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Locomotive Emissions Test Stand with Particulate Matter Measurement Integration

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13. ABSTRACT (Maximum 200 words) This project builds upon previous research efforts, in which a complete instruction manual and bill of materials was developed for a blueprint that allows any organization in the railroad industry to build their own locomotive emissions measurement setup. A full scale emissions test was conducted to demonstrate the feasibility of a compact and portable setup for locomotive emissions measurement. A mobile laboratory was used for this test and proved to be a quick and convenient method for emissions testing.			
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1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
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1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT (APPROXIMATE)**		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME (APPROXIMATE)**		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE (EXACT)**		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

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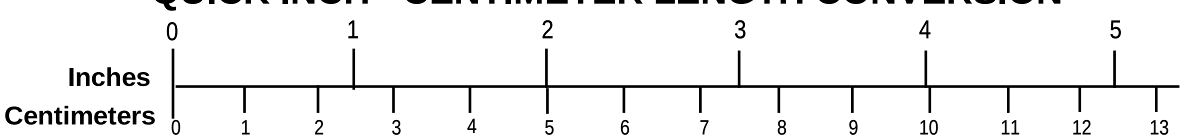

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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1. Background

Increasing locomotive fuel efficiency and controlling the emission of harmful pollutants are two of the most important elements in ensuring the viability of the nation's railroads. Recognizing this need, Environmental Protection Agency (EPA) regulations require that emissions from all new or remanufactured locomotives comply with limits as set forth in Title 40 of the Code of Federal Regulations (CFR) Parts 1033 and 1065. Before 2008, locomotive emissions were regulated under 40 CFR Part 92. These regulations specify requirements for the test procedures that measure emissions from a locomotive engine, including specific data that should be collected and the calculation method that is used for post-processing.

Presently, locomotive owners have to send their locomotives to an emissions testing laboratory or schedule an on-site visit from a very limited number of companies to perform such testing. Both of these options are very inefficient and require that the locomotive be removed from revenue service.

The Federal Railroad Administration (FRA) is responsible for overseeing the safety of railroad operations and personnel. Ambient air quality in and around railroad operations is an important aspect of safety. FRA is interested in learning about new emissions measurement and control technologies that could be used to monitor or reduce emissions. As a result, FRA has funded research efforts to develop a compact and portable emissions test setup using state-of-the-art equipment.

In previous efforts, Sharma & Associates (SA) has researched options for compact gaseous measurement systems. One of the most viable systems and necessary accessories were chosen for a proof of feasibility demonstration, an additional data acquisition system, and instrumentation were acquired. Next, calculation algorithms were developed for conversion of raw concentration data into duty-cycle weighted brake-specific emission rates. Several mock tests were conducted in a laboratory environment to ensure all chosen instruments and systems functioned as expected. A wayside locomotive emissions test was conducted to demonstrate the feasibility of using compact and portable emissions measurement equipment. Fuel mass flow measurement capability was added after this initial effort.

Next, FRA was interested in determining if such a setup would be feasible for an on-board configuration, which would allow real-world emissions under typical in-situ service conditions to be measured. This type of data could generate valuable information on route specific emissions and provide a method for corroborating EPA specified duty cycles. Therefore, a test was conducted using a completely on-board setup to demonstrate its feasibility. Both stationary and moving tests were conducted using this on-board setup.

Then FRA requested that the entire system be documented for the railroad community so members could develop their own emissions measurement stations. A detailed Bill of Materials (BOM) with pictures and an instruction manual were developed for this purpose. Schematics and instrument specifications are included in the document, which allows users to identify appropriate instruments.

Subsequently, particulate matter sampling capabilities were added to the testing setup. Next, a stationary test demonstrated the feasibility of a more complete emissions measurement configuration. All instruments were installed in a mobile laboratory that was parked beside the locomotive. After connecting sampling lines to the locomotive exhaust stack and applying various other instrumentation to the locomotive, gaseous emissions were measured and collected by a data acquisition system and particulate matter samples were collected with filters for subsequent gravimetric analysis.

During the current research effort, the instruction manual, BOM, schematics and specifications documents were updated to include the particulate matter sampling and smoke opacity measurement systems. The updated and final documents were submitted to FRA as a stand-alone deliverable in an FRA report format. Another objective of the current effort was to demonstrate a full-scale emissions test that includes particulate matter and smoke opacity measurements using a mobile laboratory setup. A third objective was to engage EPA and obtain its guidance with regards to the test setup and procedures.

In June 2013, a full scale demonstration test was conducted at the Indiana Northeastern Railroad's Hudson Engine Maintenance Facility. The test successfully demonstrated the feasibility and convenience of using a compact and portable setup for locomotive emissions testing. Because EPA was not available to attend the demonstration test, a presentation was developed and provided to FRA, who will give it to EPA for their comments.

The end goal is to increase public health and safety by creating a cost effective and practical way to test locomotive emissions and making it available to the Federal Railroad Administration (FRA) and the railroad industry. The increased efficiency will enable more testing and pre-emptive maintenance, which subsequently makes for cleaner running locomotives. As a result, the railroad industry can boost its ability to help the FRA and EPA improve air quality and subsequently the health and safety of our nation.

2. Objectives

The current research effort builds upon the work done during previous locomotive emissions research efforts (see Section 1), in which an instruction manual and a BOM were developed for a Locomotive Emissions Measurement System (LEMS). These documents described in detail various the equipment and accessories that are necessary to measure a locomotive's gaseous emissions.

The objectives of the current research effort included:

1. Adding the particulate matter (PM) system into the instruction manual and Bill of Materials developed previously. These documents could be used by the industry for setting up their own LEMS, which in turn could be utilized for on-site testing.
2. Demonstrating the full scale locomotive testing with the LEMS, preferably with EPA participation, guidance and feedback.
3. Engaging EPA to determine what steps might be necessary to get the LEMS system to a state where it could be used for compliance testing.

3. Updates to the LEMS Instruction Manual and BOM

In previous research efforts, an instruction manual and a BOM were developed for a LEMS. Information regarding a PM Partial Flow Dilution (PFD) system was not included in that version.

During the current effort, the instruction manual, the BOM and the associated schematics and setup instructions were updated to include information on a PM system.

Particulate Matter Partial Flow Sampling System

On a locomotive, the exhaust flow rate is very high. For this reason, a partial flow sampling system is necessary to keep equipment sizes manageable. A small portion of the exhaust is continuously sampled and diluted before passing it over a filter medium. The filters have to be conditioned and weighed per 49 CFR §1065 before and after the collection of the PM samples. The difference in before and after weights provides the amount of PM collected over the duration of the sampling time for each filter. Generally, for a locomotive test, one filter medium is used for each throttle notch. Knowing the dilution ratios, the sampling flow rates and the exhaust flow rates during each notch, the actual PM weight can be calculated and used in duty-cycle weighted brake-specific emissions calculations.

A highly controlled laboratory environment is required for conditioning and weighing operations. Also, a high-efficiency air purification system is required for the dilution air and high precision flow meters and control systems that are needed for this process. The size of the currently available systems makes it highly unlikely that such a Particulate Particle Flow Sample System (PPFSS) could be used in an on-board setup. A way-side or mobile laboratory setup is entirely feasible and much more practical. A mobile laboratory setup was determined to be more flexible and was thus selected for this research effort.

Sierra Instruments' BG-3 PPFSS was selected for this effort considering its wide usage in the locomotive industry and the fact that it meets 49 CFR §1065 requirements. It should be noted that real-time particulate matter measurement systems are available, but they are designed for automotive and/or off-highway applications and none were found to have the capacity required for locomotive application. In addition, such systems were not approved for compliance testing at the time that the partial flow sampling system was commissioned.

Updates to the Instruction Manual and BOM

The instruction manual and BOM for the LEMS were updated with information regarding the selected PM system and associated accessories to provide more complete versions for use by the industry. These updated documents were compiled into an FRA format report and submitted to FRA ("Locomotive Emissions Measurement System," March 2013).

4. Full Scale LEMS Demonstration Test

One of the objectives of this effort was to conduct a full scale locomotive emissions measurement test with the LEMS in the presence of EPA personnel. This would allow EPA to understand the LEMS better and permit them to provide feedback on the system as well as the process.

In the interest of completing the project within the allotted time-frame, the full scale demonstration was scheduled for June 2013. The test was conducted on an EMD GP40-3 locomotive built in 1972. This locomotive is owned by the FRA and has been the test locomotive for all previous emissions tests conducted under this research program. It has been maintained by the Indiana Northeastern Railroad (INRR) at their Hudson, IN engine maintenance facility. The full scale test was conducted at this facility using a wayside setup and with support of INRR staff. Gaseous emissions, particulate matter emissions and smoke opacity were measured during this test. Details of the test setup, procedure and collected data are provided in the following three subsections.

4.1 Test Setup

The test was set up as a two-day operation. The first day was reserved for instrumentation and cabling and performing pre-test checks on all systems, while the second day was used for pre-test calibrations, the actual test cycle and tear-down. Most of the measurement instruments were located in a mobile laboratory and instrumentation was applied to the locomotive. Figure 1 below shows the mobile lab parked beside the locomotive.

Figure 1 – Locomotive Emissions Test Setup

For gaseous emissions measurements, a compact system called SEMTECH-D, from Sensors Inc., had been used in all previous research. This system was chosen well before the adoption of the new locomotive emissions standards per 49 CFR §1033 and the new 49 CFR §1065. An effort was made to upgrade the SEMTECH-D and make it compliant with the new regulations, but the system is now discontinued. The manufacturer has a new system called ECOSTAR is available and it is said to be §1065 compliant. Other such compact systems are also available from other manufacturers, but purchasing a §1065 compliant system would have been cost prohibitive. Also, since there is an interest in understanding the ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O) profiles in locomotive exhaust emissions, SA wanted to select an instrument that is capable of measuring these gases in addition to the five gases that were being measured by SEMTECH-D.

MKS Instruments makes a system called MKS-2030, which is based on the Fourier Transform Infrared Spectrometry (FTIR) principle. This instrument captures an infrared spectrum of the gaseous sample and analyzes the spectrum using proprietary 'recipes' to predict concentrations of various gases present in the sample. Currently, FTIR-based measurements are not allowed to be used when measuring any of the gases, except N_2O, per §1065, but the manufacturer indicated that efforts were underway to get this measurement technique approved by EPA for §1065 compliant testing.

Considering the cost advantage in renting such a system and that eventually FTIR based systems may be allowed by EPA for §1065 compliant testing, SA used MKS-2030 for this demonstration test. It should be emphasized that LEMS is not dependent on any specific instruments/products, but is a blueprint that can be used to assemble a system that is fully EPA compliant. Figure 2 shows the MKS-2030 system mounted in a rack.

