Heavy-Duty Diesel Inspection and Maintenance Pilot—Phase 2

Final Report

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LIST OF ACRONYMS

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DMM – Dekati Mass Monitor

DPF – Diesel Particulate Filter

DU – University of Denver

FTIR – Fourier Transform Infrared

HC – Hydrocarbon

IR – Infrared

I/M – Inspection and Maintenance

MY – Model Year

NCTCOG – North Central Texas Council of Governments

NO_x – Oxides of Nitrogen

NO_2 – Nitrogen Dioxide

NWWS – New Waverly Weigh Station

OBD – Onboard Diagnostic

OHMS – On-road Heavy-duty Measurement System

PEMS – Portable Emissions Measurement System

PM – Particulate Matter

PPM – Parts per Million

PVC – Polyvinylchloride

SCR – Selective Catalytic Reduction

SHED – Streamlined Heavy-duty Emissions Determination

TAMU – Texas A&M University

TTI – Texas A&M Transportation Institute

EXECUTIVE SUMMARY

The On-Road Heavy-Duty Emissions Measurement System (OHMS), previously known as the Streamlined Heavy-Duty Emissions Determination (SHED) system, is an innovative technology that can be used for the characterization of emissions of heavy-duty trucks while they are in use. The technology comprises exhaust collection systems, vehicle monitoring equipment, and gas and particle analyzers housed in a large tent-like or shed structure and a trailer or room for the analyzers. Emissions are measured by sampling exhaust generated as the truck passes through the test setup.

In 2012, the Texas A&M Transportation Institute (TTI) and the University of Denver (DU) conducted a pilot study assessing the applicability of the SHED/OHMS to a potential heavy-duty diesel inspection and maintenance (I/M) program in the Dallas-Fort Worth region. This study established the OHMS as a viable option to characterize emissions of a relatively large number of trucks, with results that were comparable to those obtained using portable emissions measurement systems (PEMS).

The work summarized in this report is an expansion of the 2012 pilot study, also conducted by TTI and DU. The project's main activities included the following:

1. Identification and testing of refinements to the design of the OHMS
2. Investigating other technologies that can be logically integrated with the OHMS or be an alternative to OHMS
3. Deploying the improved OHMS for a field study.

A semi-permanent shed and test site was set up at the Texas A&M University's RELLIS campus, which houses several of TTI's research facilities. This site was used for the testing of OHMS design options and the testing of alternative technologies. The testing encompassed an investigation of various sample tube locations for the OHMS, the use of the MKS Instruments MultiGas™ 2030 Fourier transform infrared (FTIR) spectrometer with the OHMS, as well as the use of a traditional remote sensing technology (SDM 5060 from ETEST) along with the OHMS. In all cases, PEMS was used as the baseline for analysis and comparisons. The data collected were also used to investigate optimal sampling durations for the OHMS setup.

The findings from the testing of design options indicated that a shed with a gable-style roof and a central sample tube running down the length of the shed was the best-performing design for the OHMS. Further, the MKS MultiGas™ 2030 FTIR was also found to be a viable replacement or supplement to the Horiba analyzers currently used in the OHMS for gaseous measurements and the ETEST would be a suitable candidate for screening vehicles within the entire fleet.

The refined OHMS design, with a gabled roof and central sampling tube, was then deployed at a field study location in New Waverly, Texas. This was the same location as the 2012 pilot study, and data were collected from 935 trucks in just over a two-week period. The emissions of oxides of nitrogen (NO_x) and particulate matter (PM) were analyzed for these test trucks, and compared against vehicle Model Year (MY) categories where information was available. The findings were consistent with the results of the initial pilot testing, and indicated that vehicles classified as high emitters when compared to their MY category were responsible for approximately 21 percent of NO_x emissions and 38 percent of PM emissions of the entire fleet.

The findings from the testing at the test site and in the field provided several insights into the successful installation and operation of the OHMS. From a technical perspective, further research is needed in areas such as the measurement of emissions from vehicles with low exhaust stack configurations, or for the application of OHMS to light-duty vehicles.

From a programmatic perspective, the study findings reinforced the conclusion that the OHMS could serve as a viable platform for an I/M or vehicle screening program. Several aspects of the implementation of such a program, such as the target fleet, deployment location(s), definition of a high-emitting vehicle, funding, and enforcement mechanisms, require further consideration by local agencies and stakeholders.

CHAPTER 1: INTRODUCTION

BACKGROUND

To improve local air quality and to meet the requirements of the National Ambient Air Quality Standards, state and local agencies in nonattainment (NA) areas are looking for new strategies and approaches to reduce mobile source emissions. The North Central Texas Council of Governments (NCTCOG) was interested in exploring options for a heavy-duty diesel vehicle inspection and maintenance (I/M) program for the Dallas–Fort Worth (DFW) ozone nonattainment area.

NCTCOG was specifically interested in a technology called the Streamlined Heavy-Duty Emissions Determination (SHED) system. The technology comprises exhaust collection systems, vehicle monitoring equipment, and gas and particle analyzers housed in a large tent-like structure.(1) It allows for the characterization of emissions from individual vehicles as they drive through the test setup.

The Texas A&M Transportation Institute (TTI) and the University of Denver (DU) conducted a pilot study for NCTCOG, assessing the applicability of the SHED to a potential heavy-duty diesel I/M program.(2) The study assessed the performance of the SHED technology compared to in-use emissions measurements obtained through portable emissions measurement systems (PEMS). The results indicated that the technology performed relatively well in relation to PEMS, and may be a viable option for a heavy-duty I/M program. The SHED system has since been renamed[1] as the On-Road Heavy-Duty Emissions Measurement System (OHMS) and has been installed and tested at additional locations, including in Vancouver(3) and California.(4)

OHMS FOR I/M APPLICATIONS

In the context of an I/M program, it is important to understand the applications as well as limitations of the OHMS technology. The OHMS technology does not produce the type of in-use emissions measurements obtained from technologies such as PEMS or

[1] The term SHED was changed to OHMS to avoid confusion with the sheds used for evaporative emissions measurement.

chassis dynamometer testing. PEMS and dynamometer testing allow for a detailed analysis of vehicle emissions for a single vehicle over an extended operating range, but require vehicles to be taken out of service for equipment to be installed on them for testing. In contrast, the OHMS relies on measurements from a short-duration sample of exhaust, and does not require testing equipment to be installed on the vehicle. It can therefore be used to screen a large sample of vehicles while they are in regular use as part of a clean screening or to support an I/M program. By strategically implementing the OHMS, users can identify high emitters operating within a fleet or in a particular area without creating unnecessary burden on the vehicles to be pulled out of service for testing.

Phase 2 Overview

The main goal of this study was to expand on work performed in the 2012 Phase 1 pilot study conducted by TTI and DU. Specific objectives included conducting further testing and design refinements to OHMS, investigating other technologies that can be logically integrated with the OHMS or be an alternative to OHMS, deploying the improved OHMS for a field study, and developing guidance for future implementation of the OHMS technology in the field for I/M or high-emitter screening purposes.

These objectives were accomplished through three main activities:

- Testing Refinements to the OHMS—The previous installations of the OHMS technology all had slight design differences in their setup. In the initial task, different OHMS design options and possible refinements were tested with and compared to results from PEMS tests.

- Investigating Additional Technologies—The second set of tasks involved looking at other potential technologies that could be used in conjunction with the OHMS. These technologies were selected using a request for partners issued by NCTCOG and TTI. Interested parties submitted their applications to participate in the testing to compare the results of their technologies to the PEMS and OHMS. Applicants with potentially viable technologies were then invited to participate in the testing.

- Conducting a Field Study—The final set of activities involved taking the results from the initial task and conducting a field study using the enhanced OHMS. The field study, which was conducted at the same location as the pilot installation, collected additional information on the heavy-duty fleet operating in the region around the field location. The field study lasted for 2 weeks in October 2016 and collected information on over 900 trucks during this period.

REPORT OVERVIEW

This report provides a summary of work performance and key findings from the Phase 2 study. Following this introductory chapter, Chapter 2 covers the evaluation of the OHMS design modifications and the evaluation of other potential technologies to supplement the OHMS. The field testing is described in Chapter 3, including the setup and results. Chapter 4 provides conclusions and recommendations for the OHMS and other technologies as part of a potential heavy-duty I/M program.

CHAPTER 2: EVALUATION OF DESIGN MODIFICATIONS AND ADDITIONAL TECHNOLOGIES

This chapter describes the testing and evaluation conducted to study:

- Design modifications to the OHMS setup.
- Additional technologies that can be used in conjunction with OHMS.

The testing required for investigating both the design modifications and additional technologies was conducted at a test site at the Texas A&M University (TAMU) RELLIS campus. A permanent shed was installed to house the OHMS technology and to serve as a test site for all activities conducted prior to the field study. The shed was located on the TAMU RELLIS campus' existing system of paved runways, allowing for vehicles to be driven through the setup to measure emissions and collect data.

The shed was installed in January 2016 next to the TTI Environmental and Emissions Research Facility. The test setup enabled the research team to conduct repeated tests in a controlled setting without the interference of other traffic. This installation allowed for a large number of tests to be conducted with different design modifications to ensure that adequate data were collected. Figure 1 shows the shed installed at the TAMU RELLIS campus. The rationale for the selection of the particular shape (i.e., gabled roof) for the shed is discussed in later sections of this chapter.

Figure 1: Shed Installed at the TAMU RELLIS Campus

OHMS Setup and Instrumentation

As described in Chapter 1, the key elements of the OHMS setup include exhaust sampling mechanisms and exhaust analyzers integrated into the shed/tent structure. The OHMS setup is shown in **Error! Reference source not found.**Figure 2 (analyzers and sampling system) and Figure 3 (testing setup at the TAMU RELLIS campus).

Figure 2: OHMS Analyzers

Figure 3: OHMS Setup with Trailer and Test Truck

The exhaust sampling system consists of an exhaust sampling tube made of polyvinylchloride (PVC) with holes drilled into it at 1-ft spacing, along with a pumping mechanism to push air through the analyzers. The equipment used with the OHMS technology was installed in a trailer and placed next to the shed. The emissions analyzers used were the same models as those used in the Phase 1 study and included the following:

- Horiba AIA 240 carbon monoxide (CO)/carbon dioxide (CO_2) analyzer.
- Horiba FCA 240 hydrocarbon (HC)/oxides of nitrogen (NO_x) analyzer.
- Dekati Mass Monitor (DMM) particulate matter (PM) analyzer.

The Horiba units measure CO and CO_2 using infrared (IR) spectroscopy, HC using a flame-ionization detector, and NO_x using chemiluminescence. The DMM measures PM in real time using electrical impactor technology. The OHMS, because it measures the exhaust with an unknown and nonfixed dilution ratio, reports the results as a ratio of the concentrations of the pollutant of interest to concentrations of CO_2 in the exhaust.

Emissions Measurement Process

An infrared detector was installed at the front of the shed, and the OHMS was set up to begin recording data when the truck entered the shed and broke the infrared beam. The mixture of the ambient air and exhaust from the truck was measured for approximately 25 seconds, as the truck accelerated through the shed. A sample data set from the OHMS is shown in Figure 4. It represents a plot of the CO_2 and NO_x concentrations measured at 1 Hz over time for a single truck as it passed through the shed. These data were then used to plot measured concentrations of NO_x (on the y-axis) against measured concentrations of CO_2 (on the x-axis) for each instance in time. A least squares regression line was then created for the scatterplot, with the slope of that line representing the fuel-specific emissions ratio. Figure 5 shows the least squared line for the data in Figure 4, which has a slope of 0.0024. Similar plots were developed for other pollutants as well. The slope of the line and the molecular weights of the pollutants were used to calculate a g/kg of CO_2 emissions measurement for each of the pollutants.

Data Validity

For data from a test run to be considered valid, certain criteria, including a minimal increase in CO_2 of at least 150 parts per million (ppm) over the background, had to be met. All the calculations, including the validity checks, used in the OHMS are described in the Appendix. Any runs not meeting these criteria were deemed to be invalid. For some tests, especially those in the field testing when drivers did not drive through the shed according to the directions, the OHMS data were not valid and thus were not used in the analysis.

