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ONBOARD LOCOMOTIVE EXHAUST EMISSIONS MEASUREMENT

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ABSTRACT

Limiting harmful locomotive exhaust emissions is important to the Nation's health and safety. The Environmental Protection Agency (EPA) has comprehensive gaseous exhaust emissions (or referred to as emissions hereto) testing requirements in place. All current tests are conducted on stationary locomotives. This paper discusses the development of an efficient stationary emissions measurement system that is compact, portable, easy to use, and applicable to onboard locomotives for in-use, over-the-road testing. More efficient locomotive emissions testing and better understanding of in-use emissions would be beneficial to all stakeholders.

Sharma & Associates, Inc., (SA) adapted an off-the-shelf, portable, on-road, heavy-duty diesel truck emissions analyzer for locomotive use. This process included development of the necessary peripheral equipment and a computer program to take the raw emissions and report them as brake-specific emissions rates and duty cycle emissions. This paper describes the use of this system on a stationary locomotive. The system is currently being fitted and tested for over-the-road use.

The measurement of particulate matter and smoke opacity were out of scope of the phase of the project that this paper is based on and not addressed hereto.

BACKGROUND

The Office of Research and Development of the Federal Railroad Administration (FRA) is responsible for conducting research to improve safety in railroad operations. To this end, FRA has been funding development of a system that utilizes a compact, portable, emissions measurement and reporting analyzer and other state-of-the-art technology, such as mass flow meters for efficient stationary testing of locomotives and/or for onboard use in over-the-road emissions measurement. The data from onboard tests can be used to better understand how the Environmental Protection Agency's (EPA) stationary tests correlate to locomotive emissions when in normal over-the-road use.

EPA regulations require that emissions from all new or remanufactured locomotives comply with limits as set forth in 40 CFR Part 92. These regulations also specify requirements for the test procedures to be used in measuring and determining emissions from a locomotive engine, including the specific data to be collected and the calculation method to use for post-processing.

Due to how emissions testing evolved [1] and the available technology during the period of evolution, most equipment used today is large and elaborate. This paper discusses a system that can be applied on board a locomotive for over-the-road use or in a location for stationary testing. The system design criteria outlines it to be portable, easy to handle, and, at the same time, produce accurate emissions information. The project's initial requirements do not include development to exact EPA standards but to prove viability of the system to meet EPA standards in the future.

SYSTEM SETUP/INSTRUMENTATION

EMISSIONS ANALYZER

Measurement of diesel engine emissions requires sophisticated instrumentation as follows:

1. Heated Flame Ionization Detector (FID) analyzer for Total Hydrocarbon (THC) measurement
2. Non-Dispersive Ultra-Violet (NDUV) analyzer for nitric oxide and nitrogen dioxide (NO_x) measurement (EPA calls for Chemiluminescent NO_x analyzer)
3. Short-path Non-Dispersive Infra-Red (NDIR) analyzer for carbon dioxide (CO_2)measurement
4. Long-path NDIR analyzer for carbon monoxide (CO) measurement
5. Heated sample line to collect engine exhaust sample
6. Dilution tunnel for particulate matter (PM) measurement
7. Light extinction meter for smoke opacity

An exhaust gas sampling and handling system is also required to properly condition the gas for analysis. This system typically includes sample lines, pumps, filters, chillers and water traps, dryers, flow meters, and appropriate atmospheric venting of the sampled gas.

Sharma & Associates, Inc. (SA) found a few commercial-off-the-shelf (COTS) portable, in-use type diesel engine emissions analyzers and chose one for the beginning of this research, SEMTECH-D, sold by Sensors, Inc. The analyzer is a compact and portable system capable of measuring THC, NO, NO_2, CO, and CO_2 (Figure 1).

The analyzer is accompanied by host software that is used to operate and monitor the system, as well as to convert the collected raw concentration data into a usable format.

Figure 1. A Portable Emissions Analyzer

In addition to the emissions analyzer, a variety of auxiliary equipment is required in the emissions measurement process; the following describes some of this equipment.

