Additional Analyses of the Monte Carlo Model Developed for the Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program

United States
Environmental Protection
Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
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NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data generated in the associated test program. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position, or regulatory action.

EPA United States Environmental Protection Agency

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EXECUTIVE SUMMARY

This report documents the program conducted by Southwest Research Institute® (SwRI), on behalf of the U.S. Environmental Protection Agency (EPA), the objective of which was to perform additional analyses on the Portable Emissions Measurement Systems (PEMS) Monte Carlo simulation models in order to determine validation of the three emissions ($BSNO_X$, BSNMHC and BSCO) using three calculation methods.

Several steady-state error surfaces were modified based on recommendations from the Heavy-Duty In-Use Testing (HDIUT) Steering Committee. These included modifications to the steady-state NO_X, exhaust flow rate, CO and CO_2 error surfaces. Several reference NTE events were run which produced validation results from all three emissions and all three calculation methods.

Measurement allowances were computed for two of the simulation strategies based on using 50 reference NTE events. The Mod 1 strategy involved changing the steady-state CO, CO_2 and exhaust flow rate error surfaces to eliminate bias while changing the steady-state NO_X to a level independent error surface including all the test data. The Mod 2 strategy was the same as Mod 1 except the steady-state NO_X error surface was also changed to a level independent error surface but excluded several questionable low NO_X values from one of the test engines. The measurement allowance values by calculation method determined at the conclusion of these analyses are summarized in Table 1. This report details the process used to determine the measurement values reported in Table 1.

TABLE 1. MEASUREMENT ALLOWANCES FOR MOD 1 AND MOD 2

Pollutant	Calculation Method	Mod 1 Measurement Allowance, g/hp-hr	Mod 2 Measurement Allowance, g/hp-hr
NO_X	1	0.232	0.211
	2	0.178	0.151
	3	0.192	0.171
NMHC	1	0.015	0.014
	2	0.014	0.014
	3	0.014	0.014
CO	1	0.268	0.266
	2	0.258	0.250
	3	0.270	0.262

LIST OF ACRONYMS

Brake-Specific	BS
California Air Resources Board	CARB
Center for Environmental Research & Technology	CE-CERT
Code of Federal Regulations	CFR
Electronic Flow Meter	EFM
Empirical Distribution Function	EDF
Engine Control Module	ECM
Engine Manufacturer's Association	EMA
Environmental Protection Agency	EPA
Heavy Duty In-Use Testing	HDIUT
Heavy Heavy Duty	HHD
Light Heavy Duty	LHD
Median Absolute Deviation	MAD
Medium Heavy Duty	MHD
Memorandum of Agreement	MOA
Mobile Emissions Laboratory	MEL
Not To Exceed	NTE
Portable Emissions Measurement System	PEMS
Root Mean Square	RMS
SEMTECH-DS SN G05-SDS04	PEMS 1
SEMTECH-DS SN G05-SDS02	PEMS 2
SEMTECH-DS SN G05-SDS03	PEMS 3
SEMTECH-DS SN G05-SDS01	PEMS 4
SEMTECH-DS SN D06-SDS01	PEMS 5
SEMTECH-DS SN D06-SDS06	PEMS 6
SEMTECH-DS SN F06-SDS02	PEMS 7
Southwest Research Institute	SwRI
Standard Deviation	SD

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Southwest Research Institute completed a Portable Emissions Measurement System (PEMS) program on behalf of the U.S. Environmental Protection Agency (EPA) in early April 2007. The purpose of this project was to determine the brake-specific (BS) measurement allowances for the gaseous pollutants regulated under the Heavy-Duty In-Use Testing (HDIUT) program [Ref 1]. The study was performed under cooperation between the EPA, the California Air Resources Board (CARB), and the Engine Manufacturer's Association (EMA). All efforts during this program were conducted under the direction of a joint body, the HDIUT Measurement Allowance Steering Committee, referred to in this report simply as the Steering Committee.

The program consisted of modeling various PEMS measurement errors using a statistical Monte Carlo modeling simulation. The simulation results were used to generate the brake-specific measurement allowances based on three calculation methods for BS emissions of NO_x, NMHC and CO. To confirm the results of the simulation, a SEMTECH-DS PEMS was operated in-use with the CE-CERT Mobile Emission Laboratory (MEL) over several routes in California. The differences between the PEMS and MEL gaseous emission measurements were used to validate the SwRI Monte Carlo modeling simulation results.

Calculation Methods 2 (BSFC based) and 3 (ECM Fuel Specific) did not validate for $BSNO_x$ based on the CE-CERT MEL emissions and the Monte Carlo PEMS simulations. Given this result, EPA contracted with SwRI in April 2007 to conduct additional analyses to identify possible causes as to why the $BSNO_x$ did not validate. The results of these analyses are included in this report.

2.0 ERROR SURFACE MODIFICATIONS

Since calculation Methods 2 and 3 did not validate for $BSNO_x$ after the Monte Carlo model simulation runs during the original PEMS study, the associated Steering Committee chose to modify key error surfaces in order to determine if such alterations would effect the validation of Methods 2 and 3. Over the course of several meetings, the Steering Committee brainstormed to generate alternate error surface processing methods. The Committee decided to modify Steady-State CO, CO_2, Exhaust Flow Rate, and NO_x, as these surfaces had significant influence on the Model results based on the sensitivity analyses.

In reprocessing the error surfaces, the Steering Committee agreed that it would be necessary to remove any biases that were recorded in the SwRI laboratory. It was assumed that these bias errors were due to the limited number of PEMS units and comparative observations, and that if more PEMS and Sensors Inc. exhaust flow meters were tested the biases *may* have been eliminated. Therefore, to remove the biases the original steady-state error surfaces were transformed to be a symmetric error surface with the 50^{th} percentile errors set to zero and the 5^{th} and 95^{th} percentile errors modified to be a mirror image of one another. Two analysis methods were used to generate the revised error surfaces. If the recorded error data showed an emissions level dependency, an envelope was generated to encompass the extreme 5^{th} or 95^{th} percentile error data. The envelope segments with the largest absolute error were then mirrored to generate a symmetric error surface. A more rigorous analysis was used to reprocess level independent error surfaces.

2.1 Steady-State Exhaust Flow Rate Error Surface

Figure 1 shows the reprocessed, level-dependent steady-state exhaust flow rate error surface as well as the exhaust flow error surface data that was used in the original MC model runs. The largest errors recorded during laboratory testing were positive deltas measured during Engine 3 testing with the 3-inch EFMs. The 3-inch EFM errors defined the 95^{th} percentile error contours for the original error surface as well as the reprocessed error surface. The difference between the two 95^{th} percentile contours was due to a correction of the 3-inch EFM calibrations when the exhaust flow rate error surface was reprocessed. SwRI and Sensors Inc. had recalibrated the 3-inch flow meters using data generated at SwRI. The SwRI calibration increased the slope multiplier by approximately 4 % for each 3-inch flow meter. Later in the program, Sensors Inc. discovered the 3-inch EFMs were likely not operating correctly on the SwRI flow stand due to EFM pressures below ambient levels. Therefore, each 3-inch flow meter calibration was corrected to the original coefficients generated by Sensors. The corrected 3-inch flow meter data generated the 95^{th} percentile contour shown in Figure 1. Because the 95^{th} percentile errors were larger than the 5^{th} percentile errors, the 95^{th} percentile data was mirrored to generate the 5^{th} percentile contour in the reprocessed error surface.

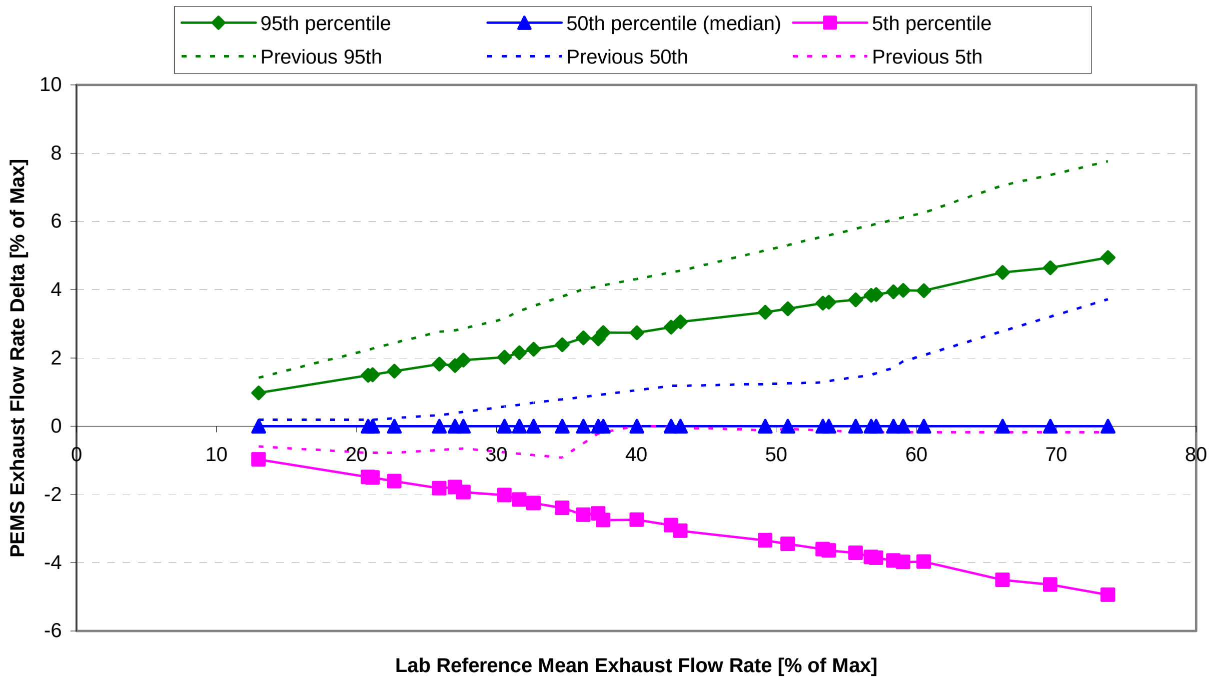

FIGURE 1. REVISED ERROR SURFACE FOR STEADY-STATE EXHAUST FLOW RATE

2.2 Steady-State CO_2 Error Surface

Figure 2 shows the reprocessed, level-dependent CO_2 error surface. The 95th percentile contour represents the envelope that was created to encompass the original 95th percentile error data. Line segments were used to connect the most extreme points from the original 95th percentile data. The 95th percentile contour was mirrored to produce the 5th percentile error data, with the 50th percentile deltas set to zero. The reprocessed error surface was meant to encompass all possible PEMS CO_2 measurement errors, not just those measured at SwRI.

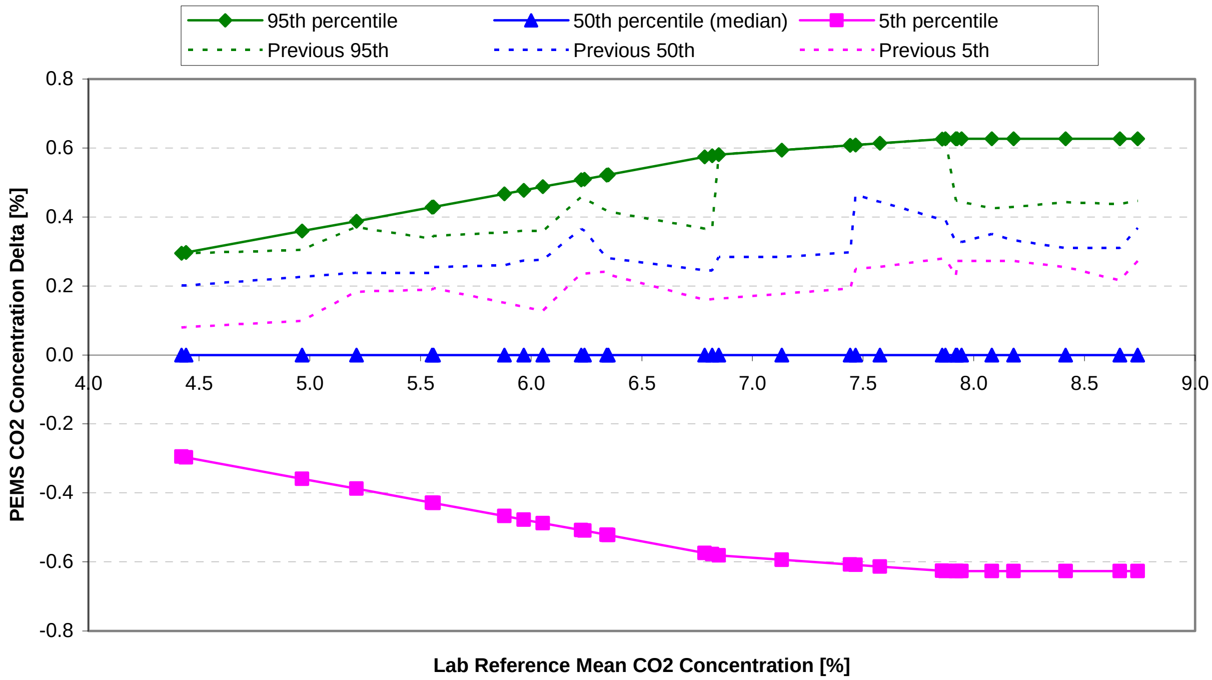

FIGURE 2. REVISED ERROR SURFACE FOR STEADY-STATE CO_2

2.3 Steady-State CO Error Surface

Figure 3 shows the revised steady-state error surface for CO. Because the CO error data showed no level dependence, a statistical calculation process, developed by Bill Martin from Cummins Inc., was used to generate the reprocessed CO error surface. The total standard deviation of the pooled CO error data was calculated by combining the variance of the PEMS mean delta standard deviation about zero and the PEMS pooled estimate of repeatability standard deviation. The calculation of the total standard deviation is shown below.

$$SD_{total} = \sqrt{SD_{repeatability}{}^2 + SD_{mean,zero}{}^2}$$

$$SD_{repeatability} = \sqrt{\frac{\sum_{1}^{n} SD_{indiv,pems}{}^2}{n}}$$

$SD_{indiv,pems}$ = standard deviation of each PEMS calculated over 20 repeats of each steady-state point

n = 10 steady-state points per engine * 3 engines * 3 PEMS = 90

$$SD_{mean,zero} = \sqrt{\frac{\sum_{1}^{n}\left(PEMS_{indiv,mean} - 0\right)^2}{n-1}}$$

$PEMS_{indiv,mean}$ = mean delta of each PEMS calculated over 20 repeats of each steady-state point

Shown below, the multiplier for a 90% confidence interval assuming a normal distribution for the errors was applied to the total standard deviation (48.84 ppm = 0.004882%) to generate the constant 5th and 95th percentile error values.

$$5^{th}\,\% = -1.645 * SD_{total} = -0.008\%$$

$$95^{th}\,\% = 1.645 * SD_{total} = +0.008\%$$

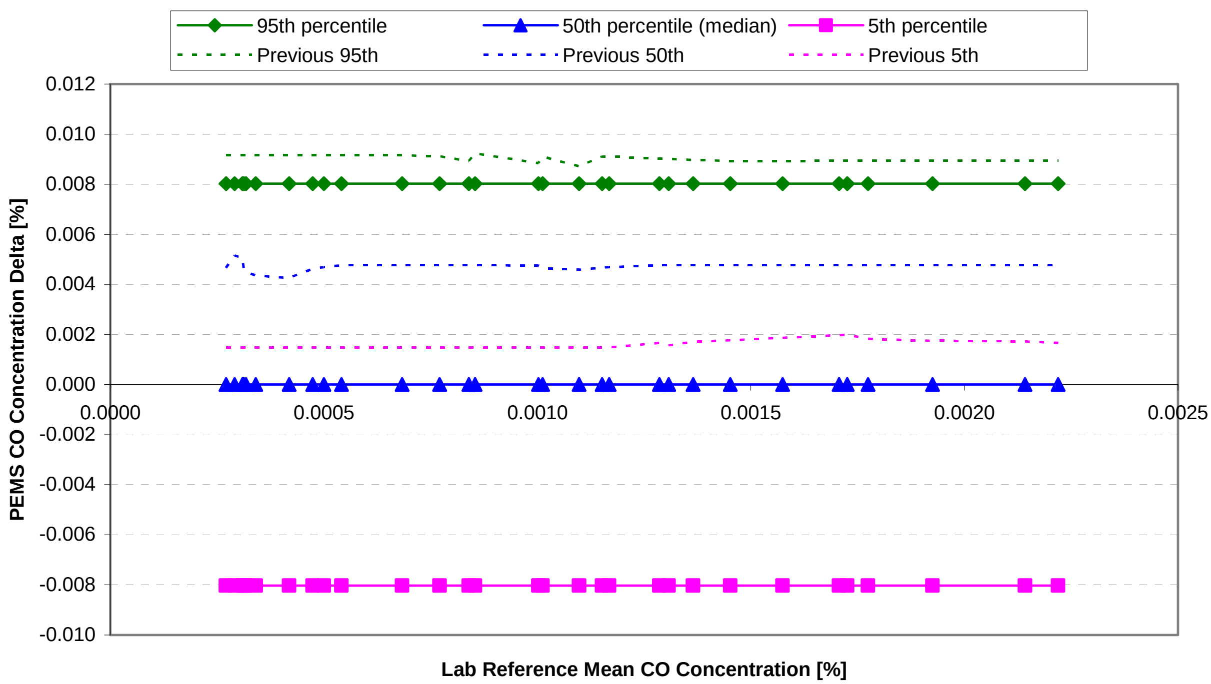

FIGURE 3. REVISED ERROR SURFACE FOR STEADY-STATE CO

2.4 Steady-State NO_x Error Surface

For reprocessing the original steady-state NO_x, three different methods were used to generate three NO_x concentration error surfaces. For each of the three modified NO_x error surfaces, the original set of Engine 2 steady-state data was added to the original pooled data set. The Engine 2 steady-state data was collected in a repeat run in the original study due to PEMS failures that caused a large time gap in the original data. The time gap was associated with a NO_x concentration shift. Since the NO_x shift would have caused problems with the steady-state variance correction of the transient data the repeat run data was used. However, the original Engine 2 delta data was later determined to be valid and thus was included in the modified data set to increase the PEMS delta observations.

The first NO_x error surface modification (Mod 1) followed a procedure similar to the steady-state CO error surface. Using the complete NO_x delta data set, the 5th and 95th percentile error values were calculated with the total standard deviation (15.08 ppm). The results of the first NO_x error surface modification are shown in Figure 4 with the 5th and 95th percentiles set to ±24.80 ppm.

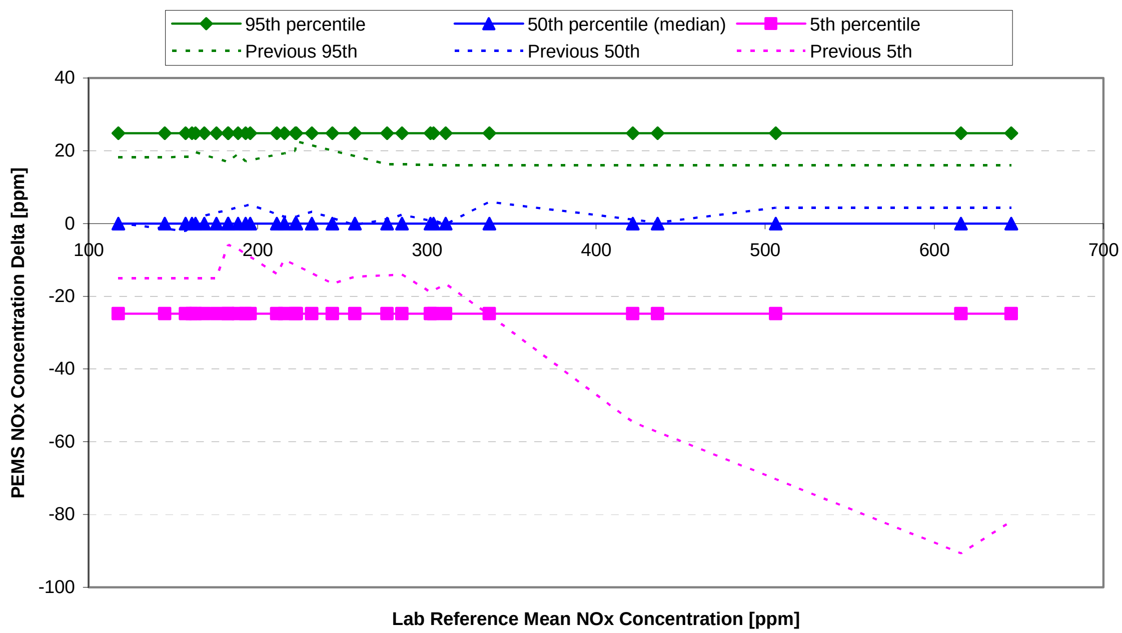

FIGURE 4. REVISED ERROR SURFACE MOD 1 FOR STEADY-STATE NO_X

The second NO_x error surface modification (Mod 2) was similar to the first modification except six outlying low delta values recorded during Engine 3 testing were removed from the pooled data set. During Engine 3 steady-state testing, PEMS 1 and 6 showed extremely low deltas at high NO_x concentration levels. PEMS 4 also showed low biases at high NO_x levels; however, the biases were not as large as those measured for the other PEMS. Therefore, PEMS 1 and 6 delta measurements at the three highest NO_x levels measured during engine testing were removed from the data set. This resulted in a total standard deviation equal to 9.39 ppm and the 5th and 95th percentile deltas equal to ±15.45 ppm. The results of this analysis are shown in Figure 5.

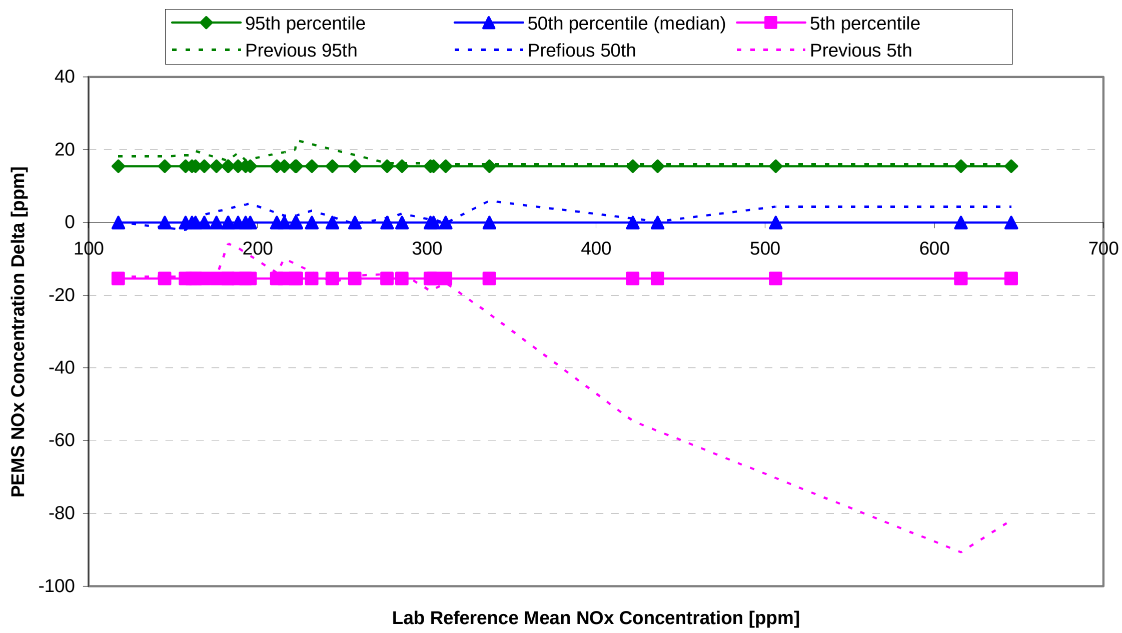

FIGURE 5. REVISED ERROR SURFACE MOD 2 FOR STEADY-STATE NO_X

Shown in Figure 6, the third NO_x error surface modification (Mod 3) combined the level-dependent and level-independent analysis methods. Below 311 ppm, the delta data was assumed to be level independent. Therefore, a statistical method similar to that used for CO was used for the NO_x delta data below 311 ppm. The total standard deviation for the level-independent data was 9.41 ppm and the resulting 5th and 95th percentiles were ± 15.48 ppm. Above 311 ppm, the original 5th percentile profile was used and mirrored to the 95th percentile to generate a symmetric error surface.

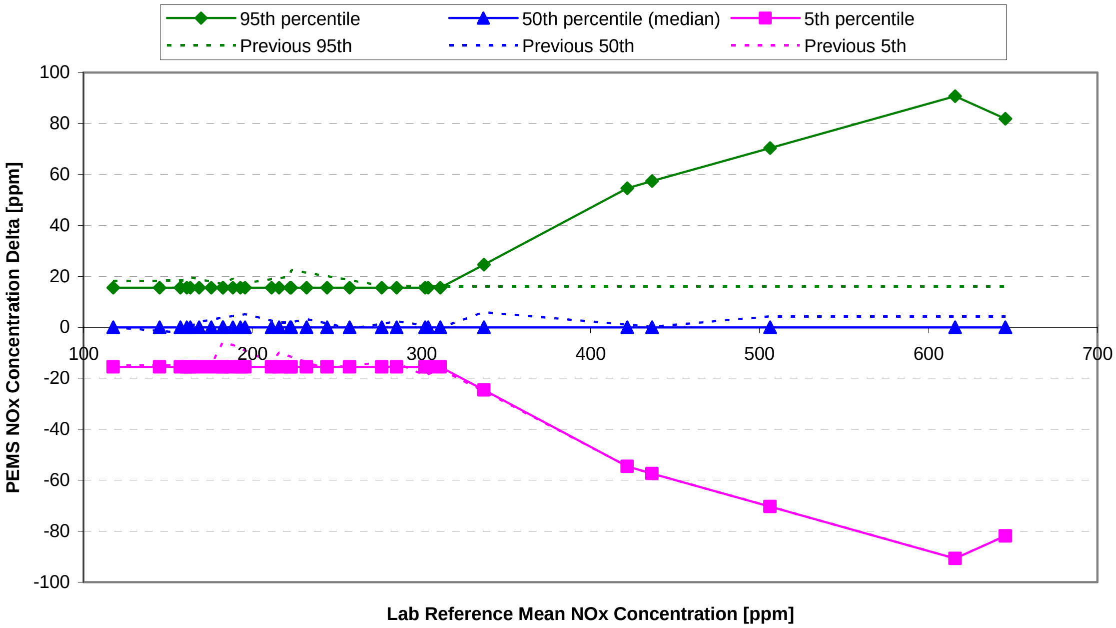

FIGURE 6. REVISED ERROR SURFACE MOD 3 FOR STEADY-STATE NO_X

In addition to running the MC simulations with the three different changes to the steady-state NO_X error surface, it was useful to run a simulation with the original steady-state NO_X error surface and only include the revised steady-state exhaust flow rate and steady-state CO_2 error surfaces. This set of simulations is called the Mod B runs. Table 2 provides a summary of the four MC simulation runs made in this study with the revised error surfaces that were included in each run. All the other error surfaces that are not listed in Table 2 are the same as those run in the original PEMS study.

TABLE 2. REVISED ERROR SURFACES USED IN MONTE CARLO SIMULATIONS

Steady-State Exhaust Flow Rate	X	X	X	X
Steady-State CO_2	X	X	X	X
Steady-State CO		X	X	X
Steady-State NO_x Mod 1		X		
Steady-State NO_x Mod 2			X	
Steady-State NO_x Mod 3				X

3.0 REFERENCE NTE EVENTS

The Monte Carlo simulation results from the original study included a reference data set consisting of 195 NTE events gathered from a number of sources. These included five engine manufacturers, SwRI transient lab tests and pre-pilot CE-CERT data. The investigations performed in this modified program included only a subset of the original 195 reference NTE events. Simulations from three different subsets of the original NTE events were run to study the validation of the emissions by the three calculation methods using the revised error surfaces.

Table 3 lists the NTE events along with their ideal $BSNO_x$ values selected for each simulation. The various NTE subsets are described as follows:

- 13 Reference Events – These are the same 13 NTE events chosen during the original study to investigate the error surface sensitivities due to bias and variance. These events were selected to bound the $BSNO_x$ threshold of 2.6820 g/kW-hr. These 13 NTE events were used to examine the error surface sensitivities for both the validation and full model simulation runs.
- 23 Reference Events – Ten additional NTE events were added to the original 13 NTE events described above in order to increase the sample size for generating the validation EDF plots using the drift corrected CE-CERT data.
- 50 Reference Events – After the model validation was confirmed for the three emissions across the three calculation methods, Mods 1 and 2 were chosen for continued analysis. Twenty-seven additional reference NTE events were simulated with the Monte Carlo model in order to estimate the measurement allowances for each emission. The selection of the additional 27 reference NTE events was based on maintaining a similar distribution of ideal $BSNO_x$ values for Method 1 established from the original study containing 195 reference NTE events.

Figure 7 shows comparison histograms of the Method 1 $BSNO_x$ values for the 23 reference NTE events (lower histogram) and the 195 reference NTE events (upper histogram) while Figure 8 compares the Method 1 $BSNO_x$ histograms for the 50 reference NTE events (lower histogram) and the 195 reference NTE events (upper histogram). Descriptive statistics of $BSNO_x$ for these NTE subsets are detailed in Table 4.