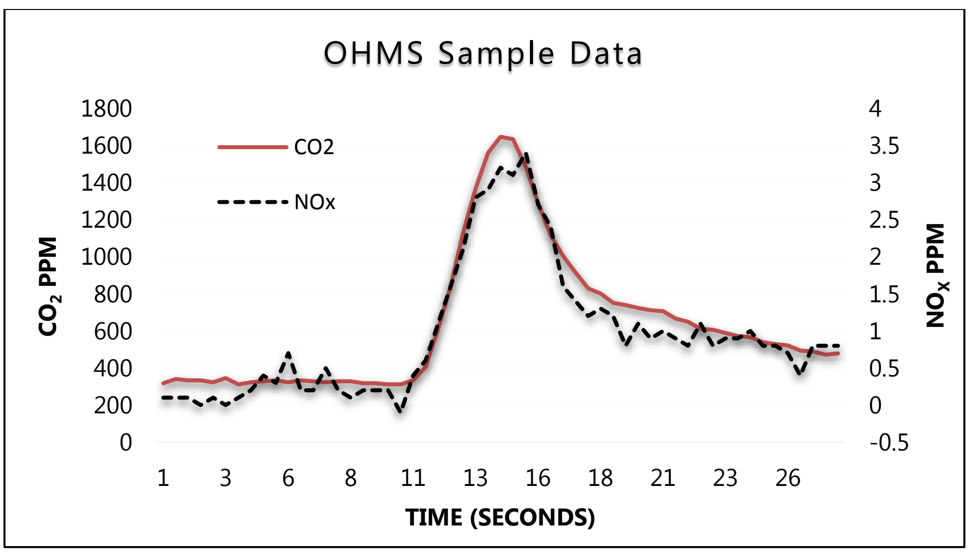

Figure 4: OHMS Sample Data

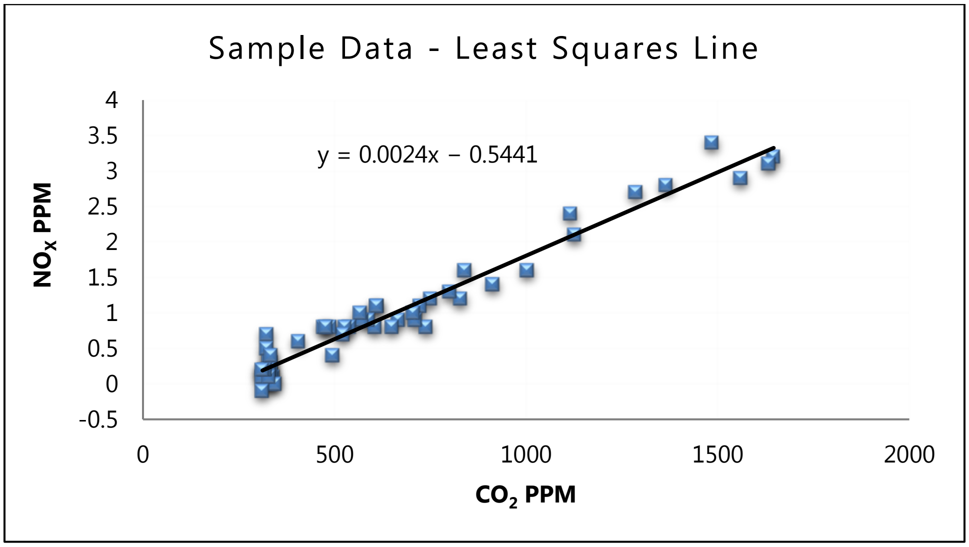

Figure 5: Least Squares Regression Line for Sample Data

INVESTIGATING OHMS DESIGN MODIFICATIONS

The initial task for this project was to look at the potential design modifications for the OHMS technology to improve its performance in terms of sampling of vehicle exhaust and accuracy of emissions estimates. Within the broad parameters of the OHMS setup, key variables that could possibly influence performance included:

- Design of roof of the shed.
- Location of sampling tube.
- Duration of sampling.

During previous installations of the OHMS, two major differences were seen in the design of the sheds. One difference was the roof design, and the other was the location of the exhaust sampling tube. The different setups for each study are as shown in Figure 6**Error! Reference source not found.**. The first installation, during the Phase 1 pilot, used a sloped roof with the sample tube located along the passenger side of the shed (top left in Figure 6). The installation in Vancouver used a gable-style roof with the sample tube running down the center (top right in Figure 6), and the California installation used a gable roof with the sample tube running down the passenger side (bottom of Figure 6).

The research team determined that it would be infeasible to install multiple permanent sheds to test each roof design option, so the roof design selection was made based on the study goal and practical considerations. The gable-style roof was selected over the sloped version based on two main factors. First, a sloped-style roof cannot accommodate the center location for the sample tube. Further, a sloped roof has a lower height limit for a truck entering the shed compared to the gable style, for the same height of side supports. Since the design needed to accommodate a wide variety of truck heights in the field, the research team identified the gable-style roof as the best option for a standard deployment of the OHMS.

Figure 6: Previous OHMS Installations [2,3,4]

Three sample tube locations were tested for comparison. The two locations previously used in OHMS installations (the passenger side location and center of the roof location) were tested as part of this phase. In addition, a third sample location, running across the entrance of the shed, was also used. Unlike the other two options, this design had the sample tube running across the width of the shed, rather than down the length of it. This sample tube location was selected on the basis of an air flow analysis conducted to model the exhaust flow of heavy-duty trucks. The analysis was conducted using flow modeling software that uses the principles of computational fluid dynamics to predict exhaust flow patterns. This analysis determined that as a truck moves forward, the exhaust is pulled toward the back of the trailer by the air flow around the truck. This flow is illustrated in Figure 7, which shows how the exhaust exits the truck stack and is directed to the back of the trailer. Based on this analysis, the third location, across the shed entrance, was included for testing as a potential option to capture the exhaust samples better. All three sample tube locations investigated in this study are shown in Figure 8.

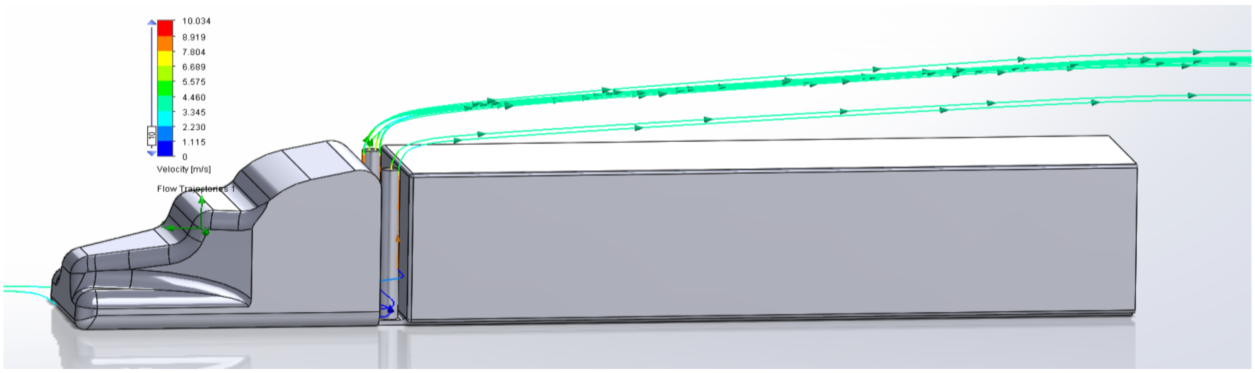

Figure 7: Simulated Exhaust Flow Streamlines

Figure 8: Sample Tube Locations in Shed

In addition to the physical design modifications, the study also evaluated the impact of data analysis methods in optimizing the performance of the OHMS. Specifically, the impact of the duration of the sampling for the OHMS was investigated by post-processing the collected data using different sample durations. During the Phase 1 study, researchers found that many of the trucks would drive though the shed at varying speeds, while the duration of the sampling in the system was set at a constant. This led to cases where the analyzers continued producing readings beyond the sampling period. By post-processing the data to cover different time intervals, the research team was able to study the impact of sample duration on the results, specifically in cases where the sample duration ended before the collected readings had returned to ambient measurements.

Validation of OHMS Data Using PEMS

Similar to the Phase 1 study, PEMS were used to provide a baseline for validation of the OHMS data. All data collected from the testing at the TAMU RELLIS campus were validated using a PEMS device as the reference point. The PEMS device used was the ECOSTAR system from Sensors Inc. The ECOSTAR system is able to measure gas concentrations, as well as total mass emissions, when used with the high-speed flow meter attached to the vehicle's exhaust. The system measures CO, CO_2, NO_x, and total hydrocarbons. For validating the OHMS data, a truck equipped with PEMS was driven through the shed, with the exhaust passing through the PEMS and flow meter, exiting the truck stack, and being sampled by the OHMS. Pictures of the PEMS installed on the truck are shown in Figure 9. The picture includes the flow meter (left) connected to the vehicle exhaust and the gas measurement system (right) inside the cab of the truck.

The comparison of measurements from the OHMS and PEMS has some inherent difficulties due to the different approaches of the technologies in measuring emissions. As previously described, the OHMS samples exhaust diluted in an unknown ratio and reports a ratio of the mass of each pollutant normalized by CO_2 emissions over a sample duration of approximately 25 seconds. The PEMS, on the other hand, measures second-by-second concentrations of each pollutant, as well as the exhaust flow of the vehicle. Using the raw concentrations (ppm) and the exhaust flow data, a total mass of emissions, in g/s, can be calculated on a second-by-second basis from the PEMS data.

Figure 9: PEMS Installation on Test Truck

To compare the two sets of measurements, researchers averaged the data from the PEMS system over the time that the truck was passing under the OHMS shed. This amount represents the PEMS data for the sample of exhaust pulled into the OHMS analyzers.

The first step in comparing the PEMS and OHMS data was to identify the time period in the PEMS data that was being measured by the OHMS. In addition to the emissions data, the PEMS also reported vehicle speed, via both a global positioning system and vehicle interface data from the J1939 onboard diagnostic (OBD) port of the truck. Prior to each test run, the truck driver was instructed to stop in front of the shed for approximately 5 seconds before accelerating through the shed. This deliberate pause helped the research team identify when the truck was entering the shed. The truck then took approximately 5 seconds to go through the shed, and the data from those 5 seconds were used in the comparison with the OHMS results. A g/kg of CO_2 was calculated for each pollutant using the g/s data from the PEMS for that pollutant and for CO_2, and this amount was compared to the OHMS data. As noted in the previous section, approximately 25 seconds was used as the sampling time for OHMS data, compared to 5 seconds for the PEMS. This difference is due to the fact that the OHMS sampling system takes time to pass the exhaust through the analyzers, and a longer sampling duration is required to cover the time spent by the truck under the shed.

OHMS Design Modification Results

Options for sample tube location and sample duration were compared based on OHMS and PEMS data collected through a large number of test runs conducted at the permanent shed setup on the TAMU RELLIS campus. To ensure repeatability and consistency, a single truck was used for all testing of the design modifications. The truck used was a 2006 model year (MY) Freightliner truck owned by TTI. The truck pulled a water tanker trailer, also owned by TTI, for each test. For all testing of the sample tube locations, the truck was stopped at the entrance of the shed and then accelerated through, reaching approximate speeds of 8–10 mph as it exited the shed.

Sample Tube Location

The test plan for comparing the results for different sample tube locations called for 30 runs through the shed using each of the sample locations. The results from the OHMS for each of the locations were then compared to the PEMS results from the same runs. The PEMS data from the different sample locations were also compared to each other. This comparison ensured that the truck was operating similarly each time and that there were no major differences in the testing results due to the test truck.

The initial tests were conducted using the center tube location. Of the 30 runs, 28 were valid. The results for the valid runs are shown in Figure 10. The error bars for each OHMS run are the calculated errors for each run using the formulas shown in the Appendix.

