Such a comparison of the theoretical to the actual yaw rates has been discussed previously by Ellis [Ellis, p. 162, 1969] and Blundell [Blundell, p. 411, 2004]. When discussing the comparison of the ideal path and the actual path a car takes including any transient effects, Ellis states, "The actual path will not be coincident with the ideal path due to the finite response times of the car, but the divergence can be measured as a lateral displacement or path error and a difference in heading angles, the course error." Blundell calls the Ackermann yaw rate the idealized or geometric yaw rate and provides his definition of understeer as the geometric yaw rate divided by the actual yaw rate. When this quotient is less than 1 the vehicle is oversteering. Stonex described the same method of observing transient understeer and oversteer in his paper published in 1940 [Stonex, 1940]. Using these definitions the handling characteristic of vehicles will be investigated for the transient reaction of a maneuver to determine what is occurring with the vehicle versus what a driver may be feeling. Generally, the characteristic that will contribute to a transient oversteer will be the yaw radius of gyration versus the wheel base. Dixon quantifies this relationship as

$$ab < k^2 \qquad (2.)$$

where *a* is the distance from the center of gravity (CG) to the front wheels, *b* is the distance to the rear wheels from the CG, and *k* is the radius of gyration about the z axis [Dixon, p 469]. He says, "If $ab<k^2$, it [the rear slip angle] will initially develop in the wrong direction and will undergo a reversal before reaching steady state." The results of this testing will illustrate this effect. To correct for this problem Dixon states that moving the wheels out to the corners increases the *ab* of the vehicle and therefore the vehicle becomes more agile. Similar observations were made in the 1930's by Olley and reported in a 1962 monograph published at General Motors, then published for the public in 2002 [Milliken, p. 250, 2002]. He said, "What is clear is that, for positive ['good' or 'desirable'] handling – without 'faking' the geometry by exaggerated roll understeer at the rear tires – it is essential to have an adequate wheelbase, and that this should give a k^2/ab ratio considerably less than 1.0."

Another way of reducing the transient oversteer of the vehicle is to increase the lateral stiffness of the rear tires. In the case of the 15-passenger van, this can be done by installing dual tires. These effects will also be illustrated.

TRANSIENT OVERSTEER IN J-TURN MANEUVERS

A J-Turn is a standard maneuver used to test for the transient response of a vehicle to a step input. For any dynamic system, the response to a step input is observed by measuring the rate that the system approaches the steady state condition. In this case, that steady state condition is defined by the steering angle of the front wheels. Response time and overshoot are typical observations for dynamic systems. One can describe a system by the length of time it takes for the response to approach the steady state, the magnitude of the overshoot or the number of oscillations around the prescribed steady state condition of the new trim of the system. *Figure 3* illustrates a typical underdamped dynamic system with significant overshoot.

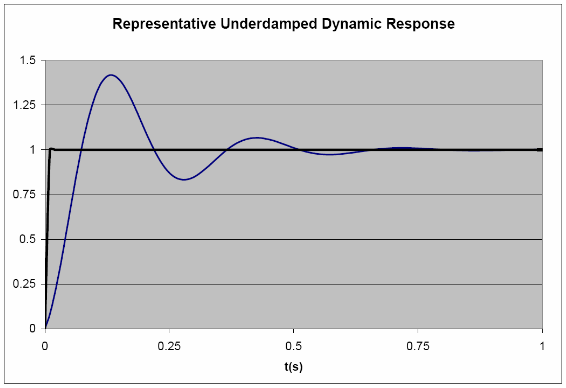

Figure 3. Typical dynamic response to a step input.

However, in a standard J-Turn the response will not be an approach to a horizontal line on a graph. Yaw rate versus time during a typical sub-limit (low speed) J-Turn would step up to the AYR determined by the steering angle, wheel base and velocity, then decrease with time as the velocity decreases as shown in *Figure 4.*

In a standard 35 mph J-Turn test with 300 degrees of steering input, the steering input graph will appear as shown in *Figure 5.* For the particular case shown, a J-Turn test utilizing a 2001 Ford E-350 15-passenger van, the yaw rate response is shown in *Figure 6.*

Upon gross comparison of the two curves, the vehicle's yaw rate response actually appears to undershoot the expected steady-state response to a typical step input. However, in the above case, velocity falls off to zero after four seconds because the J-Turn test protocol involves a sudden reduction of accelerator input to zero simultaneously with the steering input. Thus, the vehicle coasts to a near stop (and approximately zero measurable yaw rate) a few seconds after the steering is applied.

