LIGHT VEHICLE ESC PERFORMANCE TEST DEVELOPMENT

Garrick J. Forkenbrock
Patrick L. Boyd
NHTSA
United States
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ABSTRACT

On September 18, 2006 the National Highway Traffic Safety Administration (NHTSA) announced a proposal that would require installation of electronic stability control (ESC) as standard equipment on all light vehicles by model year 2012 [1]. The decision to mandate ESC required that NHTSA develop an ESC compliance test and evaluation criteria. This paper describes the proposed test maneuver and discusses the methods proposed to interpret the data generated by that maneuver.

NHTSA's ESC proposed compliance test maneuver, the Sine with Dwell, was used to produce all the data described in this paper. This maneuver is based on a single cycle, 0.7 Hz steering input, with a 500 ms pause between the third and fourth quarter cycles. Output from Sine with Dwell tests is used to evaluate both the lateral stability and responsiveness of ESC-equipped light vehicles.

NHTSA proposes acceptable lateral stability be assessed with two performance criteria, intended to encourage yaw rate to decay in a controlled manner. These criteria compare the yaw rates measured 1.0 and 1.75 seconds after completion of the maneuver's steering inputs to the first local yaw rate peak produced after the second steering reversal. These "yaw rate ratios" must be less than or equal to 35 and 20 percent, respectively.

To ensure that a balance between lateral stability and the ability of the vehicle to effectively respond to the driver's inputs is maintained, NHTSA has proposed a responsiveness metric supplement that used to assess lateral stability. The proposed metric is based on vehicle lateral displacement calculated 1.07 seconds after initiation of the maneuver's steering inputs.

INTRODUCTION

As part of a comprehensive plan for reducing the serious risk of rollover crashes and the risk of death and serious injury in those crashes, NHTSA has proposed a new Federal motor vehicle safety standard (FMVSS). FMVSS No. 126, Electronic Stability Control Systems, would require ESC systems on passenger cars, multipurpose passenger vehicles, trucks and buses with a gross vehicle weight rating of 4,536 Kg (10,000 pounds) or less [1].

Preventing single-vehicle loss-of-control crashes is the most effective way to reduce deaths resulting from rollover crashes. This is because most loss-of-control crashes culminate in the vehicle leaving the roadway, which dramatically increases the probability of a rollover. Based on the best available data drawn from crash data studies, NHTSA estimates that the installation of ESC will reduce single-vehicle crashes of passenger cars by 34 percent and single vehicle crashes of sport utility vehicles (SUVs) by 59 percent, with a much greater reduction of rollover crashes. NHTSA estimates that ESC has the potential to prevent 71 percent of the passenger car rollovers and 84 percent of the SUV rollovers that would otherwise occur in single-vehicle crashes.

NHTSA estimates ESC will save 5,300 to 9,600 lives and prevent 156,000 to 238,000 injuries in all types of crashes annually once all light vehicles on the road are so equipped. The Agency further anticipates that ESC could substantially reduce the more than 10,000 deaths each year on American roads resulting from rollover crashes (by 4,200 to 5,500).

Manufacturers equipped about 29 percent of model year (MY) 2006 light vehicles sold in the U.S. with ESC, and intend to increase the percentage to 71 percent by MY 2011. As proposed, FMVSS No. 126 requires installation of ESC in 100 percent of light vehicles by MY 2012 (with exceptions for some vehicles manufactured in stages or by small volume manufacturers).

SINE WITH DWELL TEST MANEUVER

All tests described in this paper were performed with a test maneuver known as the 0.7 Hz Sine with Dwell maneuver (referred to as simply the "Sine with

Dwell" for the remainder of this paper). Considerable effort was used to select this maneuver from a comprehensive group of twelve other candidates. However, for the sake of brevity this paper will only discuss details pertaining to the Sine with Dwell. A detailed discussion of the maneuver selection process is available in [2,3].

As the name implies, the Sine with Dwell maneuver is based on a sinusoidal steering input. Specifically, a single cycle input is performed at a frequency of 0.7 Hz, with a 500 ms pause between completion of the third quarter cycle and initiation of the fourth quarter cycle, as shown in Figure 1.

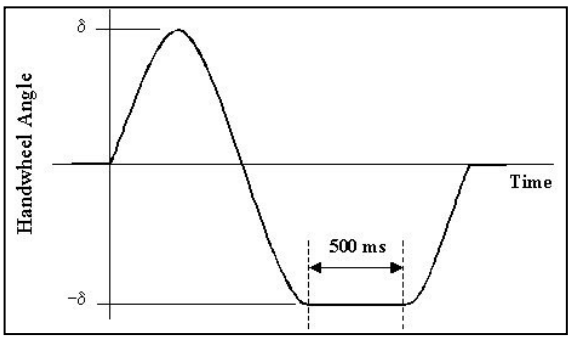

Figure 1. Sine with Dwell steering profile.

To begin the maneuver, the driver accelerates the vehicle to a speed of approximately 52 mph, at which point the throttle is released and a programmable steering controller is engaged. Once the vehicle has coasted down to a speed of 50 mph, the steering machine automatically executes the steering wheel angle profile previously shown in Figure 1.

Since the maneuver entrance speed is always 50 mph, increasing the magnitude of the steering wheel angles is used to increase maneuver severity. This is accomplished by multiplying the steering wheel angle capable of producing a lateral acceleration of 0.3g during Slowly Increasing Steer testing ($\delta_{0.3g}$) by a series of scalars [4]. The steering wheel angles nominally begin at $1.5*\delta_{0.3g}$, and are increased in increments of $0.5*\delta_{0.3g}$ until a termination criterion has been satisfied. For the data discussed in this paper, four termination conditions were used:

- The final heading angle of the vehicle, measured four seconds after completion of the Sine with Dwell steering input, was 135 degrees or more.

- A steering wheel angle of $6.5*\delta_{0.3g}$ or 270 degrees is used (whichever was greater) without the final heading angle of the vehicle reaching 135 degrees.