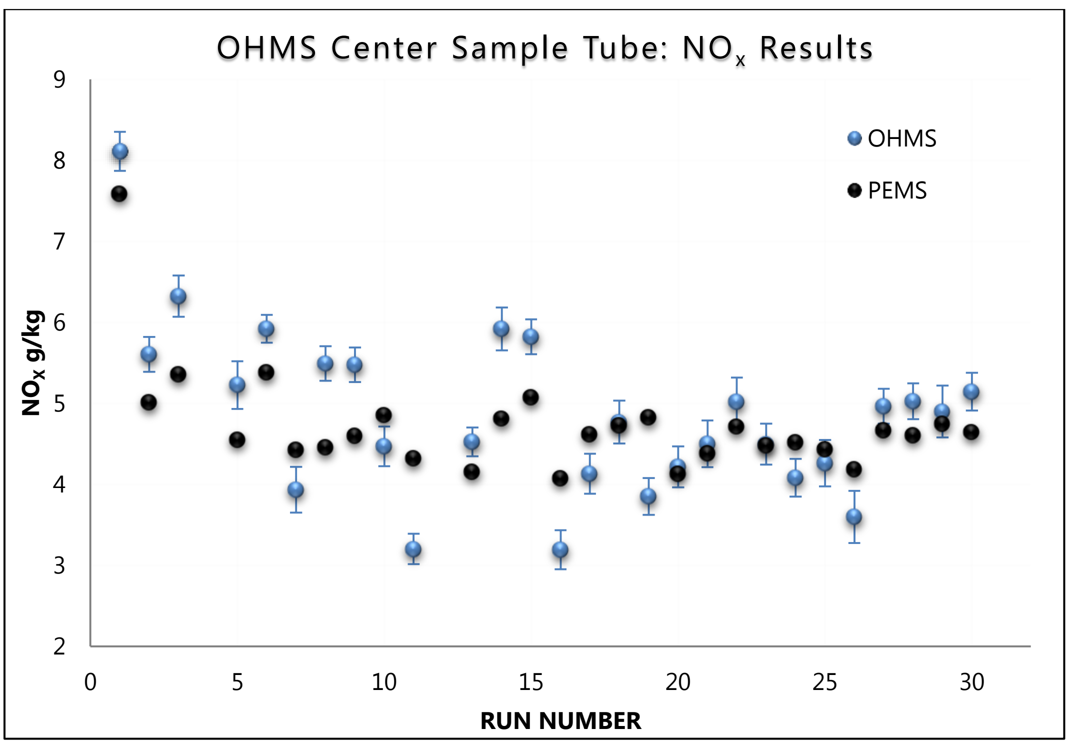

Figure 10: Center Sample Tube PEMS Comparison

As seen in the graph in Figure 10, the first run was conducted just after the truck was started and not sufficiently warmed up; therefore, its reading is much higher than the others. The exhaust temperature for the first run was approximately 100°C cooler than the temperature during Runs 8–30, when the exhaust reached its highest temperature of approximately 180°C. This first run was therefore not included in the calculations of the mean and standard deviation values for comparing the OHMS and PEMS data. The average NO_x value for the valid OHMS runs was 4.74 g/kgCO_2, with a standard deviation of 0.82. The PEMS values for the same runs averaged 4.62 g/kgCO_2, with a standard deviation of 0.33.

Following the testing of the center sampling location, the side sampling location testing was conducted in a similar manner. Of the 30 side sample runs, only 20 were valid, as shown in Figure 11. For the valid runs (excluding the first run since the truck had cooled down in the time between tests), the OHMS average was 4.67 g/kgCO_2 with a standard deviation of 1.2, and the PEMS average was 4.68 g/kgCO_2 with a standard deviation of 0.36.

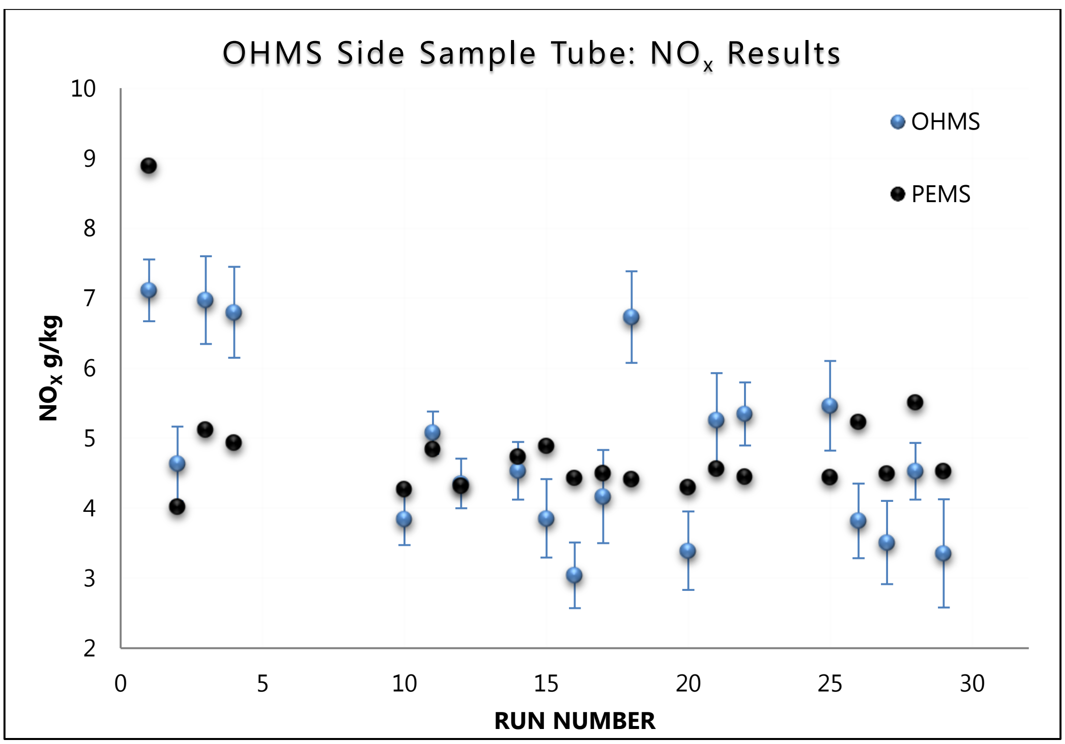

Figure 11: Side Sample Tube PEMS Comparison

The final round of testing was with the front sample tube running across the entrance of the shed. Just as with the center and side sample locations, the test plan called for 30 runs to be conducted. However, after conducting five runs, the research team observed that none of the runs produced valid data. Examination of the data for each run (a sample is shown in Figure 12) revealed that the vehicle exhaust was not getting pulled through the sample tube, evidenced by the absence of a clear spike in pollutant measurements above ambient levels. The plume that was expected based on the flow modeling (shown in Figure 4) did not appear in the field conditions, or was not adequately captured by the front tube design. It was therefore decided to not continue testing of this configuration.

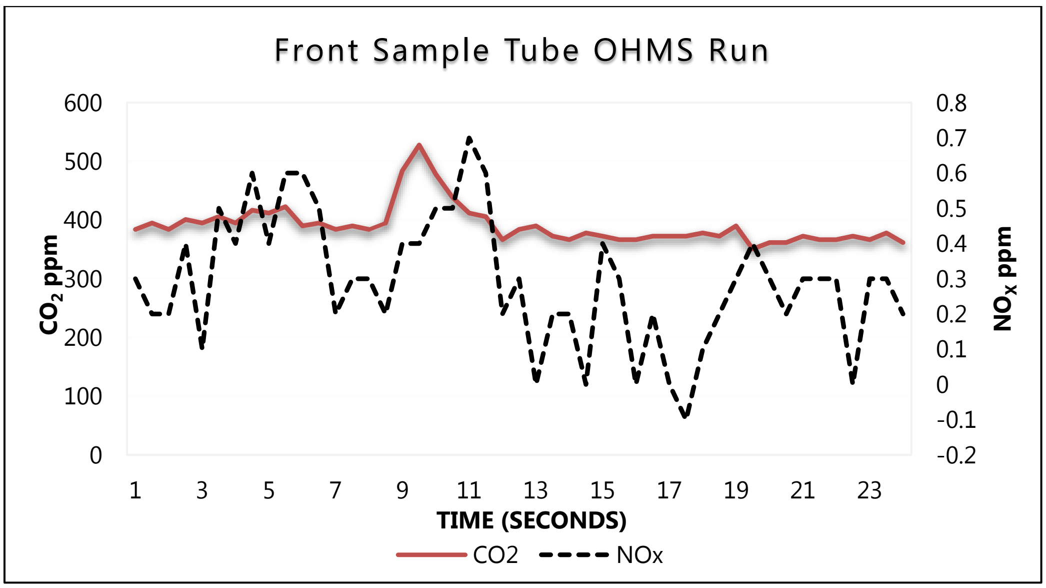

Figure 12: Front Sample Tube Test Data

Further analysis of the center and side sample tube configurations included comparing the PEMS data obtained from the two data sets, to confirm that they provided a consistent baseline for testing the OHMS configurations. Figure 13 shows the NO_x readings from the center (blue) and side (red) sample results. As the figure shows, there were no real differences between the two data sets, meaning that the PEMS values were consistent.

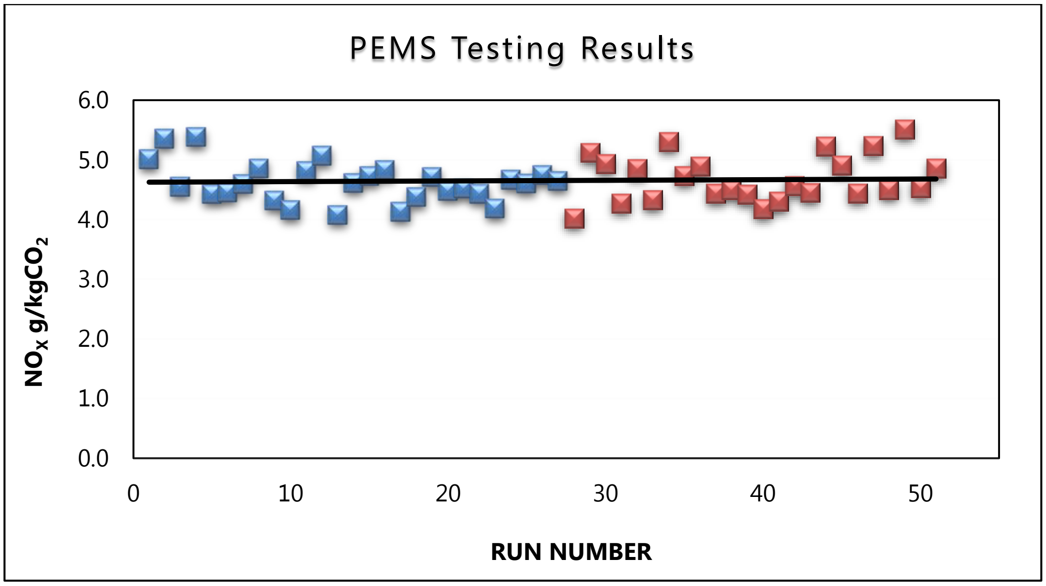

Figure 13: PEMS NO_x Measurements (Center [blue] and Side [red] Sample Tube)

For both design options, the main goal of the location of the sample tube is to ensure that the vehicle exhaust is captured. The OHMS analyzers are the same for all designs, so the performance of each modification is determined by the efficacy of delivering the vehicle exhaust to the analyzers. In order to determine how efficient each design delivered the exhaust to the analyzers, the peak values of each plume were examined. The peak value of each plume is the calculated difference between the maximum and minimum CO_2 ppm value measured during the run. This value was calculated for both the OHMS and PEMS data. For the center sample, the average OHMS plume was 1.43 percent of the PEMS plume, with an average CO_2 plume, measured by the OHMS, of 820 ppm. The side sample average was 0.57 percent, with an average CO_2 plume of 300.7 ppm. This finding shows that the center tube sampling location was able to get a greater amount of the vehicle exhaust to the analyzers. Thus, the researchers determined that the center tube performed better than the side tube. As stated previously, when comparing the OHMS to the PEMS overall averages, data from both locations were very close to the PEMS results. However, when the data were examined on a run-by-run basis, the center tube performed better than the side tube. The average run to run NO_x g/kgCO_2 difference was 11.4 percent for the center tube location and 21.3 percent for the side tube location. These averages do not include the increased number of invalid readings that were seen on the side sample. Based on a combination of the plume numbers with the run-by-run comparison, the center sample tube location is the better option for future designs.

Sample Duration

The second modification to the design that was considered dealt with the data collection and analysis; specifically, the research team sought to determine if the duration of the sampling event improves the OHMS performance. To test this, an additional 60 runs were conducted using the center sampling location, selected based on the previous test results. All 60 runs were valid, using the same duration as the sample tube location testing, and had an average OHMS NO_x value of 4.82 g/kgCO_2 and a PEMS average of 4.52 g/kgCO_2. The average difference between the OHMS and PEMS values for each separate run was 12.0 percent, similar to the results found in the previous testing.

To test whether the sampling duration impacted the results, the OHMS data from these tests were reanalyzed using shorter sampling durations. This meant that portions of the data at the end of the sample period were ignored in the additional analysis. Reducing the duration meant that all the data used in the analysis were from before the readings returned to ambient levels. The data were reprocessed using five different durations, with cutoff points as shown in Figure 14. As the figure shows, the cutoff points were chosen to see how the OHMS performed if the data collection was stopped both before, during, and after the plume from the truck exhaust had reached the OHMS analyzers.

