ABSTRACT

CHOI, HYUNG-WOOK. Measurement and Modeling of the Activity, Energy, and Emissions of Conventional and Alternative Vehicles. (Under the direction of Dr. H. Christopher Frey.)

Since the transportation sector is a significant contributor of air pollution, the capabilities of estimating fuel use and emissions for various vehicles is important to air quality studies as well as the development of environmental guidelines and policy recommendations. In this thesis, a common or similar modeling approach based on second-by-second data using portable emission measurement system (PEMS) was developed to estimate energy and emission estimation for a wide variety of on-road and non-road sources with conventional and alternative technology.

Based on vehicle-specific power (VSP) and speed-acceleration modal models, two correction factors were developed to estimate fuel consumption and emissions for vehicles which were driven with high and constant speed on highway. The corrected emission factors for NO_x, HC, CO, and CO_2 were significantly higher for high speeds and lower for low speeds than base emission factors estimated using MOBILE6 which is based on transient test cycles with durations on the order of 10 minutes.

A similar methodology was used to estimate energy use and emissions for a plug-in hybrid diesel-electric school bus (PHSB) and conventional diesel school bus (CDSB) for typical school bus routes in NC. To quantify the reduction of fuel use and emissions between PHSB and CDSB for same driving routes, the mixed-modal models based on manifold absolute pressure and VSP versus emissions were developed. Plug-in hybrid technology

showed significant emission reductions for stop-and-go driving pattern. These results could provide a support for transportation and air quality management.

This thesis also introduces a simplified emission estimation methodology for locomotives based on rail-yard measurements using PEMS. This alternative measurement method is faster and cheaper than a federal reference method (FRM). The fuel-based emission rates based on PEMS measurement were comparable to FRM. It should serve as a useful basis of comparison to data in future measurement campaigns.

Measurement and Modeling of the Activity, Energy, and Emissions of Conventional and Alternative Vehicles

by
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BIOGRAPHY

Hyung-Wook Choi received his Bachelor of Science degree in Environmental Science from Kyung Hee University, Yongin, South Korea, in 2000. After his graduation, he continued his graduate studies in the department of Environmental Science at Kyung Hee University in spring 2000 and earned his Master of Science degree in February 2002. After he earned masters degree, he worked as an environmental engineer in the department of Eco-machinery Engineering in Korea Institute of Machinery and Materials (KIMM) for two and half years. In August 2005, he joined in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University, Raleigh, NC, pursuing his PhD degree. He was a research assistant at the Computational Laboratory for Energy, Air, and Risk (CLEAR) under the guidance of Dr. H. Christopher Frey. His research was mainly focused on emission measurements and modeling for on-road and non-road sources such as light duty gasoline vehicles (LDGV), diesel vehicles (DV), locomotives, and plug-in hybrid electric vehicles (PHEVs).

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PART I INTRODUCTION

1.1 Introduction

The emissions of vehicle pollutants are an important health issue that affects nearly everyone (Holguin, 2008; Ivanenko *et al.*, 2007; Kampa and Castanas, 2008).

Transportation accounts for 28% of U.S. energy use and contributes 34% of U.S. CO_2 emissions (EIA, 2008). Surface transport contributes 40% of national annual nitrogen oxides (NO_x) emissions, 56% of CO, and 28% of volatile organic compounds (VOC) (EPA, 2007).

In 2007, vehicle emissions are the largest contributors for national NO_x and CO emissions and second largest for HC. The transportation sector is the second largest energy user, representing approximately 29 percent of the total (EPA, 2007). These emissions are significant and it is needed to estimate vehicle emissions.

Highway vehicles contribute nationally 35% of nitrogen oxides (NO_x), 55% of carbon monoxide (CO), and 27% of hydrocarbons (HC) in the U.S. National Emission Inventory (EPA, 2007). Non-road vehicle emissions are also significant source of air pollution. For example, railroad emissions contribute nationally 4% of NO_x (EPA, 2007).

NO_x may cause a respiratory problem. CO can attach to hemoglobin approximately 220 times more strongly and decrease the delivery of oxygen in the blood (Cooper and Alley, 2002). HC and NO_x can produce ground level ozone (O_3) as a precursor. Ozone can decrease the ability of the lung functions.

Recently, there is increasing concern regarding near-roadway air quality and localized effect of traffic control measures (TCMs), transportation improvement projects (TIPs), and vehicle operation, which motivates accurate micro-scale vehicle Energy Use and

Emissions (EU&E) data. Approximately 12% of households in the U.S. are located within 100 meters of a four-or-more lane roadway (Brugge *et al.*, 2007). Many researchers reported a strong relationship between living near-road way and adverse health effects such as asthma, premature mortality, and cancer (Dales *et al.*, 2008; Hoek *et al.*, 2002; Jerrett *et al.*, 2008).

There is interest in improving the quantification of human exposure to air pollutants near roadways (EPA, 2009). However, there is a limitation of existing emission model, such as MOBILE6 to estimate accurate highway emissions. Since MOBIEL6 was developed based in driving cycle, it produces for average emission for entire cycle but not accurate for short segment of highway which vehicle drive

The Oregon Environmental council commented that air pollutants from non-road source such as locomotive diesel engine contribute to a public health threats (EPA, 2008). The off-highway mobile source such as locomotive is considered as an important source in urban area, especially non-attainment area because air pollutants from off-highway source can contribute to serious public health problems. Under the National Ambient Air Quality Standards (NAAQS), a total of 32 counties in North Carolina are in non-attainment area for ozone.

Because of concern regarding greenhouse gases and toxic air pollutants, alternative technologies related to vehicle emission are being introduced. For example, new technology vehicles, such as flex-fuel vehicle, hybrid electric vehicles, advanced diesel, electric, and fuel cell vehicles, may make up more than 27% of the total new light duty vehicle sales in 2030 (EIA, 2008). According to some studies, plug-in hybrid electric vehicles could consume

50% less gasoline than conventional vehicles (CVs) (Gonder and Simpson, 2007; Markel and Simpson, 2006). Whereas plug-in hybrid electric vehicles (PHEVs) do not require major short-term infrastructure changes (Samaras and Meisterling, 2008), wide-scale PHEV deployment will couple transportation and electricity sectors and shift energy and emissions patterns.

Increasing concern over greenhouse gas emissions, (e.g., CO_2), motivates a broad-based approach to evaluating direct and indirect (secondary) impacts of PHEVs on energy mix, technology choice, and system-wide (regional, national) CO_2 emissions.

In order to reduce emissions in transportation sector, it is important to accurately estimate on-road and non-road emissions to improve air quality and reduce an adverse health effects. The key problems to be addressed by this study are: (1) lack of estimation of the fuel use and emissions for gasoline and diesel vehicles for relatively short segments of highway; (2) lack of quantification of real-world energy use and emissions for non-road vehicles such as locomotive; and (3) lack of quantification of the fuel use and emissions for alternative technology vehicles such as plug-in hybrid electric vehicles.

To estimate emissions from vehicle sources, U.S. Environmental Protection Agency (EPA) developed emission factor models, such as MOBILE6 and NONROAD. MOBILE6 is used widely for variety of air pollutions. Recently, EPA just introduced a new emission model. The draft version of Motor Vehicle Emission Simulator (MOVES) can cover wide variety of emission sources. However, there is a still lack of ability to estimate fuel use and emission rates for highway vehicles that drive at constant high speed such as 80 mph or advanced technology vehicles such as PHEVs, and locomotive under real-world situation. This work here can contribute to improve comprehensive emission factor model such as MOVES.

1.2 Objectives

The objectives of this study are to:

(1) Characterize vehicle activities and emissions under real-world driving cycles for light duty gasoline vehicles, diesel vehicles, locomotives, and plug-in hybrid vehicles;

(2) Estimate emissions for highway light duty gasoline and diesel vehicles that are operated at high and constant speeds;

(3) Demonstrate methodology for in-use measurement of diesel-electric passenger railroad locomotives and plug-in hybrid diesel school bus using a portable emission measurement system (PEMS);

(4) Quantify the reduction of fuel use and emissions for plug-in hybrid diesel vehicles; and

(5) Determine whether common or similar methods can be used for a wide variety of vehicles, duty cycles, and application.

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PART II OVERVIEW OF METHODOLOGY

This chapter shows an overview of methodologies for modal emission models based on engine vehicle-specific power (VSP), speed-acceleration mode, throttle notch position, and engine load with manifold absolute pressure (MAP). Since most studies in this paper are used a second-by-second emission data using PEMS, the explanations of data collection and data quality assurance for PEMS are also briefly introduced in this chapter.

2.1 Data Collection using Portable Emission Measurement System

In this section, the general methodologies for data collection and data analysis for PEMS are explained.

2.1.1 Emission Measurement Methods

Commonly used methods for measuring vehicle emissions include engine dynamometers, chassis dynamometers, tunnel studies, remote sensing, and on-board measurement.

The engine dynamometer is used to measure fuel use, horsepower output, and emissions for heavy-duty engines such as locomotive. This data are reported in units of g/bhp-hr, which are not directly relevant to in-use emissions estimation. Many engine dynamometer test cycles are based upon steady-state modal tests that are not likely to be representative of real world emissions. For example, locomotive engine dynamometer test cycles involve operating the engine at 8 throttle notch positions plus idle position. For each notch position, the engine is operated for a sufficient amount of time to produce approximately stabilized emission rates with respect to time (EPA, 1998). After measuring all notch positions, the emission measurements from each notch positions are combined using a weighted averaging scheme.

For onroad vehicle, particularly light-duty vehicle emissions are usually measured by chassis dynamometer measurements. As vehicle size increases, the cost of chassis dynamometer facility increases a lot. Thus, there are fewer heavy-duty chassis dynamometer facilities than that for light-duty vehicles (Wang *et al.*, 1999). Chassis dynamometer tests provide emissions data in units that are more amenable to the development of emission inventories, such as grams of pollutant emitted per mile of vehicle travel. This emission factor can be multiplied by estimates or measurements of vehicle miles traveled to arrive at an inventory.

Tunnel studies are typically used for onroad vehicles. Tunnel studies are limited in their ability to discriminate among specific vehicle types. However, tunnel studies are based upon measurements for a specific link of roadway and thus are not representative of an entire duty cycle (NARSTO, 2005).

Remote sensing can be used to measure emissions from any vehicle of onroad or nonroad that passes through an infrared beam and, if available, ultraviolet beams that are used to measure pollutant concentrations. Each measurement is only a snap shot at a particular location, and thus cannot characterize an entire duty cycle (Frey and Eichenberger, 1997).

On-board emissions measurement systems offer the advantage of being able to capture real world emissions during an entire duty cycle. In particular, Portable Emissions

Measurement Systems (PEMS) that are more easily installed in multiple vehicles than complex on-board systems are selected for use in this study.

2.1.2 Portable Emissions Measurement Systems

PEMS data are used increasingly for development of emission models, such as EPA's draft 2009 Motor Vehicle Emission Simulator (MOVES) (EPA, 2009; Frey *et al.*, 2002b; Younglove *et al.*, 2005).

The advantage of a PEMS over a complex on-board measurement system is that installation is easier for a wide variety of vehicles (Vojtisek-Lom and Allsop, 2001). For example, in this study, PEMS is used to measure emissions for light-duty gasoline vehicle (LDGVs), locomotives, and heavy-duty diesel vehicles (HDDVs).

For this study, the OEM-2100 "Montana" system manufactured by Clean Air Technologies International (CATI) is used. The Montana is comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, a global positioning system (GPS), and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxide (NO), and oxygen (O_2) in the vehicle exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. A sensor array is used to measure manifold absolute pressure (MAP), intake air temperature (IAT), and engine RPM in order to estimate air and fuel use. A GPS system measures vehicle position. The on-board computer synchronizes the incoming emissions, engine, and GPS data. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (Vojtisek-Lom and Cobb, 1997).

The gases and pollutants measured include CO, CO_2, HC, NO, O_2, and PM using the following detection methods:

- HC, CO and CO_2 using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used (Vojtisek-Lom and Allsop, 2001; Vojtisek-Lom and Cobb, 1997).
- NO measured using electrochemical cell. On most vehicles with Tier 2 or older engines, NO_x is comprised of approximately 95 volume percent NO (Bromberg *et al.*, 2000; Jimenez *et al.*, 2000).
- PM is measured using light scattering, with measurement ranging from ambient levels to low double digits opacity (Vojtisek-Lom and Allsop, 2001; Vojtisek-Lom and Cobb, 1997).

Manifold Air Boost Pressure Sensor. In order to measure MAP, a pressure sensor is installed on the engine. For most heavy duty diesel engines, there is a port on the engine after the turbocharger. In a regular engine performance check, this port is used for performance testing of the turbocharger. An existing bolt is removed and a barb fitting is screwed into the port. However, when the existing port is not available, modification of pipe or duct in the engine manifold might be needed to make a MAP port. For example, Figure 2-1 depicts the location of a fabricated port on the intake air manifold of EMD12-710 engine for F59 locomotive. Plastic tubing is used to connect the MAP sensor to the barb fitting. The MAP sensor is attached to a convenient location in the engine, away from a hot surface, using plastic ties. The MAP sensor provides manifold air pressure data for the computer of the main unit through a cable that connects the sensor to the MAP port located in the back of the main unit.

Engine Speed Sensor. The engine speed sensor is an optical sensor used in combination with reflective tape to measure the time interval of revolutions of a pulley that rotates at the same speed as the engine crankshaft. The engine speed sensor has a strong magnet to attach easily on metal materials. The reflective tape must be installed on a pulley that is connected to the crankshaft. The placement of the reflective tape and the optical sensor for a Cummins ISX-500 engine is shown in Figure 2-2. Some of the key factors in placement of the sensor include: (1) avoid proximity to the engine cooling fan and other moving components; (2) place the sensor in a location where the magnet can securely affix the sensor to a surface; and (3) place the sensor so that its cable can reach the sensor array box, which is also located in the engine compartment. The signal from the RPM sensor is transmitted by cable to a sensor array box, which in turn transmits the signal by a second cable to the main unit of the Montana system.

Intake Air Temperature Sensor. The engine intake air temperature sensor needs to be installed in the intake air flow path. The sensor has a metal part that can detect temperature. Installation of the intake air temperature sensor is somewhat easy compared to the engine speed and MAP sensors. Using duct tape or a plastic tie, one can fix the intake air temperature sensor near the intake air flow where the MAP port is located.

Sensor Array. The sensor unit is the device which connects the intake air temperature and engine speed sensors to the main unit. Plastic ties are used to secure the sensor unit on the vehicle. If the sensor unit can not be affixed to the vehicle using plastic ties, duct tape can be used to secure the sensor unit.

Operating Software. The Montana System includes a laptop computer that is used to collect and synchronize data obtained from the engine scanner, gas analyzers, and GPS system. Data from all three of these sources are reported on a second-by-second basis. Upon startup, the computer queries the user regarding information about the test vehicle, fuel used, test characteristics, weather conditions, and operating information. The details of the definition and significance of each of these are detailed in the Operation Manual of the instrument (CATI, 2003).

Validation and Calibration. The Montana System gas analyzer utilizes a two-point calibration system that includes "zero" calibration and "span" calibration. Zero calibration is performed using ambient air at frequent intervals (every 5-15 minutes at power up, every 30 minutes once fully warmed up). The ambient air pollutant levels are negligible compared to those found in undiluted exhaust; therefore, ambient air is viewed as sufficient for most conditions. For zero calibration purposes, it is assumed that ambient air contains 20.9 *vol*-% oxygen, and no NO, HC, or CO. CO_2 levels in ambient air are approximately 300 ~ 400 ppm, which are negligible compared to the typical levels of CO_2 in exhaust gases.

Span calibration is performed using a BAR-90 concentration calibration gas mixture, which has a known gas composition. The calibration gas includes a mixture of known concentrations of CO_2, CO, NO, and hydrocarbons, with the balance being N_2. Span gas calibration is recommended once every three months.

2.1.3 Field Data Collection

Field data collection includes the following main steps: (1) pre-installation; (2) final installation; (3) data collection; and (4) decommissioning.

Pre-installation was performed the afternoon or evening before a scheduled test. This step involves installing on the vehicle the exhaust gas sampling lines, power cable, and engine data sensor array. Exhaust gas sampling lines have a probe that is inserted into the tailpipe. The probe is secured to the tailpipe using a hose clamp. The sampling line is secured to various points on the chassis of the vehicle using plastic ties. For prime mover engine of locomotive, sample line are directly connected from Montana to a fabricated sample port on the exhaust gas duct in the engine room. In order to obtain engine data such as MAP, IAT, and RPM, sensor array for heavy-duty vehicles and OBD-II data logger for light-duty vehicles are used.

Final installation was performed in the morning prior to field data collection. The Montana system was secured in the cab of the vehicle and was connected to the exhaust sample lines, engine data cables, and power cable. In addition, a GPS receiver was deployed. As part of final installation, the Montana system main unit was warmed up for about 45 minutes. The research assistant entered data into the Montana system regarding vehicle characteristics and fuel type.

Data collection involved continuously recording, on a second-by-second basis, exhaust gas concentration, engine, and GPS data. The research assistant followed the test vehicle in a car and periodically checked on the status of the PEMS during a break in work activity, in order to determine quickly if any problems arose during data collection that could be corrected. For example, sometimes there can be a loss of signal that can be corrected by checking connections in a cable. Sometimes the gas analyzers "freeze" (they fail to continuously update) which can be corrected by rebooting the gas analyzer. However, these problems did not occur during the testing.

Decommissioning occurs after the end of the test period. During decommissioning, the research assistant discontinued data collection, copied data that have been collected, powered down the Montana system, and removed the exhaust sample lines, power cable, data cable, and GPS receiver and cable.

2.2 Data Quality Assurance

For quality assurance purposes, the combined data set for a vehicle run is screened to check for errors or possible problems. If errors are identified, they are either corrected or the data set is not used for data analysis. Detailed procedure of quality assurance is given in Appendix A.

The predominant types of errors or problems are following: (1) engine data error; (2) gas analyzer error; (3) zeroing procedure; (4) negative emission values; and (5) loss of power to instrument.

2.3 Emission Rates Calculation

For light duty gasoline vehicles, the engine pipe modification is usually needed to use a sensor array because most light-duty vehicles do not have exiting MAP port. Thus, usually OBD data logger with a laptop computer is used separately with PEMS. After getting engine data from OBD data logger, the engine data including MAP, IAT, and RPM is need to be synchronized to tailpipe emission concentrations from PEMS and recalculate fuel use and emission rates. Therefore, the recalculation procedure is developed based on the chemical mass balance. The major component is explained below.

Intake air molar flow rate (M_a) is estimated based on the engine data, including engine speed, intake air temperature, intake manifold air pressure, engine displacement, compression ratio, and engine volumetric efficiency. Thus, the intake air molar flow rate is calculated as (Vojtisek-Lom and Allsop, 2001):

$$M_a = \frac{\left(P_M - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES}{30 \times EC}\right) \times \eta_{ev}}{R \times \left(T_{int} + 273.15\right)} \qquad (2\text{-}1)$$

Where,

ER = engine compression ratio (typically 18 for heavy duty diesel engine)

ES = engine speed (RPM)

EC = engine stroke cycle (i.e. 2 or 4)

EV = engine volume (liters)

M_a = intake air molar flow rate (mole/sec) assumed to be a mixture of 21 vol-% O2 and 79 vol-% N2

P_M = manifold absolute pressure (kPa)

P_B = barometric pressure (typically 101kPa)

R = ideal gas constant (8.314 kPa-l/mol-k)

T_{int} = intake air temperature (◦C)

η_{ev} = engine volumetric efficiency (typically 0.95)

Exhaust molar flow rate on a dry basis (Me) is estimated based on the intake air molar flow rate (Ma). The equation 2-2 is derived from mass balance. Details for mass balance is reported by Frey *et al*. (Frey *et al.*, 2008a).

$$M_{e,t} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2+\frac{x}{2}-z\right) y_{CO2,t,dry} + \left(1+\frac{x}{2}-z\right) y_{CO,t,dry} + 2y_{O2,t,dry} + y_{NO,t,dry} + \left(3x-7-6z\right) y_{C6H14,t,dry}}$$

(2-2)

Where,

$M_{e,t}$ = dry exhaust molar flow rate (mole/sec) for time t

$y_{i,t,dry}$ = mole fraction of species i on dry basis (gmol/gmol dry exhaust gases) for time t

x, z = elemental composition of hydrogen and oxygen in fuel CHxOz

x = gram mole of hydrogen per gram mole of carbon in fuel CHxOz

y = gram mole of oxygen per gram mole of carbon in fuel CHxOz

Fuel molar flow rate (M_f) is calculated based on the dry exhaust flow rate (M_e) from equitation 2-2.

$$M_{f,t} = (y_{CO2,t,dry} + y_{CO,t,dry} + 6 \times y_{C6H14,t,dry}) \times M_{e,t} \times MW_{fuel} \qquad (2\text{-}3)$$

Where,

$M_{f,t}$ = molar flow rate of the fuel (mole/sec) for time t

MW_{fuel} = molecular weight of fuel

Molecular weights for exhaust gas are needed to evaluate the emission rates as the units of g/sec.

$$MW_{exh} = y_{CO2,t,dry} \times \frac{44\,g}{mole} + (1 - y_{CO2,t,dry}) \times \frac{28\,g}{mole} \qquad (2\text{-}4)$$

Where,

MW_{exh} = molecular weight for dry exhaust gas (g/mol)

The mass emissions rates (g/sec) based upon the mole fraction on a dry basis, dry exhaust molar flow rate, and molar weight of exhaust gas are estimated by the following equation:

$$E_{i,t} = y_{i,t,dry} \times M_{e,t} \times MW_i \tag{2-5}$$

Where,

$E_{i,t}$ = mass emission rate of pollutant i (g/sec)

i = NO, HC, CO, and CO_2

$M_{e,t}$ = exhaust molar flow rate (mole/sec) on a dry basis for time t

MW_i = molecular weight of pollutant species i (g/mol)

2.4 Modal Emission Model

In order to estimate emission rates based on real-world driving cycle, several researchers have developed the modal emissions models. In this study, four different modal models are used based on vehicle specific power, engine load, throttle notch position, and speed-acceleration matrices (Frey *et al.*, 2002b).

For second-by-second data, typically, there is the relationship between members of a time series of observations such as second-by-second emission concentration. To reduce the influence of autocorrelation in vehicle activity and exhaust emissions, a summarization technique in which emission rates are binned into predefined intervals is used.

2.4.1 Vehicle Specific Power (VSP)

Vehicle specific power (VSP) is function of vehicle speed, acceleration, and road grade. The terms in the VSP equation account for vehicle movement, acceleration due to gravity, rolling resistance, and aerodynamic drag (Jimenez-Palacios, 1999). VSP is used usually to estimate onroad vehicle emissions.

Vehicles have typical values of these coefficients for each vehicle type (Jimenez-Palacios, 1999; Nam, 2003; Zhai *et al.*, 2008). VSP is calculated using the following equation (Frey *et al.*, 2002b).

$$VSP = v \times (a + g \times \sin(\varphi) + \psi) + \zeta \times v^3 \tag{2-6}$$

Where,

VSP	=	vehicle specific power (kW/ton)
v	=	vehicle speed (m/s)
a	=	vehicle acceleration (m/s^2)
g	=	gravitational acceleration (9.81 m/s^2)
φ	=	road grade (dimensionless)
ψ	=	rolling resistance term coefficient

ζ = drag term coefficient

To calculate VSP, the speed profile is typically measured based on electronic control unit (ECU) data obtained using on-board diagnostics II (OBD-II) data logger. The elevation could be measured by GPS or altimeter to estimate road grade. In this study, barometric pressure altimeter was used. Based on second-by-second elevation data, the road grade is calculated for every 0.1 mile segment.

When ECU data is not available, the vehicle speed can be calculated based on GPS coordinate data. The equation for speed calculation with GPS coordinates is given in equation 2-7. The length of one degree for latitude is approximately 110,955 meter. The length of one degree for longitude is 111,319 meter at equator. The length of one degree for longitude decreases as latitude increases. Thus, cosine function was used to calculate exact length of one degree of longitude.

$$S\ (m/sec) = \sqrt{\{(Lat_i - Lat_{i-1}) \times 110{,}955\}^2 + \{(Lon_i - Lon_{i-1}) \times 111{,}319 \times COS(Lat_i)\}^2} \qquad (2\text{-}7)$$

Where,

S = vehicle speed (m/sec)

Lat_i = latitude at time i (degree)

Lon_i = longitude at time i (degree)

However, if speed data for ECU is available, ECU data is preferred rather than speed for GPS. GPS speed data is accurate but imprecise, especially for stationary position. It affects an error for acceleration estimation.

2.4.2 MAP-based Modal Model

The MAP-based modal model analysis can explain the fuel use and emission rate relative to engine load because MAP is a surrogate indicator of engine load. MAP-based modal model is used to estimate fuel use and emission rates for onroad and nonroad vehicles (Frey and Kim, 2006; Frey *et al.*, 2008b).

The engine-based modal rates are estimated with respect to normalized MAP. Normalized MAP is calculated on a second-by-second basis based on the minimum and maximum values of MAP observed during the test, and divided into 10 ranges. These ranges are referred to as modes. An average fuel use or emission rates were estimate for each MAP mode. The ranges of MAP are approximately from 101 to 250 kPa. MAP is measured by the sensor array used with the Montana system. MAP takes into account all factors that cause load on the engine, such as vehicle speed, acceleration, and road grade. Normalized MAP is defined as:

$$MAP_i^o = \frac{MAP_i - MAP_{min}}{MAP_{max} - MAP_{min}} \qquad (2\text{-}8)$$

Where,

MAP_i^o = normalized MAP for one second of specific dataset

MAP_i = measured MAP for one second of specific dataset

MAP_{max} = maximum observed MAP for specific dataset

MAP_{min} = minimum observed MAP for specific dataset.

Average modal emission rates were estimated for each MAP mode. This modal model can be used to estimate emission rate for different trip based on MAP distribution.

$$ER_{i,j} = \sum_{m=1}^{10} ER_i^m \times F_j^m \qquad (2\text{-}9)$$

Where,

$ER_{i,j}$ = fuel use and emission rates (g/s) for species i for driving cycle j

ER_i^m = average fuel use and emission rates (g/s) of MAP mode m for VT365 engine for species i

F_j^m = fraction of time spent in MAP mode m for driving cycle m,

i = species for pollutants and fuel use

m = MAP mode

2.4.3 Notch Position Modal Model

Notch position modal model is used to estimate locomotive emissions. The engine load for a locomotive is controlled by a throttle that has predetermined "notch" settings. The steady-state emission factors for each notch setting are weighted to arrive at an average emission rate for a duty cycle. EPA developed locomotive emissions standards based on the notch emission factors weighted by two typical duty cycles: line-haul and switching. The passenger duty cycle is not used in regulation. Since line-haul and passenger duty cycles are similar each other, EPA believes that it is not necessary to use passenger duty cycle (EPA, 1998). EPA duty cycles for locomotive are shown in Table 2-1.

2.4.4 Speed-Acceleration Modal Model

Speed-Acceleration modal model is developed to estimate fuel use and emission rate typically for onroad vehicles. Vehicle emissions are sensitive to vehicle speed and acceleration (Frey *et al.*, 2008c; Frey *et al.*, 2002a). Since speed-acceleration modes can be used to represent a wide variety of driving cycles, engine load is estimated based on vehicle speed and acceleration (Coelho *et al.*, 2009; Yoon *et al.*, 2005).

This methodology is somewhat different from, but conceptually similar to, that used in EPA's recently released Draft MOVES 2009 model (EPA, 2009). The MOVES model uses a modal approach based on vehicle specific power, which is a function of speed, acceleration, and road grade. A speed-acceleration matrix approach can account for road grade effects by adding a correction to the acceleration estimate (Frey *et al.*, 2002a).

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Table 2-1. EPA Duty Cycles for the Locomotives (EPA, 1998)

Throttle Notch	Percent of Time in Notch		
	Line-haul	Switch	Passenger
Idle	38.0	59.8	47.4
Dynamic Brake	12.5	0	6.2
1	6.5	12.4	7.0
2	6.5	12.3	5.1
3	5.2	5.8	5.7
4	4.4	3.6	4.7
5	3.8	3.6	4.0
6	3.9	1.5	2.9
7	3.0	0.2	1.4
8	16.2	0.8	15.6

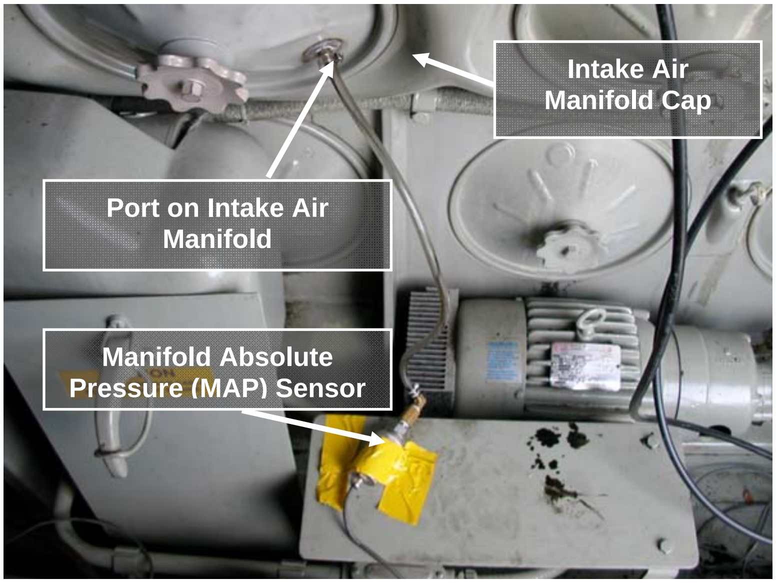

Figure 2-1. Placement of the Manifold Absolute Pressure Sensor on the EMD 12-710G3 Engine of the F59 Locomotive (NC1755)

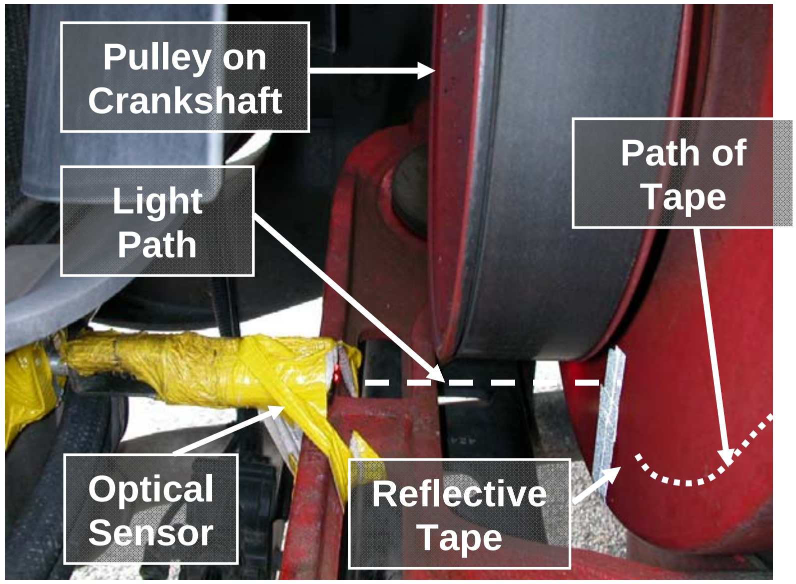

Figure 2-2. Example Photo of Placement of Optical Engine RPM Sensor and Reflective Tape (Cummins ISX-500 Engine).