When this linear deceleration throughout the J-Turn maneuver is accounted for, it becomes clear that the yaw rate response in the particular case shown at right is in fact a transient overshoot of the ideal yaw rate expected from the twin step inputs of steering and accelerator release. For, while the steering is a classic step input, the ideal yaw rate will actually be a declining curve as velocity bleeds off to zero.

Oversteer is evident after about 2.7 seconds in *Figure 7*, as the measured yaw rate exceeds the ideal yaw rate expected from the steering input and deceleration. It could be argued that the vehicle is always transiently oversteering in this case if the slope of the Ackermann yaw rate versus time is compared to the converging slope of measured yaw rate versus time.

In this particular case, there was no tipping or significant loss of contact between tires and the ground as the vehicle oversteered.

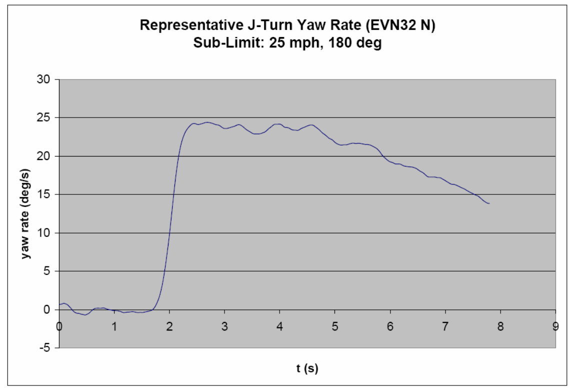

Figure 4. Measured yaw rate versus time in a low-speed J-Turn.

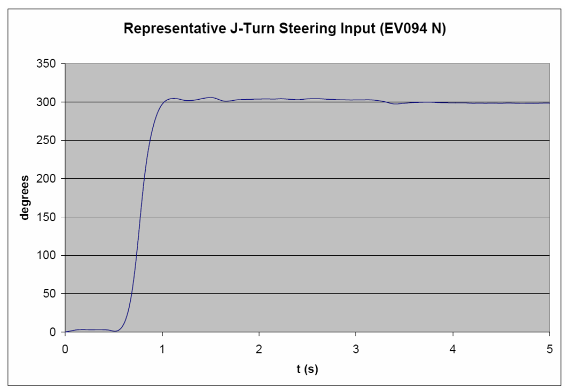

Figure 5. Representative J-Turn Steering Input.

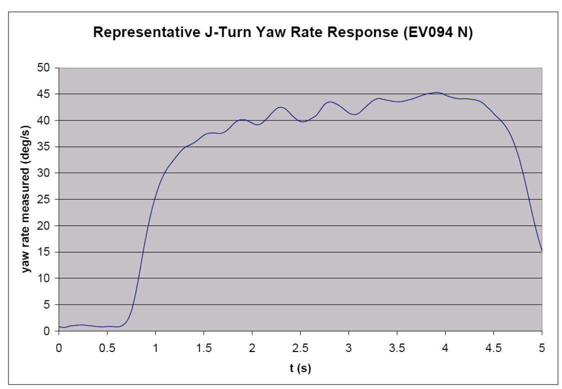

Figure 6. Typical yaw response observed with a loaded 15-passenger van.

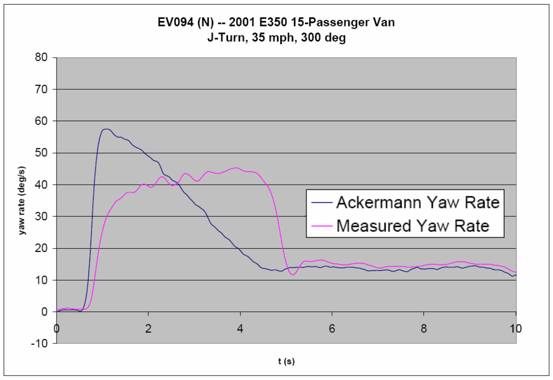

Figure 7. AYR versus Actual yaw rate. (Data from same test as shown in *Figures 5* and *6*.)