EXHAUST COLLECTION EQUIPMENT

An exhaust sampling probe is used to collect exhaust gas from the locomotive stack. A stack extension is used to securely mount the exhaust sampling probe on the exhaust stack.

SA designed and built (Figure 2) the exhaust sampling probe using EPA locomotive testing guidelines. SA also developed the stack extension that allows secure mounting and proper orientation of the exhaust sampling probe. The exhaust stack extension includes appropriate brackets on the outside to securely connect the heated sample line to the sample probe.

Figure 2. Exhaust Stack Extension

PERIPHERAL DATA RECORDING EQUIPMENT

Data collection equipment is required to measure and record various engine, locomotive, and ambient parameters, such as engine speed, main generator (MG) volts, MG amperes, MG field amperes, air-box temperature, air-box pressure, water-in temperature, oil-in temperature, fuel rate, ambient air temperature, site barometer, and relative humidity.

The fuel mass flow rate was measured using a subsystem that was connected to the supply and return fuel lines. This subsystem included a mass flow meter, day tank, float valves, pump and filter. The subsystem measures net fuel usage in the engine.

SA instrumented an air-box cover to measure air-box temperature and pressure. The remaining above referenced parameters, except fuel rate, were available through the locomotive computer.

MOBILE LAB

The analyzer requires a steady and clean source of power to operate its various components and to heat up and maintain the temperature of the sample line. SA acquired the appropriate power supply, a heavy-duty battery, and a gas-electric generator for this purpose.

For ease of transport and mobility, SA also developed a mobile lab using a full-size cargo van. The analyzer, sample line, calibration gas bottles, power supply, battery, and generator were mounted in shelves in the van while taking into consideration the ease of use and safety of the equipment and operator. Figure 3 shows the mobile lab in use.

Figure 3. Mobile Lab

IN-LABORATORY ANALYZER REPEATABILITY TESTS

SA conducted a number of tests in a laboratory environment to verify operation of the emissions measurement system and to collect multiple sets of data. Raw concentrations of various gases were measured and recorded. These laboratory tests generated a significant amount of data that were then analyzed for system repeatability.

EMISSIONS CALCULATIONS

The locomotive emissions calculation procedure follows established EPA measurement and reporting requirements for locomotive emissions, as published in 40 CFR Part 92.

The calculation procedure features the well-known fuel-based mass measurement logic to derive the locomotive exhaust constituent mass emission rates from the measured volume concentration and fuel flow rate. This procedure is well documented and widely accepted throughout the automotive, heavy-duty diesel engine, and off-road industries.

As described by Stivender [2], the determination of mass-based exhaust emissions requires two major measurement parameters: the concentration of each exhaust constituent and an associated flow term. In order to utilize the engine fuel consumption measurement for mass calculations, the observed exhaust constituent concentrations must be converted to a fuel basis.

Using a balanced chemical equation for the complete combustion reaction of a typical hydrocarbon fuel, the moles of reactants and products can be defined on the basis of a single mole of fuel, CHx, where x represents the fuel atomic Hydrogen-Carbon ratio. When the combustion equation is balanced with respect to the number of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) atoms appearing in both the reactants and products, the molar relationship between reactants and products can be established. By performing a carbon balance, the molar concentration of each reactant and product per mole of carbon can be determined, serving as the basis for the fuel-based mass emissions measurement procedure used herein.

A chemical analysis of the fuel used during the emissions measurement procedure establishes the weight percent composition of H, C, N, and S, and allows for the determination of specific chemical properties, such as fuel Hydrogen/Carbon Mole Ratio, Fuel Molecular Weight, and HC Mole Fraction of CH_x in the fuel. These fuel parameters establish the basis for the carbon balance and subsequent calculations utilizing the molar concentrations of reactants and products in the balanced combustion equation.