TABLE 3. REFERENCE NTE EVENTS USED IN MONTE CARLO SIMULATIONS

1	4.0713	X	X	X
3	3.0668		X	X
4	3.5832			X
7	5.2516		X	X
11	1.8583			X
16	2.3511			X
20	3.7245		X	X
22	4.7916			X
23	3.1483			X
25	5.4061	X	X	X
29	5.5261		X	X
37	5.4511			X
38	0.0250	X	X	X
40	4.1675			X
43	1.1473			X
44	1.0730	X	X	X
46	2.6958	X	X	X
51	2.8299	X	X	X
57	4.3382		X	X
63	2.6670	X	X	X
65	2.7437			X
66	3.9378			X
67	5.8600			X
69	3.0257	X	X	X
71	6.6867			X
82	2.4569	X	X	X
86	1.7132			X
87	1.5207	X	X	X
89	2.2566		X	X
92	1.6041			X
96	1.6224		X	X
99	1.8147			X
103	1.9186			X
115	1.3854			X
125	2.3214			X
127	3.3005			X
136	2.6782		X	X
139	2.4018		X	X
146	2.3053			X
148	1.9985	X	X	X
157	3.4666	X	X	X

160	2.0773			X
162	2.1405			X
163	2.5908	X	X	X
168	1.5859			X
176	1.9671		X	X
177	1.7507			X
179	2.2023			X
191	6.0815			X
193	5.7521			X

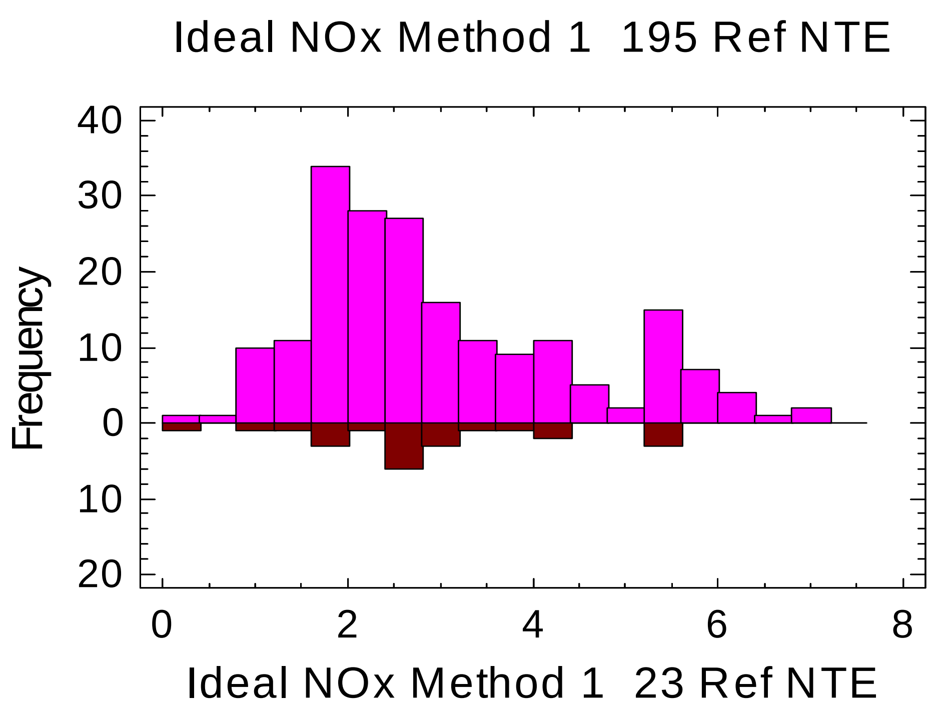

FIGURE 7. DISTRIBUTION OF IDEAL NOX (G/KW-HR) METHOD 1 FOR 23 SELECTED REF NTE EVENTS AND 195 REF NTE EVENTS

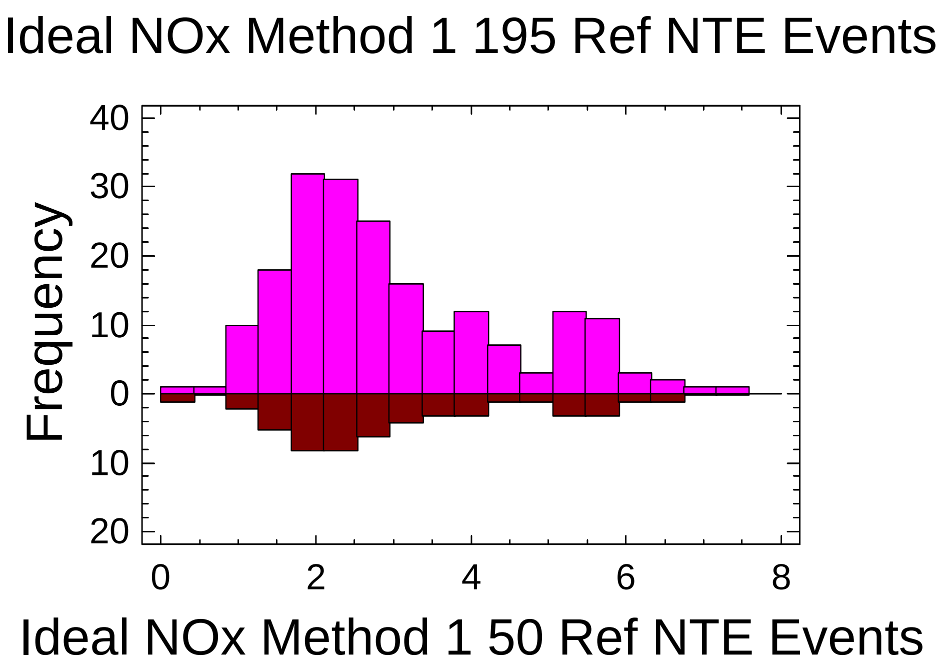

FIGURE 8. DISTRIBUTION OF IDEAL NOX (G/KW-HR) METHOD 1 FOR 50 SELECTED REF NTE EVENTS AND 195 REF NTE EVENTS

TABLE 4. DESCRIPTIVE STATISTICS FOR IDEAL BSNO$_X$ (G/KW-HR) FOR VARIOUS NTE SUBSETS

Minimum	0.0249	0.0249	0.0249
Maximum	5.5261	6.6867	7.1927
Mean	2.8983	3.0068	3.0071
Median	2.6782	2.6289	2.6033
Standard Deviation	1.3671	1.5175	1.4807

4.0 CE-CERT MEASUREMENTS

The CE-CERT on-road measurements collected during the original PEMS study included delta BS emissions for all three emissions and three calculation methods. As part of this study to investigate all possible reasons why $BSNO_x$ did not validate for Methods 2 and 3, the 100 NTE events from the CE-CERT data were examined for correctness by EPA. Since the CE-CERT data had not been drift corrected in the original PEMS study, EPA performed drift corrections on all three emissions for the 100 CE-CERT NTE events. As a result, several CE-CERT NTE events did not pass the drift check criteria and, therefore, were not included in the simulation performed for this study. In addition, time alignment problems were found in a few of the 100 CE-CERT NTE events and these were also excluded from the simulation. After deleting the NTE events due to drift check or time alignment problems, the on-road delta BS emissions were calculated from 81 NTE events for $BSNO_x$ and 87 NTE events for BSNMHC and BSCO. These remaining CE-CERT NTE events were all drift corrected. In contrast, the original PEMS program did not use drift correction in the CE-CERT on-road NTE events.

5.0 MONTE CARLO VALIDATION RESULTS FROM 23 REFERENCE NTE EVENTS USING MOD 1, MOD 2 AND MOD 3

The Monte Carlo simulations performed using the 23 reference NTE events listed in Table 3 included modifications for the error surfaces listed in Table 2. All the error surfaces from the original MC simulations were used except those listed as revised in Table 2. Each of the 23 reference NTE events were run using the error surfaces revised for Mod 1 for either 10,000 or 30,000 trials. If the ideal $BSNO_X$ for an NTE event was less than 2.68204 g/kW-hr then the simulation was run for 10,000 trials. Otherwise, the NTE was simulated using 30,000 trials. Once the MC simulations were completed using the Mod 1 revised error surfaces, the same 23 NTE events were simulated a second time with the error surface modifications for Mod 2. Lastly, the 23 reference NTE events were simulated using the error surface modifications for Mod 3.

In Mod 1, Mod 2, and Mod 3 simulation runs, all three emissions converged within 1% of the emissions threshold value by all three calculation methods. Table 5 lists the convergence criteria for all three brake-specific emissions. Thus, all 23 reference NTE events met the convergence criteria.

TABLE 5. CONVERGENCE CRITERIA BY EMISSION

BSNOx	0.02682
BSNMHC	0.00282
BSCO	0.26015

From the MC simulations, the validation 5th and 95th percentile delta BS emissions were extracted from the output files for each of the 23 reference NTE events. These delta emissions were then plotted as empirical distribution functions (EDF) to form a validation interval for the on-road data. Also plotted was the EDF computed from the on-road CE-CERT NTE events. Figure 9 through Figure 11 represent the validation plots for the $BSNO_x$ for calculation methods 1, 2 and 3, respectively. Each of the validation plots includes 5th and 95th percentile EDFs for the Mod 1, Mod 2, and Mod 3 runs. Figure 12 through Figure 17 depict the validation plots for the BSNMHC and BSCO simulation runs, respectively. The validation criteria set by the Steering Committee for the original study was used in the modified program. It included the following criteria:

- At least 90% of the CE-CERT emissions deltas must be within the 5th and 95th percentiles of the MC validation cumulative emissions deltas.
- No more than 10% of the CE-CERT emissions deltas may fall less than the 5th percentile or greater than the 95th percentile. This may indicate that the model is biased low or high.
- Validation must be shown for all three calculation methods.

A summary of the $BSNO_x$ validation conclusions based on the 23 reference NTE events is provided in Table 6. All $BSNO_X$, BSNMHC and BSCO emissions validated for all three calculation methods and all three Mod runs.

TABLE 6. $BSNO_X$ VALIDATION RESULTS BASED ON 23 REFERENCE NTE EVENTS

Mod 1	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID	· All CE-CERT data > 5th percentile · 1% of CE-CERT data > 95th percentile · VALID	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID
Mod 2	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID	· All CE-CERT data > 5th percentile · 1% of CE-CERT data > 95th percentile · VALID	· All CE-CERT data > 5th percentile · 1% of CE-CERT data > 95th percentile · VALID
Mod 3	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID	· All CE-CERT data > 5th percentile · All CE-CERT data < 95th percentile · VALID

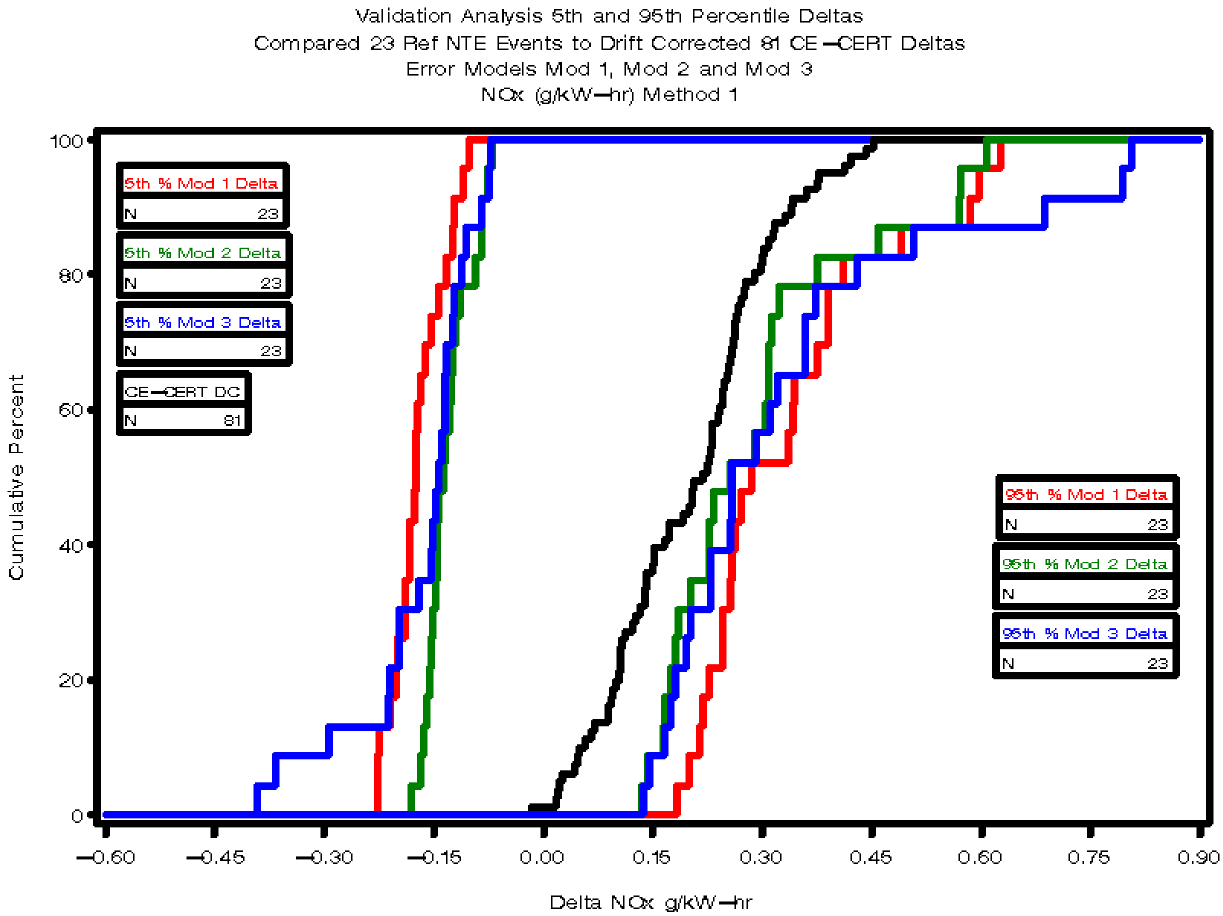

FIGURE 9. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 1 MODS 1, 2 AND 3

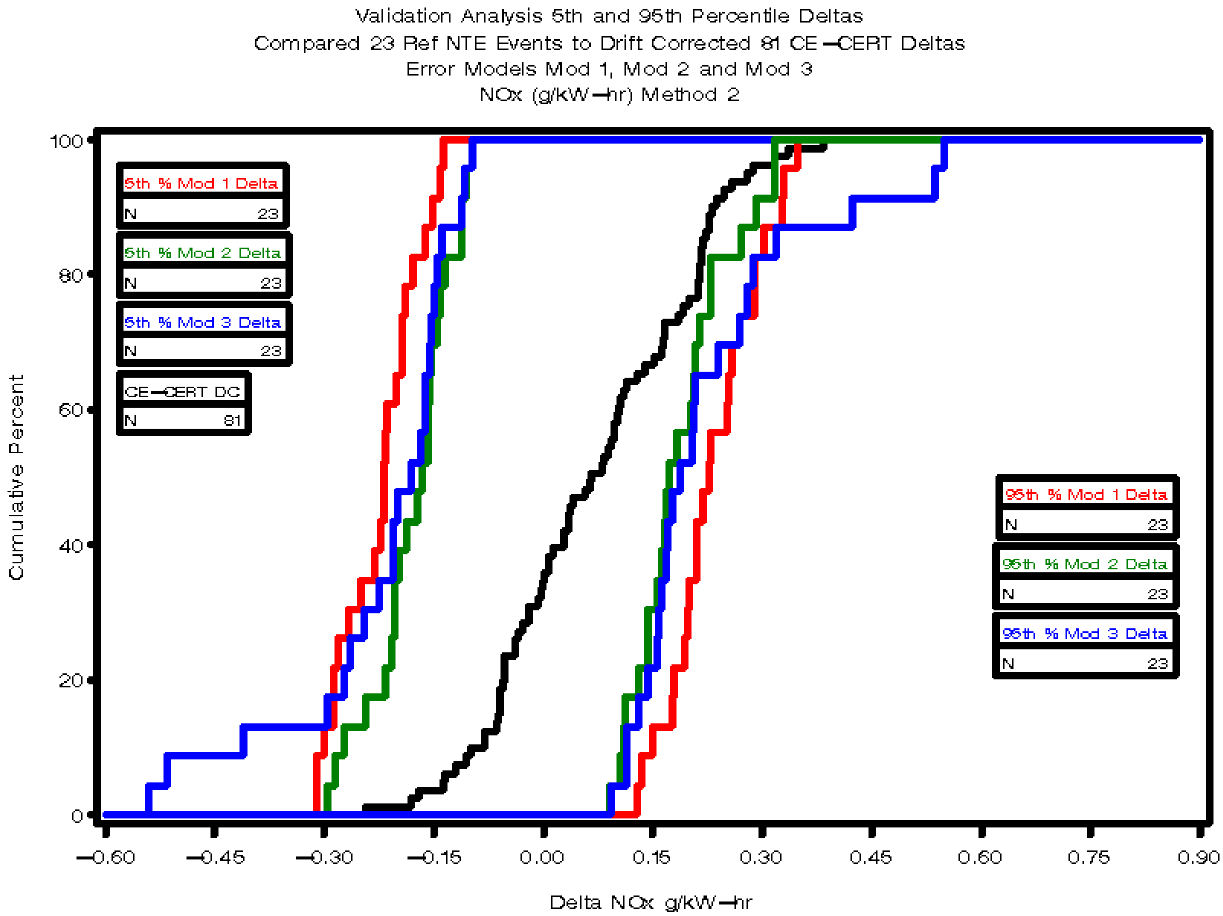

FIGURE 10. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 2 FOR MODS 1, 2 AND 3

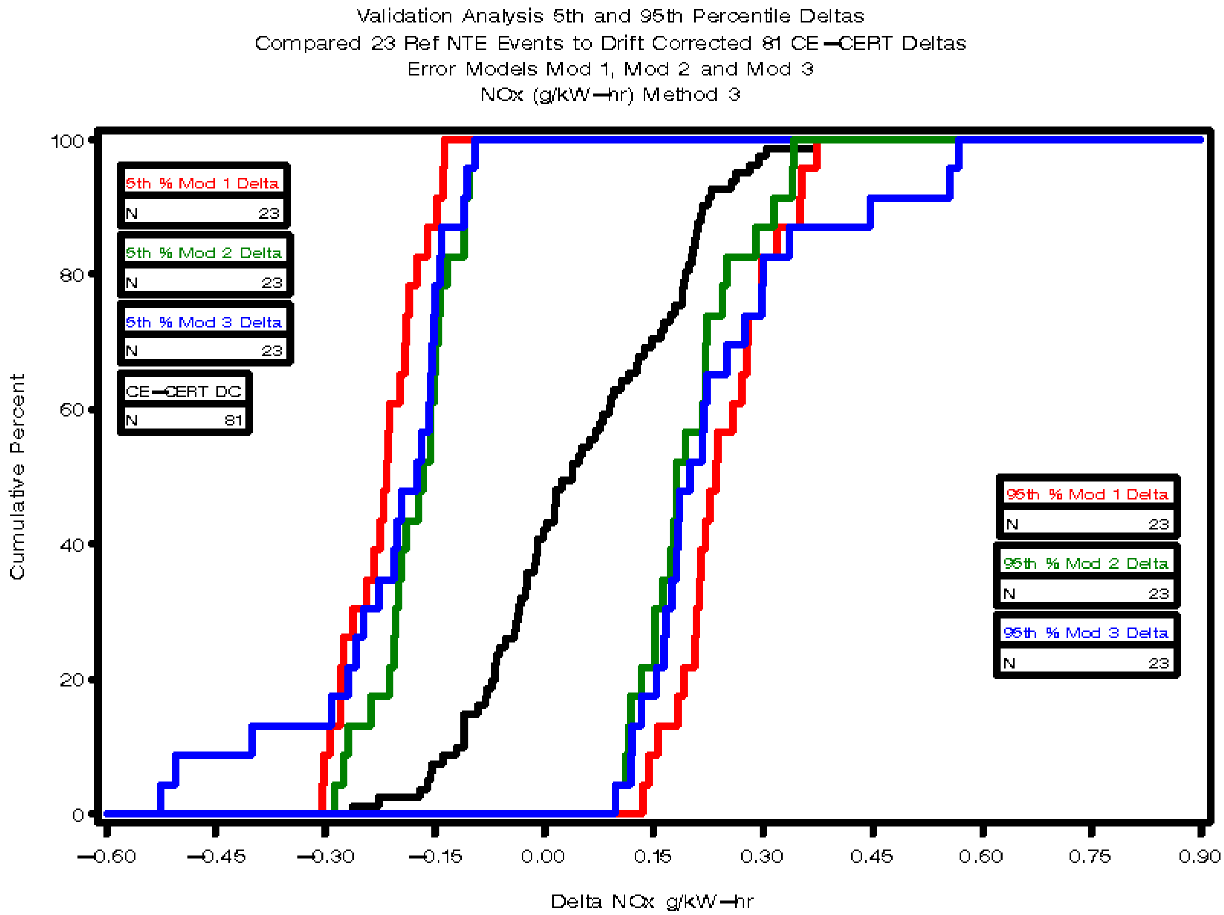

FIGURE 11. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 3 FOR MODS 1, 2 AND 3

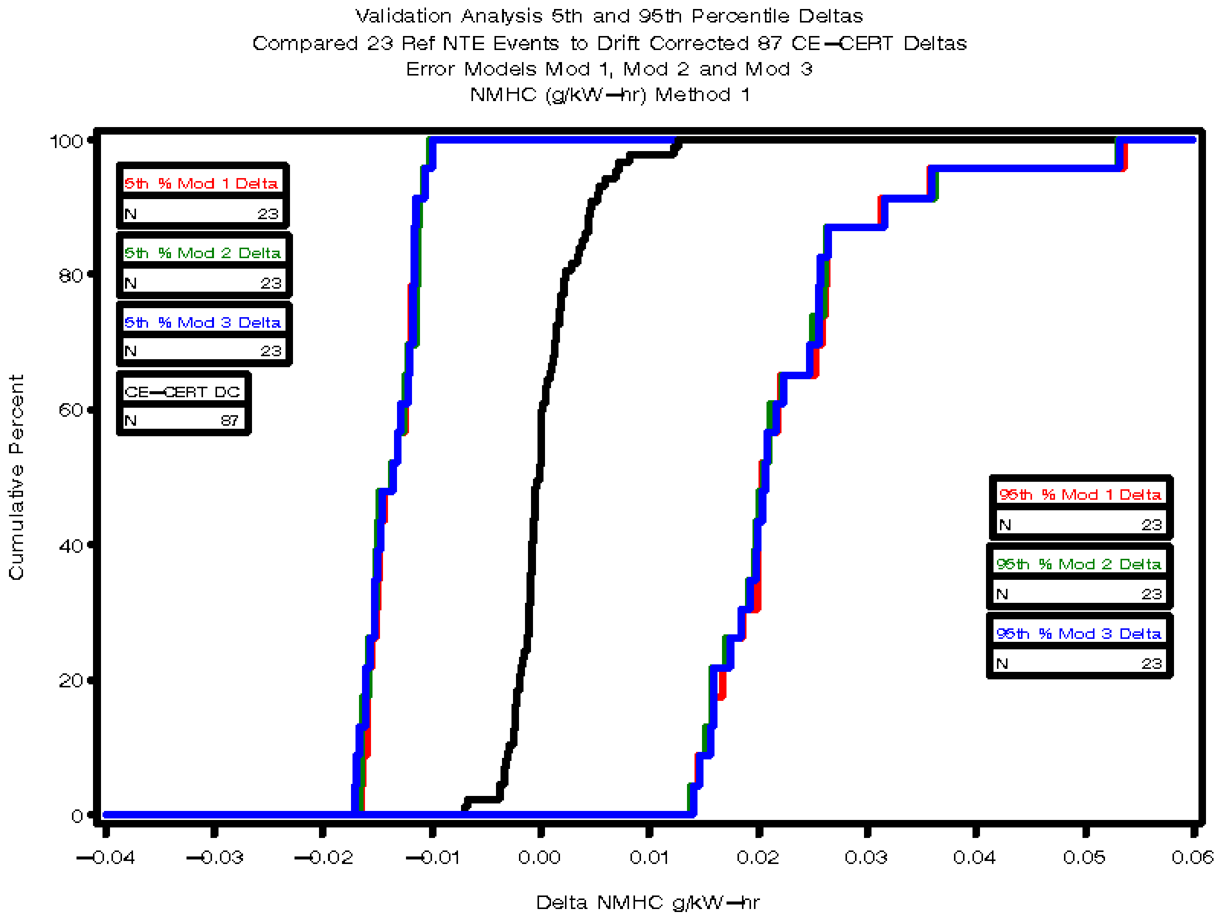

FIGURE 12. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 1 FOR MODS 1, 2 AND 3

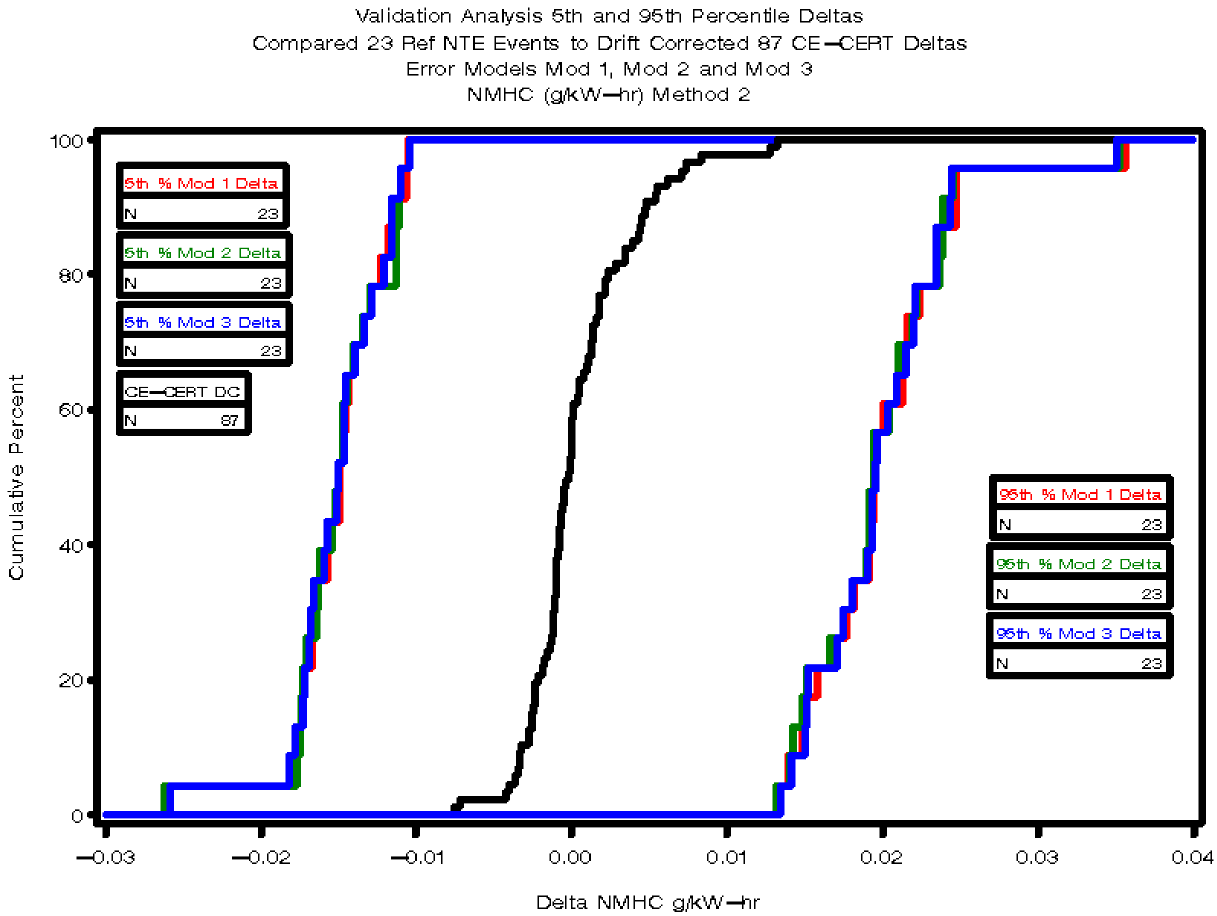

FIGURE 13. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 2 FOR MODS 1, 2 AND 3

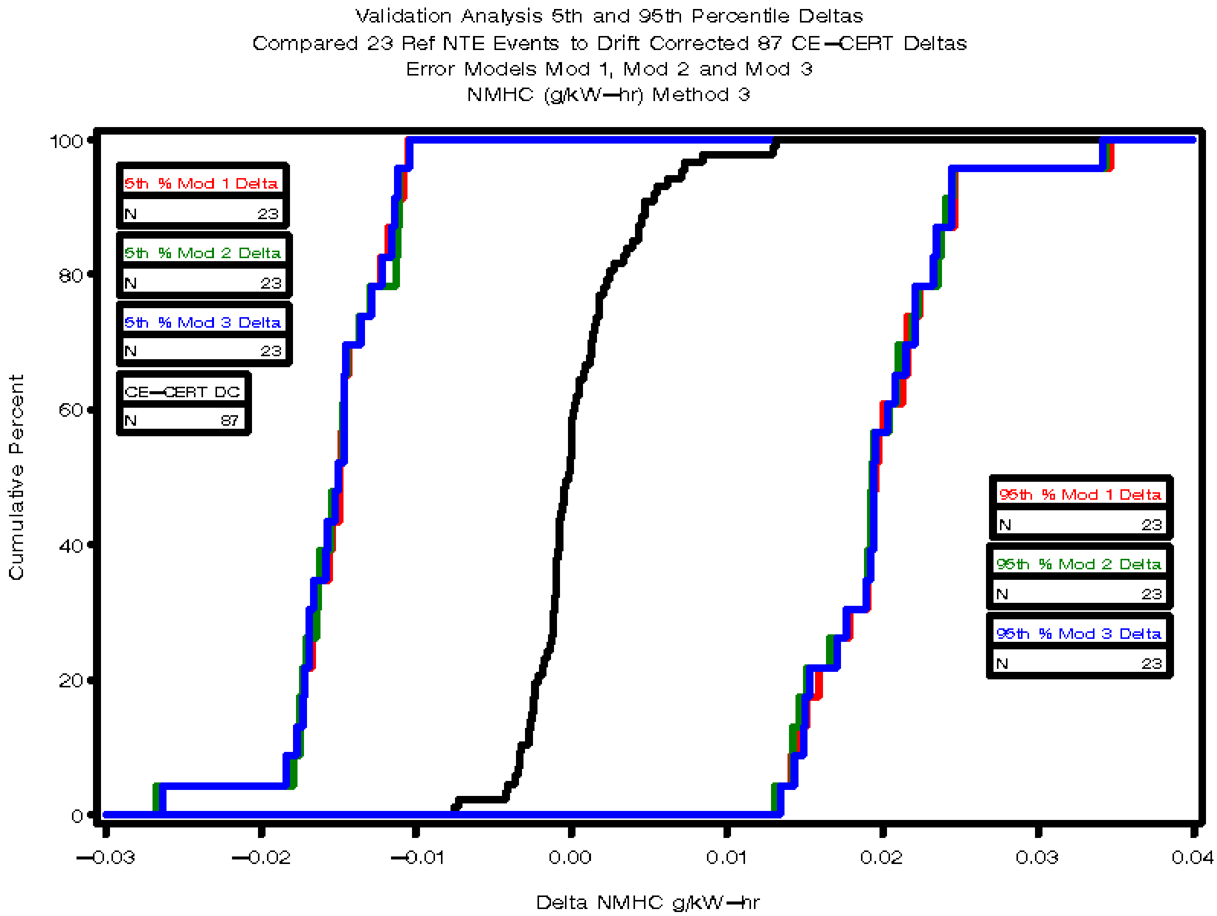

FIGURE 14. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 3 FOR MODS 1, 2 AND 3

