A REPEATABILITY EXAMINATION OF NHTSA'S PROPOSED FMVSS 126 ESC EVALUATION METHOD AND METRICS

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ABSTRACT

NHTSA's proposed FMVSS 126 ESC evaluation method and performance requirements are repeatedly tested by three vehicle manufacturers and NHTSA using two vehicle configurations, five test sites (tracks) and three temperature ranges. The results are examined to determine the sources of variability. Conclusions are presented on the variation of observed results. The initial experiment was designed considering directional stability metrics. The scope of the study was later expanded to include the responsiveness metric.

INTRODUCTION

In June, 2005, NHTSA employed subjective evaluation techniques that identified two vehicle configurations representing "diminished ESC performance" that defined NHTSA's subjective threshold for acceptable vehicle directional stability performance. One configuration was slightly above this threshold (Threshold+) and the other was slightly below this threshold (Threshold-). These subjective assessments were later confirmed by NHTSA's investigation of stability using a statistical model [1]. Sine with Dwell tests [2] were conducted on these "diminished mode ESC" vehicle configurations as part of the Phase 2a research [1]. Note that these vehicle configurations in the variability study represent "diminished mode ESC performance". The baseline calibrations of these vehicles are shown in Figure 1 by the light blue-gray lines with the round event markers. It can be seen that the normalized yaw rate response of the baseline calibrations return to the desired zero state more quickly than response of the respective diminished mode calibrations indicating a significant improvement in directional stability.

A designed experiment was constructed that allowed the investigation of the vehicle directional stability metrics for sensitivity to track, sensitivity to temperature, and testing variability [3]. This involved repeated tests of the aforementioned threshold vehicle configurations at different test sites and within different temperature ranges. The performance results (test metrics) would be useful for examining the variability of metrics described in the FMVSS 126 NPRM [4] used to characterize vehicle directional stability performance near the threshold of acceptance.

Testing of the vehicle configurations was conducted between August, 2005 and March, 2006 in order to accommodate testing and shipping logistics and to allow for testing within the desired temperature ranges. Figure 1 provides a comparison of the normalized yaw rates (yaw rate divided by the second peak yaw rate) for the threshold vehicle configurations versus the entire population of vehicles measured. It can be seen that the threshold configurations form a "boundary" of the ESC ON and ESC OFF configurations.

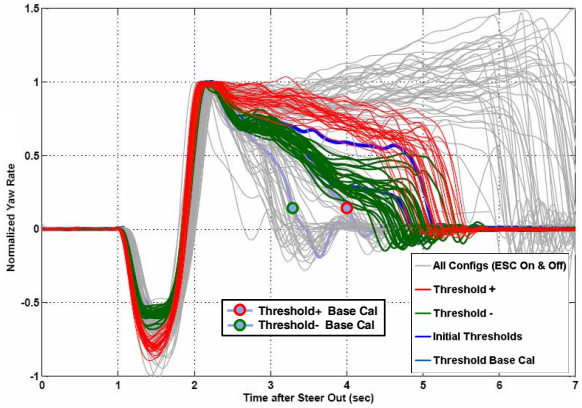

Figure 1. Rationale for configurations selected.

After completion of the aforementioned study, focus shifted to determining the variability for vehicle responsiveness metrics near the threshold for acceptable vehicle responsiveness. The best method to analyze the variation of responsiveness as it pertains to the proposed acceptance criteria is to measure a small number of vehicles whose

responsiveness performance is near the acceptance criteria at a number of different tracks and temperatures. As there was not time available to collect this data, the next best method is to examine the variability of responsiveness of the two configurations used in the stability variability study [5]. The Threshold+ configuration is one of the most responsive (approximately 98th percentile) of vehicles tested to date, while the Threshold- configuration represented the ~50th percentile for responsiveness.

Although the study included a number of directional stability and responsiveness metrics, the scope of this paper is limited to the metrics proposed by NHTSA in the FMVSS 126 NPRM.

DESCRIPTION OF EXPERIMENT

The experiment was designed to execute a test series on each of the two threshold vehicle configurations to determine the variability at five different test tracks. The tracks were chosen in different parts of the United States since tracks tend to be built using local materials. The tracks were located in Arizona, California, Michigan, Ohio, and South Carolina. Aerial photographs of each track are shown in the Appendix. The dates for testing at each location were chosen, based on historical data, to achieve ambient temperatures in the desired temperature range. The experiment was also designed to conduct a test series on the two vehicle configurations at the same test track to determine the effects of testing at three different temperature ranges: Cold (~30 deg F), Medium (~60 deg F), and Hot (~90 deg F).

A test series consisted of four repetitions of the Sine with Dwell maneuver and the associated Slowly Increasing Steer maneuver; once in the early morning and once in the afternoon of each day for two days. This protocol was designed to generate test data at the temperature extremes of each test day. New tires were installed on the vehicle before each Slowly Increasing Steer/Sine with Dwell test combination to minimize the effect of tire wear on the results.

The test matrix for track effect and for temperature effect can be seen in Tables 1 and 2 respectively. The **Threshold+** configuration was labeled **M32** and the **Threshold–** configuration was labeled **302**. These descriptors will be used interchangeably throughout this paper. Note that there were 56 Sine with Dwell tests conducted in total: 28 on the M32 configuration and 28 on the 302 configuration. The initial tests of the M32 and 302 configurations conducted by NHTSA in the spring, 2005 can also be included for comparison purposes. The same vehicles were used, although the tires used in the initial tests were not from the same lot purchased for the repeatability study.

Note that the track sensitivity study only included the Medium temperate range data. The temperature sensitivity study for each vehicle configuration included the data from a single track at which the vehicle was tested at all three temperature ranges (MI for the 302 configuration, and OH for the M32 configuration).

Table 1.
Track Effect Test Matrix

Test Series	Config.	Test Track	Temp.	Tester	Temp or Track Effect
1	302	MI	Hot	GM	Temp
2	M32	OH	Hot	NHTSA	Temp
5	302	OH	Med.	NHTSA	Track
6	M32	MI	Med.	GM	Track
3	302	MI	Med.	GM	Temp / Track
4	M32	OH	Med.	NHTSA	Temp / Track
7	302	SC	Med.	NHTSA	Track
8	M32	SC	Med.	NHTSA	Track
9	302	CA	Med.	Ford	Track
10	M32	CA	Med.	Ford	Track
11	302	AZ	Med.	DCX	Track
12	M32	AZ	Med.	DCX	Track
13	302	MI	Cold	GM	Temp
14	M32	OH	Cold	NHTSA	Temp

Table 2.
Temperature Effect Test Matrix

Test Series	Config.	Test Track	Temp.	Tester	Temp or Track Effect
1	302	MI	Hot	GM	Temp
2	M32	OH	Hot	NHTSA	Temp
5	302	OH	Med.	NHTSA	Track
6	M32	MI	Med.	GM	Track
3	302	MI	Med.	GM	Temp / Track
4	M32	OH	Med.	NHTSA	Temp / Track
7	302	SC	Med.	NHTSA	Track
8	M32	SC	Med.	NHTSA	Track
9	302	CA	Med.	Ford	Track
10	M32	CA	Med.	Ford	Track
11	302	AZ	Med.	DCX	Track
12	M32	AZ	Med.	DCX	Track
13	302	MI	Cold	GM	Temp
14	M32	OH	Cold	NHTSA	Temp

Assumptions

A number of assumptions were made in order to conduct the experiment and interpret the results:

- The two test vehicles are not changing during the experiment
- The variation in instrumentation and measurement systems (between the three manufacturers & NHTSA) is small compared to the variation in a test vehicle configuration

As the scope of the project expanded to determine the variability of the responsiveness metric, further assumptions were necessary:

- The variability in responsiveness of vehicle configurations well above the responsiveness performance requirement is similar to the variability of vehicles configurations near the responsiveness performance requirement when considering the following components of variability:
  - Track sensitivity
  - Temperature sensitivity
  - Run-to-run variability
- The diminished ESC modes of these vehicle configurations have no significant effect on the variability of responsiveness

Factors Not Controlled In This Experiment - It should be noted that brake temperatures and ESC algorithm changes with driving history and ignition resets were not controlled in this experiment; however it is unlikely that these factors had an effect on the results.