- Simultaneous wheel lift of the inside front and rear tires ≥2.0 inches occurred during any test.

- Rim-to-pavement contact and/or tire debeading occurred during any test.

Note: these conditions differ slightly from those actually proposed for FMVSS No. 126 as they were used for maneuver development purposes.

Sine with Dwell tests are performed with left-right and right-left steering. To produce the data featured in this paper, tests were performed with ESC fully enabled, then fully disabled on the same tire set. Additionally, if a vehicle offered an additional driver-specified ESC setting, it was evaluated with a second tire set. The proposed FMVSS No. 126 would only require Sine with Dwell tests be performed with ESC fully enabled.

LATERAL STABILITY

NHTSA believes a vehicle equipped with an effective ESC system should not spinout during any Sine with Dwell test performed with the system fully enabled. Unfortunately, while the term "spinout" is easy for most people to visualize, it is a somewhat ambiguous description of an excessive oversteer event. Therefore, before a means of quantifying lateral stability could be identified (i.e., for use in a compliance test), an objective definition of what NHTSA means by "excessive oversteer" needed to be determined.

Note that ESC systems are designed to mitigate excessive over- *and* understeer. However, the Sine with Dwell maneuver and performance criteria described in this paper were specifically developed to facilitate the evaluation of excessive oversteer only. NHTSA is presently performing ESC understeer mitigation research; however results from these tests are not yet available.

Definition of an Excessive Oversteer Model

To quantify excessive oversteer, the output of a logistic regression model, based on the SAS Genmod procedure, was used. Specifically, this model describes how well the percent of the vehicle's second peak yaw rate (subsequently referred to as the

yaw rate ratio, or "YRR"), measured at different time intervals occurring after completion of the maneuver's steering inputs would predict the trial outcome, represented by a binary response variable. In the case of the excessive oversteer model, the binary variable was taken to be whether the heading angle of the vehicle, measured four seconds after completion of the maneuver's steering inputs, was greater than or equal to 90 degrees from the initial path; yes or no. Separate analyses were performed for fifteen different instants in time, beginning at the instant the maneuver's steering inputs were complete (t_0), and continuing in 250 ms increments from t_0 to t_0 + 4 seconds. These instants are referred to as the times after completion of steer, or COS.

Figure 2 summarizes the ability of a particular YRR and time after completion of steer (subsequently referred to as "YRR and COS combination" for brevity) to predict if the vehicle would be expected to satisfy NHTSA's definition of spinout. The color of each cell describes the confidence intervals associated with each YRR and COS combination.

A dark green cell indicates a model using that cell's particular YRR and COS combination is 95 percent confident the vehicle will not achieve a final heading angle greater than 90 degrees. For these cells, the Chi-Squared probability statistic is less than 0.05, and both confidence interval boundaries are lower than the 95th percentile confidence level (i.e., excessive oversteer is predicted less than 5 percent of the time).

The light green region indicates it is unlikely that the vehicle will exhibit excessive oversteer. For these cells, the Chi-Squared probability statistic is less than 0.05, but at least one of the confidence interval boundaries are outside of the 95th percentile confidence level.

The yellow cells represent regions of uncertainty, where the Chi-Squared probability statistic is greater than 0.05, and the confidence interval boundaries are both less than and greater than 50 percent. This implies the model cannot predict whether the vehicle will exhibit excessive oversteer or not.

The pink cells indicate if the vehicle will likely exhibit excessive oversteer. For these cells, the Chi-Squared probability statistic is less than 0.05, but at least one of the confidence interval boundaries are outside of the 95th percentile confidence level. From a statistics stand point, the pink regions are conceptually equivalent to the light green regions, however the physical meaning is different.

Finally, a red cell indicates a model using that cell's particular YRR and COS combination is 95 percent confident the vehicle will exhibit excessive oversteer. For these cells, the Chi-Squared probability statistic is less than 0.05, and both confidence interval boundaries are greater than the 95th percentile confidence level.

Application of Excessive Oversteer Model Output

The primary reason for developing a metric to evaluate lateral stability was to provide the Agency with a means of objectively ascertaining whether a vehicle's ESC is capable of mitigating excessive

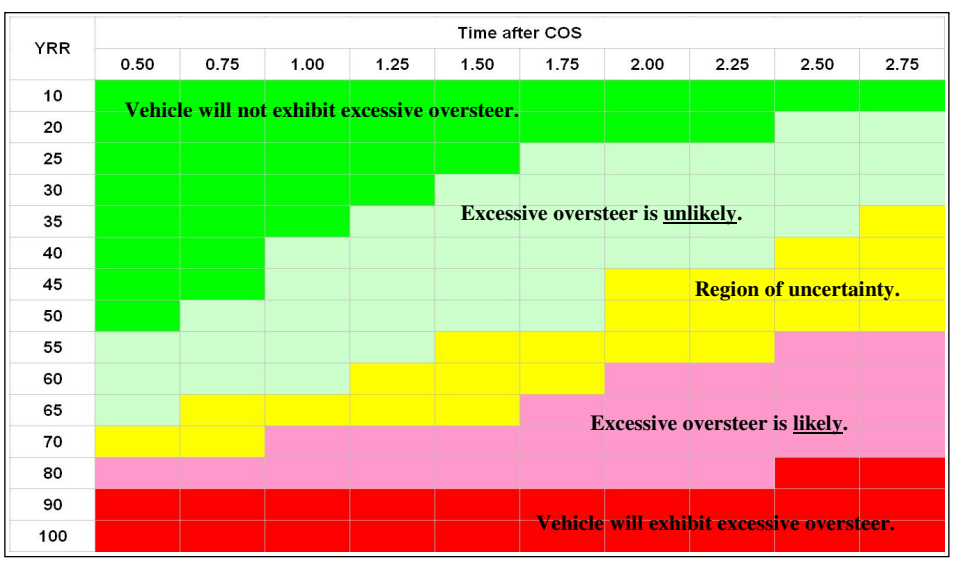

Figure 2. YRR confidence interval based spinout predictions.

oversteer. Therefore, the data contained in Figure 2 provided a valuable way to define lateral stability thresholds. Since the YRR and COS combinations shown in the dark green cells indicate the likelihood of a vehicle exhibiting excessive oversteer is less than five percent, and that the light green cells indicate the likelihood of exhibiting excessive oversteer is greater than five percent but less than 50 percent, NHTSA researchers decided the dark green YRR and COS combinations that define boundary between the dark and light green regions provided the best combination of prediction certainty and meaningfulness[1].