MASS EMISSION RATES

In a simplified form, the calculation can be expressed as:

Grams of Constituent/ hour =

$$\frac{\text{Vol\% of constituent x constituent MW x Fuel Consumption}}{\text{Fuel MW x Vol\% Carbon balance sum}}$$

Where:

Vol% of constituent = the measured % concentration of CO, HC, or NO_x

Constituent MW = the molecular weight of CO, HC, or NO_x

Fuel Consumption = the grams/hour of fuel consumed by the engine

Fuel MW = the molecular weight of the fuel hydrocarbon represented by the fuel H/C mole ratio

Vol% Carbon balance sum =the total Vol% of all measured carbon compounds in the exhaust, generally the sum of the Vol% CO_2 + CO + HC in the exhaust sample stream

BRAKE SPECIFIC MASS EMISSION RATES

Brake Specific Component =

$$\frac{\text{Grams of Constituent/ hour}}{\text{Engine brake horsepower}}$$

= Constituent grams/BHP-hr

The above presentation of emissions calculations is purposefully simplified for this paper.

DUTY CYCLES

Diesel-electric locomotive operation can be characterized by a series of discrete steady-state operating modes, commonly referred to as throttle notch (t/n) positions. Anywhere from 9 to 15 modes exist in which a locomotive may be operating. These modes include the following:

- Throttle notch positions 1 to 8
- Low Idle, Idle, and High Idle
- Dynamic Brake–typically one to three unique modes
- Main Reservoir Air Pumping

All U.S. interchange locomotives have eight throttle positions and Idle. Most freight locomotives have various combinations of the other operating modes. The locomotive engineer directly selects the majority of these operating modes, whereas some modes are controlled automatically by the locomotive's internal control system. Passenger locomotive operation tends to be more complex and may have several unique operating modes not seen with the typical freight models. For this reason, passenger locomotive duty cycles need to be considered on an individual basis.

EPA EMISSIONS STANDARDS

Freight locomotives operate with a range of trailing tonnage over a variety of terrains and speeds. This variety of tonnage, terrain, and speed produces many different duty cycles that are usually grouped and labeled by the Association of American Railroads as heavy, medium, and light duty cycles. Duty cycles specified by EPA are now used to characterize locomotive emissions for regulation purposes. Switcher locomotives have their own operational duty cycles.

The Federal EPA emission standards for locomotives and engines used in locomotives are presented in 40 CFR.[1] As explained in 40 CFR,[2] the emission standards are calculated as duty cycle brake-specific CO, HC, and NO_x and reported as duty cycle g/BHP-hr. The calculation process is shown below:

Duty Cycle Brake Specific Component =

$$\frac{\Sigma\text{ (component mass x duty cycle weight)}}{\Sigma\text{ (BHP x duty cycle weight)}}$$

EPA specifies locomotive duty cycle weights for use with the above calculation; these are presented in 40 CFR.[3] The use of a specific set of duty cycle weighting factors is determined by the particular locomotive model being tested and its end use application, either line-haul or switcher. The set of values consisting of the duty cycle weighted brake-specific mass emission rate for each component (duty cycle g/BHP-hr) is compared to EPA's emissions standards.

SA developed a custom computer program that incorporates the complete calculation procedure described above. The program was first validated using hand calculations with appropriate values for constituent raw concentrations, fuel rates, and engine output parameters. SA further validated the program with a comparative analysis using locomotive emissions test data.

[1] 40 CFR § 92.8 (a), Tables A8-1, A8-2, A8-3, A8-4, and A8-5
[2] 40 CFR § 92.8 (a)
[3] 40 CFR § 92.132 (b), Table B132-1

Constituent raw concentrations, fuel rates, and engine output parameters were input into SA's computer program, and final brake-specific mass emission rates were compared to the test data. The results were within 0.1 percent of that test data.

LOCOMOTIVE EMISSIONS TEST

SA used a locomotive emissions test procedure that applies to all in-service locomotives certified to EPA Tier 0, Tier 1, or Tier 2 locomotive emissions regulations per 40 CFR Part 92.