TRANSIENT OVERSTEER IN RAPID REVERSAL MANEUVERS

Transient oversteer behavior was analyzed in several rapid reversal steering tests conducted with Ford E-350 15-passenger vans. All tests were conducted featuring initial left turns followed rapidly by right steering inputs, and frame-by-frame video analysis was conducted to match vehicle behavior (such as incidence of wheel lift or outrigger contact) with recorded data to determine whether vehicle events were occurring during phases of oversteer or understeer, as plotted from the collected data.

Testing illustrated in *Figure 8* was conducted with an initial velocity of approximately 33 mph and exhibited oversteer in both the left and right steering phases. In the right steer (the second steering phase of the test), the right front wheel lifted off the ground, which would normally cause understeer. However, the van began to oversteer during the first instance of wheel lift.

The test illustrated in *Figure 9* was conducted with an initial velocity of approximately 39 mph and exhibited oversteer in both the left and right steering phases. In the latter phase, the vehicle tipped over and loaded the outriggers. However, the onset of oversteer occurred before wheel lift. Note how the higher speed causes greater transient oversteer.

Testing on a 1997 E-350, illustrated in *Figure 10*, was conducted with an initial velocity of approximately 35 mph and exhibited oversteer in the initial steering phase. In the latter phase, oversteer was also observed after the vehicle had tipped over and loaded the outriggers. (Velocity data was lost after approximately 5 seconds, and thus the Ackerman yaw rate is not shown beyond that point in *Figure 10*.)

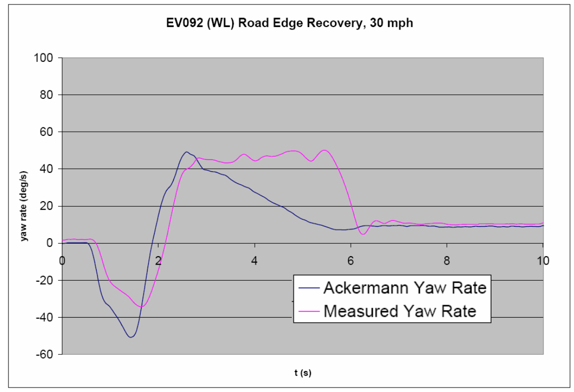

Figure 8. Test 1 – NHTSA Fishhook at 33 MPH.

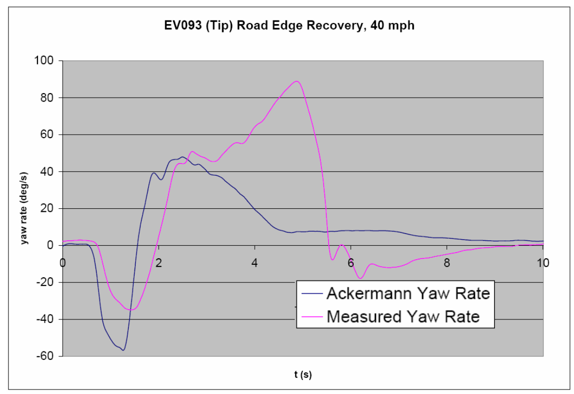

Figure 9. Test 2 – NHTSA Fishhook at 39 MPH.

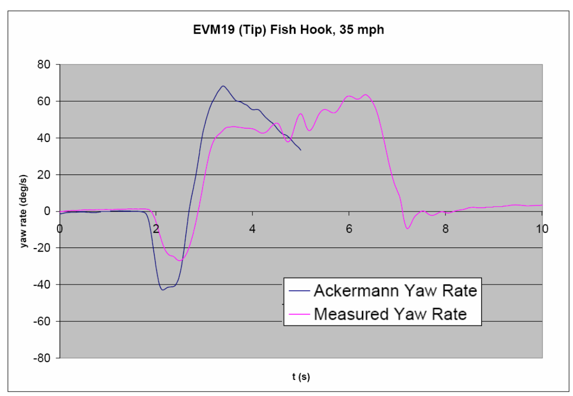

Figure 10. Test 3 – NHTSA Fishhook at 35 MPH. (Velocity data was lost after ~5 s.)