To assess how each YRR and COS combination defining the boundary between the dark and light green regions were able to define a minimum lateral stability threshold, data collected during evaluation of 24 diverse light vehicles were considered. The YRRs of each vehicle were calculated, and plotted as a function of time after completion of steer. Data from fully enabled and fully disabled ESC tests were used. Additionally, data collected during tests performed with two vehicles in partially disabled ESC modes were included.

Yaw Rate Ratio (YRR) Selection

Review of the data produced by the previously mentioned 24 vehicles showed considerable differences between the yaw rate responses of the vehicles evaluated with fully enabled and fully disabled ESC. The differences were particularly pronounced at 1.5 to 1.75 seconds after COS, where the yaw rates of the vehicles equipped with fully enabled ESC systems had decayed to approximately zero while those associated with the fully disabled tests remained quite high.

To identify which of these two times after COS provided the better discriminatory capability, additional data were considered. The larger data set, comprised of 62 light vehicles, ultimately revealed the time of 1.75 seconds after COS was able to most clearly distinguish the lateral stability of vehicles with ESC from those not so equipped (represented by the fully disabled ESC configuration).

[1] If a threshold based on a particular YRR and COS combination is too conservative, the ability of the lateral stability metric to define acceptable ESC performance is compromised. In such as case, even a vehicle with a poorly performing ESC may pass the minimum performance criterion.

Although use of the YYR at 1.75 seconds after COS possessed good discriminatory capability, NHTSA researchers believed that metric alone would do little to require a vehicle's yaw rate to decay in a controlled and predictable manner (since only one threshold would need to be satisfied and it occurred nearly 2 seconds after the maneuver had been completed). Therefore, a second YRR performance threshold was deemed necessary; one that occurred as soon after completion of steer as possible, but late enough to still provide good discrimination between vehicles with and without ESC. Based on consideration of all available test data, NHTSA ultimately decided a metric based on the YRR 1.0 seconds after COS would meet the two requirements and effectively augment the later value, as indicated in Figure 3.

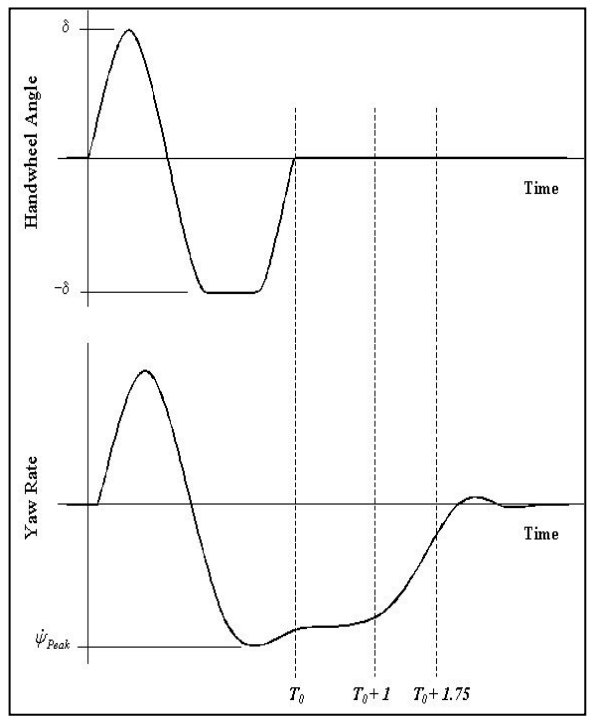

Figure 3. Steering wheel position and yaw rate information used to assess lateral stability.

Once the two time intervals after COS had been established, determination of the YRR performance thresholds associated with each time were required. To establish these criteria, NHTSA researchers used the output of the SAS model presented previously in Figure 2. At 1.0 seconds after COS, the model was 95 percent confident that light vehicles will not exhibit excessive oversteer if the YRR is 35 percent or less. At 1.75 seconds after COS, the model was 95 percent confident that light vehicles will not exhibit

excessive oversteer if the YRR is 20 percent or less. These thresholds define what NHTSA researchers believe the minimum levels of acceptable lateral stability for an ESC-equipped vehicle should be. A formal definition of the lateral stability performance criteria is provided below.

Criteria #1:

$$Percent\ \dot{\psi}_{Peak,COS=1.0\,sec} \leq 35\%$$

where,

$$Percent\ \dot{\psi}_{Peak,COS=1.0\,sec} = 100 * \left(\frac{\dot{\psi}\,(t_0 + 1.0)}{\dot{\psi}_{Peak}} \right)$$

Criteria #2:

$$Percent\ \dot{\psi}_{Peak,COS=1.75\,sec} \leq 20\%$$

where,

$$Percent\ \dot{\psi}_{Peak,COS=1.75\,sec} = 100 * \left(\frac{\dot{\psi}\,(t_0 + 1.75)}{\dot{\psi}_{Peak}} \right)$$

In both criterion,

$\dot{\psi}_{Peak}$ = first local yaw rate peak produced after the second steering reversal

$\dot{\psi}(t_0 + x)$ = yaw rate at x seconds after completion of a maneuver's dynamic steering inputs

Ability of Contemporary Vehicles to Satisfy the Proposed Lateral Stability Criteria

Figures 4 and 5 provide lateral stability results for the various YRR and COS combinations for a larger population of 62 vehicles, including very large pickups, and a stretched limousine (238.2 inch wheelbase). Left-right and right-left steering tests are shown, respectively. Test vehicles evaluated with fully enabled ESC are presented in green and fully disabled ESC tests are shown in red. The partially disabled ESC mode results for a 2005 BMW M3, 2006 BMW 525i, 2005 Chrysler 300C, 2005 Infiniti Q45, 2005 Nissan 350Z, 2005 Mercedes SLK350, and a 2006 Porsche Boxster are provided in yellow. Finally, results produced during BMW 525i tests performed with fully disabled active steering and fully disabled ESC are shown in blue.