TEST RESULTS AND ANALYSIS

Graphical and statistical techniques were used to analyze the data and examine variability. Yaw Rate Ratio (YRR) and normalized yaw rate, the yaw rate divided by the second peak yaw rate, are used interchangeably in this paper.

Graphical Analysis

Graphical analysis was used to examine vehicle performance characteristics for major trends and to highlight variation of performance between vehicles and test conditions of interest. Graphical analysis provides an overall perspective of vehicle performance and provides direction for further statistical analysis.

Graphical analysis included:

- Plots of metrics versus time
- Cross plots of metrics and test variables
- Plot groupings for key variables such as track and temperature categories

Stability and Responsiveness metrics were examined graphically to identify overall patterns.

Stability Metrics - Yaw Rate Ratio vs. time was examined for both vehicle configurations at the five tracks and the three temperature ranges. Comparison of YRR vs. time illustrates the difference in yaw rate ratio decay between the two vehicle configurations. M32 yaw rate ratio (Figure 2) continues at a higher level and for a longer period of time than the 302 yaw rate ratio (Figure 3). This graph provides a sense of the difference in the magnitude of vehicle yaw that continues after the steering is returned to straight ahead. This data also provides an indication of performance variation between tracks.

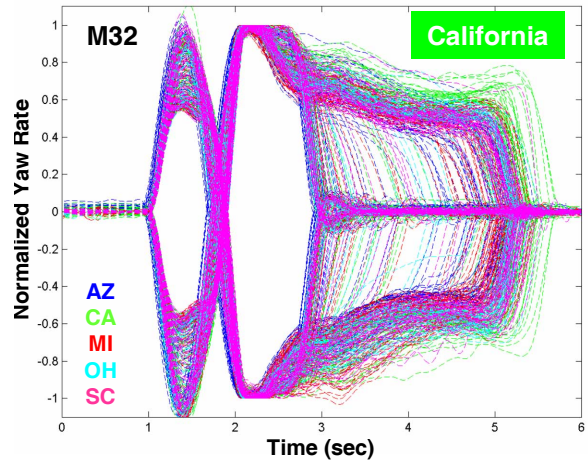

Figure 2. M32 YRR track sensitivity.

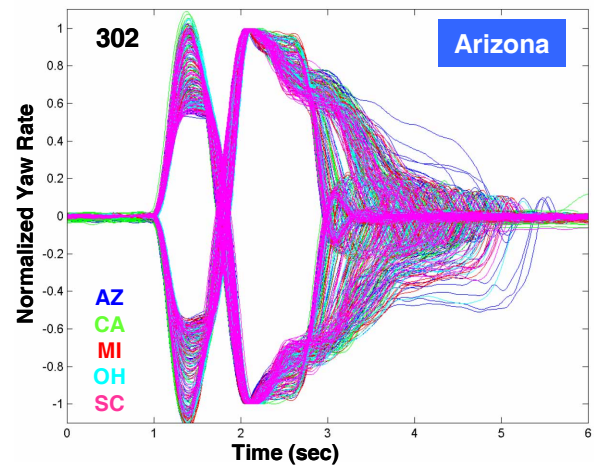

Figure 3. 302 YRR track sensitivity.

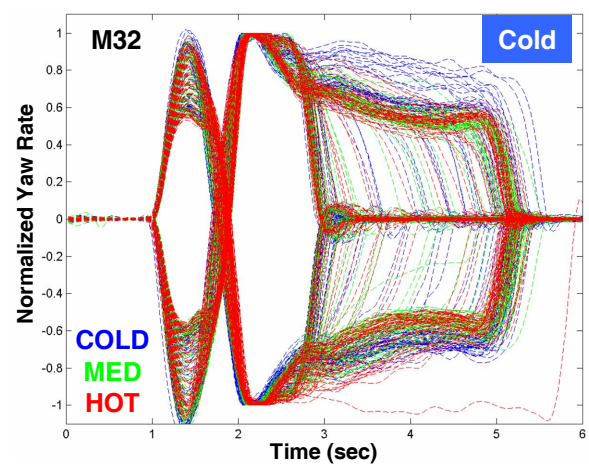

Figure 4. M32 YRR temperature sensitivity.

Examination of YRR vs. time for temperature variation indicates that the M32 configuration

(Figure 4) has a performance shift at Cold temperature that merits further examination. The 302 data (Figure 5) does not exhibit similar temperature sensitivity.

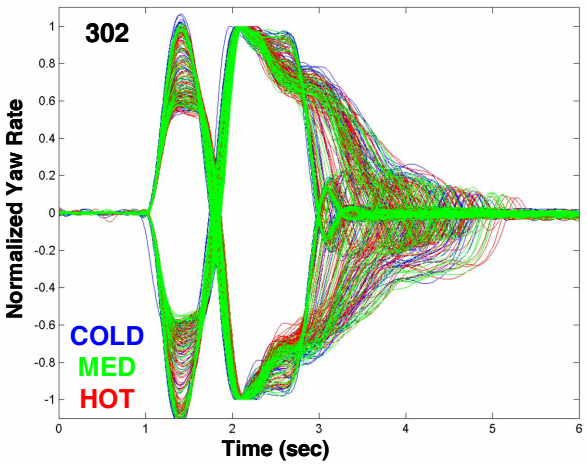

Figure 5. 302 YRR temperature sensitivity.

Plotting Peak YRR at particular times after end of steer versus all steering increments and then sorting by tracks, directions, and temperatures allows a closer examination of Yaw Rate Ratio variations.

The discussion which follows uses the following convention to denote the stability metrics in the FMVSS 126 NPRM:

YRR1 is the Yaw Rate Ratio 1.00 second after end of steer

YRR175 is the Yaw Rate Ratio 1.75 second after end of steer

Figure 6 shows that variation in YRR1 due to tracks is clearly observable for configuration M32.

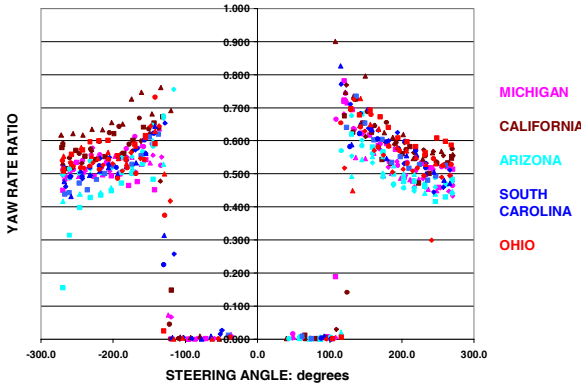

Figure 6. M32 YRR1 vs. steering angle: track sensitivity.

Figure 7 shows the temperature sensitivity in YRR1 for configuration M32.

Figure 8 shows variation in YRR175 due to tracks is observable in configuration M32.

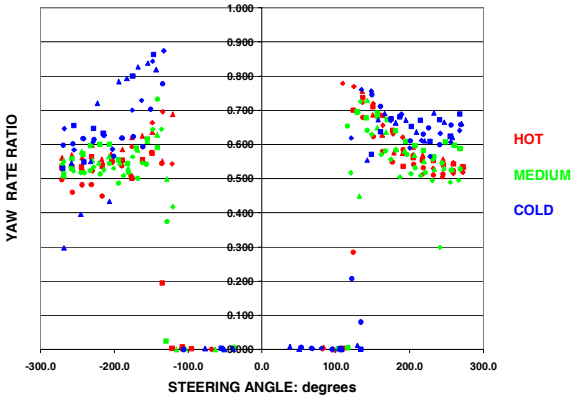

Figure 7. M32 YRR1 vs. steering angle: temperature sensitivity.

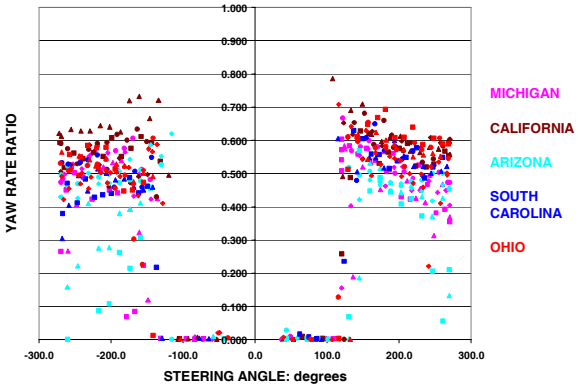

Figure 8. M32 YRR175 vs. steering angle: track sensitivity.