In comparing the three tests, a trend was observed in the relationship between the duration of initial phase oversteer and when the onset of oversteer occurred in the second phase after steering reversal. For the test with the briefest oversteer in the initial left turn, Test 3 (*Figure 10*), oversteer in the second phase did not occur until after the vehicle had already tipped over onto the outriggers and committed to rolling over.

The test with the next longest initial oversteer, Test 1 (*Figure 8*), oversteer in the second phase began earlier, during the first lift of the right front wheel. The test with the longest initial oversteer of the three, Test 2 (*Figure 9*), saw onset of oversteer in the second phase soonest of the three tests, oversteering before any wheel lift had occurred, and the vehicle ultimately tipped over onto its outriggers and committed to roll.

In summary, the trend observed in these three tests showed that the longer the period of initial oversteer, the earlier oversteer would occur in the reverse steer phase. Further frame-by-frame video analysis of available test data would have to be conducted to confirm the general validity of this trend.

EFFECT OF INCREASING LATERAL STIFFNESS OF THE REAR AXLE ON TRANSIENT OVERSTEER

Oversteer/understeer behavior was analyzed on two Fishhook tests conducted with a 1995 Ford E-350 15-passenger van, both before and after the installation of dual wheels on the rear axle to increase the lateral stiffness. Both tests were conducted on the same day with the same vehicle. The first test (see *Figure 11*) was conducted with an initial velocity of approximately 35 mph and involved right-then-left steering inputs. The vehicle exhibited transient oversteer in the initial turn, then in the second turn began to transiently oversteer, lifted the inside wheels and rolled onto the outriggers.

After installation of dual wheels on the rear axle of the test vehicle, a second test (see *Figure 12*) was conducted with an initial velocity of approximately 40 mph, and followed the same Fishhook maneuver as the first test. The vehicle exhibited brief oversteer in the initial turn, but remained well within the understeer range throughout the second phase of the maneuver. The right front wheel lifted off the pavement at least twice during the second phase.

The video frame captures provided in *Figures 11* and *12* represent approximately identical locations on the test track, and demonstrate the significant difference in vehicle behavior before and after installation of dual wheels on the rear axle. The video frame shown of the dual-equipped van in *Figure 12* captures the instant of maximum wheel lift visible in the test, and additional video analysis showed no evidence that the

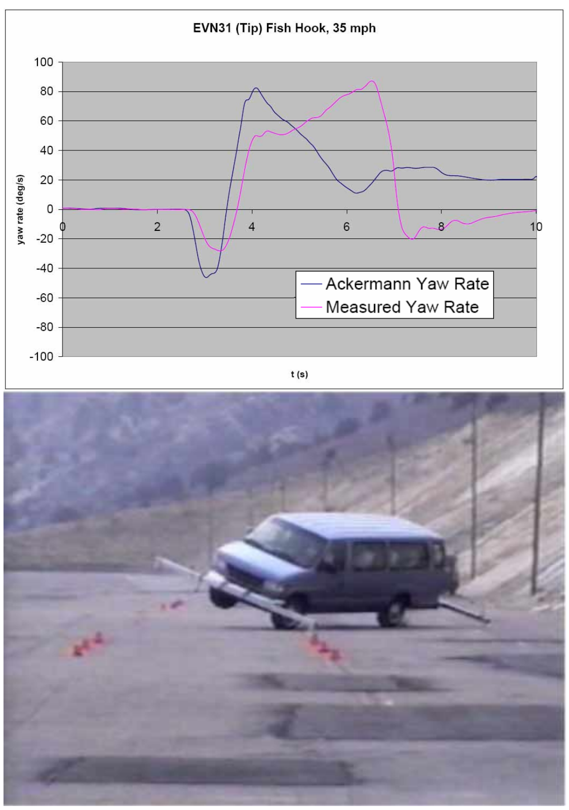

Figure 11. Test 4 – NHTSA Fishhook with unmodified vehicle and single rear wheels.