Figure 2 – Gaseous Emissions Measurement System

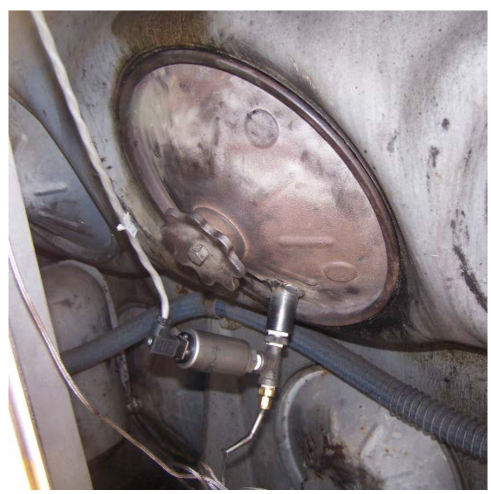
For measuring particulate matter, Sierra Instruments' BG-3 system was used. This is a partial flow dilution system that includes a patented dilution tunnel, a filter holder, a control computer, air and sampling lines, and electrical cables. A high efficiency air purification system (Air-Pack) was used to provide clean air to the BG-3 which in turn was used as dilution air. To measure smoke opacity, Wager Company's 6500-RR system was used. The 6500-RR is custom-designed for locomotive applications using heavy duty optics and a large collimated beam to allow opacity measurement across larger distances, and it includes a control panel and outputs a proportional voltage signal. To measure fuel consumption, the 6500-RR has two Coriolis-based mass flow sensors that were used; one for the supply side and one for the return side. The difference of the two signals provides net fuel consumption for each notch setting. Figure 3 shows the particulate sampling system and smoke opacity measurement system, and Figure 4 shows the fuel mass flow measurement system and one of the four instrumented airbox covers.

BG-3 Particulate Sampling System

Smoke Opacity Measurement System

Figure 3 – Particulate Sampling and Smoke Opacity Measurement System

Fuel Mass Flow Measurement System



Instrumented Airbox

Figure 4 – Fuel Mass Flow Measurement System and an Instrumented Airbox

In addition, several thermocouple probes and pressure transducers were applied as described in the LEMS instruction manual and BOM. They are listed below in Table 1.

Table 1 – Instrumentation applied to the locomotive

No.	Location	Sensor	Units
1	Airbox #2	Thermocouple	°F
2	Airbox #2	Pressure transducer	psi
3	Airbox #7	Thermocouple	°F
4	Airbox #7	Pressure transducer	psi
5	Airbox #10	Thermocouple	°F
6	Airbox #10	Pressure transducer	psi
7	Airbox #15	Thermocouple	°F
8	Airbox #15	Pressure transducer	psi
9	Inertial Grill – Driver side	Thermocouple	°F
10	Inertial Grill – Conductor side	Thermocouple	°F
11	Exhaust Stack	Thermocouple	°F
12	Fuel Inlet	Thermocouple	°F
13	Fuel Inlet	Pressure transducer	Psi
14	Ambient Air	Thermocouple	psi
15	Ambient Air	Relative Humidity probe	%

4.2 Test Procedure

All the instruments and associated sampling lines and electrical lines were set up and checked out on the first day of the test. On the second day, pre-test calibrations were performed. The locomotive was warmed up for approximately one hour. Following the warm-up, the test was conducted by setting the throttle notch in each notch setting (8 through Low Idle) for approximately 10 minutes, the only exception being throttle notch 8. In the self-load test mode, a locomotive is designed to direct all engine power to the dynamic brake resistor grid. Because these grids are not capable of dissipating the full power generated at notch 8 for a long period, the locomotive control system cuts back the engine rpm to approximately notch 7 level (called notch 8 Low) after some time to protect the grid. The power generated at notch 8 low setting is comparable to that generated at notch 7 setting. Use of an appropriately sized external resistor grid eliminates this limitation and is the recommended method for a compliance test. For the purpose of this full scale demonstration test, the locomotive was run in notch 8 high for five minutes (by default) and notch 8 low for 15 minutes. The remaining notch levels are unaffected by this limitation and 10 minutes worth of data were collected at these notch levels. Table 2 below shows the test sequence.

Table 2 – Test Sequence

Mode	Throttle Notch	Duration (minutes)
1	8 High	5*
2	8 Low	15
3	7	10
4	6	10
5	5	10
6	4	10
7	3	10
8	2	10
9	1	10
10	Idle	10
11	Low Idle	10

* Limited to 5 minutes by the locomotive control system when in Self Load test mode

For each notch setting, PM samples were collected on a separate filter. Each of these filters was weighed per §1065 requirements before the test and tracked using filter numbers. The dilution ratio was set to four (4) and the filter face velocity was maintained at ~37 cm/sec for the entire test duration. Data from the gaseous emissions system were collected on its control computer whereas data from fuel mass flow sensors, pressure transducers, thermocouples, smoke opacity meter, etc. were collected via a separate data acquisition system.

4.3 Test Data

In this section, average gaseous, particulate matter, and smoke opacity measurements for each throttle notch setting are presented. Each value is an average taken over a steady-state five minute interval from 10 minutes' worth of data collected at each notch setting. As mentioned earlier, notch 8 full power (8 High) is limited to a five minute duration by the locomotive control system and is most likely not a steady state value. However, data for notch 8 is presented for the sake of completeness. Figures 4 through 11 show average concentrations for the eight gaseous components measured at each notch setting. Figure 12 shows particulate matter mass collected over five minutes at each notch setting. Figure 13 shows average smoke opacity measured at each notch setting. Figures 14, 15, and 16 show the average exhaust temperature, average air box temperature (all four locations) and average air box pressures (all four locations), respectively, for each notch setting. Figure 18 shows the average fuel consumption (in gallons per hour) for each notch setting.