Figure 9 shows temperature sensitivity in YRR175 for the Cold temperature range in configuration M32.

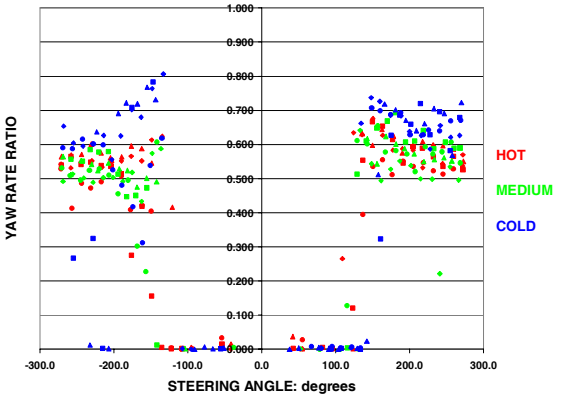

Figure 9. M32 YRR175 vs. steering angle: temperature sensitivity.

Figures 10 through 13 show the YRR metrics for configuration 302. It can be seen that configuration 302 has significantly lower yaw rate ratios compared to M32.

Track variation in YRR1 is difficult to observe, although Arizona appears to have higher than typical variation as seen in Figure 10.

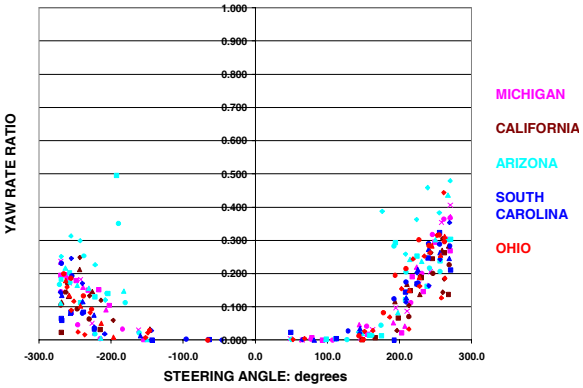

Figure 10. 302 YRR1 vs. steering angle: track sensitivity.

Temperature sensitivity is difficult to observe in configuration 302, as shown in Figure 11.

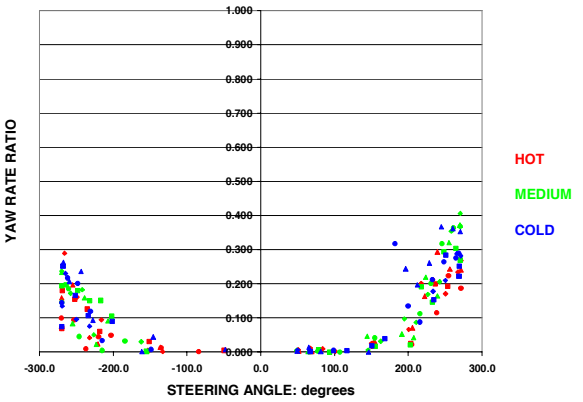

Figure 11. 302 YRR1 vs. steering angle: temperature sensitivity.

Trace amounts of yaw rate ratio are apparent at 1.75 seconds for configuration 302, as illustrated in Figures 12 and 13. Since vehicle yaw is basically complete 1.75 seconds after steer out, it is not surprising that track and temperature sensitivity is difficult to observe.

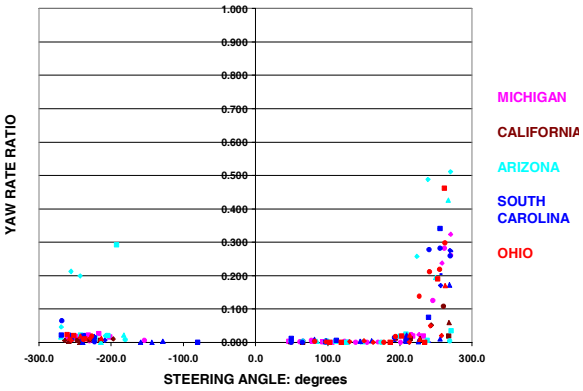

Figure 12. 302 YRR175 vs. steering angle: track sensitivity.

Graphical review of YRR for configurations M32 and 302 suggests that the M32 yaw rate ratio performance may show track and temperature sensitivity, while the 302 YRR performance is less likely to exhibit track and temperature sensitivity.

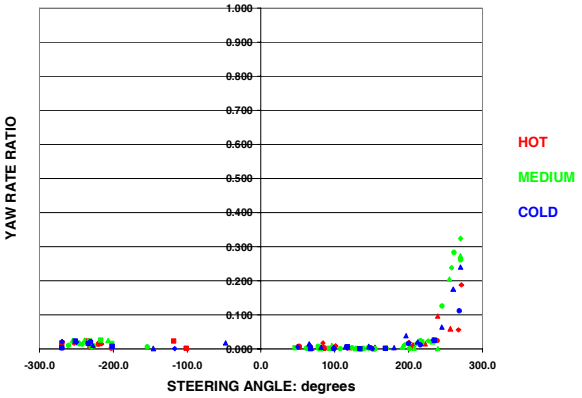

Figure 13. 302 YRR175 vs. steering angle: temperature sensitivity.

<u>Responsiveness Metric</u> – NHTSA's proposed vehicle responsiveness metric, the minimum lateral displacement observed at steering wheel angle amplitudes greater than or equal to 180 degrees (Min Dy) was calculated for the test configurations. Min Dy versus steering wheel angle was examined graphically and reviewed for run-to-run, track, and temperature variation:

Figure 14 shows variation due to tracks for configuration M32.

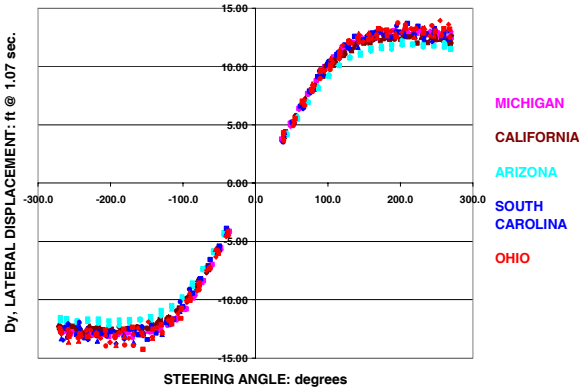

Figure 14. M32 Responsiveness vs. steering input: track variation.

Figure 15 shows that there may be some temperature sensitivity for configuration M32.

Figure 16 shows little variation due to track for configuration 302.

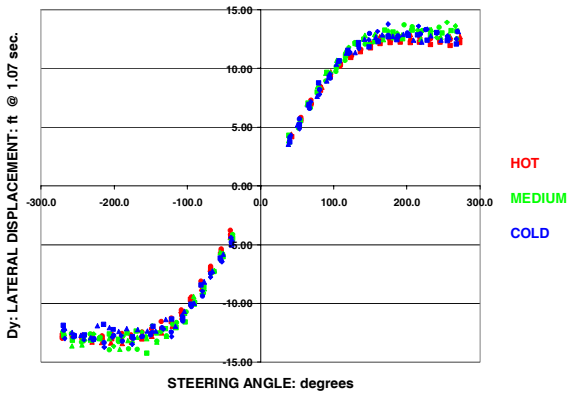

Figure 15. M32 Responsiveness vs. steering input: temperature variation.

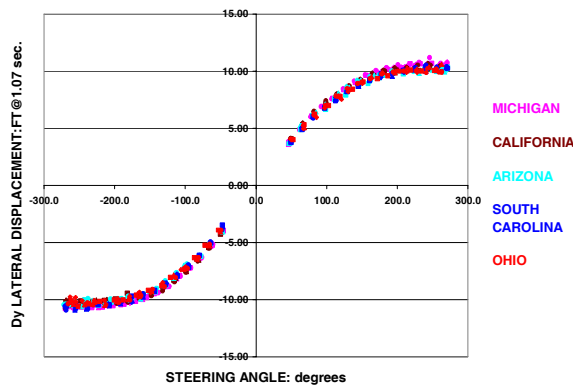

Figure 16. 302 Responsiveness vs. steering input: track variation.