PART III ESTIMATING LIGHT DUTY GASOLINE VEHICLE EMISSION FACTORS AT HIGH TRANSIENT AND CONSTANT SPEEDS FOR SHORT ROAD SEGMENTS[†]

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ABSTRACT

Vehicle emissions estimates are needed at high spatial and temporal resolution to estimate near-roadway air quality and human exposures. The MOBILE6 emission factor model is based on test cycles with transient speeds and durations on the order of 10 minutes. MOBILE6 does not report emission factors for average speeds greater than 65 mph. However, for near roadway studies, the focus may be on short segments of highway that represent only a few seconds of vehicle travel time at speeds higher than 65 mph. Two types of correction factors are developed based on vehicle-specific power (VSP)-based modal models for light duty gasoline vehicles, using second-by-second data obtained from portable emission measurement systems (PEMS). The high speed correction factor is the ratio of an emission factor at an average speed greater than 65 mph to that at 65 mph. For example, at 80 mph, the high speed correction factors are 1.32, 1.18, 1.77, and 1.1 for NO_x, HC, CO, and CO_2, respectively. To adjust to a constant speed, the VSP modal model was used to compare emission rates at constant speed versus those for transient cycles with an equivalent average speed. For example, the ratio of constant to average of transient speed emission rates range from 0.49 to 0.94 for NO_x at speeds of 20 mph and 80 mph, respectively. In addition, high speed corrections were developed for evaporative running losses. The high speed and constant speed correction factors were applied to estimate vehicle emissions for a freeway segment that included vehicle cruising speeds between 65 and 80 mph. The sensitivity of emission estimates to these correction factors is evaluated.

3.1 Introduction

Highway vehicles contribute nationally 35% of nitrogen oxides (NO_x), 55% of carbon monoxide (CO), and 27% of hydrocarbons (HC) (Environmental Protection Agency, 2008). The emissions contributions are typically larger in urban areas than for the national average. Approximately 12% of households in the U.S. are located within 100 meters of a four-or-more lane roadway (Census Bureau, 2008; Brugge *et al*., 2007). Recently, there is interest in improving the quantification of human exposure to air pollutants near roadways (Environmental Protection Agency, 2009a). Vehicle emissions are needed at high spatial and temporal resolution to estimate near-roadway air quality and human exposures. An exposure scenario of concern is a school or residential area located near a high traffic volume highway.

Since such exposures are associated with relatively short air pollutant transport distance, there is a need to characterize emissions and air quality for relatively short segments of highway, such as approximately 1,000 feet. Depending on the time of day, travel direction, and traffic volume, vehicle speeds on such segments can be well in excess of posted speed limits. Furthermore, such segments of roadway represent only a few seconds of vehicle travel, during which vehicles may be traveling at approximately constant speed, depending on traffic conditions. In contrast, existing emission factor tools, such as the MOBILE6 emission factor model, are based on test cycles with transient speeds and durations on the order of 10 minutes.

MOBILE6 does not report emission factors for average speeds greater than 65 mph. Therefore, there is a need to develop an emission factor estimation methodology for speeds higher than 65 mph and for constant, rather than transient, speed (Giannelli *et al*., 2002). Thus, the objective of this paper is to develop such a methodology and demonstrate its use.

3.2 Methodology

To estimate emission factors based on MOBILE6 at speeds greater than 65 mph on the short segment of highway, two types of correction factors are developed based on vehicle-specific power (VSP)-based modal models for light duty gasoline vehicles, using second-by-second data obtained from portable emission measurement systems (PEMS) (Frey *et al*., 2002). PEMS are designed to measure real-world emissions under actual traffic conditions. PEMS data are used increasingly for development of emission models, such as EPA's draft 2009 Motor Vehicle Emission Simulator (MOVES) (Frey *et al*., 2002; Younglove *et al*., 2005; Environmental Protection Agency, 2009b).

To estimate the two types of correction factors, emission factors for eight driving cycles that have different average speeds were calculated using the VSP modal models. The high speed correction factor is the ratio of an emission factor at an average speed greater than 65 mph to that at 65 mph. The constant speed correction factor is to adjust cycle based emission factors to a constant speed emission factors. The VSP modal model was used to compare emission rates at constant speed versus those for transient cycles with an equivalent average speed.

3.2.1 VSP-based Modal Emission Rates

In previous work, variability in fuel use and emission rates for an individual vehicle was found to be highly correlated with VSP (Nam, 2003). VSP is estimated based on speed, acceleration, and road grade:

$$\mathrm{VSP} = 0.278\, v \left[0.305a + 9.81 \sin\left(\operatorname{atan}\left(\frac{r}{100} \right) \right) + 0.132 \right] + 0.0000065 v^3 \qquad (3\text{-}1)$$

Where,

v	=	Vehicle speed (km/hr)
a	=	Acceleration (km/hr per sec)
r	=	Road grade (%)
VSP	=	Vehicle-specific power (kW/ton)

The terms in the equation account for vehicle movement, acceleration due to gravity, rolling resistance, and aerodynamic drag and are estimated for a typical light duty vehicle (Nam, 2003).

A methodology for estimating vehicle fuel use and emissions using VSP-based modes has previously been developed and applied (Frey *et al.*, 2002). The definition of the VSP mode cut-points is given in Table 3-1. Modal fuel use and emission rate models are available for four groups of vehicles, including engine sizes less than 3.5 liters and greater than 3.5 liters, and mileage accumulation less than 50,000 miles and greater than 50,000 miles. As an example, VSP modal emission rates for NO, HC, CO, and CO_2 for vehicles with engine sizes less than 3.5 liters and mileage accumulation less than 50,000 miles are shown in Figure 3-1. The VSP-based modal emission rates can be weighted by the fraction of time spent in each VSP mode for a particular driving cycle in order to estimate an average driving cycle emission factor.

3.2.2 Driving Cycles

In order to estimate the trend in average driving cycle emission factor as a function of speed, eight driving cycles were identified and analyzed.

For purposes of assessing the trend in emission factors versus average cycle speed, four EPA driving cycles developed for MOBILE6 model were selected. These four cycles include LOS E, LOS D, LOS A-C, and High-Speed, with average speeds of 31, 53, 60, and 63 mph, respectively (Beardsley, 2001; Environmental Protection Agency, 2003).

In order to estimate average emission factors for higher speeds, four additional cycles were selected based on results of real-world emission measurements conducted using PEMS in the Research Triangle Park area (Frey *et al*., 2008). These cycles are labeled as R40, R66, R70, and R78, with average speeds of 40, 66, 70, and 78 mph, respectively. All four of these cycles were measured on interstate highways under varying levels of traffic congestion. One of these cycles overlaps with the speed range of the MOBILE6 cycles, to enable evaluation of the consistency of the trend in average emission factor versus average speed within the range of speeds represented by MOBILE6. The other three cycles enable estimation of average emission rates at speeds higher than those included in MOBILE6. Table 3-2 provides a description of the EPA facility-specific driving cycles and real world driving cycles.

Time distributions among the VSP modes for the LOS E, High Speed, R70, and R78 driving cycles are shown in Figure 3-2. The most frequent modes for each cycle differ because of driving patterns. For example, Modes 1 and 4 are the most frequently occurring for the LOS E cycle, which has an average cycle speed of 31 mph. For the High-Speed cycle, Modes 5 to 7 are the most frequent modes. Since R70 and R78 are highway cycles with high average speeds, these driving cycles include a higher frequency of moderate to high VSP modes, such as Modes 7, 8, and 9.

3.2.3 High Speed Correction Factor for Exhaust Emissions

Using the VSP modal model for each of the four vehicle technology groups described earlier, average driving cycle emission rates were calculated for each of the eight selected driving cycles. Trends in average emission factors versus average cycle speeds were characterized for speed ranges of less than 65 mph, comparable to those from MOBILE6 and for 66 to 78 mph, based on real world cycles. The trend in average emission rate versus average speed was quantified by fitting a regression model, thereby enabling estimation of average cycle emission rates for speeds as high as 78 mph. These trends are normalized to the emission factor estimated at an average cycle speed of 63 mph, corresponding to the High-Speed cycle used in MOBILE6:

$$R^{63}_{1,s,j} = \frac{EF_{s,j}}{EF_{63,j}} \tag{3-2}$$

Where,

$R^{63}_{1,s,j}$ = Ratio of cycle average emission factor at speed s (mph) to average emission factor of the High-Speed driving cycle for species j

$EF_{s,j}$ = Emission factor (g/mile) of species j at cycle average speed s (mph) based on VSP modal model

$EF_{63,j}$ = Emission factor (g/mile) of species j at average speed of 63 mph, which corresponds to the High-Speed driving cycle, based on VSP modal model

Subscripts:

s = vehicle speed (mph)

j = pollutant species: NO_x, HC, CO, and CO_2

The high speed correction factor is estimated relative to a datum for a MOBILE6 driving cycle. Although MOBILE6 produces different emission factors for speeds up to 65 mph, the highest average speed among the driving cycles used to develop the model is 63 mph. Therefore, the high speed correction factor is developed by reference to an average speed of 63 mph. As a first step in developing the speed correction, a regression model was fit to describe variations in the emission factor versus average speed using 63 mph as a datum.

The final correction factor was estimated using 65 mph, rather than 63 mph, as a reference point:

$$R_{1,s,j} = \frac{R^{63}_{1,s,j}}{R^{63}_{1,65,j}} = \frac{\left(EF_{s,j}/EF_{63,j}\right)}{\left(EF_{65,j}/EF_{63,j}\right)} = \frac{\left(EF_{s,j}\right)}{\left(EF_{65,j}\right)} \tag{3-3}$$

Where,

$R^{63}_{1,s,j}$ = high speed correction factor to average emission of 63 mph which corresponds to the High-Speed cycle at speed s for species j

$R_{1,s,j}$ = high speed correction factor to average emission factor of 65 mph at speed s for species j

3.2.4 High Speed Correction Factor for Non-Exhaust HC Emission

Non-exhaust HC emissions include running and crankcase losses. Running losses are associated with heating of fuel and fuel lines, and are estimated in MOBILE6 as proportional to the time duration, not distance, of vehicle travel (Environmental Protection Agency, 2003). Therefore, running loss emission factors on a per distance basis decrease as speed increases, assuming a constant time-based rate of loss. Crankcase losses in MOBILE6 are modeled as a constant mass regardless of time or distance. The emission factor trends for exhaust and non-exhaust HC are shown in Figure 3-3.

3.2.5 Constant Speed Correction Factor

When vehicles operate at very high speeds on short segments of interstates highway, it is hypothesized that they tend to operate at approximately constant speed. A comparison of the real-world link-based driving cycles at high average speed, such as 70 and 78 mph, to those at lower average speed is consistent with this hypothesis, in that there is less variation in second-by-second speed as average speed increases. Since near-roadway air quality studies might be conducted in areas influenced by segments of roadway of only 1,000 feet or less, an assumption of approximately constant vehicle speed may be reasonable.

However, neither MOBILE6 nor the real-world driving cycles represent constant speed for such a short segment of highway. Therefore, a correction factor was developed comparing vehicle operation at a constant speed to vehicle operation at an equivalent average speed for a time-varying driving cycle. As average speed increases, we expect this ratio to approach unity. The vehicle emission rate at constant speed is estimated based on assuming zero acceleration and zero road grade, calculation of VSP, and use of the corresponding VSP modal average emission rate. The constant speed correction factor (R_2) is the ratio of an emission factor at constant speed to an average emission factor for a driving cycle with an average speed equal to the constant speed.

$$R_{2,s,j} = \frac{EF_{s,j}}{\sum_{m=1}^{14} EF_{m,j} \times F_m^s} \quad (3\text{-}4)$$

Where,

$R_{2,s,j}$ = Ratio for emission factor (g/mile) of species j at constant speed s to cycle average emission factor for average speed s

$EF_{s,j}$ = Emission factor (g/mile) of species j based on VSP modal model at constant speed s (mph) and zero acceleration

$EF_{m,j}$ = Emission factor (g/mile) of species j and VSP mode m

F_m^s = Fraction of time spent in VSP mode m on a driving cycle with average speed s (mph)

Subscripts:

m = VSP mode

3.3 Results and Discussion

Results are given here for the high speed correction factor, constant speed correction factor, and a case study of how the two factors are used together to estimate emission factors at high constant speed, such as to support near roadway air quality studies.

3.3.1 High Speed Correction Factor

The ratio of driving cycle average emission rates for each of the eight selected cycles versus the average emission rate of the High-Speed cycle is shown in Figure 3-4 for NO_x, exhaust HC, CO, and CO_2. These ratios are estimated using the VSP-based modal emission models, averaged over four vehicle technology groups. By definition, the ratio is one at an average speed of 63 mph. For speeds less than 65 mph, the results are compared with trends in MOBILE6 emission factors and generally are consistent. For example, the MOBILE6 emission factors for NO_x are relatively insensitive to speed for speeds from 30 to 65 mph, exhaust HC emission factors tend to be higher at 30 mph than at 65 mph, and CO emission factors tend to be significantly lower at lower average speed. Of the three real-world cycles, the R66 cycle tends to have similar emission rates as the High-Speed cycle. However, the R70 and R78 cycles have larger average emission rates than the High-Speed or R66 cycles. Since the goal here is to develop a model for high speeds, a trend line was fit to the emission ratios using the High-Speed cycle as a datum and inclusive of the R70 and R78 cycle results.

As an example, for an average speed of 78 mph compared to 63 mph, the average emission rate is approximately 32 percent higher for NO_x, 38 percent higher for exhaust HC, 84 percent higher for CO, and 10 percent higher for CO_2.

The large increase in CO is associated with increased frequency and duration of "open-loop" or "fuel enrichment" events, in which the air-to-fuel ratio is changed from stoichiometric to fuel-rich in order to provide additional power and to avoid overheating the catalytic converter. Enrichment leads to high levels of exhaust pollutants, especially for CO and HC, since insufficient oxygen is available to oxidize these pollutants in the catalytic converter.

The engine-out emissions of NO_x tend to be higher as engine RPM, fuel flow, or both increase, particularly if there is an increase in peak temperatures or heat release rate during combustion.

Since typically over 99 percent of carbon in fuel is converted to CO_2, the results for CO_2 emission rates imply that optimal fuel economy is obtained at average speeds of approximately 50 to 60 mph, with degradation of fuel economy at very high speed. These results are consistent with EPA's fuel economy guide, which reports maximum fuel economy at speeds between 55 and 60 mph (Environmental Protection Agency, 2009c).

Overall, the trends in the ratio of emission factors at high speeds are qualitatively consistent with expectations, theory, or experience. The CO emission rate is the most sensitive to high speed, as expected, since CO emissions are very sensitive to fuel enrichment.

The results imply that the emission rates at high average speeds are substantially different from those at speeds of less than 65 mph both in terms of magnitude and in terms of trend. For example, while NO_x emissions are shown to be relatively insensitive to variations in average speed between 30 and 60 mph, they are found to be highly sensitive to average speeds greater than 63 mph.

Because HC running loss is modeled in MOBILE6 as a constant rate with respect to time, the rate of running loss on a per mile basis will decrease as average speed increases:

$$R_{1,s,run} = 134.1 \times \frac{1}{s} - 1.064, \quad R^2=1 \tag{3-5}$$

Where, $R_{1,s,run}$ is a ratio of running loss at speed s mph to running loss at 65 mph.

Since the HC crankcase loss is assumed in MOBILE6 to be constant irrespective of distance, time, or speed, the high speed correction factor for crankcase loss is equal to one at all speeds.

3.3.2 Constant Speed Correction Factor

The results for the constant speed correction factor (R_2) are shown in Figure 3-5. In general, as average speed increases, there is less fluctuation in speed on a second-by-second basis. In order to have very high average speed, such as 78 mph, a vehicle must consistently be traveling at speeds close to this average. However, for a vehicle traveling at 30 mph on an interstate highway, speeds could vary from stop to approximately free flow speed, depending on traffic conditions. Thus, as expected, R_2 tends to increase with average speed except for CO, as explained below. Although there appear to be some differences in the scatter of the data for the EPA driving cycles versus those of the real-world cycles, the overall results are not sensitive to these apparent differences. For example, for the NO_x, HC, and CO_2 correction factors, the trend is for an increase in R_2 versus speed regardless of which set of cycles is used. For CO, both sets of driving cycle data imply that R_2 is approximately constant regardless of speed.

For CO_2, R_2 reaches a value of approximately 1 at speeds of 60 to 80 mph. This implies that at such speeds, there is little difference in CO_2 emission rate, and fuel economy, between driving at constant speed versus driving with typically small fluctuations in speed that are characteristic of these average speeds. However, at lower speeds, such as for 30 to 53 mph, R_2 is approximately 0.8 to 0.9, indicating that there are benefits to maintaining a constant speed rather than having fluctuations in speed.

For NO_x and HC, the results are qualitatively similar. In both cases, R_2 increases with average speed. Furthermore, R_2 may be asymptotically approaching a value of 1. There are significant emission penalties at low speeds for the fluctuations associated with typical driving cycles compared to constant speed. For example, the NO_x emission rate at a constant speed of 30 mph is more than 40 percent less than the emission rate for a driving cycle with speed variations that has an average speed of 30 mph. For HC, at 30 mph, the emissions are approximately 35 percent lower. At approximately 70 to 78 mph, the NO_x emission rates at constant speed are similar to those from speed-varying driving cycles with the same average speed. However, for HC, there is still a 10 to 20 percent reduction in average emission rate for constant versus varying speed at this range of high speeds. Since non-exhaust HC emissions are caused by heating of the fuel and fuel line and are assumed to occur at a constant rate, these emissions are not estimated to be correlated to vehicle acceleration.

The results for R_2 for CO are unique compared to the other three pollutants. The value of R_2 is relatively insensitive to speed, although it increases slightly as speed increases. The CO emissions at constant speed are approximately 40 to 50 percent lower than for transient cycles with the same average speed. We hypothesize that these results are based on episodes of fuel enrichment that can occur at high engine power demand under a wide variety of conditions. For example, high engine power demand can occur if a vehicle accelerates from low to high speed. However, high engine power demand can also occur if a vehicle cruising at high speed accelerates to an even higher speed in order to pass another vehicle. Short term episodes of high CO emissions can dominate the cycle or link average emissions. In contrast, driving at a constant speed would typically eliminate many enrichment events, with the exception of changes in engine demand associated with climbing a changing grade under constant speed.

3.3.3 Case Study with High Speed and Constant Speed Correction Factors

The application of the correction factors for high speed and constant speed are illustrated based on an example case study. The case study is based on ambient conditions of 75 °F, 50% relative humidity, and 30 inches Hg barometric pressure. The results of the case study are shown in Figure 3-6 for vehicle speeds varying from 40 mph to 80 mph. The base emission rate from MOBILE6 is shown in the figure. MOBILE6 does not predict any change in the emission rate as average speed increases above 65 mph. Therefore, the base emission rates shown for speeds of 70 and 80 mph are the same for each pollutant.

The correction for average speed, R_1, is indicated in Figure 3-6 for each pollutant. For speeds of less than 65 mph, this correction factor is not needed because MOBILE6 is sensitive to average speeds in this range. Thus, R_1 is equal to 1 for speeds of 40, 50, and 60 mph. For speeds of 70 and 80 mph, R_1 generally is greater than 1 for each pollutant. R_1 is the most sensitive to higher speed for CO. For example, R_1 for CO is approximately 1.8 at 80 mph. R_1 is the least sensitive for CO_2, which is also highly correlated with the rate of fuel consumption.

The values of R_2 are shown for all speeds and illustrate the ratio of the average emission rate at constant speed versus the average emission rate for transient speeds typically of driving cycles with the same average speed. Except for CO, R_2 is typically the smallest at the lowest average speed shown at 40 mph, and approaches a value of 1 as speed increases to 80 mph. For CO, driving at constant speed would eliminate episodes of fuel enrichment that produce very high emissions; thus, R_2 is less sensitive to average speed than for other pollutants, and generally remains approximately constant.

The combined effect of the base emission rate, R_1, and R_2 is shown in the corrected emission factor. The corrected emission factor represents an estimate of the emission rate at constant speed for the indicated speed. The effect of R_2 on the corrected emission factor is significant for speeds of 40 to 60 mph. At 70 mph, the two correction factors almost compensate for each other. However, at 80 mph, the high speed correction factor has a more significant effect on the corrected emission factor than the constant speed correction factor.

For total HC including exhaust and non-exhaust emission, the constant speed correction is the dominant influence on the corrected emission factor for speeds of 40 to 70 mph. At 80 mph, the two correction factors almost compensate for each other.

For CO, the constant speed correction factor is the dominant influence on the corrected emission factor for speeds of 40 to 70 mph. At 80 mph, the two correction factors approximately compensate for each other.

For CO_2 emission rate, which is indicative of fuel consumption, the corrected emission factor is approximately 14 percent lower at 40 mph and 13 percent higher at 80 mph. R_2 is a more significant influence at lower speed, whereas R_1 is a more significant influence at high speed.

At high speed, the emission factors for NO_x are sensitive to the high speed correction factor, whereas for HC and CO the two correction factors tend to compensate to a large extent. As expected, the CO_2 emission factor is estimated to increase at 80 mph compared to lower speeds.

3.4 Conclusions

Emission factors are estimated to be sensitive to increases in average speed from the maximum of 65 mph that is considered in MOBILE6 to real-world link-based speeds as high as 78 mph. CO emission factors are more sensitive to such high speeds compared to the other emission factors. The CO_2 emission rate is a surrogate for fuel consumption since most of carbon is emitted as CO_2 in tailpipe. Thus, low CO_2 emission rates indicate low fuel use rate. The CO_2 emission rate per distance of vehicle travel is lowest at average speed range of approximately 50 to 60 mph. Therefore, optimum fuel economy for light duty gasoline vehicles may be achieved at this speed range.

In general, emission factors for NO_x, HC, and CO_2 are found to be sensitive to the difference between constant versus transient speed for low speeds, with this difference decreasing on a relative basis as speed increases. In contrast, CO emissions are more sensitive to the difference between constant and transient speed at all speeds evaluated here.

NO_x emissions at constant speed are significantly different than for transient operations. For example, at an average speed of 40 mph, constant speed operation can reduce the NO_x emission rate by 36 percent. However, as average speed increases, there is less difference in emission rate for constant versus transient speed operation. For example, at 80 mph, driving at constant speed would reduce emissions by only 6 percent. Taking into account both constant and high speed correction factors, the NO_x emission rate at 80 mph is 113 percent higher than at 40 mph. Hence, the NO_x emission rate is sensitive both to average speed and whether a vehicle is operated at constant or transient speeds.

The CO emission factor is highly sensitive to average speed, and increases by 125 percent when comparing transient driving at 80 mph to 40 mph. However, at all speeds considered from 30 to 80 mph, there were substantial benefits to operating a vehicle at constant rather than transient speeds, leading to reductions in emission rate of approximately 50 percent.

The trend in total HC emissions rates for tailpipe and non-exhaust was weakly sensitive to average speed. For example, for transient operations, the total HC emission rate at 80 mph was 6 percent higher than at 40 mph. At all speeds considered, there was a reduction in total HC emissions associated with operations at constant, rather than transient, speed, ranging from 12 to 23 percent.

When estimating emission rates at high constant speed, such as 80 mph, the key findings are that the NO_x and CO_2 emission rates were most sensitive to the combined effect of the high speed and constant speed correction factors. The corrected emission factors for these two pollutants were 24 and 13 percent higher, respectively, than base emission factors estimated using MOBILE6. For CO and HC, the two correction factors compensate for each other at 80 mph, leading to differences of only 2 percent for both.

At moderate speeds, the emission factors for all four pollutants were sensitive to corrections for constant versus transient speeds. For example, at a constant speed of 40 mph, the estimated emission factors for NO_x, HC, CO, and CO_2 were lower by 36, 23, 49, and 14 percent, respectively, than for transient operations at the same average speed.

The implications of these results is that on-road emissions, and hence near-roadway air quality and exposure, are sensitive to characteristics of vehicle operations that are not accounted for in the MOBILE6 model, including operations at constant speed, high speed, or both. The potential error from not accounting for these operating conditions on short segments of highway can be as large as 49 percent at moderate speed and 24 percent at high speed.

The methodology demonstrated here can be applied to estimate emission factors for real-world link-based situations in which vehicles are driving at constant speed, high average speed, or both. This methodology is applicable to the estimation of emissions on short segments of highway for which vehicles may be driving at approximately constant speed. Such estimates are useful as part of assessment of emissions and air quality in the near vicinity of a roadway. A similar methodology should be developed and demonstrated for diesel vehicles. The methodology demonstrate here can also be applied with the modal emission factors that are the basis of the Draft MOVES 2009 model.

3.5 Acknowledgments

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Table 3-1. Definition of VSP Modes for Light Duty Gasoline Vehicles.

VSP Mode	VSP Range (kW/ton)
1	VSP ≤ -2
2	-2 < VSP < 0
3	0 ≤ VSP < 1
4	1 ≤ VSP < 4
5	4 ≤ VSP < 7
6	7 ≤ VSP < 10
7	10 ≤ VSP < 13
8	13 ≤ VSP < 16
9	16 ≤ VSP < 19
10	19 ≤ VSP < 23
11	23 ≤ VSP < 28
12	28 ≤ VSP < 33
13	33 ≤ VSP < 39
14	39 ≤ VSP

Source: Frey *et al*., 2002.

Table 3-2. Description of Facility-Specific and Real World Driving Cycles.

Driving Cycle	Average Speed (mph)	Maximum Speed (mph)	Maximum Acceleration (mph/s)	Standard Deviation (mph)	Duration (sec)	Length (miles)
Freeway, LOS E	31	63	5.3	15.8	456	3.9
R40	40	50	3.7	5.7	250	2.7
Freeway, LOS D	53	71	2.3	9.9	406	6.0
Freeway, LOS A-C	60	73	3.4	5.9	516	8.6
Freeway, High-Speed	63	74	2.7	4.5	610	10.7
R66	66	70	1.9	1.7	321	5.9
R70	70	74	2.5	2.7	306	5.9
R78	78	83	2.5	2.4	324	7.0

Source: Environmental Protection Agency, 2003; Frey *et al*., 2008.

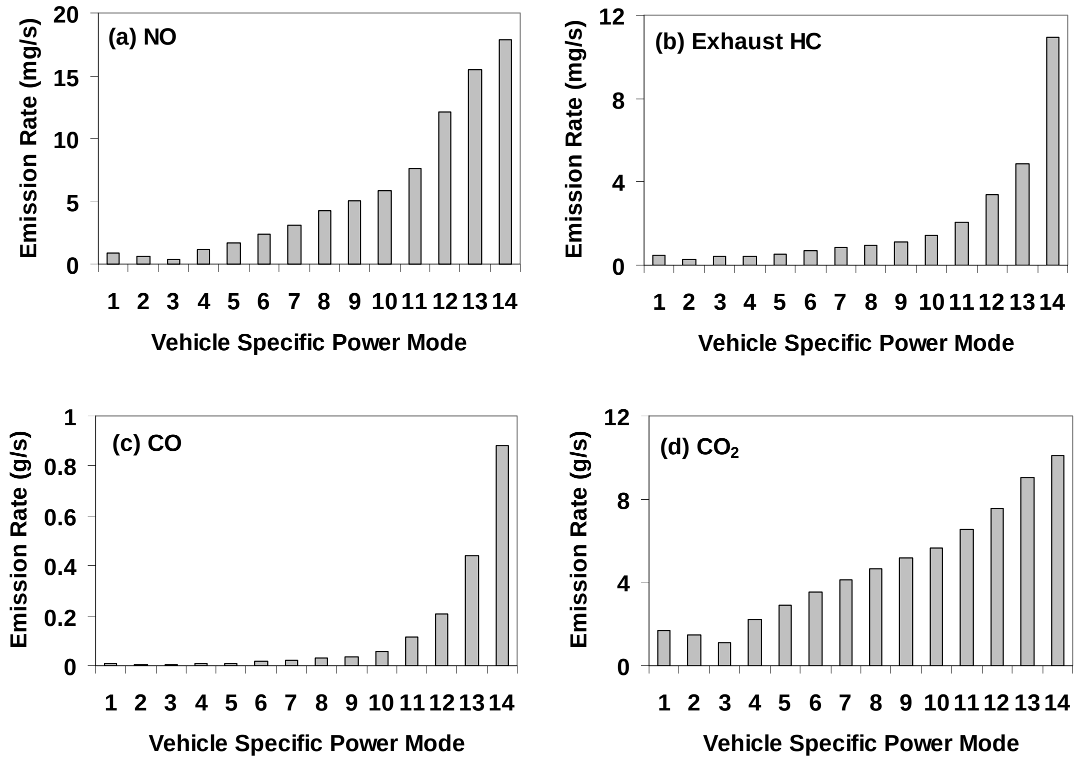

Figure 3-1. VSP Modal Tailpipe Emission Rates for NO, Exhaust HC, CO, and CO_2 for Vehicles with Engine Sizes less than 3.5 Liters and Mileage Accumulation less than 50,000 Miles (Frey et al., 2002).