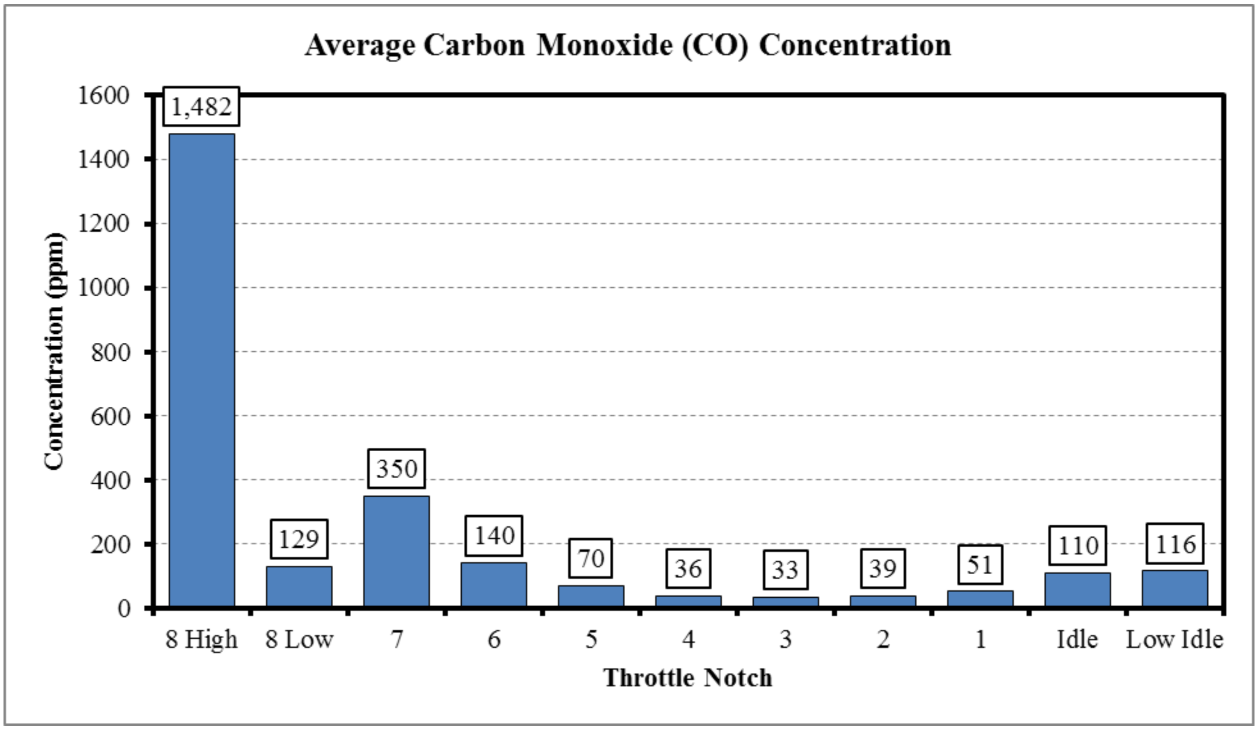


Figure 5 – Average Carbon Monoxide Concentration

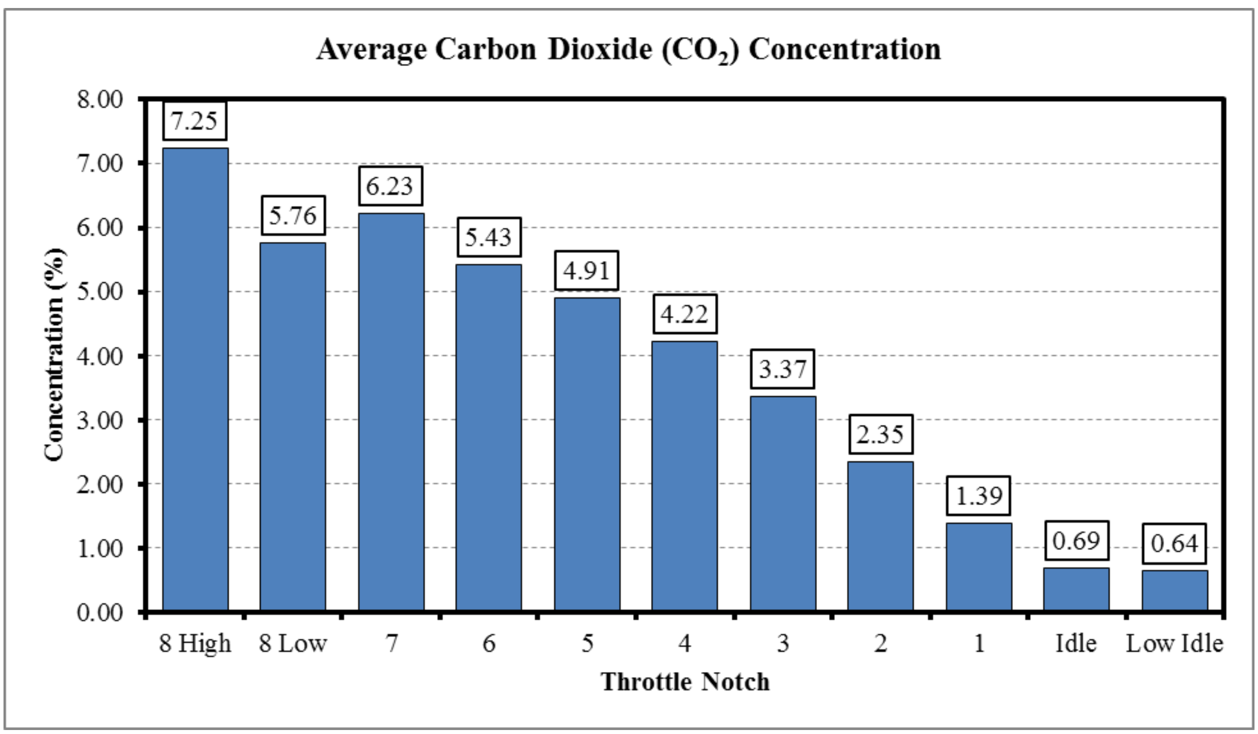


Figure 6 – Average Carbon Dioxide Concentration

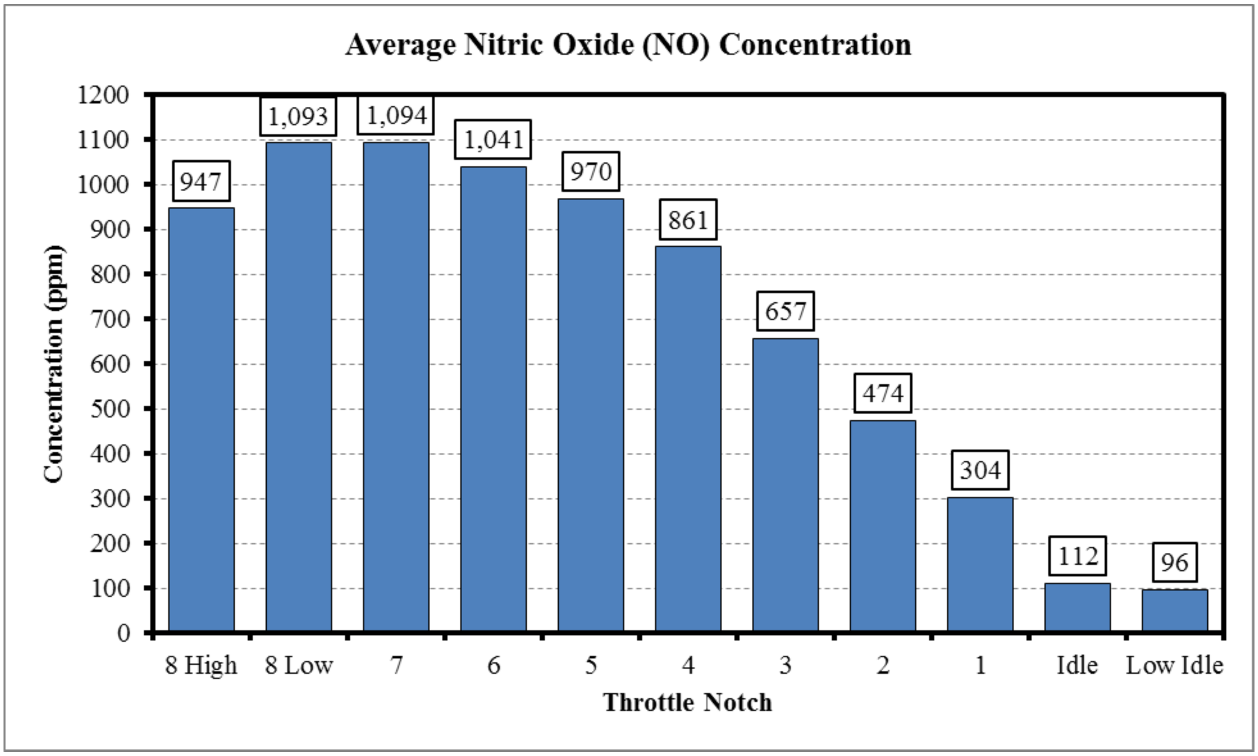


Figure 7 – Average Nitric Oxide Concentration

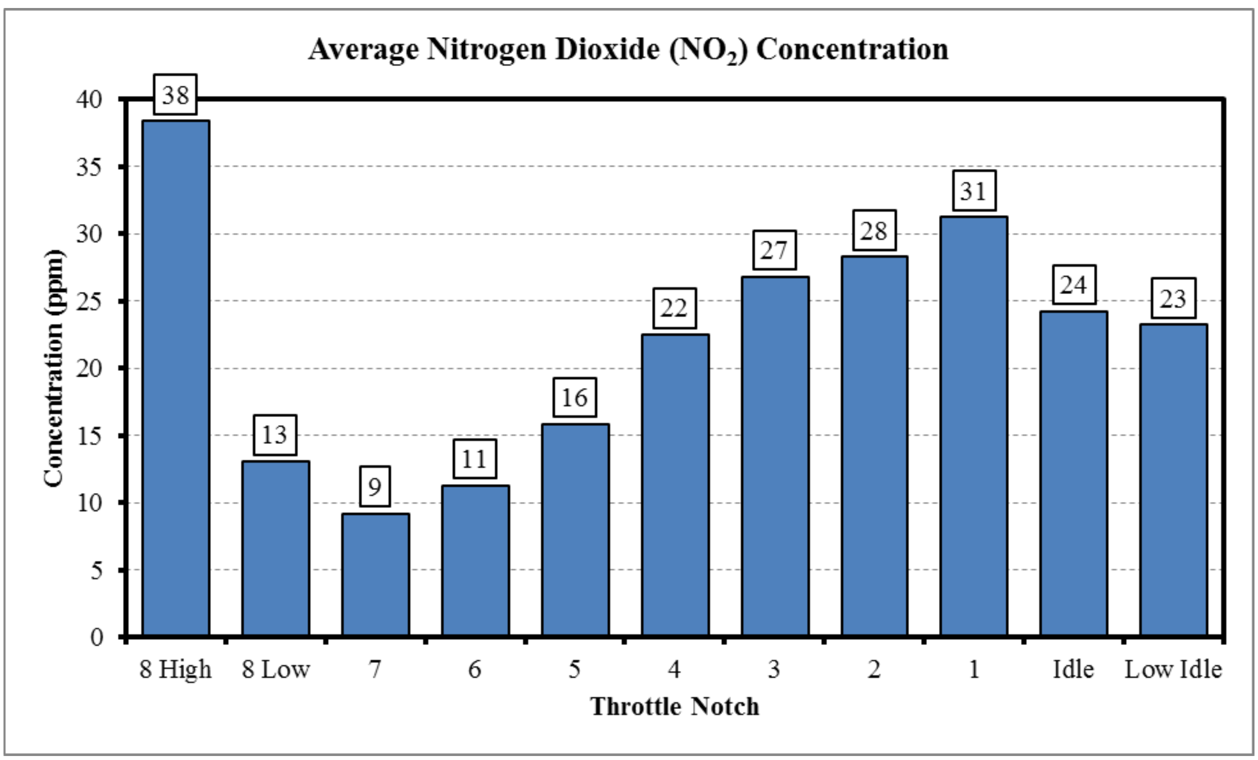


Figure 8 – Average Nitrogen Dioxide Concentration

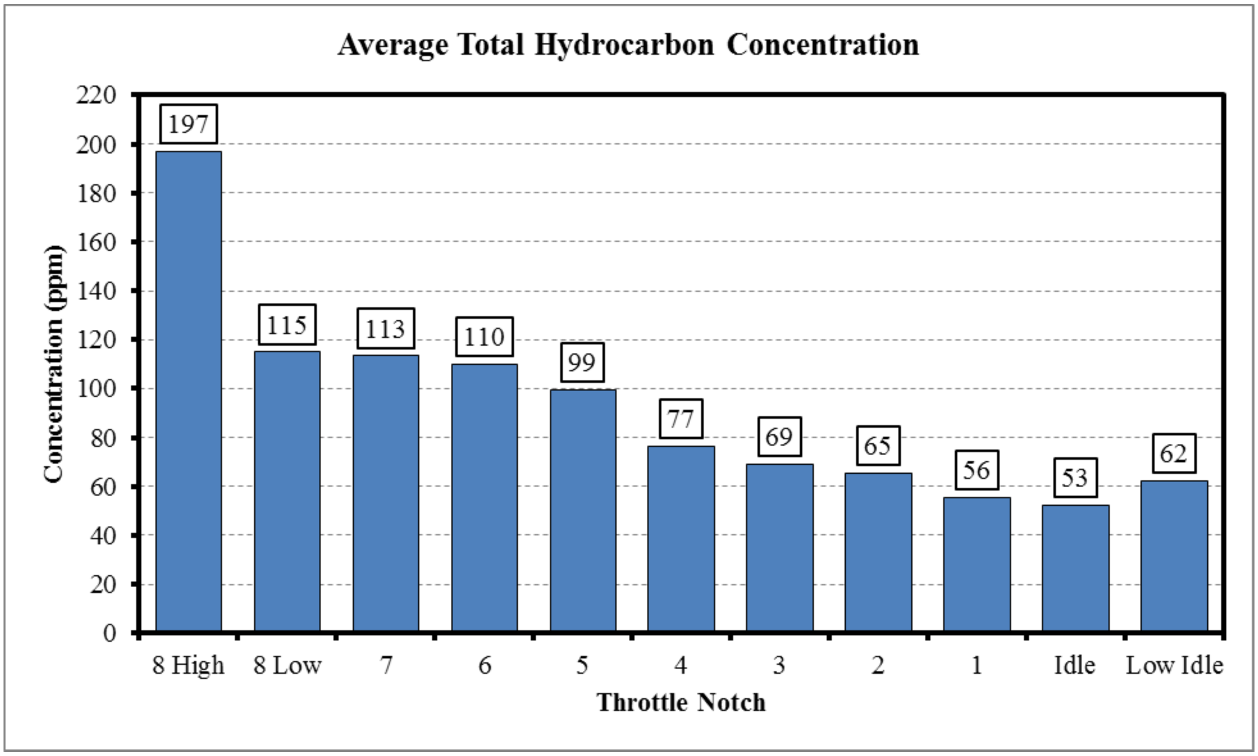


Figure 9 – Average Total Hydrocarbon (THC) Concentration

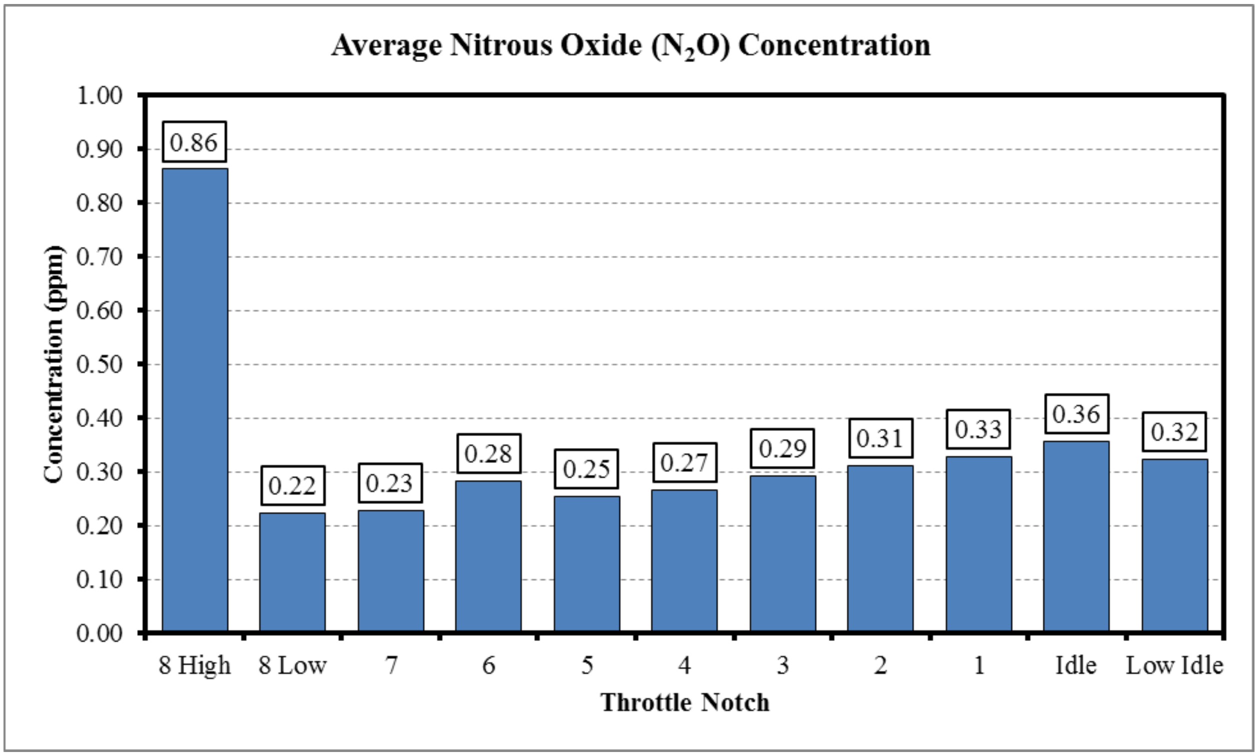


Figure 10 – Average Nitrous Oxide Concentration