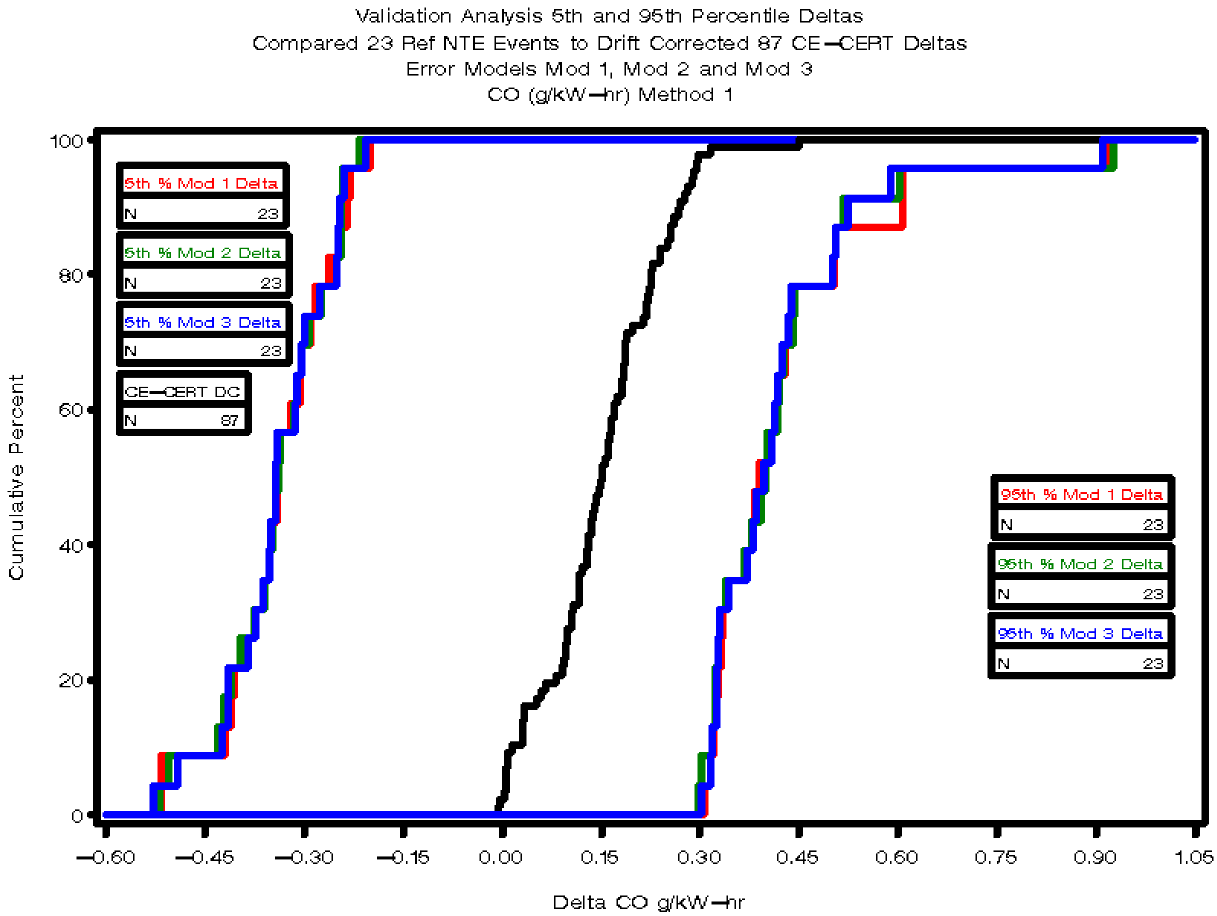

FIGURE 15. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 1 FOR MODS 1, 2 AND 3

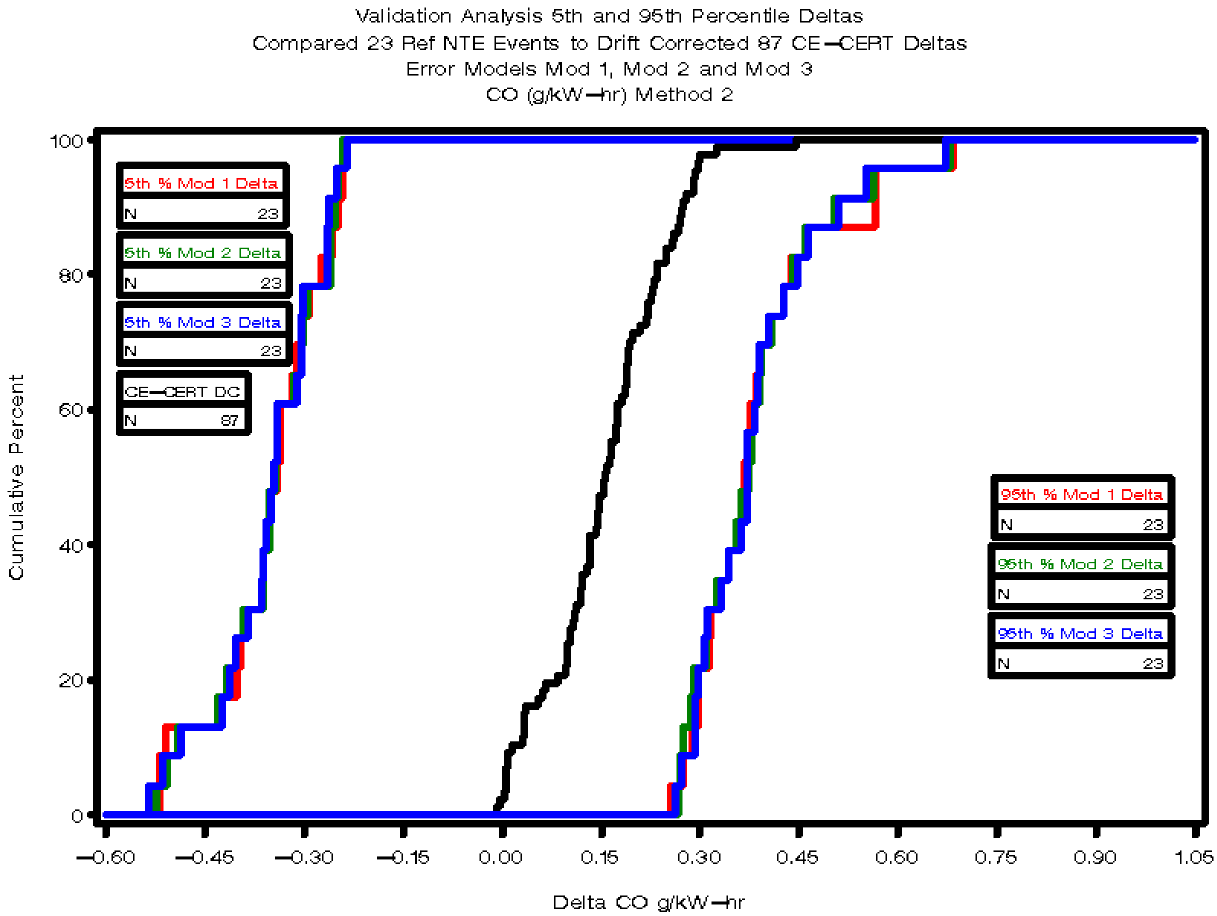

FIGURE 16. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 2 MODS 1, 2 AND 3

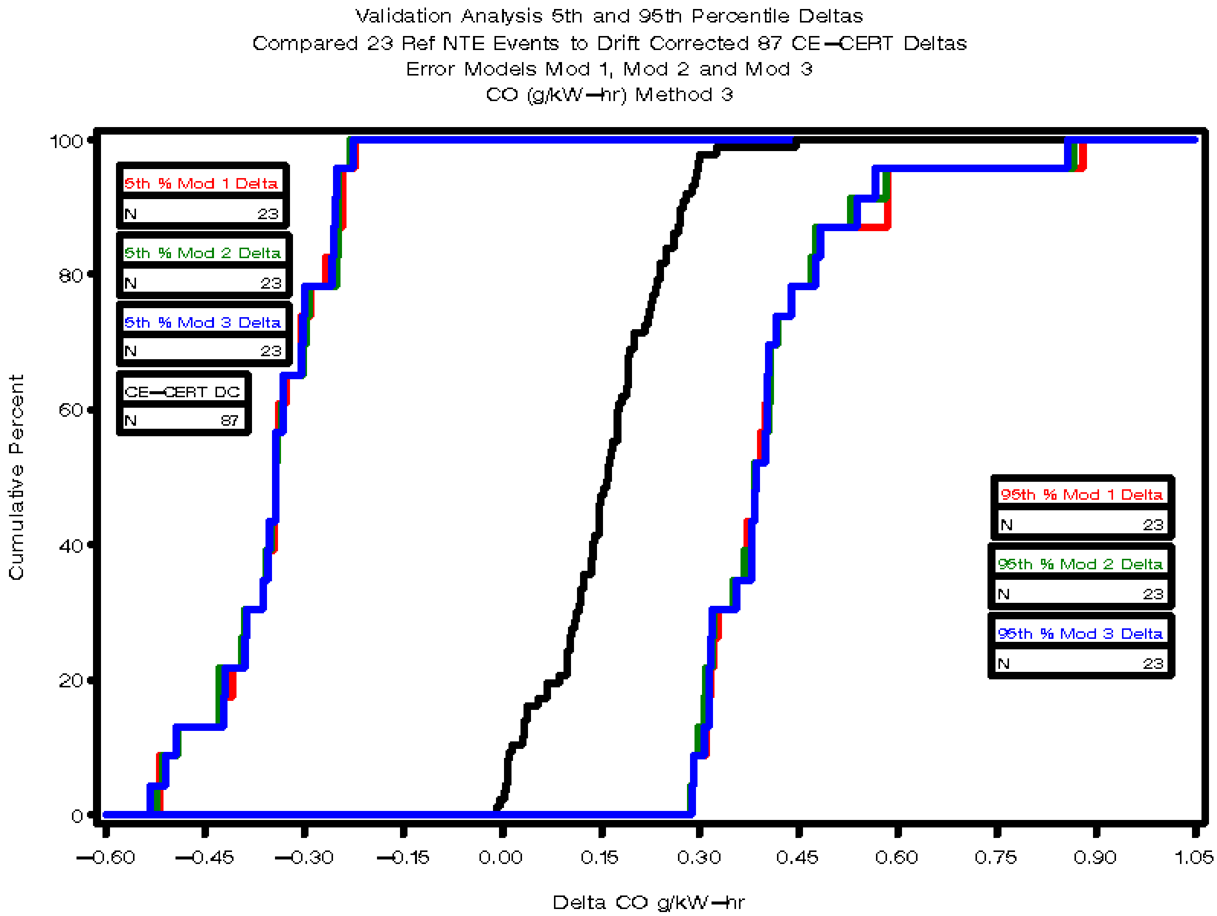

FIGURE 17. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 3 FOR MODS 1, 2 AND 3

6.0 MONTE CARLO VALIDATION RESULTS FROM 23 REFERENCE NTE EVENTS USING MOD B

Since all three methods validated using the 23 reference NTE events by all three modification runs for $BSNO_x$, BSNMHC and BSCO, the question arose as to which of the revised error surfaces had the most influence in the validation. Three possible explanations included (1) the steady-state CO_2 bias had been eliminated, (2) the change in the steady-state NO_X error values, and (3) the bias in the steady-state exhaust flow rate had been eliminated. To study these possible explanations, none of the revised $SSNO_x$ error surfaces or the SSCO error surface was used in the simulations. These error surfaces were set to their original format in the original PEMS study. Therefore, only the steady-state exhaust flow rate and the steady-state CO_2 error surfaces were revised and the other remaining validation error surfaces were set to their original definitions for running the 23 reference NTE events for the Mod B MC simulation. This set of simulations is referred to as the 'Mod B' runs. Again, the simulations were performed at 10,000 trials for NTE events with ideal BSNOx values less than 2.68204 g/kW-hr and at 30,00 trials otherwise. All 23 reference NTE events met the convergence criteria listed in Table 5.

From the Mod B MC simulations, the validation 5^{th} and 95^{th} percentile delta BS emissions were extracted from the output files for each of the 23 reference NTE events. These delta emissions were then plotted as empirical distribution functions (EDF) to form a validation interval for the on-road data. Also plotted was the EDF computed from the on-road CE-CERT NTE events. Figure 18 through Figure 20 represent the validation plots for the $BSNO_x$ for calculation methods 1, 2 and 3, respectively. Each of the validation plots includes 5^{th} and 95^{th} percentile EDFs for the Mod B runs and the on-road CE-CERT data. Figure 21 through Figure 26 depict the validation plots for the BSNMHC and BSCO simulation runs, respectively. All BSNOx, BSNMHC and BSCO emissions validated for all three calculation methods for the Mod B runs.

Conclusions made from the results of the Mod B analysis were that the steady-state NO_X error surface changes did not have as much of an effect on the validation as the bias elimination in the steady-state CO_2 and steady-state exhaust flow rate error surfaces.

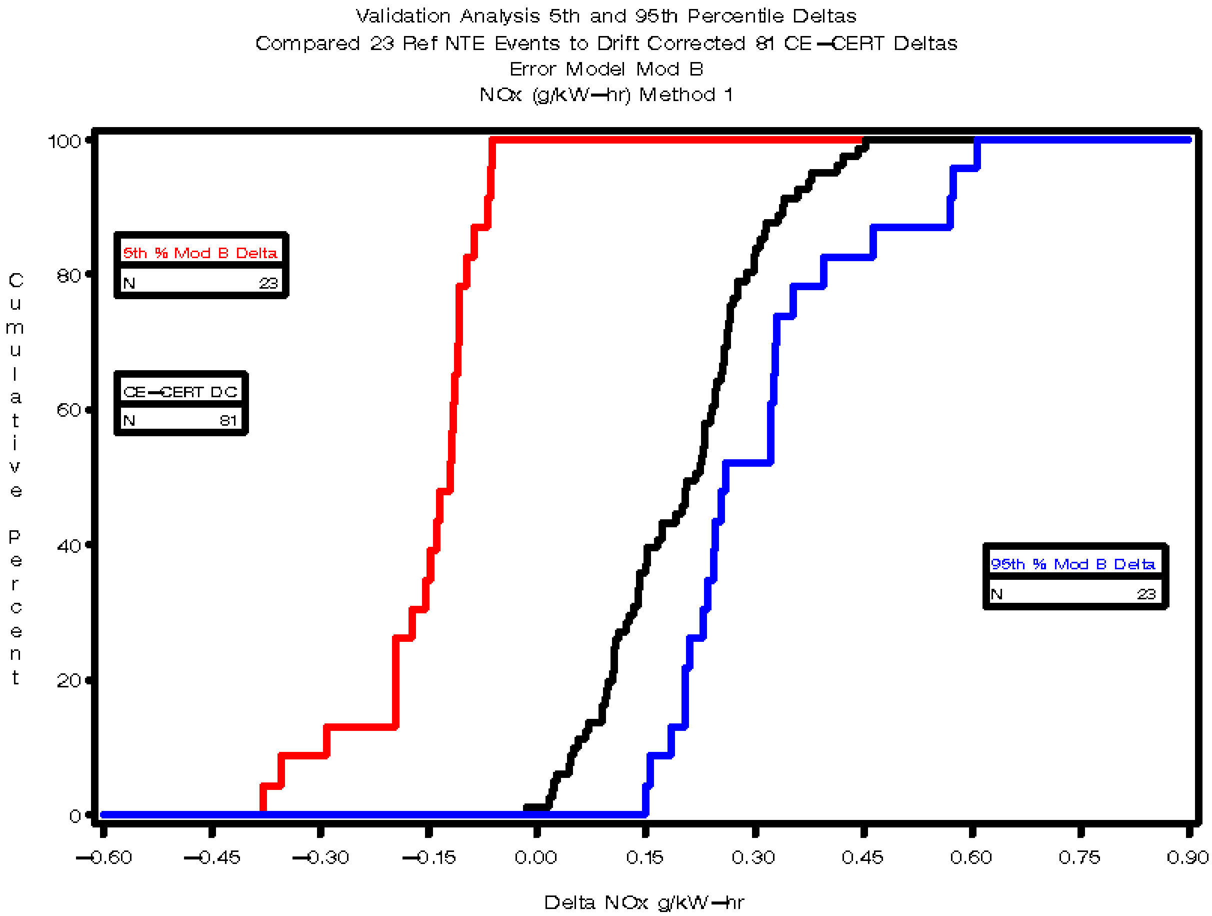

FIGURE 18. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 1 MOD B

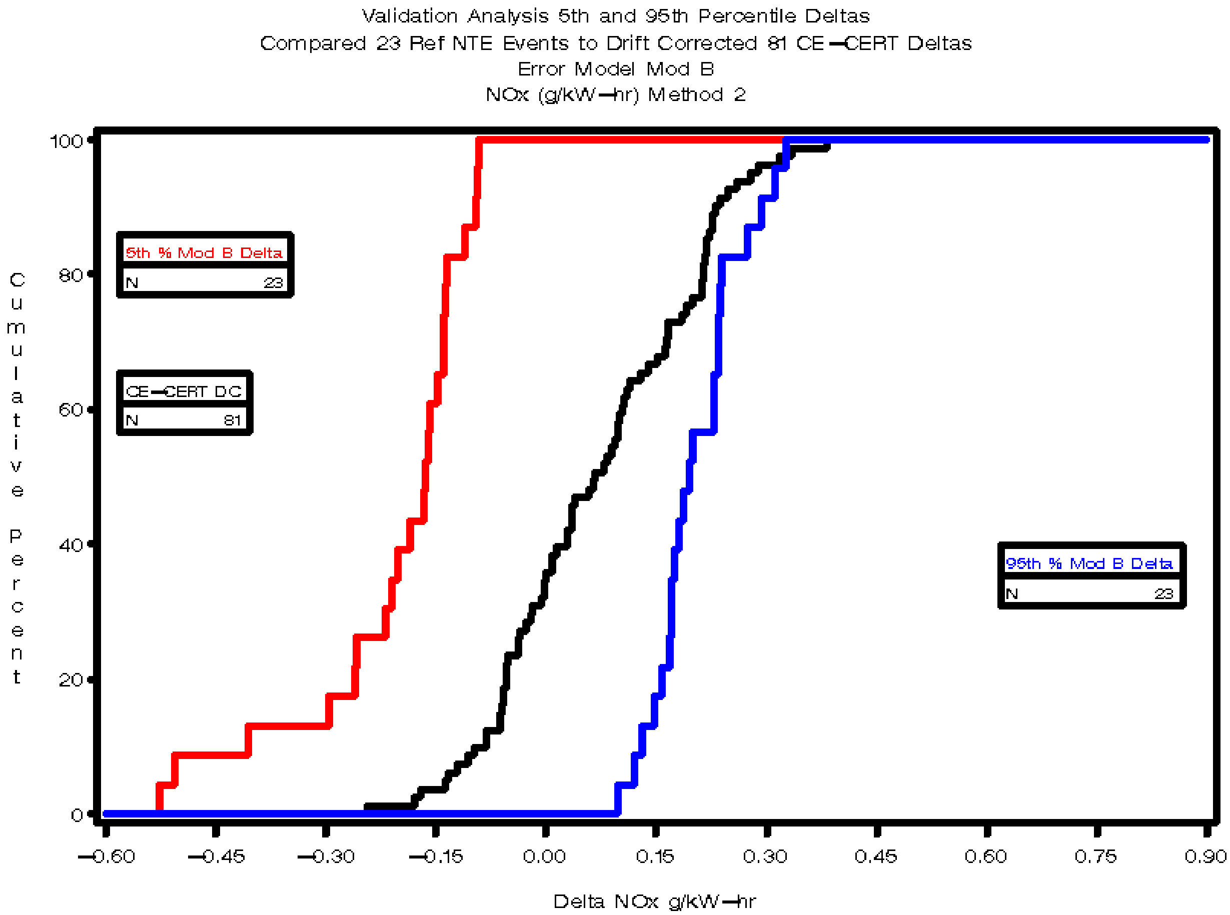

FIGURE 19. VALIDATION NTE EVENTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 2 MOD B

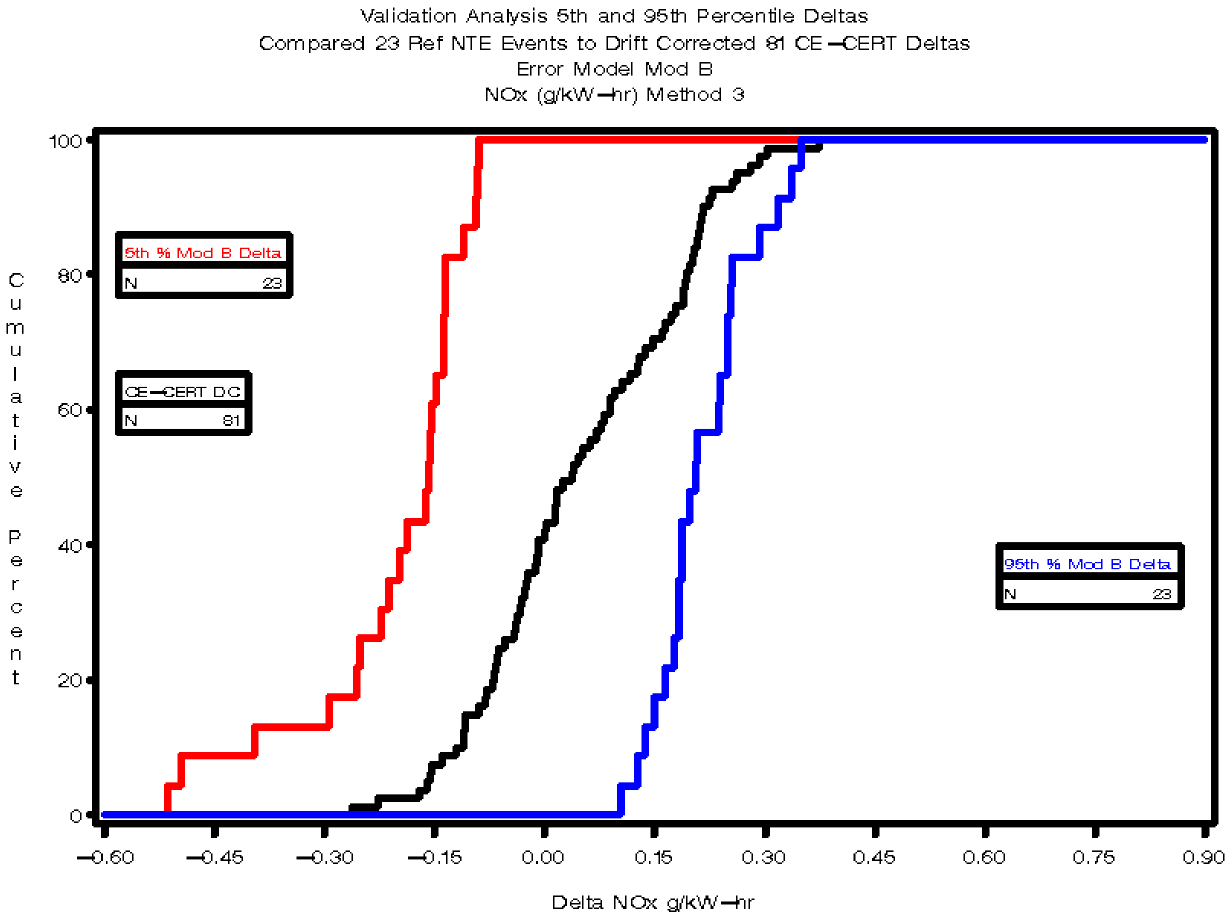

FIGURE 20. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NO_X METHOD 3 MOD B

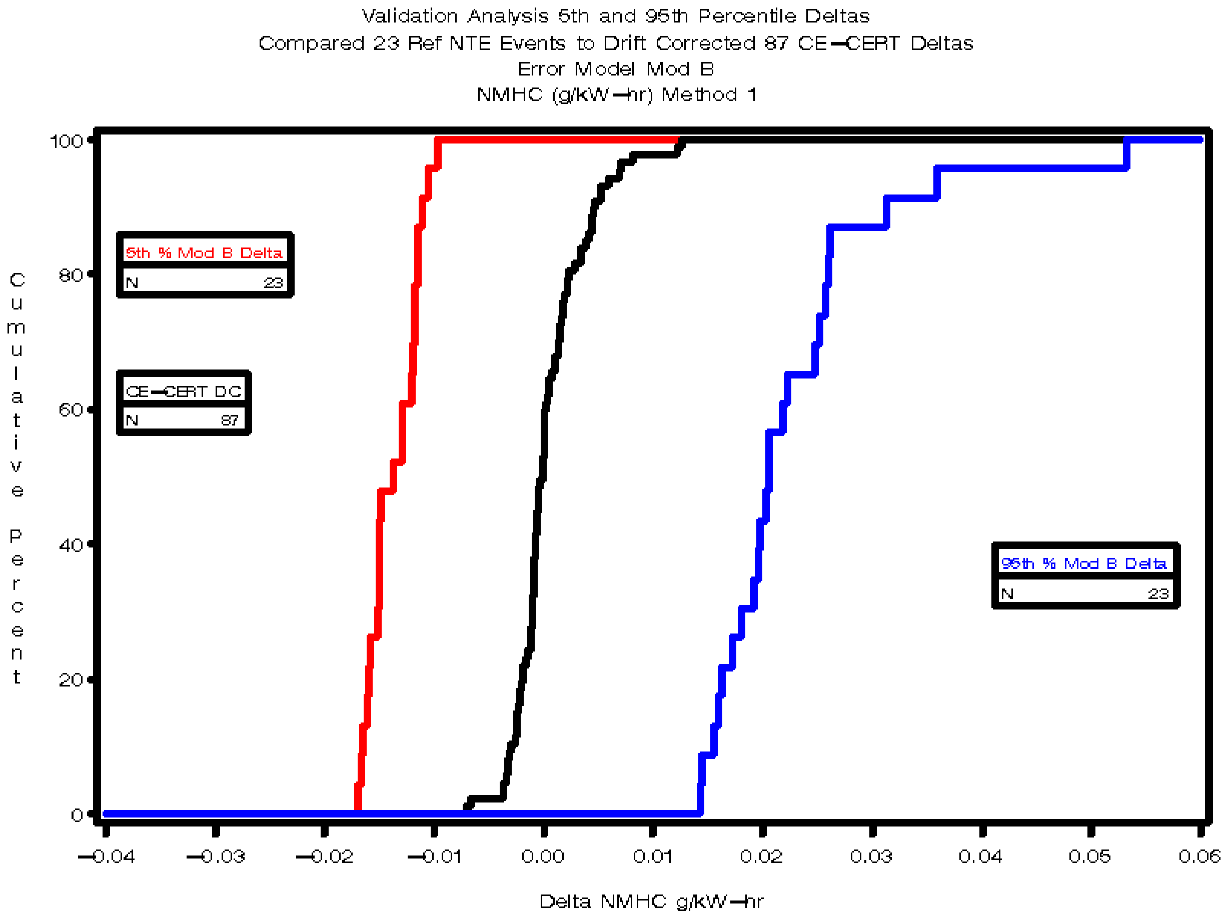

FIGURE 21. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 1 MOD B

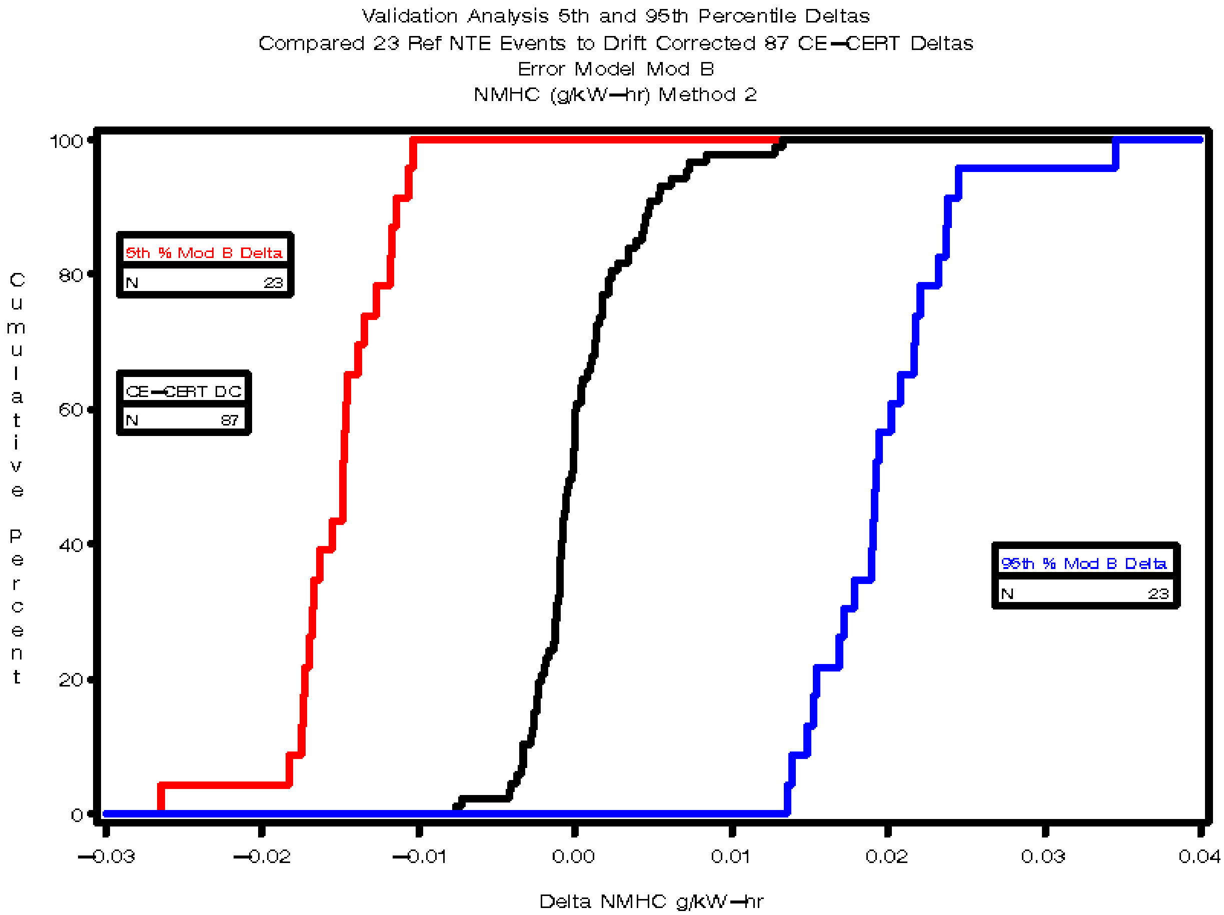

FIGURE 22. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 2 MOD B

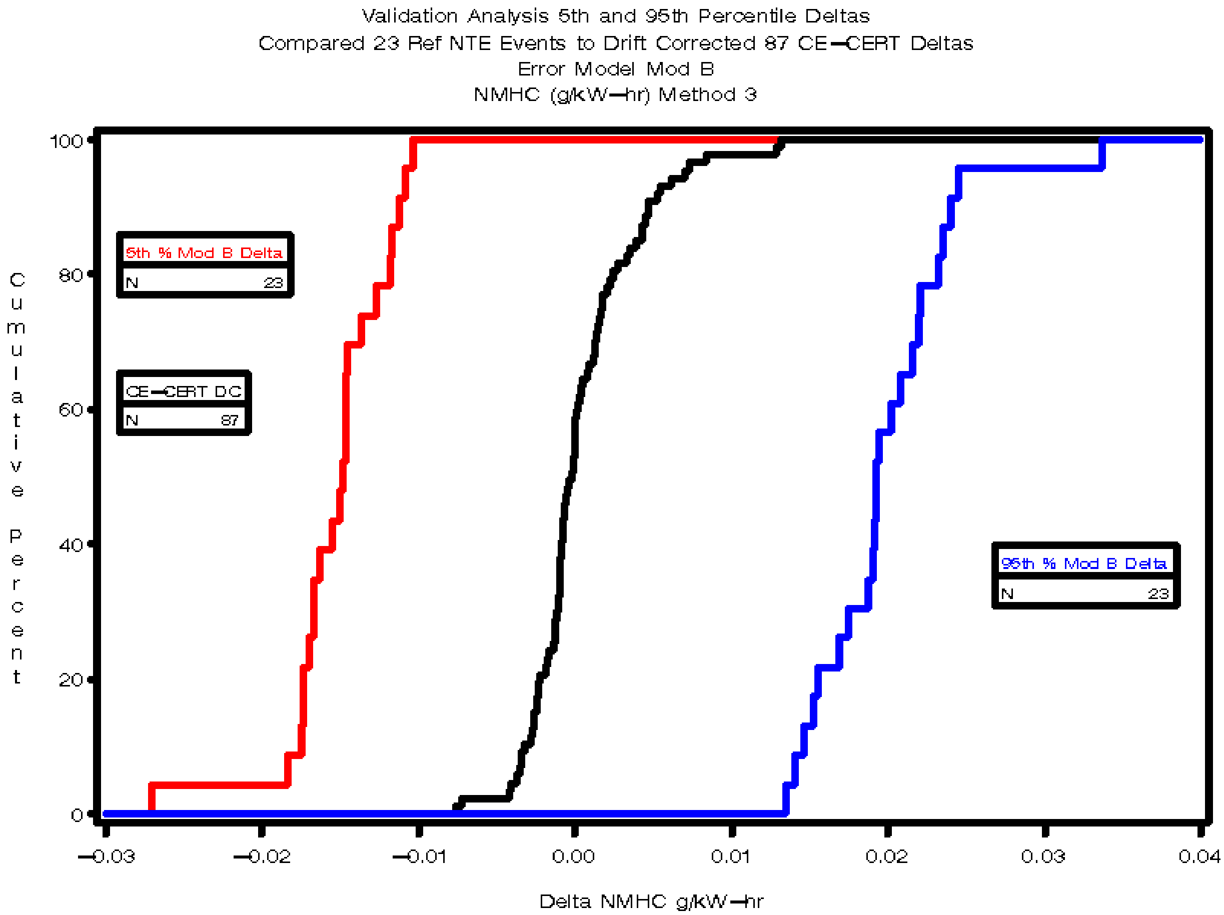

FIGURE 23. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR NMHC METHOD 3 MOD B