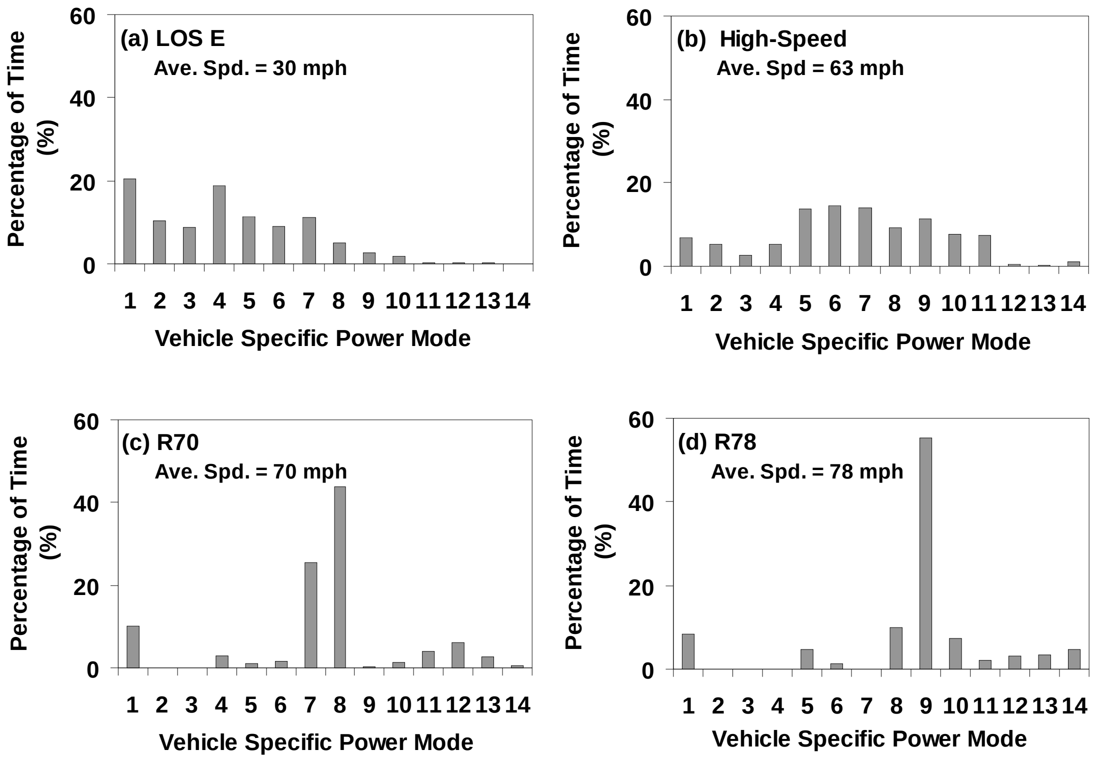

Figure 3-2. Time Distribution of VSP Modes for LOS E, High-Speed, R70, and R78 Cycles.

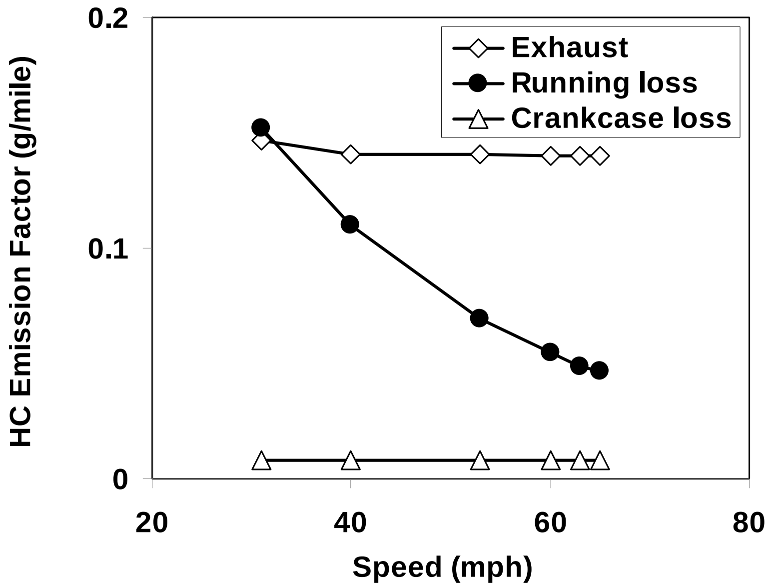

Figure 3-3. HC Emission Factors (g/mile) for Exhaust and Non-exhaust Emissions under Base Case Conditions for Light Duty Gasoline Vehicle. Note: The base case condition is temperature = 81°F, relative humidity = 76%, and barometric pressure = 29.6 inches Hg.

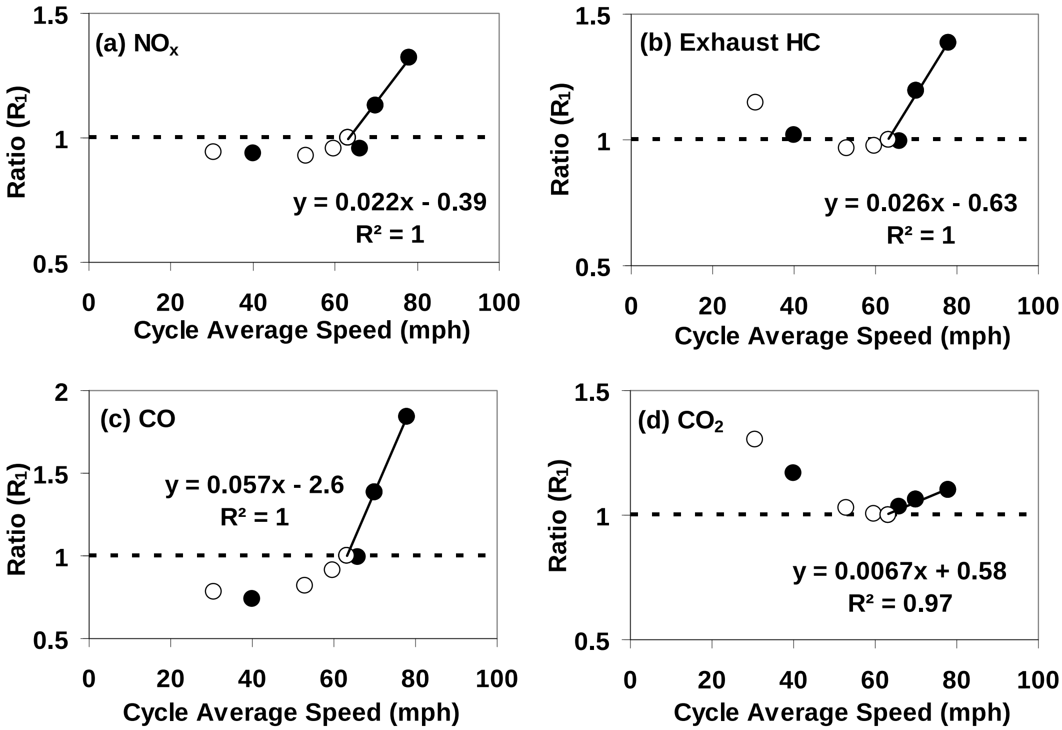

Figure 3-4. High Speed Correction Factors (R_1) based on Ratio of Cycle Emission Factors to High-Speed Cycle Average Emission Factors using VSP-Modal Model for Exhaust Emissions for LDGV. Note: Blank circles are EPA facility-specific cycles and dark circles are real-world cycles.

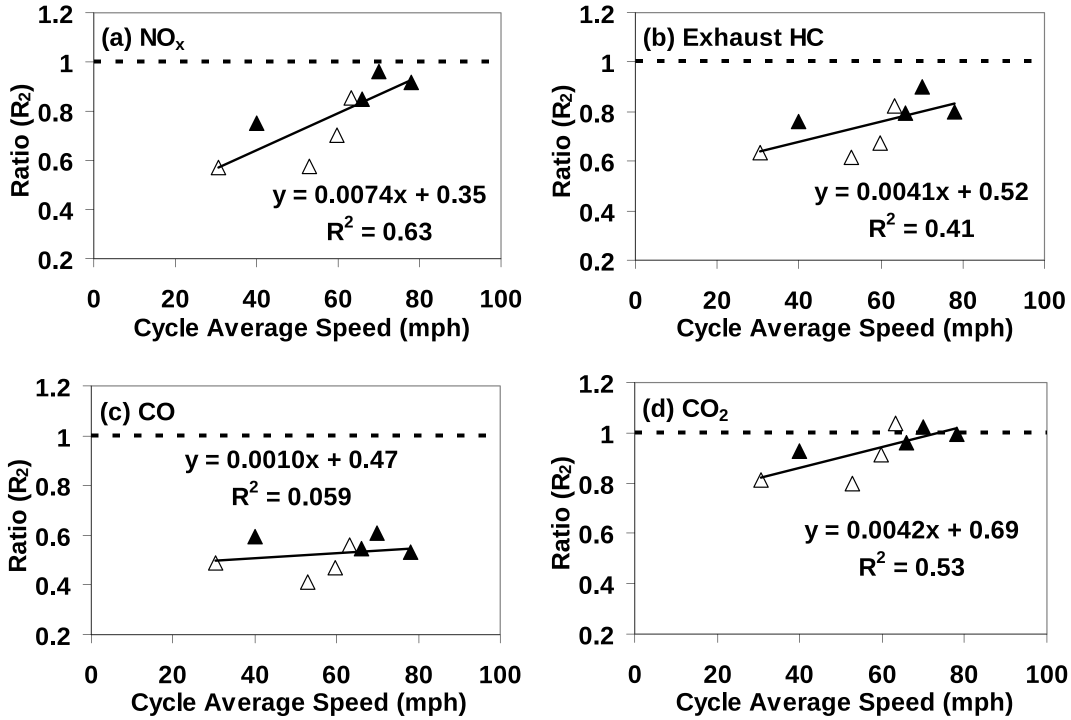

Figure 3-5. Constant Speed Correction Factors (R_2) based on Average Ratio of Constant Speed Emission Factors to Cycle Average Emission Factors for the Same Driving Cycle Speed using VSP-Modal Model for LDGV. Note: Blank triangles are EPA facility-specific cycles and dark triangles are real-world cycles.

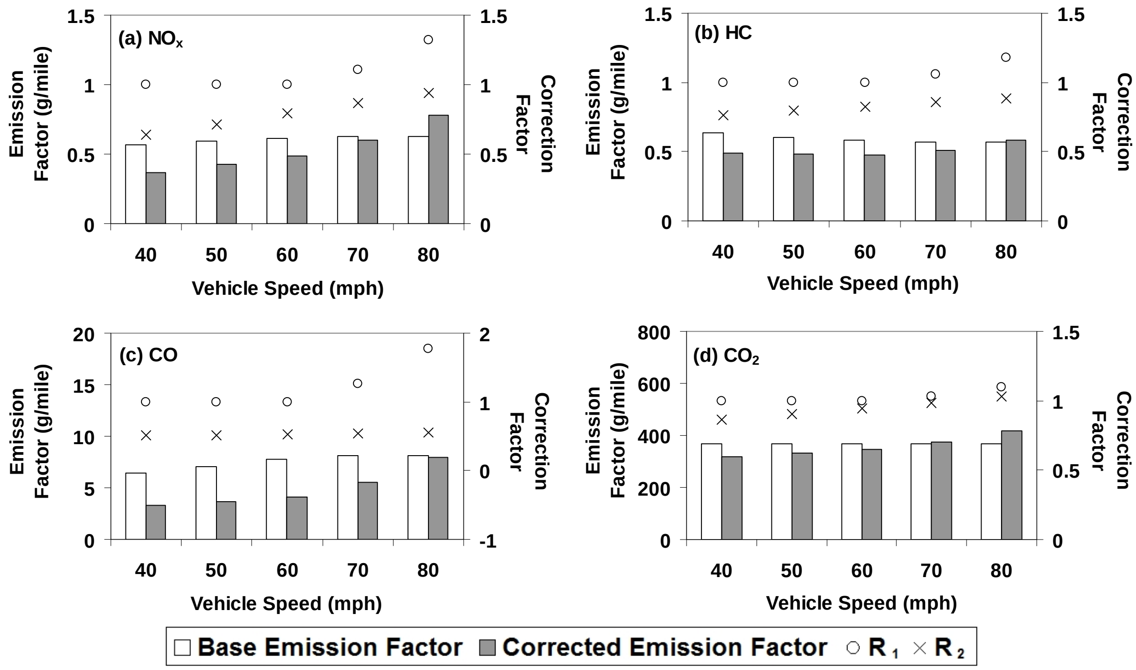

Figure 3-6. Comparison of Base Emission Factors from MOBILE6 versus Corrected Emission Factors based on High Transient and Constant Speed Correction Factors (R_1 and R_2).

PART IV ESTIMATING DIESEL VEHICLE EMISSION FACTORS AT CONSTANT AND HIGH SPEEDS FOR SHORT ROAD SEGMENT[†]

[†] This manuscript was submitted to *Transportation Research Record: Journal of Transportation Research Board*.

ABSTRACT

To estimate near-roadway air quality and human exposure, vehicle emission estimates are needed with high spatial and temporal resolution. The U.S. Environmental Protection Agency (EPA)'s MOBILE6 emission factor model is based on test cycles with transient speeds and durations on the order of 10 minutes. MOBILE6 does not report emission factors for average speeds higher than 65 mph. However, for near-roadway studies, emission factors are needed for short highway segments that represent only a few seconds of vehicle travel time at approximately constant speed and speeds greater than 65 mph. The constant and high speeds correction factors for nitrogen oxides (NO_x), hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO), were developed based on 59,286 seconds of EPA dynamometer emission data for diesel vehicles from which speed-acceleration modal models were derived. The constant speed correction factor is the ratio of emission factor at constant speed versus that for transient cycles with an equivalent average speed. For example, the constant speed correction factor for CO_2 increases from 0.71 to 1 as speed increases from 31 to 78 mph. High speed correction factors are based on the ratio of emission factors at a constant speed greater than 65 mph to that at a constant speed of 65 mph. For example, at 80 mph, the high speed correction factor is approximately 1.5 for CO_2. Sensitivity analysis of emission estimates to these correction factors was conducted for speeds of 40 to 80 mph.

4.1 Introduction

Highway diesel vehicles contribute nationally 16% of nitrogen oxides (NO_x) (EPA, 2005). The emissions contributions are typically larger in urban areas than for the national average. During the 1990s, the sales of heavy duty pickup trucks has increased approximately 38 percent (Davis and Truett, 2003). Approximately 12% of households in the U.S. are located within 100 meters of a four-or-more lane roadway (Brugge *et al.*, 2007; Bureau, 2003). Recently, there is interest in improving the quantification of human exposure to air pollutants near roadways (EPA, 2009b). Vehicle emissions are needed at high spatial and temporal resolution to estimate near-roadway air quality and human exposures. An exposure scenario of concern is a school or residential area located near a high traffic volume highway.

Since such exposures are associated with relatively short air pollutant transport distance, there is a need to characterize emissions and air quality for relatively short segments of highway, such as approximately 1,000 feet. Depending on the time of day, travel direction, and traffic volume, vehicle speeds on such segments can be well in excess of posted speed limits. Furthermore, such segments of roadway represent only a few seconds of vehicle travel, during which vehicles may be traveling at approximately constant speed, depending on traffic conditions. In contrast, existing emission factor tools, such as the MOBILE6 emission factor model, are based on test cycles with transient speeds and durations on the order of 10 minutes.

MOBILE6 does not report emission factors for average speeds greater than 65 mph. Therefore, there is a need to develop an emission factor estimation methodology for speeds higher than 65 mph and for constant, rather than transient, speed (Giannelli *et al.*, 2002). Thus, the objective of this paper is to develop such a methodology and demonstrate its use for diesel vehicles.

4.2 Methodology

To estimate emission factors based on MOBILE6 at speeds greater than 65 mph for short segments of highway, two types of correction factors were developed. These factors were derived based on speed-acceleration-based modal models for heavy duty diesel vehicles, using EPA second-by-second dynamometer emissions data based on several test cycles.

Emission factors for eight driving cycles that have different average speeds were estimated using the speed-acceleration modal models. The constant speed correction factor is based on the ratio of the emission factor of a given pollutant at constant speed to that for an average emission factor of a transient driving cycle with the same average speed. The high speed correction factor is the ratio of an emission factor at an average speed greater than 65 mph to that at 65 mph.

4.2.1 Speed-Acceleration Modal Emission Rates

Vehicle emissions are sensitive to vehicle speed and acceleration (Frey *et al.*, 2008a; Frey *et al.*, 2002). Since speed-acceleration modes can be used to represent a wide variety of driving cycles, engine load is estimated based on vehicle speed and acceleration (Coelho *et al.*, 2009; Yoon *et al.*, 2005).

To estimate constant and high speed correction factors, speed-acceleration modal models for NO_x, HC, CO, and CO_2 were developed based on 59,286 seconds of chassis dynamometer data from the EPA Mobile Source Observation Database (MSOD) for five diesel vehicles (EPA, 2004).

These data were selected for several reasons. Second-by-second data are needed in order to develop a modal emissions model that can be used to estimate emission rates for transient cycles and for constant speed. Chassis dynamometer data are preferred to engine dynamometer data since the chassis dynamometer measurements are associated with specific values of speed and acceleration. However, there are relatively few chassis dynamometer data in the MSOD for which second-by-second data are available. Most dynamometer data are reported only as average over an entire cycle or for "bags" of a cycle. The latter are shorter but continuous portions of a cycle. There are few heavy duty chassis dynamometer second-by-second data. Hence, data from light duty chassis dynamometer were more readily available. The five vehicles selected were the largest that could be tested as a light duty chassis dynamometer. These five vehicles are used as surrogates for highway diesel vehicles. Of the available diesel vehicle second-by-second chassis dynamometer data, the most recent available model years were selected. Furthermore, the selected data are for the same driving cycles that were used to develop the speed correction factors in MOBILE6.

For each selected truck, there are 11,272 to 12,354 seconds of emissions data for several test cycles, including FTP, LA92, US06, ART-CD, FWY-E, FWY-G, FWY-High, and NYCC. Table 4-1 lists the characteristics of the selected vehicles. Since HDDV are defined as being greater than 8,500 pounds in gross vehicle weight (GVW), the selected five vehicles are classified as HDDV (Browning, 2002).

In order to calculate average emission rates for each speed-acceleration mode, 16 speed bins and 5 acceleration bins were created for a total of 80 modes. The speed mode ranged from 0 to 80 mph in 5 mph increments. Acceleration modes are defined as follows:

- High acceleration : acceleration ≥ 2 mph/sec
- Low acceleration : 0.5 mph/sec ≤ acceleration < 2 mph/sec
- Cruise : – 0.5 mph/sec < acceleration < 0.5 mph/sec
- Low deceleration : – 2 < acceleration ≤ – 0.5 mph/sec
- High deceleration : acceleration ≤ – 2 mph/sec

This methodology is somewhat different from, but conceptually similar to, that used in EPA's recently released Draft MOVES 2009 model (EPA, 2009a). The MOVES model uses a modal approach based on vehicle specific power, which is a function of speed, acceleration, and road grade. A speed-acceleration matrix approach can account for road grade effects by adding a correction to the acceleration estimate (Frey *et al.*, 2002).

4.2.2 Driving Cycles

In order to estimate the trend in average driving cycle emission factors as a function of speed, eight driving cycles were identified and analyzed.

For purposes of assessing the trends in emission factors versus average cycle speed, four EPA driving cycles developed for MOBILE6 model were selected. These four cycles include LOS E, LOS D, LOS A-C, and High-Speed, with average speeds of 31, 53, 60, and 63 mph, respectively (Beardsley, 2001; EPA, 2003).

To estimate average emission factors for higher speeds, four additional cycles were selected based on results of real-world emission measurements conducted using PEMS in the Research Triangle Park area (Frey *et al.*, 2008b). These cycles are R40, R66, R70, and R78, with average speeds of 40, 66, 70, and 78 mph, respectively, and were measured on interstate highways under varying levels of traffic congestion. One of these cycles overlaps with the speed range of the MOBILE6 cycles, to enable evaluation of the consistency of the trend in average emission factor versus average speed within the range of speeds represented by MOBILE6. The other three cycles enable estimation of average emission rates at speeds higher than those included in MOBILE6. Table 4-2 provides a description of the EPA facility-specific driving cycles and real world driving cycles.

As an example, time distributions among the speed-acceleration modes for the LOS E, R40, High-Speed, and R70 driving cycles are shown in Figure 4-1. The most frequent mode for each cycle differs because of driving patterns. For example, for the LOS-E cycle which has an average cycle speed of 31 mph, the mode for speed range from 20 to 25 mph at cruise occurs most frequently. For R40 cycle, the most frequent speed mode was from 40 to 45 mph at cruise. For the High-Speed cycle, modes for speeds from 55 to 70 at cruise are most frequent. Since R70 is highway cycle with high average speed, the most frequent mode is for speeds from 70 to 75 mph at cruise.

4.2.3 Constant Speed Correction Factor

When vehicles operate at very high speeds on short segments of interstates, it is hypothesized that they tend to operate at approximately constant speed. A comparison of the real-world link-based driving cycles at high average speed, such as 70 and 78 mph, to those at lower average speed is consistent with this hypothesis, in that there is less variation in second-by-second speed as average speed increases. Since near-roadway air quality studies might be conducted in areas influenced by segments of roadway of only 1,000 feet or less, an assumption of approximately constant vehicle speed may be reasonable.

However, neither MOBILE6 nor the real-world driving cycles represent constant speed for such a short segment of highway. Therefore, a correction factor was developed comparing vehicle operation at a constant speed to vehicle operation at an equivalent average speed for a time-varying driving cycle. As average speed increases, we expect this ratio to approach unity. The vehicle emission rate at constant speed is estimated based on assuming zero acceleration and zero road grade, and use of the corresponding speed-acceleration modal average emission rate. The constant speed correction factor (R_C) is the ratio of an emission factor at constant speed to an average emission factor for a driving cycle with average speed equal to the constant speed:

$$R_{C,s,j} = \frac{EF_{s,j}}{\sum_{m} EF_{m,j} \times F_{m}^{s}} \tag{4-1}$$

Where,

$R_{C,s,j}$ = Ratio for emission factor (g/mile) at constant speed s to cycle average emission factor for average speed s for species j

$EF_{s,j}$ = Emission factor (g/mile) of species j based on speed-acceleration modal model at constant speed s (mph) and zero acceleration

$EF_{m,j}$ = Emission factor (g/mile) of species j and speed-acceleration mode m

F_{m}^{s} = Fraction of time spent in speed-acceleration mode m at driving cycle with average speed s (mph)

Subscripts and Superscripts:

m = Speed-acceleration mode

s = Vehicle speed (mph)

j = Pollutant species: NO_x, HC, CO, and CO_2

4.2.4 High Speed Correction Factor

The high speed correction factor (R_H) is the ratio of modal average emission rates for each speed mode to the modal average emission rates for mode at speed ranged from 60 to 65 mph. Using the speed-acceleration modal model, modal average emission factors were used for each of the 16 speed modes for cruise to estimate emission factors for speeds greater than 65 mph. Trends in average emission factors versus modal average speeds for each speed mode were characterized for speed modes ranging from 3 to 80 mph. In order to estimate high speed correction factors, the trend in mode average emission factor versus median speed for each speed mode was quantified by fitting a regression model, thereby enabling estimation of average emission rates for speeds as high as 78 mph. These trends are normalized to the emission factor estimated at an average speed of 63 mph, corresponding to the speed mode for 60 to 65 mph at cruise.

$$R^{63}_{H,s,j} = \frac{EF_{s,j}}{EF_{63,j}} \tag{4-2}$$

Where,

$R^{63}_{H,s,j}$ = Ratio of average emission factor at average speed s (mph) for each speed mode to average emission factor for speed mode at average speed of 63 mph for cruise acceleration mode for species j

$EF_{s,j}$ = Emission factor (g/mile) of species j at average speed s (mph) for cruise based on speed-acceleration modal model

$EF_{63,j}$ = Emission factor (g/mile) of species j at average speed of 63 mph, which is midpoint of the speed range from 60 to 65 mph, for cruise based on the speed-acceleration modal model

When the MOBILE6 input speed is greater than 65 mph, MOBILE6 reports same emission rates as for 65 mph. Therefore, it is not necessary to correct emission rates for speed less than 65 mph. For speeds greater than 65 mph, the high speed correction factor can be used to correct emission factors for speeds higher than 63 mph.

The high speed correction factor is estimated relative to a datum for a MOBILE6 driving cycle. Although MOBILE6 produces different emission factors for speeds up to 65 mph, the highest average speed among the driving cycles used to develop the model is 63 mph. Therefore, the high speed correction factor is developed by reference to an average speed of 63 mph. As a first step in developing the speed correction, a regression model was fit to describe variations in the emission factor versus average speed using 63 mph as a datum. The final correction factor was estimated using 65 mph, rather than 63 mph, as a reference point:

$$R^{65}_{H,s,j} = \frac{R^{63}_{H,s,j}}{R^{63}_{H,65,j}} = \frac{\left(EF_{s,j}/EF_{63,j}\right)}{\left(EF_{65,j}/EF_{63,j}\right)} = \frac{\left(EF_{s,j}\right)}{\left(EF_{65,j}\right)} \qquad (4\text{-}3)$$

Where,

$R^{63}_{H,s,j}$ = High speed correction factor for 63 mph basis. Ratio of emission factor at speed i to emission factor at 63 mph for cruise acceleration mode for species j

$R^{65}_{H,s,j}$ = High speed correction factor for 65 mph basis. Ratio of emission factor at speed i to emission factor at 65 mph for cruise acceleration mode for species j

4.3 Results and Discussion

Results are given here for the speed-acceleration modal model, constant speed correction factor, high speed correction factor, and a case study of how the two factors are used together to estimate emission factors at constant high speed, such as to support near roadway air quality studies.

4.3.1 Speed-Acceleration Modal Emission Rates

Figure 4-2 shows speed-acceleration modal emission rates for diesel vehicle. These are based on pooling the data from the five identified vehicles for which chassis dynamometer data were available on a second-by-second basis for the MOBILE6 speed correction driving cycles. Since the trend of emission factors versus speed-acceleration modes are similar among each of the five vehicles, the average emission rates of five diesel trucks were used for each speed-acceleration mode.

The average emissions rates were found to differ significantly between speed-acceleration modes. In general, modal emission rates are significantly higher at high speed and high acceleration than those at low speed and deceleration.

NO_x emission rates tend to increase as speed and acceleration increase. For speeds greater than 75 mph, the NO_x emission rate is approximately a factor of 5 greater than at speed range from 0 to 5. When comparing high acceleration versus high deceleration for NO_x, the emission rates are approximately a factor of 1.2 for speed modes ranged between 0 and 5 mph. As speed increases, NO_x emission rate is more sensitive to increases in acceleration. For example, NO_x emission rate is a factor of 5 greater for high acceleration than for high deceleration at speeds from 70 to 75 mph.

In most cases, the emission rates tend to increase with speed and acceleration. For example, for NO_x emissions, the response surface shown in Figure 4-2(a) monotonically increases with both speed and acceleration. CO_2 emission rate, which is a surrogate for fuel flow rate, also increases monotonically. The NO_x and CO_2 emissions are very sensitive to differences in speed and acceleration. For example, when comparing extreme modes for the lowest speed and acceleration to the highest speed and acceleration, the NO_x emission rate varies by a factor of 10 and the CO_2 emission factor varies by a factor of 15. The apparent peak in CO_2 emission rate at 68 mph and high acceleration is an artifact of small sample size.

The HC emission factor is less sensitive, on a relative basis, to variations in speed and acceleration compared to NO_x and CO_2. HC emission rates tend to be more sensitive to air-to-fuel ratio than other pollutants (Flagan and Seinfeld, 1988; Ropkins *et al.*, 2007). Since diesel engines operate with substantial excess air over all engine load ranges, the HC emissions do not vary strongly. For example, comparing the lowest speed and acceleration mode to the highest the emission rates varies by a factor of only 4.7, much lower than that for NO_x and CO_2. At lower speeds, the HC emission rate is weakly sensitive to acceleration.

The CO emission rate tends to increase monotonically with speed. At low speeds, the CO emission rate has little sensitivity to acceleration. Some of the modal average emission rates for CO are based on very small sample sizes. For example, at high acceleration and average speeds of 48 to 68 mph, the sample sizes are less than 37. Excluding these modes, the CO emission rate varies by a factor of 2.2 when comparing highest to lowest modal emission rates.