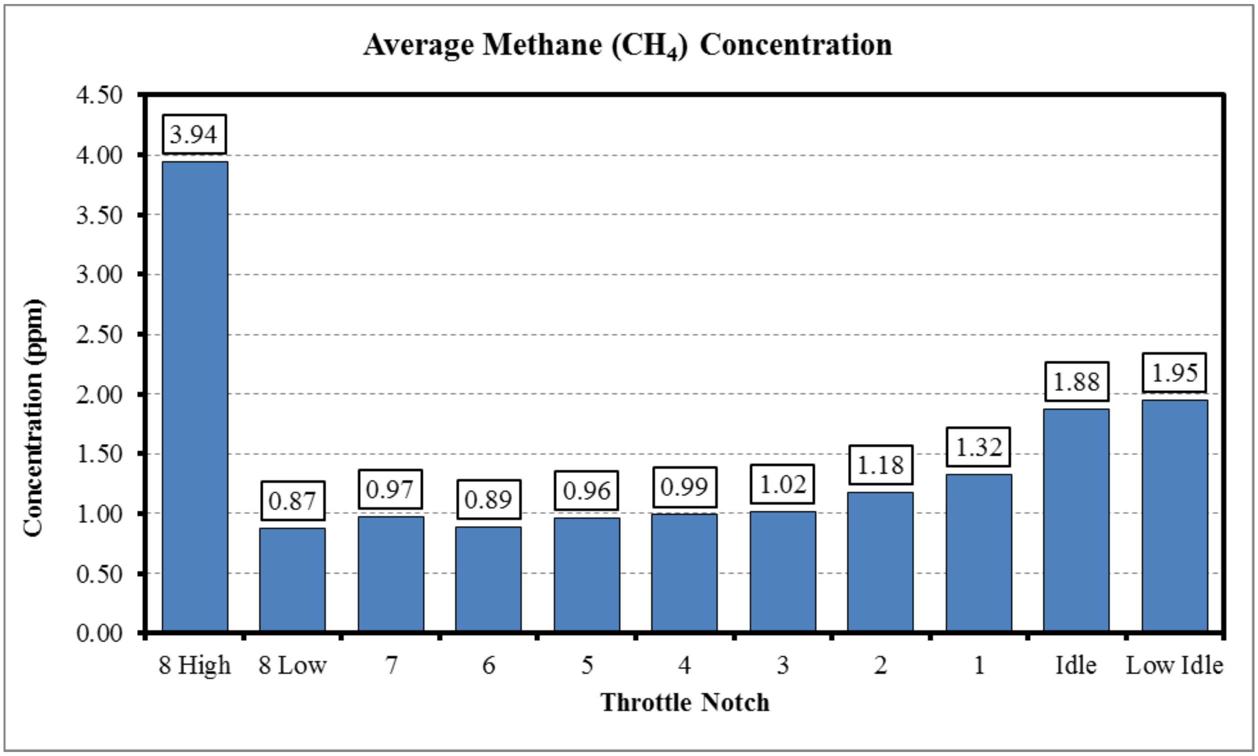


Figure 11 – Average Methane Concentration

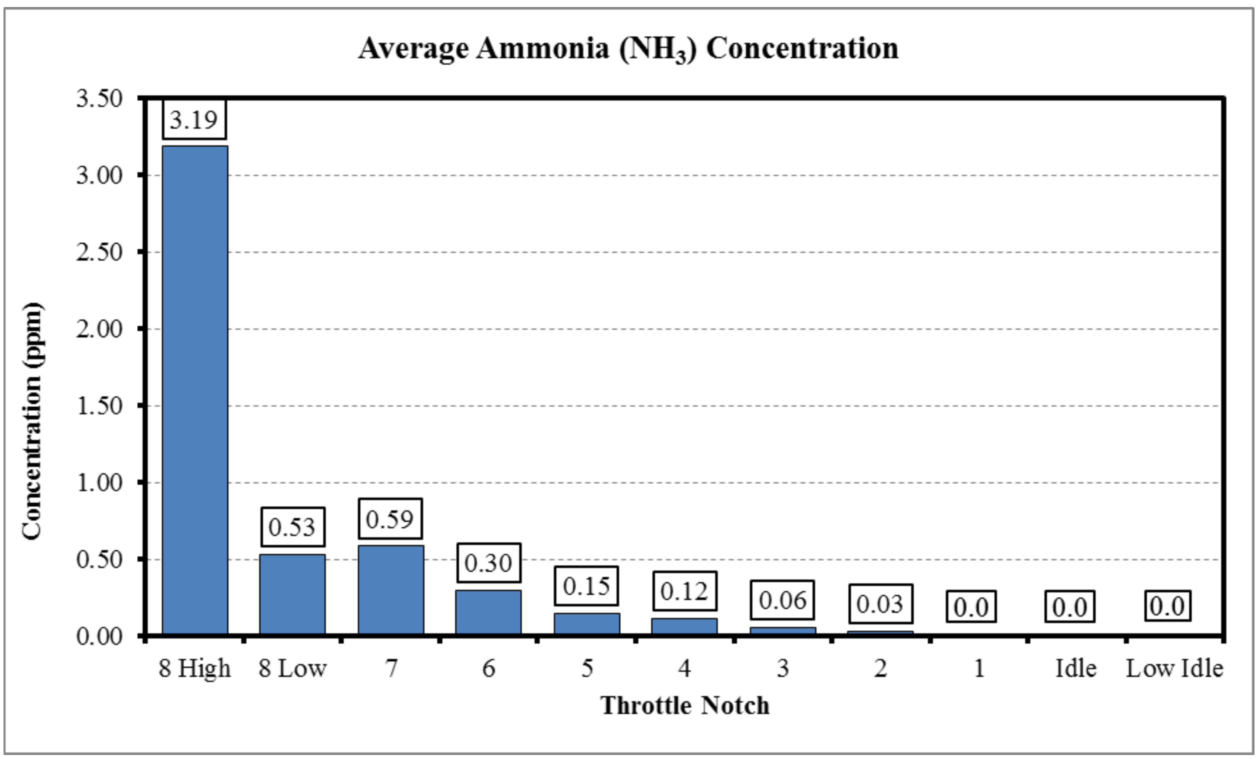


Figure 12 – Average Ammonia Concentration

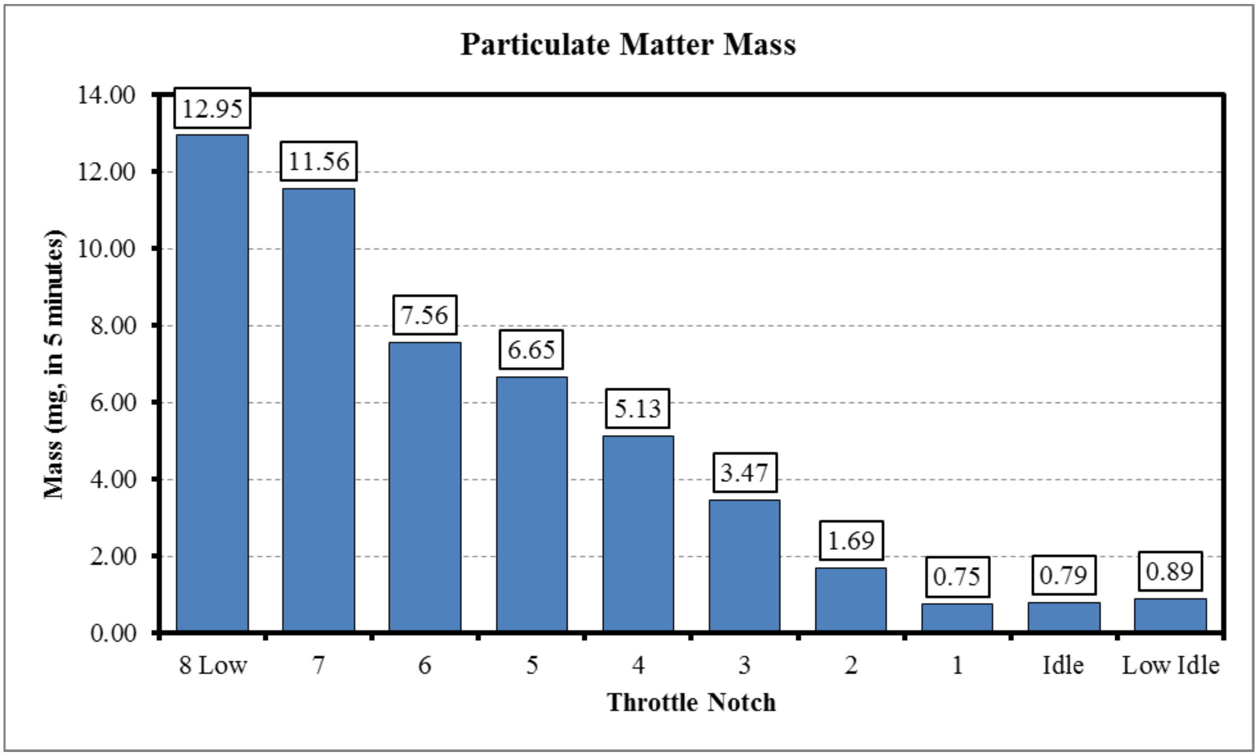


Figure 13 – Particulate Matter Mass

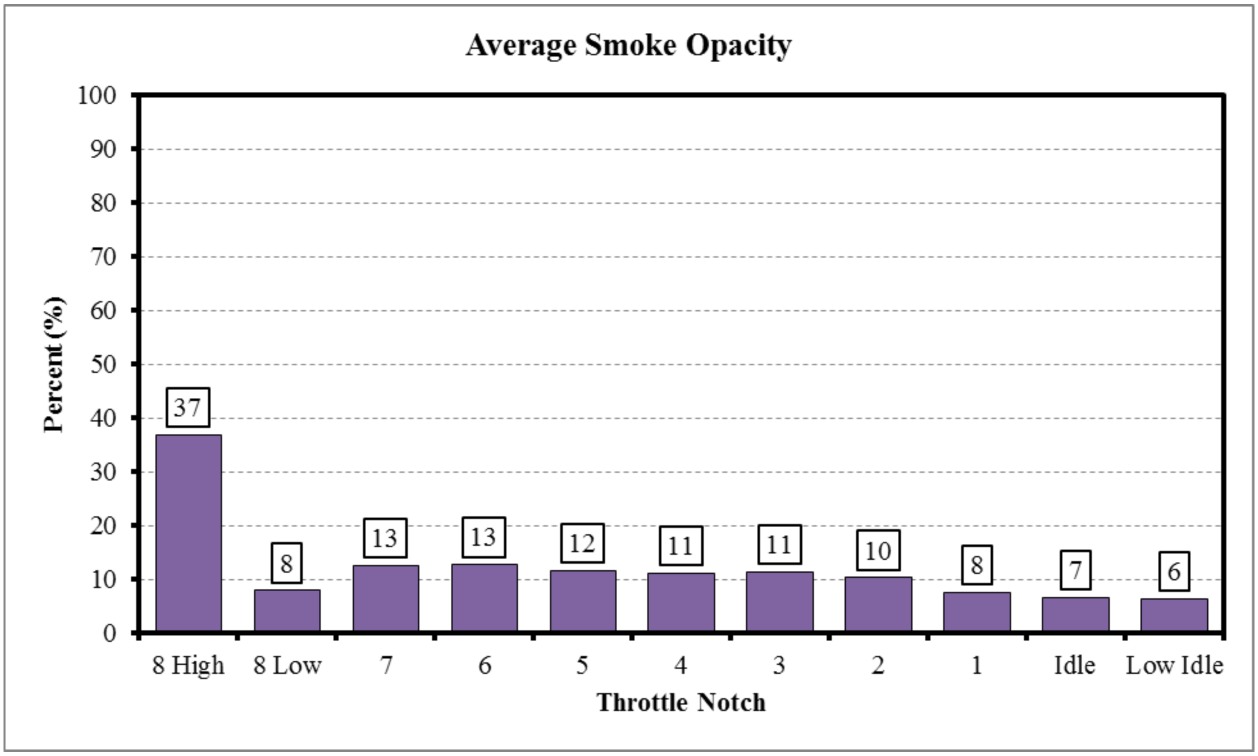


Figure 14 – Average Smoke Opacity

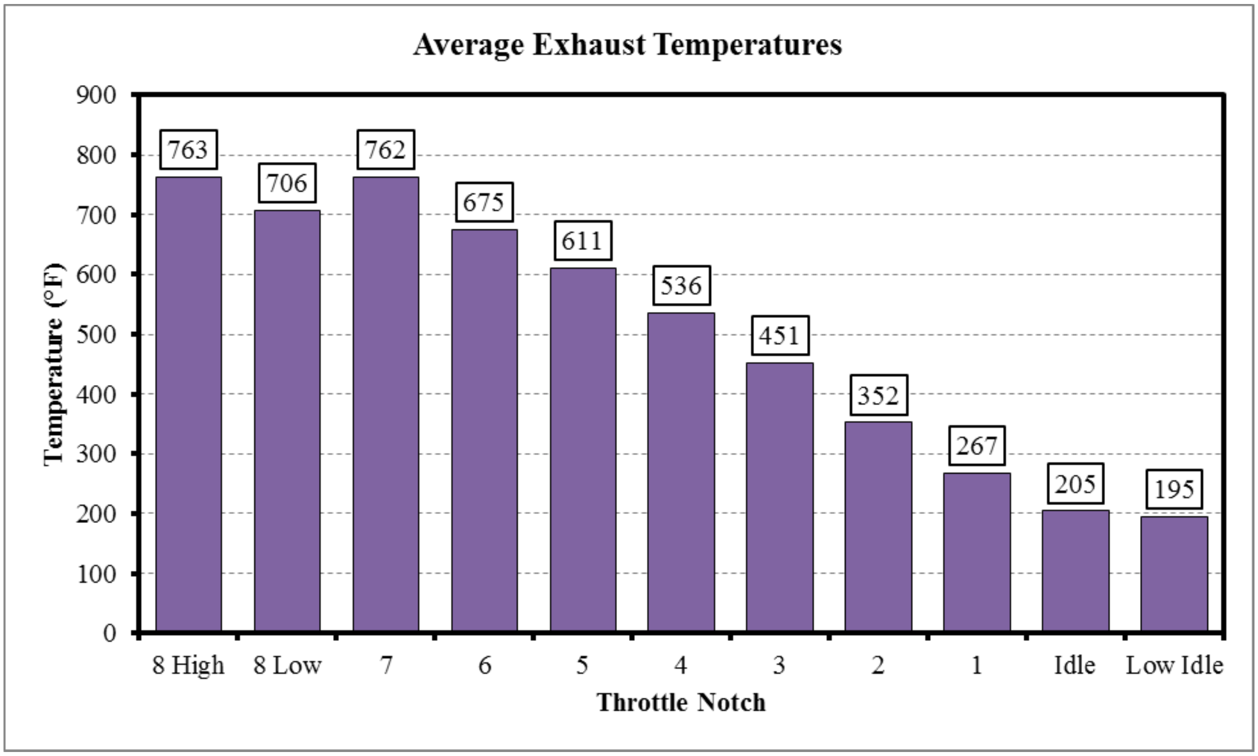


Figure 15 – Average Exhaust Temperatures

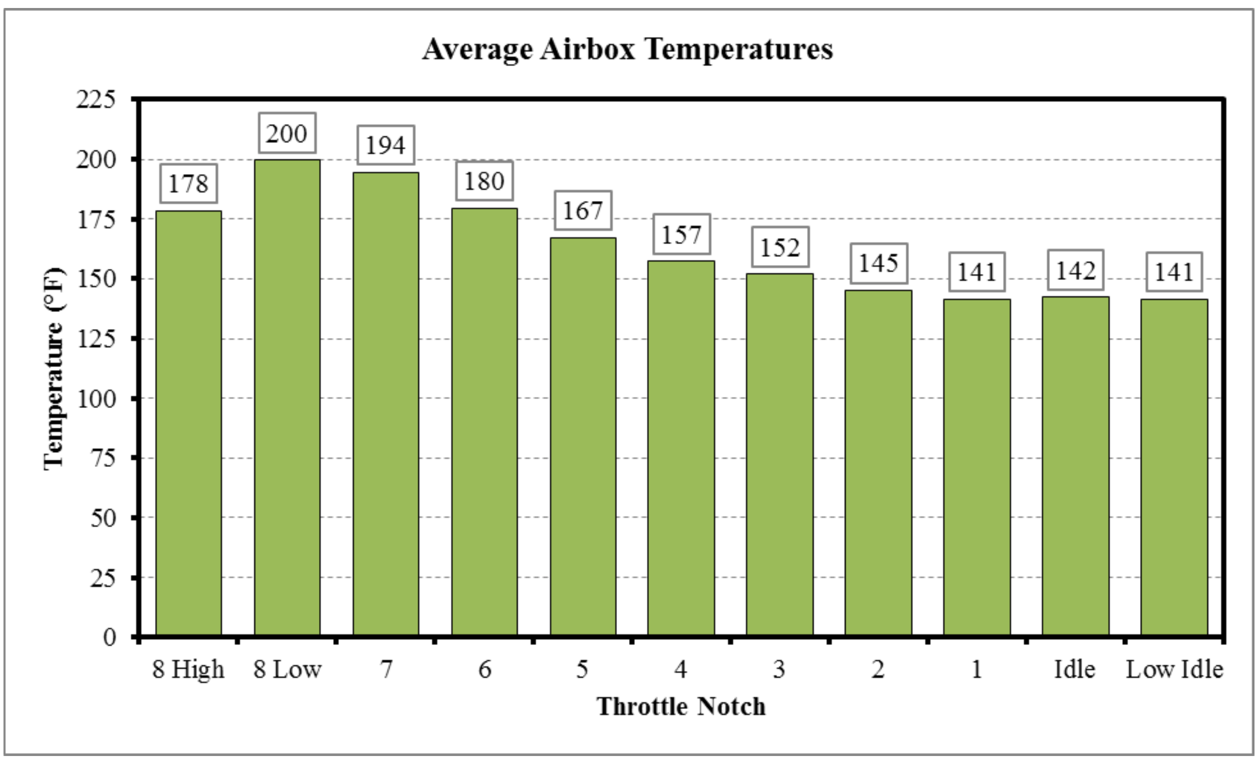


Figure 16 – Average Airbox Temperatures

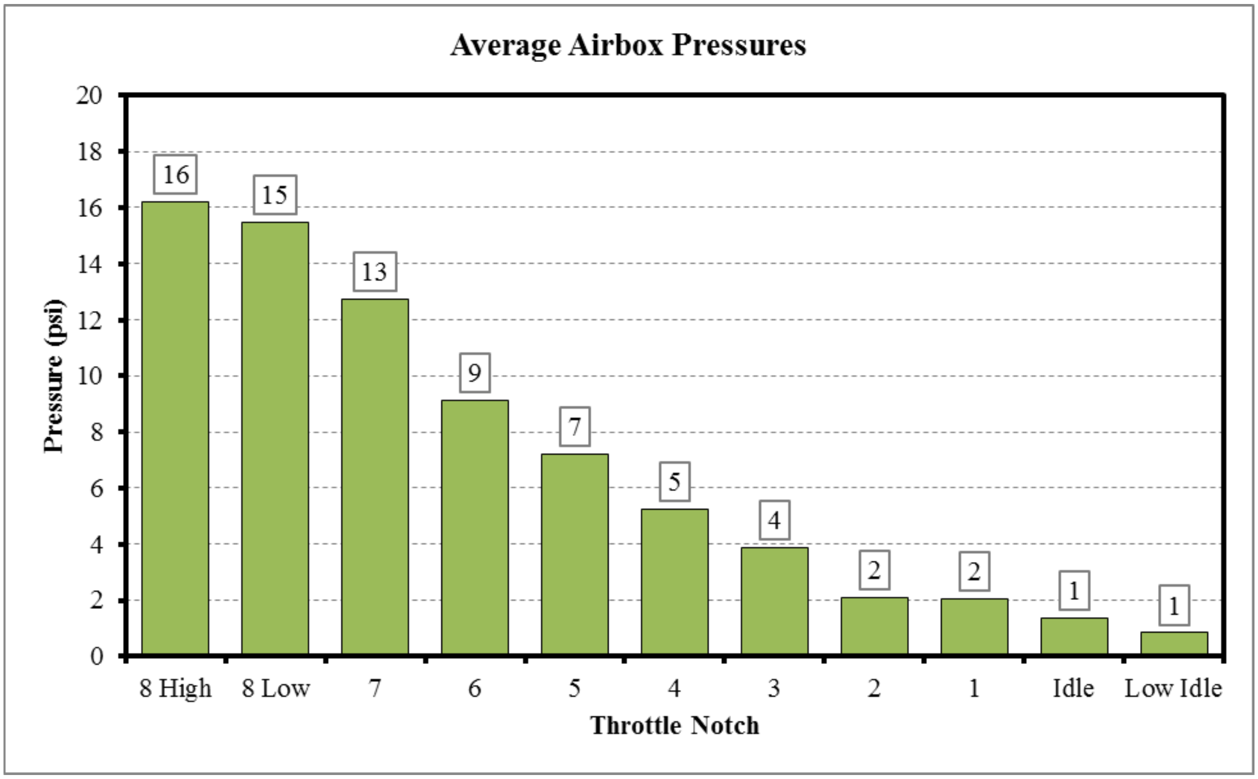


Figure 17 – Average Airbox Pressures