Figure 17 shows some temperature sensitivity for configuration 302.

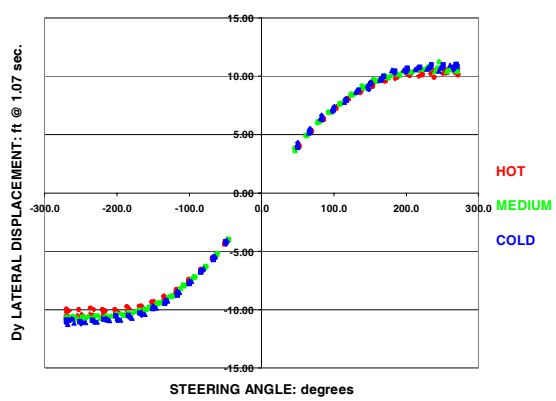

Figure 17. 302 Responsiveness vs. steering input: temperature variation.

Graphical review of the responsiveness plots for possible track and temperature sensitivity reveals probable track and temperature sensitivity for M32 and probable temperature sensitivity for 302. Statistical analysis was used to further quantify these sensitivities to track and temperature.

Statistical Methods

The statistical analysis techniques used in this variability study are described in this section. The detailed results generated by these methods are found in the section discussing a specific metric and in the VARIABILITY RESULTS SUMMARY section.

The analysis methods used in this study consisted of:

- Signal to Noise Ratios
- Confidence Interval Comparison
- Temperature Sensitivity
- Analysis of Variance (ANOVA)
- Pooled Standard Deviation

Different methods for combining standard deviations were also investigated.

Signal to Noise Ratio Calculations – Signal to Noise Ratio (S/N) is a good indicator of the robustness and discrimination capability of a given metric. A higher value is better. The ratio is calculated by dividing the difference between the metrics of each of the two vehicle configurations by the noise in the data.

$$S/N = 2\frac{|\mu_1 - \mu_2|}{CI_1 + CI_2} \qquad (1).$$

Where

μ_1 is the average of vehicle configuration 1's data for the considered runs

μ_2 is the average of vehicle configuration 2's data for the considered runs

CI_1 is the width of the 90% confidence interval for vehicle configuration 1's considered runs

CI_2 is the width of the 90% confidence interval for vehicle configuration 2's considered runs

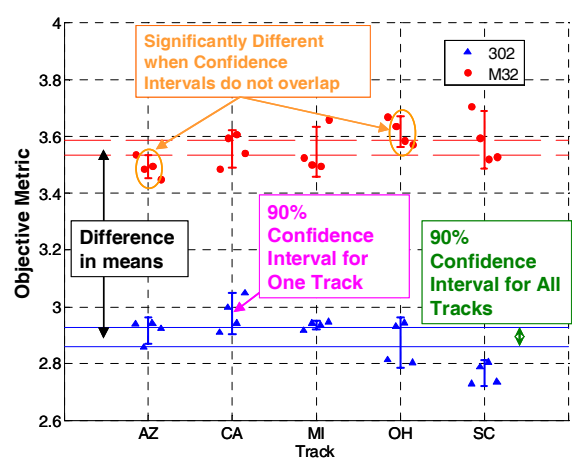

Figure 18. Example of elements of S/N calculation.

Confidence Interval Comparison – Using the sensitivity to track as an example, if variability were zero, it would be possible to get the same result at any track. One comparison metric is the number of times two tracks are statistically different (i.e. 90% confidence intervals do not overlap). This is shown in Figure 18. For five tracks, there are ten possible track pairings. Since there are two vehicle configurations, there are 20 possible track-by-vehicle pairings. A smaller number of non-overlapping pairs are preferred because the overlap shows that the results are track independent.

Pooled Standard Deviation – Since there are some statistically significant track differences, the run-to-run variation was calculated using a pooled standard deviation, where the variation about the mean of each vehicle at each track was summed so that track differences are not included in the run-to-run variability.

Variability due to tracks can be estimated by averaging all four test sequences at each track to get an average value for that track. Considering each vehicle separately, this collapses the data down to 10 values (5 tracks x 2 vehicles). Since the vehicles are statistically significantly different, the pooled standard deviation was calculated using 2 means (1 for each vehicle).

Temperature Sensitivity – The experiment was designed to examine tests conducted in three temperature ranges: Cold, Medium, and Hot by testing at three different times of year. Temperature sensitivity was examined using both the temperature category and the continuous range of temperature.

Once the sensitivity of a metric to temperature has been established, it is useful to know how significant the change due to temperature is compared to typical values of the metric. One method to answer this question is to consider a ΔT defined as the temperature change needed to make the metric change equal to the difference between the two vehicle configurations.

$$\Delta T = \frac{(M_1 - M_2)}{S} \qquad (2).$$

Where

M_1 is the metric value of vehicle configuration 1. This is calculated by doing a linear fit of the metric versus temperature and evaluating the linear fit at 50 deg F

M_2 is the metric value for vehicle configuration 2 at 50 deg F

S is the slope of the metric with respect to temperature

Metrics with higher ΔT values would rank vehicles more consistently across a broader range of temperatures. Temperature sensitivity is only calculated for a vehicle configuration when the slope (S) is statistically significant

Figure 19 shows a typical temperature sensitivity plot. In this case, only the slope for vehicle 302 is statistically significant, and it would take a 489 deg F temperature change to span the gap between the two vehicles at 50 deg F.

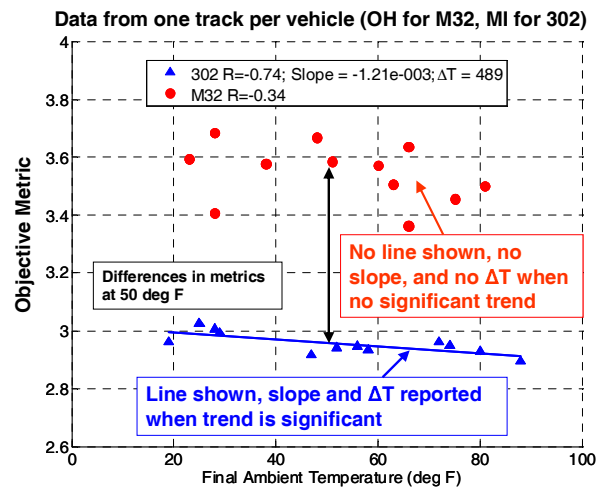

Figure 19. Example of Temperature Sensitivity method .

Another method for understanding the significance of temperature sensitivity is to multiply the sensitivity times the range of allowable temperatures so that the relative change in a metric due to temperature can be compared to the changes due to track and run-to-run variability.

Analysis of Variance – Results were calculated using DEXPERT, an expert system for the design and analysis of experiments [6]. Studies to investigate the effects of track and temperature range were conducted. The track sensitivity study only used the medium temperature range test configurations as they were common for every track. The temperature study used the MI track for the 302 configuration and the OH track for the M32 configuration, as these pairings consisted of testing each configuration over all three temperature ranges.

The components of variability that can be estimated from the structure shown in Table 3 are:

- Vehicle configuration, either 302 or M32
- Location, either MI, OH, SC, CA, or AZ
- Vehicle by Location interaction
- Time of Day, either AM or PM
- Vehicle by Time of Day interaction

- Location by Time of Day interaction
- Vehicle by Location by Time of Day interaction
- Day within Vehicle-Location combination
- Time of Day by Day within Vehicle-Location combination

Table 3.
Track Effect Design Structure

	300C										M3									
	MI		OH		SC		CA		AZ		MI		OH		SC		CA		AZ	
	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20
AM	x	x	x	x	x	x	x	x	x	x	X	x	x	x	x	x	x	x	x	x
PM	x	x	x	x	x	x	x	x	x	x	X	x	x	x	x	x	x	x	X	x

The structure of the temperature sensitivity experiment shown in Table 4 is similar to the track sensitivity experiment except that instead of track, temperature is used. It should be noted that there is a confounding effect caused by the fact that configuration 302 was tested in MI and M32 was tested in OH. The results show that these tracks have similar characteristics, so the confounding effect is small.