4.3.2 Constant Speed Correction Factor

The results for the constant speed correction factor (R_C) are shown in Figure 4-3. In general, as average speed increases, there is less fluctuation in speed on a second-by-second basis. In order to have very high average speed, such as 78 mph, a vehicle must consistently be traveling at speeds close to this average. However, for a vehicle traveling at 30 mph on an interstate highway, speeds could vary from stop to approximately free flow speed, depending on traffic conditions. Thus, as expected, the constant speed correction factor tends to increase with average speed, and to asymptotically approach unity, for most pollutants.

For NO_x and HC, the constant speed correction factors increase with average speed for both pollutants. R_C for NO_x is highly sensitive to speed but weakly sensitive for HC. Furthermore, R_C asymptotically approaches a value of 1. For NO_x, there are emission penalties at low speeds for the fluctuations associated with typical driving cycles compared to constant speed. For example, the NO_x emission factor at a constant speed of 31 mph is more than 14 percent less than the emission rate for a driving cycle with speed variations that has an average speed of 31 mph. For HC, at 31 mph, the emissions are approximately 4 percent lower. At 78 mph, the NO_x emission factors at constant speed are similar to those from speed-varying driving cycles with the same average speed.

The results for R_C for CO are unique compared to the other three pollutants. The value of R_C is relatively insensitive to speed. R_C has a value of approximately 1 at all speed ranges. As shown in speed-acceleration modal emission rates earlier, the CO emission rate is less sensitive to vehicle acceleration than is the case for NO_x and HC.

For CO_2, R_C reaches a value of approximately 1 at speeds of 80 mph. This implies that at such speeds, there is little difference in CO_2 emission rate, and fuel economy, between driving at constant speed versus driving with typically small fluctuations in speed that are characteristic of these average speeds. However, at lower speeds, such as for 31 to 60 mph, R_C varies from approximately 0.7 to 0.9, indicating that there are benefits to maintaining a constant speed rather than having fluctuations in speed.

4.3.3 High Speed Correction Factor

The results for the distance-based high speed correction factor (R_H) at speeds greater than 63 mph are shown in Figure 4-4 for NO_x, HC, CO, and CO_2, along with data illustrating the trend in emissions factors for a wide range of speeds. R_H is estimated using the speed-acceleration-based modal emission models under cruise modes. By definition, the R_H is one at an average speed of 63 mph. Since the goal here is to develop a model for high speeds, a trend line was fit to the emission ratios using the speed-acceleration mode at 63 mph as a datum and inclusive of cruising modes at modal average speeds of 63 mph and higher.

For NO_x, R_H is not sensitive to high speed. For example, R_H for NO_x is 0.97 at 78 mph. While the NO_x emission rate increases in speed-acceleration modal model at cruise at high speed range, NO_x emissions per distance of vehicle travel are approximately constant since the increase of the time-based emission rates is approximately linear with respect to an increase in speed.

For HC, R_H slightly decreases as speed increases at high speed. For example, R_H for HC is 0.87 at 78 mph. For CO, R_H increases as speed increases above 63 mph. For example, for an average speed of 78 mph compared to 63 mph, the average emission rate for CO is approximately 26 percent higher.

For CO_2, R_H increases from approximately 1 to 1.5 for average speeds from 63 to 78 mph. Since typically over 99% of carbon in fuel is converted to CO_2, the results for CO_2 imply that optimal fuel economy is obtained at average speeds of approximately 28 to 58 mph, with degradation of fuel economy at very high speed. Typically, diesel vehicles have relatively low fuel economy above approximately 60 mph (Park *et al.*, 2008). For low speeds, for emission factor decreases as speed increases from 8 to 28 mph and tend to be approximately constant at speed from 28 to 58 mph.

Overall, the trends in the ratio of emission factors for CO and CO_2 at high speeds are qualitatively consistent with expectations, theory, or experience. In other studies, the emission rates of CO and CO_2 are sensitive to vehicle speed at high speeds such as 60 to 80 mph. However, the NO_x and HC emission factors are relatively insensitive to speeds above 63 mph (Rakha *et al.*, 2004). Since HC emission rates are associated primarily with the air-to-fuel ratio (Ropkins *et al.*, 2007), which for diesel engines is always based on excess air over all load ranges, HC emissions tend to be less sensitive to speed than other pollutants. Similar to results in Figure 4-4(a) for NO_x, Weinblatt *et al*. reports that the NO_x emission rate per distance slightly decreases as speed increases above 60 mph (Weinblatt *et al.*, 2003).

4.3.4 Sensitivity Analysis of High Speed and Constant Speed Correction Factor

The application of the correction factors for constant speed and high constant speed are illustrated based on a sensitivity analysis. The results of the analysis are shown in Figure 4-5 for vehicle speeds varying from 40 mph to 80 mph. The base emission factor from MOBILE6 is shown in the figure. MOBILE6 does not predict any change in the emission rate as average speed increases above 65 mph. Therefore, the base emission factors shown for speeds of 70 and 80 mph are the same for each pollutant.

The values of R_C are shown for speeds less than 63 mph. For speeds of greater than 63 mph, only R_H is used.

Except for CO, R_C is typically the smallest at the lowest average speed shown at 40 mph, and approaches a value of 1 as speed increases to 80 mph. For CO, emission rates under cruise are approximately same values to those under acceleration for each speed mode; thus, R_C is less sensitive to speed than for other pollutants, and generally remains approximately constant.

For speeds of 70 and 80 mph, R_H generally is greater than 1 for CO and CO_2. R_H is the most sensitive to higher speed for CO_2, which is also highly correlated with the rate of fuel consumption.

The corrected emission factor represents an estimate of the emission factor at constant speed for the indicated speed. The effect of R_C on the corrected emission factor is significant for NO_x and CO_2 for speeds of 40 to 60 mph.

The NO_x emission factor is insensitive to the high speed correction factor at high speed. For example, the NO_x emission factor is 3 percent lower than base emission factor at 80 mph. For low speeds, the corrected emission factor at 40 mph is 14 percent lower than the base emission factor.

For HC, both correction factors have generally less influence compared to the other pollutants. For example, the corrected emission factor is two percent lower than the base emission factor at 60 mph. However, at 80 mph, the corrected emission factor is 16 percent lower than base emission factor.

For CO, the correction factors are relatively insensitive for speeds ranged from 40 to 70 while the high speed correction factor is the dominant influence on the corrected emission factor for speed of 80 mph. At 80 mph, the corrected CO emission factor is 44 percent higher than the base emission factor.

For CO_2, which is indicative of fuel consumption, the corrected emission factor is approximately 24 percent lower at 40 mph and 51 percent higher at 80 mph.

4.4 Conclusions

The assessment of near-roadway air quality and human exposure to air pollutants is expected to receive increasing attention in both the research and regulatory communities. For example, there is increasing interest in quantification of near roadway CO concentrations to support the technical basis for revising the National Ambient Air Quality Standards. Hence, factors that lead to variability in onroad emissions and that influence near roadway air quality and exposure are of increasing concern.

The key findings are that distance-based emission rates for diesel vehicles are estimated to be significantly different at high constant speed compared to estimates that are obtained from the MOBILE6 model. This is particularly the case for CO and CO_2 emission factors. For example, at a constant speed of 80 mph, the estimated emission factors are approximately 40 to 50 percent higher than those estimated using MOBILE6. For NO_x and HC emission factors, the differences are less pronounced, and the high constant speed emission factors are estimated to be slightly lower than those obtained using MOBILE6.

Other useful findings are that diesel vehicle emission rates at constant speed tend to be lower than those at transient speeds for NO_x, HC, and CO_2, except at very high speed. For very high speeds, and for CO emission rates at all speeds, there is little difference in emission rates when comparing transient versus constant speed operations. The findings for NO_x, HC, and CO_2 imply that traffic management or driver behavior efforts that lead to constant speed vehicle operations could reduce emissions and fuel use by as much as 15 to 30 percent without any change in vehicle miles travelled.

The results obtained using speed-acceleration modal emission rate models enable assessment of transient versus constant speed operations, and of operations at varying constant speeds. An implication of the latter is that distance-based emission and fuel use rates tend to be the lowest for moderate ranges of speed, such as 30 to 60 mph. Although these insights are not new, they are derived using a different methodology than that which underlies the MOBILE6 model, and thus provide additional confidence regarding the robustness of the insights.

The methodology demonstrated here can be applied to estimate emission factors for real-world link-based situations in which vehicles are driving at constant speed, high average speed, or both. A similar methodology can be applied with the expected final release of EPA's MOVES model, which also will have modal emission rates that can be weighted to represent a wide variety of driving cycles. The key limitations of this work are the relatively small sample sizes of data for some of the speed-acceleration modes, and the limited sample of vehicles for which second-by-second data were available for a wide variety of driving cycles. Over time, these limitations are expected to be addressed as second-by-second data become available from a variety of sources, including in-use measurements with portable emission measurement systems.

This methodology demonstrated here is applicable to the estimation of emissions on short segments of highway for which vehicles may be driving at approximately constant speed. Such estimates are useful as part of assessment of emissions and air quality in the near vicinity of a roadway.

4.5 Acknowledgments

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Table 4-1. Heavy Duty Diesel Vehicle Information for Speed-Acceleration Modal Models

Make	Model	Engine Power (HP)	Engine Displacement (L)	Gross Vehicle Weight (lbs)
Ford	F250	235	7.3	8,800
Ford	F350 4x4	235	7.3	9,900
Ford	F350 4x4	235	7.3	9,900
Dodge	Ram 2500	230	5.9	8,800
Dodge	Ram 2500 4x4	230	5.9	8,800

Note: All vehicles are 1999 model year.

Table 4-2. Description of Facility-Specific and Real World Driving Cycles

Driving Cycle	Average Speed (mph)	Maximum Speed (mph)	Maximum Acceleration (mph/s)	Standard Deviation (mph)	Duration (sec)	Length (miles)
Freeway, LOS E[a]	31	63	5.3	15.8	456	3.9
R40[b]	40	50	3.7	5.7	250	2.7
Freeway, LOS D[a]	53	71	2.3	9.9	406	6.0
Freeway, LOS A-C[a]	60	73	3.4	5.9	516	8.6
Freeway, High-Speed[a]	63	74	2.7	4.5	610	10.7
R66[b]	66	70	1.9	1.7	321	5.9
R70[b]	70	74	2.5	2.7	306	5.9
R78[b]	78	83	2.5	2.4	324	7.0

Notes : R40, R66, R70, and R78 are real-world driving cycles.
Source: [a] Environmental Protection Agency (EPA, 2003) and [b] Frey *et al*. (Frey *et al.*, 2008b).

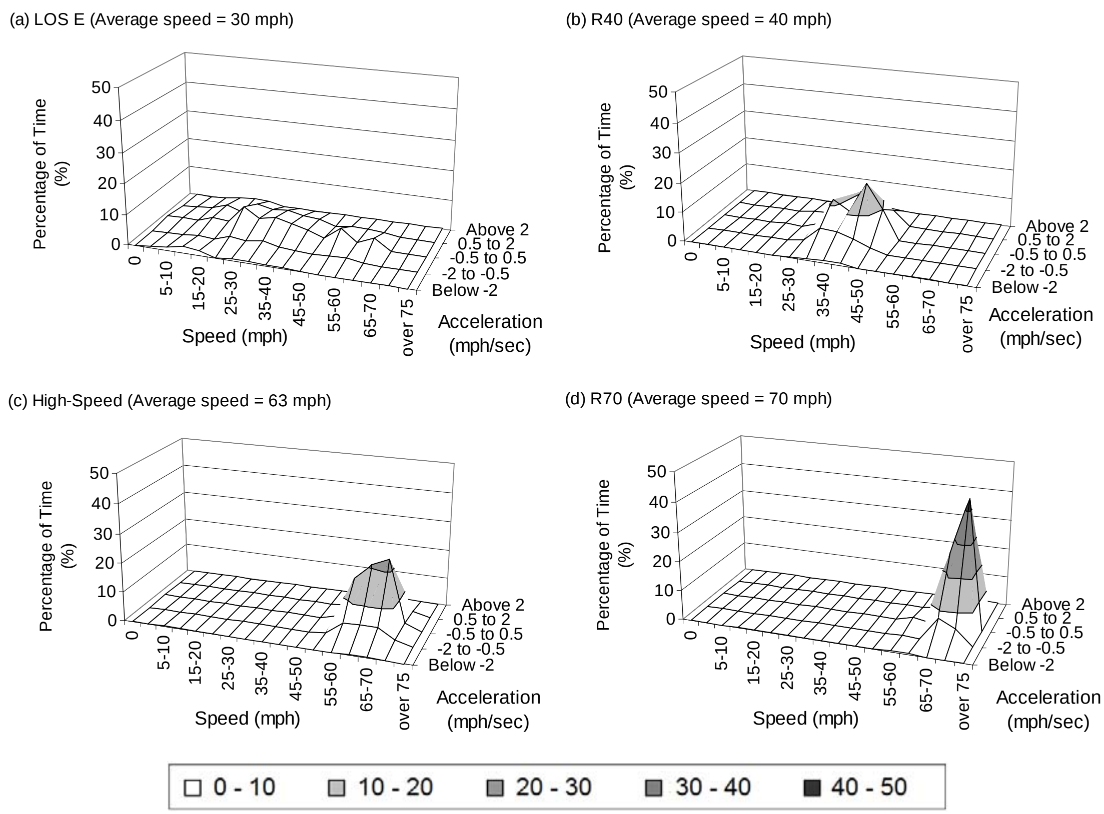

Figure 4-1. Time Distribution of Speed-Acceleration modes for LOS E, R40, High-Speed, and R70 Cycles.

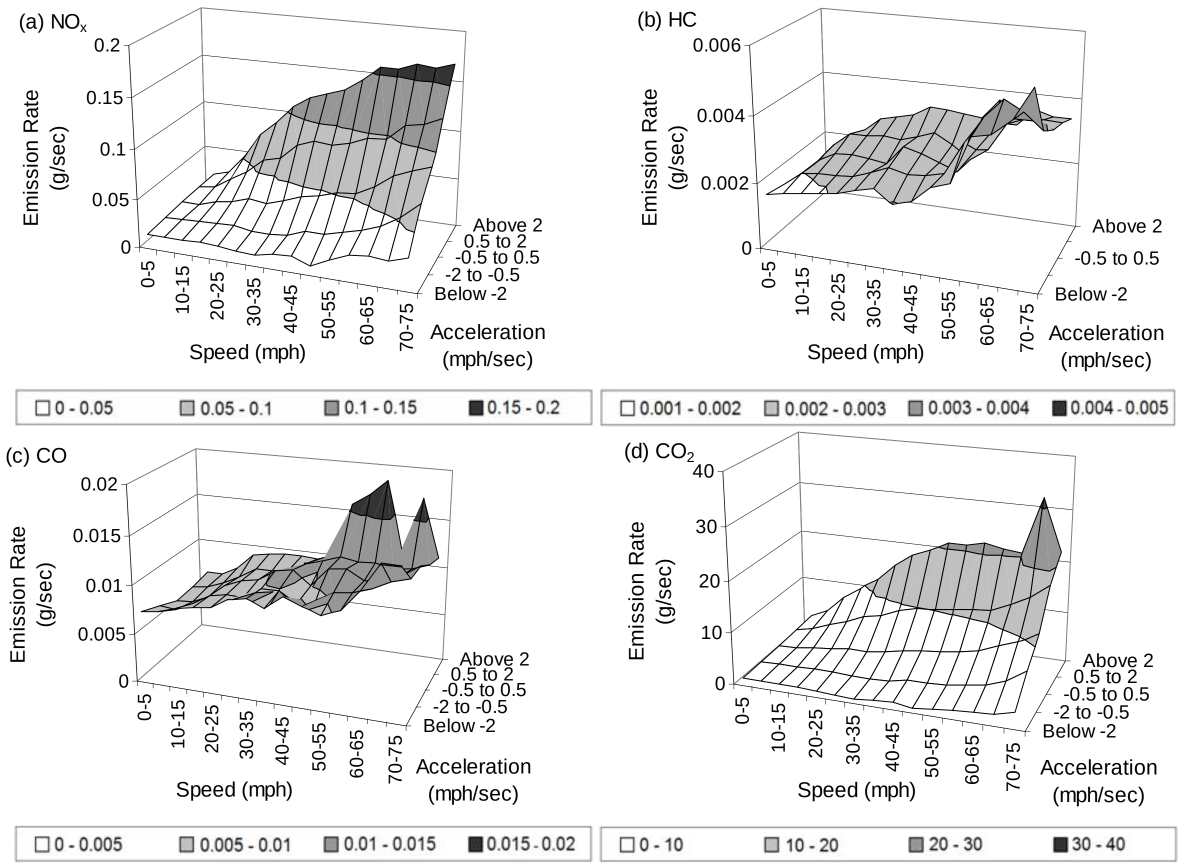

Figure 4-2. Speed-Acceleration Matrix Profiles for Average Emission Rates based on 62,419 Seconds of Data for 5 Diesel Vehicles.

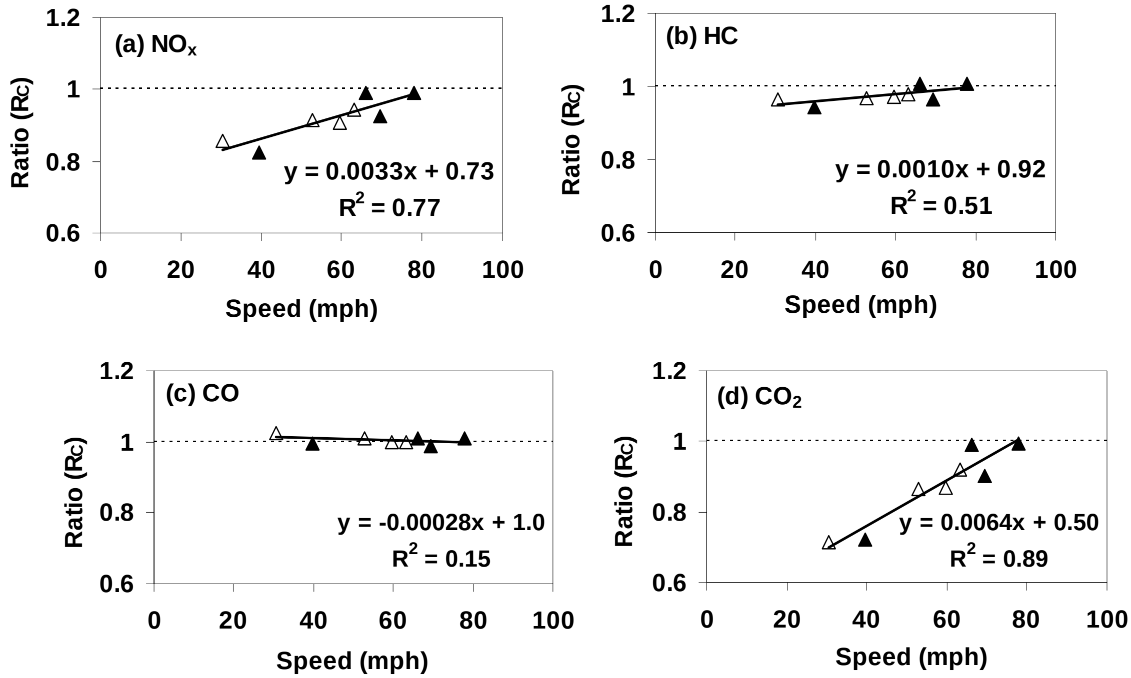

Figure 4-3. Constant Speed Correction Factors (RC) based on Ratio of Constant Speed Emission Factor to Cycle Average Emission Factors for the Same Driving Cycle Speed on a Distance Basis. Note: Blank triangles are EPA facility-specific driving cycles and dark triangles are real-world driving cycles.

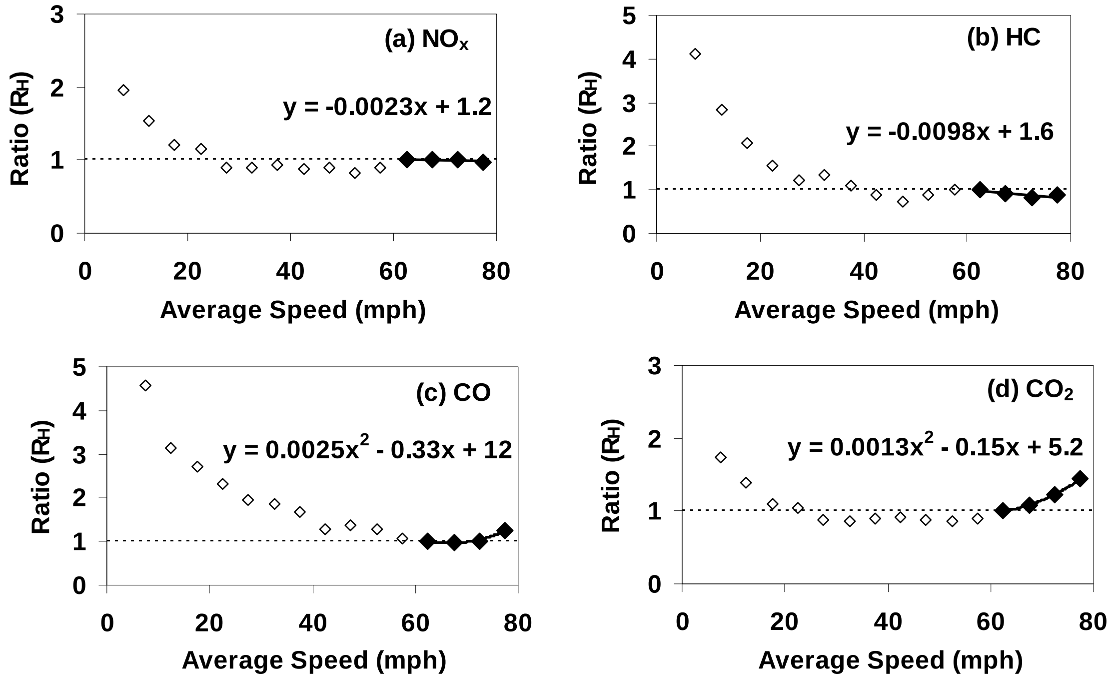

Figure 4-4. High Constant Speed Correction Factors (R_H) based on Ratio of Distance-based Emission Factors to Emission Factors at 63 mph during Cruise.
Note: The four data points (dark diamond) above 63 mph are used for regression models. Data points below 63 mph (blank diamond) are shown for only information.

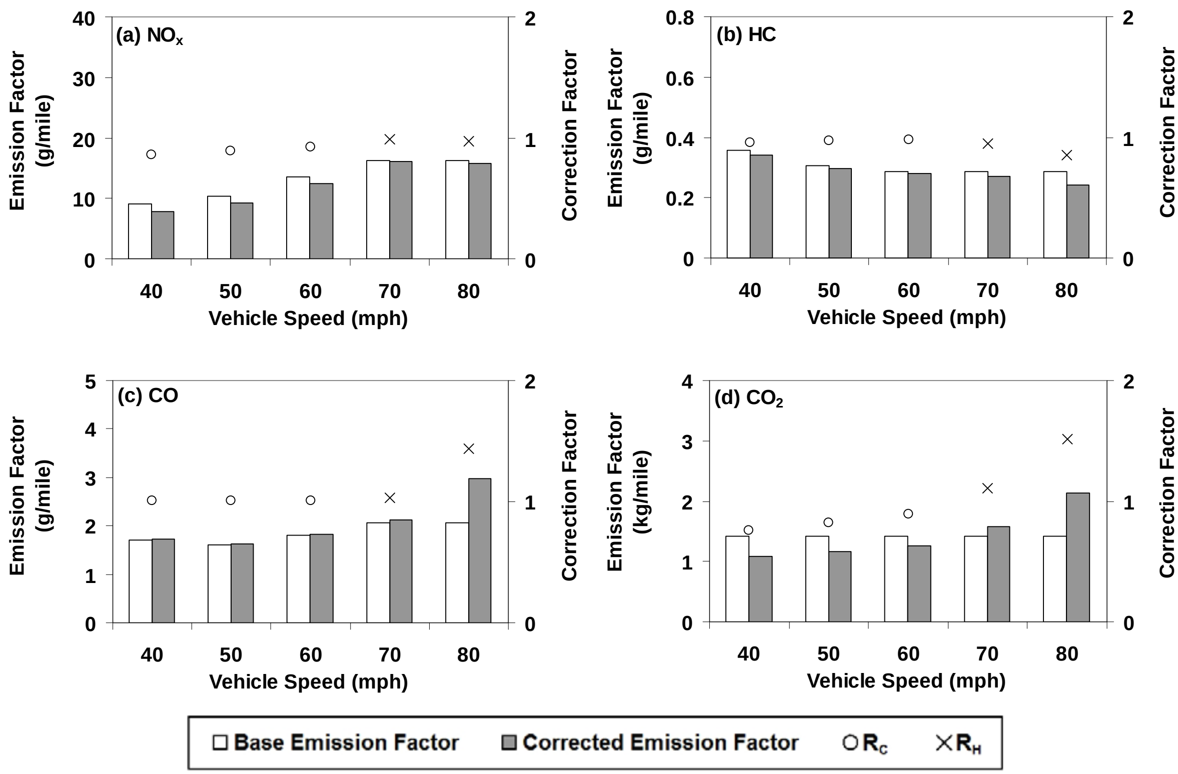

Figure 4-5. Comparison of Base Emission Factors from MOBILE6 versus Corrected Emission Factors based on Constant and High Speed Correction Factors (R_C and R_H).

PART V MEASUREMENT OF EMISSIONS OF PASSENGER RAIL LOCOMOTIVES USING A PORTABLE EMISSION MEASUREMENT SYSTEM[†]

[†] This manuscript is in preparation for submission to *Journal of Air & Waste Management Association.*

ABSTRACT

The purpose of this study is to demonstrate methodology for in-use measurement of diesel-electric passenger railroad locomotives using a Portable Emission Measurement System (PEMS). The methodology was developed and demonstrated based on railyard load tests of three locomotives, including one GP40 and two F59PHIs. These locomotives have mechanically governed prime mover engines ranging from 140 to 169 liters displacement and with approximately 3,200 hp output. Each locomotive also has a "head-end power" (HEP) engine of 19 to 27 liters that produce approximately 600 hp. The engines were measured using ultra-low sulfur diesel (ULSD) fuel. Each engine was instrumented to measure manifold absolute pressure (MAP), engine RPM, intake air temperature, and exhaust concentrations of selected gases and particles. The prime mover engines are operated at each throttle notch setting. For the HEP engines, three electrical loads were applied based on power usage for one, two and four passenger cars, respectively. Over 97 percent of the raw data survived a multi-step quality assurance process. The data obtained from the PEMS for the main engines were found to be comparable, on a fuel-basis, to data reported by others, particularly for NO_x and CO. The key results from this work are establishment of a simplified methodology for future tests and development of baseline data.

5.1 Introduction

There are 23,732 Class I locomotives in the United States in 2006.[1] The U.S. Environmental Protection Agency (EPA) estimates that locomotives consume approximately 4 billion gallons of diesel fuel each year.[2] Locomotive diesel engines are significant sources of air pollution.[3, 4]

The prime mover engine has eight predetermined "notch" settings in addition to idle.[5] The measurements in a notch setting are typically conducted during steady-state. The steady-state emission factors for each notch setting are weighted to arrive at an average emission rate for a duty cycle. EPA developed locomotive emissions standards based on notch emission factors weighted by two typical duty cycles: line-haul and switching. Line-haul freight engines typically have large engines (e.g., 3,000 to 6,000 hp) and switching locomotives have engines of 2000 horsepower or less. EPA has developed duty cycle for passenger locomotives but it is not used in the regulation since the passenger duty cycle is similar to the line-haul cycle and the passenger rail service is a small contributor to total railroad fuel use and emissions on a national basis.[6]

Emissions from locomotive engines are typically measured based on engine dynamometer tests. However, such test is expensive and time consuming. For the certification test, federal procedure is prohibitively costly and there are few facilities with this capability. Therefore, there is a need to quantify emissions from locomotive engines with a less expensive measurement. The purpose of this paper is to introduce an alternative measurement approach for locomotive engine.

The emission measurement using a Portable Emission Measurement System (PEMS) is introduced as an alternative method for locomotives. PEMS is more easily installed and measures exhaust emission rates. In the past a decade, the use of PEMS expanded to measure various engine emissions.[7-9]

New regulations for locomotives were finalized by EPA in March, 2008.[10] The regulation defines that a locomotive becomes "new" under the standard when it is remanufactured. The 2008 standard has more stringent emission limits for the Tier 0 to 2 standards compared to the 1997 standard, and introduces new Tier 3 and 4 standards.

The objectives are to: (1) develop and apply a simplified methodology for assessment of the activity, fuel use, and emission rates for locomotives; (2) measure emission levels of locomotive engines using PEMS; and (3) evaluate the use of PEMS as an alternative to engine dynamometer measurement.

5.2 Technical Approach

The technical approach includes: (1) study design; (2) Portable Emission Measurement System (PEMS) instrumentation; (3) field data collection; (4) quality assurance and quality control; (5) data analysis; and (6) benchmark comparisons.

5.2.1 Study Design

Field study design includes specifying which engines are to be tested, when they are to be tested, what fuel will be used, what type of duty cycle will be performed, and who will operate the locomotives.

The selected locomotives are a GP40, NC1792, and two F59PHIs, NC1755 and NC1797, owned and operated by the North Carolina Department of Transportation (NCDOT) for a passenger rail service between Raleigh, NC and Charlotte, NC. Each locomotive has a prime mover engine used to provide direct current electric power for propulsion, and a second head-end power (HEP) engine used to generate alternating current power for "hotel services" in the passenger train.[11] Emissions for each engine from each locomotive were measured, for a total of six engines.