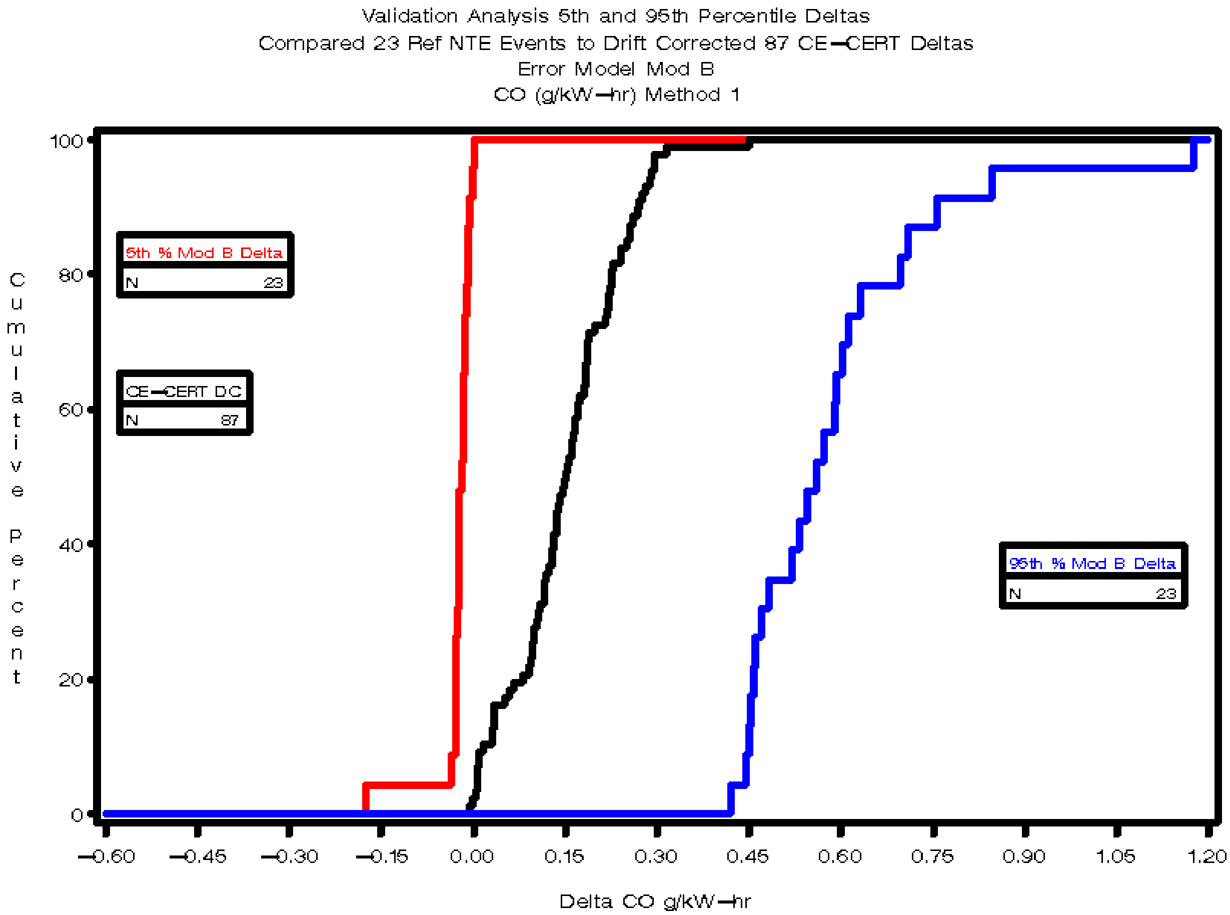

FIGURE 24. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 1 MOD B

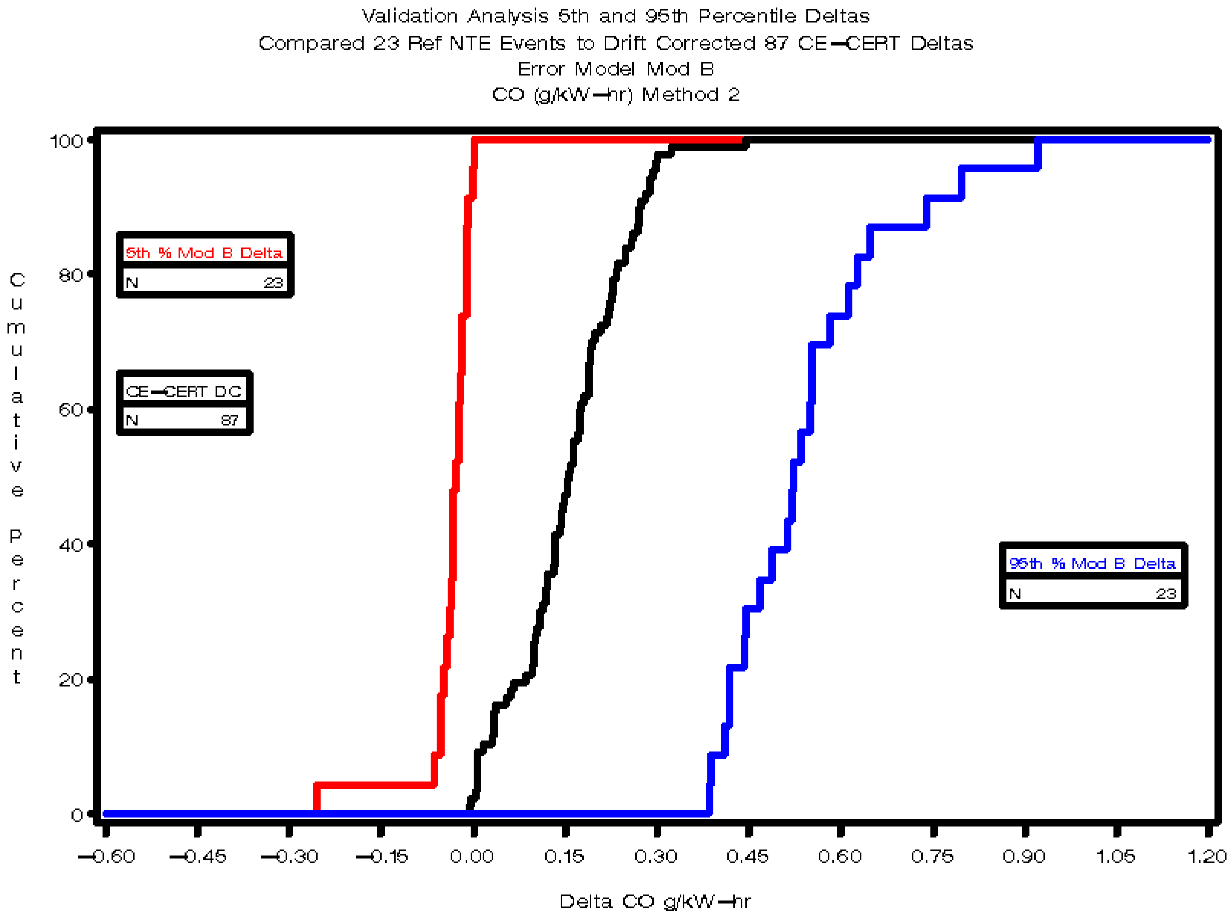

FIGURE 25. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 2 MOD B

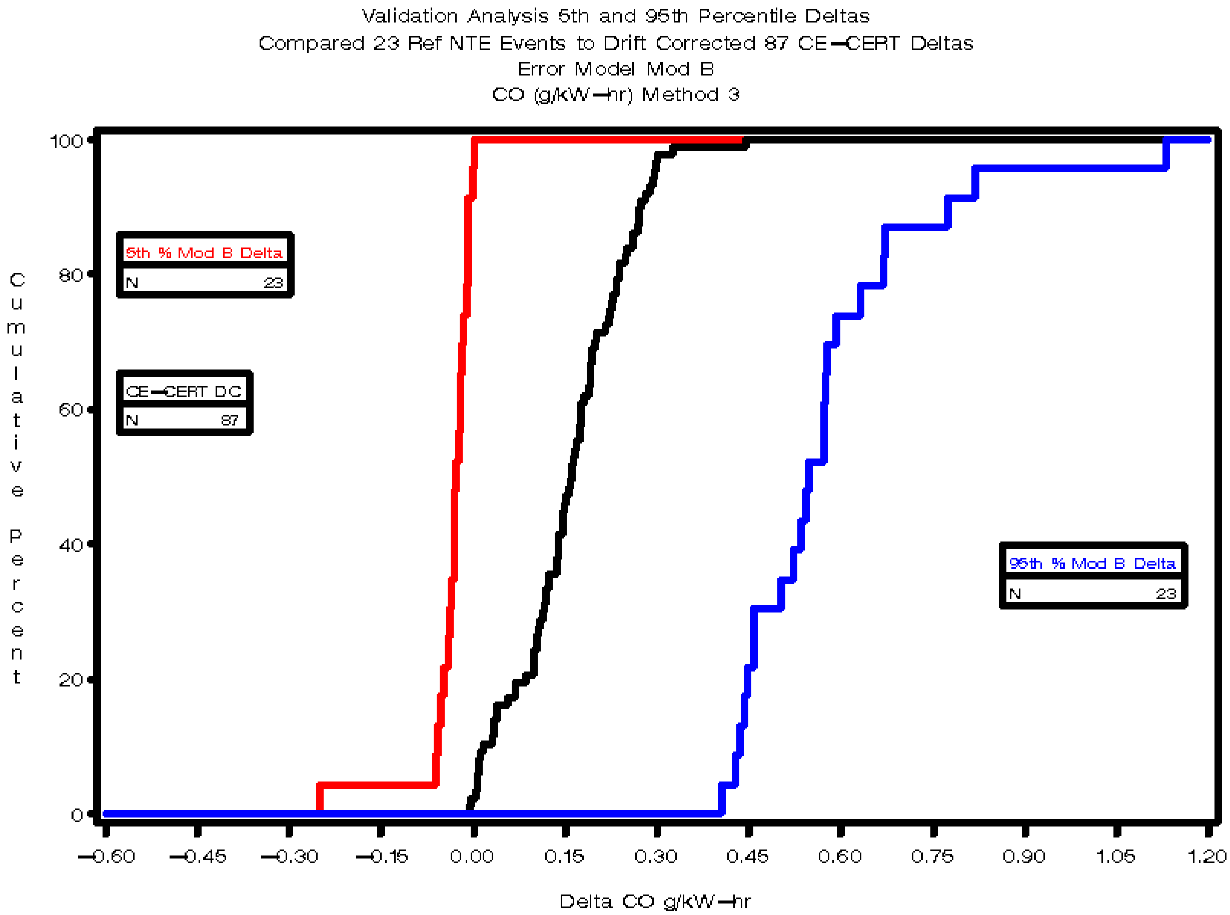

FIGURE 26. VALIDATION EDF PLOTS USING 23 REFERENCE NTE EVENTS FOR CO METHOD 3 MOD B

7.0 MONTE CARLO VALIDATION RESULTS FROM 50 REFERENCE NTE EVENTS USING MOD 1

Based on the information provided in the validation plots for the Mod 1, Mod 2, Mod 3 and Mod B runs, changes made to the various steady-state error surfaces resulted in the validation of the MC model for all three emissions and all three calculation methods for each of the four Mod runs using the 23 reference NTE events. EPA chose to continue the simulation runs using only the Mod 1 and Mod 2 revised error surfaces by running an additional 27 reference NTE events (total = 50 reference NTE events) through the MC model. These two Mods were chosen because they both represented steady-state NOx error surfaces that were level independent (as compared to the Mod 3 steady-state error surface that represented a combination of level dependent and level independent NO_X errors). The results from these 50 simulations were used to calculate the measurement allowances provided in Section 9.0 of this report. This section details the results of the validation based on the 50 reference NTE events run with Mod 1.

The Mod 1 simulations were performed at 10,000 trials for NTE events with ideal $BSNO_X$ values less than 2.68204 g/kW-hr and at 30,00 trials otherwise. All 50 reference NTE events met the convergence criteria listed in Table 5.

From the Mod 1 MC simulations, the validation 5th and 95th percentile delta BS emissions were extracted from the output files for each of the 50 reference NTE events. These percentiles were then plotted as empirical distribution functions (EDF) to form a validation interval for the on-road data. Also plotted was the EDF computed from the on-road CE-CERT NTE events. Figure 27 through Figure 29 represent the validation plots for the $BSNO_x$ for calculation methods 1, 2 and 3, respectively. Each of the validation plots includes 5th and 95th percentile EDFs for the Mod 1 runs and the on-road CE-CERT data. Figure 30 through Figure 35 depict the validation plots for the BSNMHC and BSCO simulation runs, respectively. All $BSNO_X$, BSNMHC and BSCO emissions validated for all three calculation methods for the Mod 1 runs with the 50 reference NTE events.

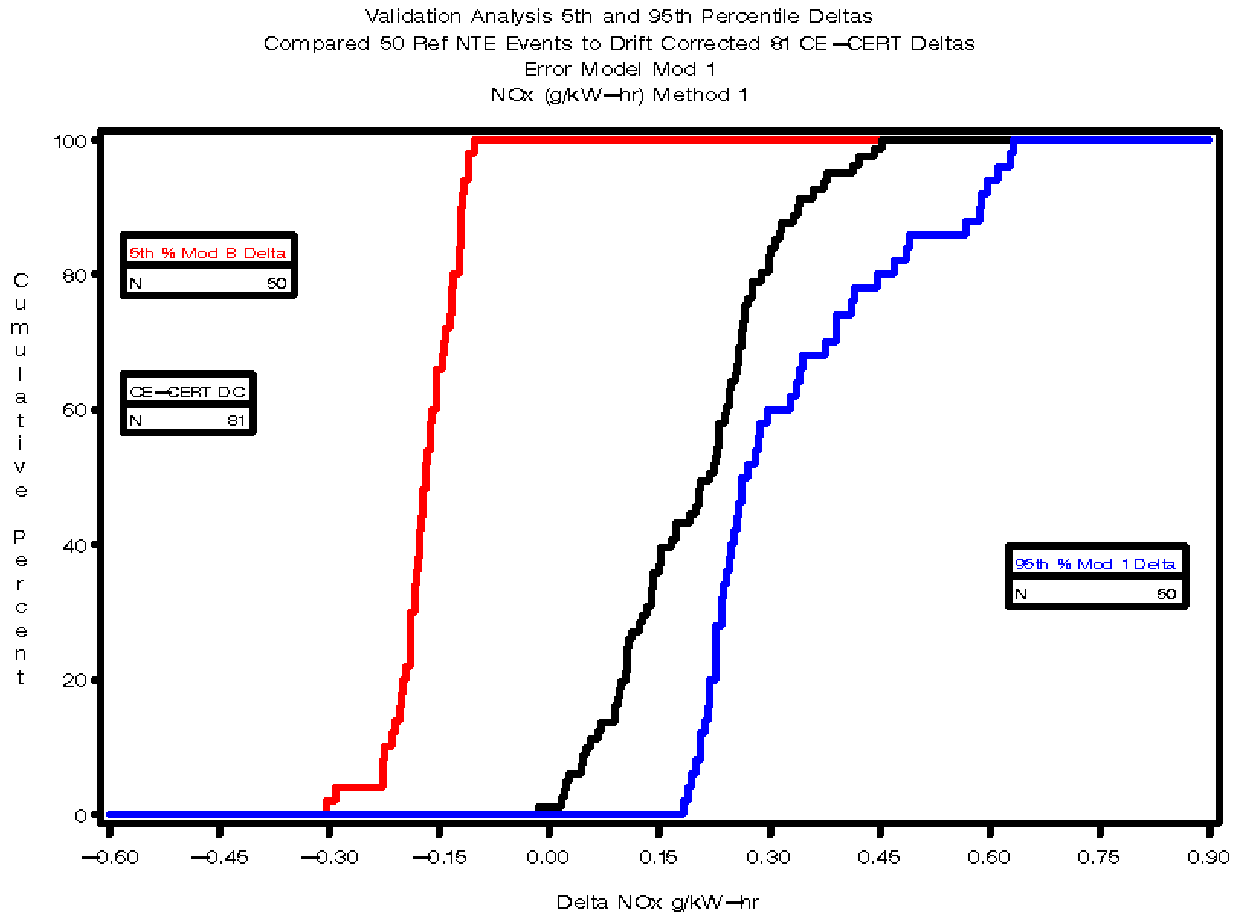

FIGURE 27. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NO_X METHOD 1 MOD 1

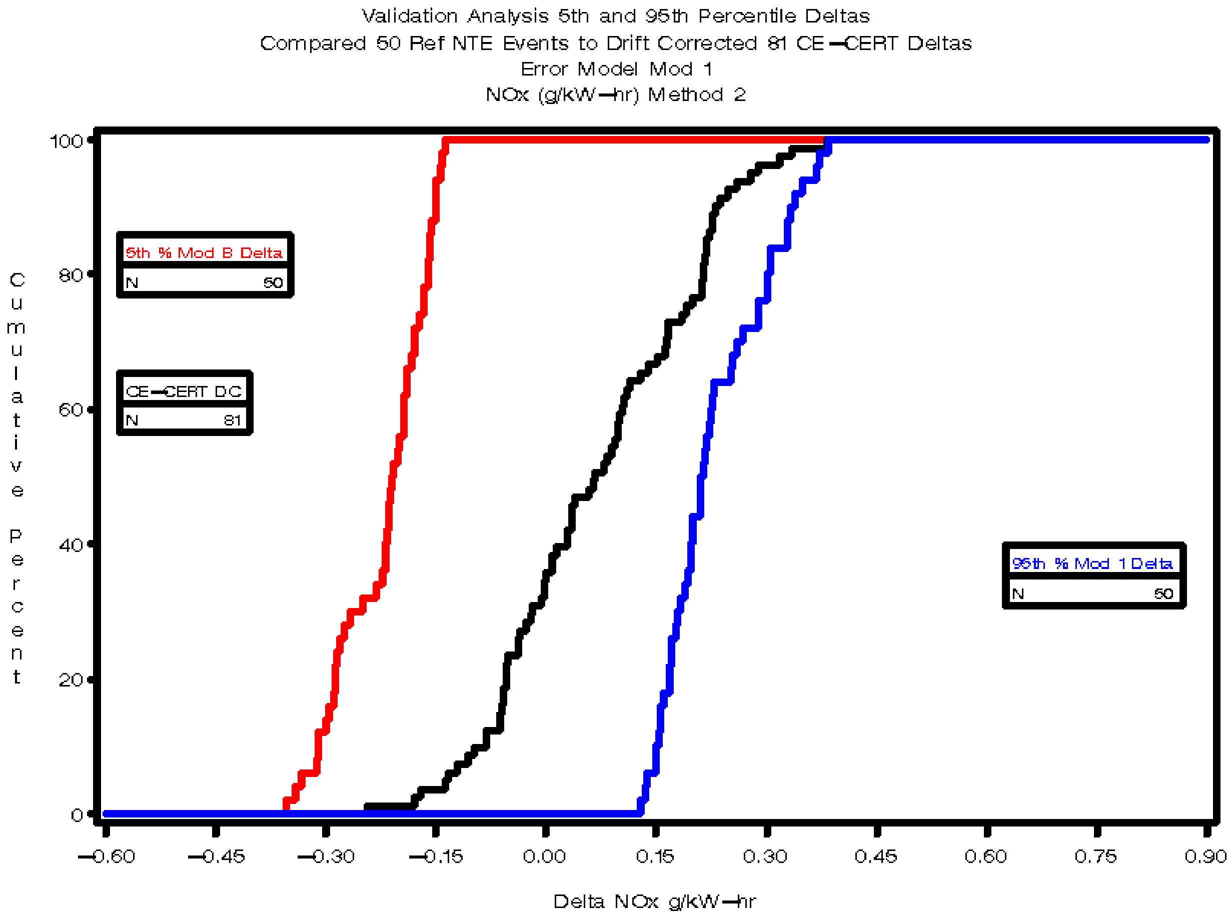

FIGURE 28. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NO_X METHOD 2 MOD 1

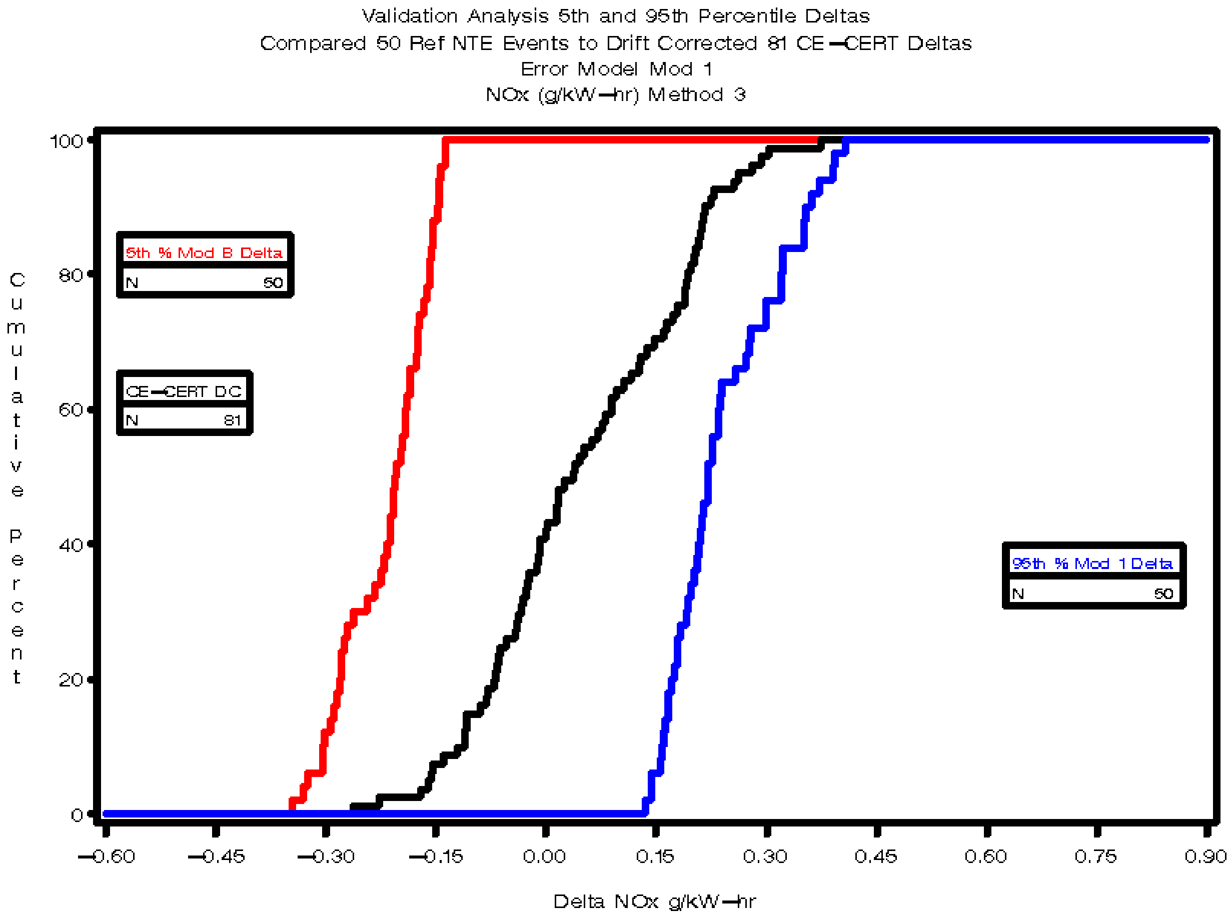

FIGURE 29. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NO_X METHOD 3 MOD 1

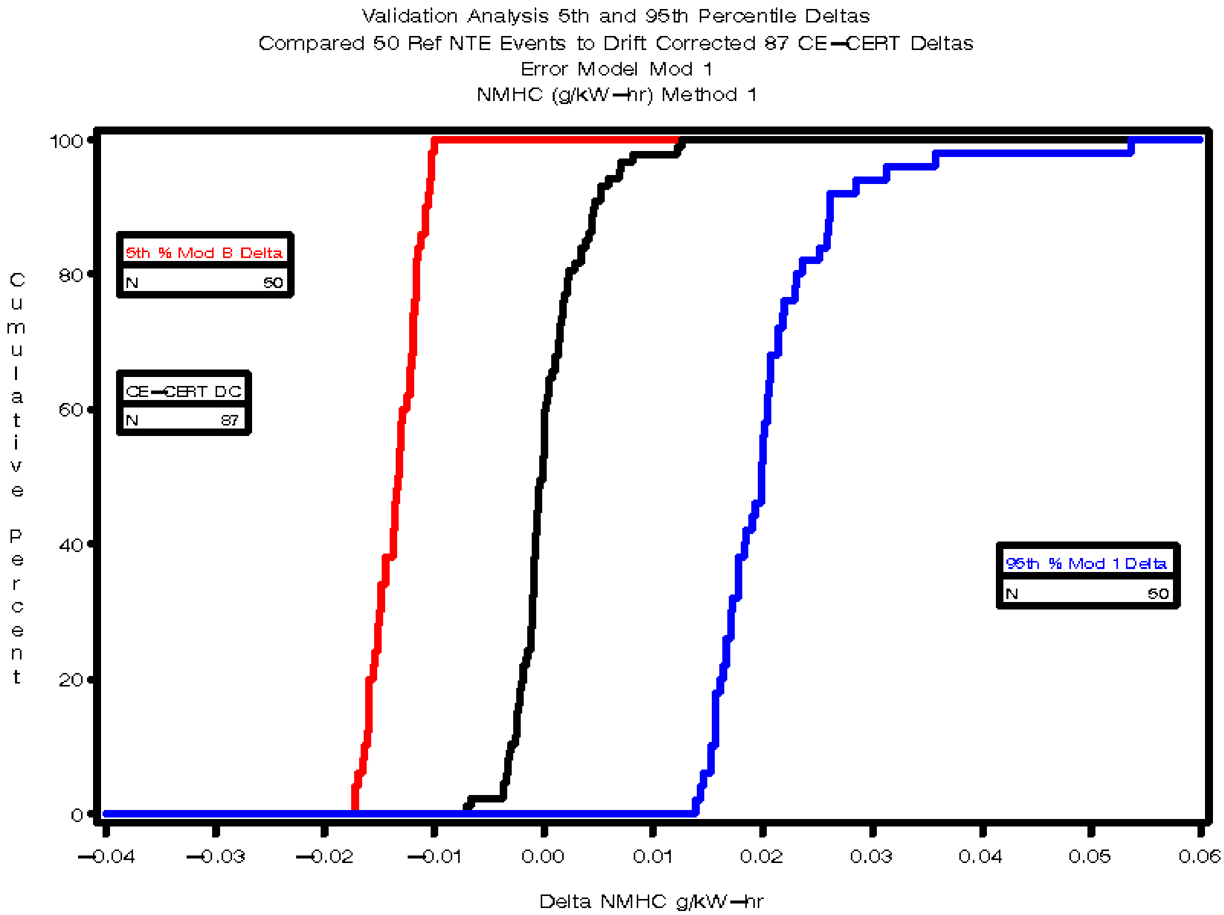

FIGURE 30. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NMHC METHOD 1 MOD 1