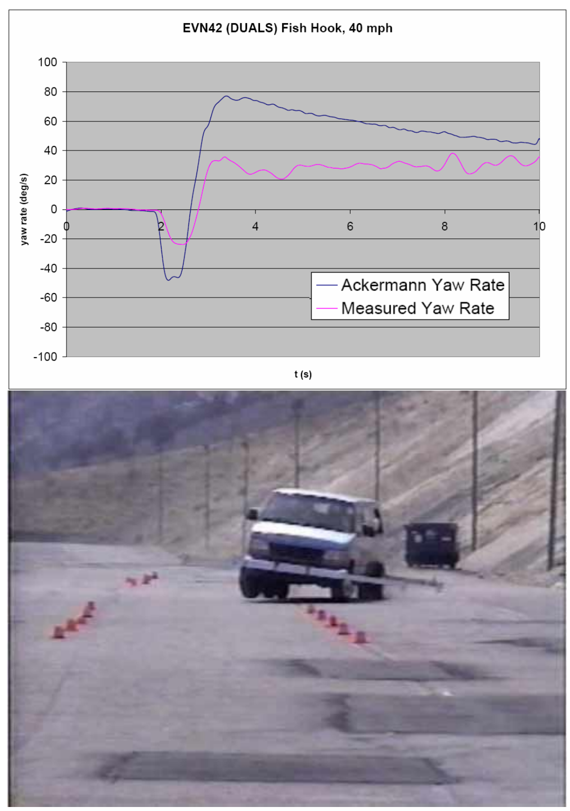

Figure 12. Test 5 – NHTSA Fishhook after installation of dual rear wheels.

right rear tires ever lost contact with the pavement. While the frame provided here appears to show open space between the right rear outer tire and the pavement, frames examined 1/25th of a second before and after the provided frame show the tires apparently in full contact with the pavement.

EFFECT OF FULL LOAD VERSUS LIGHT LOAD

As reported by NHTSA [NHTSA, 2001], the center of gravity of a fully loaded 15-passenger van moves several inches rearward and upward when compared with a lightly loaded (e.g., driver only) condition. The fact that a full load of passengers increases the van's propensity to roll over was demonstrated with two 1995 Ford E-350 15-passenger vans in 40 mph Fishhook Maneuvers. Quasi-static understeer/oversteer characteristics are still shown to be understeer with oversteer at the limit even for the fully loaded van as was shown in *Figure 1*. Here it will be shown the effect of loading the van on the transient oversteer characteristics.

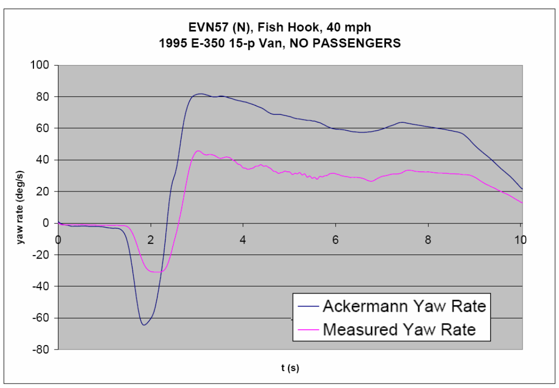

Figure 13. Test 6 – NHTSA Fishhook with vehicle at light loading condition.

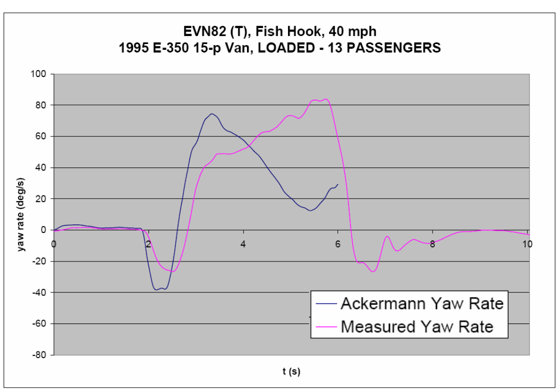

Figure 14. Test 7 – NHTSA Fishhook with full ballast loading. (Velocity data lost after ~6 s.)

In the Fishhook test conducted without passengers, the steering inputs were approximately 270° and 360°, and neither wheel lift nor transient oversteer occurred (see *Figure 13*). In the Fishhook test conducted at this speed and fully loaded with ballast in all passenger positions, the result was tipover and rapid transition to oversteer in a maneuver with steering inputs of approximately 180° and 360° (see *Figure 14*).