LOCOMOTIVE INSPECTION

Before starting emissions collection, the locomotive was inspected to ensure satisfactory operating condition and verify the presence of specific accessory components that will contribute to the final brake horsepower (BHP) recorded for each throttle notch (t/n) during the test. It is important to check all engine hardware components and settings to verify compliance with original engine manufacturer specifications or to establish that approved modifications are consistent with EPA certification criteria.

EQUIPMENT SETUP

Measuring raw gas concentrations in the exhaust sample line requires connecting a heated sample line and a sample probe between the locomotive exhaust stack and the emissions analyzer. The mobile lab was parked close to the locomotive (Figure 4). The sample line and probe were connected between the emissions analyzer and the exhaust stack.

Figure 4. Emissions Test

The weather probe, which measures the ambient temperature and relative humidity, was mounted on the outside of the van.

The emissions analyzer was warmed up for 1 hour. Following this warmup, the flame ionization detector flame was lit and allowed to stabilize for 15 minutes. The analyzer was then zeroed, calibrated, and audited using the appropriate gas bottles, and the data were recorded automatically by the system.

LOCOMOTIVE OPERATION

Following accepted industry procedures, the locomotive was operated in a static, self-load test mode using an external resistance load-box. The configuration of the test locomotive was typical of the EMD production Model GP40, circa 1965. It was also upgraded to an EM-2000 controller. Stable weather conditions prevailed throughout the duration of testing.

After engine start, the throttle was advanced as the engine warmed, leveling at t/n-8 to stabilize all operating parameters related to engine performance and emissions.

The engine was then operated in steady state in t/n-8 for approximately 45 minutes to stabilize all engine operating temperatures. This engine performance and emissions stabilization process in t/n-8 was compromised by the imposed power limit restriction. However, testing was conducted with the best operating conditions obtainable. When the engine and emissions equipment were deemed ready for testing, the 5-minute load test switch was enabled, raising the horsepower to the nominal t/n-8 level. During this 5-minute test run, engine performance and emissions data were collected.

Engine performance parameters required for the emissions data calculations process were collected. Each of the observed parameters included on the test data sheet can have an impact on the level of measured emissions and can reflect unique operating conditions under which the emissions were generated. Current SA locomotive emissions testing includes automated acquisition of these data for improved accuracy and efficiency.

Subsequent t/n positions were run for approximately 6 minutes each, as per the prescribed EPA test timetable. The t/n positions were run in descending order, t/n-7 to idle, then low idle, and finally dynamic brake (notch 4, unloaded). Data for each throttle position were collected in a manner similar to that used during the t/n-8 test described above. The descending order test sequence was judged best to capture consistent engine performance and emissions stabilization with respect to operating temperatures.

The engine and locomotive performed in a manner consistent with good mechanical/electrical condition and proper maintenance. After viewing the collected engine data, the test was deemed to be a good representation of typical GP40 performance.

EMISSIONS MEASUREMENT AND POST-TEST ACTIVITIES

The locomotive engine was run in each t/n position for at least 6 minutes, and the raw gas concentrations were measured using the emissions analyzer. The time stamps of changing t/n positions were communicated between the engine personnel and emissions personnel via two-way radios and were manually recorded. These time stamps are used to segregate the t/n position data.

Upon completion of the raw gas concentration measurement, the analyzer was again zeroed, calibrated, and audited. The system automatically recorded the data. The analyzer recorded all raw data and operating parameters, such as power supply voltage, sample line temperature, and system pressures, onto a compact memory card. The raw data were converted into a usable format using the analyzer host software. These data were then post-processed with SA's computer program.

EMISSIONS DATA

ENGINE DATA

Fuel consumption measurement

As mentioned previously, the fuel consumption rate was measured using a fuel measurement subsystem consisting of a mass flow meter, day tank, filter, pump, and motor and hose assemblies. The fuel supplied to the locomotive engine was routed through this subsystem and any fuel unused by the engine was returned to this subsystem instead of to the locomotive fuel tank. This allowed for the measurement of net fuel consumption.