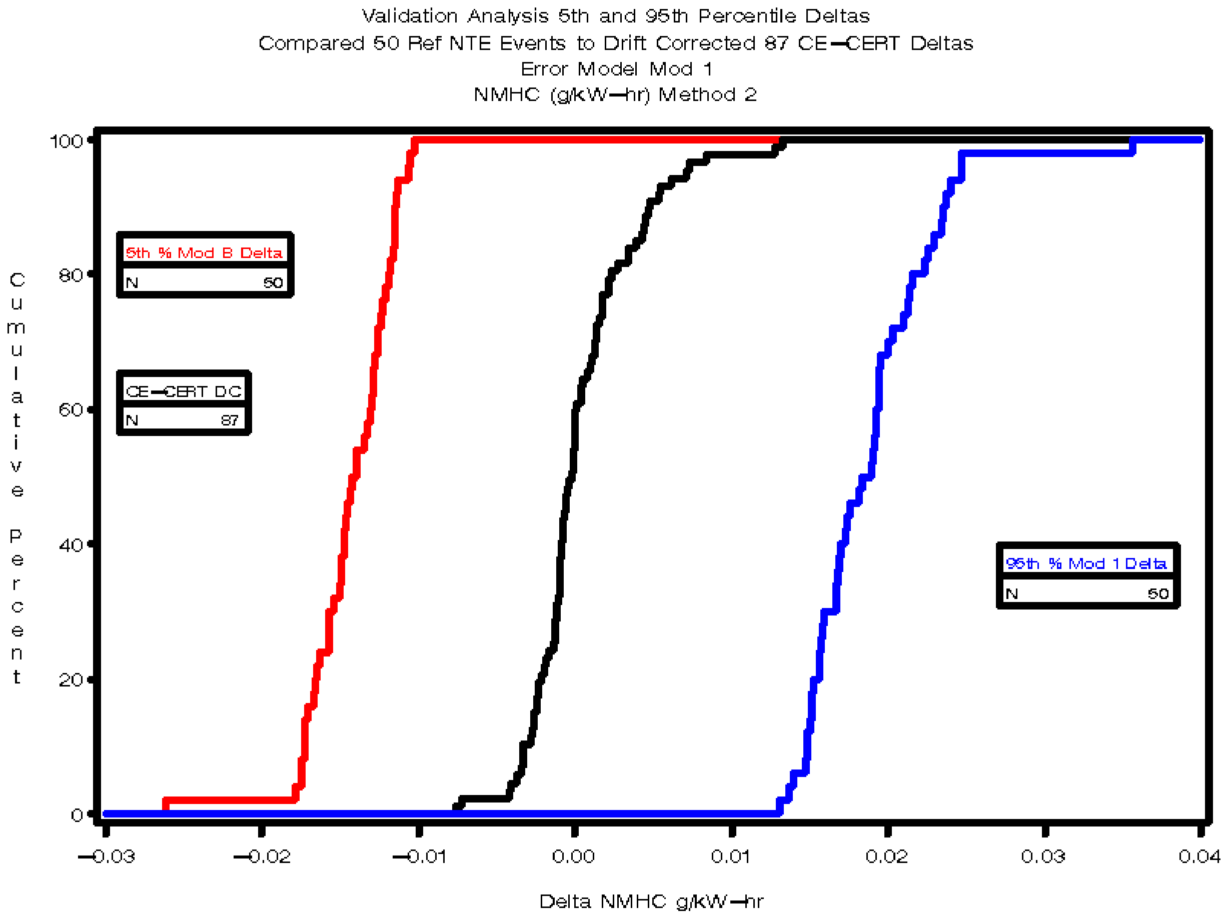

FIGURE 31. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NMHC METHOD 2 MOD 1

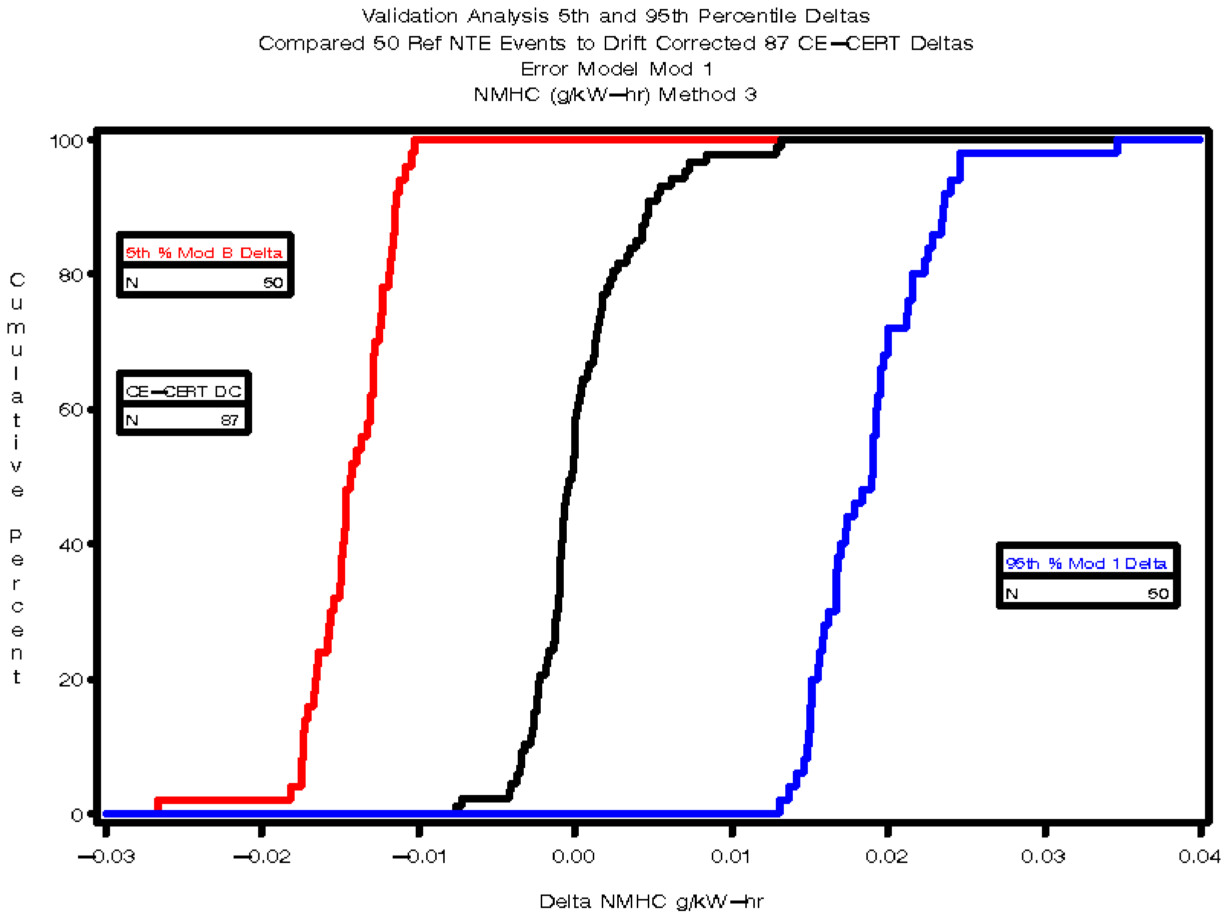

FIGURE 32. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NMHC METHOD 3 MOD 1

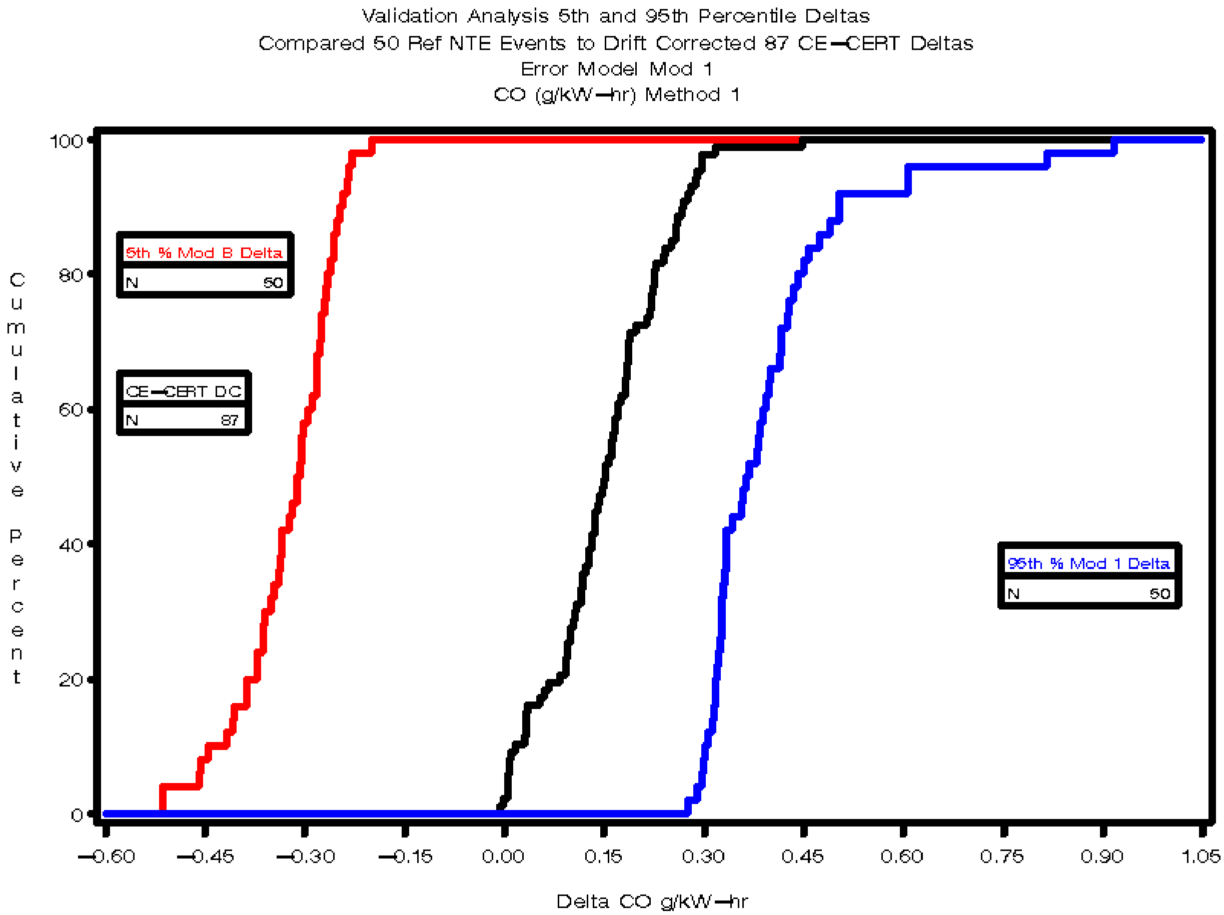

FIGURE 33. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 1 MOD 1

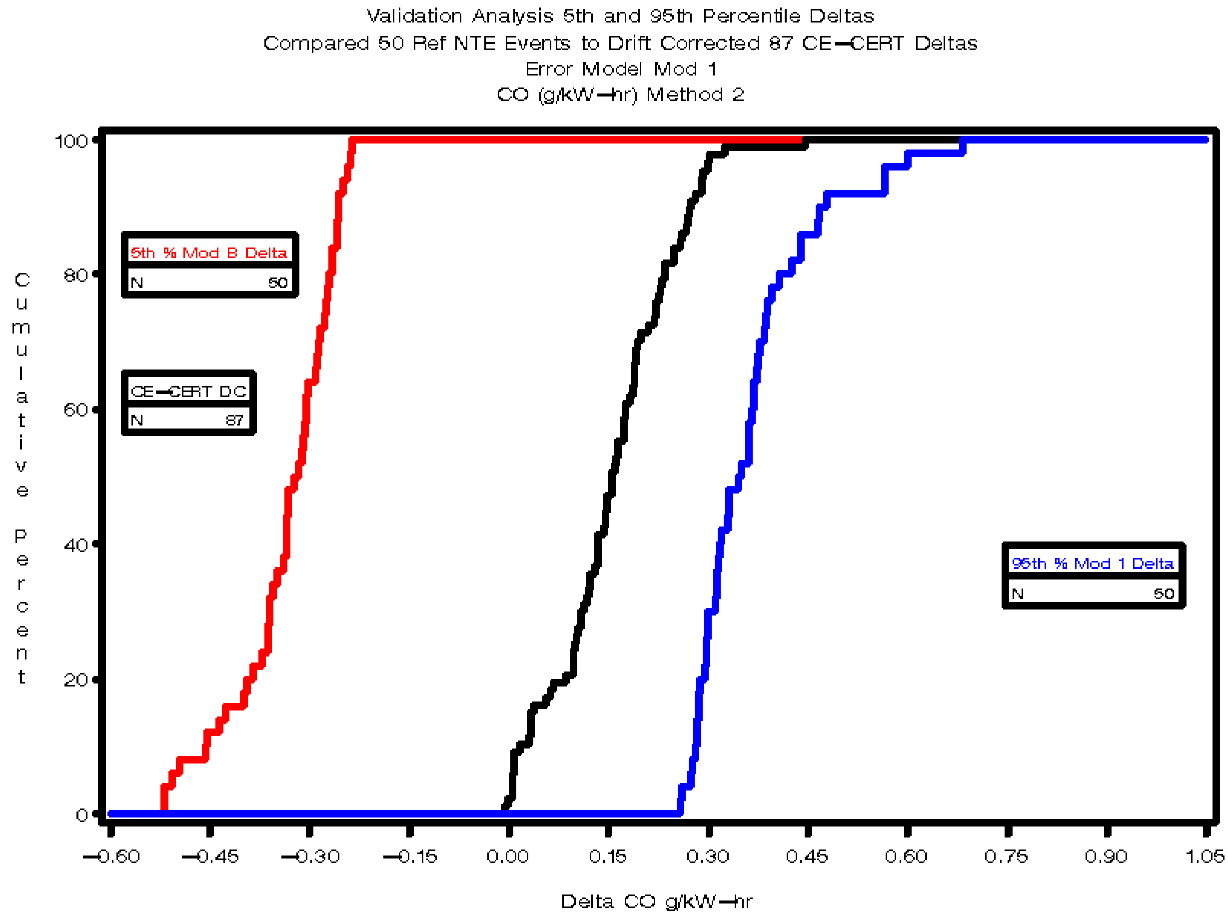

FIGURE 34. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 2 MOD 1

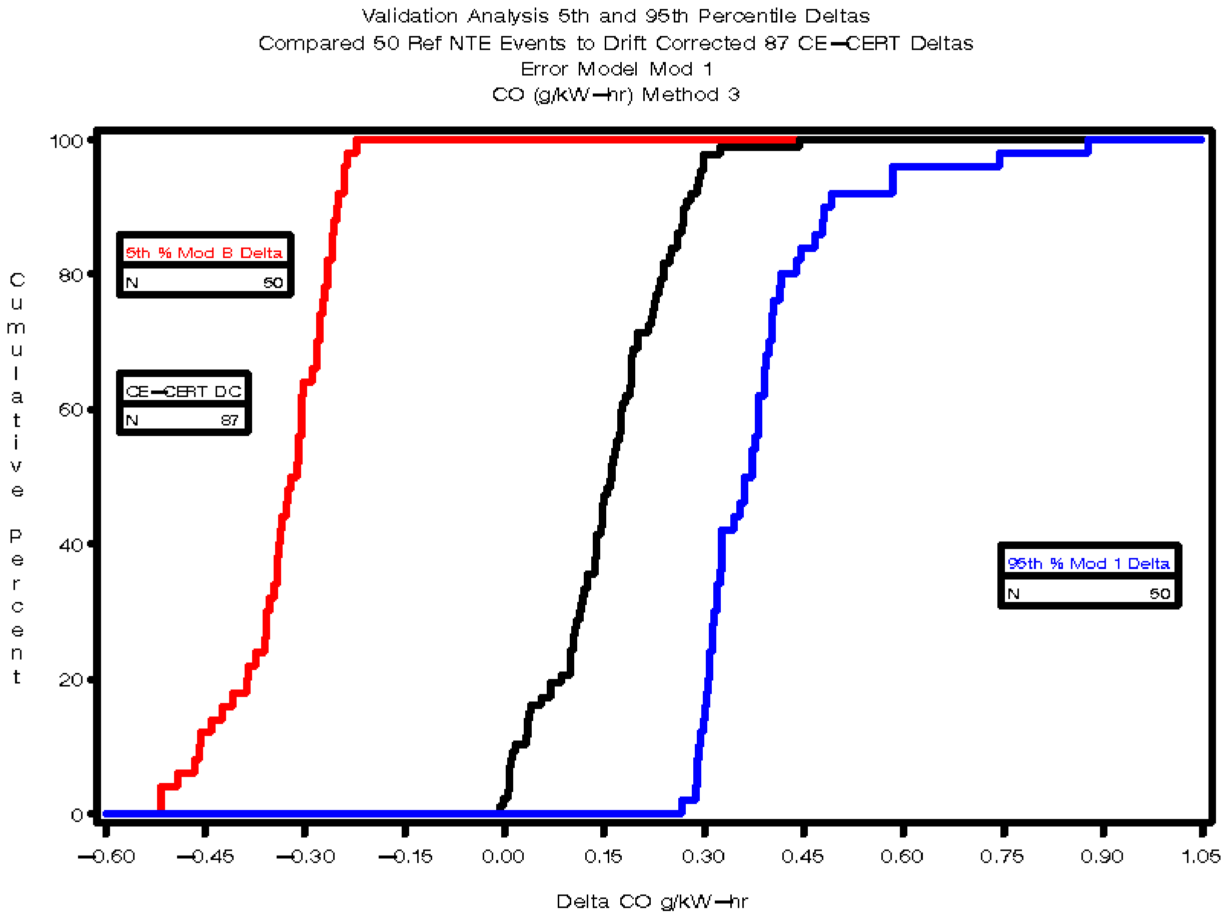

FIGURE 35. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 3 MOD 1

8.0 MONTE CARLO VALIDATION RESULTS FROM 50 REFERENCE NTE EVENTS USING MOD 2

This section details the results of the validation based on the 50 reference NTE events run with Mod 2. EPA chose to continue simulations using the Mod 1 and Mod 2 revised error surfaces by running an additional 27 reference NTE events (total = 50 reference NTE events) through the MC model. These two Mods were chosen because they both represented steady-state NOx error surfaces that were level independent (as compared to the Mod 3 steady-state error surface that represented a combination of level dependent and level independent NO_X errors).

The Mod 2 simulations were performed at 10,000 trials for NTE events with ideal $BSNO_X$ values less than 2.68204 g/kW-hr and at 30,00 trials otherwise. All 50 reference NTE events met the convergence criteria listed in Table 5.

From the Mod 2 MC simulations, the validation 5th and 95th percentile delta BS emissions were extracted from the output files for each of the 50 reference NTE events. These percentile delta emissions were then plotted as empirical distribution functions (EDF) to form a validation interval for the on-road data. Also plotted was the EDF computed from the on-road CE-CERT NTE events. Figure 36 through Figure 38 represent the validation plots for the $BSNO_x$ for calculation methods 1, 2 and 3, respectively. Each of the validation plots includes 5th and 95th percentile EDFs for the Mod 2 runs and the on-road CE-CERT data. Figure 39 through Figure 44 depict the validation plots for the BSNMHC and BSCO simulation runs, respectively. All $BSNO_X$, BSNMHC and BSCO emissions validated for all three calculation methods for the Mod 2 runs with the 50 reference NTE events.

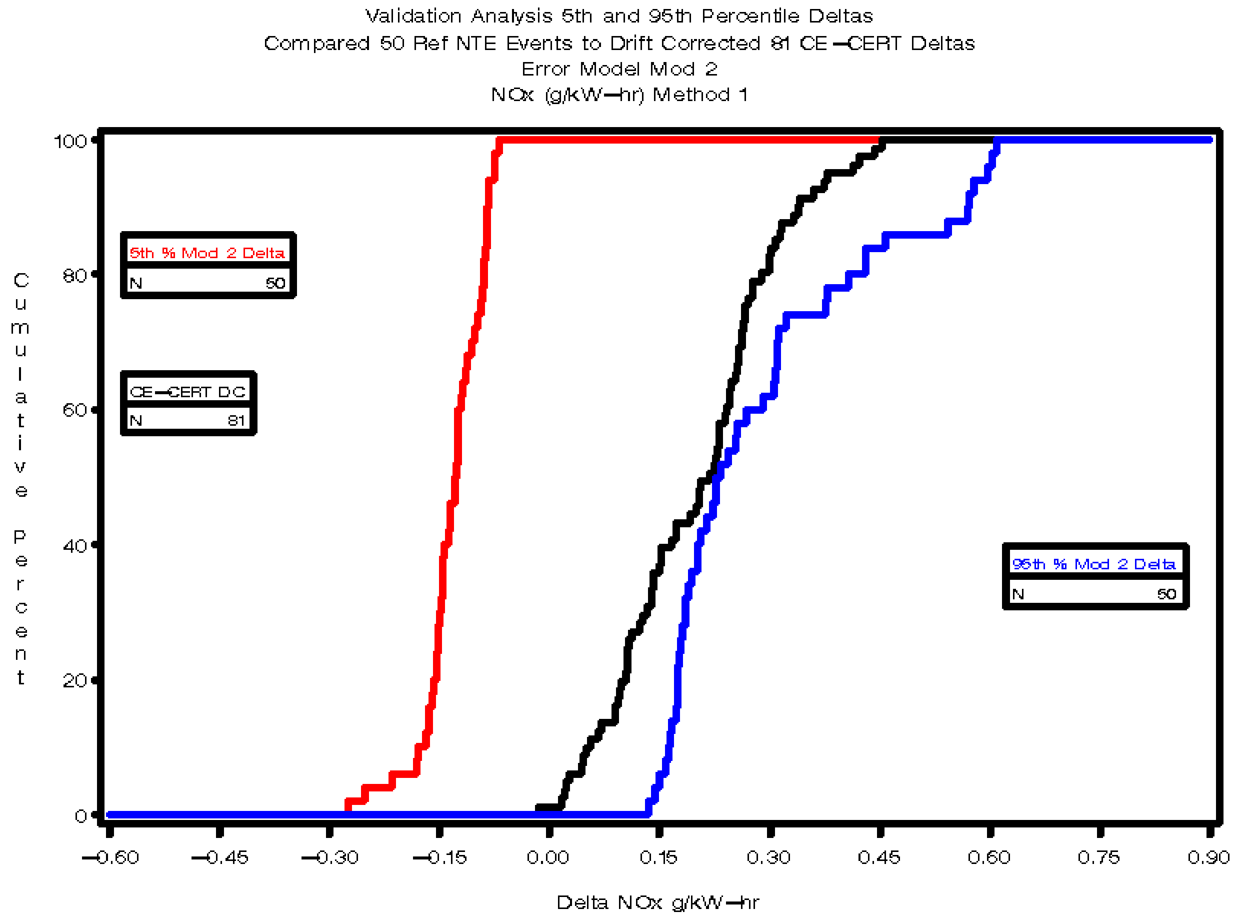

FIGURE 36. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NO_X METHOD 1 MOD 2

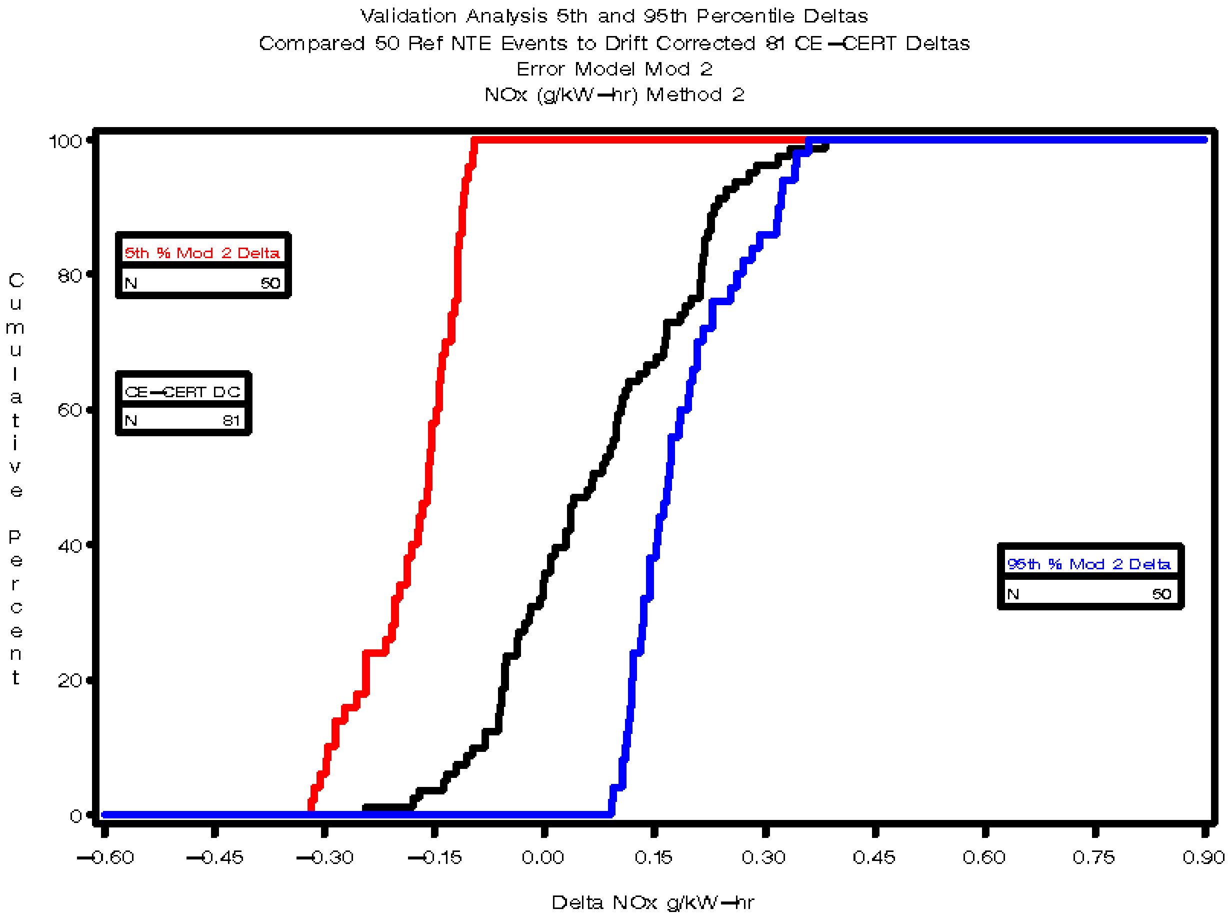

FIGURE 37. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NO_X METHOD 2 MOD 2