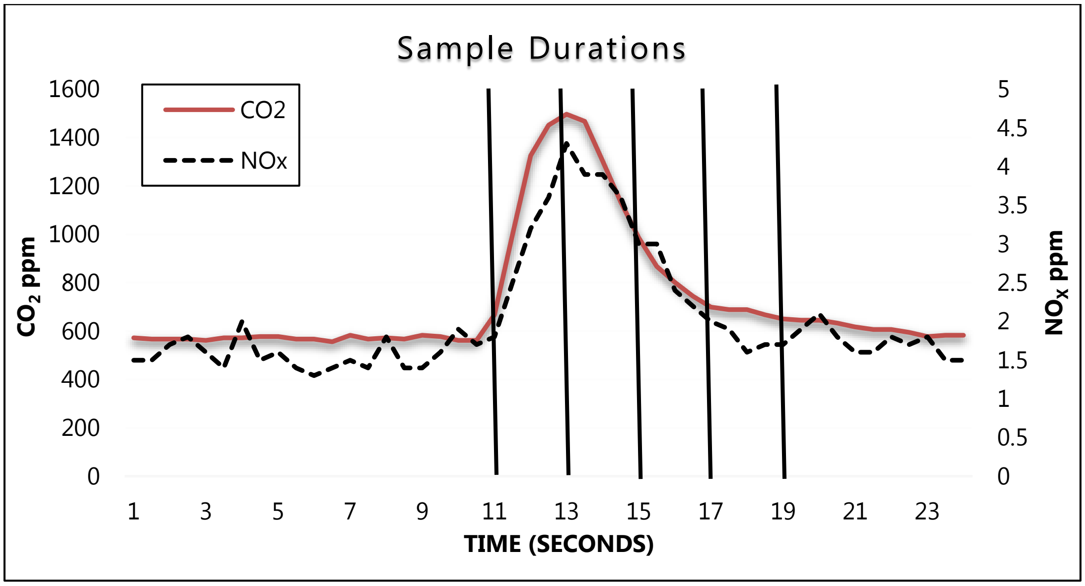

Figure 14: Sample Duration Cutoffs

Table 1 shows the results when the sampling duration changed. As seen in the data, the durations of 15, 17, and 19 seconds all had results that were similar to the original results, which had a duration of 25 seconds. These durations all included the plume of the truck exhaust reaching the analyzers and then the readings beginning to return to ambient levels. The results for the 19-second duration were the same as the full test results, and at this point, the readings were very close to the ambient levels. The results with a duration of 13 seconds, which was just at the time when the plume was reaching the apex, were slightly worse than the other durations, approximately 15 percent worse than the initial results. Going to a duration of 11 seconds did not return any valid results, as expected, since the plume had not yet reached the analyzers and only the ambient data were being used in the calculations. As these results show, the total duration of sampling is not important if the duration is long enough to see the plume of the truck reach the analyzers and the data begin to return to ambient levels.

Table 1: OHMS Sample Duration NO_x Results

Sample Duration (seconds)	11	13	15	17	19	25
Average NO_x (g/kg)	Invalid	4.12	4.67	4.84	4.85	4.85
Difference from PEMS (Average difference of individual runs)	Invalid	17.1%	11%	11.9%	12.2%	12.2%

Evaluation of Other Technologies

In addition to the design modifications of the OHMS, two other technologies were tested as part of this study. Of the two technologies tested, one was tested as an addition/enhancement to the current OHMS analyzers, and the other was a stand-alone technology that could be deployed on its own or alongside the shed as a secondary measurement system. The purpose for testing these additional technologies was to determine if the OHMS was the best option for an I/M screening application, or if one of the other options would be better suited for an implementation.

MKS MultiGas™ 2030 FTIR

The first technology tested was the MKS MultiGas™ 2030 FTIR. The 2030 system is a 5-Hz Fourier transform infrared (FTIR) spectrometer that measures a wide array of gases, including those measured by the instrumentation currently used in the OHMS. The FTIR was configured with a 9-micron detector and a 10-m gas path cell. For this project, the 2030 unit was tested as an addition/enhancement to the OHMS technology. The 2030 unit provides potential improvements to the current OHMS setup through its ability to measure a wide range of gases, including CO_2, CO, NOx, nitrogen dioxide (NO_2), nitric oxide (NO), ammonia, and methane.

The MKS 2030 unit was tested at the TAMU RELLIS site on July 20, 2016. The unit was placed in line with the Horiba units that the OHMS uses so that it was sampling the air at the same time as the analyzers in the OHMS. The MKS 2030 reported the data, just as the Horiba units, in ppm, and the data for NO, NO_2 and NOx were collected in this study. To compare the MKS performance to the PEMS and OHMS, the research team calculated the MKS data using the same formulas as the OHMS, producing a g/kg value for each pollutant that was then compared to the PEMS values. Figure 15 shows the

MKS 2030 unit (left) and how it was installed for the comparison testing next to the OHMS (right).

Figure 15: MKS Instrument Testing Setup

To compare the MKS results to the PEMS values, researchers followed the same procedures that were used to compare the different modifications made. For all testing with the MKS system, the center sampling tube was used. The testing was done with the same truck and trailer combination used during the previous testing at the TAMU RELLIS campus. For this test, a total of 62 runs were completed, with the PEMS, OHMS, and MKS 2030 all recording data. The results are shown in Figure 16. The data include the measurement values from the PEMS, OHMS, and MKS, and the calculated errors from the OHMS. The PEMS results from this test are similar to the results from the design modification testing, with an average value of 5.3 g/kgCO_2 and a standard deviation of 0.29. The results for the OHMS and MKS FTIR were 5.45 and 5.69 g/kgCO_2, respectively, with standard deviations of 0.47 and 0.79.

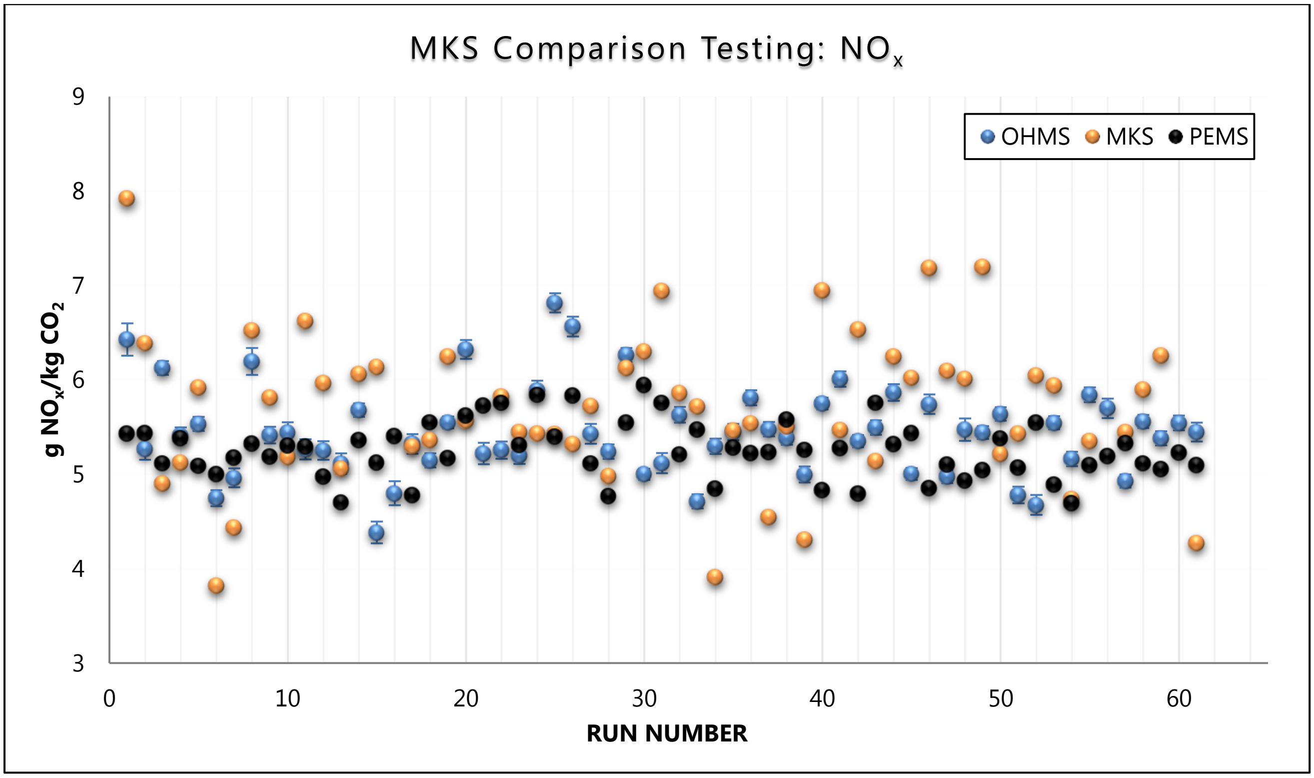

Figure 16: MKS Comparison Data

Based on the overall data, the average for the MKS data was 8.2 percent higher than the PEMS values, which was slightly higher than the OHMS difference of 3.8 percent when compared to the PEMS values. On a run-by-run basis, the average difference for the MKS, compared to the PEMS values, was 14 percent, while the OHMS difference was 9.2 percent. The overall averages are closer to the PEMS that the run-by-run numbers due to some measurements being slightly higher than the PEMS and some being slightly lower.

Overall, the MKS system proved to be a viable instrument for integration into the OHMS. It could serve as an alternative to the Horiba analyzers used, or integrated into the existing system for the measurement of additional pollutants. While the results from the original OHMS were slightly closer to the PEMS than the results from the MKS instrument, the research team anticipates that configuring the MKS system for this type of application could allow the results to be improved further. The MKS 2030 unit also has the further benefit of being able to measure additional gases that are not being measured with the current instruments.

ETEST Corp SDM 5060

The second technology tested under this project was the SDM 5060 from ETEST Corporation. The 5060 system uses infrared and ultraviolet beams of light to remotely analyze the exhaust of a vehicle as it passes by the system. The system has both a transmitter and a receiver unit, which are placed on opposite sides of the roadway or another area where the vehicle will pass through. The 5060 is a remote sensing technology that has been used in the past for other clean screening programs, such as the RAPIDPASS Virginia, which is currently operated by ETEST.[2] The setup used for testing the SDM 5060 is shown in Figure 17. As shown in the figure, the transmitter (right) and receiver (left) towers were set up just outside the shed for the OHMS testing. The test began with the truck parked a few feet in front of the SDM 5060, and the truck then accelerated through the shed and turned around for the next run.

Figure 17: ETEST Test Setup

[2] https://www.rapidpass.org/VaPublic/.

The SDM 5060 system takes a very quick measurement, 0.5 seconds in duration at a very high rate of 200 Hz, when a vehicle passes. This short duration of measurement made comparison to the PEMS, which measures at a much slower rate of 5 Hz, not as straightforward as the OHMS comparisons. In addition, since the sampling period from the SDM data only lasted for 0.5 seconds, it was difficult to make an exact determination, in the PEMS dataset, of when the truck exhaust passed through the beam path of the SDM. Since the approximate time the vehicle passed the beam from the SDM data unit was known, a rolling average was created around that point in the PEMS data. The rolling average was taken from the 5-Hz data, from approximately 0.5 seconds before the truck was expected to be crossing the beam to approximately 1 second after the truck had passed. The rolling averages were calculated in 0.6-second intervals (or 3 data points from the 5-Hz data), for the 1.5-second interval. The average value of all the 0.6-second intervals were then averaged together again for a single value for each test run to compare to the SDM data.

Testing of the SDM 5060 unit was conducted in November 2016. The same truck and trailer combination that was used for the MKS and OHMS testing was used. However, in this test, during some of the runs, NO_2 was added to the exhaust path of the truck. The NO_2 was added via a gas cylinder manually controlled with a valve to the exhaust stream prior to reaching the PEMS analyzer. The NO_2 was added on some runs in order to increase the amount of NO_2 in the exhaust, which was low coming out of the truck. This was done in order to test how well the SDM 5060 unit could detect NO_2 at different levels. Figure 18 shows the NO_2 line, including the location where it was injected into the exhaust flow.

Figure 18: NO_2 Injection Line Location

The testing for the SDM 5060 included a total of 50 runs—26 with no NO_2 injected and 24 with NO_2 injected. The SDM unit measured 45 valid runs, and the remaining five were invalid. The most likely cause of the invalid runs for this test was determined to be human error during testing. The SDM 5060 unit used for this test had no automatic triggering for the start of a measurement; therefore, startup had to be done manually. The research team determined that for the invalid runs, the trigger for starting the measurement was likely pressed either early or late, which resulted in the exhaust plume being missed by the unit and causing an invalid result.