A PROPOSAL FOR QUANTIFYING THE TRANSIENT OVERSTEER CHARACTERISTIC

With transient oversteer characteristics now demonstrated as being observable in terms of traditional dynamic system response, a metric for quantifying the magnitude of the characteristic will now be proposed. Over a set of ten tests of Ford E-350 15-passenger vans, the metric shows good correlation to a range of desirable and undesirable vehicle responses.

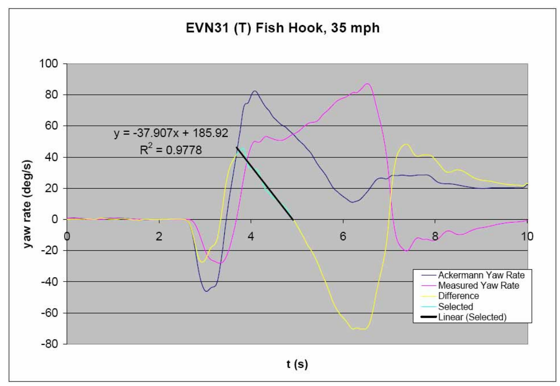

Figure 15. Test 4 (see Figure 11) with transient oversteer metric applied.

The metric is developed by plotting the difference between Ackermann and measured yaw rates. This difference is shown as the yellow plot in *Figures 15-17*. A portion of the difference plot is selected for examination (highlighted in bright blue in the figures) and a linear curve fit applied. As will be explained below, the slope of the examined portion is taken as a transient oversteer metric due to its physical relevancy to vehicle behavior.

In cases of rapid reversal steering maneuvers such as the Fishhook or Road Edge Recovery tests, the examined portion of the difference plot is bounded by two clearly defined points. (See *Figure 15* above.) The first is the point at which the measured yaw rate crosses zero at the start of the second half of the steering maneuver, or equivalently, the point at which the difference plot equals the Ackermann yaw rate. The second point is defined as the location where the difference curve equals zero, or equivalently, the point at which the Ackermann and measured yaw rate plots intersect (if, indeed, they do).

(For some maneuvers, such as the single J-Turn test evaluated, the first point of interest was simply identified as the peak of the difference curve, since it had no clear intersection with the Ackermann curve. This method is shown in *Figure 16*. For other maneuvers, the second point of interest was identified as the minimum of the difference curve, since it never reached zero, and this method is shown in *Figure 17*.)

In purely theoretical terms, the intersection of the two yaw rate lines represents the switch from theoretical understeer to theoretical oversteer, although it should be noted that the transient oversteer characteristic of the actual vehicle behavior is intrinsic to the entire dynamic response portion of the curve. But in the sense that the difference plot represents the actual vehicle's deviation from the theoretical ideal, the metric proposed here evaluates that portion of the curve that is "understeer": that is, the portion over which the measured yaw rate is less than the Ackermann yaw rate. It is the rate at which this measured yaw rate approaches (and often overshoots) the Ackermann yaw rate that is the fundamental characteristic quantified by this proposed metric.

In a mathematical sense, the slope of the examined portion of the difference curve has units of angular acceleration (deg/s^2), and corresponds to the physical rate of change of the vehicle's yaw angular velocity. Its significance to transient oversteer characteristics and undesirable vehicle responses, such as tipping over, is that it allows transient oversteer to be described as the rate at which a vehicle's yaw response overtakes the declining ideal yaw rate in dropped-throttle, limit steering maneuvers.

In the ten examined E-350 van tests, a high absolute value for the metric (i.e., a steep slope to the examined portion of the difference curve) correlated well to high oversteer and/or rollover to outrigger contact. A low absolute value for the metric (i.e. a shallow slope) correlated to successful tests in which all four of the vehicle's tires remained in contact with the ground.

The values of this transient oversteer metric computed for the ten tests are presented in *Table 1* on the following page. Absolute values ranged from 2.8 to 55.0. All three tests with metrics of 4.9 or less resulted in no wheel lift. All seven remaining tests had metrics of 7.5 or greater, and all but two of those resulted in tipping over. One of the two exceptions resulted in single wheel lift only, and that run had the lowest tested speed (30 mph) of the set. The other exception was the sole J-Turn examined, which did not result in wheel lift, but did result in significant oversteer.