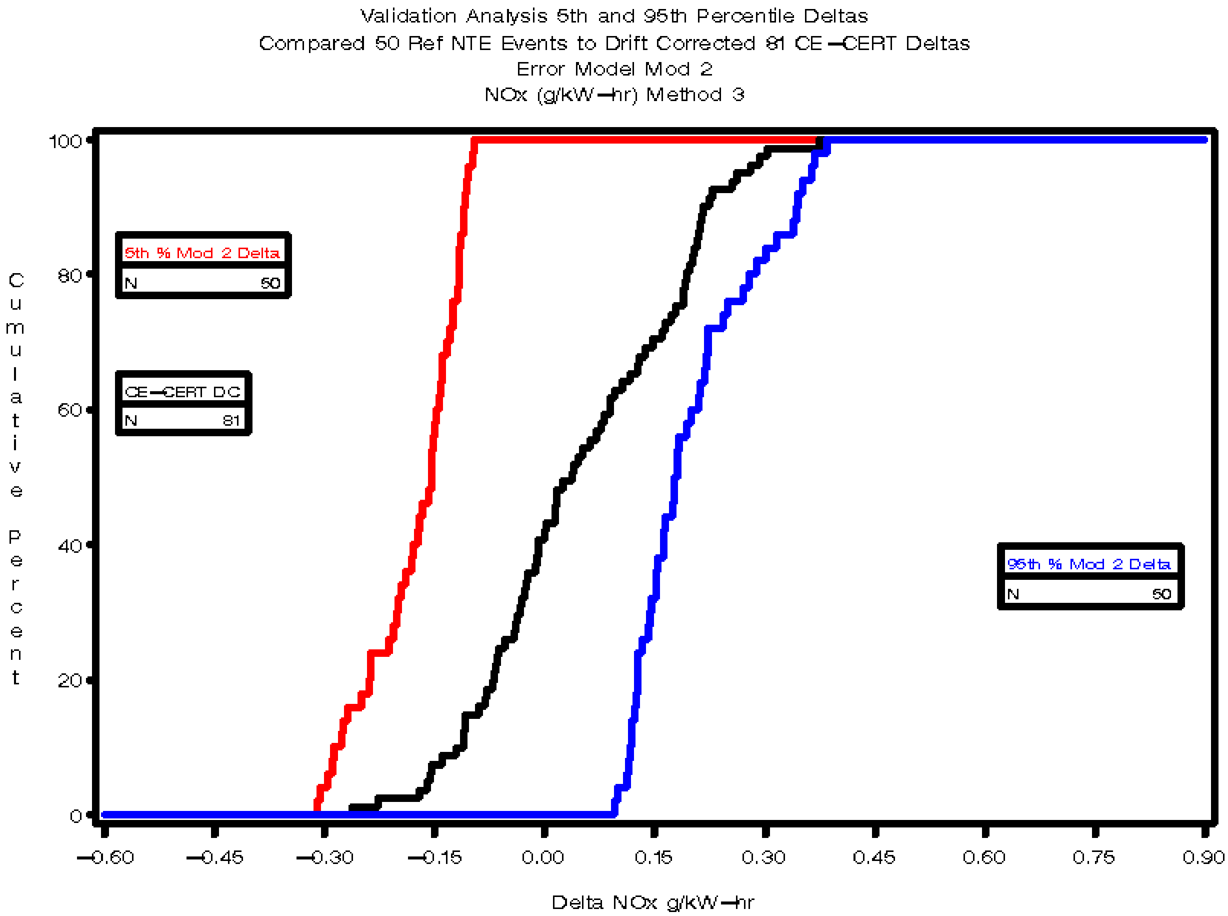

FIGURE 38. VALIDATION EDF PLOTS FOR 50 REFERENCE NTE EVENTS FOR NO_X METHOD 3 MOD 2

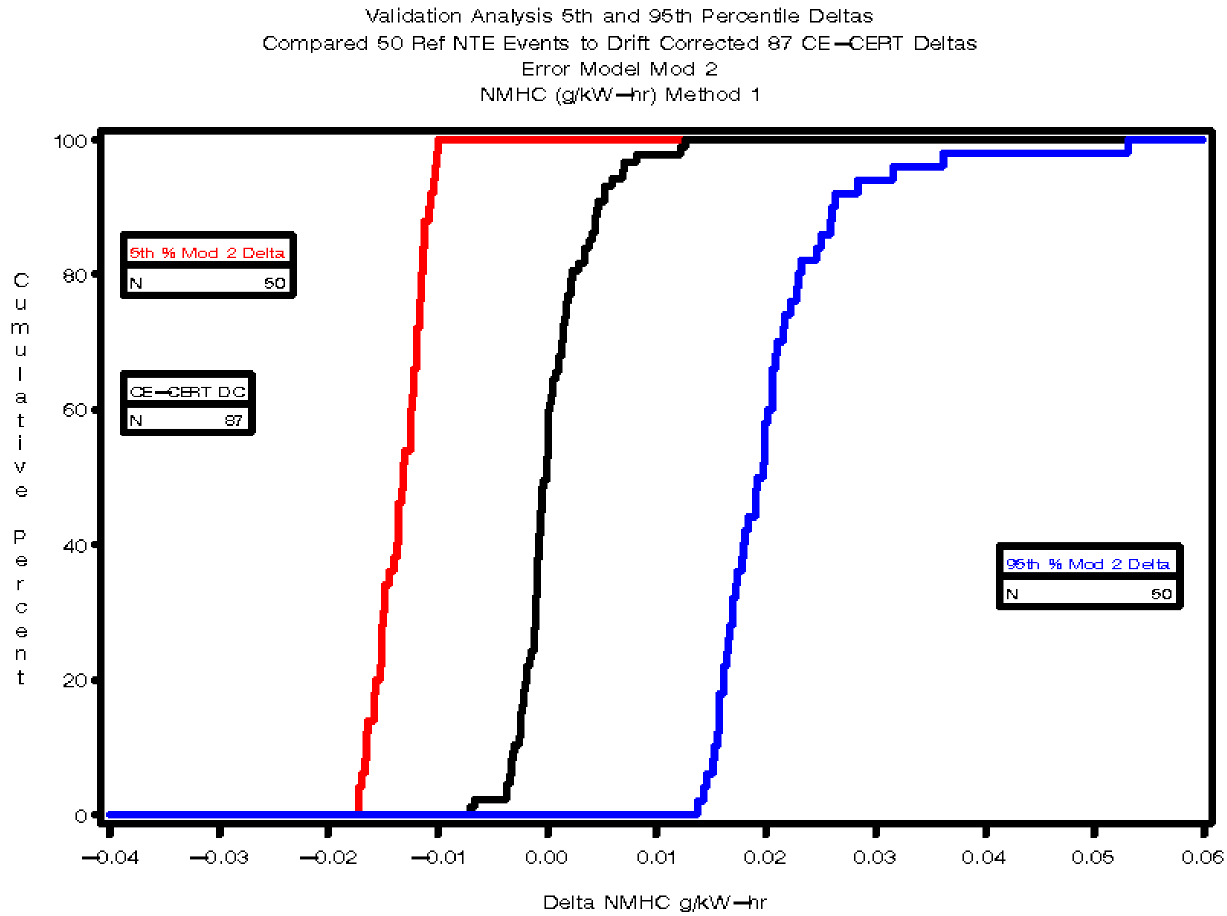

FIGURE 39. VALIDATION EDF PLOTS FOR 50 REFERENCE NTE EVENTS FOR NMHC METHOD 1 MOD 2

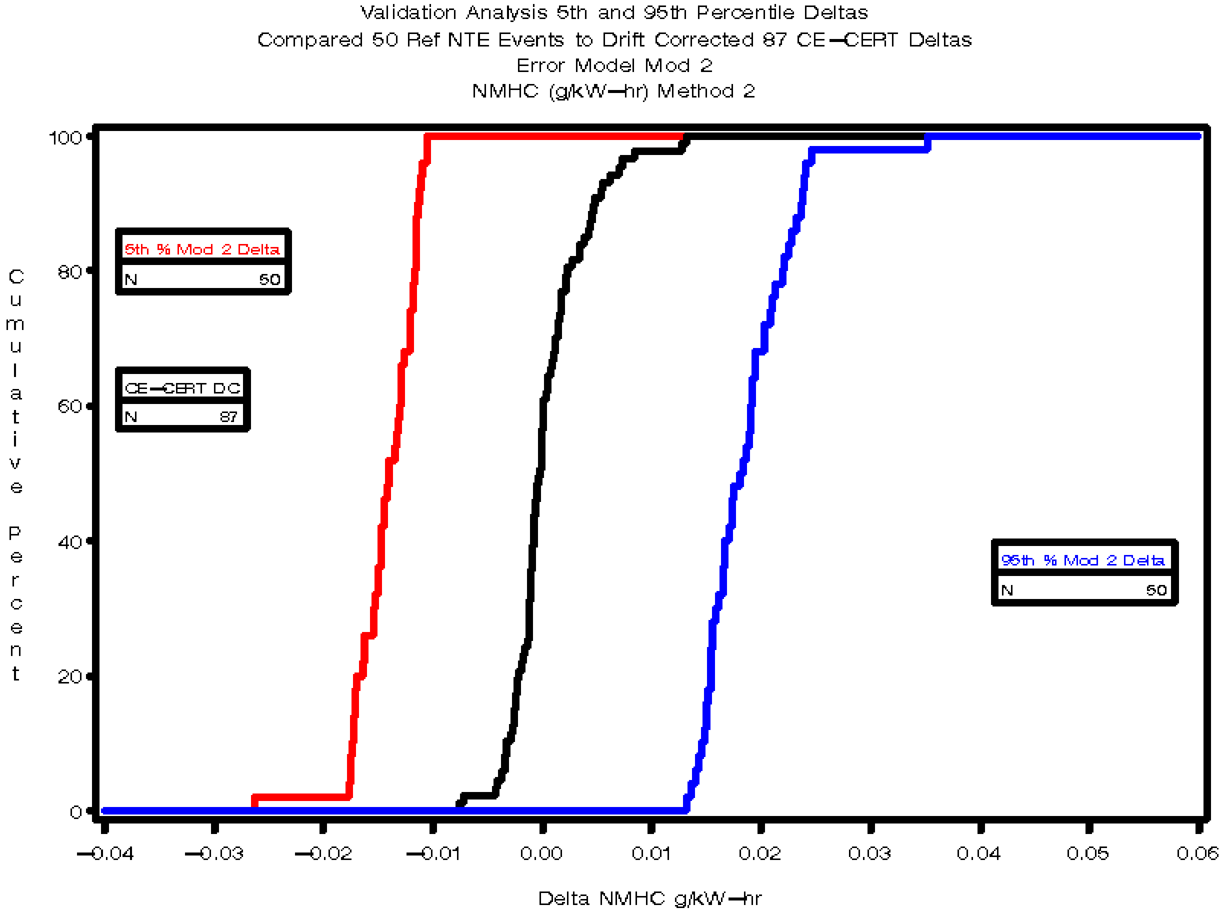

FIGURE 40. VALIDATION EDF PLOTS FOR 50 REFERENCE NTE EVENTS FOR NMHC METHOD 2 MOD 2

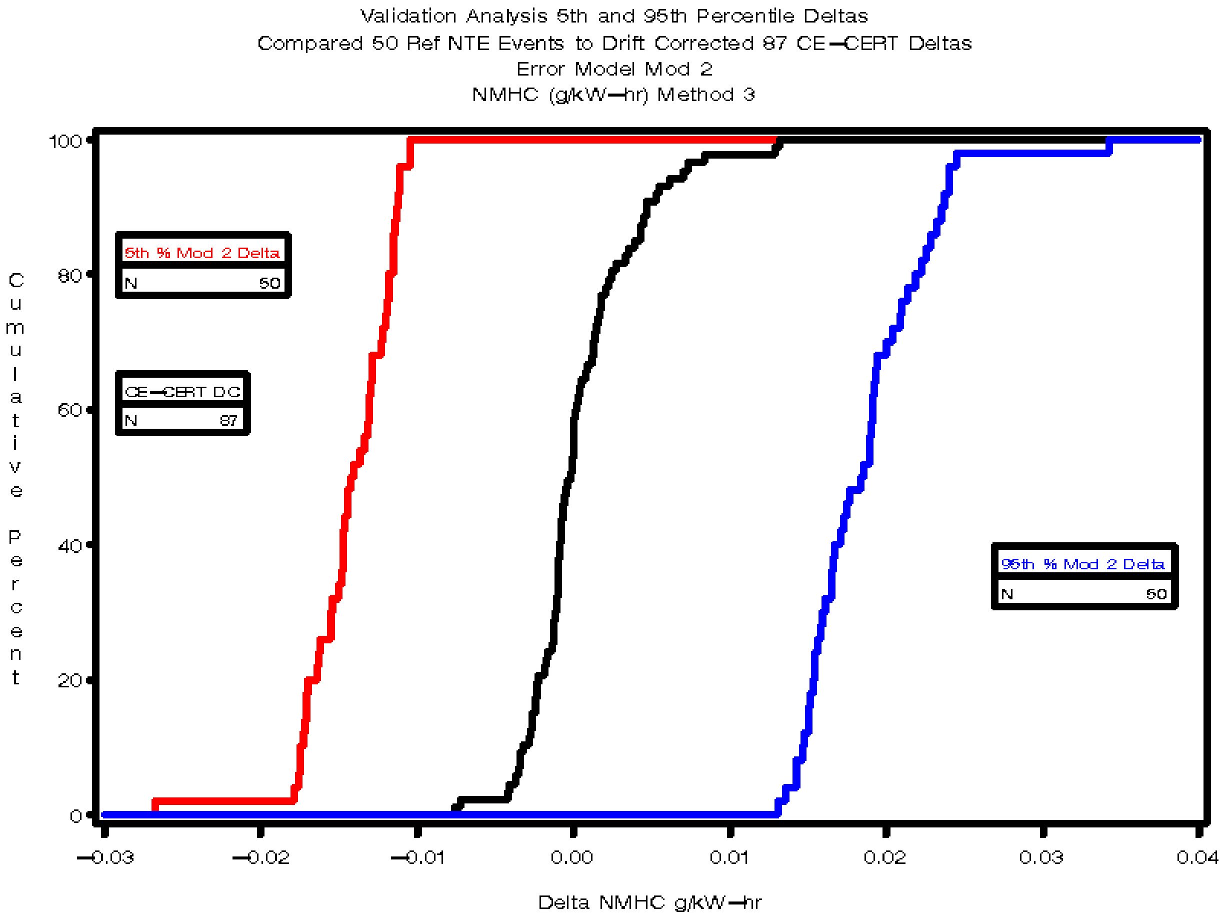

FIGURE 41. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR NMHC METHOD 3 MOD 2

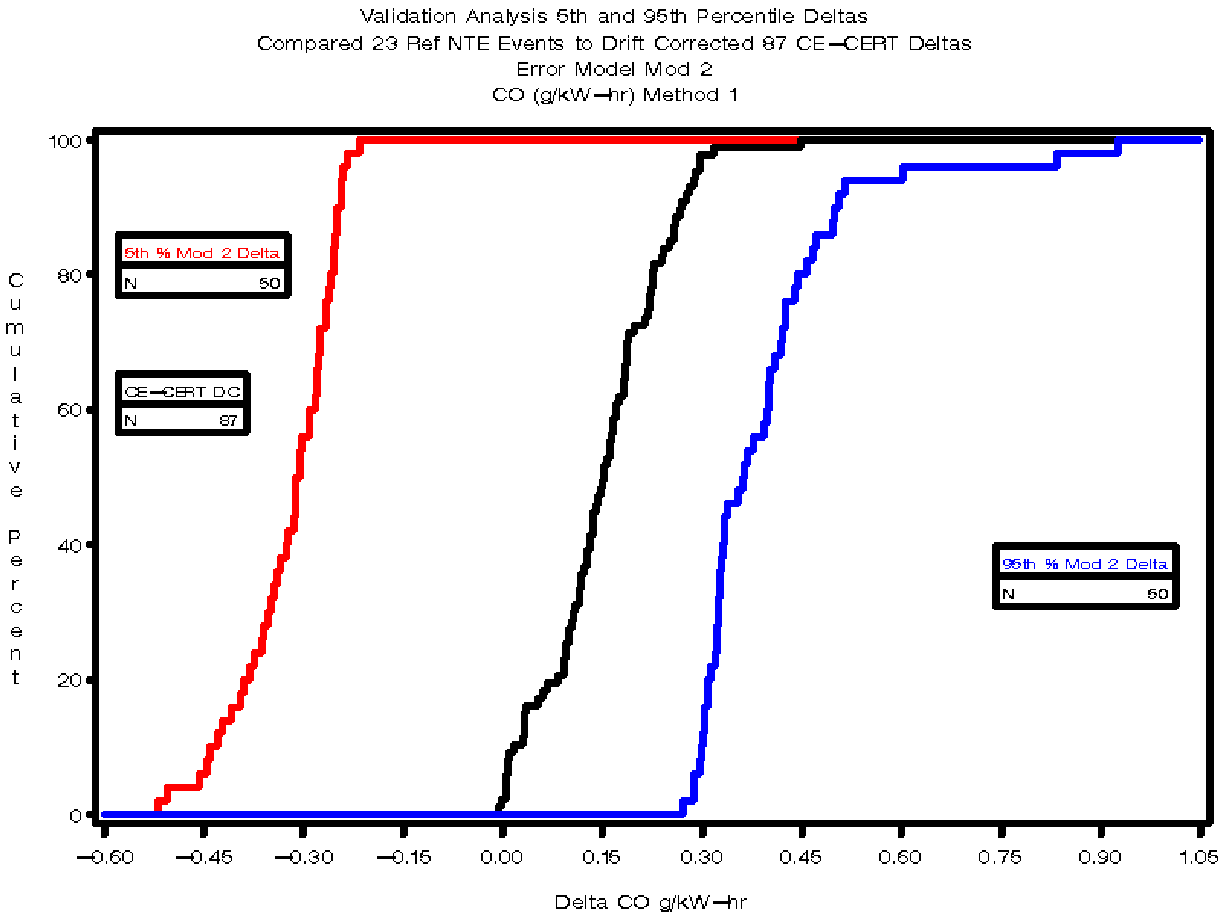

FIGURE 42. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 1 MOD 2

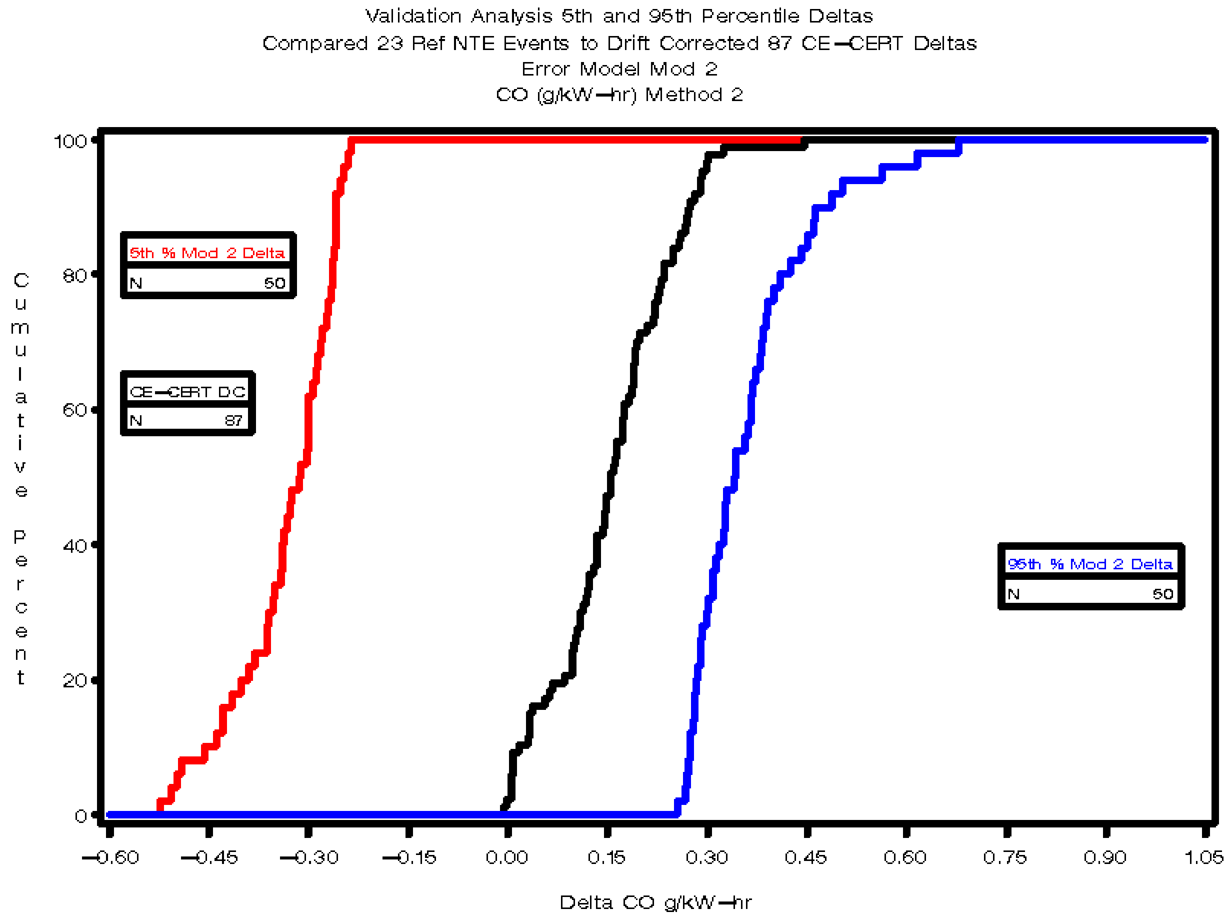

FIGURE 43. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 2 MOD 2

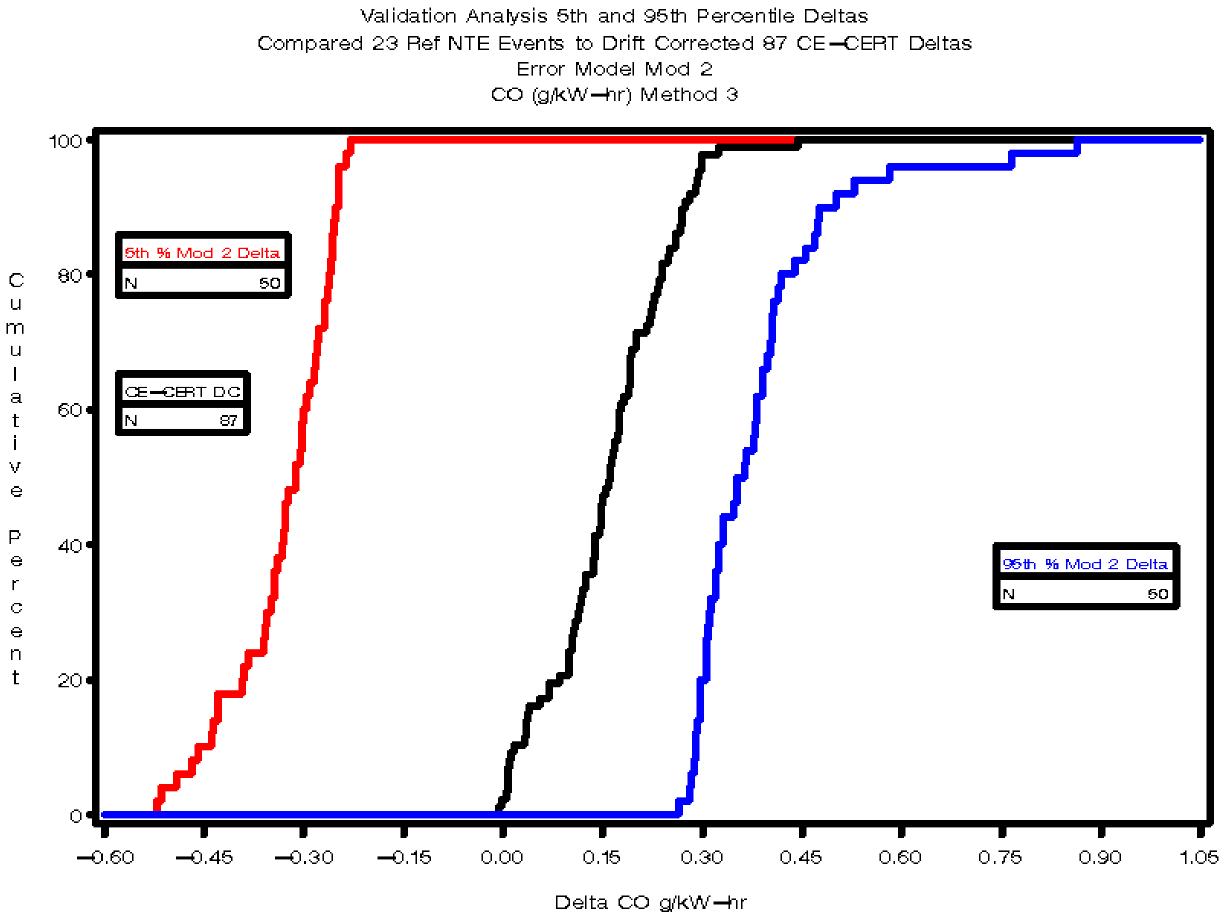

FIGURE 44. VALIDATION EDF PLOTS USING 50 REFERENCE NTE EVENTS FOR CO METHOD 3 MOD 2

Table 7 provides a summary of all the validation results for the various MC simulations as described in the above sections of this report. All emissions and all calculation methods validated using the Mod 1 and Mod 2 runs with 50 reference NTE events while the Mod 3 and Mod B runs validated using 23 reference NTE events.

TABLE 7. SUMMARY OF VALIDATION RESULTS

$BSNO_X$ Method 1	Validated	Validated	Validated	Validated	Validated
$BSNO_X$ Method 2		Validated	Validated	Validated	Validated
$BSNO_X$ Method 3		Validated	Validated	Validated	Validated
BSNMHC Method 1	Validated	Validated	Validated	Validated	Validated
BSNMHC Method 2	Validated	Validated	Validated	Validated	Validated
BSNMHC Method 3	Validated	Validated	Validated	Validated	Validated
BSCO Method 1		Validated	Validated	Validated	Validated
BSCO Method 2		Validated	Validated	Validated	Validated
BSCO Method 3		Validated	Validated	Validated	Validated

9.0 MEASUREMENT ALLOWANCE CALCULATIONS

As detailed in the original PEMS study, the measurement error allowances were computed using both a regression method and a median method to determine the measurement allowance. The procedure was applied to the simulation data for the 50 reference NTE events from the Mod 1 and Mod 2 runs for each of the three emissions and all three calculation methods.

Figure 45 contains a regression plot of the 95th percentile delta $BSNO_x$ values (using Method 1 Mod 1) versus the ideal $BSNO_x$ values for the 50 reference NTE events. Included within the plot is the equation for the fitted regression line and the R-square (R^2) value. Table 8 includes a comparison of the results of the regression method based on Figure 45 and the median method (described in Ref 1). Under the heading "Regression Method" in the table, it is shown that the R-square criterion is not met by the data (R-square must be > 0.90). Thus, the median method must be used. Under the heading "Median Method" in the table, the measurement error at the $BSNO_x$ threshold, based on using the median of the fifty 95th percentile delta $BSNO_x$ values, is 11.5932% when expressed as a percent of the threshold value of 2.68204 g/kW-hr.

Similar regression plots and measurement error tables are provided in the remaining part of this section for the Mod 1 and Mod 2 results based on the 50 reference NTE events. Figure 45 through Figure 47 and Table 8 through Table 10 provide results for $BSNO_x$ Mod 1. Figure 48 through Figure 50 and Table 11 through Table 13 provide results for BSNMHC Mod 1, and Figure 51 through Figure 53 and Table 14 through Table 16 provide results for BSCO Mod 1. Mod 2 results for $BSNO_x$ can be found in Figure 54 through Figure 56 and Table 17 through Table 19, BSNMHC results are shown in Figure 57 through Figure 59 and Table 20 through Table 22 and BSCO results are shown in Figure 60 through Figure 62 and Table 23 through Table 25.

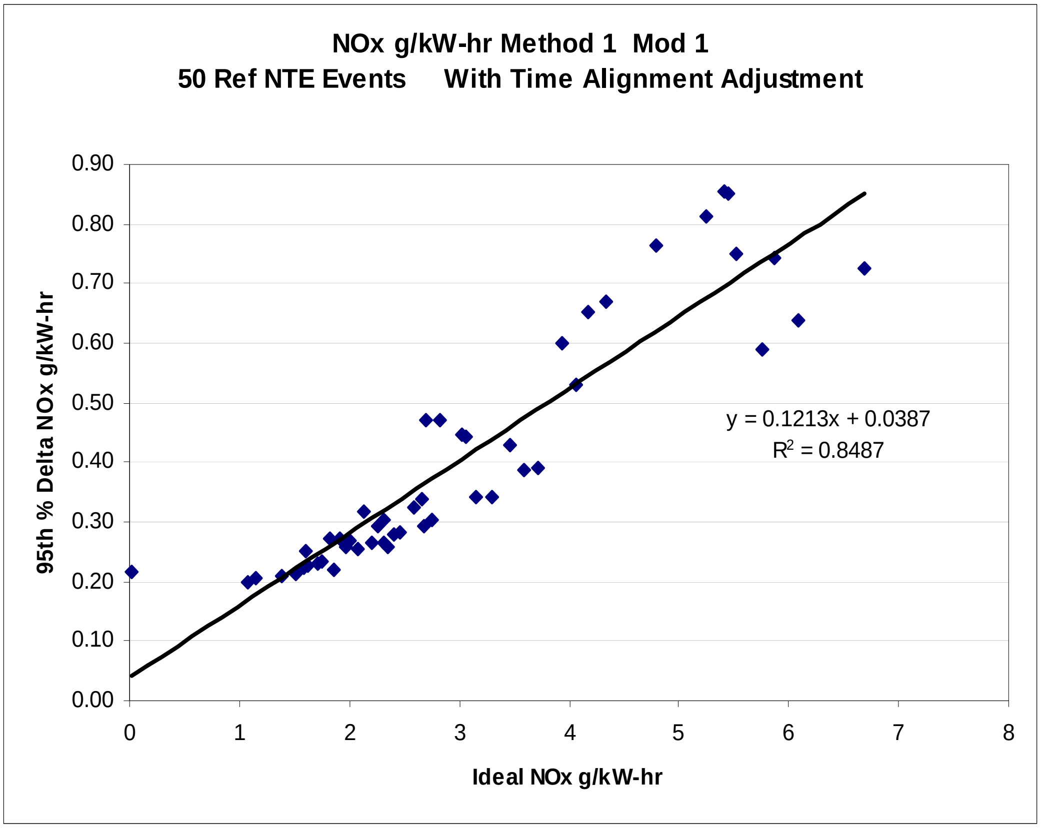

FIGURE 45. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNO$_X$ VERSUS IDEAL BSNO$_X$ FOR METHOD 1 MOD 1

TABLE 8. MEASUREMENT ERROR AT THRESHOLD FOR BSNO$_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 1

R^2	0.8487	Did Not Meet Criteria		
RMSE(SEE)	0.0785	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.3640		Median 95th% Delta	0.3109
Measurement Error @ Threshold=2.68204	13.5729%		Measurement Error @ Threshold=2.68204	

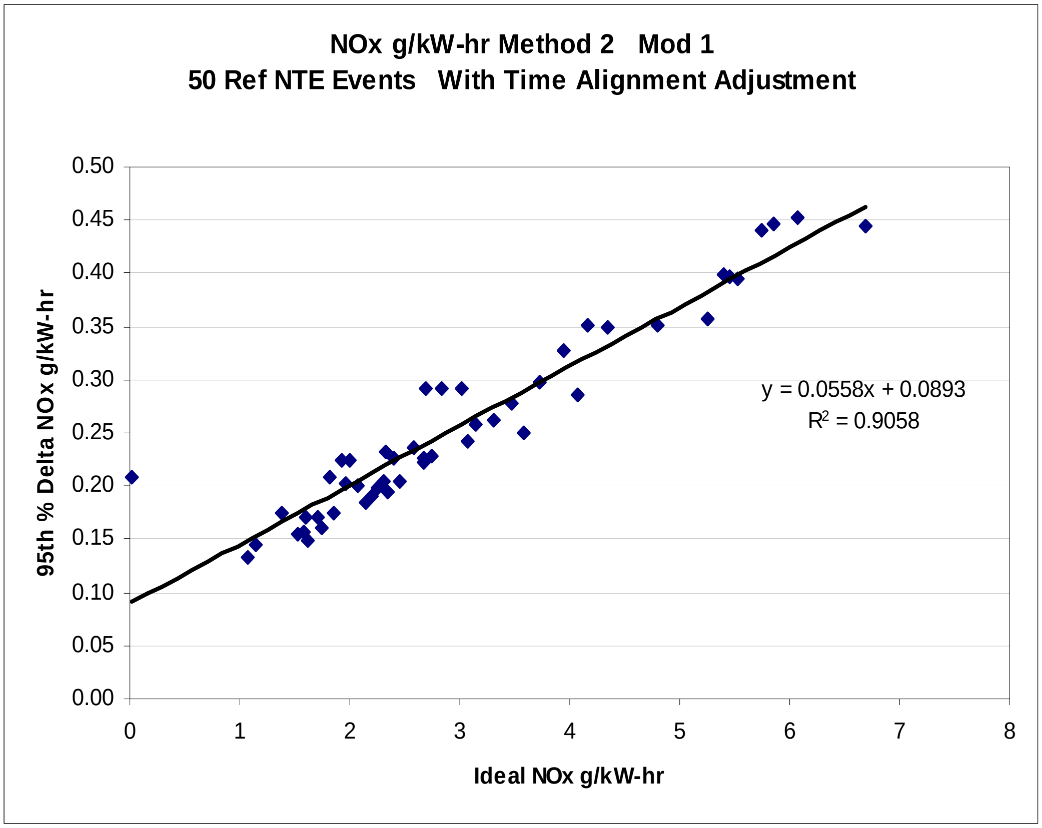

FIGURE 46. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNO$_X$ VERSUS IDEAL BSNO$_X$ FOR METHOD 2 MOD 1

TABLE 9. MEASUREMENT ERROR AT THRESHOLD FOR BSNO$_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 1

R^2	0.9058	Met Criteria		
RMSE(SEE)	0.0276	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.2390		Median 95th% Delta	0.2270
Measurement Error @ Threshold=2.68204			Measurement Error @ Threshold=2.68204	8.4641%

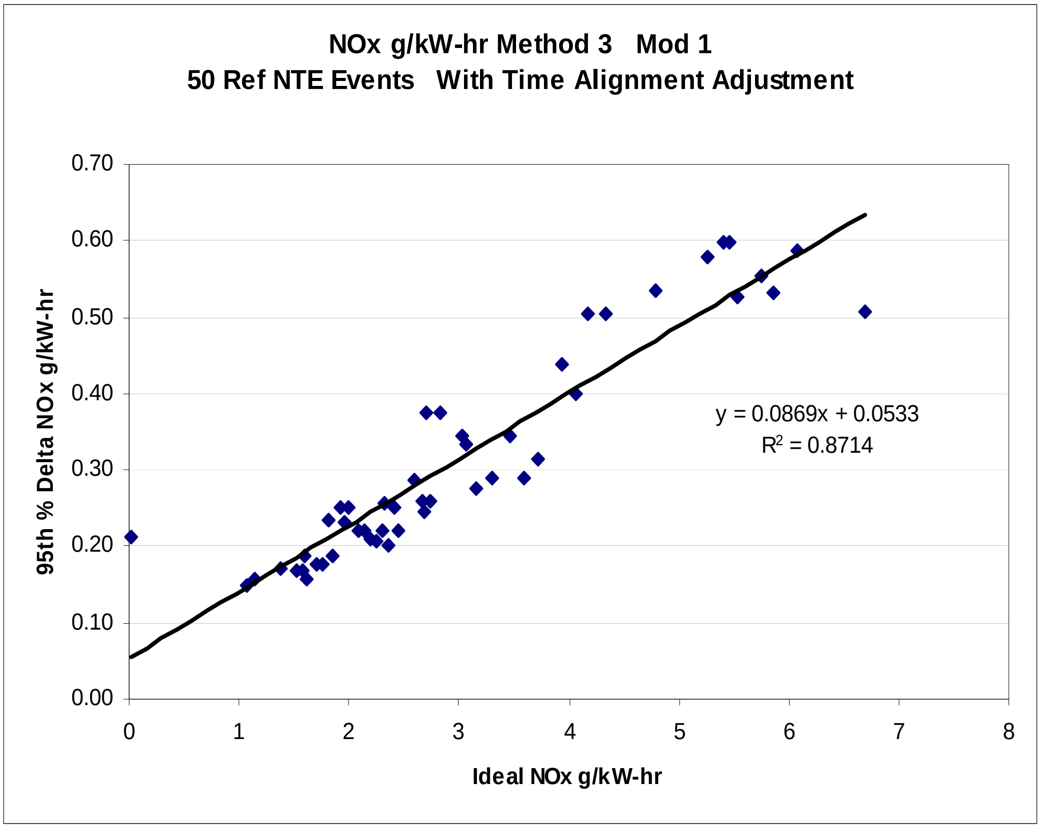

FIGURE 47. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNO$_X$ VERSUS IDEAL BSNO$_X$ FOR METHOD 3 MOD 1

TABLE 10. MEASUREMENT ERROR AT THRESHOLD FOR BSNO$_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 1

R^2	0.8714	Did Not Meet Criteria		
RMSE(SEE)	0.0512	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.3000		Median 95th% Delta	0.2572
Measurement Error @ Threshold=2.68204	11.1845%		Measurement Error @ Threshold=2.68204	