Of the 58 *ESC-equipped* vehicles used to develop the lateral stability criteria discussed in the previous section, only the performance of a 2006 BMW 525i would be unable to satisfy both conditions when evaluated with ESC fully enabled.

RESPONSIVENESS

The data shown in Figures 4 and 5 clearly indicate ESC can offer tremendous improvements in lateral stability. However, NHTSA believes these benefits should not come at the expense of a vehicle not being able to sufficiently respond to the driver's steering inputs. An extreme example of this could potentially be having an ESC lock both front wheels as the driver begins an abrupt obstacle avoidance maneuver. Assuming the road is reasonably level, and the surface friction is uniform, it is very likely the wheel lock would suppress any tendency for the vehicle to spinout or rollover. However, having the wheels lock would also prevent the vehicle from responding to the driver's steering inputs. This would cause the vehicle to plow straight ahead and collide with the obstacle the driver was trying to avoid. Clearly, this is not a desirable compromise.

To ensure that a balance between lateral stability and the ability of the vehicle to effectively respond to the driver's inputs is maintained, NHTSA researchers believe a "responsiveness" metric must supplement the lateral stability criteria established by the Agency.

Responsiveness Metric Evaluation Criteria

NHTSA researchers considered a wide variety of metrics capable of quantifying responsiveness. Some were developed by NHTSA, others by vehicle dynamics experts outside of the Agency [5,6]. The candidate responsiveness metrics included methods based on the vehicle's ability to achieve lateral displacement, lateral acceleration, lateral velocity, and/or sideslip. Some metrics were comprised of a single evaluation criterion, while others incorporated multiple factors into a single composite metric. However, one commonality shared by each candidate was that they all used data produced during the same Sine with Dwell test series used to assess lateral stability. Also, since the later part of the maneuver is what excites the vehicle's tendency toward oversteer, each metric only used data produced by the first half cycle of the Sine with Dwell's steering inputs (i.e., the "obstacle avoidance" component of the maneuver).

When evaluating the various responsiveness metric candidates, NHTSA researchers considered the following factors: (1) face validity, (2) objectivity, and (3) ease of computation. In the context of

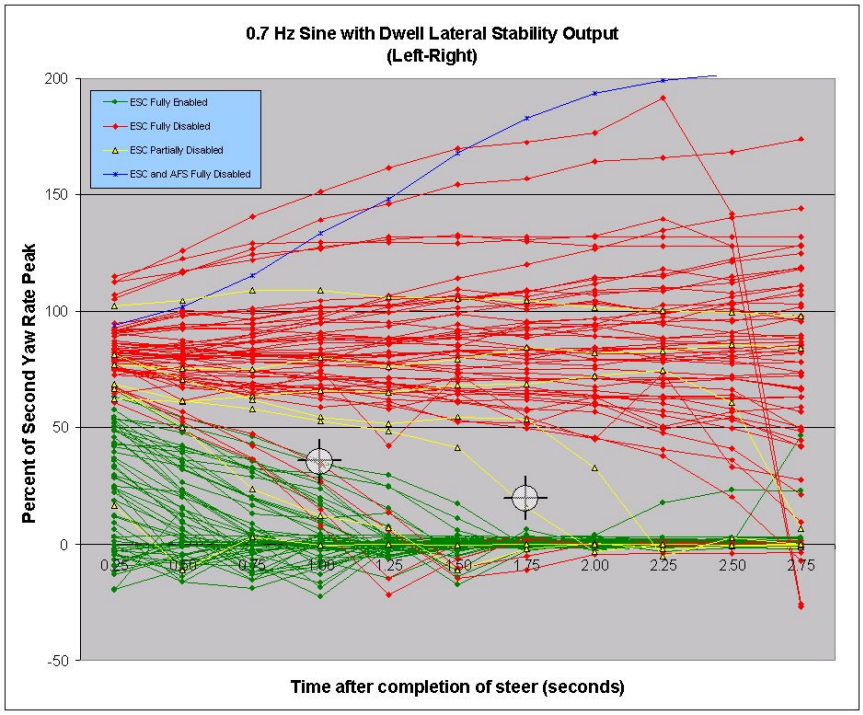

Figure 4. Yaw rate ratio plotted as a function of time after completion of steer for tests performed with left-right steering. NHTSA's proposed lateral stability thresholds are indicated by the two black crosshairs. Results from 62 vehicles are shown.