The results from the SDM testing are shown in Figure 19. The figure shows the average values calculated from the PEMS results, with an error bar of ± 1 standard deviation. The SDM 5060 values are shown with an error bar of 10 percent. The overall average values from the PEMS data come to 9.82 $gNO_x/kgCO_2$, while the SDM 5060 average is 11.68, a difference of 18.96 percent. While these differences are higher than the OHMS to PEMS comparisons, part of this can also be attributed to the variability introduced by the manual triggering of the unit to start the measurement. While some of these caused invalid runs, others may have met the validity criteria but still not been adequately aligned with the PEMS data. Broader deployment of the SDM 5060 may require investigation of solutions such as automatic triggering of the unit and additional testing to determine if the new modifications improve the performance.

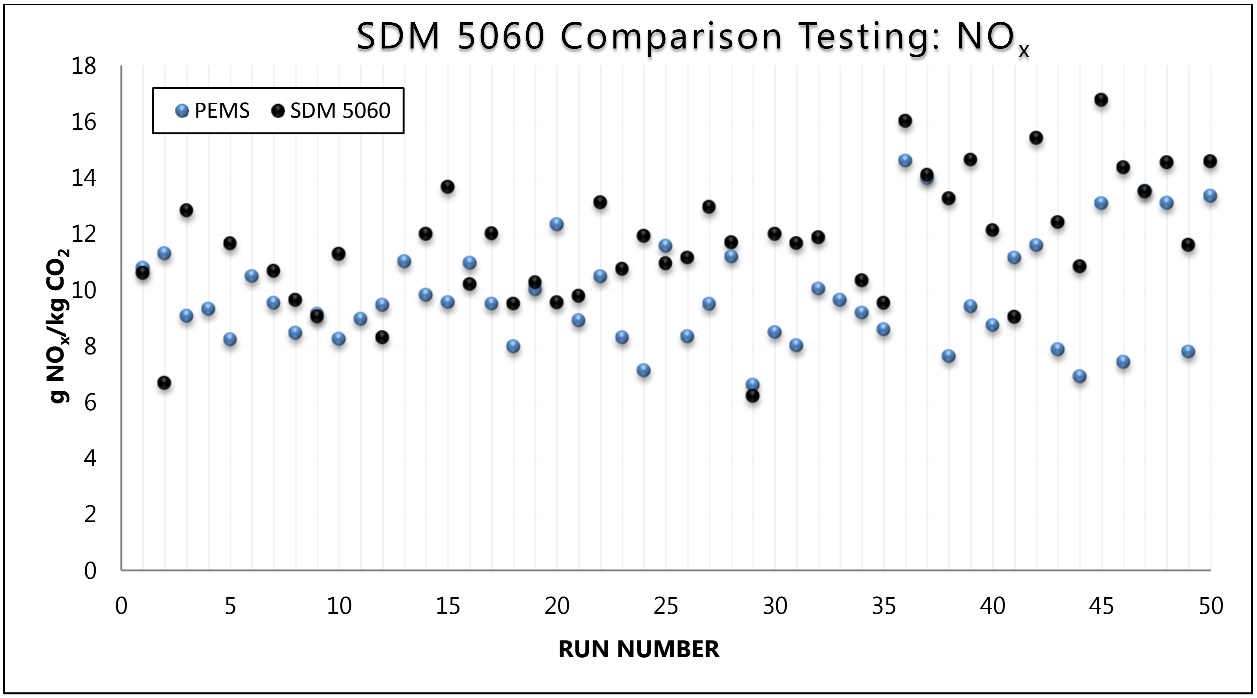

Figure 19: SDM 5060 Testing Results

SUMMARY

As discussed in this chapter, two design modifications (sample tube location and sample duration) were tested for the OHMS design as part of the project. In addition, two other technologies were tested, one that works with the OHMS and another remote sensing technology that could allow for high volume measurements of vehicles for high emitter detection.

The results are consistent with previous findings, and show that the OHMS is a viable tool for characterizing emissions of vehicles, and identifying high emitters within a fleet of vehicles, in this case heavy-duty trucks. The overall design of the OHMS, especially the location of the sample tube and roof design, is important to how well it performs. The best design among the options explored for the system is a gable-style roof with the sample tube running down the length of the shed in the center of the roof. This design provides the best performance for measuring the exhaust of vehicles as they travel through the system.

For the other technologies, testing showed that the MKS MultiGas™ 2030 FTIR would be a suitable replacement to the current gaseous analyzers used by the OHMS. The FTIR performs similarly to the current equipment used but can also measure additional gases if desired. The SDM unit did show good correlation on many runs, but was inconsistent and overall not as close to the PEMS as the OHMS. This is likely due to the variability introduced in the process due to manual operation of the unit. Table 2 shows the summary results of both the MultiGas™ 2030 and SDM 5060 comparison tests.

Table 2: MultiGas 2030 and SDM 5060 Comparison

Test Unit	Test Runs	Average $gNO_x/kgCO_2$ Value	Average PEMS $gNO_x/kgCO_2$	Average Difference (%)*
MultiGas™ 2030	62	5.69	5.3	14
SDM 5060**	45	11.68**	9.82**	18.96

*** Average difference is computed on a run-by-run basis**

**** Some runs with the SDM had NO_2 injected, leading to higher average NO_x readings compared to other tests.**

CHAPTER 3: FIELD TESTING

The field testing was conducted on heavy-duty trucks passing through the New Waverly Weigh Station (NWWS), located on I-45 North in New Waverly, Texas. This same location was used for the Phase 1 pilot study. The weigh station is approximately 150 miles south of Dallas. As noted in the Phase 1 study, a majority of the trucks passing through the NWWS eventually pass through the DFW region. That fact, combined with the number of trucks that pass the site daily, made it an ideal candidate for testing under this phase of the project. It also enabled comparisons to be made between the findings from the Phase 1 pilot and testing conducted under this study.

TEST SETUP

Testing at the NWWS was conducted from October 19 through October 31, 2016. The NWWS includes five covered lanes, as shown in Figure 20, along with a bypass lane. Two of the lanes were utilized for the installation of the shed. The shed was set up in Lane 2, and the trailer with the analyzers was set up in Lane 1. The setup can be seen in Figure 21.

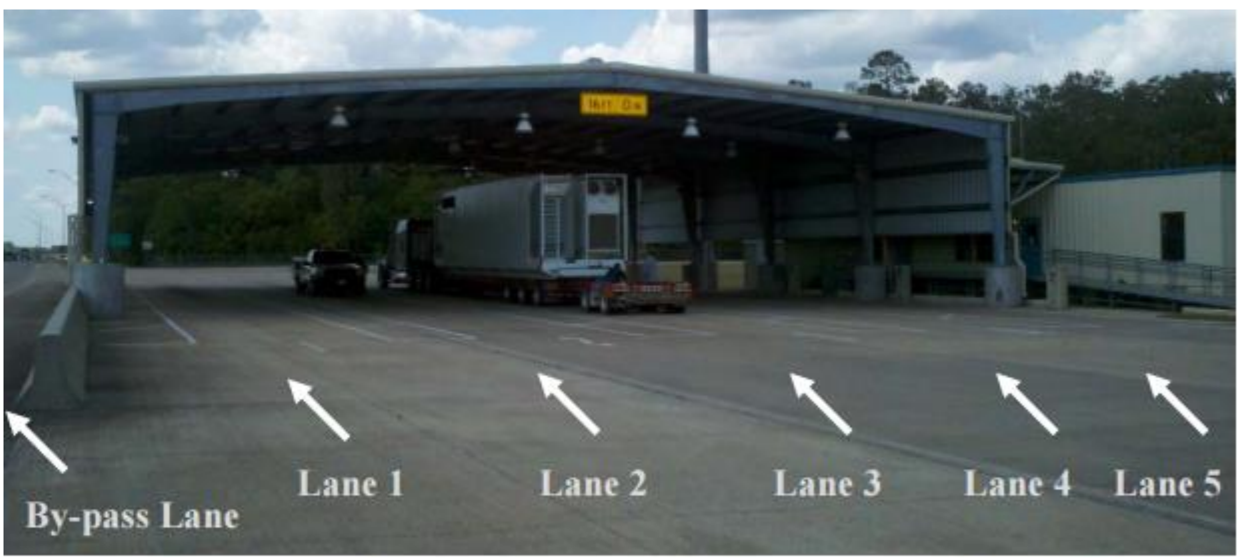

Figure 20: Field Test Location at New Waverly

Figure 21: Shed at NWWS

The design of the shed used in the field testing was based on the results from the design modification testing conducted at the RELLIS campus of TAMU. The shed design that was utilized had the gable-style roof with the sample tube running down the center of the shed. The roof design and the sample tube can be seen in Figure 22. This design is slightly different than the one used in the pilot study in 2012, which had a sloped-style roof with the sample tube on the passenger side of the shed.

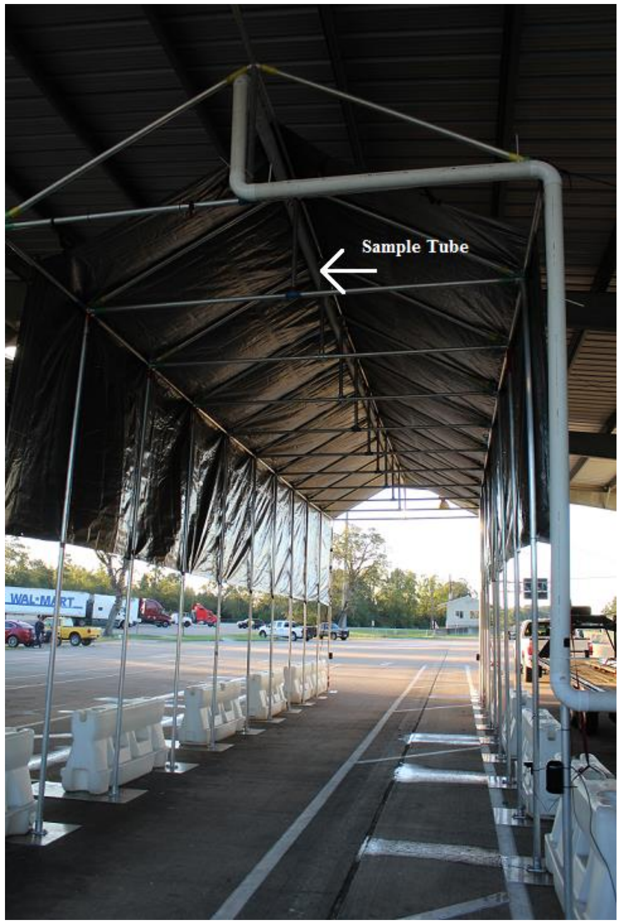

Figure 22: Shed Design at NWWS

The NWWS also includes a control center, which allows operators to turn on signal lights that inform truck drivers they need to enter the weigh station. During testing, the signal lights stayed on, and northbound trucks entered the station from I-45. Figure 23 shows a truck entering the station, with the control center on the passenger side of the truck. As trucks entered the station, they were directed to stop in front of the shed, where researchers gathered information such as the license plate details. The drivers were then instructed to accelerate through the shed and resume travel on the highway. While most trucks followed these instructions, not all accelerated through as instructed, and some crept through the shed or simply stopped halfway through. In these cases, the trucks did not register valid runs, and therefore no results were obtained for these vehicles. As trucks entered the weigh station, a line began to form in times of heavy truck traffic. To ensure that the line of trucks going through the shed did not interfere with the operations of the weigh station, or traffic on I-45, several trucks were allowed to bypass the shed and return back to the interstate. During these times, it is estimated that approximately 20 percent of the trucks were tested, while the remaining were allowed to bypass the shed. During times with fewer trucks entering the weigh station, the rate of trucks that went through the shed was close to 100 percent.

Figure 23: Truck Entering NWWS

Testing was conducted for approximately 6 hours per day, based on the schedule of the Department of Public Safety troopers at the weigh station. Due to regulations, the station could not be operated without a trooper present. A total of 935 trucks were sent through the shed during the field testing.

FIELD TESTING RESULTS

This section outlines the results from the field testing conducted in October 2016. During the field testing, the team collected both NO_x and PM data for each vehicle. As previously discussed, the units used in this report are grams of NO_x (or PM) per kilogram of CO_2, which is the standard reporting result for the OHMS and other remote sensing technologies.