Table 4.
Temperature Effect Design Structure

	300C						M3					
	Hot		Med		Cold		Hot		Med		Cold	
	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
AM	x	x	x	x	x	x	x	x	x	x	x	x
PM	x	x	x	x	x	x	x	x	x	x	x	x

The components of variability that can be estimated from the structure shown in Table 4 are:

- Vehicle configuration, either 302 or M32
- Temperature Range, either Hot, Medium, or Cold
- Vehicle by Location interaction
- Time of Day, either AM or PM
- Vehicle by Time of Day interaction
- Location by Time of Day interaction
- Vehicle by Location by Time of Day interaction
- Day within Vehicle-Location combination
- Time of Day by Day within Vehicle-Location combination

The ANOVA results are shown in the variability results summary section.

Yaw Rate Ratio 1 sec after Steer-Out (YRR1)

Figure 20 illustrates the normalized yaw rate responses for the variation study configurations versus a large number of test configurations conducted by NHTSA and the Alliance [1, 2, 7, 8]. Note that the initial test of the Threshold- configuration represented the central tendency of that configuration while the initial test of the Threshold+ configuration represented the lower boundary of that configuration.

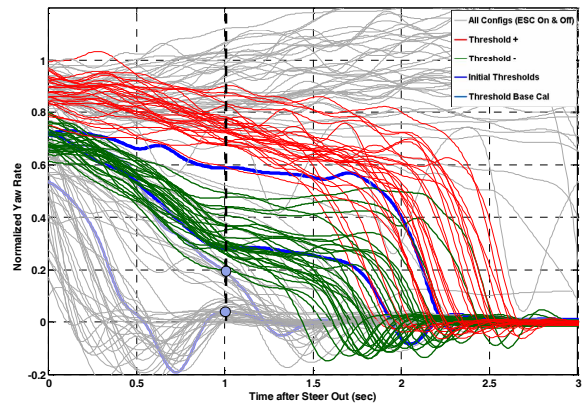

Figure 20. YRR1 variability configuration results vs. tested population.

The results in Figure 21 indicate good discrimination as there is no overlap in the YRR1 metric between the Threshold- and Threshold+ configurations.

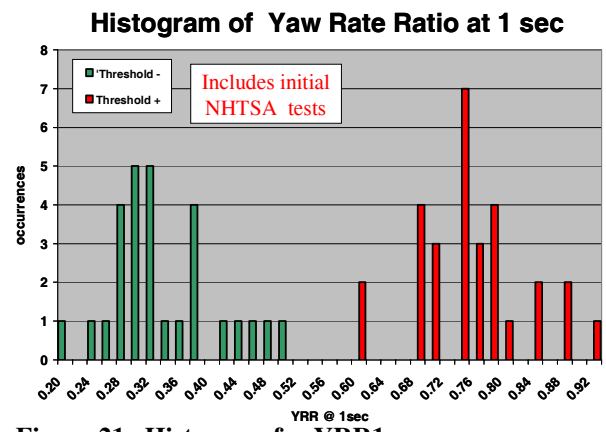

Figure 21. Histogram for YRR1.

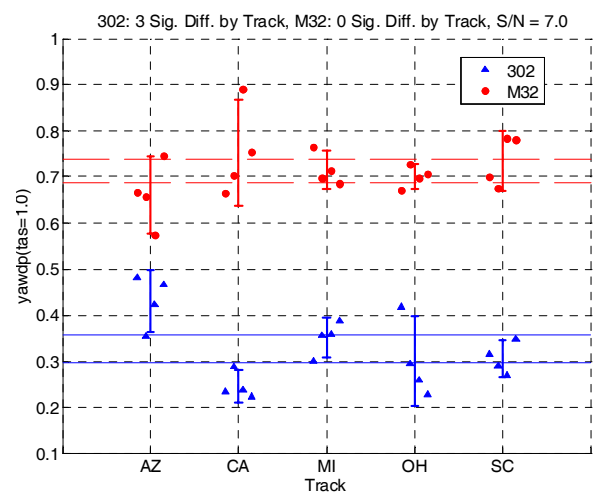

Figure 22. Three Track Differences for YRR1.

Figure 22 shows the yaw rate ratio measurements for each track. Configuration 302 shows three significant differences by track (CA different than MI, CA different than AZ, and AZ different than SC). The

pooled standard deviation for run-to-run variability is estimated at 0.06. The standard deviation for the tracks is estimated at 0.05.

Figure 23 shows the YRR1 versus temperature. Only vehicle M32 showed a statistically significant temperature sensitivity of 0.0022 /deg F. At higher temperatures the yaw rate at 1 second decayed more quickly.

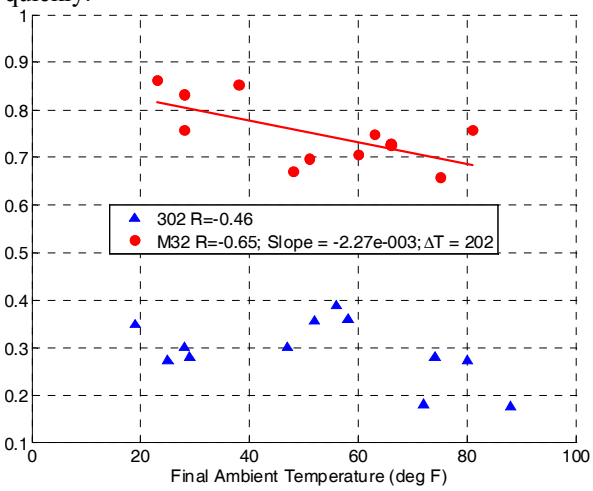

Figure 23. Temperature Sensitivity for YRR1.

Yaw Rate Ratio 1.75 sec after Steer-Out (YRR175)

Figure 24 illustrates the normalized yaw rate responses for the two vehicle configurations versus a large number of test configurations tested previously by NHTSA and the Alliance [1, 2, 7, 8]. Again, the initial test of the Threshold- configuration represented the central tendency of that configuration while the initial test of the Threshold+ configuration represented the lower boundary of that configuration for this performance metric.

The results in Figure 25 indicate reasonable discrimination capability as that there is no observed overlap in the YRR175 metric between the Threshold- and Threshold+ configurations. Although there is no observed overlap, the largest value for the Threshold- configuration is only marginally smaller than the smallest value for the Threshold+ configuration indicating that there would be a statistical overlap.

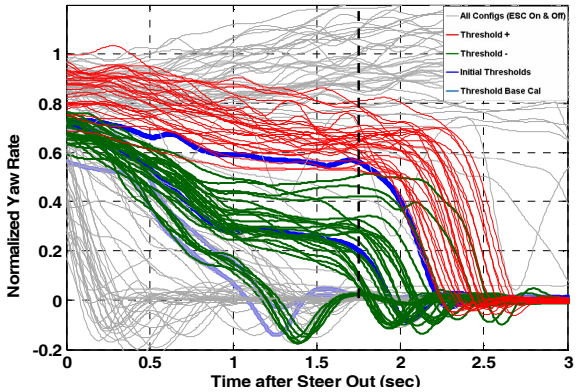

Figure 24. YRR175 variability configuration results vs. tested population.

Also note the bimodal nature of the Threshold- configuration. One central tendency is at 4 to 6 percent, and the other central tendency is at 28 to 30 percent. The cause for this result is not known, but it is hypothesized that the response of the vehicle may be near a threshold level of the ESC algorithm.

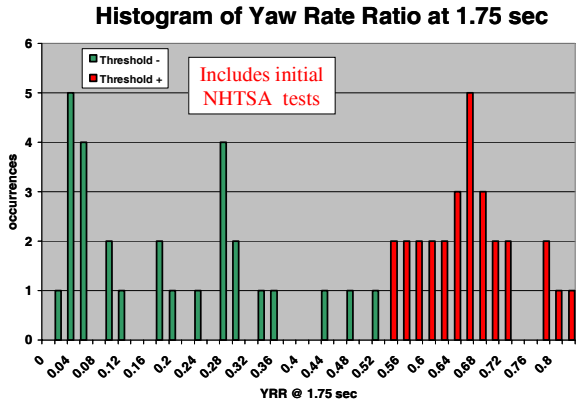

Figure 25. Histogram for YRR175.