The specifications of the prime mover and HEP engines of NC1792 (GP40), NC1755 (F59PHI), and NC1797 (F59PHI) are summarized in Table 1. Measurements are based on ultra low sulfur diesel (ULSD).

5.2.2 Portable Emission Measurement System

The PEMS used is the OEM-2100 Montana system manufactured by Clean Air Technologies International, Inc.[12] The Montana system is comprised of two parallel five-gas analyzers, a particulate matter (PM) measurement system, an engine sensor array, and an on-board computer.

The gases and pollutants measured include O_2, HC, CO, CO_2, NO, and PM using the following detection methods:

- HC, CO, and CO_2 using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used.[9, 13]
- NO measured using electrochemical cell. For diesel engines, NO_x is comprised of approximately 92 volume percent NO.[14, 15]
- PM is measured using light scattering, with measurement ranging from ambient levels to low double digits opacity.[9, 13]

The performance of the Montana system has been verified in comparison to that of a laboratory grade chassis dynamometer measurement system.[16] The coefficients of determination (R^2) exceeded 0.86 for all pollutants, indicating good precision. The slopes of parity plots for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy, and ranged from 0.62 to 0.79 for HC. The bias for HC is a well-known result of the NDIR detection method.[17] The PEMS is calibrated in the laboratory using a cylinder gas and in the field periodically recalibrates to ambient air to prevent instrument drift.

A temporarily mounted sensor array is used to measure manifold absolute pressure (MAP), engine RPM, and intake air temperature (IAT) in order to estimate air and fuel use. The engine sensor array includes an MAP sensor that is connected to a fabricated port on the intake air manifold of the engine. The RPM sensor is based on an optical device that detects the reflection of light from reflective tape that is placed on a pulley wheel that rotates at the same RPM as the engine. IAT is measured with a thermocouple. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb.[13]

5.2.3 Field Data Collection Procedure

Field data collection includes: (1) pre-installation; (2) final installation; and (3) data collection.

After installation, the PEMS was warmed up for about 45 minutes. During the warm-up period for the PEMS, the engines of locomotives were also warmed up.

After warm-up period, the prime mover engine was run at notch position 8 for a period of approximately 3 minutes, after which the engine is returned to idling. During testing under load, the electrical power produced by the DC generator connected to the prime mover engine is dissipated in an electrical resistance grid that is referred to as the dynamic brake grid. There are cooling fans above the grid that are used for forced-air cooling. However, the grid is not intended for sustained operation at high electrical current. To prevent overheating, operation at notches 6 through 8 was limited to 3 minutes. The load test at each of these notches was immediately followed by a period of idling to allow the grid to cool for 5 minutes. Thereafter, testing occurred sequentially for notch positions 5, 4, 3, 2, 1, and idle without any intermediate idling.

The HEP engine was run at multiple electrical loads for a period of approximately 10 minutes per load. The electrical load conditions were none, low, medium, and high. The loads were imposed by attaching passenger rail cars and operating the lighting and air conditioning in each. The low, medium, and high loads correspond to the combined space conditioning and lighting loads for one, two, and four passenger cars, respectively. Voltages and currents were measured to estimate the electrical loads.

During the data collection, exhaust gas concentrations and engine data, on a second-by-second basis, were continuously recorded in an on-board computer.

5.2.4 Quality Assurance and Quality Control

For quality assurance purposes, the combined data set for a engine test is screened to check for errors or possible problems. If errors are identified, they are either corrected or the data set is not used for data analysis. Details of the quality assurance procedures are given by Frey *et al*.[8] Three of the most common types of errors or problems are briefly described.

On occasion, an invalid reading is obtained for engine RPM from the optical sensor that is temporarily installed on the engine. For example, the prime mover engines, which are large 2-stroke engines, typically operate between 250 to 950 RPM. Values outside of this range are typically considered to be invalid and are removed prior to further data analysis.

"Freezing" refers to situations in which a value that is expected to change dynamically on a second-by-second basis remains constant over an unacceptably or implausibly long period of time. On occasion, the gas analyzer output fails to update and appears to be "frozen" at a constant value.

Each gas analyzer is referred to as a "bench." Most of the time, both benches are in use. Occasionally, one bench is taken off-line for "zeroing." For data quality control and assurance purpose, each gas analyzer bench is zeroed alternatively every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. Therefore, most of the time, the emissions measurements from each of the two benches can be compared to evaluate the consistency between the two. If both benches are producing consistent measurements, then the measurements from both are averaged to arrive at a single estimate on a second-by-second basis of the emissions of each pollutant.

When the relative error in the emissions measurement between both benches is within a predetermined "maximum allowable discrepancy" (MAD), and if no other errors are detected, then an average value is calculated based upon both of the benches.

However, if the relative error exceeds the MAD due to problem in one bench, such as a leakage in the sample line, overheating, or problems with the sampling pump, then only data obtained from the other bench was used for emissions estimation.

5.2.5 Data Analysis

The data are analyzed to estimate the average fuel use and emission rates on a mass per time basis for each throttle notch position. Furthermore, emission rates for each throttle notch position were estimated on a mass per gallon of fuel consumed basis. Weighted average emission factors were estimated based on the proportion of time spent in each throttle notch setting according to data reported by the U.S. EPA.[6] The data analysis methodology used here is analogous to similar methods developed for other non-road vehicles, such as construction equipment.[8]

5.3 Results

The results include the field data collection schedule, quality assurance, overall comparison of engines, and comparison to independent data.

Field data collection occurred during a period from March 11, 2008 to July 24, 2008. The prime mover engines were tested for locomotives NC 1755 and NC1792 in March. In July, the prime mover of locomotive NC1797, was tested. In addition, measurements were made in July on the HEP engines of all three locomotives.

5.3.1 Quality Assurance

On average, 97 percent of the raw second-by-second data were valid and useful for estimation of fuel use and emission rates for each engine that was tested. The leading causes of loss of data were unusual engine RPM (which occurred only for one engine), gas analyzer freezing, and inter-analyzer discrepancy. These each accounted for, on average, loss of 0.8, 0.7, and 1.2 percent of the raw data. During the test of the HEP engine for locomotive NC 1792, 85 seconds of unusual engine RPM data occurred because the reflective tape needed for the RPM sensor detached. Since the HEP engine was running normally when RPM data was missing, and normal operation is a steady state of 1,800 RPM to match the rotational requirements of the 60 Hz AC generator, the missing RPM data were imputed to be 1,800 RPM.

5.3.2 Prime Mover Engines

Fuel use and emission rates for all engines were calculated directly from the quality assured data produced by the PEMS. Furthermore, fuel-based emission factors were calculated for all engines.

The engine RPM for each of the three tested 3,000 hp 2 stroke engines associated with each throttle notch position is approximately the same when comparing the three engines. At idle, the engines operate at approximately 250 RPM, while at notch 8 they operate at approximately 900 RPM. MAP varies from approximately 103 to 276 kPa, depending on the notch positions and engine.

The exhaust concentrations for NO and CO_2 tend to increase as notch position increases. For example, as shown in Figure 1, the NO concentration for the EMD16-645 engine of the GP40 increases monotonically from 164 to 1555 ppm between idle and notch 8. The NO and CO_2 concentrations for the EMD12-710 engines of the F59PHIs increase from idle to notch 7 and are lower at notch 8 than notch 7 because of introduction of excess air. NO_x formation strongly depends on a combustion temperature.[18] For example, NO concentration of NC1755, which has EMD12-710 engine, increases from 160 to 1,360 ppm between idle and notch 7. At notch 8, NO concentration is 1,170 ppm. The observed concentrations for HC and CO are less sensitive to notch positions because they are often at or below the detection limit of gas analyzers. The observed levels were between 0.6 to 19 ppm for HC and 0.0008 to 0.085 *vol*-% for CO.

The NO emission rates increase monotonically between idle and notch 8 for each of three locomotives. For example, NO emission rates for NC 1755 are from 0.13 to 11 g/sec between idel and notch 8. The NO emission rates for EMD16-645 engine are generally higher than EMD12-710 engines. For example, the NO emission rate of EMD16-645 at notch 8 is 22 and 28 percent higher than those for EMD12-710 engines of NC1755 and NC1797, respectively.

Fuel-based emission factors, given in Table 5-2, were calculated for each prime mover engine and notch position based on a carbon balance of the exhaust components, molar ratio of exhaust components to CO_2, and fuel carbon content. In addition, a cycle average emission factor was estimated based on the line-haul freight locomotive duty cycle. The EPA duty cycle includes a mode for dynamic braking which was not part of the stationary load test procedure. The percentage of time assigned to dynamic braking in the EPA cycle was assigned to the idle mode. The cycle average emission rate was calculated based on the total emissions for the cycle divided by the total fuel use for the cycle.

For example, the NO_x emission rate for the NC 1755 F59PHI locomotive varies from approximately 170 to 240 g/gallon among the notch positions. Although a large percentage of time for the freight line haul cycle occurs in the idle mode, the majority of the fuel consumed (65 to 67 percent, depending on the engine) is estimated to occur at notch 8. The rate of fuel consumption at notch position 8 is approximately two orders-of-magnitude higher than at idle. Given the high fuel consumption rate at high engine load, the fuel-based cycle average emission factors are most influenced by the modal emission factors at high engine load. The weighted cycle average NO emission rate in this case is 220 g/gallon.

The two F59PHI locomotives have similar cycle average NO_x and opacity-based PM emission rates. Although there appear to be difference between the two F59PHIs with respect to average HC and CO emission rates, these differences are not significant. The average concentrations were below the detection limit of 13 ppm for HC and 0.012 *vol*-% for CO in these cases. The GP40 has a similar average PM emission rate compared to the F59PHIs, and a somewhat higher average NO_x emission rate. The average HC and CO emissions rates for the GP40 are within the range of those for the F59PHIs and subject to similar limitations because of measurements below the detection limit.

A comparison of the fuel-based emission factors from the three locomotives versus the range and average of values reported by EPA[6, 19] is given in Table 5-2. For NO_x, the measured emission factors are comparable to those reported by EPA, although they tend to be at the low end of the range reported by EPA. One possible reason for this is that the PEMS measures NO but not total NO_x. Thus, if an adjustment were made to account for this, the measured emission factor would be increased by a ratio of 1.087 (1/0.92), leading to values of 230 to 260 g/gallon. These values are also within the range of the EPA data. Overall, the NO emission measurements are deemed to be reasonable.

For HC, the measured emission factors are low compared to the weighted average from the EPA reported data. For one F59PHI, the measured average emission factor is less than the minimum value estimated based on EPA's data. However, the measured average emission factors for the GP40 and the other F59PHI are slightly higher than the minimum value. The HC measurement is based on NDIR, which is known to be accurate for straight chain hydrocarbons but is less accurate for more complex molecules (such as aromatics). Typically, NDIR HC measurements may need to be adjusted with a bias correction of 2 or more to correspond to the actual total hydrocarbon load in the exhaust.[17] If a factor of 2 adjustment is applied here, then the measured emission factors would be 3.8 to 9.4 g/gal. While still at the low end of the range of data inferred from EPA's report, these values are consistent with the benchmark data.

As noted earlier, the CO exhaust gas concentrations are typically below the detection limit of the gas analyzers, and thus are subject to uncertainty. Nonetheless, the average emission factors estimated from the measurements are comparable to the data reported by EPA, when converted to a fuel basis.

The opacity-based PM measurements are clearly lower than the benchmark data. As noted earlier, these measurements are based on a light scattering laser photometer detection method. These measurements are useful for relative comparisons of data obtained using the same method, but are not appropriate for characterization of the absolute total emissions. The data here suggest that the three locomotives have comparable PM emission rates. The data also showed that the opacity-based PM emission rates are approximately a factor of 4 lower than the average estimated fuel-based rate based on data reported by EPA.

The brake-specific fuel consumption for these locomotives is not known because there is no measurement of shaft torque nor is there an electronic control module that reports estimates of such data based on engine maps. Thus, it is not possible to directly estimate emission factors in units of g/bhp-hr for comparison to the EPA emission standards. However, it is possible to make an estimate of g/bhp-hr emission factors for notch 8 using a typical value for brake specific fuel consumption (BSFC). EPA reports a typical BSFC of 0.048 gal/bhp-hr.[6, 19] Typically, the measured BSFC at notch 8 is equal to 0.048 gal/bhp-hr for EMD16-645 and EMD12-710 engines.[20, 21] Estimated brake specific emission factors for notch 8 position are shown in Table 5-3. Notch 8 is used as a point of reference since it contributes the most to the line-haul freight duty cycle that is the basis of recent emission standards.

For NO_x for notch 8, it appears that two of the prime movers have higher emission rates than the Tier 0 standard of 8.0 g/bhp-hr for line-haul freight locomotives. According to previous locomotive research, NO_x emission rates for EMD16-645 were reported in the range approximately from 12 to 13 g/bhp-hr.[22] EPA reported 14 and 11 g/bhp-hr of ling-haul duty cycle average NO_x emission rates for EMD16-645 and EMD12-710 engines, respectively.[6] The older engines are not required to comply with the new standards until such time as they would undergo engine rebuilds. Furthermore, the measurements conducted here are intended to evaluate relative difference among notches and engines, and are not a Federal Reference Method (FRM).

For HC, it appears likely that NC 1792 and NC1797 has an emission rate that is higher than the Tier 4 standard of 0.14 g/bhp-hr but less than the Tier 3 standard of 0.3 g/bhp-hr. The NC 1755 emission rate is likely to be below the Tier 4 standard. For CO, it seems likely that the NC 1755, NC 1792, and NC 1797 locomotives can comply with any of the Tiers of the locomotive standards. For PM, there is considerable uncertainty given the semi-qualitative nature of the measurement method. The PM emissions from these engines are likely to be comparable to the Tier 0 standard of 0.22 g/bhp-hr.

5.3.3 Head-End Power Engines

The HEP engine measurements are intended to serve as a baseline for future comparisons. During "none" load, some power was consumed to maintain charge on batteries in the locomotive. When the HEP engines were being tested, the prime mover engines were not operating. For NC 1797, the emissions were measured for idle, 2, and 4 passenger cars. The use of only one rail car as part of the load test schedule was identified as potentially useful when conducting the tests of the other two HEP engines.

Table 5-4 shows the fuel rate and fuel-based emission rates for the HEP engines versus electrical load. The variation in electrical load for a given number of passenger cars from one test to another is because of variability in ambient temperature and solar irradiation, which affects the cooling load. For all engines, the rate of fuel use, CO_2 emissions, and NO emissions increase as the electrical load increases. HC emission rates for diesel engines are not primarily sensitive to load and typically depend more on factors such as air-to-fuel ratio.[23] The CO emission rate tends to be highest at no load, which is a relatively inefficient operating condition compared to higher load. Fuel-based PM emission rates are approximately similar among various loads.

As expected, the fuel use and CO_2 emission rates of the two CAT3412 engines are similar for comparable loads. The NO emission rates are of similar magnitude but appear to be slightly higher for NC 1755 than for NC 1797. The HC, CO, and PM emission rates are comparable in magnitude. The Cummins KTA19 engine of NC 1792 has lower fuel use and emission rates than the CAT3412 engines. The Cummins engine was rebuilt in 2005.

We have not been able to identify published data on the same make and model of HEP engines. As a bench mark, EPA certification data for similar size engines manufactured by Cummins and CAT in 2003 were compared to fuel-based emission factors here. Since EPA certification data was reported in units of gram per brake-horsepower-hour, the emission factors in gram per gallon of fuel were calculated based on engine BSFC for each engine.

The Cummins 3CEXL019 is 19 liter non-road diesel engine with BSFC of 0.0427 gal/bhp-hr. The certification emission rates are 140, 9, 36, and 5.2 g/gal for NO_x, HC, CO, and PM. NO_x emission factors are less than the certification data. For HC and CO, emission rates with electrical loads are less than those for EPA data while these emission rates are greater at idle than certification data.

For comparison to CAT3412 engine, the emission factors of CAT 3CPXL27 engine are used. The CAT 3CPXL27 is 27 liter non-road diesel engine with BSFC of 0.0515 gal/bhp-hr. NO_x emission factors are generally higher than the certification data except idle.

For HC and CO, emission rates are higher than those for certification data. For PM, the emission factors for opacity-based PM are less than those of certification data.

The fuel-based NO emission rates of the HEP engines are substantially lower than those of the prime mover engines. The fuel-based HC emission rates were of comparable magnitude for the HEP and prime mover engines. For CO, the fuel-based rates ranged from 38 to 82 g/gallon for the CAT3412 engines. These rates tend to be higher than those for the prime mover engines. The CO emission rates for the Cummins engine are comparable to those of the prime mover engines. Similar to the prime mover engines, the average exhaust CO concentrations for the Cummins engine are typically below the detection limit. The fuel-based PM emission rates for all three HEP engines were approximately similar and appear to be higher than for the substantially larger main engines. There is not a strong trend of fuel-based PM emission rate with respect to load.

5.4 Conclusions

A procedure was developed and implemented via which to sample exhaust gas from the duct of the prime mover engines and obtain measurements of engine data, including RPM, manifold absolute pressure, and intake air temperature. The latter were needed because the engines are mechanically controlled and do not have an electronic control unit; thus, there is no equivalent of on onboard diagnostic interface via which to obtain engine data. Now that fittings have been developed to enable measurement of the main engine exhaust gas and engine data for all engines, the pre-installation time for future stationary load tests in the railyard should be reduced. Of course, the pre-installation time is only a small component of the overall project effort when considering other preparation, data collection, decommissioning, data analysis, and reporting.

The data obtained from the PEMS for the prime mover engines were found to be comparable, on a fuel-basis to data reported by others, particularly for NO_x and CO. The measured HC emission factors are slightly low compared to benchmark data, which is easily explained by the known bias in NDIR measurements of the type made here. For PM, the measurements made here are a semi-qualitative method analogous to opacity that is useful for relative comparisons to data obtained with the same method. The estimated PM mass emission rates from these data were approximately a factor of 2 to 6 lower than the benchmark data.

The most robust findings of this study are the fuel-based emission factors for NO, CO, and HC. However, regulations for locomotives are in units of mass of emission per brake horsepower hour of engine output. It was not possible to measure brake specific fuel consumption (BSFC) in this work, since it is not practical to conduct an in-use measurement of shaft torque nor are engine map data readily available. Hence, the emission rates in units of g/bhp-hr were estimated for notch 8 with maximum engine horsepower.

It is likely that the NO_x emissions of all three locomotives are marginally higher than the Tier 0 line-haul standard. However, these emissions could be brought down by various methods, which may include the use of alternative fuels. The emissions of both HC and CO are likely to be below the Tier 0 standard. For the NC 1755 F59PHI, the HC emissions are likely to be comparable to the Tier 4 standard. For the GP40 and the NC 1797 F59, the HC emissions may be comparable to the 2008 Tier 1 standard. The CO emissions are lower than any standard for NC 1755 and NC 1792. NC 1797 is below the Tier 0 standard for CO and approximately comparable to the Tier 2 standard. It seems possible that the locomotives have PM emissions comparable to the Tier 2 standard.

Overall, the emissions measurements suggest that the locomotives have emissions comparable to or less than the Tier 0 standard except for NO_x. The GP40 was manufactured prior to the initial model year for which the Tier 0 standard is applicable. The NC 1755 F59PHI was manufactured during the period to which the Tier 1 standard applies, and the NC 1797 F59 was manufactured the next year. The main priority for emissions reduction at this point would be the NO_x and PM emissions of both locomotives. These conclusions are based solely on the main engines.

For HEP engines, fuel use and emissions are measured under no, low, medium, and high electrical loads. The fuel-based emission factors for the HEP engines are generally lower than those for the main engines for NO_x, similar for HC, and higher for CO and PM. However, since the EPA standards are based upon freight locomotive duty cycles, there are not specific data for HEP engines or a separate HEP engine standard for comparison.

Overall, the data appear to be reasonable and should serve as a useful basis of comparison to data that could be collected in future measurement campaigns. Examples of factors that could be assessed in comparative studies with the results of this project include the effect of substitution of alternative fuel, such as B20 biodiesel, for ultra low sulfur diesel. The same or similar methodology can be applied to other locomotives.

The methodology could be adapted for in-use measurement of locomotives in over-the-rail service. The advantage of this type of measurement would be to obtain real-world duty cycles that may be unique to passenger rail service, as opposed to the freight duty cycles assumed by EPA. Furthermore, such measurements would be based on a real load profile for the HEP engines.

Overall, this study has established a methodology for measurement of passenger locomotive main and HEP engines using a portable emission measurement system, provided data regarding fuel use and emissions, and created a baseline for comparisons with future work.

5.5 Disclaimer

The contents of this paper reflect the views of the authors and not necessarily the views of the University. The authors are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation, the Federal Highway Administration, or the Institute for Transportation Research and Education at the time of publication. This report does not constitute a standard, specification, or regulation.

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Table 5-1. Specifications of the Main Prime Mover and Head-End Power (HEP) Engines of the Tested Locomotives.

Item	NC 1792 (GP40)		NC 1755 and NC 1797 (F59)	
	Main	Head-End Power	Main	Head-End Power
Engine Make	EMD	Cummins	EMD	CAT
Engine Model	16-645E3	KTA19	12-710G3	3412
No. Strokes	2	4	2	4
No. Cylinders	16	6	12	12
Displacement (L)	169	19	140	27
Horsepower (hp)	3,160	600	3,200	625

Note: NC 1755 and NC 1797 are model F59 locomotives that were built in 1998 and 1997, respectively. NC 1792 is model GP40 locomotive that was built in 1968. The main engine and head-end power (HEP) engines of the GP40 were rebuilt in 1992 and 2005, respectively.

Table 5-2. Fuel-Based Emission Factors based on Notch Position for the GP40 and F59 Locomotive Main Engines.

Locomotive No, Model, and Engine	Notch Position	Fuel Use Percentage (%)[a]	NO as NO_2 (g/gal)	HC[d] (g/gal)	CO[d] (g/gal)	Opacity-based PM (g/gal)
NC 1792, GP40, EMD16-645	Idle	2.8	240	*14*	*52*	3.5
	1	0.8	260	*9.3*	*34*	2.0
	2	1.9	230	*8.2*	*16*	2.5
	3	2.8	240	*5.9*	*8.4*	2.0
	4	3.7	260	*3.1*	*3.9*	1.8
	5	5.0	260	*1.6*	*2.5*	1.6
	6	7.4	260	*0.6*	*5.1*	1.3
	7	8.8	260	*1.6*	*6.4*	1.1
	8	67	230	*3.5*	14	1.5
	Cycle Average[b]		240	3.5	13	1.6
NC 1755, F59PHI, EMD12-710	Idle	2.1	240	*1.7*	*13*	5.3
	1	1.0	170	*1.2*	*5.9*	2.4
	2	2.3	200	*5.8*	*3.3*	2.6
	3	3.5	190	*4.4*	*1.1*	2.1
	4	4.6	200	*1.6*	*5.3*	2.3
	5	5.7	210	*1.3*	*5.9*	2.2
	6	7.6	200	*0.4*	*7.4*	2.1
	7	8.8	230	*2.7*	*19*	1.5
	8	65	220	*1.8*	*12*	1.2
	Cycle Average[b]		220	1.9	11	1.6
NC 1797, F59PHI, EMD12-710	Idle	2.5	250	*14*	*5.5*	9.4
	1	1.4	190	*7.8*	*13*	4.2
	2	2.2	210	*7.0*	*11*	2.6
	3	3.4	230	6.9	*2.2*	2.2
	4	4.5	230	*4.1*	*5.3*	1.7
	5	5.4	230	*1.2*	*12*	1.5
	6	7.1	210	*1.2*	14	1.4
	7	8.9	200	*2.8*	21	1.1
	8	65	200	5.1	16	1.1
	Cycle Average[b]		210	4.7	15	1.5
EPA[c]	Minimum		220	3.1	11	5.0
	Maximum		320	15	51	8.5
	Fleet Average		260	10	32	6.3

[a] The fraction of fuel use for freight line-haul cycle is calculated based on time-based fuel use rate and line-haul duty cycle. The fraction of fuel use is adjusted in that dynamic braking is assigned to the idle mode.

[b] This is a cycle average emission factor based on adjusted line-haul cycle.

[c] Source: Data based on EPA reports converted to a fuel basis.[6, 19]

[d] Italic numbers indicate emission rates based on exhaust concentrations that are below the detection limit of gas analyzers. The detection limits for HC and CO are 13 ppm and 0.012 *vol*-%, respectively.

Note: More information of the calculations for a, b, and c is provided in Supporting Materials.

Table 5-3. Average Brake Specific Emission Factors for Throttle Notch 8.

Locomotive No, Model, and Engine	NO (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity based PM (g/bhp-hr)
NC1792, GP40, EMD16-645	11	0.17	0.65	0.073
NC1755, F59PHI, EMD12-710	11	0.09	0.58	0.060
NC1797, F59PHI, EMD12-710	8.8	0.25	0.76	0.054

Note: Brake specific emission factors were estimated based on fuel-based emission factors in Table 2 and brake specific fuel consumption (BSFC) of 0.048 gal/bhp-hr.[6, 19-21]

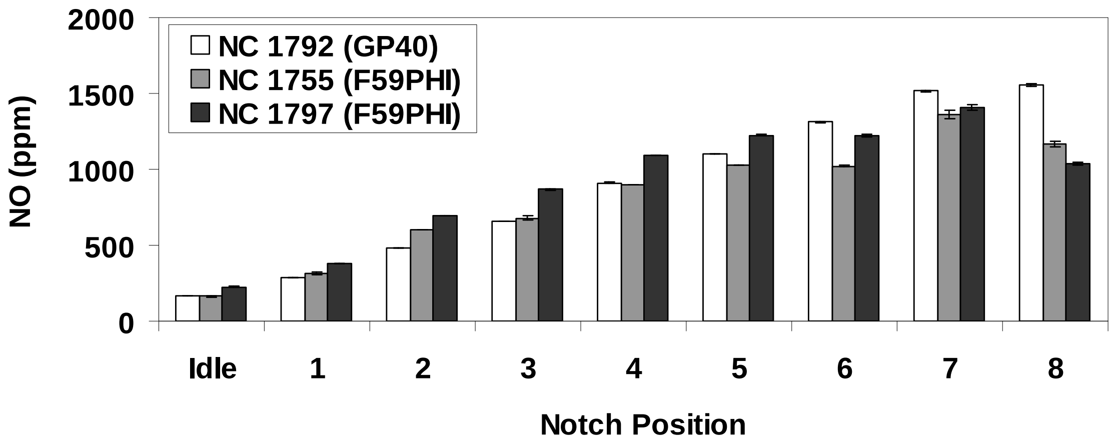
Table 5-4. Fuel-Based Emission Factors of Head-End Power Engine for the GP40 and F59 Locomotives

Locomotive No (Model, Engine)	Electrical Load Level[a]	Electrical Load (kW)	Fuel Use (g/sec)	NO as NO_2 (g/gal)	HC[b] (g/gal)	CO[b] (g/gal)	Opacity-based PM (g/gal)
NC 1792 (GP40, Cummins KTA19)	None	1.4	4.1	39	9.6	41	1.4
	Low	24	4.8	43	*3.7*	*19*	1.6
	Medium	37	5.8	50	*3.6*	*11*	1.7
	High	62	7.7	63	*3.4*	*9.4*	1.6
NC 1755 (F59PHI, CAT 3412)	None	1.3	5.2	130	12	82	2.4
	Low	17	6.0	150	8.9	60	1.6
	Medium	27	6.8	150	8.0	52	2.1
	High	53	9.2	170	6.5	38	2.1
NC 1797 (F59PHI, CAT 3412)	None	1.8	5.3	110	*7.9*	74	2.2
	Low	n/a	n/a	n/a	n/a	n/a	n/a
	Medium	37	7.4	130	9.1	50	2.6
	High	62	9.3	140	6.3	39	2.3

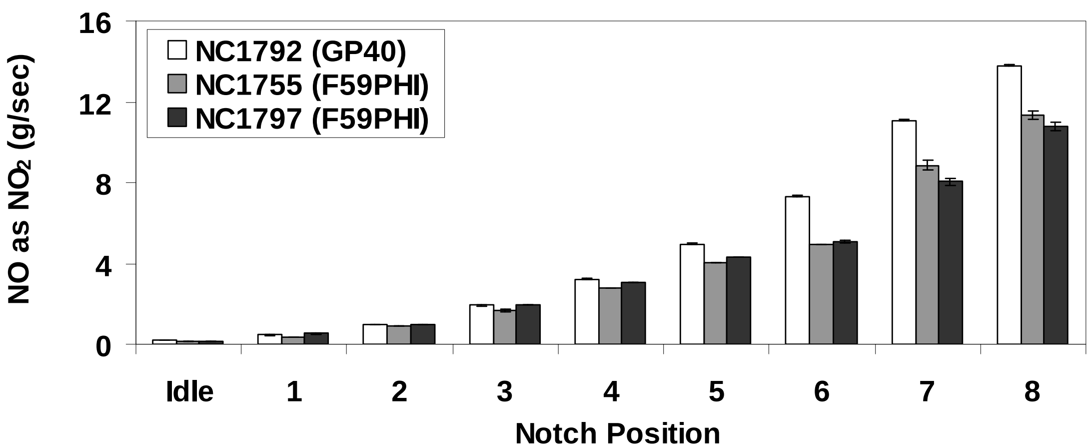
[a] For each car, all lights were turned on and the air conditioning was run at daytime thermostat setting (72 °F).