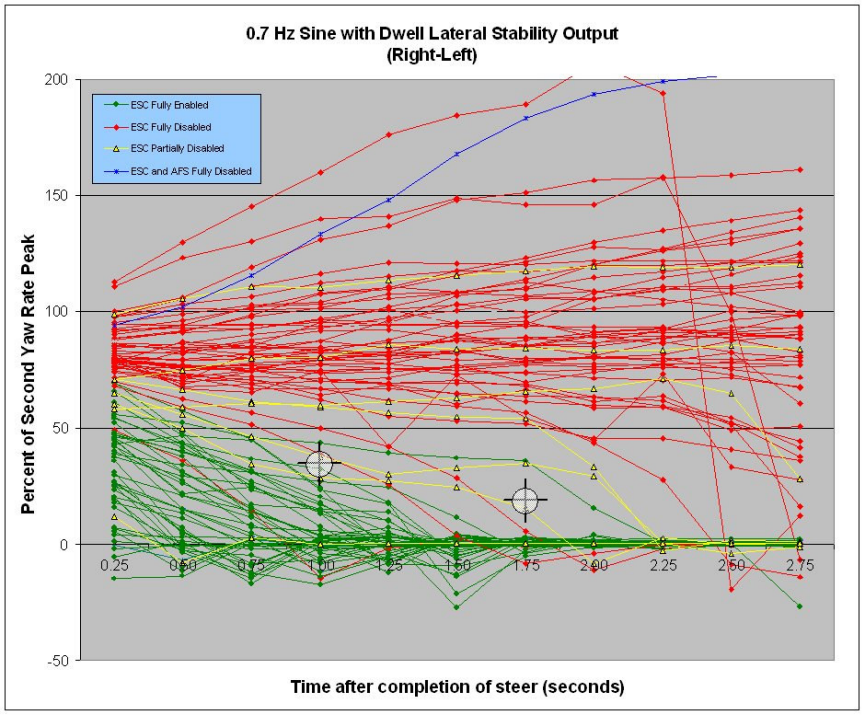

Figure 5. Yaw rate ratio plotted as a function of time after completion of steer for tests performed with right-left steering. NHTSA's proposed lateral stability thresholds are indicated by the two black crosshairs. Results from 62 vehicles are shown.

responsiveness, these factors may be defined as follows:

Face validity. This refers to the real world relevance of the metric. A responsiveness metric with high face validity relates well to situations encountered on public roadways. High face validity increases the ability of the Agency to explain the metric's meaning to the general public.

Objectivity. A good responsiveness metric should be able to consider the performance of all light vehicles equally. This is difficult given the diversity of the vehicles sold in the United States. The output of a robust responsiveness metric should allow NHTSA to directly compare the performance of all light vehicles with good discriminatory capability.

Ease of Computation. Although this attribute is of less importance than the other two, it is of practical significance to NHTSA and the automotive industry. A metric based on data that are difficult and/or time consuming to collect is generally less appealing than one requiring simple analytical techniques.

For sake of brevity, only those responsiveness metrics based on lateral displacement are discussed in this paper. Of the many responsiveness metrics considered, NHTSA believes those based on lateral displacement are the most appealing since they have the most obvious and direct relation to obstacle avoidance.

Multiple metrics based on lateral displacement were explored, differing only in when the measurement occurred in time. Specifically, metrics based on when overall maximum lateral displacement occurred, at 1.0 and 1.75 seconds after COS (i.e., the times used in the assessment of lateral stability), at the completion of the initial steer (i.e., the first quarter-cycle), and at completion of the second steer (i.e., the third quarter-cycle) were used. In the context of responsiveness, lateral displacement was defined as the perpendicular distance of the vehicle's center of gravity from a line defined by the vehicle's initial heading (i.e., before the test maneuver was initiated). If a maneuver was performed with left-right steering, lateral displacement to the driver's left was measured. If right-left steering was used, the lateral displacement to the driver's right was measured.

Maximum Lateral Displacement

While a responsiveness metric that simply considers the vehicle's maximum lateral displacement possesses high face validity, it was found to suffer from low discriminatory capability. There was significant variability in the longitudinal positions (measured from initiation of the steering wheel input) of the vehicles at the instant maximum lateral displacement was recorded. NHTSA researchers believe a vehicle that achieves its maximum lateral displacement with a short longitudinal displacement (i.e., earlier in time) should be deemed more responsive that a vehicle requiring a longer longitudinal distance. However, a responsiveness metric based on maximum lateral displacement would be unable to differentiate such vehicles.

The discriminatory capability of the maximum lateral displacement metric is a significant problem; however it is not the metric's only shortcoming. For some vehicles, such as the 2006 Mercedes ML350 evaluated during this research, maximum lateral displacement may be indeterminate. In some instances, the vehicle may effectively respond to the "avoidance" component of the maneuver's steering input, but not to the later "recovery" phase, a response often associated with the aggressive braking present during roll stability control (RSC) intervention. For some vehicles, RSC intervention remains engaged past the point in the maneuver where effective steering may occur. In these instances, the heading angle of the vehicle may not change much beyond that established with the initial steering input, causing lateral displacement to increase over time. By impeding the ability for the vehicle to respond to the recovery input, the responsiveness of the vehicle is clearly reduced. However, if maximum lateral displacement is used to quantify responsiveness, the vehicle would receive a very favorable assessment – the maximum lateral displacement is limited only to the duration of the sampling interval used for data collection.

Figure 6 helps to explain this phenomenon by presenting the lateral positions of two vehicles, a 2006 Mercedes ML350 and 2005 BMW M3, over time. Both tests were performed with ESC fully enabled using peak steering wheel angles of approximately 230 degrees. The BMW M3 achieved a maximum lateral displacement of 17.1 feet (5.2 m), 108 feet (32.9 m) after initiation of the maneuvers steering inputs. With the Mercedes ML350, a peak lateral displacement is never established. For this vehicle, lateral displacement continues to increase up to the point data collection is terminated, approximately 6 seconds after initiation of the maneuver's steering input.

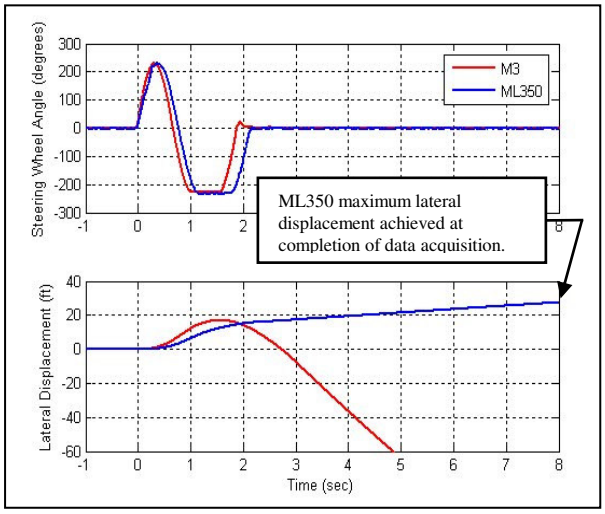

Figure 6. 2006 Mercedes ML350 and 2005 BMW M3 lateral displacements observed over time.