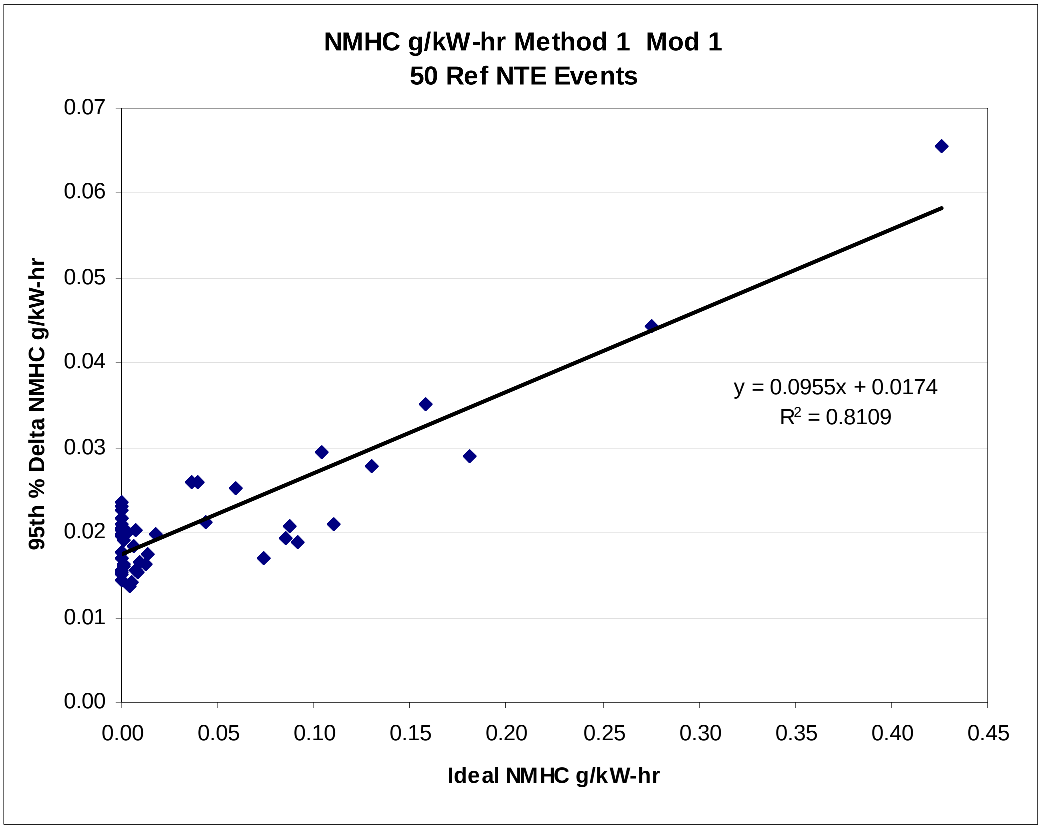

FIGURE 48. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 1 MOD 1

TABLE 11. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 1

R^2	0.8109	Did Not Meet Criteria		
RMSE(SEE)	0.0037	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0443		Median 95th% Delta	0.0197
Measurement Error @ Threshold=0.28161	15.7288%		Measurement Error @ Threshold=0.28161	

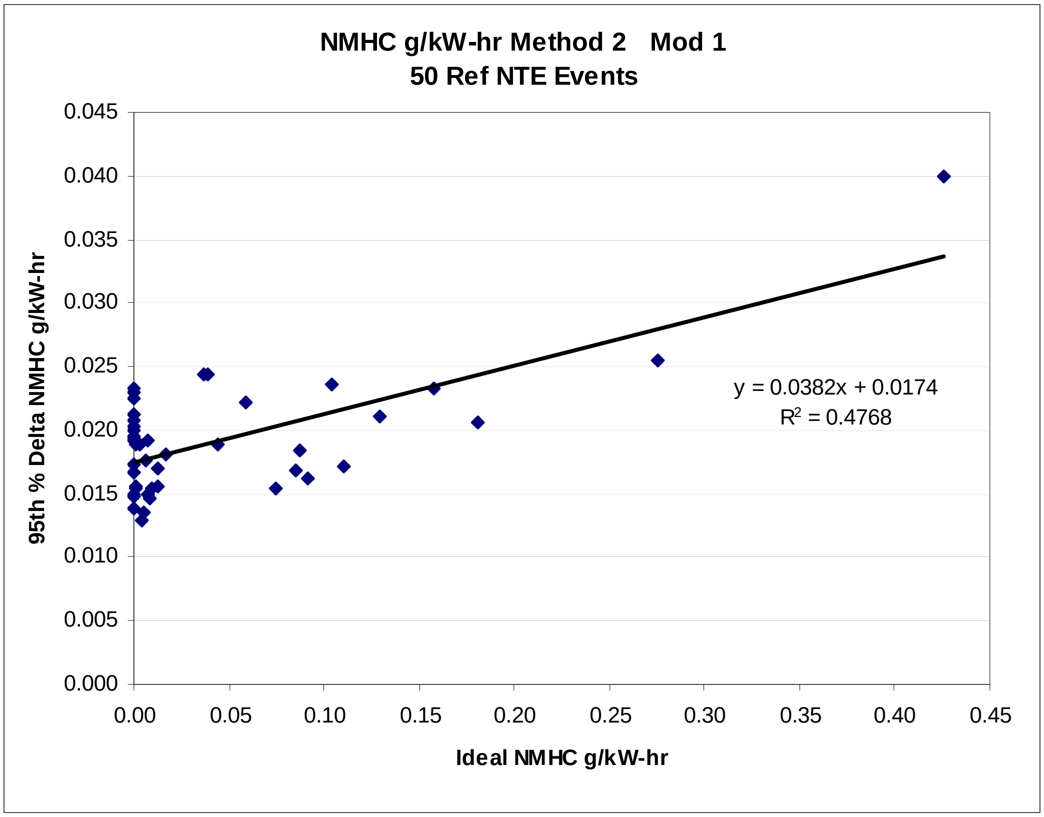

FIGURE 49. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 2 MOD 1

TABLE 12. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 1

R^2	0.4768	Did Not Meet Criteria		
RMSE(SEE)	0.0032	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0282		Median 95th% Delta	0.0187
Measurement Error @ Threshold=0.28161	9.9988%		Measurement Error @ Threshold=0.28161	

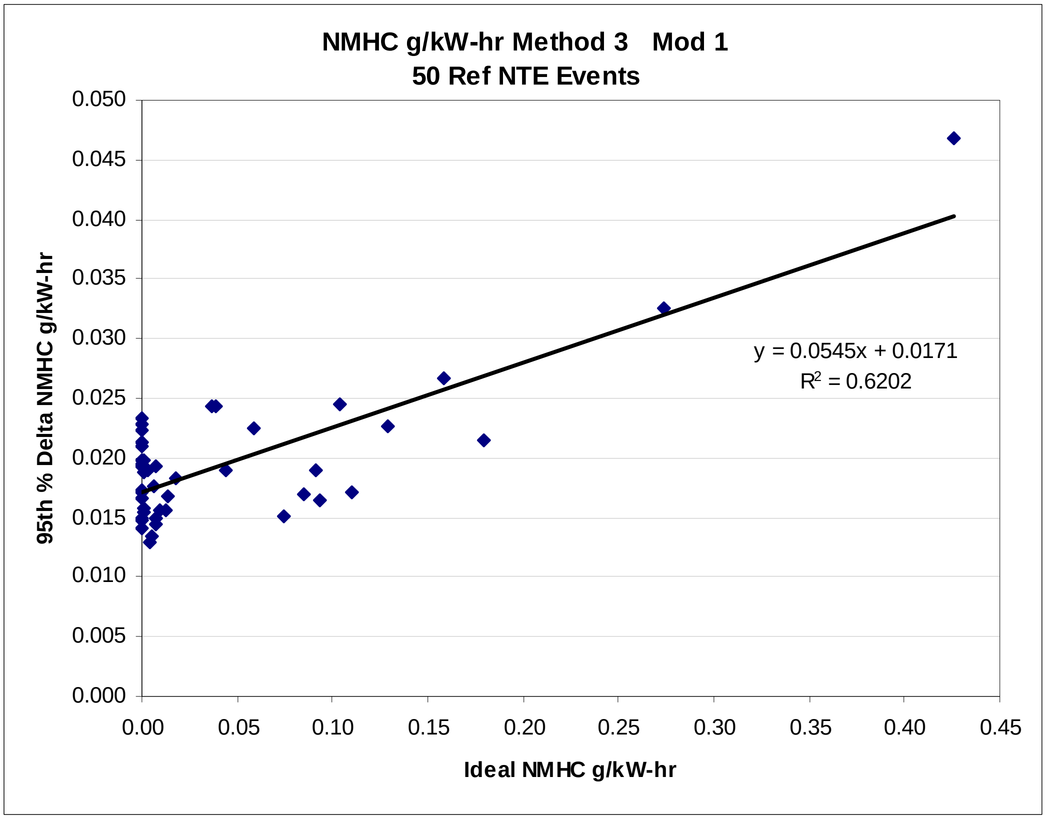

FIGURE 50. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 3 MOD 1

TABLE 13. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 1

R^2	0.6202	Did Not Meet Criteria		
RMSE(SEE)	0.0034	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0324		Median 95th% Delta	0.0188
Measurement Error @ Threshold=0.28161	11.5222%		Measurement Error @ Threshold=0.28161	

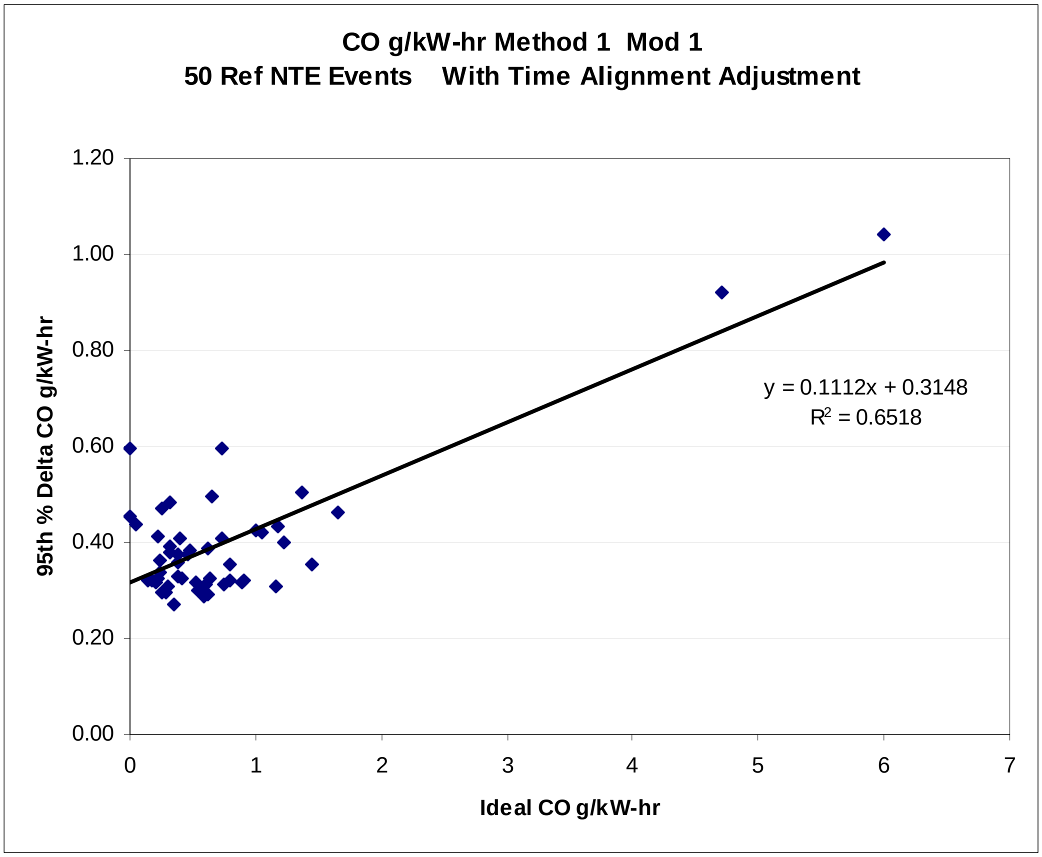

FIGURE 51. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 1 MOD 1

TABLE 14. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 1

R^2	0.6518	Did Not Meet Criteria		
RMSE(SEE)	0.0846	Did Not Meet Criteria		
5% Median Ideal	0.0249			
Predicted 95th% Delta at Threshold	0.9814		Median 95th% Delta	0.3600
Measurement Error @ Threshold=26.015	3.7726%		Measurement Error @ Threshold=26.015	

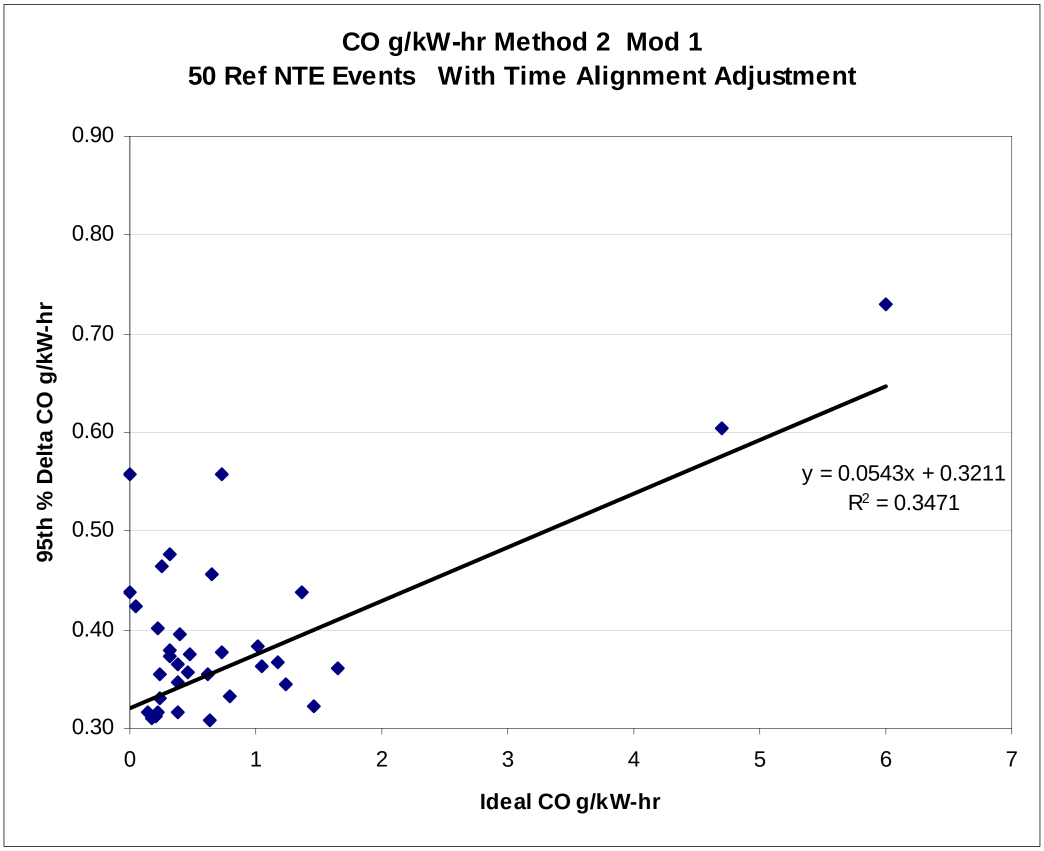

FIGURE 52. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 2 MOD 1

TABLE 15. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 1

R^2	0.3471	Did Not Meet Criteria		
RMSE(SEE)	0.0775	Did Not Meet Criteria		
5% Median Ideal	0.0249			
Predicted 95th% Delta at Threshold	0.6466		Median 95th% Delta	0.3451
Measurement Error @ Threshold=26.015	2.4856%		Measurement Error @ Threshold=26.015	

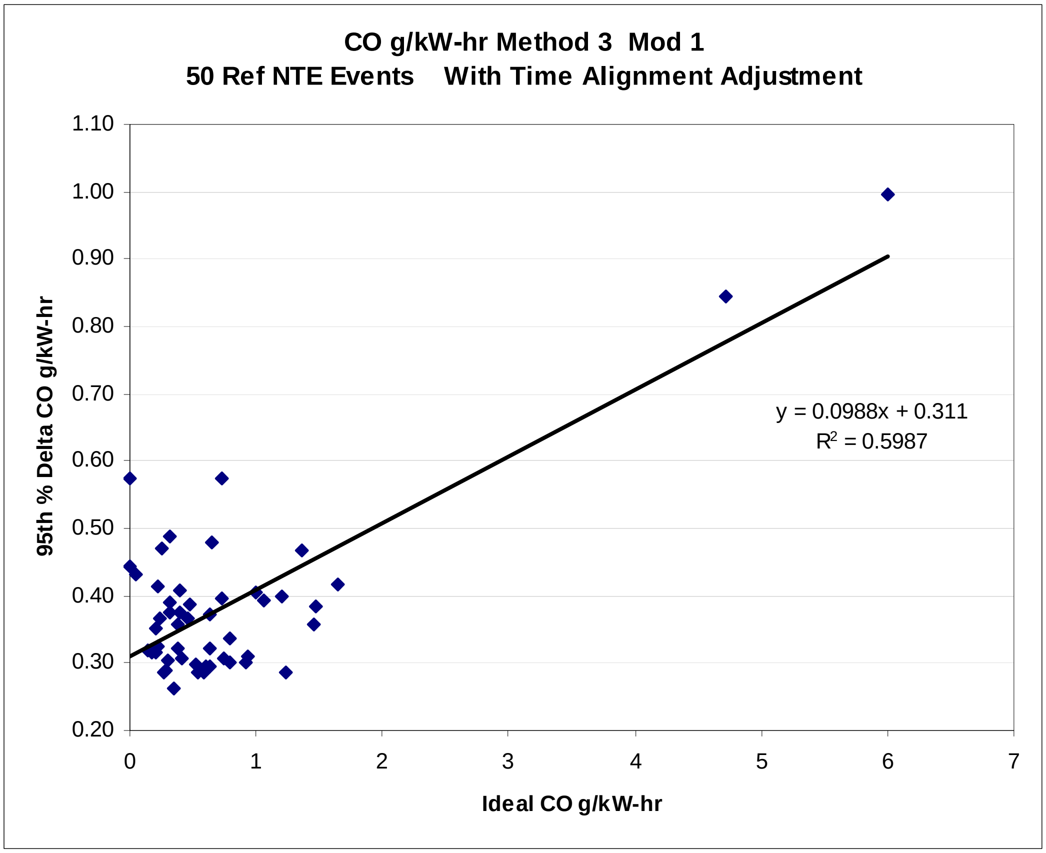

FIGURE 53. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 3 MOD 1

TABLE 16. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 1

R^2	0.5987	Did Not Meet Criteria		
RMSE(SEE)	0.0846	Did Not Meet Criteria		
5% Median Ideal	0.0249			
Predicted 95th% Delta at Threshold	0.9033		Median 95th% Delta	0.3621
Measurement Error @ Threshold=26.015	3.4722%		Measurement Error @ Threshold=26.015	

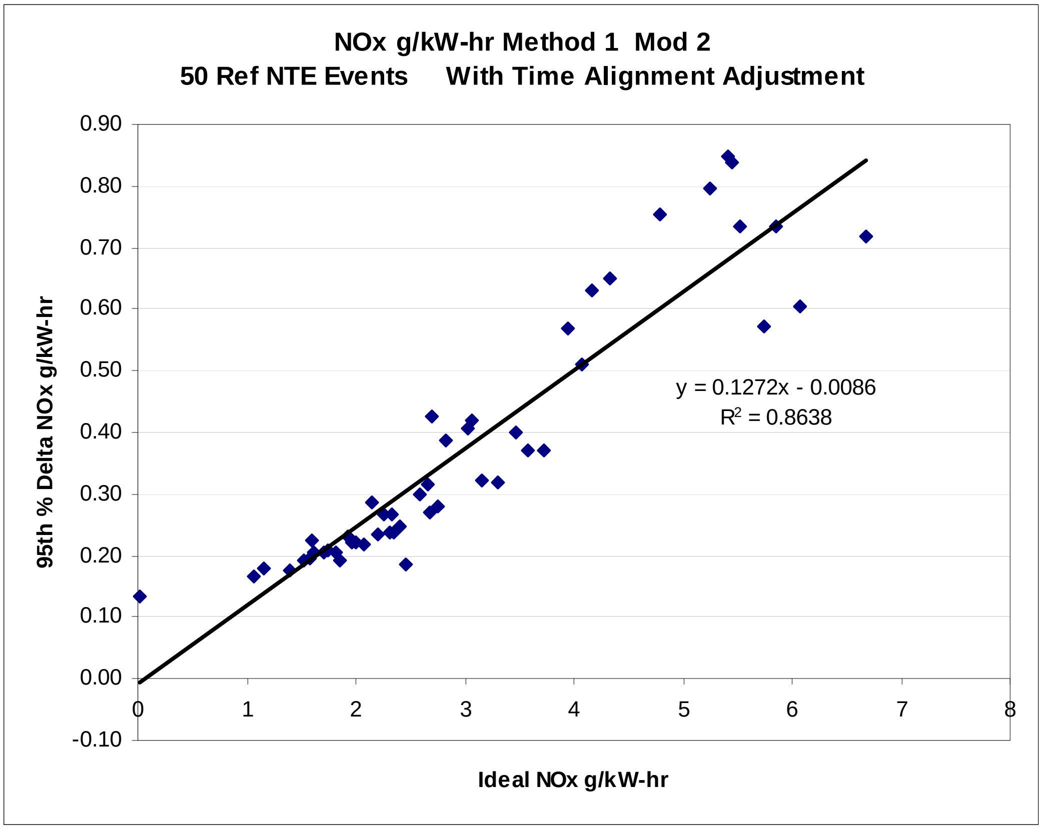

FIGURE 54. REGRESSION PLOT OF 95TH PERCENTILE DELTA $BSNO_X$ VERSUS IDEAL $BSNO_X$ FOR METHOD 1 MOD 2

TABLE 17. MEASUREMENT ERROR AT THRESHOLD FOR $BSNO_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 2

R^2	0.8638	Did Not Meet Criteria		
RMSE(SEE)	0.0774	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.3326		Median 95th% Delta	0.2834
Measurement Error @ Threshold=2.68204	12.3993%		Measurement Error @ Threshold=2.68204	

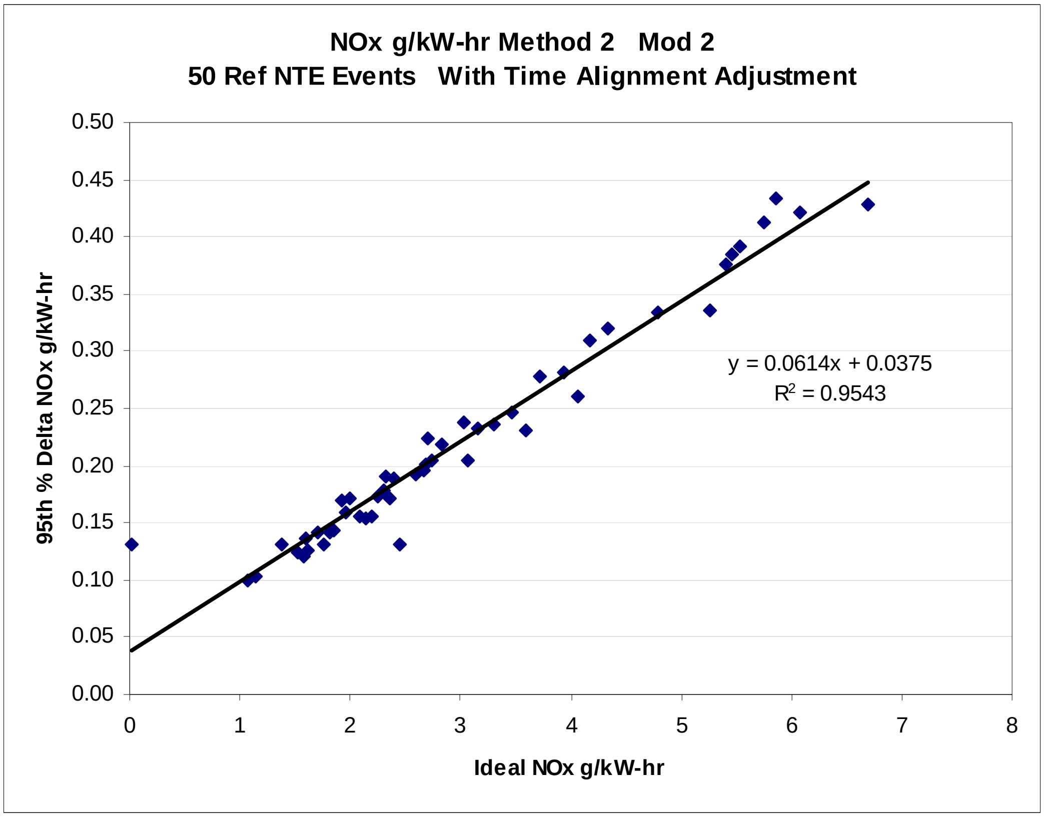

FIGURE 55. REGRESSION PLOT OF 95TH PERCENTILE DELTA $BSNO_X$ VERSUS IDEAL $BSNO_X$ FOR METHOD 2 MOD 2

TABLE 18. MEASUREMENT ERROR AT THRESHOLD FOR $BSNO_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 2

R^2	0.9543	Met Criteria		
RMSE(SEE)	0.0206	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.2022		Median 95th% Delta	0.1935
Measurement Error @ Threshold=2.68204			Measurement Error @ Threshold=2.68204	7.2141%

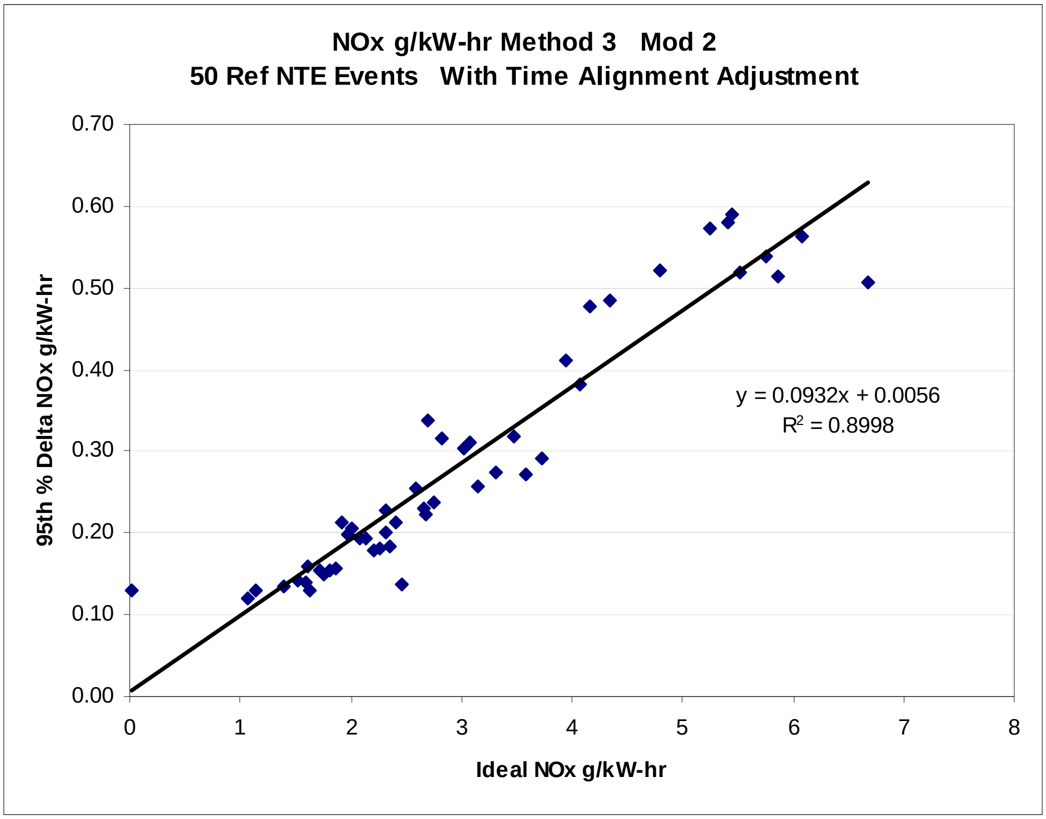

FIGURE 56. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNO$_X$ VERSUS IDEAL BSNO$_X$ FOR METHOD 3 MOD 2

TABLE 19. MEASUREMENT ERROR AT THRESHOLD FOR BSNO$_X$ USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 2

R^2	0.8998	Did Not Meet Criteria		
RMSE(SEE)	0.0477	Met Criteria		
5% Median Ideal	0.1314			
Predicted 95th% Delta at Threshold	0.2556		Median 95th% Delta	0.2295
Measurement Error @ Threshold=2.68204	9.5288%		Measurement Error @ Threshold=2.68204	