Figure 26 shows the YRR175 for all the tracks. For each vehicle there are 3 significant track differences. The pooled standard deviation for the tracks is 0.08 and for run-to-run it is 0.11. Note that variability for YRR175 is higher than that for YRR1 because the YRR versus time curve (see Fig. 20) for configuration M32 is relatively steep near 1.75 seconds and therefore small differences in time to return to zero can result in large differences in YRR.

The temperature sensitivity for YRR175, seen in Figure 27, is similar to that for YRR1; only configuration M32 has a statistically significant slope. The temperature sensitivity of YRR175 is 0.0028 /deg F.

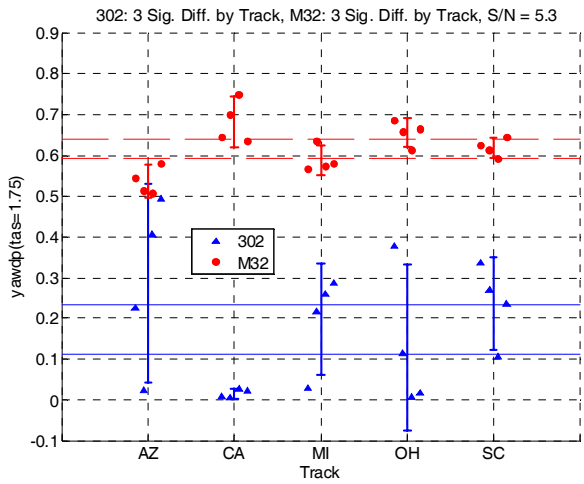

Figure 26. Six Track Differences for YRR175.

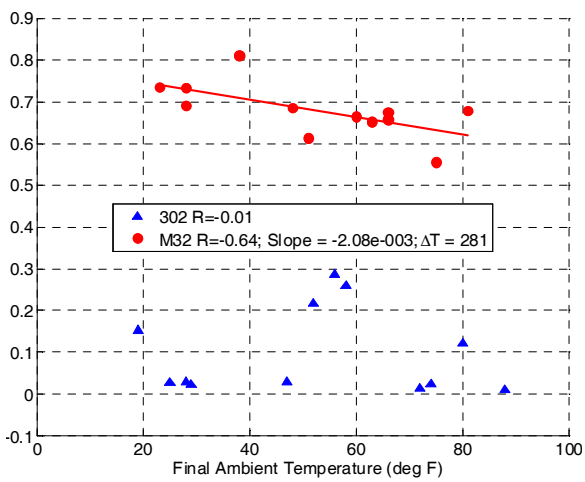

Figure 27. Temperature Sensitivity for YRR175.

RESPONSIVENESS TEST RESULTS

Figure 28 illustrates the lateral displacement response characteristics for the variation study configurations compared to a large number of vehicle tests conducted by NHTSA and the Alliance [1, 2, 7, 8].

The minimum lateral displacement observed at steering wheel angle amplitudes greater than or equal to 180 degrees (Min Dy), was calculated at the 90% confidence level and examined for track, temperature, and run-to-run sensitivities.

Ten significant track differences were observed in the proposed responsiveness metric, Min Dy. The range of track averages observed for Min Dy was 1.05 ft for configuration M32 and 0.55 ft. for configuration 302. This range is approximately ±5% of the overall mean.

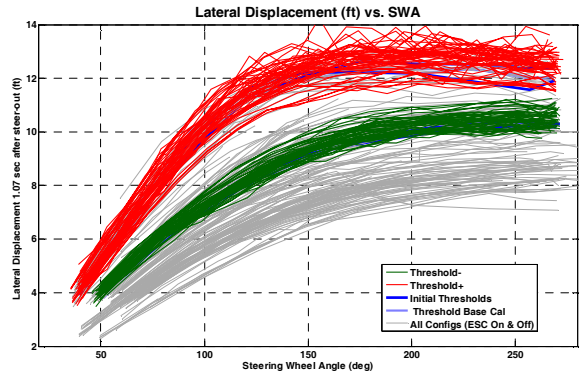

Figure 28. Responsiveness of M32 and 302 configurations vs. tested population.

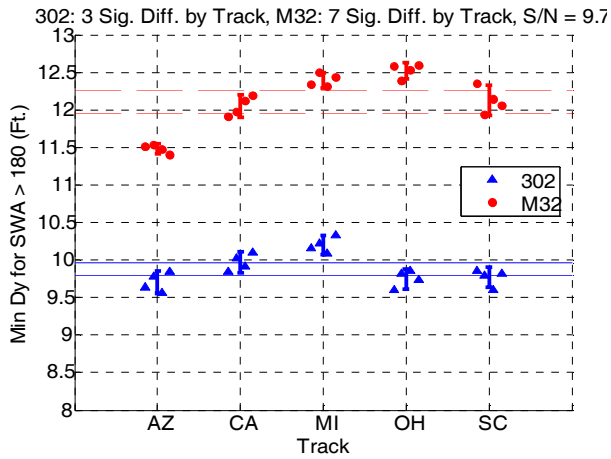

Figure 29. Track Sensitivity of Responsiveness (Min Dy).

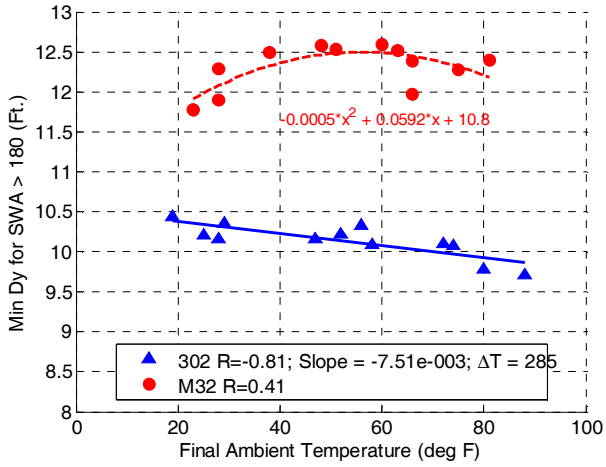

Figure 30. Min Dy temperature sensitivity.

Different patterns of temperature sensitivity were observed for M32 and 302 responsiveness metrics shown in Figure 30. The M32 exhibits a quadratic behavior with a peak in the mid-range of temperature. Configuration 302 exhibits linear behavior and is more responsive at lower temperatures. These same trends were noted in the graphical examination.

Configuration M32 was equipped with high-performance tires. High-performance tires are known to be sensitive to cold temperatures because the higher glass transition temperature of high-performance tire compounds results in lower adhesion at low temperatures. The data for configuration 302 is more typical of all season tires and is consistent with testing observations made during fishhook and other nonlinear vehicle handling tests.

This data indicates that testing variability can be reduced by narrowing the allowable temperature range, especially for vehicles equipped with all season tires.

Further investigation at a constant steering wheel angle, such as at 180 degrees, may shed light on vehicle, track, temperature, and run-to-run variation without the confounding effect of sorting by Min Dy, which occurs at steering angle input greater than 180 degrees.

Run-to-run Variation

Data acquired to assess track sensitivity was used to assess the run-to-run variation caused by random variation in the vehicle, instrumentation, and random variation in the specifics of a particular track (i.e. surface contamination, wind speed and direction, etc.). Track sensitivity can be estimated by pooling the standard deviations calculated for each series of four runs are summarized in Table 5. Pooling can be by configuration and for both configurations

Table 5.
Summary of Standard Deviations for Min Dy

Medium Temperature Only						
	AZ	CA	MI	OH	SC	Pooled
302	0.07	0.31	0.11	0.13	0.11	0.17
M32	0.06	0.13	0.08	0.07	0.18	0.12
					Pooled Run-to-Run	0.14
					Temperature Compensated Pooled Run-to-Run:	0.12

The standard deviations of the Medium temperature data are similar, so the data was combined to calculate the pooled standard deviation. The pooled standard deviation for run-to-run variation is calculated to be 0.12 feet or approximately 1.3% of the overall mean of Min Dy.

Since all the Medium temperature range data was not collected at the same temperature, statistically significant temperature sensitivities were removed before calculating the temperature-compensated, pooled run-to-run standard deviation.