For the reasons discussed in this section, the contradictory, unrepresentative results produced from the maximum lateral displacement responsiveness metric were deemed unacceptable and alternative metrics were explored.

Lateral Displacement at 1.0 and 1.75 seconds after Completion of Steer

For each test, performed with every vehicle, maximum lateral displacement (when it could be accurately determined) was achieved before the 1.0 and 1.75 seconds after completion of steer data points. Since the intent of the responsiveness metric was to consider the vehicle's reaction to the avoidance component of the maneuver's steering input, but not to the later recovery phase, use of these times was deemed inappropriate. As such, the idea of assessing lateral displacement at 1.0 and 1.75 seconds after completion of steer was abandoned.

Lateral Displacement at Completion of the Initial Steer

A second attempt to use lateral displacement to define responsiveness used the lateral displacement measured at completion of the initial steering input. Unlike the previously described technique, where lateral displacements measured at 1.0 and 1.75 seconds after completion of steer were found to occur too late in the maneuver to quantify responsiveness, lateral displacement measured at completion of the initial steer proved to be too early.

Since all Sine with Dwell tests were performed with a commanded frequency of 0.7 Hz, completion of the initial steer occurs approximately 357 ms after initiation of the maneuver's steering inputs. Perusal of the test data indicated this interval is so short that the vehicles are not given sufficient time to generate significant lateral acceleration and, consequentially, lateral displacement. Due to the low magnitude of the responses, and the similarity among all vehicles considered, NHTSA researchers ultimately concluded the lateral displacements output with this analysis technique offer little practical insight into light vehicle responsiveness. For these reasons, the concept of measuring lateral displacement at completion of the first steering input was discarded.

Lateral Displacement at Completion of the Second Steer

Having defined instants in time that occurred both too early and too late to be used for the effective quantification of light vehicle responsiveness, NHTSA researchers surmised the instant the completion of the second steering input occurred would likely provide more useful lateral displacement data. During a September 7, 2005 briefing to NHTSA, the Alliance of Automobile Manufacturers announced their considerable and collective responsiveness research had lead them to the same conclusion, indicating that times much beyond completion of the second steering input may result in a metric with considerable disparity [6]. This is because the test data showed the overall maximum lateral displacements always occurred after completion of the second steering input, often during or slightly after the 500 ms pause that immediately followed its occurrence.

Theoretically, completion of the 0.7 Hz Sine with Dwell second steering input should always occur 1.07 seconds after initiation of the maneuver's first steering input. However, the inability of a vehicle's power steering system to keep the actual steering input in phase with the programmable steering machine's commanded input (a phenomenon known as power steering "pump catch") can affect when completion of the second steering input actually occurs. Regardless of whether it is the intention of the vehicle manufacturer or not, the inability of the power steering system to keep up with the demands of the Sine with Dwell maneuver is somewhat common, especially when large steering wheel angles and rates are used.

For this reason, consistently determining when the instant completion of the second steering occurs can be difficult. Not only can pump catch affect the

phasing of the actual versus commanded inputs, but many times the transition from completion of the second steering input to the Sine with Dwell's 500 ms pause is not crisp. Rather, the steering inputs in this region are smoothed as the steering machine attempts to overcome the increased torque demand imposed by pump catch. When considering the resulting data in post-processing, this can contribute to disparity in how and/or when completion of the second steering input is reported. Practically speaking, this makes the reporting of lateral displacement at the same instant in time, an attribute intended to consider the performance of all light vehicles fairly and objectively, impossible.

To avoid this complication, analyzing lateral displacement data a specific point in time (i.e., independent of actual steering wheel position) in the vicinity of the completion of the second steering input was recommended [6]. Since 1.07 seconds after initiation of the maneuver's first steering input represents the theoretical instant completion of the second steering input should occur, this time was suggested. NHTSA researchers believe this is a very reasonable approach, and lateral displacement at 1.07 seconds after initiation of the maneuver's first steering input provides an excellent way of quantifying light vehicle responsiveness. Figure 7 summarizes this analysis technique.

A Simplified Approach to Measuring Lateral Displacement

Use of the lateral displacement at 1.07 seconds after initiation of steer represents the best way to quantify light vehicle responsiveness known to NHTSA. To provide the data necessary for this metric, NHTSA has had to record vehicle position over time using GPS-based measurements. Once the raw data have been collected, they are corrected with a differential post-processing technique and carefully synchronized with the other test data (collected on a second in-vehicle computer). Although this method is capable of producing highly accurate vehicle position data, the acquisition and manipulation of these data are time consuming and expensive.