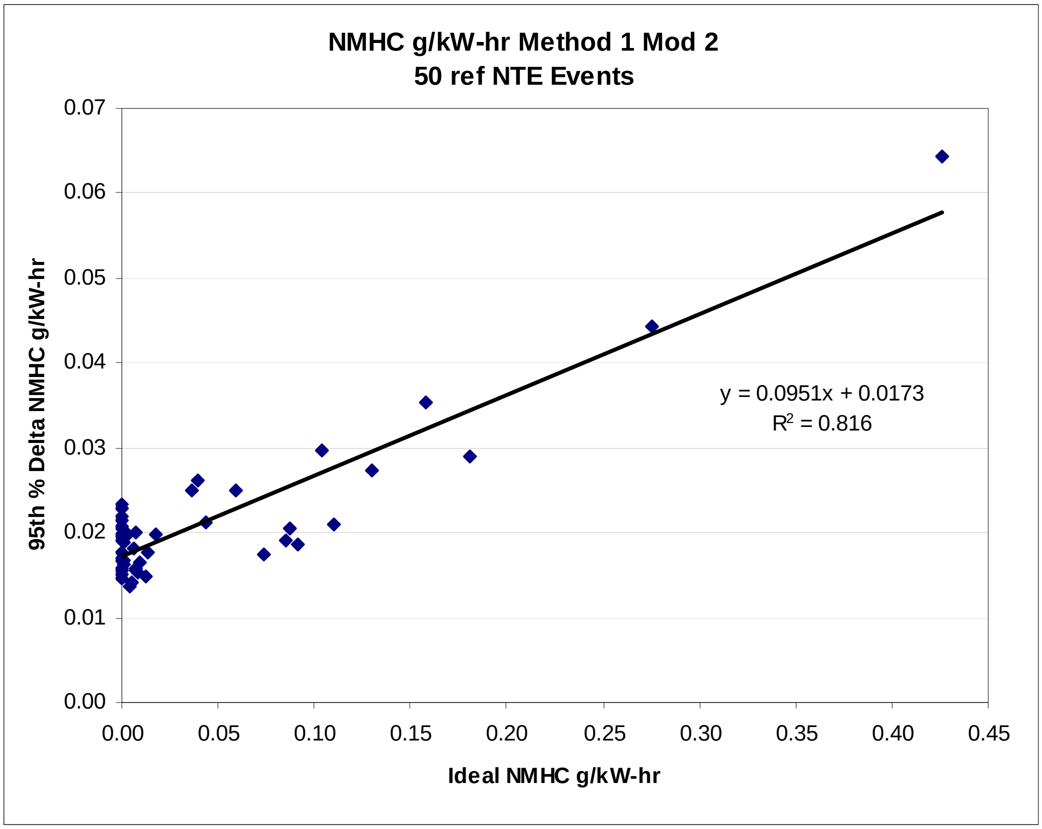

FIGURE 57. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 1 MOD 2

TABLE 20. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 2

R^2	0.8160	Did Not Meet Criteria		
RMSE(SEE)	0.0036	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0441		Median 95th% Delta	0.0194
Measurement Error @ Threshold=0.28161	15.6533%		Measurement Error @ Threshold=0.28161	

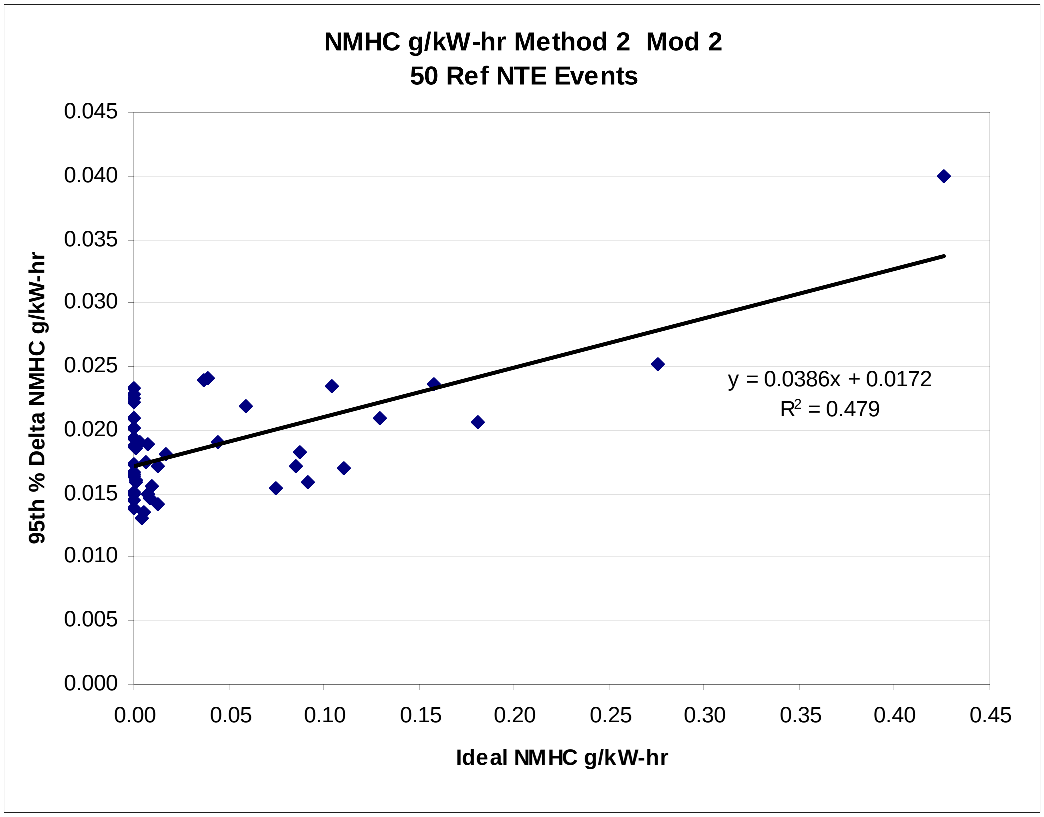

FIGURE 58. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 2 MOD 2

TABLE 21. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 2

R^2	0.4790	Did Not Meet Criteria		
RMSE(SEE)	0.0032	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0281		Median 95th% Delta	0.0182
Measurement Error @ Threshold=0.28161	12.3993%		Measurement Error @ Threshold=0.28161	

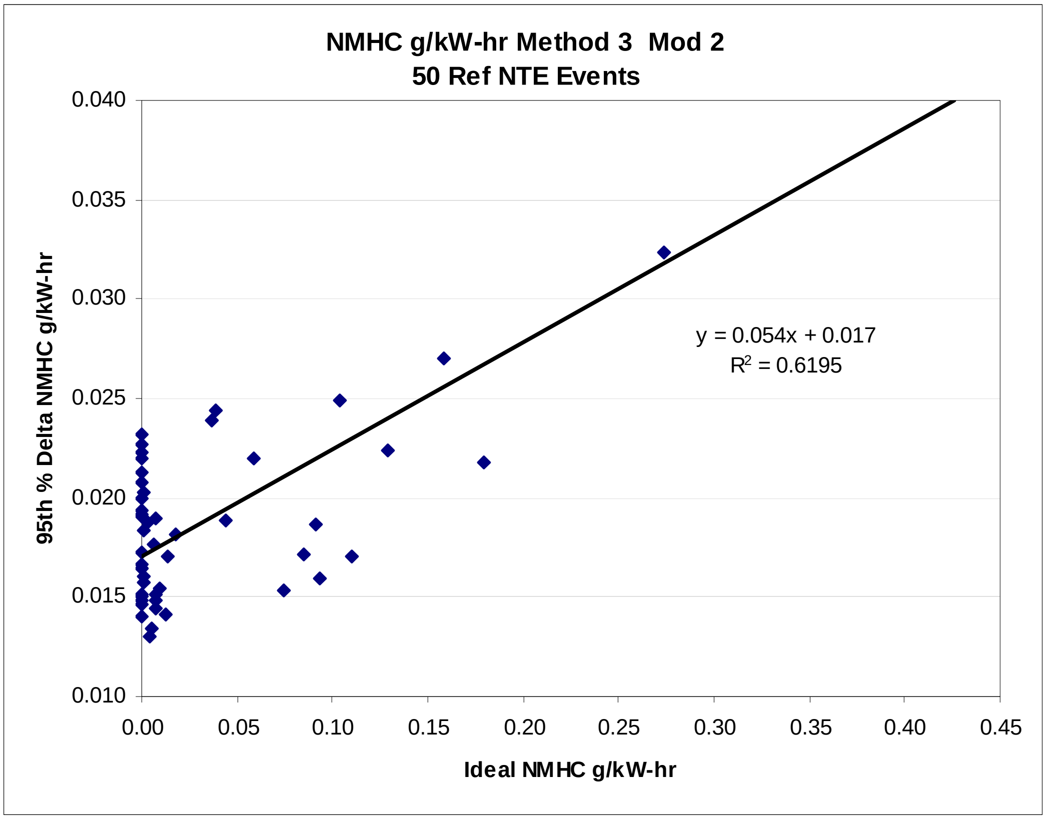

FIGURE 59. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSNMHC VERSUS IDEAL BSNMHC FOR METHOD 3 MOD 2

TABLE 22. MEASUREMENT ERROR AT THRESHOLD FOR BSNMHC USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 2

R^2	0.6195	Did Not Meet Criteria		
RMSE(SEE)	0.0034	Did Not Meet Criteria		
5% Median Ideal	0.0002			
Predicted 95th% Delta at Threshold	0.0322		Median 95th% Delta	0.0182
Measurement Error @ Threshold=0.28161	11.4367%		Measurement Error @ Threshold=0.28161	

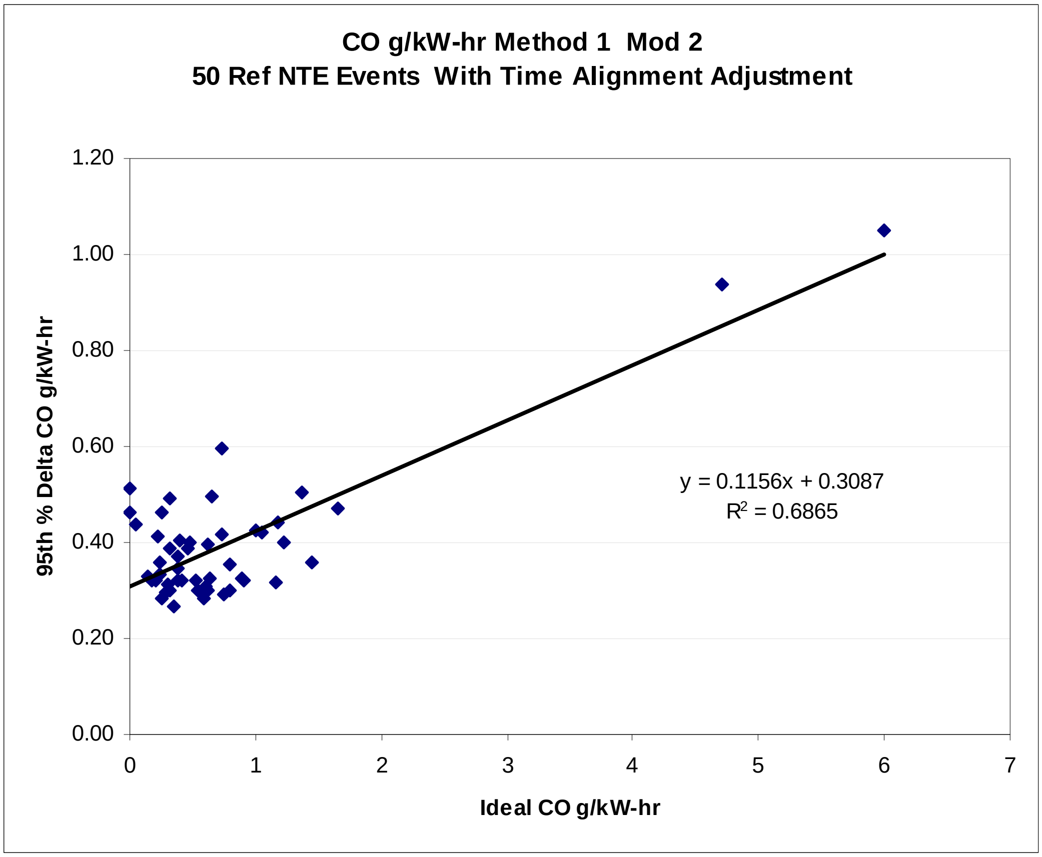

FIGURE 60. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 1 MOD 2

TABLE 23. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 1 MOD 2

<table>
<tr><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td>R^2</td><td>0.6865</td><td>Did Not Meet Criteria</td><td colspan="2" rowspan="3"></td></tr>
<tr><td>RMSE(SEE)</td><td>0.0813</td><td>Did Not Meet Criteria</td></tr>
<tr><td>5% Median Ideal</td><td>0.0249</td><td></td></tr>
<tr><td>Predicted 95th% Delta at Threshold</td><td>1.0017</td><td></td><td>Median 95th% Delta</td><td>0.3576</td></tr>
<tr><td>Measurement Error @ Threshold=26.015</td><td>3.8505%</td><td></td><td>Measurement Error @ Threshold=26.015</td><td></td></tr>
</table>

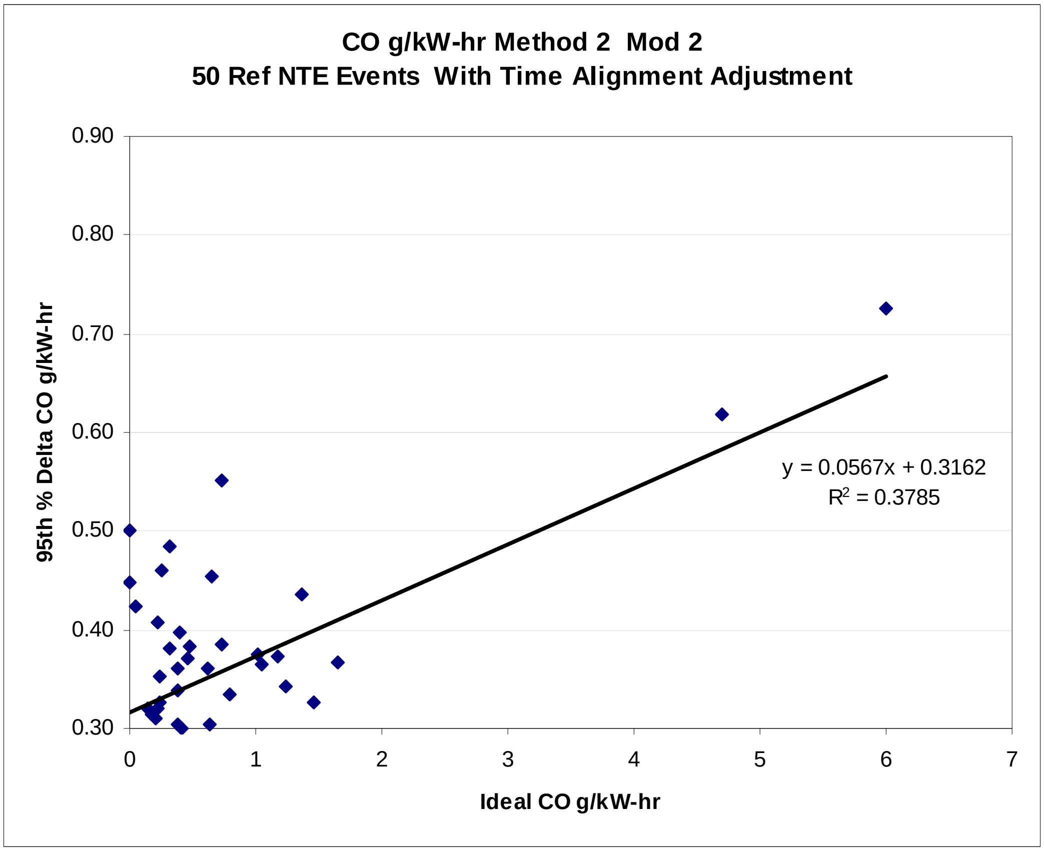

FIGURE 61. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 2 MOD 2

TABLE 24. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 2 MOD 2

R^2	0.3785	Did Not Meet Criteria		
RMSE(SEE)	0.0756	Did Not Meet Criteria		
5% Median Ideal	0.0249			
Predicted 95th% Delta at Threshold	0.6561		Median 95th% Delta	0.3361
Measurement Error @ Threshold=26.015	2.5221%		Measurement Error @ Threshold=26.015	

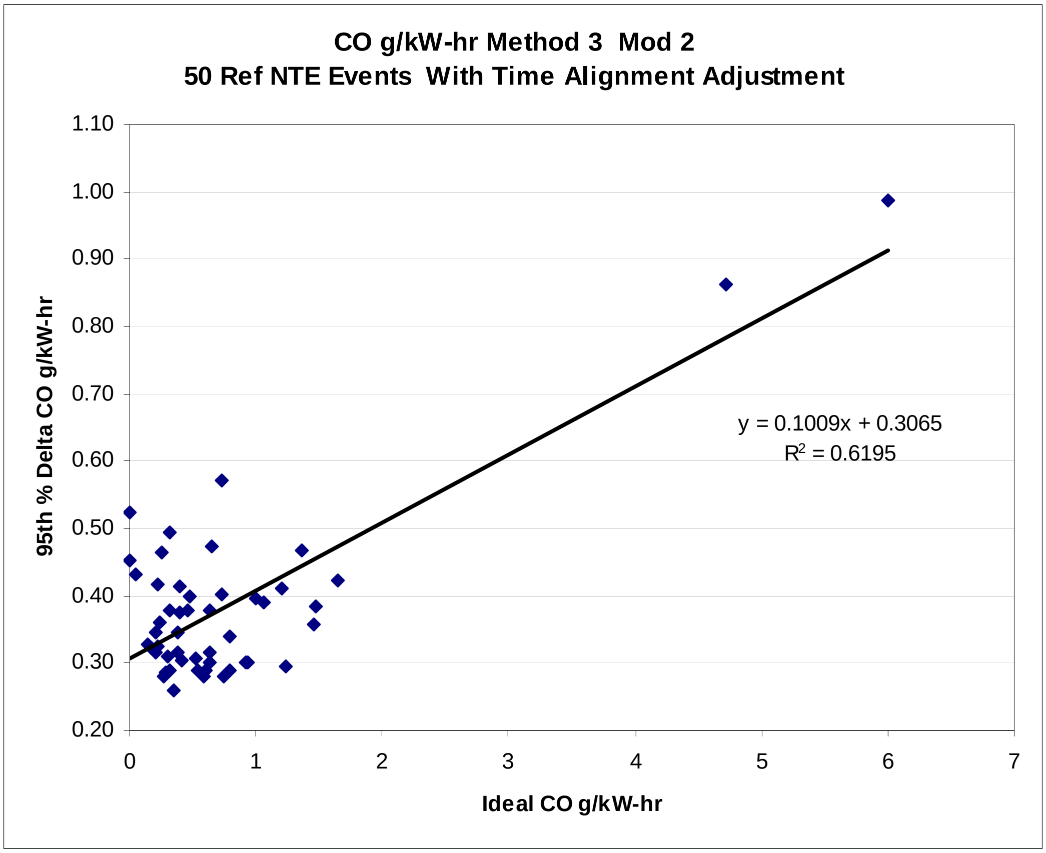

FIGURE 62. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSCO VERSUS IDEAL BSCO FOR METHOD 3 MOD 2

TABLE 25. MEASUREMENT ERROR AT THRESHOLD FOR BSCO USING REGRESSION AND MEDIAN METHODS FOR METHOD 3 MOD 2

R^2	0.6195	Did Not Meet Criteria		
RMSE(SEE)	0.0827	Did Not Meet Criteria		
5% Median Ideal	0.0249			
Predicted 95th% Delta at Threshold	0.9114		Median 95th% Delta	0.3513
Measurement Error @ Threshold=26.015	3.5033%		Measurement Error @ Threshold=26.015	

Although only 23 reference NTE events were simulated under the Mod 3 and Mod B runs, the measurement errors were computed for all three emissions and calculation methods using the same regression and median methods. Table 26 lists a summary of the measurement errors computed from simulation results in this study along with the results from the original PEMS study. Note that $BSNO_x$ for methods 2 and 3 and BSCO for all three methods did not validate in the original study.

TABLE 26. SUMMARY OF MEASUREMENT ERRORS AT RESPECTIVE THRESHOLD (%)

$BSNO_X$	195	Original	22.30	**4.45***	**6.61***
	50	Mod 1	11.59	8.91	9.59
	50	Mod 2	10.56	7.54	8.56
	23	Mod 3	11.78	8.01	10.78
	23	Mod B	11.93	8.26	10.33
BSNMHC	195	Original	10.08	8.03	8.44
	50	Mod 1	7.00	6.63	6.68
	50	Mod 2	6.88	6.45	6.48
	23	Mod 3	7.28	6.90	6.87
	23	Mod B	7.25	6.82	6.78
BSCO	195	Original	**2.58***	**1.99***	**2.11***
	50	Mod 1	1.38	1.33	1.39
	50	Mod 2	1.37	1.29	1.35
	23	Mod 3	1.52	1.41	1.48
	23	Mod B	2.19	1.99	2.16

* Methods did not validate

The final BS measurement allowances were computed by multiplying each of the three measurement errors (in percent) times their corresponding threshold values. Table 27 lists the measurement allowances for all simulation Mod runs and the original PEMS study. The emissions thresholds (g/hp-hr) are provided in the first column of Table 27.

TABLE 27. SUMMARY OF MEASUREMENT ALLOWANCE, G/HP-HR

BSNOx	195	Original	0.446	**0.089***	**0.132***
	50	Mod 1	0.232	0.178	0.192
Threshold=2.0	50	Mod 2	0.211	0.151	0.171
	23	Mod 3	0.236	0.160	0.216
	23	Mod B	0.239	0.165	0.207
BSNMHC	195	Original	0.021	0.017	0.018
	50	Mod 1	0.015	0.014	0.014
Threshold=0.21	50	Mod 2	0.014	0.014	0.014
	23	Mod 3	0.015	0.014	0.014
	23	Mod B	0.015	0.014	0.014
BSCO	195	Original	**0.501***	**0.386***	**0.409***
	50	Mod 1	0.268	0.258	0.270
Threshold=19.40	50	Mod 2	0.266	0.250	0.262
	23	Mod 3	0.295	0.274	0.287
	23	Mod B	0.425	0.386	0.419

* Methods did not validate

10.0 VALIDATION SENSITIVITY RESULTS FROM 13 REFERENCE NTE EVENTS

Simulation results for Mod 1, Mod 2, Mod 3 and Mod B from the 13 reference NTE events chosen in the original study produced sensitivity values from the validation runs due to variance and bias for all three 95th percentile delta emissions by all three calculation methods. The tables below summarize the error surfaces in which either the contribution-to-variance normalized sensitivity average value or the 'on/off' bias check for the error surface was at least 5% in absolute magnitude compared to all the other error surfaces. If the label in the error surface contains the words 'OnOff' then it represents a check for bias; otherwise, the error surface indicates a check for variance. If at least 5 of the 13 reference NTE events resulted in a sensitivity average value > 5% or < -5% then the average contribution to variance is included in the tables.

Table 28 lists the $BSNO_X$ sensitivity error surfaces associated with the original PEMS study for Mod B, Mod 1, Mod 2 and the Mod 3 Monte Carlo validation simulations performed during this project. Note in the output results that the bias due to steady-state exhaust flow rate in Method 1 in the original study has been eliminated in the four modification simulations. In addition, the steady-state CO_2 bias has been eliminated, but a sensitivity component due to variance has been added for Methods 2 and 3.

Table 29 lists the sensitivities due to BSNMHC. Note that no changes have occurred for the four modifications relative to the original study. This is due to the fact that the revised error surfaces did not effect the NMHC calculations. Table 30 summarizes the results of the BSCO sensitivities wherein the steady-state CO bias found in the original modeling has been eliminated in Mod 1, Mod 2 and Mod 3 and replaced by an increased sensitivity due to variance.

TABLE 28. SENSITIVITY RESULTS COMPARING 13 REFERENCE NTE EVENTS ACROSS 5 MONTE CARLO VALIDATION SIMULATIONS FOR $BSNO_X$

			Original				
1	1	SSNOx	29.0	33.2	42.9	32.0	36.3
	20	SS Exhaust Flow	9.6	19.2	16.6	20.4	18.8
	51	NOx Time Alignment	9.0	10.7	9.1	10.9	10.6
		Pulse_Flow_OnOff	25.8	30.5	26.3	33.1	29.1
		SS Exhaust Flow_OnOff	20.4				
2	1	SSNOx	37.0	46.9	57.8	44.6	52.5
	2	TRNOx		5.5		6.6	
	45	SSCO2		-40.1	-33.7	-43.6	-37.7
	51	NOx Time Alignment		6.7	7.5	7.6	6.2
		SSCO2_OnOff	-54.3				
3	1	SSNOx	35.6	44.0	54.9	41.6	49.4
	45	SSCO2		-37.0	-31.3	-39.6	-34.8
	51	NOx Time Alignment	10.4	13.9	11.5	15.8	12.9
		SSCO2_OnOff	-50.9				

DEFINITIONS	
Original	April 2007 Study: All original error surfaces
Mod B	Revised SS Exhaust Flow and SS CO2 error surfaces
Mod 1	Revised SSNOx Mod 1, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 2	Revised SSNOx Mod 2, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 3	Revised SSNOx Mod 3, SS Exhaust Flow, SSCO and SSCO2 error surfaces

TABLE 29. SENSITIVITY RESULTS COMPARING 13 REFERENCE NTE EVENTS ACROSS 5 MONTE CARLO VALIDATION SIMULATIONS FOR BSNMHC

			Original				
1	13	SSNMHC	7.1	7.1	7.0	6.9	6.6
	19	NMHC Ambient	60.9	62.8	63.2	62.5	63.2
		SS NMHC_OnOff	14.5	14.3	13.5	12.9	14.2
2	13	SSNMHC	6.7	6.8	6.8	6.9	6.4
	19	NMHC Ambient	64.5	66.6	66.7	66.3	66.9
		SS NMHC_OnOff	14.3	12.9	13.5	13.2	12.8
3	13	SSNMHC	6.7	6.9	6.8	7.0	6.4
	19	NMHC Ambient	64.4	66.5	66.6	66.1	66.8
		SS NMHC_OnOff	14.4	13.0	13.6	12.5	13.0

DEFINITIONS	
Original	April 2007 Study: All original error surfaces
Mod B	Revised SS Exhaust Flow and SS CO2 error surfaces
Mod 1	Revised SSNOx Mod 1, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 2	Revised SSNOx Mod 2, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 3	Revised SSNOx Mod 3, SS Exhaust Flow, SSCO and SSCO2 error surfaces

TABLE 30. SENSITIVITY RESULTS COMPARING 13 REFERENCE NTE EVENTS ACROSS 5 MONTE CARLO VALIDATION SIMULATIONS FOR BSCO

			Original				
1	7	SSCO	6.2	6.5	79.3	79.1	79.3
	52	CO Time Alignment	10.3		11.0	10.1	10.7
		SSCO_OnOff	82.0	82.2			
2	7	SSCO	6.4	6.7	82.9	83.0	83.0
	52	CO Time Alignment			10.5	11.8	10.4
		SSCO_OnOff	83.6	84.6			
3	7	SSCO	6.2	6.3	77.9	78.0	77.9
	52	CO Time Alignment	11.8	10.1	19.2	17.9	19.0
		SSCO_OnOff	80.8	81.0			

DEFINITIONS	
Original	April 2007 Study: All original error surfaces
Mod B	Revised SS Exhaust Flow and SS CO2 error surfaces
Mod 1	Revised SSNOx Mod 1, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 2	Revised SSNOx Mod 2, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 3	Revised SSNOx Mod 3, SS Exhaust Flow, SSCO and SSCO2 error surfaces

11.0 FULL MODEL SENSITIVITY RESULTS FROM 13 REFERENCE NTE EVENTS

This section contains a summary of the error surfaces that contributed the most to bias and variance of the $BSNO_X$ emissions based on the full MC model. Simulation results from the 13 reference NTE events produced sensitivity values for all three 95th percentile delta emissions by all three calculation methods. Table 31 lists the error surfaces in which either the contribution-to-variance normalized sensitivity average value or the 'on/off' bias check for the error surface was at least 5% in absolute magnitude compared to all the other error surfaces for $BSNO_X$. If at least 5 of the 13 reference NTE events resulted in a sensitivity average value > 5% or < -5% then the average contribution to variance is included in the table. The sensitivity results from the original study are included for comparison.

The results from the $BSNO_X$ Method 1 sensitivities show that the steady-state exhaust flow rate bias from the original study has been eliminated in Mod B, Mod 1, Mod 2, and Mod 3. There is also a slight increase (from the original study) in the average sensitivity due to variation in the steady-state exhaust flow rate with all the modification runs. Slight increases in the average sensitivity for the steady-state NO_X error surface are seen in all modification runs except Mod 2.

Method 2 results for $BSNO_X$ show that the steady-state CO_2 bias effect and the NO_X time alignment variation effect were eliminated in all the modification runs. However, new error surfaces that showed sensitivities in the modification runs were the steady-state CO_2 variation effect and the BSFC DOE Test bias effect. There were also slight increases in the average sensitivity due to variation for the steady-state NO_X error surface in all the modification runs.

The steady-state CO_2 bias effect for Method 3 was eliminated in all the modification runs and a variation effect due to steady-state CO_2 was included. Also, there was a slight increase in the average sensitivity due to variation for the steady-state NO_X error surface in all the modification runs.

TABLE 31. SENSITIVITY RESULTS COMPARING 13 REFERENCE NTE EVENTS ACROSS 5 MONTE CARLO FULL MODEL SIMULATIONS FOR $BSNO_X$

			Original				
1	1	SSNOx	21.0	22.3	31.2	20.8	25.4
	20	SS Exhaust Flow	6.3	10.2	9.5	11.0	10.4
	31	Warm-up torque	-23.2	-23.8	-20.7	-23.7	-22.6
	35	Engine Manuf Torque	-9.8	-9.9	-8.7	-9.9	-9.4
	51	NOx Time Alignment	6.1	5.5	5.0	5.5	5.6
		Pulse_Flow_OnOff	14.7	15.1	13.8	16.4	14.8
		SS Exhaust Flow_OnOff	14.6				
2	1	SSNOx	29.5	33.3	43.9	30.4	37.1
	38	Warm-up BSFC	6.3	5.9	5.2	6.2	5.6
	42	Engine Manuf BSFC	13.6	14.1	12.3	15.8	14.0
	45	SSCO2		-23.2	-20.0	-24.1	-21.9
	51	NOx Time Alignment	6.1				
		BSFC DOE Test_OnOff		-5.9	-5.3	-6.5	-6.1
		SSCO2_OnOff	-34.9				
3	1	SSNOx	23.6	25.6	35.1	34.2	29.2
	31	Warm-up Torque	-27.8	-28.5	-25.0	-29.4	-27.0
	35	Engine Manuf Torque	-11.7	-11.9	-10.4	-12.6	-11.8
	45	SSCO2		-16.3	-14.8	-16.8	-15.6
	51	NOx Time Alignment	6.0	5.4	4.8	5.8	5.3
		SSCO2_OnOff	-25.2				

DEFINITIONS	
Original	April 2007 Study: All original error surfaces
Mod B	Revised SS Exhaust Flow and SS CO2 error surfaces
Mod 1	Revised SSNOx Mod 1, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 2	Revised SSNOx Mod 2, SS Exhaust Flow, SSCO and SSCO2 error surfaces
Mod 3	Revised SSNOx Mod 3, SS Exhaust Flow, SSCO and SSCO2 error surfaces

12.0 REFERENCES

1. Feist, M.D., Sharp, C. A., Mason, R.L., and Buckingham, J.P., “Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program,” SwRI Project 03-12024, U.S. Environmental Protection Agency, California Air Resources Board and Engine Manufacturers Association, April 20.