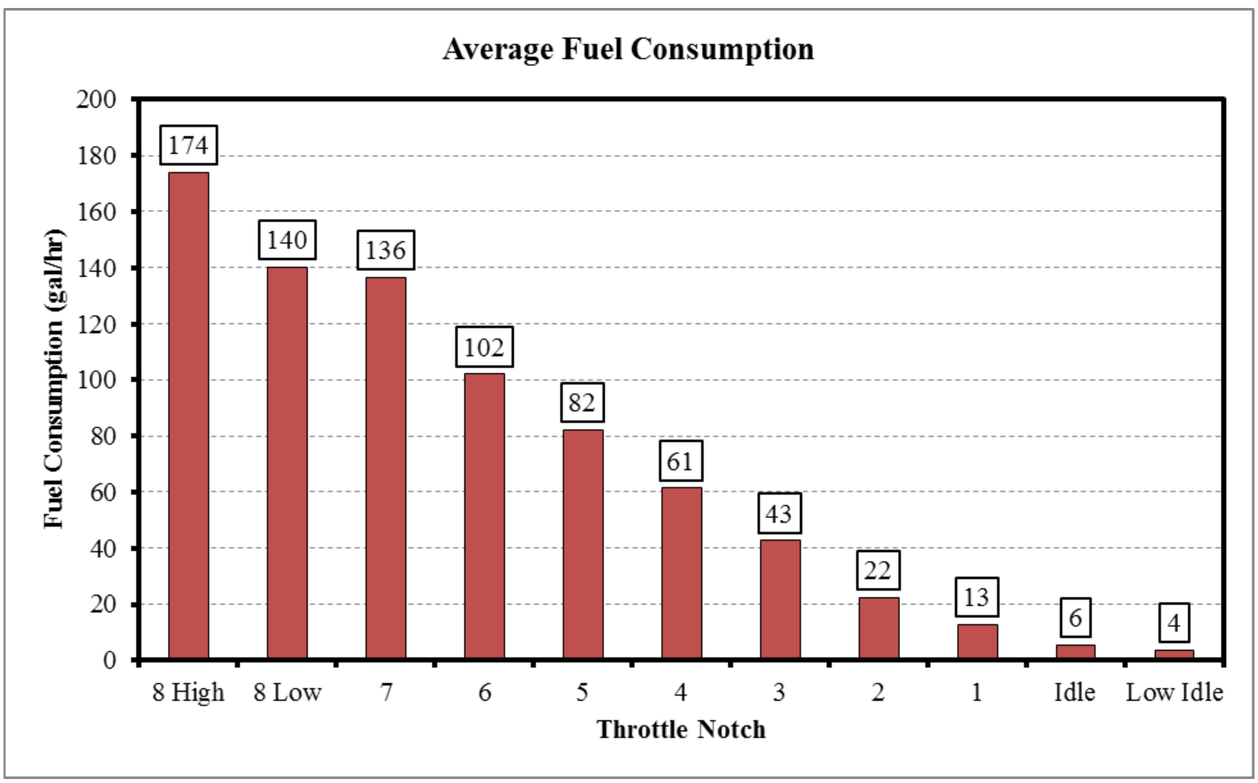


Figure 18 – Average Fuel Consumption

4.4 Comparison to Previous Test

This subsection presents a series of comparisons between data measured during an emissions test conducted in 2009 and data measured in the most recent test (2013). Since the same locomotive was used in both tests, these results may also provide insight into the locomotive's health as well as insight into any potential measurement concerns. Data for Notch 8 High are presented for sake of completeness only; actual measurements may be lower when a test is conducted using external resistor grids, which will allow a longer duration with the Notch 8 setting.

It can be observed from Figures 19 through 25 that the data from the two tests show the same general trend for magnitudes at given notch settings. Differences in magnitude levels are most likely due to variations in ambient temperatures and the overall health of the locomotive. Lower emissions values from the 2013 test are plausible, given the fact that the locomotive had been maintained in operational state during the months prior to the test.