VARIABILITY RESULTS SUMMARY

A summary of the FMVSS 126 proposed stability and responsiveness metrics for the two threshold vehicle configurations are shown in Table 6. The bimodal nature of the YRR175 metric for configuration 302 can be seen in the differences between the median and mean values. Also note the minimum values of Min Dy for both configurations (9.43 feet and 11.42 feet) are significantly larger than the proposed minimum required value of 6 feet.

Table 6.
Overall Summary of FMVSS 126 Metrics

	YRR @ 1 sec	YRR @ 1.75 sec	Min Dy @ swa>=180 deg (ft)
Median - **302**	**0.30**	**0.17**	**9.87**
Mean - **302**	**0.33**	**0.18**	**9.95**
St Dev	**0.07**	**0.15**	**0.28**
St Dev as % of mean	24%	88%	3%
Max	0.49	0.51	10.46
Min	0.20	0.02	9.43
Range	0.30	0.49	1.02
Range as % of mean	97%	289%	10%
Median - **M32**	**0.73**	**0.64**	**12.21**
Mean - **M32**	**0.74**	**0.65**	**12.12**
St Dev	**0.07**	**0.08**	**0.36**
St Dev as % of mean	9.8%	11.6%	3.0%
Max	0.90	0.81	12.60
Min	0.59	0.53	11.42
Range	0.31	0.28	1.18
Range as % of mean	42%	43%	10%

The standard deviations for the FMVSS 126 proposed performance metrics calculated using both the ANOVA and pooled standard deviation methods are shown in Table 7. The results from these two analysis methods show similar trends, except for temperature, where the data was treated differently. The temperature data in the ANOVA was segregated by temperature range and the temperature data in the Pooled method was the observed temperature at end of test.

Table 7.
Variability of Metrics

	ANOVA			POOLED		
Metric	YRR1	YRR175	min Dy SWA ≥ 180 deg (ft)	YRR1	YRR175	min Dy SWA ≥ 180 deg (ft)
Track (1σ)	0.05	0.06	0.40	0.05	0.08	0.31
Run-to-Run (1σ)	0.05	0.08	0.14	0.06	0.11	0.12
Temperature (1σ)	0.04*	0.03*	0.21*	0.12**	0.15**	0.41**

* 1 standard deviation in tested range
** worst case change over a range of 54 degrees F (104-50)

Tables 8 and 9 summarize the percent contribution of each factor in the experiment for each performance metric. The percent variation is given by:

$$\% \, Variation = \frac{V_{component}}{V_{total}} \quad (3).$$

Where

$V_{component}$ is the variation in the performance metric from the component examined

V_{total} is the total variation in the performance metric

Factors that Contribute to Variability

Table 8 shows the contribution of the track-related factors and their interactions (up to 3-way) on performance metrics. It can be seen that the effects of track itself are not present for the YRR metrics, but are present in the Min Dy metric. All metrics show the significant interaction of track sensitivity with vehicle configuration.

Table 8.
Percent Contribution for Track Study

	YRR @ 1 Sec	YRR @ 1.75 Sec	Min Dy for swa ≥ 180 deg	Legend
Vehicle (V)	91	82	94	90% Confidence
Location (L)	0	0	2	
V x L	5	5	3	75-90% Confidence
Time of Day (t)	0	0	0	
V x t	0	0	0	Comparison Only
L x t	0	0	0	
V x L x t	0	0	0	No Statistical Difference
Day (D)	0	7	0	
t x D	4	6	0	
Error	-	-	1	

Table 9.
Percent Contribution for Temperature Study

	YRR @ 1 Sec	YRR @ 1.75 Sec	Min Dy for swa ≥ 180 deg	Legend
Vehicle (V)	94	92	94	90% Confidence
Temperature (T)	1	1	1	
V xT	3	3	2	75-90% Confidence
Time of Day (t)	0	0	0	
V x t	0	0	1	Comparison Only
T x t	0	0	1	
V x T x t	0	0	0	No Statistical Difference
Day (D)	0	0	0	
t x D	2	4	0	
Error	-	-	1	

Table 9 shows the contribution of the temperature range-related factors and their interactions (up to 3-way) on performance metrics. It can be seen that the effects of temperature are present, but are overshadowed by the interaction of temperature sensitivity with vehicle configuration.

Robustness of Metrics to Variability

Table 10 summarizes robustness of the performance metrics to variability as assessed by the following measures:

- Signal/Noise Ratio
- Variance Ratio
- Number of Significant Track Differences
- Temperature Sensitivity

The various indicators for robustness show similar trends for the two YRR metrics. YRR1 appears to be more robust. It has a higher signal-to-noise ratio, a higher ratio of vehicle variance to random error, lower track sensitivity and similar temperature sensitivity.

The trends are mixed for Min Dy. Min Dy exhibits the highest values for signal-to-noise and variation ratio. This is confirmed by noting it has the lowest standard deviation as a percentage of the mean in Table 6. However, Min Dy is the most sensitive metric to different tracks.

YRR and Min Dy temperature sensitivity metrics can not be compared directly because the differences in responsiveness between the two configurations are much larger than the differences in stability.

Table 10.
Robustness to Variability Indicators

Metric Name	S/N	$\sqrt{\frac{s^2 \text{Vehicle}}{s^2 \text{ Random}}}$	# Sig. Track Differences	302 ΔT	M32 ΔT
YRR1	**7.0**	**4.3**	**3**	**----**	**207**
YRR175	**5.3**	**3.6**	**6**	**----**	**196**
Min Dy for swa ≥ 180 deg	**9.7**	**9.5**	**10**	**285**	**----**

CONCLUSIONS

Similar variability findings were obtained using both ANOVA and pooled standard deviation techniques.

In all cases the individual variability components of the performance metrics are in the neighborhood of 3 to 5 percent of the differences seen between the two vehicle configurations.

Yaw Rate Ratio Metrics

The yaw rate ratio metrics discriminated between the two configurations with little to no overlap between these two vehicle configurations which, as previously noted, are near the proposed stability acceptance criteria for FMVSS 126.

The standard deviations of Yaw Rate Ratio @ 1 second due to track and run-to-run had similar values of approximately 0.05. The variation due to temperature was found to be ~0.12 over a 54 deg F temperature range.

Yaw Rate Ratio @ 1.75 seconds had a track to track standard deviation of ~0.07, a run-to-run standard deviation of ~0.10, and a variation of ~0.15 over a 54 deg F temperature range.

Responsiveness metric

The responsiveness metric discriminated, with no overlap, between these two vehicle configurations. Sensitivities to track and ambient temperature were found that are vehicle dependent.

Responsiveness (Min Dy) has a track-to-track standard deviation of approximately 0.31 feet or 2.8% of the mean. The range of observed Min Dy at five tracks is 10% of the mean. The run-to-run standard deviation is ~0.13 feet or 1.2% of the mean. The temperature sensitivity is 0.41 feet over a 54 deg F temperature range.