- None = only recharging of batteries
- Low = 1 passenger car
- Medium = 2 passenger cars
- High = 4 passenger cars
- n/a = not available

[b] Italic numbers indicate emission rates based on exhaust concentrations that are below the detection limit of gas analyzers. The detection limits for HC and CO are 13 ppm and 0.012 *vol*-%, respectively.



(a) Concentration



(b) Emission Rate

Figure 5-1. Average NO Concentration for the Prime Mover Engines of GP40 and F59PHIs versus Throttle Notch Position.

PART VI METHOD FOR IN-USE MEASURMENT AND EVALUATION OF THE ACTIVITY, FUEL USE, ELECTRICITY USE, AND EMISSIONS OF A PLUG-IN HYBRID DIESEL-ELECTRIC SCHOOL BUS[†]

[†] This manuscript was submitted to *Environmental Science & Technology*.

ABSTRACT

The purpose of this study is to demonstrate a methodology for characterizing at high resolution the energy use and emissions of a plug-in hybrid diesel-electric school bus (PHSB) to support assessments of sensitivity to driving cycles and comparisons to a conventional diesel school bus (CDSB). Data were collected using onboard instruments for a first-of-a-kind prototype PHSB and a CDSB of the same chassis and engine, operated on actual school bus routes. The engine load was estimated based on vehicle specific power (VSP) and an empirically derived relationship between VSP and engine Manifold Absolute Pressure (MAP). VSP depends on speed, acceleration, and road grade. For the PHSB, the observed electrical discharge or recharge to the traction motor battery was characterized based on VSP. The direct and indirect energy use and emission rates of the PHSB were estimated for five real-world driving cycles, and compared to the engine fuel use and emissions of the CDSB. The PHSB had the greatest advantage on arterial routes and less advantage on highway or local routes. The coupled VSP-MAP modeling approach enables assessment of a wide variety of driving conditions and comparisons of vehicles with different propulsion technologies.

Key words: Plug-in hybrid vehicle, vehicle specific power, emissions, diesel buses

6.1 Introduction

In the U.S., there are 450,000 school buses of which 87 percent use diesel fuel (*1*). These buses consume 1.1 billion gallons of diesel fuel a year and emit nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), and carbon dioxide (CO_2) (*2*). School districts in 12 states have purchased 19 prototype plug-in hybrid diesel-electric school buses (PHSBs) for evaluation (*3*). However, there is lack of a methodology and real-world data for comparing the energy use and emissions of PHSBs versus conventional diesel school buses (CDSBs) on a consistent basis for real-world cycles.

Typical methods for measuring vehicle emissions are engine or chassis dynamometers, tunnel studies, remote sensing, and on-board measurement (*4-6*). Most emissions data for heavy duty diesel vehicles are from engine dynamometers (*7*). Such measurements are for standardized driving cycles that do not represent real-world driving (*8*). Remote sensing and tunnel studies measure emissions only at fixed locations (*9*), and thus cannot represent an entire duty cycle. Portable Emission Measurement Systems (PEMS) can measure real-world activity, fuel use, and emissions (*10-12*) for a driving cycle, and are useful for development of emission models, such as the Environmental Protection Agency's (EPA) draft 2009 Motor Vehicle Emission Simulator (MOVES) (*13-15*).

Most previous estimates of fuel consumption of plug-in hybrid electric vehicles (PHEVs) are based on cycle averages, and do not account for variability at high temporal resolution. For example, the average fuel consumption for selected light duty gasoline PHEVs and conventional vehicles (CVs) were compared based on EPA fuel economy data obtained from chassis dynamometer tests using driving cycles such as the Federal Test Procedure (FTP) (*16-19*). Light duty PHEVs are estimated to reduce direct fuel consumption by approximately 40 to 50% (*16, 20, 21*). However, fuel consumption varies depending on driving cycle (*22*). A methodology based on second-by-second fuel use and emissions data is needed to estimate the real-world energy use and emissions under various driving conditions.

PHEVs include an internal combustion engine (ICE) and one or more traction electric motors (EMs). In order to compare fuel use and emission rates of a PHSB to CDSB for the same driving route, a modeling approach applicable to both types of vehicles is needed. Vehicle-specific power (VSP), which is a function of second-by-second speed, acceleration, and road grade, is highly correlated with conventional gasoline and diesel vehicle emissions (*9, 11, 15*). However, for PHSBs, the VSP-based methodology must be adapted to represent the distribution of power between the engine and the battery of the hybrid system. Hence, a mixed approach based on vehicle power demand and the portion of that demand that is met by the engine is needed.

The key objectives are to: (1) develop and demonstrate a methodology for characterization of a PHSB, taking into account diesel fuel and electricity consumption and emissions associated with each; and (2) assess whether and under what conditions the new technology has lower fuel use and emissions.

6.2 Methodology

This section describes: (1) design of a field study; (2) PEMS instrumentation; (3) field data collection; (4) data quality assurance; (5) estimation of indirect energy use and emissions; (6) manifold absolute pressure (MAP)-based emission model; (7) VSP-based emission model; and (8) coupled VSP-MAP mixed model.

6.2.1 Design of a Field Study

Field study design includes specification of all test conditions that are controllable including choice of test vehicle, driver, fuel, initial state-of-charge (SOC), route, and time of day for each route. Uncontrollable factors include traffic and ambient conditions.

The PHSB is equipped with an International VT365 diesel engine and an Enova System, Inc. parallel hybrid system. The CDSB is equipped with the same model of engine. The VT365 is a 230 hp 6.0 liter V-8 engine. Both buses are IC Bus (formerly IC Corporation) 2006 models. The PHSB has a 3-phase induction electric motor contained in the trans-axle that assists the engine. During deceleration, the battery is recharged by regenerative braking. The as-tested system does not allow the diesel engine to shut off when the PHSB is at rest, such as at a traffic light. The PHSB has a 35 kWh capacity Li-Ion battery manufactured by Valence Technologies, Inc. The 1,400 lb battery pack is located on the left-side. To balance the vehicle, 1,400 lb of ballast weight is located on the right-side. In later modifications, implemented after these measurements were completed, the battery weight was redistributed and the ballast removed.

The buses were operated on ultra low sulfur diesel (ULSD). The PHSB was recharged overnight. After the morning run, the PHSB was recharged for approximately four hours at a school bus parking lot until the start of the afternoon run.

Wake County, North Carolina school bus drivers operated the PHSB and CDSB on typical school bus routes for the morning and afternoon. Each bus served multiple schools in one day, including an elementary and high school. Both buses had as many as 50 students onboard at a given time.

6.2.2 PEMS Instrumentation

The OEM-2100 "Montana" system PEMS manufactured by Clean Air Technologies International (CATI) Inc., is comprised of two parallel five-gas analyzers, an engine scanner, a global positioning system (GPS), and an on-board computer. The gas analyzers measure exhaust concentrations of CO, CO_2, and HC using non-dispersive infrared (NDIR) and of O_2 and NO using electrochemical cells. NO_x is typically comprised of 92 volume percent NO (*23*); therefore, NO emissions converted to an equivalent NO_2 mass basis are an indicator of total NO_x emissions. The performance of the Montana system has been verified in comparison to that of a laboratory grade chassis dynamometer measurement system (*24*). The coefficients of determination (R^2) exceeded 0.86 for all pollutants, indicating good precision. The slopes of parity plots for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy, and ranged from 0.62 to 0.79 for HC. The bias for HC is a well-known result of the NDIR detection method (*25*). The PEMS is calibrated in the laboratory using a cylinder gas and in the field periodically recalibrates to ambient air to prevent instrument drift.

To measure GPS coordinates and elevation, a Garmin GPS with barometric altimeter was used. A temporarily mounted sensor array is used to measure MAP, intake air temperature (IAT), and engine RPM in order to estimate air and fuel use. A Panther diagnostic data logger was used to obtain electronic control unit (ECU) data from the hybrid system controller. The ECU data included vehicle speed, engine RPM, and electric current to or from the battery.

6.2.3 Field Data Collection

Field data collection occurred on December 20, 2007 for PHSB and on November 30, 2007 for CDSB. Data collection includes: (1) recording engine and chassis characteristics; (2) operating the PEMS, GPS, and ECU data logger; and (3) periodically checking the PEMS to identify and correct (if possible) data collection and quality assurance problems.

6.2.4 Data Quality Assurance

The processing of raw data from the data logger, PEMS, and GPS with altimeter included: (1) interpolation of the data to a second-by-second basis, if necessary; (2) synchronization of the data from multiple instruments into a single database; and (3) screening and evaluation of the data for possible errors, correction of errors where possible, and removal of invalid data that could not be corrected.

6.2.5 Indirect Energy Use and Emissions

From ECU data, the voltage and current to or from the plug-in battery, and the battery SOC, was observed. The net electricity obtained from the grid for battery recharging was used to estimate the diesel-equivalent amount of fuel consumed by power plants. The national average heat rate for power plants is 10,132 BTU of fuel energy input per kWh of power generated (*26*). The heating value of ULSD is approximately 139,000 BTU/gallon (*27*), and its density is 3,180 g/gallon (*28*).

Since the PEMS does not have a gas analyzer for sulfur dioxide (SO_2), the emission factor for SO_2 is estimated based on the sulfur content for ULSD, which averages 7.7 ppm (*29*).

6.2.6 MAP-based Emission Model

Fuel flow and emission rates are typically a monotonic function of MAP (*8, 30*). MAP indicates the portion of total vehicle power demand for the PHSB that is served only by the engine. MAP takes into account all factors that cause load on the engine, such as vehicle speed, acceleration, and road grade, less the portion of power supplied by the traction motor.

MAP-based modal rates are estimated with respect to normalized MAP. Normalized MAP is calculated on a second-by-second basis based on the minimum and maximum values of MAP observed during the test, and divided into 10 ranges. The MAP-based modal model is used to estimate the average fuel use or emission rate for a given duty cycle or route.

$$ER_{i,j} = \sum_{m=1}^{10} ER_i^m \times F_j^m \qquad (6\text{-}1)$$

Where:

$ER_{i,j}$ = fuel use or emission rates (g/s) for species i for driving cycle j,

ER_i^m = average fuel use and emission rates (g/s) of MAP mode m for VT365 engine for species i,

F_j^m = fraction of time spent in MAP mode m for driving cycle j,

i = species for pollutants (i.e. NO_x, CO, HC, PM, and CO_2) and fuel,

j = driving cycle, and

m = MAP mode.

6.2.7 VSP-based Emission Model

VSP is an estimate of the total power demand on the vehicle propulsion system excluding internal accessory loads (*13*):

$$VSP = v \times \left(a + 9.81 \times \sin\left(\frac{r}{100}\right) + 0.092 \right) + 0.00021 \times v^3 \qquad (6\text{-}2)$$

Where:

VSP = vehicle specific power (kW/ton),

v = vehicle speed (m/s),

a = vehicle acceleration (m/s^2), and

r = road grade (%).

The terms in the equation account for vehicle movement, acceleration due to gravity, rolling resistance, and aerodynamic drag. Typical coefficients for transit buses are used (*9, 31, 32*).

VSP is used to account for the *energy* demand of the PHSB and *fuel* demand of the CDSB. VSP is an estimate of the power output required of the drive-train in order to propel the vehicle. In a PHSB, this power output is met by both the ICE and EM. The energy use can be traced to diesel fuel consumption and electricity consumed from the grid, respectively. For the CDSB, engine fuel use is expected to be approximately constant for negative values of VSP, and to increase linearly with positive VSP.

6.2.8 VSP-MAP Mixed Model

The portion of VSP that is allocated to engine load is estimated using an empirical relationship between MAP and VSP. The MAP-based modal models are used to estimate fuel use and emission rates. The portion of VSP that is allocated to the traction motor is based on an empirical relationship between battery electricity discharge or recharge versus VSP. For the CDSB, an empirical relationship between MAP and VSP is also used. The use of the MAP-based modal model enables estimates of fuel use and emission rates to be made for both buses using an average result for both observed VT365 engines. The use of an average engine removes inter-engine variability from the comparisons between the two buses, enabling insights to focus on differences in duty cycles with respect to the hybrid versus conventional system.

6.3 Results and Discussion

Results are given regarding: (1) data quality assurance; (2) vehicle activity patterns; (3) MAP-based modal average fuel use and emission rates; (4) measured energy use versus VSP; (5) estimated direct fuel use and emission rate versus VSP; (6) indirect energy use and emissions; and (7) comparison of energy use and emissions for selected routes.

6.3.1 Data Quality Assurance

A total of 15,378 and 13,424 seconds of data were collected for PHSB and CDSB, respectively. Of these data, 93 and 91 percent were valid, respectively. The most frequent data quality issues were low exhaust gas concentrations associated with occasional high exhaust dilution during idle and discrepancies exceeding statistical limits between the parallel gas analyzers for some pollutant concentrations.

6.3.2 Vehicle Activity Patterns

The PHSB was measured for Route 1 and the CDSB was measured for Route 2. Route 1 was 150 miles roundtrip, of which approximately 61 percent was on highways. Route 2 was 95 miles roundtrip, of which approximately 86 percent was on signalized arterial and local roads. The average speed on Route 1 was 28 mph versus 19 mph on Route 2. Three additional duty cycles were considered to evaluate variability in driving conditions. The Highway cycle is based on the highway portion of Route 1 and is 15 miles long with an average speed of 43 mph. The Arterial cycle is based on the arterial portion of Route 2 and is 9.5 miles long, with an average speed of 22 mph. The local cycle, which is based on the local portion of Route 2, is 3.9 miles long with an average speed of 12 mph. For each cycle, the distribution of VSP was quantified based on second-by-second speed and acceleration measured on each route, and road grade estimated every one-tenth of a mile using the barometric altimeter.

6.3.3 Engine Average Fuel Use and Emission Rates

The engine-based modal rates were estimated with respect to normalized MAP. MAP is from 101 to 251 kPa for both buses. Figure 6-1 shows the modal average fuel use and emission rates for each VT365 engine and for the average of the two engines. Typically, fuel use rate and emission rates increase monotonically with normalized MAP. The two engines have similar fuel use, CO_2 emissions, and PM emissions rates for each MAP mode. The NO_x and CO emission rates for the two engines are approximately similar in trend and magnitude and thus are considered to be comparable. Since the HC concentration measurements for the two buses are below the detection limit of 15 ppm for the gas analyzers, the apparent differences between the MAP-based modal emission rates are not considered to be significant.

The difference of emission and fuel use rates between PHSB and CDSB based on normalized MAP is due to inter-engine variation. Although some of the differences are statistically significant, as a practical matter the estimated rates for both engines are of similar trend and magnitude. In order to remove inter-engine variability as a confounding factor in the comparisons between the two buses, the average of the rates for both engines are used in subsequent analyses.

6.3.4 Engine Average Fuel Use and Emission Rates

Figure 6-1 shows the modal average fuel use and emission rates for each VT365 engine and for the average of the two engines. The two engines have similar fuel use, CO_2 emissions, and PM emissions rates for each MAP mode. The NO_x and CO emission rates for the two engines are approximately similar in trend and magnitude and thus are considered to be comparable. Since the average HC concentration measurements for both buses were below the gas analyzer detection limit of 15 ppm, the apparent differences between the rates for a given mode are not considered to be significant.

The difference in MAP-based emission and fuel use rates between the PHSB and CDSB reflects inter-engine variation. Although some of the differences are statistically significant, as a practical matter the estimated rates for both engines are of similar trend and magnitude. In order to remove inter-engine variability as a confounding factor in the comparisons between the two buses, the average of the rates for both engines are used in subsequent analyses.

6.3.5 Measured Energy Use versus Vehicle Specific Power

The trend for engine load in terms of MAP versus VSP is shown in Figure 6-2 for each bus based on empirical data. As expected, the hybrid bus has lower average engine load than the conventional bus at high VSP because the traction motor provides supplemental power. At low VSP, the engine loads for both buses are not statistically different; however, the engine load appears to be slightly higher for the hybrid bus. For negative VSP, energy can be lost in the torque convertor between the engine and electric motor when the vehicle slows down. The extra weight in the PHSB due to the traction battery pack and ballast increases engine load and is estimated to decrease fuel economy by 0.2 mpg (*33*).

For the PHSB, the electricity use for the traction battery versus VSP is shown in Figure 6-3. Positive values of electricity use are for discharge of the traction battery to provide power to the traction motor. Negative values are associated with recharging from regenerative braking, during which the traction motor acts as a generator.

Based on the distribution of second-by-second VSP for Route 1, 44 percent of time was in discharge. The amount of power generated from regenerative braking was 58 percent of that consumed during discharge. Hence, 42 percent of the power, or 20 kWh, associated with discharge was obtained from the grid. For Route 2, which has a higher proportion of time spent on arterials, there was a higher percentage of regenerative braking, such that only 22 percent of the power, or 7.7 kWh, associated with discharge was obtained from the grid.

6.3.6 Estimated Direct Fuel Use and Emission Rates versus VSP

Using the distribution of VSP for each route, the relationship between MAP and VSP from Figure 6-2, and the MAP modal models of Figure 6-1, the direct fuel use and emissions of the engines for both buses were estimated. As an example, Figure 6-4(a) shows the estimated engine fuel use rates versus VSP. The PHSB has lower estimated fuel use rates than the CDSB at high VSP because of assistance from the traction motor. For negative

VSP, the fuel use rates for the PHSB are slightly but not significantly higher than that for the CDSB because of energy loss in the torque convertor. The trend in estimated NO_x emission rate in Figure 6-4(b) is similar to that for fuel use rate.

6.3.7 Indirect Energy Use and Emissions

The traction battery had 100 percent SOC at the start of the morning run. During the morning run, the battery was depleted to 68 percent SOC, corresponding to consumption of 11 kWh of electricity. After the morning run, the battery was recharged from 9:00 am to 1:45 pm to 93 percent SOC. During the afternoon run, the battery was depleted to 65 percent SOC, corresponding to consumption of 10 kWh of electricity. All observed operations were in charge depleting mode. The battery has an SOC set-point of 25 percent for the transition from charge depletion to charge sustaining mode. During the observed day of operations, only 60 percentage points of SOC were consumed; hence, it is not likely that charge depletion mode would have ended in the afternoon even if the battery had not been recharged mid-day.

The indirect emission factors (g/kWh) for grid electric power were estimated based on the EPA eGRID database for CO_2 and NO_x and from the National Emission Inventory for CO, HC, and PM (*34, 35*). These emission factors are based on 63 percent contribution of fossil fuel power generation to the total energy mix, which is typical in North Carolina. A transmission efficiency of 7.2 percent was assumed (*36*).

6.3.8 Comparison of Energy Use and Emissions for Selected Routes

The estimated direct and indirect fuel use and emission rates per mile for Routes 1 and 2, and for the Highway, Arterial, and Local cycles, are shown in Table 6-1. The fraction of time spent in each MAP mode was estimated based on the second-by-second distribution of VSP and the relationship between MAP versus VSP of Figure 6-2. The direct engine fuel use and emission rates were estimated for both buses for a given route using the MAP modal models of Figure 6-1 for the average VT365 engine. Using the empirically observed relationship between battery electricity use and VSP of Figure 6-3, the net indirect energy use was estimated for each route.

The engine-load cycle weighted average fuel use and emission rates for each bus were calculated based on the faction of time spent in each MAP mode for a given route. The route average rates were multiplied by total time duration of the round-trip for each route and divided by the round-trip mileage in order to estimate average emissions per mile of vehicle travel.

The estimated fuel use and emissions rates based on the VSP-MAP mixed model are generally similar to measured fuel use. For example, the differences in estimated versus measured cycle fuel use rates for the PHSB are within 3 percent for Routes 1 and 2. For the CDSB, the errors are within 4 percent.

The direct engine fuel use and emissions for the PHSB are lower than those for the CDSB, depending on the driving cycle. For example, the direct engine fuel use rates per mile are significantly lower by 5, 7, and 9 percent for Route 1, Route 2, and the Arterial, respectively. However, the fuel use rate is not significantly different for the Highway and Local cycles.

Except for SO_2, the indirect grid-based emission rates per mile were low compared to those from the tailpipe. For example, the tailpipe NO_x emission factors varied from 5 to 15 g/mile depending on bus type and route, versus a grid emission rate ranging from 0.05 to 0.17 g/mile, depending on the route. The indirect SO_2 emission rates of 0.2 to 0.7 g/mile are much higher than the direct emission rates of 0.01 g/mile or less.

The total of direct and indirect fuel consumption and emissions per mile for the PHSB is lower than for CDSB for Route 2 and the Arterial cycle, except for SO_2. For the Highway cycle, the total fuel consumption and emissions of SO_2 and PM are significantly higher, whereas the differences for NO_x, HC, and CO are not significant. The Highway and Arterial cycles represent the bounding cases for the relative difference, compared to the CDSB, in fuel consumption and emissions of NO_x, HC, SO_2, and PM. For example, the fuel consumption for the Highway cycle is 9.2 percent greater than for the CDSB but for the Arterial cycle is 6.8 percent lower. The stop-and-go pattern typical of the Arterial cycle takes advantage of regenerative braking. The ECU data indicate more frequent use of the EM under Arterial compared to Highway driving. For example, the average rate of battery discharge during Arterial driving is 0.37 kWh/mile, and the average rate of recharge is 0.32 kWh/mile. For the Highway cycle, these rates are only 0.21 and 0.03 kWh/mile, respectively. Somewhat counter-intuitively, the Local cycle did not produce the most favorable comparison for the PHSB. For the Local cycle, the fuel use reduction is not significant. The vehicle load is lower than for other cycles due to low vehicle speeds. In the low positive VSP range, the ICE is the dominant power source and the EM provides relatively little assistance compared to higher VSP ranges more characteristic of Arterial driving.

The PHSB direct tailpipe emission rates per mile are generally less than or equivalent to those of the CDSB. The PHSB total direct and indirect emissions are typically lower than for the CDSB except for SO_2 for all cycles, CO and HC for each of three cycles, and PM for two cycles. For example, for the Route 2 and Arterial cycles, the total NO_x emission factors are 6.3 to 8 percent lower.

6.4 Discussion

The methodology demonstrated here can be applied to estimate fuel use and emission factors for real-world driving cycles for plug-in hybrid vehicles. The results given here are not generalizeable to all PHSBs. The PHSB evaluated is a first-of-a-kind prototype that has not been optimized for maximum efficiency or lowest possible emissions. The method demonstrated here for estimating the power split between the engine and traction motor based on an empirically-directed relationship between engine load versus VSP and battery current versus VSP can be applied to refined PHSBs as they become available.

The use of two sources of energy for a vehicle raise questions regarding how to report or characterize fuel economy. For PHEVs, energy economy should be estimated taking into account the fuel equivalent of the energy required to generate the electricity consumed by the vehicle. The “energy economy” was found to be higher for the PHSB versus the CDSB by

3.8 and 7.3 percent for the Route 2 and Arterial cycles, respectively, lower by 2.2 and 8.4 percent for the Route 1 and Highway cycles respectively, and not significantly different for the Local cycle. The direct "diesel fuel economy" for the PHSB was approximately 3.2 to 9.5 percent better than for the CDSB, depending on the route.

The PHSB performed best, in comparison to the CDSB, when operated on arterial routes and when there were moderate engine loads under stop and go conditions. The comparative of the advantage of the PHSB was less when operating under steady cruising highway conditions or low engine power demand local driving. These attributes depend on the type of hybridization and control strategy of the hybrid system, and thus could differ for other PHSB designs.

The emissions from the grid associated with electricity used to recharge the PHSB occur at a different time and location than the tailpipe emissions. The tailpipe emissions occurred simultaneously with the on-road driving during morning rush hour and in the afternoon, and thus were distributed over the routes driven during the daytime. The indirect emissions occurred partly during mid-day and in the evening. For severe air quality days related to photochemical smog, the PHSB has adequate battery capacity to be entirely recharged overnight, in order to shift more of the electricity related emissions burden to night-time hours, while still being able to operate in charge depleting mode the following day.

A limitation of this work is that measurements were made only for one PHSB. There is inter-vehicle variability in energy use and emissions for the same year, make, and model of vehicle. To capture inter-vehicle variability, there is a need to test additional vehicles. To account for differences in vehicle design, additional generations of PHSBs should be tested as they become available.

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Table 6-1. Estimated Tailpipe and Indirect Emission Factors for each Route.

Route[a]	Vehicle[b]		Fuel (gal/mile)	NO_x (g/mile)	HC[c] (g/mile)	CO (g/mile)	SO_2[d] (g/mile)	PM (g/mile)
1	PHSB	Direct	0.13	5.8	0.34	3.2	0.0062	0.041
		Indirect[e]	0.010	0.13	0.0016	0.019	0.49	0.0063
		Total	0.14	6.0	0.35	3.2	0.50	0.048
	CDSB	Direct	0.14	6.2	0.35	3.3	0.0066	0.047
	Difference (%)	Direct	-5.5	-5.8	-1.5	-2.5	-5.5	-11
		Total	2.2	-3.7	-1.1	-1.9	7500	2.1
	Uncertainty[f] (%)		1.4	1.1	1.0	0.5	1.4	1.6
2	PHSB	Direct	0.17	7.6	0.45	4.2	0.0081	0.053
		Indirect[e]	0.006	0.079	0.00095	0.012	0.30	0.0038
		Total	0.17	7.7	0.45	4.3	0.31	0.057
	CDSB	Direct	0.18	8.2	0.46	4.4	0.0088	0.062
	Difference (%)	Direct	-7.2	-7.2	-2.0	-3.0	-7.2	-14
		Total	-3.7	-6.3	-1.8	-2.8	3400	-8.3
	Uncertainty[f] (%)		1.6	1.3	1.0	0.5	1.6	1.9
Highway	PHSB	Direct	0.11	4.8	0.27	2.4	0.0053	0.036
		Indirect[e]	0.014	0.17	0.0021	0.025	0.65	0.0083
		Total	0.12	5.0	0.27	2.4	0.66	0.044
	CDSB	Direct	0.11	5.0	0.3	2.4	0.0055	0.038
	Difference (%)	Direct	-3.1	-4.0	-0.1	-0.6	-3.1	-6.3
		Total	9.2	-0.6	0.7	0.5	12000	15
	Uncertainty[f] (%)		3.2	2.0	1.1	0.8	3.2	3.4
Arterial	PHSB	Direct	0.19	8.5	0.49	4.4	0.0092	0.062
		Indirect[e]	0.0040	0.050	0.00061	0.0075	0.19	0.0024
		Total	0.19	8.5	0.49	4.4	0.20	0.065
	CDSB	Direct	0.21	9.3	0.51	4.6	0.010	0.075
	Difference (%)	Direct	-8.7	-8.5	-3.6	-5.4	-8.7	-17
		Total	-6.8	-8.0	-3.5	-5.2	1900	-14
	Uncertainty[f] (%)		4.0	2.8	1.8	1.3	4.0	4.4
Local	PHSB	Direct	0.29	14.3	0.89	8.3	0.0144	0.097
		Indirect[e]	0.0067	0.083	0.0010	0.012	0.32	0.0040
		Total	0.30	14.4	0.89	8.3	0.33	0.10
	CDSB	Direct	0.30	14.8	0.88	8.3	0.015	0.10
	Difference (%)	Direct	-1.3	-3.3	0.4	-0.6	-1.3	-5.1
		Total	0.9	-2.7	0.5	-0.5	2200	-1.1
	Uncertainty[f] (%)		5.0	3.5	2.4	1.5	5.0	5.8

[a] Routes 1 and 2 are actual school bus routes for the hybrid bus and control bus, respectively. Highway is based on the highway portion of Route 1. Arterial is based on the arterial portion of Route 2. Local is based on the local portion of Route 2.

[b] PHSB = Plug-in Hybrid Electric School Bus. CDSB = Conventional Diesel School Bus.

[c] The average concentrations for HC were below the gas analyzer detection limit of 15 ppm.

[d] Tailpipe SO_2 emission factor is estimated based on average sulfur content of 7.7 ppm for ultra low sulfur diesel (*29*).

[e] For indirect fuel use or emissions, emissions per electricity generation (g/kWh) are calculated based on EPA eGRID for CO_2 and NO_x and NEI data for CO, HC, and PM for 2005 data (*34, 35*). eGRID: CO_2 = 553 g/kWh and NO_x = 0.809 g/kWh. NEI: CO = 0.13 g/kWh, HC = 0.0095 g/kWh, and PM = 0.044 g/kWh. These emission factors are estimated based on a 63 percent contribution of fossil fuel power generation to the total energy mix, which is typical in NC. The electricity use is estimated based on electricity vs. VSP. An electric transmission efficiency of 7.2 percent was used (*36*).. The average rates of electricity consumed from the grid are 0.13, 0.081, 0.18, 0.05, and 0.08 kWh/mile for Route 1, Route 2, Highway, Arterial, and Local, respectively.

[f] Uncertainty is calculated based on the full range of 95 percent confidential intervals on mean values for PHSB and CDSB. Thus, the 95 percent confidence interval is the mean plus or minus one half of the range shown.