Fleet Analysis

During the testing, the license plate for each of the trucks passing through the weigh station was recorded, which allowed the team to determine the make and MY of most of the vehicles that were sent through the shed. Of the 935 trucks that were measured, MY information was obtained for 635 trucks through license plate matching using publicly-available online databases. The MY distribution of truck counts, for trucks whose information was available, is shown in Figure 24. The graph also shows the distribution recorded in the Phase 1 testing in 2012, where MY information on 706 vehicles was obtained. As illustrated, the trend is very similar through MY 2012. The number of vehicles peaked for MY 2007, in both the Phase 1 and Phase 2 tests. Phase 1 also had a peak in MY 2000, which was not seen as much in the Phase 2 testing, likely due to some of those vehicles no longer being in the fleet. After 2007, the numbers generally increased through 2015, which is also seen in the 2012 data until MY 2012, when the testing was being conducted. Figure 25 shows the age distribution of the fleets for both the 2012 and 2016 tests. As seen, looking at the 2016 numbers, there are still a large number of vehicles, aver 12% MY 2007 along, which are pre-selective catalytic reduction (SCR) and diesel particulate filter (DPF), which make for good replacement or retrofit candidates.

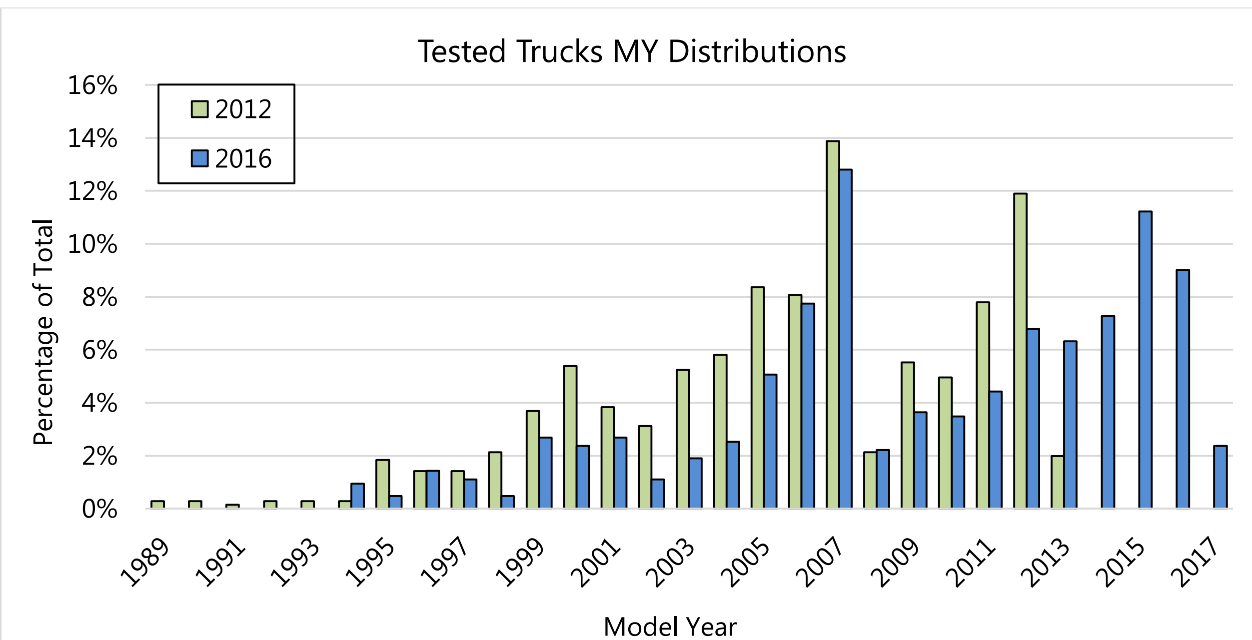

Figure 24: Tested Truck Model Year Distributions, 2012 and 2016

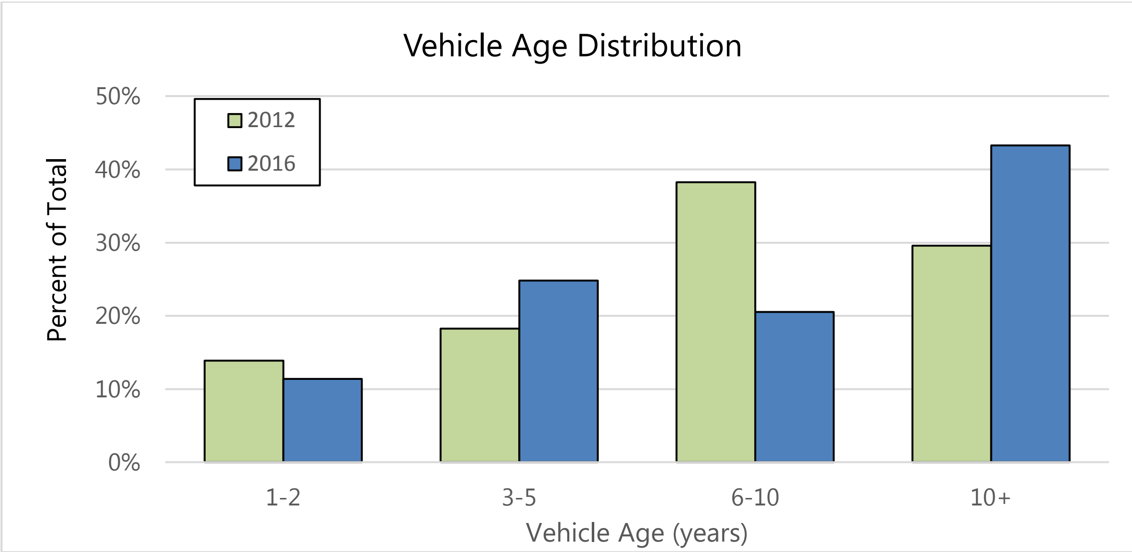

Figure 25: Age Distribution of Vehicles

NO_x Results

Of the 935 total trucks that passed through the shed, 649 had valid NO_x measurements and 286 had invalid measurements. A large majority of the invalid runs occurred on a single day, where the wind was higher than the other days, with average speeds over 10 mph during most of the testing. Additionally, communication challenges with some drivers caused them to not properly follow the researchers' instructions, leading to invalid results.

To compare the fleet data collected during Phase 1 to the data from Phase 2, the Phase 2 data were broken into eight different ranges of $gNO_x/kgCO_2$, with increments of 5 g/kg for each range, just as was done for Phase 1. The data from both field tests are shown in Figure 26. During Phase 1, there were approximately the same number of trucks in the 0–5 and 15–20 ranges (19 percent and 21 percent, respectively). The vehicles in Phase 2 had many more vehicles (39 percent) in the 0–5 range than the Phase 1 results, which can be explained by the MYs of the Phase 2 fleet being overall newer than the Phase 1 fleet.

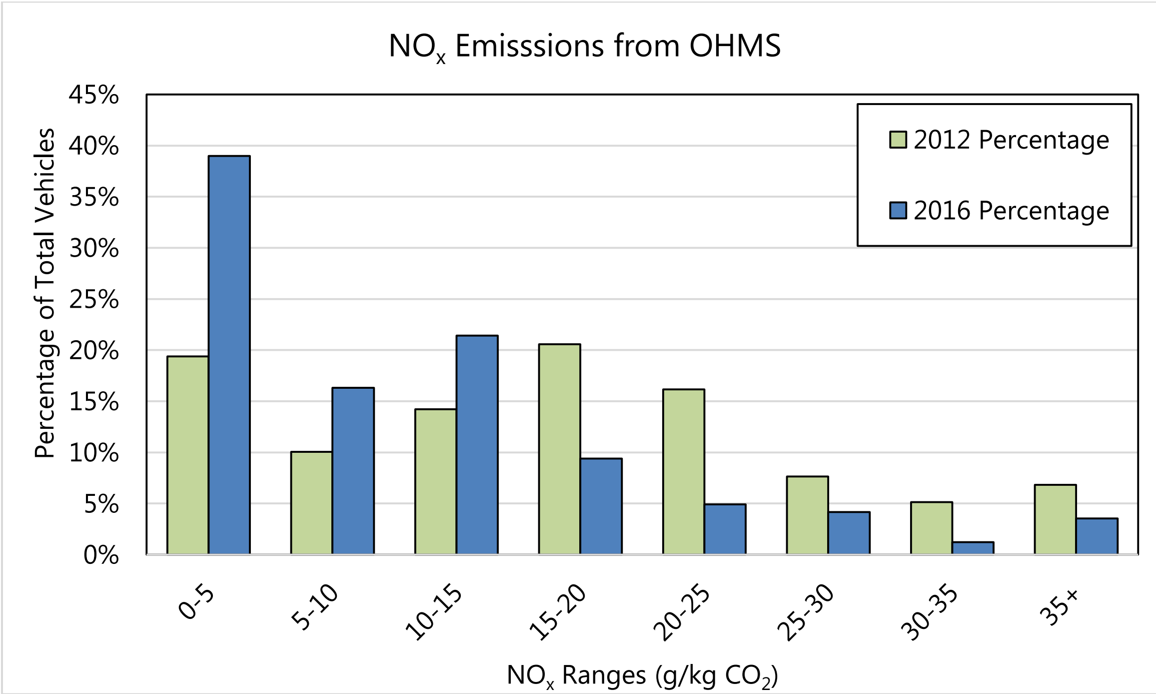

Figure 26: Truck NO_x Emissions Rates, 2012 and 2016

To determine which vehicles would be considered high emitters, as well as the potential reduction in total NO_x emissions, the vehicles were broken out by model year. The average and 95th percentile values for each model year were calculated. Any truck whose value was higher than the 95th percentile value within a given model year was considered a high emitter. Figure 27 shows the averages and 95th percentile values from the fleet measured in Phase 2, these values come from the 450 trucks that had MY information on and valid runs.

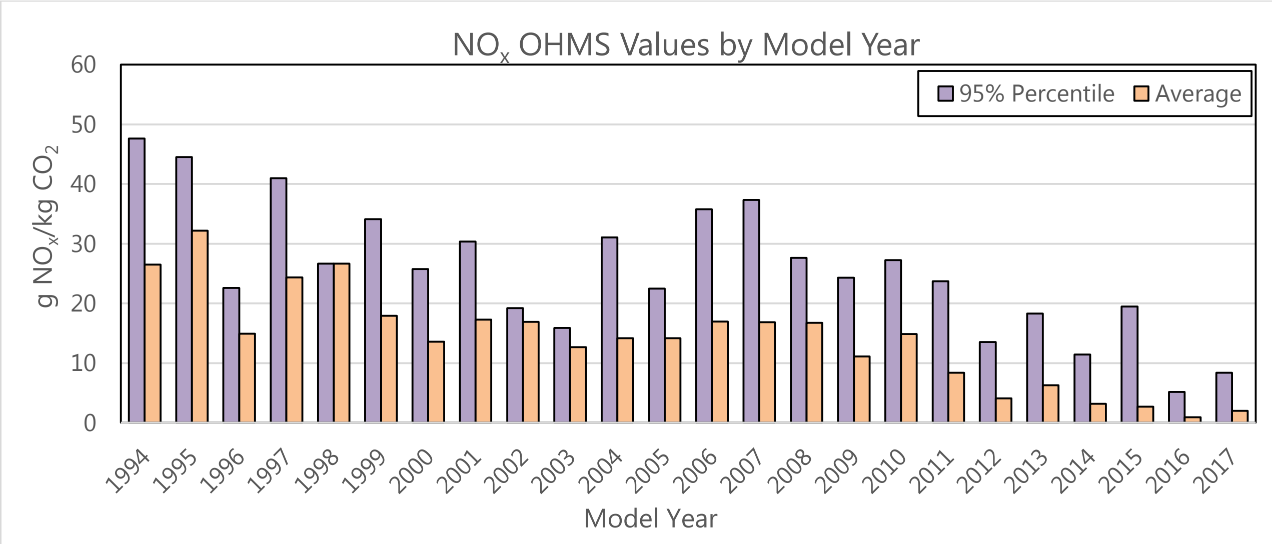

Figure 27: MY Averages and 95th Percentiles

Thirty-three vehicles were classified as high emitters using these criteria[3], with an average $gNO_x/kgCO_2$ value of 30.36. These 33 vehicles accounted for a total of 21 percent of the total emissions. In order to extrapolate these findings to a potential impact in the DFW area, the research team examined the regional emissions estimates from a previous Texas Commission on Environmental Quality (TCEQ) report.[(5)] Based on the report, it is estimated that in 2017, a total of 38.57 tons of NO_x would be emitted per summer weekday from pass-through (non-local) diesel sources. Assuming a similar proportion and contribution of high emitters as seen in the OHMS dataset, it is estimated that removing the targeted high emitters from the fleet and replacing them with average emitters from the same model year could reduce the total NO_x emissions in the DFW area from pass-through diesel vehicles by 5.15 tons a day (from 38.57 tons to 33.42 tons). This figure is lower than the similarly calculated estimate from the 2012 report (8.7 tons, based on a reduction from 65.2 tons to 56.5 tons daily), which can be

[3] It should be noted that in this dataset, some model years had limited number of trucks, and the 95th percentile value in this case does not represent the true 95th percentile of the distribution, but rather the highest measured emissions level in that model year category. These values were still considered to represent the 95th percentile/high emitter value for purposes of this analysis, with the exception of the MY1998 category that only had a single truck. In a real-world implementation of this approach, it is anticipated that a larger dataset would be used in the definition of high emitters, allowing for the 95th percentile value to better represent true outliers in the dataset.

explained by the overall lower average emissions of the 2016 truck fleet compared to 2012.