Fuel properties analysis

A fuel sample was collected on test day and sent for analysis at an outside lab. Certified data from the lab were used in the analysis.

RAW EMISSIONS DATA

The initial review and assessment of the emissions test data indicated that measured concentration levels of gaseous constituents in the exhaust (i.e., CO_2, CO, NO, NO_2, and unburned HC) were consistent with, and typical of, the EMD production Model GP40 locomotive.

SA generated concentration versus time plots of the emissions data and reviewed the results to check for excessive transient measurement drift during the 6-minute sample period for each t/n. With the exception of t/n-8, the transient drift was well within EPA guidelines.[1] The observed t/n-8 drift was the direct result of the power shift that resulted when the 5-minute load test switch was enabled. If the locomotive were capable of continuous operation at full t/n-8 power, significant drift would probably not occurred. From this review, the authors conclude that the portable emissions system is capable of providing steady-state locomotive emissions measurements. Figure 5 shows a 'Concentration vs. Time' data plot. The y-axis is in concentration percentage, the x-axis is in minutes, and the boxes at the top of the graph indicate each t/n position.

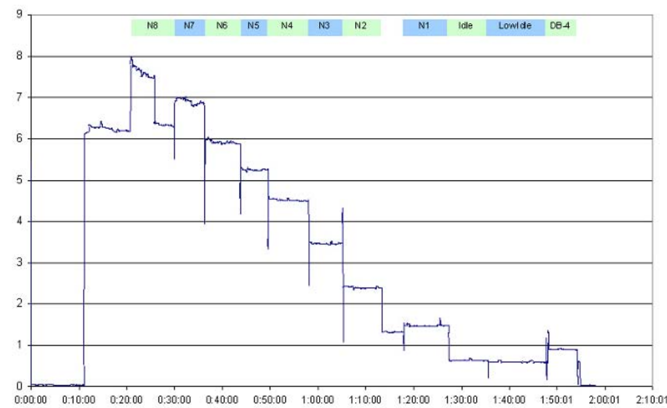

Figure 5. CO_2% concentration (Y) @ t/n versus time (X)

Table 1 presents the average values of the raw concentrations of each gaseous constituent for all the throttle notch positions.

Throttle Position	CO ppm	CO_2 %	NO ppm	NO_2 ppm	HC ppm
Low Idle	168.6	0.6	115.9	29.5	120.3
Idle	159.6	0.6	134.3	30.2	103.5
DB-4	70.8	0.9	189.8	44.6	73.7
1	40.5	1.5	418.5	38.1	69.3
2	28.8	2.4	581.0	34.1	75.2
3	29.2	3.5	798.9	34.1	84.4
4	44.6	4.5	1051.8	33.1	95.3
5	79.2	5.2	1188.7	30.8	117.8
6	143.6	5.9	1254.9	29.0	129.0
7	320.6	6.8	1296.2	24.5	133.8
8	640.6	7.5	1314.0	27.6	158.9

Table 1. Average raw concentrations for gaseous constituents

[1] 40 CFR § 92.130

BRAKE-SPECIFIC MASS EMISSIONS VALUES

Exhaust gas constituent brake-specific mass emissions are derived using measured raw concentrations, locomotive/engine data, test environment, and appropriate parameters, as described earlier in this paper. Because the test's raw emissions concentration measurements are considered acceptable, the locomotive performance is considered acceptable, and the calculation procedure has been validated; therefore the derived brake-specific mass emissions values are also acceptable.

FUTURE DEVELOPMENT

Due to the success of the project thus far, SA plans to implement the system onboard and demonstrate in-use testing. The goal is to demonstrate the collection and processing of over-the-road locomotive emissions data, real time. This information, if collected in steady-state conditions for each t/n position, could be used for comparison to traditional stationary testing.

ACKNOWLEDGMENTS

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