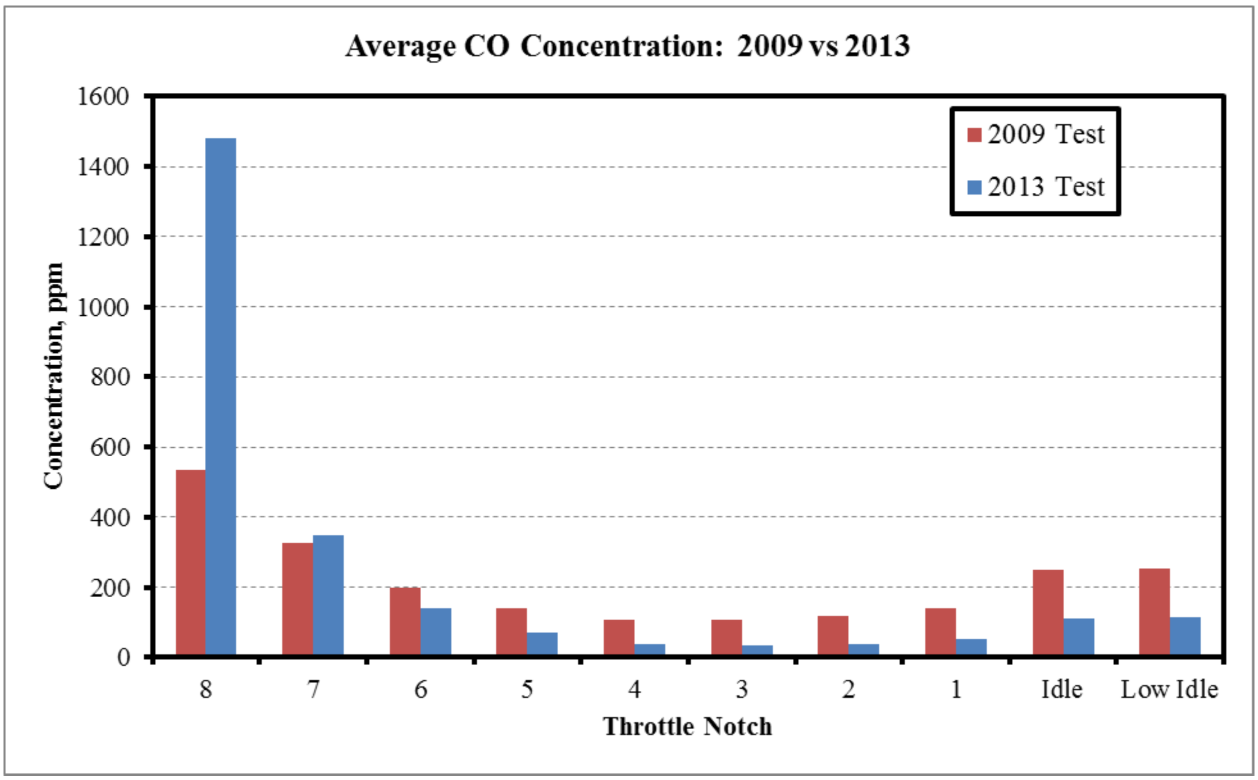


Figure 19 – Comparison of CO measurements – 2009 vs 2013

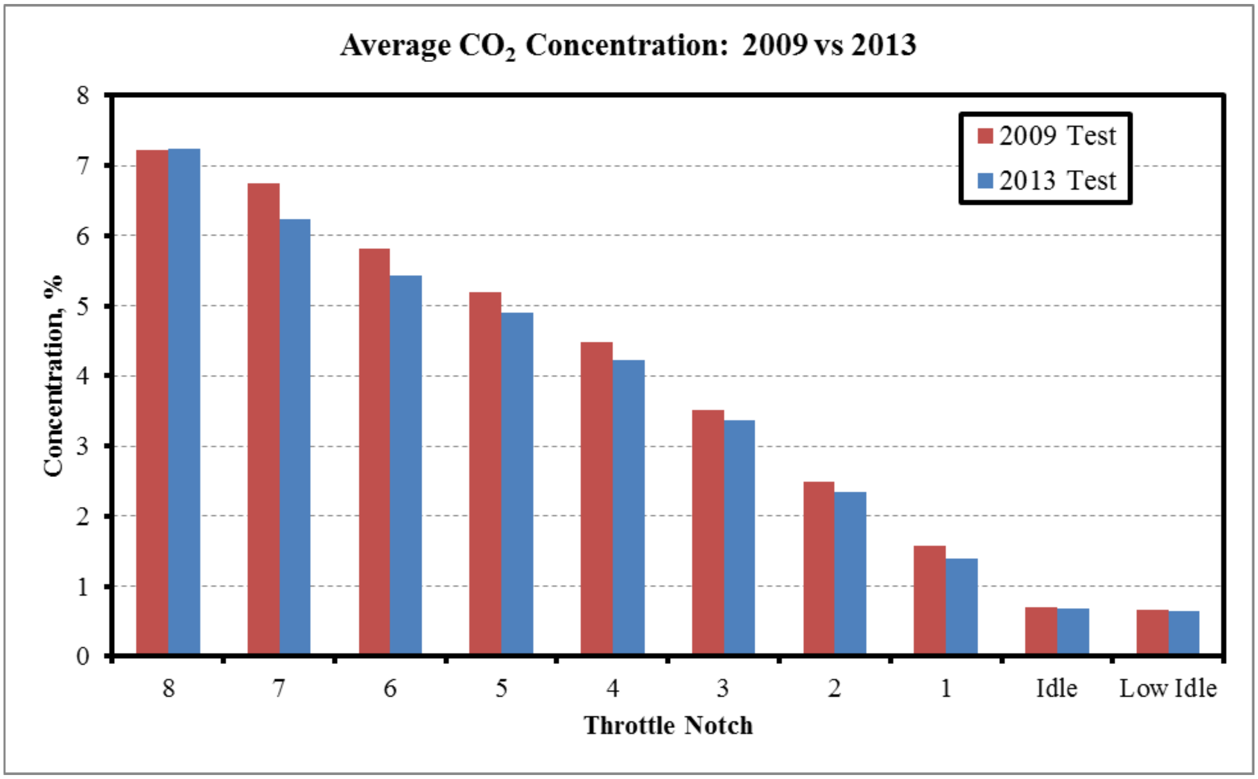


Figure 20 – Comparison of CO_2 measurements – 2009 vs 2013

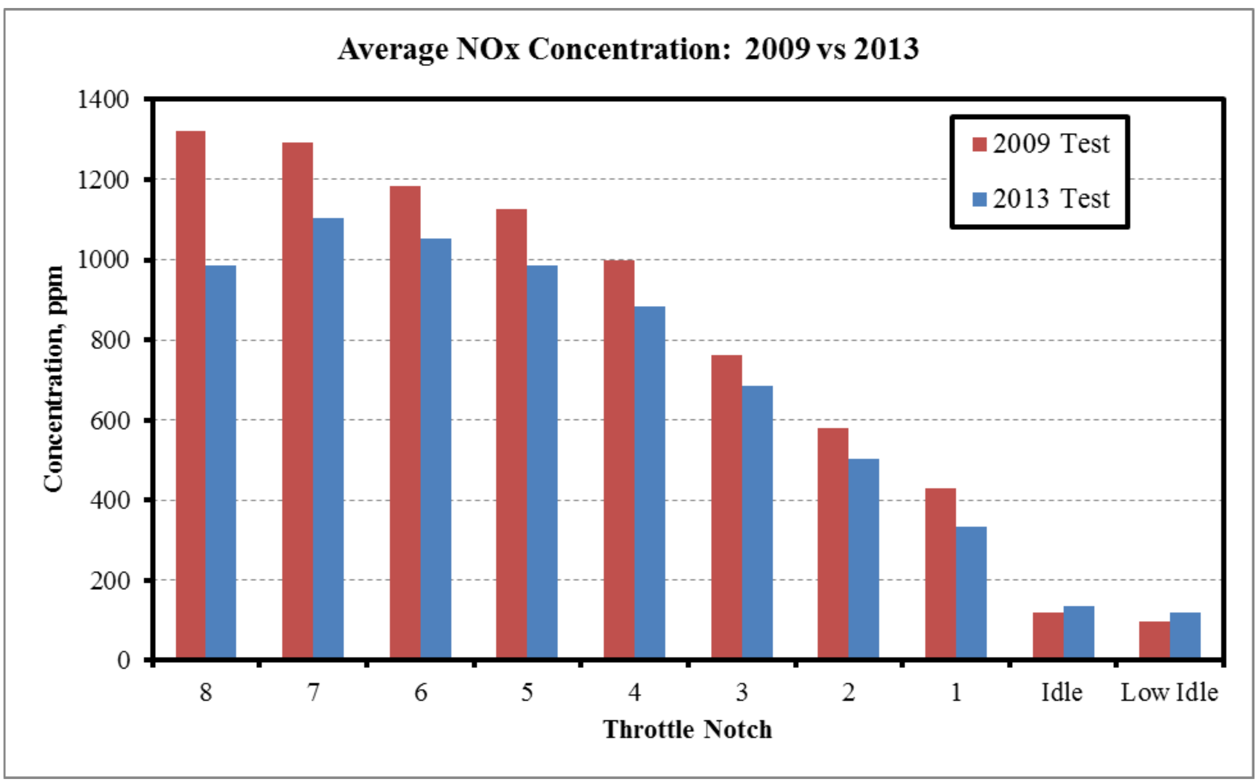


Figure 21 – Comparison of nitrogen oxide (NOx) measurements – 2009 vs 2013

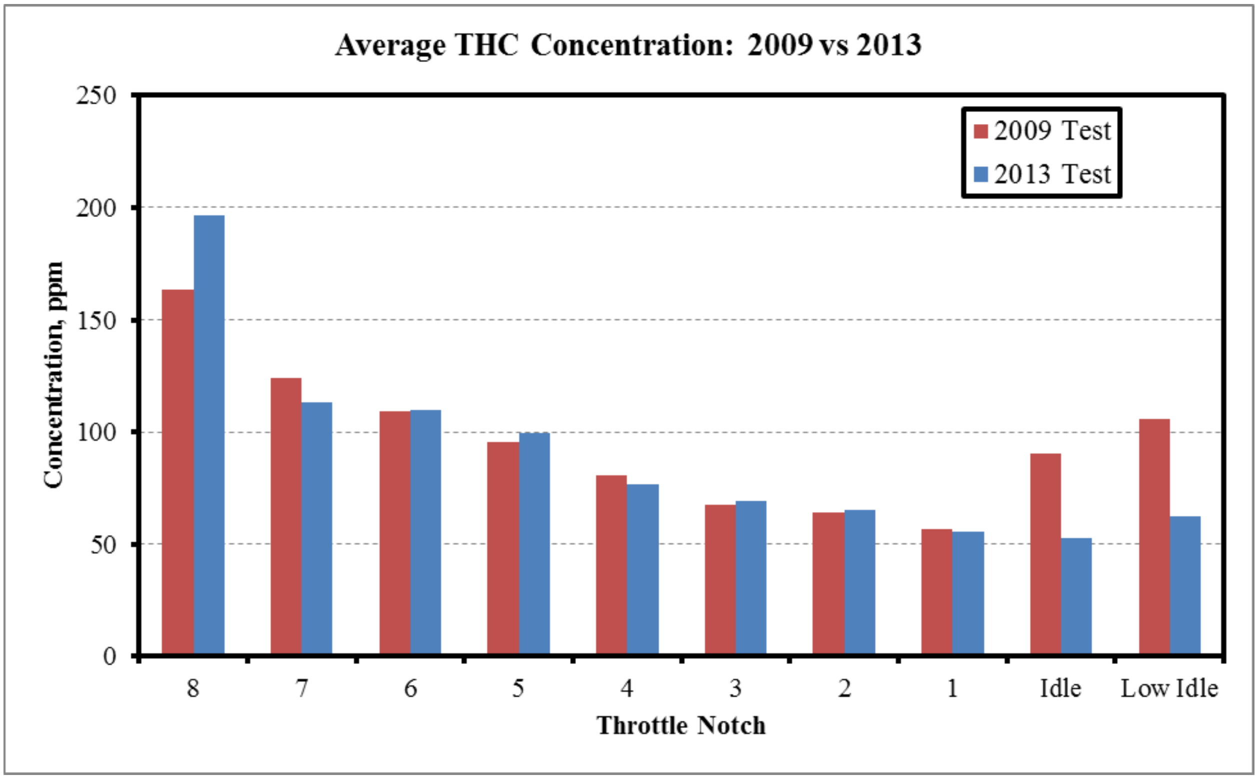


Figure 22 – Comparison of THC measurements – 2009 vs 2013

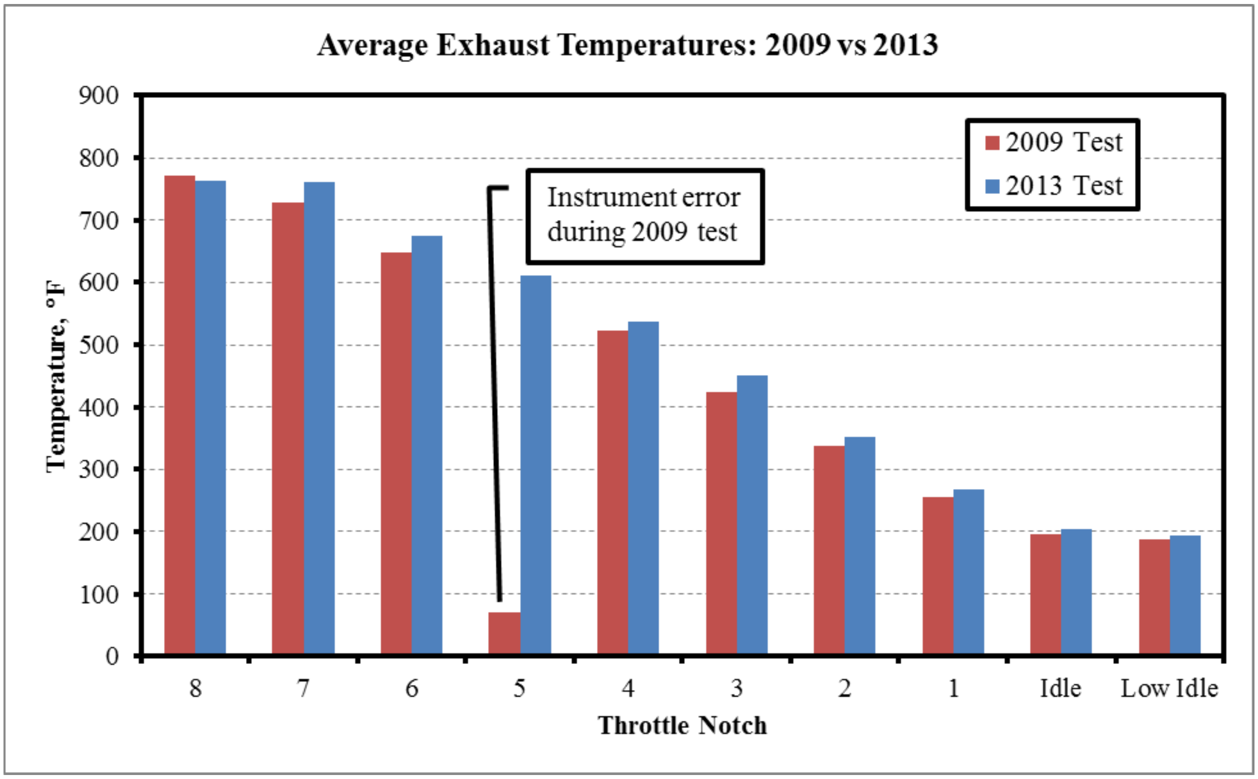


Figure 23 – Comparison of Exhaust Temperatures – 2009 vs 2013

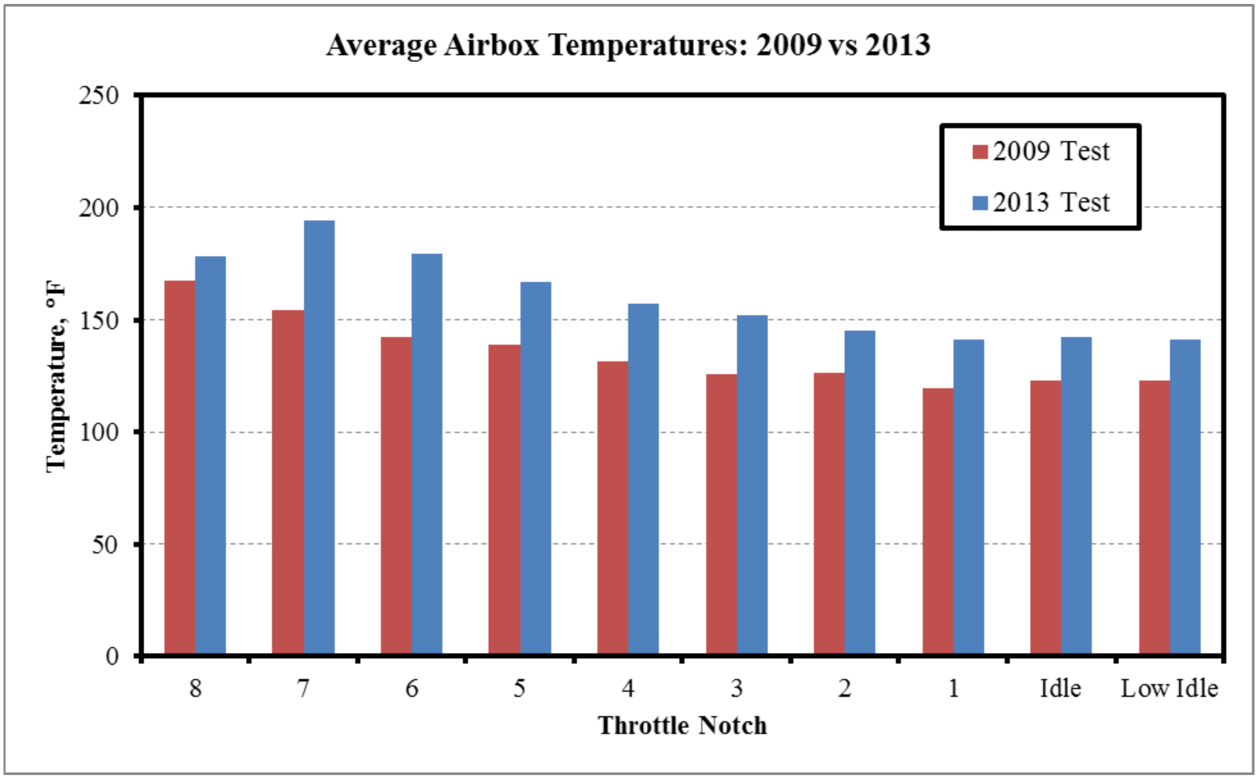


Figure 24 – Comparison of Airbox Temperatures – 2009 vs 2013

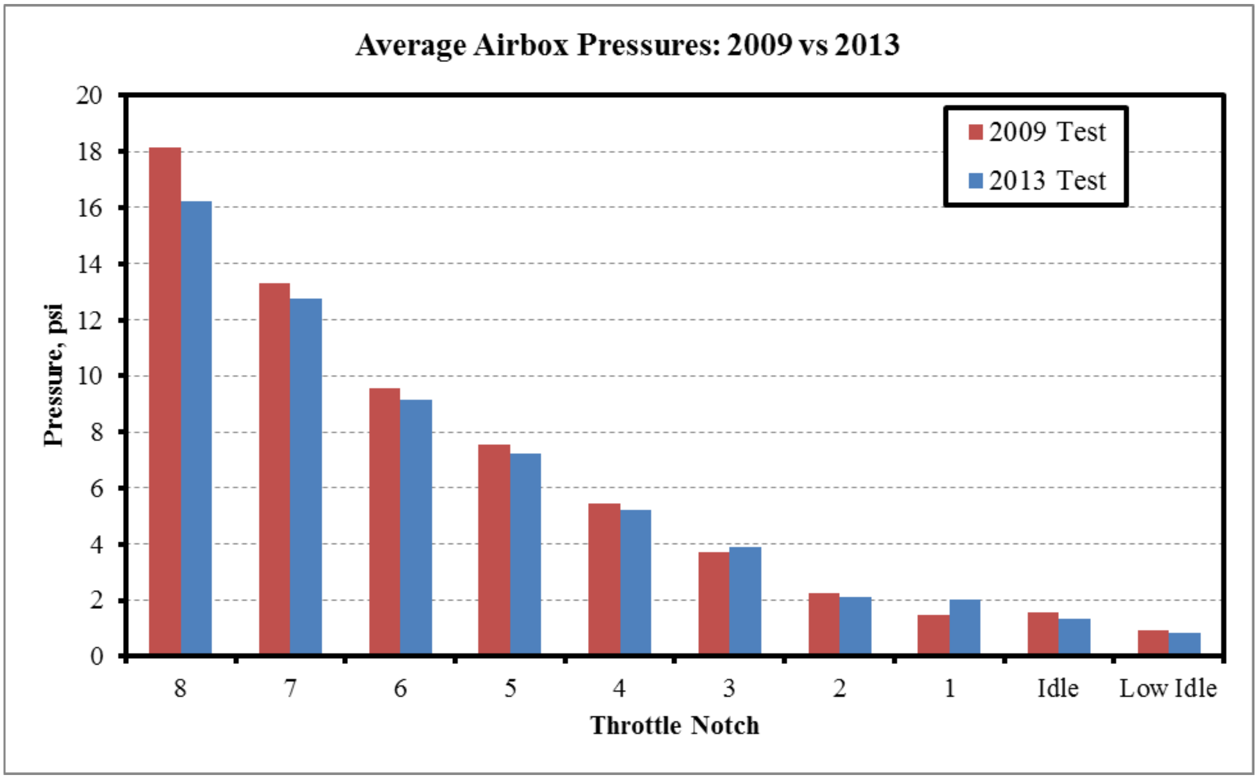


Figure 25 – Comparison of Airbox Pressures – 2009 vs 2013

5. Conclusion

The instruction manual, BOM, associated schematics, and instrument specifications documents have been updated to include a particulate matter sampling system. These documents, when used as a set, provide a blueprint for the industry to build their own LEMS.

A full scale locomotive emissions test was conducted to demonstrate the feasibility of a compact and portable setup for emissions measurement. The setup included gaseous measurement, particulate sampling, smoke opacity measurement, and fuel mass flow measurement systems, in addition to various necessary as well as optional sensors to provide a complete picture of the locomotive health from an emissions point of view. The entire test was completed in two days. This provides a significant advantage over the current options available to locomotive owners and operators.

For the purpose of obtaining guidance from EPA, efforts were made to engage them throughout this effort. A presentation has been submitted to FRA, and it will be sent to appropriate EPA personnel in order to receive their comments and guidance for making necessary improvements to the test setup and procedures.

Overall, the entire research program, including this current effort, has successfully demonstrated that a compact and portable test setup is feasible for locomotive emissions measurements and compliance testing.