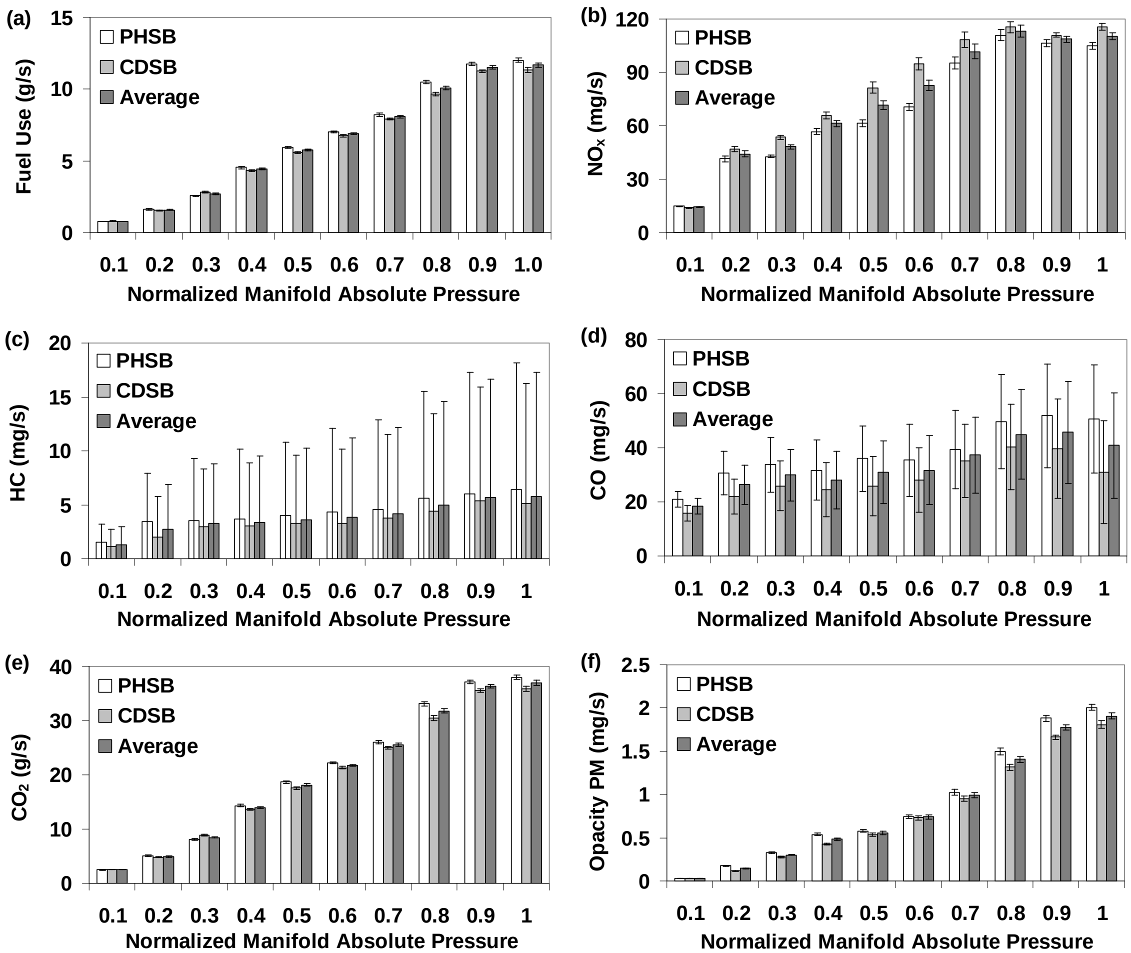


Figure 6-1. Average fuel use rate and emission rates for each manifold absolute pressure mode for VT365 engine. Note: PHSB = Plug-in Hybrid School Bus. CDSB = Conventional Diesel School Bus. Ranges shown are 95 percent confidential Intervals on mean values.

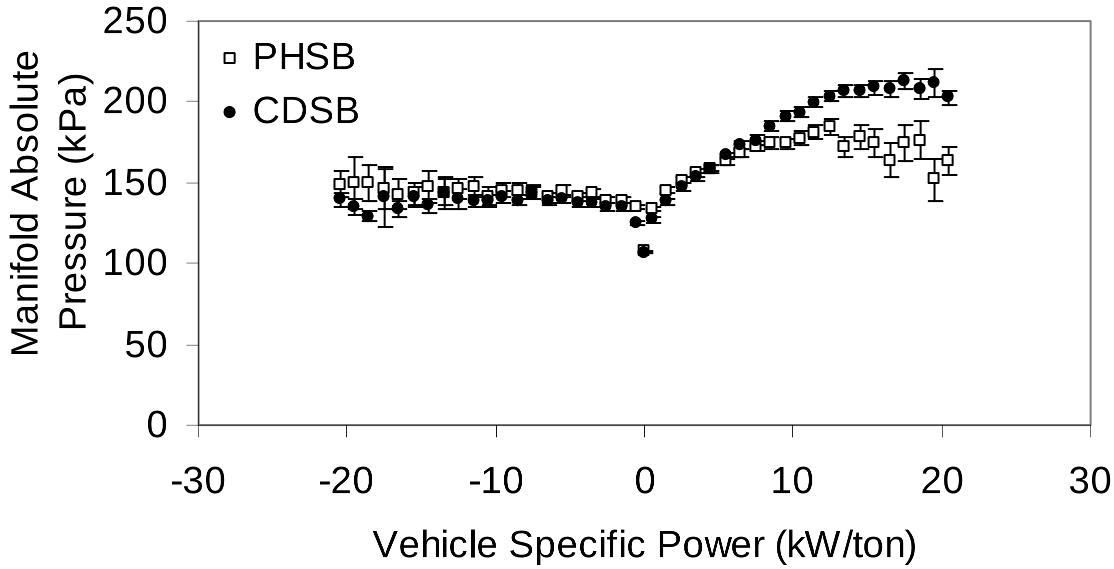


Figure 6-2. Measured Manifold Absolute Pressure versus Vehicle Specific Power.
Note: PHSB = Plug-in Hybrid School bus. CDSB = Conventional Diesel School Bus. Ranges shown are 95 percent confidential Intervals on mean values.

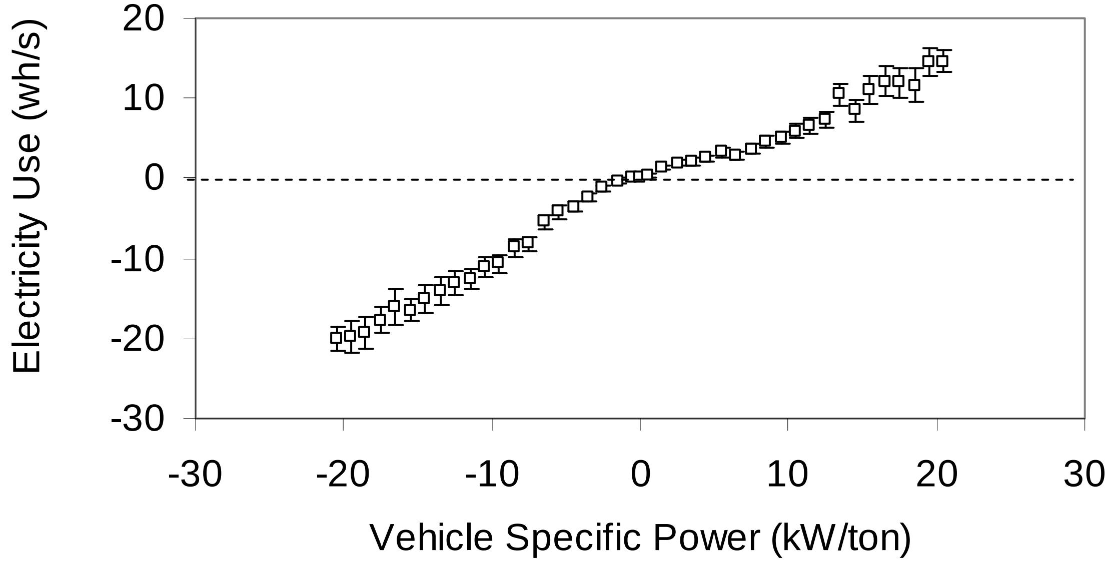
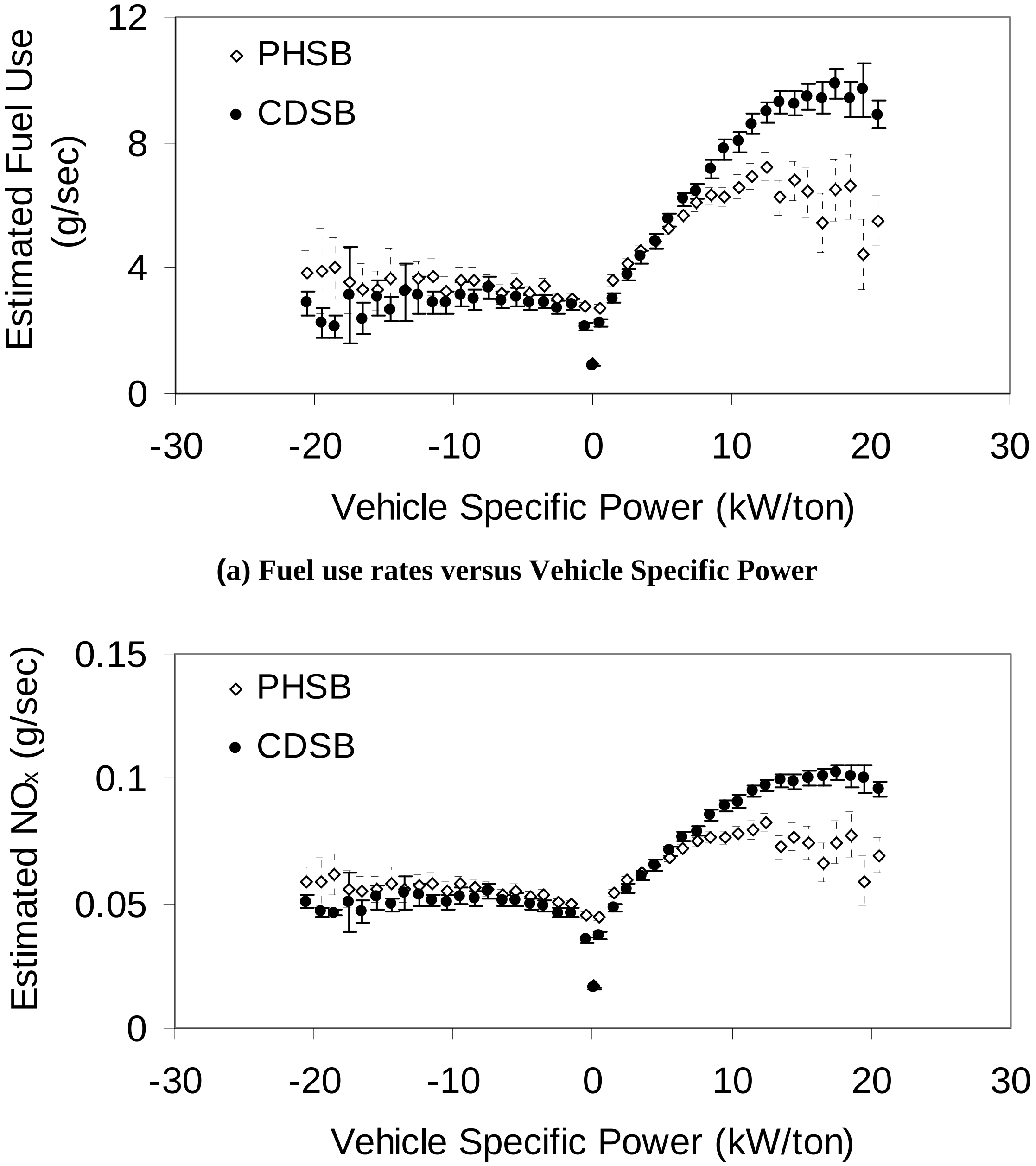


Figure 6-3. Electricity Use Rate versus Vehicle Specific Power. Note: Positive electricity use = discharge. Negative electricity use = recharge. Net fuel use for hybrid bus includes engine fuel use and equivalent fuel use for electricity use. Ranges shown are 95 percent confidential Intervals on mean values.



(a) Fuel use rates versus Vehicle Specific Power

(b) NO_x emission rates versus Vehicle Specific Power

Figure 6-4. Estimated Fuel Use and NO_x Emission Rates versus Vehicle Specific Power based on VSP-MAP Mixed Model. Note: PHSB = Plug-in Hybrid School bus. CDSB = Conventional Diesel School Bus. Ranges shown are 95 percent confidential intervals on modal weighted mean values.

PART VII CONCLUSIONS AND RECOMMENDATIONS

This chapter provides key findings, conclusions, and recommendation.

7.1 Findings

This section presents key findings regarding high and constant speed correction factors for light duty gasoline vehicles and diesel vehicles, emission rates of locomotive railyard test, and comparisons of fuel use and emissions between plug-in hybrid diesel-electric school bus and conventional diesel school bus.

7.1.1 High and Constant Speed Correction Factors for Light-Duty Gasoline Vehicles

For light-duty gasoline vehicles, emission factors for NO_x, HC, and CO_2 are found to be sensitive to the difference between constant versus transient speed for low speeds, with this difference decreasing on a relative basis as speed increases. In contrast, CO emissions are more sensitive to the difference between constant and transient speed at all speeds evaluated here.

For example of high speed, for an average speed of 78 mph compared to 63 mph, the average emission rate is approximately 32 percent higher for NO_x, 38 percent higher for exhaust HC, 84 percent higher for CO, and 10 percent higher for CO_2. The CO emission rate is the most sensitive to high speed, as expected, since CO emissions are very sensitive to fuel enrichment.

As expected, constant speed correction factor generally tends to increase with average speed. At low speeds, such as 30 to 53 mph, vehicle speed could vary from stop to approximately free flow speed. Thus, at this low speeds, there might be frequent acceleration and deceleration pattern and it leads higher exhaust emissions that for constant speed. However, at high speeds, there is little difference in emission rates and fuel economy, between driving at constant speed versus driving with typically small fluctuations in speed that are characteristic of these average speeds except CO. Constant speed correction factor (R_2) for CO is unique compared to the other three pollutants. The value of R_2 is relatively insensitive to speed, although it increases slightly as speed increases.

7.1.2 High and Constant Speed Correction Factors for Diesel Vehicles

The average emissions rates were found to differ significantly between speed-acceleration modes. In general, modal emission rates are significantly higher at high speed and high acceleration than those at low speed and deceleration. NO_x and CO_2 emission rates are relatively more sensitive to vehicle speed and acceleration than HC and CO.

In general, as average speed increases, there is less fluctuation in speed on a second-by-second basis. Thus, constant speed correction factor is generally low at low speeds such as 40 mph and high at high speed such as 78 mph except CO. The CO emission is relatively not sensitive to fluctuation in speed since diesel engine is usually operated with high air-to-fuel ratio.

The emission factors for CO and CO_2 are sensitive to high speeds such as 60 to 80 mph, as expected. However, the NO_x and HC emission factors are relatively insensitive to speeds above 63 mph.

7.1.3 Locomotive Rail-yard Test

The emission concentrations for NO and CO_2 for prime mover engines tend to increase as notch position increases. The concentrations for HC and CO are less sensitive to notch positions because they are usually less than a detection limit of Montana system.

Although a large percentage of time is estimated to occur in the idle mode, the majority of the fuel consumed is estimated to occur at the highest notch position. The rate of fuel consumption at notch position 8 is approximately two orders-of-magnitude higher than at idle.

Between test locomotives, the two F59 locomotives have very similar cycle average NO_x and PM emission rates. The GP40 has a similar average PM emission rate compared to the F59s, and a somewhat higher average NO_x emission rate.

For notch 8, it appears that the locomotives have either marginally or substantially higher NO_x emission rates than the Tier 0 standard for line-haul freight locomotives. For HC, it appears likely that NC 1792 has an emission rate that is comparable to the Tier 4 standard of 0.14 g/bhp-hr. The NC 1792 emission rate is likely to be below the Tier 4 standard of 0.14 g/bhp-hr. The NC 1797 emission rate is likely to be below the Tier 2 standard. For CO, it seems likely that the NC 1755, NC 1792, and NC 1797 locomotives can comply with any of the standards.

For Head-end-power engines (HEP), for all locomotives, the rate of fuel use, CO_2 emissions, and NO emissions increase as the electrical load increases. HC emission rates for diesel engines are not primarily sensitive to load and typically depend more on factors such as air-to-fuel ratio.

7.1.4 Plug-in Hybrid Diesel-Electric School Bus vs. Conventional Diesel School Bus

The VT365 engines for PHSB and CDSB have similar fuel use, CO_2 emissions, and PM emissions rates for each MAP mode. The NO_x and CO emission rates for the two engines are approximately similar in trend and magnitude and thus are considered to be comparable. Since the HC concentration measurements for the two buses are below the detection limit of 15 ppm for the gas analyzers, the apparent differences between the MAP-based modal emission rates are not considered to be significant.

As expected, fuel use is not sensitive to VSP for negative values, which usually represent deceleration or can represent situations in which a vehicle is traveling at constant speed on a negative road grade. For positive VSP, fuel use tends to increase as VSP increases for PHSB and CDSB. However, at these high VSP, fuel use for PHSB is significantly lower than that for CDSB because power from plug-in battery is used at high VSP range. Since the need for supplemental power from the electric motors is greatest during positive VSP, the electric consumption increases with positive VSP. Conversely, battery is recharged from regenerative brake during negative VSP.

The fuel use and emission rates are estimated for VT365 engine with same driving routes based on VSP-MAP hybrid model. To reduce inter-engine variability, engine load is estimated and fuel use and emission rates are estimated based on VSP distribution for real-world school bus driving cycles. When comparing emission rates per mile for tailpipe and grid, the grid-based emission rates per distance of vehicle travel were low compared to those from the tailpipe except for SO_2.

For comparison of emission factors for PHSB and CDSB, the overall energy (not just fuel) consumption is approximately the same regardless of the source of energy, which is to be expected. The total emission factors for PHSB are lower than those for CDSB except for SO_2 and PM. The SO_2 and PM are significantly emitted from power grid, especially due to coal-fired power plants.

7.1.4 Emission Estimation Methodology for Onroad and Nonroad Vehicle Emissions

In the study, the emissions discharged from wide variety of sources are estimated by three emission modal models using PEMS or chassis dynamometer. This study shows that similar methods can be used for various vehicle sources to estimate fuel use and emissions.

In general, the emission modal models are developed based on average emissions per vehicle activity. For example, in speed-acceleration modal model, the emissions are measured by PEMS and vehicle activity is estimated with vehicle speed and acceleration obtained from OBD or GPS data. VSP modal model can estimate more accurate real-world emissions because road grade known as a significant factor to vehicle emissions is used in model.

For non-road emissions, notch position modal model is used to estimate locomotive emissions. The cycle weighted average emission is typically estimated based on average modal emissions and typical duty cycles.

7.2 Conclusions and Recommendations

Key conclusion, recommendation and future work are summarized in this section.

7.2.1 High and Constant Speed Correction Factors for Light-Duty Gasoline Vehicles

The NO_x and CO_2 emission rates were most sensitive to the combined effect of the high speed and constant speed correction factors. For CO and HC, the corrected emission factors are lower than MOBILE6 result at speeds from 40 to 70 mph and the two correction factors compensate for each other at 80 mph, leading to differences of only 2 percent for both.

The implications of these results is that on-road emissions, and hence near-roadway air quality and exposure, are sensitive to characteristics of vehicle operations that are not accounted for in the MOBILE6 model, including operations at constant speed, high speed, or both. The potential error from not accounting for these operating conditions on short segments of highway can be as large as 49 percent at moderate speed and 24 percent at high speed.

The optimal fuel economy is obtained at speed of approximately 50 to 60 mph. At these speed ranges, exhaust emissions for NO_x and HC are also low but CO emission factor is lowest at approximately 40 mph. The CO emissions at constant speed are approximately 40 to 50 percent lower than for transient cycles with the same average speed. The CO emissions are also very sensitive to high speed such as 78 mph. We hypothesize that these results are based on episodes of fuel enrichment that can occur at high engine power demand under a wide variety of conditions.

For case study, uncertainty analysis in estimated emission factors is needed. Uncertainties for each speed might be quantified based on uncertainties for VSP modal emission rates for each VSP bin.

7.2.2 High and Constant Speed Correction Factors for Diesel Vehicles

The distance-based emission rates for diesel vehicles are estimated to be significantly different at high constant speed compared to estimates that are obtained from the MOBILE6 model.

For CO_2, which is indicative of fuel consumption, the emission factor is sensitive to acceleration and high speed. NO_x emission is more sensitive to acceleration than high speed. During acceleration, high engine temperature due to high engine load might lead high NO_x emission. HC emissions are less sensitive to acceleration and high speeds because diesel vehicle usually is operated with excess air. CO emission is sensitive to high speed. At high speed, diesel vehicle keeps high air-to-fuel ratio but the engine efficiency might be low.

The diesel vehicle emission rates at constant speed tend to be lower than those at transient speeds for NO_x, HC, and CO_2, except at very high speed. The findings for NO_x, HC, and CO_2 imply that traffic management or driver behavior efforts that lead to constant speed vehicle operations could reduce emissions and fuel use by as much as 15 to 30 percent without any change in vehicle miles travelled.

The methodology demonstrated here can be applied to estimate emission factors for real-world link-based situations in which vehicles are driving at constant speed, high average speed, or both. A similar methodology can be applied with the expected final release of EPA's MOVES model, which also will have modal emission rates that can be weighted to represent a wide variety of driving cycles.

The key limitations of this work are the relatively small sample sizes of data for some of the speed-acceleration modes, and the limited sample of vehicles for which second-by-second data were available for a wide variety of driving cycles. Over time, these limitations are expected to be addressed as second-by-second data become available from a variety of sources, including in-use measurements with portable emission measurement systems. This methodology demonstrated here is applicable to the estimation of emissions on short segments of highway for which vehicles may be driving at approximately constant speed. Such estimates are useful as part of assessment of emissions and air quality in the near vicinity of a roadway.

7.2.3 Locomotive Rail-yard Test

The emissions measurements suggest that the locomotives have emissions comparable to or less than the Tier 0 standard except for NO_x. The GP40 was manufactured prior to the initial model year for which the Tier 0 standard is applicable. The NC 1755 F59 was manufactured during the period to which the Tier 1 standard applies, and the NC 1797 F59 was manufactured the next year.

For HEP engines, fuel use and emissions are measured under no, low, medium, and high electrical loads. The fuel-based emission factors for the HEP engines are generally lower than those for the main engines for NO_x, similar for HC, and higher for CO and PM.

Overall, the data appear to be reasonable and should serve as a useful basis of comparison to data that could be collected in future measurement campaigns. Examples of factors that could be assessed in comparative studies with the results of this project include the effect of substitution of alternative fuel, such as B20 biodiesel, for ultra low sulfur diesel. Furthermore, the effect of hardware or operational modifications to the engines on emissions could be assessed. The same or similar methodology can be applied to other locomotives.

The methodology could be adapted for in-use measurement of locomotives in over-the-rail service. The advantage of this type of measurement would be to obtain real-world duty cycles that may be unique to passenger rail service, as opposed to the freight duty cycles assumed by EPA. For real-world locomotive tests, a key challenge for an in-use over-the-rail test will be the placement of the main unit of the Montana system so that it is not adversely affected by the high temperatures reached in the engine compartments.

The other concern for future work is to measure engine output power. The regulations for locomotives are in units of mass of emission per brake horsepower hour of engine output. However, it was not possible to measure brake specific fuel consumption (BSFC) in this work, since it is not practical to conduct an in-use measurement of shaft torque nor are engine map data readily available. Hence, the emission rates in units of g/bhp-hr were estimated for notch 8 with maximum engine horsepower. For future work, it is needed to measure horsepower of engine output for each notch position.

7.2.4 Plug-in Hybrid Diesel-Electric School Bus vs. Conventional Diesel School Bus

The methodology demonstrated here can be applied to estimate fuel use and emission factors for real-world driving cycles for plug-in hybrid diesel vehicles. VSP is a useful external observed variable to predict fuel use and emission rates with real-world driving cycles. For plug-in hybrid vehicles (PHVs), energy economy (not only fuel economy) should be estimated taking into account the fuel equivalent of the energy required to generate the electricity consumed by the vehicle.

Plug-in hybrid technology shows better emission reduction for stop-and-go driving patterns. This technology could be good for large fleet owners such as school bus or Fedex in urban areas.

The emission factors for plug-in hybrid diesel-electric school bus are lower than those for conventional diesel school bus except for SO_2 and PM emissions. This implies acid rain or particulate matter issues might arise in the future under existing electricity utility mix when PHEV significantly shares a market.

The key limitation of this work is that measurements were made only for one PHSB. There is inter-vehicle variability in energy use and emissions for the same year, make, and model of vehicle. Furthermore, there are differences in design of PHEVs. Some recent models of PHEVs might have better energy efficiency or have recent hybrid technology such as engine shut off during less power demands. Additional data collections for other models of PHEVs under wide variety of real-world driving cycles are needed to evaluate the effect of emissions from PHVEs.

7.2.5 Emission Estimation Methodology for Onroad and Nonroad Vehicle Emissions

The advantages of this methodology are (1) wide capability of estimation for fuel use and emissions for various emission sources; and (2) flexibility for controllable test conditions.

As mentioned earlier in section 7.1, this method can be applied to various types or advanced technologies of vehicle to estimate fuel use and emission rates.

When the emission inventory which means modal average emission data is set up, the modal model can estimate vehicle emissions under different controllable test conditions. For example, with an external observable variable data such as GPS coordinate and elevation data, cycle average emission rates can be simply estimated. The limitation of this method is that enough data collections are needed to estimate modal average fuel use and emission rates.

7.3 Overall Recommendations

This section is given overall findings and recommendations.

7.3.1 Air Quality Issue

Key findings: (1) The current emission factor model can mislead estimation of emission rates to evaluate near-roadway air quality; (2) Locomotive emission can affect air

quality in non-attainment area, such as Charlotte, NC; and (3) Adverse health effect to children from old diesel school bus.

Since the existing emission factor models such as MOBILE6 or MOVES are developed based on driving cycle average, highway emissions for short segments might be underestimated or overestimated.

In non-attainment area, the emissions produced from locomotives are significant problem. For example, locomotive NO_x emissions in the train station of Charlotte, NC can contribute significant local air pollution problem, such as ground ozone issue. According to EPA report, the idle time fractions of locomotives are very high. For example, average percentage of idle for passenger locomotives is 47.4 percent (EPA, 1998).

In Wake County, more than 75,000 students are transported on 900 buses each day. According to EPA, about a third of all diesel school buses were manufactured before 1990. These buses are not equipped with recent emission control devices such as diesel particulate filter (DPF) (WCPSS, 2009). In this study, emissions for PHSB are found to be lower than those for CDSB. Even if total emission rates between PHSB and CDSB, tailpipe emissions of PHSB are lower than CDSB.

Recommendations: **(1) To estimate valid emission rates in near road way, the emission correction factors that developed in the study should be used; (2) For locomotive emissions, a real-world duty cycle and emission rates should be measured during operation on railway; and (3) Old school buses should be replaced to new advanced school bus, such as PHSB.**

In this study, to support air quality studies, correction factors for emission factor model are developed. Estimated emissions could be compared to measured ambient air pollutants for future work.

The methodology for emission measurement and modeling are shown. In the future work, data collection for real-world passenger duty cycle is needed. In addition, data collections for HEP engine emission are needed.

For school buses, fleet owner or local government should consider the replacement of old school bus to advanced school bus to reduce adverse health effect for students.

7.3.2 Emission Reduction Strategies

Key findings: (1) Vehicle speed for optimum fuel economy and emissions are approximately speeds from 50 to 60 mph for light duty gasoline vehicles and from 30 to 60 mph for diesel vehicles; (2) To reduce locomotive emissions, new locomotive standard was released by EPA in 2008. Due to stringent standard, fleet owners might want to test their rebuilt locomotives with cost and time efficient method; and (3) Idle emission of school bus might be significant for public health.

For both gasoline and diesel engines, optimum fuel economy is achieved below 60 mph. The vehicle emissions are generally sensitive to acceleration. Thus, to reduce highway emissions, traffic strategies are important. For example, the congestion or speeding at highway should be avoided for environment aspect as well as economy and safety.

In 2008, new EPA standard for locomotive was introduced (CFR, 2008). This standard is more stringent than old standard. When fleet owners rebuild locomotives, they have to consider stringent emission standard but engine dynamometer facilities are not common like that for light duty vehicles. The emission measurement using PEMS is introduced as an alternative measurement method.

In this study, more than half hour of idle period was found during school bus waited student in the school parking lot each day. School bus drivers turned on engine to get electricity power for A/C or heater. According to EPA, some of school districts and local government have developed idle time regulations to reduce school bus idling (EPA, 2005).

Recommendations: **(1) Stake holder should keep current highways speed limit such as 60 mph for air quality; (2) The measurement for second-by-second emission data using PEMS could be an useful and inexpensive method; and (3) To reduce idle emission from school buses, federal government may give support local school districts to purchase advanced school bus such as PHSB. To develop advanced hybrid technology such as engine shut-off technology for idling, federal or local government could give incentive for innovation to vehicle manufacturer.**

To improve air quality, government need to invest and encourage for research regarding highway traffic design, new standard, and advanced vehicle technologies.

7.4 References

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APPENDICES

APPENDIX A: DATA QUALITY ASSURANCE

This appendix describes data screening and data quality assurance procedures in detail.

Engine Data Errors

On occasion, communication between the vehicle's onboard computer and the engine scanner may be lost, leading to loss of data. Sometimes the loss of connection is because of a physical loss of electrical contact, while in other cases it appears to be a malfunction of the vehicle's on-board diagnostic system. This rarely happens. However, when it happens, this error can be solved easily by rebooting the system in the field. After rebooting, the computer begins logging a new data file automatically. Thus, when this is noticed in the field, this error can be addressed. Loss of engine data is also obvious from the data file, since the missing data are evident and any calculations of emission rates are clearly invalid.

Gas Analyzer Errors

The Montana system has two gas analyzers, which are referred to as “benches.” Most of the time, both benches are in use. Occasionally, one bench is taken off-line for “zeroing.” Therefore, most of the time, the emissions measurements from each of the two benches can be compared to evaluate the consistency between the two. If both benches are producing consistent measurements, then the measurements from both are averaged to arrive at a single estimate on a second-by-second basis of the emissions of each pollutant.