One practical way to avoid the burden imposed by the use of GPS to measure lateral displacement is to calculate it via double integration of lateral

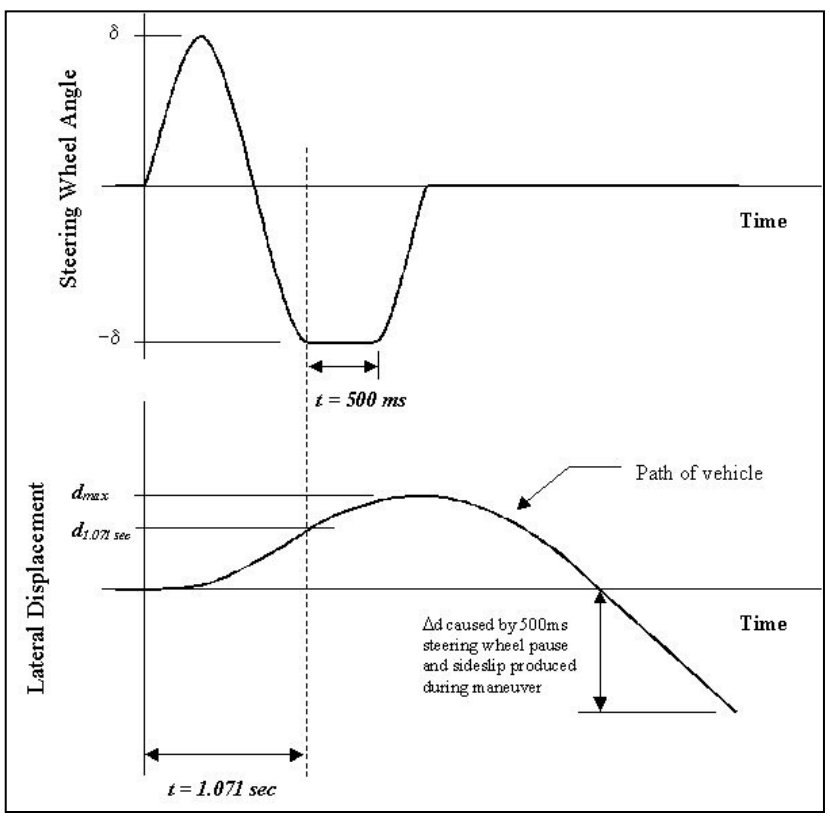

Figure 7. NHTSA's measure of light vehicle responsiveness. Steering wheel angle and lateral displacement data are used for this metric.

acceleration [6]. Although this process is not recommended as a general practice because small errors in zeroing, etc. can produce large errors in calculated displacement over time (see Figure 8), a responsiveness metric based on data 1.07 seconds after initiation of the maneuver's first steering input only requires lateral acceleration be integrated over a short time interval. Therefore, it was expected there would be good agreement between calculated and measured lateral displacements.

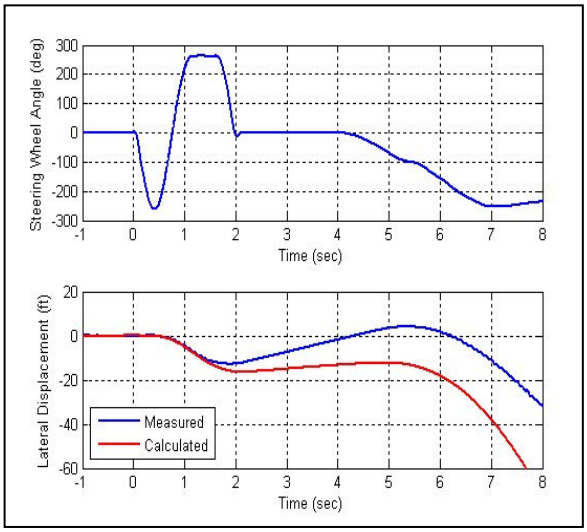

Figure 8. Comparison of measured and calculated lateral displacements over time.

After comparison of GPS-based lateral displacement measurements and those calculated via the careful double integration of lateral acceleration data, NHTSA researchers concluded: (1) measured and calculated lateral displacements are comparable 1.07 seconds after initiation of the maneuvers' steering inputs, and (2) use of a calculated lateral displacement 1.07 seconds after initiation of the maneuvers' steering inputs is an acceptable way by which it may be quantified. **Note:** Careful zeroing for offset and drift greatly improved the accuracy of calculated lateral position. For this reason, NHTSA researchers zeroed the lateral acceleration data before and after the first integration, and then again after the final integration.

Proposed Responsiveness Thresholds

Figure 9 shows the lateral displacements calculated from lateral acceleration data collected 1.07 seconds after initiation of the maneuvers' steering inputs. This figure presents the entire suite of data collected during evaluation of 62 light vehicles. All steering scalars and ESC configurations are represented, as are both directions of steer. Most passenger cars, wagons, minivans, and SUVs are shown in black. All pickups are shown in white. A series of left-right tests performed with a 2004 GMC Savana 3500 15-passenger van, when tested with ESC fully enabled, is shown in blue. The lateral displacements calculated for tests performed with a 2005 Jeep Grand Cherokee and 2005 Lincoln Town Car limousine are presented in red and green, respectively. In the case of the Jeep Grand Cherokee, the tests shown in red were performed with ESC fully enabled. The green Lincoln limousine tests were performed without ESC (the vehicle was not so-equipped).

The vehicles shown in Figure 9 were late-model production vehicles, comprised of model years 2002 to 2006, with a diverse range of handling characteristics. The results shown in this figure make good physical sense (e.g., sports cars such as the Porsche Boxster, BMW M3, and Mazda RX-8 are shown to be highly responsive, whereas sport utility vehicles with aggressive RSC systems, large heavy pickups, and the stretched limousine reside at the bottom of the responsiveness scale), and provide the foundation upon which NHTSA ultimately selected its responsiveness performance thresholds.

To ensure that the responsiveness of future vehicles is not degraded much beyond that present in the contemporary population, NHTSA researchers used the data shown in Figure 9 to establish the "Proposed Region of Noncompliance." The intent of this region was to ensure a minimum level of responsiveness is maintained throughout a range of steering wheel inputs attainable by actual drivers in severe obstacle avoidance situations.

As proposed, there are two criteria used to establish the boundaries of the Proposed Region of Noncompliance [7]. The vertical boundaries were used to define the range of steering wheel angles for which lateral displacement capability was to be assessed. The lower bound of this range was taken to be 180 degrees. This value was used since increases in steering wheel angle beyond this magnitude did not typically coincide with significantly more lateral displacement. The upper boundary of steering angle magnitudes was simply the overall maximum used without producing a termination condition for a given vehicle.