It should be noted that this calculation did not target the overall highest emitters from the fleet, but rather vehicles that showed higher emissions than others in their particular model year. Targeting only the overall highest emitters would target older vehicles, which in general emit more than newer MY vehicles. If the criterion for high emitters is changed to any vehicle that is higher than the 95th percentile of the entire fleet, and those vehicles are replaced with an average vehicle from the entire fleet, the potential savings goes from 5.15 tons to 5.49 tons per day. A larger reduction is possible by completely removing the high emitters from the road and replacing them with a new vehicle (in this analysis, an average 2017 vehicle from the fleet measured in this study). This analysis gives a total possible reduction of 6.98 tons per day.

PM Results

Similar to the NO_x results, there were 658 valid PM runs conducted during the field testing. Figure 28 shows the comparison to the 2012 results. As in 2012, a majority of the trucks sampled fell in the 0–0.25 range, 62.3 percent in 2016 compared to 70.1 percent in 2012. However, unlike 2012, the results did not trend downward for the remaining ranges. In 2016, the percentage of trucks that had PM values greater than 1 totaled 11.7 percent, versus 5.5 percent in 2012. The average values seen in 2016 were also higher than in 2012, with values of 0.428 (2016) and 0.337 (2012) $gPM/kgCO_2$.

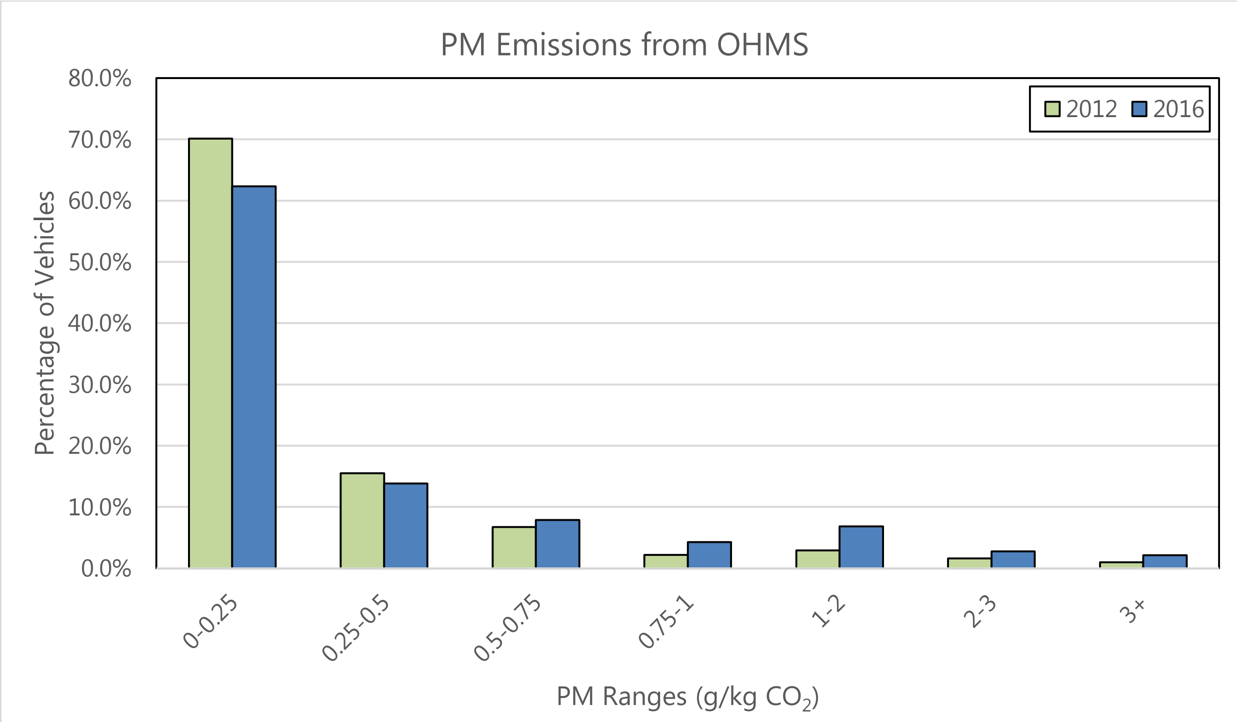

Figure 28: Truck PM Emissions Rates, 2012 and 2016

Determination of high emitters for the PM measurements was done the same way as with the NO_x high emitters, by MY. The MY numbers are shown in Figure 29, which includes 454 trucks with valid runs and MY information. Using these criteria, 35 vehicles were classified as high emitters, with an average PM value of 2.49 gPM/kgCO_2. These vehicles accounted for 38.2 percent of the total emissions. Based on the same TCEQ report[(5)] as used with the NO_x analysis, there is an expected 1.713 tons of $PM_{2.5}$ to be emitted per summer weekday in the DFW area from pass-through diesel vehicles. Replacing the high emitters with a vehicle from the same MY with average emissions can remove a total of 0.625 tons of $PM_{2.5}$ emissions per day from the DFW area. Alternatively, if identifying high emitters as those that are over the 95th percentile value of all trucks measured, the 5% of vehicles classified as high emitters would account for 39.2 percent of the total emissions. By replacing these vehicles with average polluters from the fleet, a possible 0.621 tons of $PM_{2.5}$ per day could be removed.

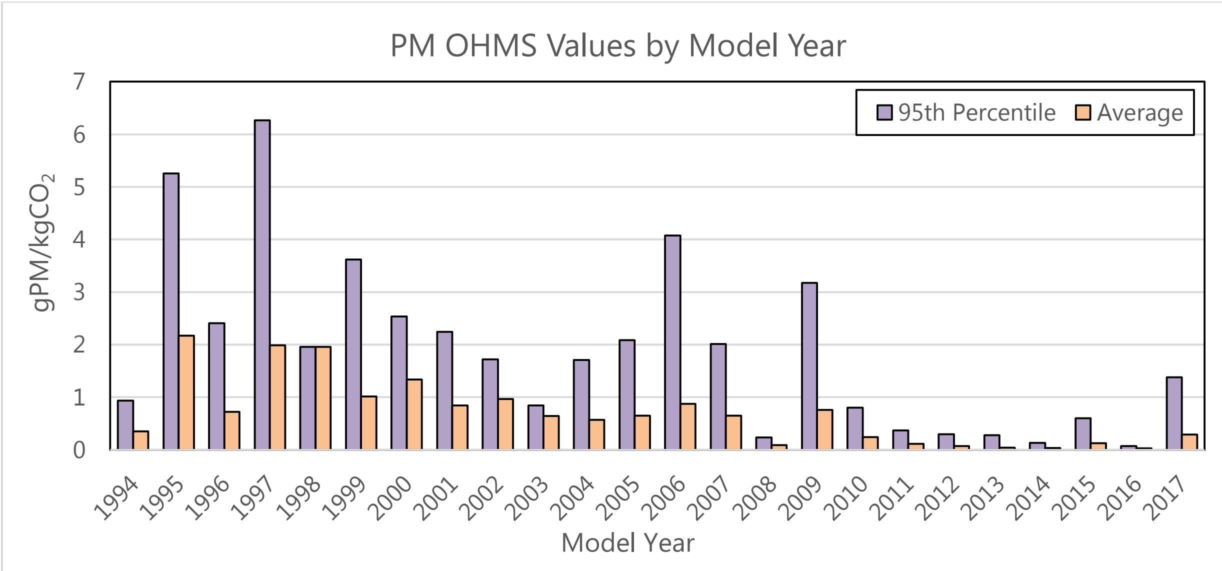

Figure 29: MY PM Field Testing Results

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

This chapter outlines key conclusions from study and recommendations on the implementation of future OHMS installations as part of a heavy-duty I/M program. The chapter also discusses the potential design modifications that could be implemented as part of a permanent OHMS installation.

RELEVANT TECHNOLOGIES AND INSTRUMENTATION

The study focused on the applicability of OHMS and other technologies to a heavy-duty vehicle I/M program, a high emitter screening program, or other programs that require the accurate characterization of emissions of large numbers of vehicles. This project tested the performance of two different technologies, OHMS and a conventional remote sensing device (ETEST). The OHMS was tested using two different instruments for gaseous measurements, the Horiba 240 units (which are a part of the current OHMS setup) as well as the MultiGas™ FTIR from MKS (as an alternative or supplementary instrumentation option).

When comparing the conventional remote sensing device with OHMS, it is seen that both technologies tested had both positive and negative aspects for implementation. When PEMS is used as the baseline, the OHMS technology (with both the Horiba and MKS instrumentation) was seen to be more accurate than the ETEST device. The average differences compared to PEMS were 9.2%, 14%, and 18.95% for OHMS with Horiba instrumentation, OHMS with MKS instrumentation, and ETEST respectively. It should also be noted that the ETEST device was a prototype device, and is not yet commercially available. Some of error associated with the ETEST performance was likely due to the manual triggering of the instrumentation used for this study. The requirement for vehicles to stop and then accelerate through the shed and the longer sampling period also allows for data to represent a consistent mode of operation between the test vehicles. However, the OHMS does require more infrastructure and effort for initial setup, including the installation of a shed structure.

The ETEST system can also screen a larger number of vehicles in a given period of time compared to OHMS, and can measure vehicles as they operate on the road, without requiring them to be diverted or stopped for testing. The ETEST system can be set up in an area of high truck traffic volumes in order to get a large sample size over a short duration. Some caution needs to be made to ensure that the vehicles tested are operating under similar conditions to ensure a better comparison between the vehicles.

OHMS Installation and Operation

Based on the results and experience gained from this project, the research team developed several recommendations and considerations for future deployments of OHMS, for I/M or other applications. These include options for design, infrastructure, and operations, described below. These recommendations are based on the current setup of OHMS, which is designed to primarily capture emissions from trucks with high (i.e. elevated vertical) exhaust stack positions[4].

1) It is recommended that the shed utilize a gable style roof with a center sample tube, since this design option was shown to capture the exhaust from trucks better than other options that utilized the sloped roof or side sample tube location.

2) The sides of the shed structure were enclosed all the way to the ground in the testing setup for this project. While this is not necessarily required for the OHMS to function as designed, it is recommended for locations that have other sources of emissions nearby, to avoid contamination of the results.

3) The prevailing wind direction should be taken into consideration in a permanent setup of the OHMS technology. High winds, especially in the same direction as the shed, can impact the results, sometime resulting in a large number of invalid runs due to low amounts of exhaust entering the OHMS analyzers. If possible the setup should ensure that predominate winds hit perpendicular to the shed to lower the impact.

4) Testing the OHMS under different vehicle speeds showed that the emissions of a vehicle can change greatly, depending on the speed and operating condition at

[4] Sampling systems to capture exhaust from trucks with high or low exhaust stack positions may also be characterized based on the resultant exhaust flow as updraft exhaust or downdraft exhaust sampling systems. This terminology is used in some publications, such as in description of the California Air Resources Board's Portable Emissions Acquisition System (PEAQS),

the time of the measurement. The OHMS was also found to be more accurate in characterizing emissions at lower speeds. Therefore, testing using the OHMS should be done for a "stop and go" operation to minimize the difference in operational speeds of each vehicle and to ensure overall low speeds. Instructing vehicles to stop at the entrance to the shed and accelerate through allows for this to be implemented consistently. Care should be taken to ensure that the vehicles are at a normal operating temperature before being tested, which could be a problem if they idle to long and the exhaust temperature drops below the optimal temperature range for an SCR.