6. Recommendations for Future Development

There is renewed interest and enthusiasm for adoption of natural gas as an alternative fuel for powering locomotives. This interest is primarily driven from an economic point of view due to a significant cost difference between diesel and natural gas on an energy basis.

Research so far has indicated that natural gas engines could also provide decent levels of emissions reduction compared to diesel engines. There is a large population of aging locomotives that could potentially benefit in terms of emissions compliance by converting to natural gas (Straight or Duel Fuel) from diesel. A cleaner locomotive fleet is essential to the safety of railroad personnel and the public.

Sharma & Associates recommends the following research efforts:

1. Literature survey on past and current studies that address the differences in gaseous and PM emissions between natural gas and diesel including determinations of projected NG exhaust emissions with respect to Tier 4 requirements.
2. Quantification and comparison of emissions profiles of an older diesel engine and the same engine converted to use natural gas. The FRA owned GP40-3 locomotive with an EMD 645 engine would be an ideal candidate for this research effort.
3. Detailed characterization of Dual Fuel (diesel and natural gas) high horsepower engine emissions. Although a natural gas engine will most likely result in lower NOx and PM emissions, a full characterization of emissions from a locomotive equipped with Dual Fuel engines would be beneficial.

Abbreviations and Acronyms

BOM	Bill of Materials
CFR	Code of Federal Regulations
EPA	Environmental Protection Agency
FRA	Federal Railroad Administration
MSRP	Manual of Standards and Recommended Practices
NOx	Nitrogen Oxide
PFD	Partial Flow Dilution
PPFSS	Particulate Particle Flow Sample System
PM	Particulate Matter
SA	Sharma & Associates
THC	Total Hydrocarbons