The horizontal boundary of the Proposed Region of Noncompliance was created to ensure light vehicle responsiveness was not degraded beyond what the

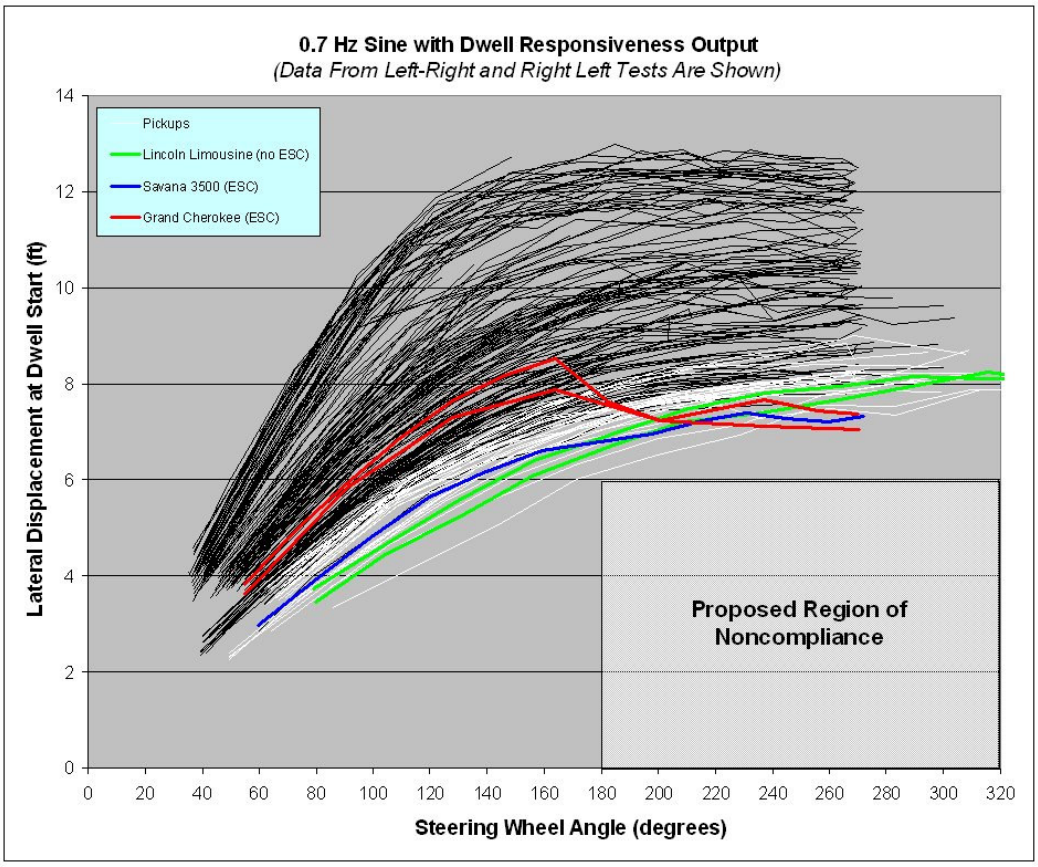

Figure 9. Lateral displacements produced during Sine with Dwell tests.

data presented in this paper have shown to exist for a vast majority of the contemporary light vehicle fleet. NHTSA's research has indicated a minimum lateral displacement of 6.0 feet, (1.83 m) measured 1.071 seconds after initiation of the maneuvers' steering inputs, is a reasonable threshold, as each of the 62 vehicles were able to satisfy this performance criteria, regardless of whether they were equipped with ESC.

CONCLUSIONS

NHTSA's decision to mandate ESC on all light vehicles is expected to have a tremendously positive impact on safety. To facilitate this mandate, development of test procedures and a series of minimum performance criteria to ensure acceptable ESC effectiveness were required. This paper has provided an overview how the performance criteria proposed for FMVSS No. 126 were developed.

NHTSA proposes the Sine with Dwell test maneuver be used to assess ESC compliance on the test track. This maneuver is based on a single-cycle, 0.7 Hz steering input, with a 500 ms pause between the third and fourth quarter cycles. Output from Sine with Dwell tests provides data used to evaluate lateral stability and responsiveness compliance of ESC-equipped light vehicles.

As proposed, acceptable lateral stability requires compliance with two performance criteria, intended to encourage yaw rate to decay in a controlled manner. This is accomplished by comparing the yaw rates measured 1.0 and 1.75 seconds after completion of the maneuver's steering inputs to the first local yaw rate peak produced after the second steering reversal. These "yaw rate ratios" must be less than or equal to 35 and 20 percent, respectively.

To ensure that a balance between lateral stability and the ability of the vehicle to effectively respond to the driver's inputs is maintained, a responsiveness metric supplements that used to assess lateral stability. As proposed, FMVSS No. 126 would require all light vehicles produce a lateral displacement of at least 6 feet (1.83 m), assessed 1.07 seconds after initiation of the maneuver's steering inputs

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REFERENCES

[1] See Docket Number NHTSA 2006-25801

[2] Forkenbrock, Garrick J., Elsasser, Devin H., O'Harra, Bryan C., "NHTSA's Light Vehicle Handling and ESC Effectiveness Research Program," ESV Paper Number 05-0221, June 2005.

[3] Forkenbrock, Garrick J., Elsasser, Devin H., O'Harra, Bryan C., "Development of Electronic Stability Control (ESC) Performance Criteria," DOT HS 809 974, September 2006.

[4] Forkenbrock, G.J., O'Harra, B.C., Elsasser, D., "A Demonstration of the Dynamic Tests Developed for NHTSA's Light Vehicle Rollover Research Program – Phase VIII of NHTSA's Light Vehicle Rollover Research Program," NHTSA Technical Report, DOT HS 809 705, August 2004.

[5] See Docket Number NHTSA 2004-19951-17

[6] See Docket Number NHTSA 2004-19951-21

[7] See Docket Number NHTSA 2006-25801-1