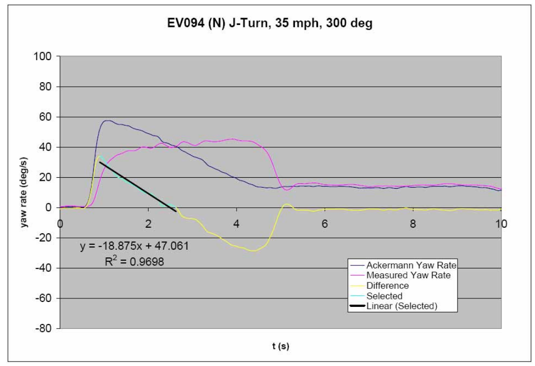

Figure 16. J-Turn test (see Figure 7) with transient oversteer metric applied.

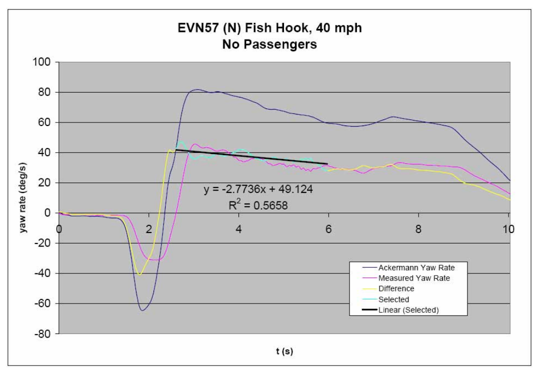

Figure 17. Test 6 (see Figure 13) with transient oversteer metric applied.

The metric correlates well to the loading conditions of the 15-passenger vans tested, confirming the relationship between unsafe vehicle responses and a full load of passengers. Three of the four tests with the lowest metric were those tests with the lowest loading condition – either driver/instruments only or ballast loading short of the full 15-passenger complement. The remaining test was fully loaded but had the modification of dual wheels installed on the back axle, dramatically improving its rollover resistance and minimizing any transient oversteer.

The transient oversteer metric could be only weakly correlated to test speed or maneuver type, but does suggest that a 15-passenger van's loading condition is a greater influence on rollover propensity than the speed of an emergency steering maneuver.

The results suggest that a metric value between 4.9 and 7.5 represents the boundary between desirable and undesirable vehicle handling response. This value boundary may be particular to the 15-passenger van, whereas other vehicles may have different values for acceptable performance.

CONCLUSION

A simple method for the quantification of transient oversteer has been illustrated. By comparing the theoretical or Ackermann yaw rate to the actual measured yaw rate, the overshoot of a step input or a series of inputs can be analyzed. As has been shown here, when the yaw moment of inertia increases, so does the transient oversteer. As the yaw momentum increases due to vehicle velocity, so does the yaw overshoot. Control of the yaw overshoot to the steering input can be gained by increasing the lateral stiffness of the rear tires as has been predicted in the previous literature. This tool will allow the analysis of testing results to quantify what may have heretofore been heuristic results reported by the drivers of the vehicle and reported as merely a subjective score.

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Table 1.
Transient oversteer metrics for a suite of 10 steering tests on late model Ford E-350 15-passenger vans.

Test Name	Maneuver	Loading	Speed	Result	Transient Oversteer Metric*
EV093	Road Edge Recovery	Ballast in all positions	40 mph	Tipped	**55.0**
EVN31	Fish Hook	Ballast in all positions	35 mph	Tipped	**37.9**
EV092	Road Edge Recovery	Ballast in all positions	30 mph	Wheel Lift	**31.1**
EVN82	Fish Hook	Ballast in all positions	40 mph	Tipped	**27.7**
EV094	J-Turn	Ballast in all positions	35 mph	(No Lift)	**18.9**
EVM19	Fish Hook	Ballast in all positions	35 mph	Tipped	**17.6**
EVN60	Fish Hook	Ballast in 12 positions	35 mph	Tipped	**7.5**
EVN42	Fish Hook	Ballast in all, DUALS	40 mph	(No Lift)	**4.9**
EVN56	Fish Hook	Driver only	35 mph	(No Lift)	**3.9**
EVN57	Fish Hook	Driver only	40 mph	(No Lift)	**2.8**

*Given in absolute values.
Actual computations result in negative quantities.