5) In addition to the validity criteria used to identify valid OHMS data runs, it is also recommended that a minimum speed or maximum time criteria be used as an additional check to ensure that vehicles properly accelerate through the shed when the data are being collected. During field testing, it was observed several vehicles would simply creep idle, or stop halfway through the shed. In these instances, the vehicle is not operating in the same operating mode, i.e. acceleration, as the other vehicles. While a majority of such cases did not provide enough exhaust for the OHMS (resulting in an invalid run based on the data), a few exceptions still met the data validity criteria. An additional speed or time constraint would allow for these exceptions to also be eliminated, ensuring that a vehicle has actually accelerated through the shed and not simply coasted through.

6) Some emissions reduction technologies, such as SCR devices, only work at certain operating temperatures. In order for the SCR to be operating efficiently the exhaust temperature must be above a certain temperature ranges (250°-427° C). [6] The field testing for this project diverted trucks from an interstate highway, where it is expected that the engine is already operating at high temperatures. However, this may not be the case for the implementation of OHMS at other certain locations, such as truck stops. It is therefore recommended that the temperature of the exhaust be recorded to cross-check SCR functionality, or that trucks with an SCR be allowed to warm up prior to testing.

7) There are several infrastructure requirements for candidate locations for an OHMS setup, as follows;

a. The site should ideally have a source of electricity to operate the instrumentation used in the OHMS. Using generators to power the instruments is not recommended as it can adversely impact the measurements through the emissions they generate. If generators are required at a location care should be taken to place them so the exhaust is not entering the shed. Power requirements are low, with three 100 Volt outlets with 15 amp breakers providing sufficient power for necessary equipment.

b. The site should have enough space for both the shed and the instrumentation to be safely installed without impacting existing traffic or causing a safety hazard. Generally, the required space for an installation is at least 125 feet in length (50 feet for the shed and 75 feet for a truck and trailer to be stopped in front of the shed) and at least 25 feet wide. This includes space for the shed as well as a small trailer, or building, to be located next to the shed with the instruments inside.

c. The installation should be far enough away from any other source of emissions (including other traffic) so that it does not impact the measurements.

d. The site should have some mechanism of directing the trucks through the shed. Sites such as weigh stations have existing signs that tell drivers they must enter the station, which can be used to divert the trucks. For other potential sites, such as truck stops or rest areas, it is important to take into consideration how trucks would be directed out of traffic to pass through the shed.

e. The shed can be a permanent or a temporary structure. While a permanent structure can be used, temporary structures like the one used at New Waverly, allows for relatively quick installation and dismantling that enables moving the OHMS from site to site. From the experience at New Waverly, it is estimated that the OHMS (including the shed) can be set up in around 4 hours.

8) Software is needed to operate the OHMS, collecting the data and analyzing the results. Software can be designed for specific applications or for a general installation of the OHMS technology. The software includes data acquisition cards that connect to the instruments and allow the computer to read and calculate the values. The software used for this study was developed in-house as part of the study.

OHMS Implementation

Based on the findings outlined in this report the OHMS technology is seen as viable option for several potential applications, including a traditional I/M program, clean screening of vehicles, or identifying high emitters from a fleet. The final implementation will depend on the application that the system will be used for, based on the needs and priorities of the local stakeholders and relevant public agencies. The design of the program must consider:

- *Target Fleet* - The target fleet, for instance long haul versus short haul trucks, may impact the location of the OHMS setup. Long haul trucks do not generally operate in the same areas as the short haul fleet, and the location of the OHMS will need to ensure that the target vehicles are appropriately captured/represented.
- *Definition of a High Emitter (Comparison Group)* - In the analysis in Chapter 3, two different approaches were used to define high emitters for a simple analysis. One scenario compared the vehicles to other vehicles within the same MY, while the other scenario compared the entire fleet. The overall goal of the program would drive the comparison group used in defining high emitters. For a true I/M program, whose goal is to identify vehicles that emit more than they are expected to based on their MY/engine standard, comparing vehicles within a MY or MY range may be preferred. However, if the goal is to identify vehicles for potential replacement or retrofit through a grant program, identifying high emitters in relation to the overall fleet may be a better option. This will likely target the older vehicles in the fleet more than the newer vehicles, and so the program design in this case should ensure that there is no penalty to the driver for merely operating an older vehicle.

- *Definition of a High Emitter (Cutoff Levels)* - In the analysis in Chapter 3, the 95th percentile was used was the cutoff point to define high emitting vehicles, both within an MY category and overall. As acknowledged in Chapter 3, larger amounts of data from measured vehicles will allow for more robust 95th percentile values that represent the true distribution of the observed emissions. However, it is also open to question whether the 95th percentile is an appropriate the cutoff point to identify true outliers, or whether a further "cushion" (such as 2 standard deviations beyond the 95th percentile value) is warranted to ensure that only vehicles that emit significantly higher than most are targeted.

FUTURE CONSIDERATIONS AND NEXT STEPS

While this study has established further support for the use of OHMS for I/M or screening applications, there are several areas for future research, including:

- *Testing vehicles with low exhaust stack position* - The current setup of the OHMS does not allow for testing of vehicles with low exhaust stacks, including some heavy-duty vehicles as well as medium-duty vehicles. The field testing for some low-stack heavy-duty vehicles resulted in invalid runs due to insufficient amounts of vehicle exhaust. It is expected that a sample tube at or near the ground level is required to address this issues. This would be best done by a sample tube that runs underneath the middle of the path of the vehicle as it passes by. The paved surface of the field study location at NWWS did not allow for such a setup, and future testing may need to be considered at a location where this sort of installation was possible. A system where the sample tube is off to the side, near the ground, could also potentially work with a system of fans that blow the exhaust to the sample tube. However further testing would be required to confirm its viability.

- *Consideration for truck loads (weights)* – To date the testing that has been done has not differentiated between truck weights for HE screening. In a proposed future project on overweight vehicles the research team is planning on looking into this scenario to determine what impact weight has on the OHMS classification of vehicles.

- *Impact of speed on HEs* – Vehicles that are classified as a HE by the OHMS is done at low (stop and go) speeds. However, it has not been determined if a vehicle that is a HE at these conditions would still be a HE at higher speeds. Further research in this area is needed to determine if a HE by OHMS standards is still a HE once travelling at higher speeds.

- *Testing of light-duty vehicles* - Light-duty vehicles cannot be tested using the current OHMS setup. Since the size of these vehicles differs greatly from that of a heavy-duty truck, a different shed would need to be constructed, as well as possibly using different sample tube locations. Testing of options for could be done in a similar manner to studies done for the heavy-duty OHMS, at the RELLIS campus or other location, to determine the best design for characterizing emissions of light-duty vehicles.

In addition to the areas for future research, additional options should also be considered for gathering registration data for the vehicles that are measured using the OHMS technology, for both locally-registered and out of state vehicles, to expand the number of vehicles that can be identified successfully in terms of model year. The availability of data could depend on the development of suitable arrangements to access registration databases from agencies such as the department of motor vehicles for different states or through other national or private sources of data.

It is envisioned that a pilot implementation based on the recommendations for OHMS implementation would be a logical next step for this study. However, it is acknowledged that program design considerations, including aspects such as financial viability (funding) and enforcement mechanisms, may depend on local stakeholders, public agencies, and legislative processes. A detailed analysis of these options is therefore outside the scope of this study.

One possible approach could be to setup a site(s) in the DFW area to collect additional information on emissions for larger number of trucks over an extended period of time. This data could be used to calibrate the distribution of observed emissions for the better definition of high emitters. The data could also then be potentially used to identify high emitters to recruit them for grant programs by agencies such as the Environmental

Protection Agency (EPA) or the Texas Commission on Environmental Quality (TCEQ) that fund vehicle retrofits or replacements.

Conference/Workshop on Related Activates

The OHMS technology was the first of its kind during the pilot study in 2012. Since then, several similar efforts have been initiated across the US investigating options for heavy-duty emissions measurement and high emitter screening. The research team is proposing that a conference or stakeholder workshop, that includes all interested parties in the OHMS and similar technologies, to further the discussion of the technologies and how they can benefit the end users. The conference would be used as a platform to discuss current findings from research, new ideas on how to implement the technologies, and further research that is needed to continue to enhance the technologies and their benefit to helping improve air quality in affected areas.

APPENDIX - OHMS CALCULATIONS

This appendix describes the steps and calculations that are used by the OHMS to calculate the pollutant ratios for each run, as well as determine if the values are valid. More details on the calculations can be found at the Fuel Efficiency Automobile Test data center.[7]

OHMS CALCULATIONS

The first step in the calculations is to calculate slope and slope errors for each of the pollutants (CO, HC, NO, NO_x). These are calculated by plotting the CO_2 values on the y-axis and the pollutant values on the x-axis.

After calculating the slopes and slope errors, the ratios are calculated using the following equations.

1) $gCO/kgCO_2$: $\frac{(28*COSlope*860)}{((1+COSlope+(3*HCSlope))*12)}$
2) $gHC/kgCO_2$: $\frac{(44*HCSlope*860)}{((1+COSlope+(3*HCSlope))*12)}$
3) $gNO/kgCO_2$: $\frac{(30*NOSlope*860)}{((1+COSlope+(3*HCSlope))*12)}$
4) $gNO_x/kgCO_2$: $\frac{(46*NOxSlope*860)}{((1+COSlope+(3*HCSlope))*12)}$
5) $gPM/kgCO_2$: $PMSlope * 1.743$

The errors are calculated using the following equations.

1) gCOError:

$$\sqrt{((668.892)^2 * (1 + COSlope + HCSlope)^2 * \ COSlope^2) + ((668.892)^2 * COSlope^2 * (COSlopeErr^2 + HCSlopeErr^2))}$$

2) gHCError:

$$\sqrt{((1051.116)^2 * (1 + COSlope + HCSlope)^2 * HCSlopeErr^2) + ((1051.116)^2 * HCSlope^2 * (COSlopeErr^2 + \ HCSlopeErr^2))}$$

3) gNOError:

$$\sqrt{((716.67)^2 * (1 + COSlope + HCSlope)^2 * NOSlopeErr^2) + ((716.67)^2 * NOSlope^2 * (COSlopeErr^2 + HCSlopeErr^2))}$$

4) gNO_xError:

$$\sqrt{((1098.894)^2 * (1 + COSlope + HCSlope)^2 * NOXSlopeErr^2) + ((1098.894)^2 * NOXSlope^2 * (COSlopeErr^2 + HCSlopeErr^2))}$$

5) gPMError: $\sqrt{1.743^2 * PMSlopeError^2}$

OHMS Validity Checks

After calculating the ratios and the errors of each pollutant, the numbers are rechecked for validity. The validity checks are as follows:

1) Are the CO_2 levels recorded during a run at least 150 ppm over the ambient background? If no, entire run is invalid.

2) If any of the following are true, then the CO reading for the run is invalid.
    - gCO/kg < −2, or
    - gCO/kg <= 6 and error > 1.5 or
    - gCO/kg > 6 and percent error > 25%

3) If any of the following are true, then the HC reading for the run is invalid.
    - gHC/kg < −10 or
    - gHC/kg <= 10 and error > 2 or
    - gHC/kg > 10 and percent error > 20%

4) If any of the following are true, then the NO reading for the run is invalid.
    - gNO/kg < −2 or
    - gNO/kg <= 10 and error > 2 or
    - gNO/kg > 10 and percent error > 20%

5) If any of the following are true, then the NO_x reading for the run is invalid.
    - gNO_x/kg < −2 or
    - gNO_x/kg <= 10 and error > 2
    - gNO_x/kg > 10 and percent error > 20%

6) If any of the following are true, then the PM reading for the run is invalid.
   - gPM/kg < −2
   - gPM/kg <= 2 and error > 1
   - gPM/kg > 2 and percent error > 50%

If NO_x, NO, or PM values are invalid, they are not reported for that run. Since both CO and HC slope values are used in the calculations of other pollutants, if either CO or HC are invalid, the ratios and errors must be recalculated for the NO and NO_x values. The new calculations for NO and NO_x, if either CO or HC calculations are invalid, are:

1) gNO/kgCO_2: $\frac{30*NOSlope*860}{12}$
2) gNOError: $\sqrt{2150.01^2 + NOSlopeErr^2}$
3) gNO_x/kgCO_2: $\frac{46*NOxSlope*860}{12}$
4) gNO_xError: $\sqrt{3296.68^2 * NOxSlopeErr^2}$

These values are then checked against the validity requirements to ensure that the new values are indeed valid.

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