ACKNOWLEDGEMENTS

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APPENDIX A

Test Tracks

Figure A1. TRC Skidpad, 1800 ft. x 1200 ft., East Liberty, OH

Figure A2. GM Milford Proving Ground Skidpad, 1600 ft. x 1500 ft., Milford, MI

Figure A3. Michelin Proving Ground Skidpad, 1600 ft. x 400 ft., Laurens, SC

Figure A4. DCX Arizona Proving Ground Skidpad, 1350 ft. x 900 ft., Whitman, AZ

Figure A5. Dynamic Research Inc. Skidpad, 800 ft. x 300 ft., Shafter, CA

APPENDIX B

Table of Results

Configuration	YRR @ 1 sec	YRR @ 1.75 sec	Min Dy @ swa>=180 deg (ft)	Test Site	Temp Range	Final Temp	Test Org
302 - NHTSA, ESC Int'	0.28	0.16	9.65	TRC	---	55	NHTSA
302 - GM, ESC Int, Hot AM 1 TS-A'	0.20	0.02	10.11	GM MPG	Hot	72	GM
302 - GM, ESC Int, Hot AM 2 TS-C'	0.22	0.02	9.72	GM MPG	Hot	74	GM
302 - GM, ESC Int, Hot PM 1 TS-B'	0.29	0.10	10.09	GM MPG	Hot	88	GM
302 - GM, ESC Int, Hot PM 2 TS-D'	0.29	0.19	9.79	GM MPG	Hot	80	GM
302 - GM, ESC Int, Medium Temp AM 1 TS-A'	0.30	0.03	10.17	GM MPG	Medium	47	GM
302 - GM, ESC Int, Medium Temp AM 3 TS-D'	0.37	0.28	10.23	GM MPG	Medium	56	GM
302 - GM, ESC Int, Medium Temp PM 1 TS-B'	0.37	0.27	10.10	GM MPG	Medium	52	GM
302 - GM, ESC Int, Medium Temp PM 2 TS-C'	0.41	0.32	10.35	GM MPG	Medium	58	GM
302 - NHTSA, ESC Int, SC, Medium Temp AM 1 TS-A'	0.32	0.34	9.80	Lauren SC	Medium	63	NHTSA
302 - NHTSA, ESC Int, SC, Medium Temp AM 2 TS-C'	0.29	0.28	9.77	Lauren SC	Medium	56	NHTSA
302 - NHTSA, ESC Int, SC, Medium Temp PM 1 TS-B'	0.27	0.17	9.57	Lauren SC	Medium	60	NHTSA
302 - NHTSA, ESC Int, SC, Medium Temp PM 2 TS-D'	0.35	0.28	9.80	Lauren SC	Medium	64	NHTSA
302 - DCX, ESC Int, AZ, Medium Temp AM 1 TS-A'	0.49	0.29	9.77	DCX APG	Medium	79	DCX
302 - DCX, ESC Int, AZ, Medium Temp AM 2 TS-C'	0.35	0.02	9.70	DCX APG	Medium	74	DCX
302 - DCX, ESC Int, AZ, Medium Temp PM 1 TS-B'	0.44	0.43	9.71	DCX APG	Medium	68	DCX
302 - DCX, ESC Int, AZ, Medium Temp P M 2 TS-D'	0.48	0.51	9.86	DCX APG	Medium	65	DCX
302 - Ford, ESC Int, Medium Temp AM 3 TS-D'	0.26	0.02	9.43	DRI	Medium	65	Ford
302 - Ford, ESC Int, Medium Temp PM 1 TS-B'	0.30	0.11	10.04	DRI	Medium	56	Ford
302 - Ford, ESC Int, Medium Temp AM 1 TS-A'	0.28	0.06	9.93	DRI	Medium	72	Ford
302 - Ford, ESC Int, Medium Temp PM 2 TS-C'	0.26	0.05	10.11	DRI	Medium	77	Ford
302 - NHTSA, ESC Int, OH, Medium Temp AM 1 TS-A'	0.44	0.46	9.60	TRC	Medium	61	NHTSA
302 - NHTSA, ESC Int, OH, Medium Temp AM 2 TS-C'	0.32	0.30	9.87	TRC	Medium	57	NHTSA
302 - NHTSA, ESC Int, OH, Medium Temp AM 1 TS-B'	0.31	0.17	9.87	TRC	Medium	68	NHTSA
302 - NHTSA, ESC Int, OH, Medium Temp AM 2 TS-D'	0.26	0.05	9.76	TRC	Medium	72	NHTSA
302 - GM, ESC Int, Cold Temp AM 1 TS-A'	0.28	0.03	10.46	GM MPG	Cold	28	GM
302 - GM, ESC Int, Cold Temp PM 2 TS-C'	0.32	0.11	10.36	GM MPG	Cold	19	GM
302 - GM, ESC Int, Cold Temp PM 1 TS-B'	0.37	0.24	10.45	GM MPG	Cold	29	GM
302 - GM, ESC Int, Cold Temp AM 2 TS-D'	0.29	0.03	10.23	GM MPG	Cold	25	GM
Average	**0.33**	**0.18**	**9.95**				
St Dev	0.07	0.15	0.28				
M32, ESC MTrack Mode'	0.59	0.54	11.57	TRC	---	44	NHTSA
M32-NHTSA, ESC MTrack Mode, OH, Hot AM 1 TS-A'	0.74	0.67	11.95	TRC	Hot	66	NHTSA
M32-NHTSA, ESC MTrack Mode, OH, Hot PM 1 TS-B'	0.68	0.56	12.22	TRC	Hot	75	NHTSA
M32-NHTSA, ESC MTrack Mode, OH, Hot AM 2 TS-C'	0.76	0.64	12.52	TRC	Hot	63	NHTSA
M32-NHTSA, ESC MTrack Mode, OH, Hot PM 2 TS-D'	0.78	0.68	12.33	TRC	Hot	81	NHTSA
M32-GM, ESC MTrack Mode, Medium AM 1 TS-A'	0.78	0.60	12.35	GM MPG	Medium	65	GM
'M32-GM, ESC MTrack Mode, Medium PM 1 TS-B'	0.74	0.67	12.50	GM MPG	Medium	69	GM
'M32-GM, ESC MTrack Mode, Medium AM 2 TS-C'	0.72	0.58	12.32	GM MPG	Medium	59	GM
'M32-3-GM, ESC MTrack Mode, Medium PM 2 TS-D'	0.68	0.57	12.45	GM MPG	Medium	69	GM
M32 - NHTSA, ESC Int, OH, Medium Temp AM 1 TS-A'	0.70	0.69	12.51	TRC	Medium	48	NHTSA
M32 - NHTSA, ESC Int, OH, Medium Temp PM 1 TS-B'	0.73	0.65	12.42	TRC	Medium	66	NHTSA
M32 - NHTSA, ESC Int, OH, Medium Temp AM 2 TS-C'	0.73	0.62	12.50	TRC	Medium	51	NHTSA
M32 - NHTSA, ESC Int, OH, Medium Temp PM 2 TS-D'	0.73	0.64	12.60	TRC	Medium	60	NHTSA
M32 - NHTSA, ESC Int, SC, Medium Temp AM 1 TS-A'	0.73	0.63	12.37	Lauren SC	Medium	60	NHTSA
M32 - NHTSA, ESC Int, SC, Medium Temp PM 1 TS-B'	0.69	0.65	11.95	Lauren SC	Medium	59	NHTSA
M32 - NHTSA, ESC Int, SC, Medium Temp AM 2 TS-C'	0.83	0.61	12.16	Lauren SC	Medium	52	NHTSA
M32 - NHTSA, ESC Int, SC, Medium Temp PM 2 TS-D'	0.77	0.71	12.04	Lauren SC	Medium	64	NHTSA
M32-Ford, ESC MTrack Mode, Cool AM 1 TS-A'	0.67	0.63	11.92	DRI	Medium	65	Ford
M32-Ford, ESC MTrack Mode, Cool PM 1 TS-B'	0.73	0.68	11.99	DRI	Medium	67	Ford
M32-Ford, ESC MTrack Mode, Cool AM 2 TS-C'	0.90	0.79	12.14	DRI	Medium	77	Ford
M32-Ford, ESC MTrack Mode, Cool PM 2 TS-D'	0.77	0.65	12.21	DRI	Medium	55	Ford
M32 - DCX, ESC Int, AZ, Medium Temp AM 1 TS-A'	0.68	0.57	11.52	DCX APG	Medium	69	DCX
M32 - DCX, ESC Int, AZ, Medium Temp PM 1 TS-B'	0.68	0.53	11.55	DCX APG	Medium	71	DCX
M32 - DCX, ESC Int, AZ, Medium Temp AM 2 TS-C'	0.60	0.53	11.48	DCX APG	Medium	70	DCX
M32 - DCX, ESC Int, AZ, Medium Temp PM 2 TS-D'	0.76	0.62	11.42	DCX APG	Medium	77	DCX
M32 - NHTSA, ESC Int, OH, Cold Temp AM 1 TS-A'	0.86	0.78	11.77	TRC	Cold	23	NHTSA
M32 - NHTSA, ESC Int, OH, Cold Temp PM 1 TS-B'	0.78	0.71	12.27	TRC	Cold	28	NHTSA
M32 - NHTSA, ESC Int, OH, Cold Temp AM 2 TS-C'	0.84	0.77	11.90	TRC	Cold	28	NHTSA
M32 - NHTSA, ESC Int, OH, Cold Temp PM 2 TS-D'	0.87	0.81	12.50	TRC	Cold	38	NHTSA
Average	**0.74**	**0.65**	**12.12**				
St Dev	0.07	0.08	0.36				