When the relative error in the emissions measurement between both benches is within five percent, and if no other errors are detected, then an average value is calculated based upon both of the benches.

However, if the relative error exceeds five percent, then further assessment of data quality is indicated. A discrepancy in measurements might be due to any of the following: (a) a leakage in the sample line leading to one bench; (b) overheating of one of the benches; or (c) problems with the sampling pump for one of the benches, leading to inadequate flow. If one of these problems is identified for one of the benches, then only data obtained from the other bench was used for emissions estimation. When problems are identified in the field, then attempts are made to resolve the problems in the field. For example, if a leak or overheating problem is detected during data collection, then the problem is fixed and testing resumes. Data recorded during the period when a leak or overheating event occurred are not included in any further analyses.

Zeroing Procedure

For data quality control and assurance purpose, each gas analyzer bench is zeroed alternatively every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. After zeroing is finished, a solenoid valve changes the intake from ambient air to the tailpipe. There is a period of transition when this occurs. In particular, the oxygen sensor needs several seconds to respond the switching of gases, since there is a large change in oxygen concentration when this switch occurs. To allow adequate time for a complete purging of the previous gas source from the system, a time delay of 10 seconds is assumed. Thus, for 10 seconds before zeroing begins, the time period of zeroing, and 10 seconds after zeroing ends, data for the bench involved in zeroing are excluded from calculations of emission rates, and the emission rates are estimated based only upon the other bench.

Negative Emissions Values

Because of random measurement errors, on occasion some of the measured concentrations will have negative values that are not statistically different from zero or a small positive value (Durbin *et al.*, 2000). Thus, it is frequently the case that HC emission measurements are very low and not substantially different from zero. Negative values of emissions estimates were assumed to be zero and were replaced with a numerical value of zero.

Loss of Power to Instrument

A loss of power to the instrument resulted in a complete loss of data collection during the time period when power was not available. However, the system saves data up to the point at which the power loss occurs. A typical cause of power loss for manual transmission vehicles is stalling of the engine due to a problem shifting. Such problems typically occur when going from idle into first gear, or for the lower gears. After a loss of power, the instrument needs to be rebooted, which takes approximately five to ten minutes. During the power loss and rebooting, no data can be collected.

Criteria for Data Quality Assurance

- Engine Data: deleting unusual engine data for engine speed (ES), manifold absolute pressure (MAP) and intake air temperature (IAT)
    - Criteria
        - Unusual ES: ES<500 rpm or ES>4000 rpm
        - Missing MAP: MAP= − 34
        - Unusual IAT: $-1°C < (IAT_{t+1} - IAT_t) < 1°C$, t=-time
- Negative value: Using the levels of detection limits as acceptable negative value (ANV). HC: 20 ppm, CO: 0.018%
    - If negative value is larger in magnitude than ANV, this value is deleted because the negative value is significantly different from 0.
- Zeroing Effect: Data that are 10 seconds before and after zeroing procedure for each of the analyzers are deleted.
- Inter-Analyzer Discrepancy (IAD): If IAD is larger than the maximum acceptable difference (MAD), data is corrected or deleted.
    - MAD: NO 50 ppm, HC 28 ppm, CO 0.04 vol-%, and CO_2 0.6 vol-%
    - If IAD>MAD, and concentration values from both analyzers are greater than the detection limits for all pollutants over 15 consecutive seconds, data is deleted.

- If IAD>MAD, and concentration values from one analyzer for one or more pollutants is lower than the detection limits, the values form the analyzer which is greater than detection limits is used.
- If IAD>MAD, and concentration values from both analyzers are lower than the detection limits, the average value is sued.

- Gas Analyzer Freezing (GAF)
  - If corresponding emissions from both analyzers are same, the GAF error is suspected while engine data varies for two consecutive seconds.
  - $C_{i,t} = C_{i,t+1} > DL_i$ and $ED_{k,t} \neq ED_{k,t+1}$

    Where,

    $C_{i,t}$: Concentration of emission i at time t and t +1

    DL_i : Detection limit of emission i

    $ED_{k,t}$: Engine data k at time t or t+1

- Air Leakage
  - When Air to fuel (AFR) is greater than 150, air leakage is suspected.
  - If AFR >150, and all pollutants are below the precision of the Montana (0.02 vol-% for CO, 4 ppm for HC, 25 ppm for NO, and 0.3 vol-% for CO_2), data is excluded.

APPENDIX B: SUPPORTING INFORMATION FOR PART V

This supporting information (SI) provides supplementary texts, tables, and figures to further describe the measurement of the emissions of passenger rail locomotives using a portable emission measurement system.

Locomotive Emission Standard

The standards for locomotive line-haul and switching duty cycles are shown in Table B-1. The 2008 standard has more stringent emission limits for the Tier 0 to 2 standards compared to the 1997 standard, and introduces new Tier 3 and 4 standards. The Tier 3 standard requires a more stringent particulate matter (PM) emission rate than the Tier 2 standard. The Tier 4 standard, which will take effect in 2015, will require substantial reductions in emissions of nitrogen oxides (NO_x) and PM. EPA anticipates that the use of high-efficiency catalytic after-treatment technology will be required to meet the Tier 4 standard. To enable this technology, EPA requires the use of ultra low sulfur diesel fuel for locomotive engines. After-treatment technology is sensitive to and poisoned by sulfur oxides in the exhaust, and thus the requirement for ultra low sulfur diesel is to promote the longevity of the catalytic and after-treatment systems.

The engine load for a locomotive is controlled by a throttle that has predetermined "notch" settings. Emissions measurements typically involve characterization of the emission factor for each notch setting for a particular engine. The measurements in a notch setting are typically a steady-state measurement. The steady-state emission factors for each notch setting are weighted to arrive at an average emission rate for a duty cycle. EPA developed locomotive emissions standards based on the notch emission factors weighted by two typical duty cycles: line-haul and switching. Line-haul freight engines typically have large engines (e.g., 4,000 to 6,000 hp). Typically, switching locomotives have engines of 2000 horsepower or less. The duty cycles for line haul and switching operations are summarized in Table B-2. EPA does not use passenger duty cycle for regulation.

Locomotive Data Collection

A procedure was developed and implemented via which to sample exhaust gas from the duct of locomotive prime mover engines and obtain measurements of engine data, including RPM, manifold absolute pressure, and intake air temperature. The latter were needed because the engines are mechanically controlled and do not have an electronic control unit; thus, there is no equivalent of onboard diagnostic interface via which to obtain engine data. Now that fittings have been developed to enable measurement of the main engine exhaust gas and engine data for all engines, the pre-installation time for future stationary load tests in the railyard should be reduced. Of course, the pre-installation time is only a small component of the overall project effort when considering other preparation, data collection, decommissioning, data analysis, and reporting.

Pre-installation involves installing the exhaust gas sampling lines, power cable, and engine data sensor array on each engine to be measured. For the prime mover engines, sampling lines were connected from the Montana system to a fabricated sampling port on the exhaust gas duct in the engine room. For the HEP engines, exhaust gas sampling probes were inserted into the exhaust pipe. The probes were secured to the exhaust pipe using a hose clamp. In order to measure MAP, the pressure sensor was attached to the engine via a port that allows the pressure of the air entering the engine to be measured. The ports were created in the intake air box and intake air pipe for the prime mover and HEP engines, respectively. For the IAT, the temperature sensor was installed in the intake air flow path. For the engine RPM, the engine speed sensor was installed in the engine manifold with a strong magnet. The reflective tape was installed on a fly wheel that rotates at the same rate as the engine crankshaft.

Final installation was performed after completing all pre-installation steps. The Montana system was on a forklift next to the each locomotive and connected to the exhaust sample lines, engine data cables, and power cable. As a part of final installation, the gas analyzers were warmed up for approximately 45 minutes. This time period is recommended in order to ensure consistency of measurements made by the instrument.[1]

Field data collection occurred during a period from March 11, 2008 to July 24, 2008, as summarized in Table B-3. After finishing the tests of the NC 1755 F59 locomotive for main and head-end power engines, tests for the main and head-end power engines of NC 1755 GP40 Locomotive were done. In July, one more F59 locomotive, NC 1797, for main and head-end power engines was tested. Also, tests with electrical loads for head-end power engines of NC 1755 and NC 1792 were done in July, 2008.

The diesel fuel properties are summarized in Table B-4.

Fraction of Fuel Use for each Notch Position

The fraction of fuel use for freight line-haul cycle is calculated based on time-based fuel use rate and duty cycle. The fraction of fuel use is adjusted in that dynamic braking is assigned to the idle mode.

$$f_{n,j}^{fuel} = \frac{\left(M_n^{time} \times f_{n,j}^{time}\right)}{\sum_{n=1}^{N}\left(M_n^{time} \times f_{n,j}^{time}\right)} \quad \text{(B-1)}$$

Where,

$f_{n,j}^{fuel}$ = fraction of fuel use in each notch position n for duty cycle j,

M_n^{time} = time-based fuel use rate (g/sec) for notch position n, and

$f_{n,j}^{time}$ = fraction of time spent for notch position n for duty cycle j.

Cycle Weighted Emission Factor

The cycle average emission rate was calculated based on the total emissions for the cycle divided by the total fuel use for the cycle.

$$EF_{i,j}^{fuel} = \left\{ \frac{\sum_{n=1}^{N} EF_{n,i}^{time} \times f_{n,j}^{time}}{\sum_{n=1}^{N} M_{n}^{time} \times f_{n,j}^{time}} \right\} \left(\frac{3{,}180\,g}{gallon} \right) \tag{B-2}$$

Where,

$EF_{i,j}^{fuel}$ = cycle weighed emission factor (g/gal) of species i for duty cycle j

$EF_{i,n}^{time}$ = time-based emission factor (g/sec) of species i for notch position n

M_{n}^{time} = time-based fuel use rate (g/sec) for notch position n

$f_{n,j}^{time}$ = fraction of time spent for duty cycle j in each notch position n

Weighted Fleet Average Emission Factor

The fleet average emission rates of total 9,691 locomotives were provided by U.S. Environmental Protection Agency. The fleet average emission rates are weighted by the product of the number of locomotives in the fleet and the average power for each type of locomotives.[3]

$$ER_{i}^{avg} = \frac{\sum_{m=1}^{M} N_{m} \times HP_{m}^{cycle} \times ER_{i}^{m}}{\sum_{m=1}^{M} N_{m} \times HP_{m}^{cycle}} \tag{B-3}$$

Where,

ER_i^{avg} = fleet average emission rate (g/bhp-hr) for species i

N_m = number of locomotives for engine model m

HP_m^{cycle} = cycle weighted average engine power (hp) of engine model m

ER_i^m = emission rate (g/bhp-hr) for species i for engine model m

Time-Based Fuel Use and Emission Rates for Head-End Power Engine

The electrical loads are based on connecting passenger rail cars to the locomotives during the tests. The "Low" load setting is based on connecting one passenger rail car. "Medium" load is based on two passenger rail cars. "High" load is based on four passenger rail cars. Each rail car has lights and air conditioning. For each car, all lights were turned on and the air conditioner was run at its default daytime thermostat setting (72 °F). Time based fuel use and emission rates for HEP are shown in Table B-5.

References

1. CATI. *OEM-2100 Montana System Operation Manual*; Clean Air Technologies International, Inc.: Buffalo, NY, November, 2003.

2. U.S. Environmental Protection Agency. *Emission Fact: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel*; EPA420-F-05-001; U.S. Environmental Protection Agency: Washington, DC, 2005.

3. U.S. Environmental Protection Agency. *Locomotive Emission Standards: Regulatory Support Document*; EPA/98-04; U.S. Environmental Protection Agency: Ann Arbor, MI, 1998.

Table B-1. 2008 EPA Standards for Locomotives that are New or Remanufactured
(National Archives and Records Administration, 2008)

Standards Apply to Year of Original Manufacture	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	PM (g/bhp-hr)
Tier 0				
Line-Haul (1973-1992) [a, d]	8.0	1.00	5.0	0.22
Switcher (1973-2001)	11.8	2.10	8.0	0.26
Tier 1				
Line-Haul (1993-2004) [a]	7.4	0.55	2.2	0.22
Switcher (2002-2004) [b]	11.0	1.20	2.5	0.26
Tier 2				
Line-Haul (2005-2011) [a]	5.5	0.30	1.5	0.10 [e]
Switcher (2005-2010) [b]	8.1	0.60	2.4	0.13 [e]
Tier 3				
Line-Haul (2012-2014) [c]	5.5	0.30	1.5	0.10 [f]
Switcher (2011-2014)	5.0	0.60	2.4	0.10
Tier 4				
Line-Haul (2015 or later)	1.3	0.14 [g]	1.5	0.03
Switcher (2015 or later)	1.3	0.14 [g]	2.4	0.03

[a] Tier 0-2 line-haul locomotives must also meet switch standards of the same tier.
[b] Tier 1-2 switch locomotives must also meet line-haul standards of the same tier.
[c] Tier 3 line-haul locomotives must also meet Tier 2 switch standards.
[d] 1993-2001 locomotive that were not equipped with an intake air coolant system are subject to Tier 0 rather than Tier 1 standards.
[e] 0.24 g/bhp-hr until January 1, 2013.
[f] 0.20 g/bhp-hr until January 1, 2013.
[g] Manufacturers may elect to meet a combined NO_x+HC standard of 1.4 g/bhp-hr for line-haul and 1.3 g/bhp-hr for switcher.

Table B-2. EPA Duty Cycles for the Locomotives

Throttle Notch	Percent Time in Notch		
	Line-Haul	Switch	Passenger
Idle	38.0	59.8	47.4
Dynamic Brake	12.5	0	6.2
1	6.5	12.4	7.0
2	6.5	12.3	5.1
3	5.2	5.8	5.7
4	4.4	3.6	4.7
5	3.8	3.6	4.0
6	3.9	1.5	2.9
7	3.0	0.2	1.4
8	16.2	0.8	15.6

Table B-3. Data Collection Schedule

Locomotive	Model	Period		Engine	
		Start	End	Prime Mover	Head-End Power
NC 1755	F59PHI	03/11/08	07/24/08	03/13/08	03/14/08 and 07/24/08
NC 1792	GP40	03/23/08	07/23/08	03/25/08	03/26/08 and 07/23/08
NC 1797	F59PHI	07/21/08	07/22/08	07/22/08	07/22/08

Table B-4. Properties of Ultra Low Sulfur Diesel (ULSD)

Determinations	Petroleum Diesel
Density (g/gal)	3,180
Heat Value (BTU/gal)	
Higher	137,000
Lower	129,000
Carbon Content (g/gal)[a]	2,778
Elemental Composition	
Carbon (wt.%)	86.4
Hydrogen (wt.%)	13.6
Sulfur (ppm)[b]	15

[a] Source: EPA, 2005.[2] Available at http://www.epa.gov/OMS/climate/420f05001.htm

[b] All tests used ultra low sulfur diesel.

Table B-5. Time-based Fuel Use and Emission Rates for the Head-End Power (HEP) Engines of the GP40 and F59PHI Locomotives

Locomotive No, Model, and Engine	Electrical Load Level[a]	Electrical Load (kW)	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC[b] (mg/sec)	CO[b] (mg/sec)	Opacity-based PM (mg/sec)
NC 1792, GP40, Cummins KTA19	None	1.39	4.1	0.05	12	53	1.9
	Low	24.0	4.8	0.06	*5.6*	*29*	2.5
	Medium	37.0	5.8	0.09	*6.6*	*20*	3.3
	High	62.4	7.7	0.15	*8.3*	*23*	4.0
NC 1755, F59PHI, CAT 3412	None	1.34	5.2	0.22	20	130	4.1
	Low	16.6	6.0	0.28	17	110	3.2
	Medium	26.9	6.8	0.33	17	110	4.7
	High	52.8	9.2	0.48	19	110	6.4
NC 1797, F59PHI, CAT 3412	None	1.82	5.3	0.18	*13*	120	3.9
	Low	n/a	n/a	n/a	n/a	n/a	n/a
	Medium	36.5	7.4	0.31	21	120	6.2
	High	62.4	9.3	0.41	18	110	7.1

[a] For each car, all lights were turned on and the air conditioning was run at daytime thermostat setting (72 °F).

- None = only recharging of batteries
- Low = 1 passenger car
- Medium = 2 passenger cars
- High = 4 passenger cars
- n/a = not available

[b] Italic numbers indicate emission rates based on exhaust concentration that are below the detection limit of gas analyzers. The detection limits for HC and CO are 13 ppm and 0.012 vol-%, respectively.

APPENDIX C: SUPPORTING INFORMATION FOR PART VI

This supporting information (SI) provides supplementary texts, tables, and figures to further describe the in-use measurement of the activity, fuel use, electricity use, and emissions of a plug-in hybrid diesel-electric school bus (PHSB). The information contained herein includes:

(1) Description of hybrid system;

(2) Engine specifications;

(3) School bus routes and driving schedule;

(4) Portable emission measurement system;

(5) Data collection;

(6) Quality assurance procedure;

(7) Vehicle specific power distributions for each route; and

(8) Manifold absolute pressure distributions for each route.

C1. Description of Hybrid System

Since a plug-in hybrid diesel-electric school bus (PHSB) has two energy sources for vehicle propulsion, PHSB has a different fuel use and emission pattern compared to a conventional diesel school bus (CDSB). This section describes the hybrid system for a PHSB that was the focus of field data collection. Figure C-1 shows a configuration for a parallel hybrid system.

The PHSB has a post-transmission parallel hybrid drive system. The parallel hybrid vehicle is driven by an internal combustion engine (ICE) and a traction electric motor. A hybrid control unit receives signals from the vehicle accelerator pedal position and brake pedal position to decide the amount of power demand for each of the motor and engine for propulsion or to command the motor to generate electricity during regenerative braking.

C2. Engine Specification

The PHSB and CDSB each include a VT-365 diesel engine built by International Corporation. The VT-365 is 6 liter engine with 8 cylinders and produces a maximum power of approximately 200 to 215 hp at 2,600 rpm. It is a 4 stroke turbocharged diesel engine. The compression ratio is 18:1. Engine weight is approximately 1,062 pounds.

C3. School Bus Driving Schedule

School bus routes for PHSB and CDSB based on field measurements are shown in Figure C-2. Route 1 was measured for PHSB and Route 2 was measured for CDSB.

Route 1: Hybrid Bus Testing on December 20, 2007. The bus left the school bus parking lot on Rock Quarry Rd. at approximately 5:45 am. The PHSB traveled toward Apex to begin pickup of high school students. The bus had several stops around Apex before arriving at Apex High School to drop high school students off. The bus remained at Apex High School for 30 to 45 minutes to allow elementary students to board. On this particular route, Apex High School serves as a drop-off point for elementary students who attend

Washington Elementary. Between 7:45 am and 8:15 am, the research assistants of North Carolina State University (NCSU) asked the bus driver to keep the bus at idle for data collection while waiting at Apex High School. This may or may not typically be the case. The bus left Apex High School at approximately 8:15 am and traveled throughout Apex while making a few stops. The bus drove on US-1 and Interstate 440 to Washington Elementary on Fayetteville Street for student drop-off before returning to the school bus parking lot for a mid-day break.

From approximately 9:00 am to 1:40 pm the engine was turned off. During the mid-day break, PHSB was recharged in the school bus parking lot. The afternoon route began at approximately 1:40 pm as the hybrid bus left the bus parking lot on Rock Quarry Rd. and traveled to Apex High School to pick up high school students. The bus spent time waiting at Apex High School for the school day to end. The bus followed the high school route until all students were dropped off. The PHSB traveled to Fayetteville Street where elementary students were waiting at Washington Elementary. The bus traveled back to Apex High School to drop some students off with their parents. A few more stops were made in the afternoon to drop off all elementary school students before the bus returned to the bus parking lot on Rock Quarry Rd. at approximately 5:00 pm. The hybrid bus had much more highway travel time then a typical school bus since it serves a route with a common drop off spot (Apex High School) for students.

Route 2: Control Bus Testing on November 30, 2007. The CDSB control bus left the public school bus parking lot on Rock Quarry Rd. at around 5:45 am, before making a series of stops around the eastern part of Raleigh to pick up high school age students. The bus dropped off the high school students at Athens Drive High School on Avent Ferry Rd at approximately 7:15 am. For about half an hour the students unloaded and the bus remained parked at Athens Drive high school until it was time for the elementary school route. The research assistant asked the bus driver to leave the engine running during this time. The bus left Athens Drive High School around 7:45 am to begin the elementary school route. It covered the western part of Raleigh to pick up elementary students on several stops. The bus delivered the students downtown at Washington Elementary school on Fayetteville Street. The bus completed its morning route by returning to the school bus parking lot on Rock Quarry Rd.

There was a large break from approximately 8:45 am to 1:40 pm when the bus is parked and not in operation. The afternoon route followed the same trend as the morning route except it is in reverse. The bus left the school bus parking lot on Rock Quarry Rd, an\d arrived at Athens Drive High School at approximately 2:00 pm, and remained at idle until the school day ended and students boarded the bus. After dropping students at their stops, the bus picked up students from Washington Elementary. The elementary students were delivered to their stops and the bus retraced the elementary route in reverse before returning to the bus parking lot on Rock Quarry Rd. for the end of day at around 4:30 pm to 5:00 pm.

C4. Portable Emission Measurement System (PEMS)

To measure real-world tailpipe emissions for PHSB and CDSB, a portable emissions measurement system (PEMS) was used. This section describes PEMS that was used for field data collections.

The OEM-2100 Montana system is comprised of two parallel five-gas analyzers, an engine scanner, a global position system (GPS), and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxide (NO), and oxygen (O_2) in the vehicle exhaust.

A sensor array was used to measure engine data, including Manifold Absolute Pressure (MAP), intake air temperature, and engine RPM.

For the PHSB, a Panther data logger was used to measure electronic control unit (ECU) data, such as engine RPM, and hybrid control unit data, such as battery state of charge (SOC).

A GPS system measured vehicle position. The on-board computer synchronizes the incoming emissions, engine, and GPS data. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1).

The gases and pollutants measured include O_2, HC, CO, CO_2, and NO using the following detection methods:

- HC, CO, and CO_2 using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used (1). NDIR responds partially depending on the mix of HC species.
- NO measured using electrochemical cell. On most vehicles, NO_x is comprised of approximately 95 volume percent NO (2).

The Montana system is designed to measure emissions during the actual use of the vehicle or equipment in its regular daily operation. The complete system comes in two weatherproof plastic cases, one of which contains the monitoring system itself, and the other of which contains sample inlet and exhaust lines, tie-down straps, AC adapter, power and data cables, various electronic engine sensor connectors, and other parts. The monitoring system weighs approximately 35 *lbs*. The system typically runs off of the 12V DC vehicle electrical system, using the cigarette lighter outlet. The power consumption is 5-8 Amps at 13.8 V DC.

The Montana system was compared and evaluated by Battelle using an laboratory level chassis dynamometer measurement system (*3*). Emissions of several vehicles were measured simultaneously on a dynamometer and with a PEMS. The coefficient of determination (R^2) was higher than 0.86 for all pollutants. The slopes of parity plots varied from 0.92 to 1.1 for CO, CO_2, and NO. The slope for HC ranged from 0.62 to 0.79 because of well-known bias for HC measurement of NDIR (*4*).

The Montana system includes a laptop computer that is used to collect and synchronize data obtained from the engine scanner, gas analyzers, and GPS system. Data from all three of these sources are reported on a second-by-second basis. The computer is controlled either by touching the screen or plugging in a keyboard. Upon startup, the computer queries the user regarding information about the test vehicle, fuel used, test characteristics, weather conditions, and operating information. Most of this information is for identification purposes. However, the fuel type and composition, engine displacement, sample delivery delays, unit configuration, intake air sensor configuration, and volumetric efficiency are critical inputs that affect the accuracy of the reported emission rates. The details of the definition and significance of each of these are detailed in the Operation Manual of the instrument (*5*). The software provides a continuous display of data during normal operation, including gas analyzer data, engine scanner data, GPS data, and calculated quantities including the emission rate in units of mass per time. The following parameters are typically available on a second-by-second basis: road speed, engine rpm, turbocharger boost pressure, concentrations of the measured pollutants, exhaust flow, air fuel ratio, fuel consumption, mass flow rates of the measured pollutants. The data are available in ASCII text, comma-delimited format, but can be supplied in any user-defined format on demand.

C5. Data Collection

There are four steps for field data collection: (1) Pre-installation; (2) Final installation; (3) Data Collection; and (4) Decommissioning.

Pre-installation was performed the afternoon or evening before a scheduled test. This step involves installing on the vehicle the exhaust gas sampling lines, power cable, and engine data link. The exhaust gas sampling lines have a probe that is inserted into the tailpipe. The probe is secured to the tailpipe using a hose clamp. The sampling line is secured to various points on the chassis of the vehicle using plastic ties. The sampling line is routed through the passenger side window of the bus so that it can be connected to the Montana system main unit. Likewise, a power cable is routed from a cigarette lighter so that it can be connected to the Montana system. An engine sensor array was used to measure manifold absolute pressure (MAP), engine revolutions per minute (RPM), and intake air temperature (IAT). MAP, RPM, and IAT are used, in combination with the measured exhaust gas composition, to estimate the fuel and air flow through the engine. The amount of time for pre-installation was approximately an hour per vehicle.

Final installation was performed in the morning prior to field data collection. The Montana system main unit was secured in the passenger seat of the bus. Since the school bus was approximately 40 feet long, the Montana was placed in rear-side seat to use a typical length of exhaust sample lines. The engine data cables and power cable were extended and connected to Montana system. In addition, a GPS receiver was deployed. As part of final installation, the Montana system main unit was warmed up for about 45 minutes. The research assistant entered data into the Montana system regarding vehicle characteristics and fuel type. Figure C-3 illustrates the installation of the PEMS, sampling hoses, GPS, sensor box, and manifold absolute pressure sensor.

Data collection involved continuously recording, on a second-by-second basis, exhaust gas concentration, engine, and GPS data. The research assistant periodically checked on the status of the PEMS, in order to determine quickly if any problems arose during data collection that could be corrected. For example, sometimes there can be a loss of signal that can be corrected by checking connections in a cable. Sometimes the gas analyzers "freeze" (they fail to continuously update) which can be corrected by rebooting the gas analyzer. However, these problems did not occur during the testing.

Decommissioning occurs after the end of the test period. During decommissioning, the research assistant discontinued data collection, copied data that were collected, powered down the Montana system, and removed the exhaust sample lines, power cable, sensor array, ECU data logger, and GPS receiver.

C6. Data Quality Assurance

For quality assurance purposes, the combined data set for a vehicle run is screened to check for errors or possible problems. If errors are identified, they are either corrected or the data set is not used for data analysis.

Engine Data Errors. On occasion, communication between the sensor array and the Montana may be lost, leading to loss of data. Sometimes the loss of connection is because of a physical loss of electrical contact, while in other cases it appears to be a malfunction of the sensor array. This rarely happens. However, when it happens, this error can be solved easily by rebooting the system in the field. After rebooting, the computer begins logging a new data file automatically. Thus, when this is noticed in the field, this error can be addressed.

Loss of engine data is also obvious from the data file, since the missing data are evident and any calculations of emission rates are clearly invalid.

- *Unusual Engine RPM*: Engine RPM typically varies from not less than 600 RPM during idling to about 3,000 RPM during most kinds of vehicle operation. As a conservative estimate, the bounds for possible engine RPM were set as greater than or equal to 600 RPM and less than or equal to 10,000 RPM (*6*). Thus, if engine RPM is less than 600 or greater than 10,000 RPM, those data need to be removed. However, this problem did not occur in any of the data collected in our previous work for NCDOT.
- *Engine RPM Freezing*: "Freezing" refers to situations in which a value that is expected to change dynamically on a second-by-second basis remains constant over an unacceptably or implausibly long period of time. Engine RPM tends to fluctuate on a second-by-second basis even if the engine is running at approximately constant RPM. Therefore, we performed a check to identify situations in which engine RPM remained constant for more than three seconds. This problem occurs only in situations where the engine scanner became physically disconnected from the data logging computer. This type of error is rare.

Gas Analyzer Errors. There are several data quality checks regarding the gas analyzer, including removal of data during "zeroing," checking for situations with excessive exhaust dilution that lead to imprecision in exhaust concentration measurements, comparison of results between the two gas analyzers, and treatment of exhaust concentrations that appear to be negative values. The Montana system has two gas analyzers, which are referred to as "benches." Most of the time, both benches are in use. Occasionally, one bench is taken off-line for "zeroing."

- **Zeroing:** To prevent instrument drift, each gas analyzer bench is zeroed alternatively every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. After zeroing is finished, a solenoid valve changes the intake from ambient air to the tailpipe. There is a period of transition when this occurs. In particular, the oxygen sensor needs several seconds to respond the switching of gases, since there is a large change in oxygen concentration when this switch occurs. To allow adequate time for a complete purging of the previous gas source from the system, a time delay of 10 seconds is assumed. Thus, for 10 seconds before zeroing begins, the time period of zeroing, and 10 seconds after zeroing ends, data for the bench involved in zeroing are excluded from calculations of emission rates, and the emission rates are estimated based only upon the other bench.

- **Excess dilution**: A high dilution of exhaust gas might be observed either in the sampling hoses or inside the main unit of the Montana system. Such situations typically occur at or near engine idle conditions, when the air-to-fuel ratio (AFR) in the engine is high. The dilution of exhaust concentrations can lead to non-detection of exhaust components by the gas analyzers. To indicate the possibility of excess dilution, the AFR is used as an indicator.

- o When AFR is greater than 150, excess dilution is suspected.
- o If AFR >150, and all pollutants are below the precision of the Montana (0.02 vol-% for CO, 4 ppm for HC, 25 ppm for NO, and 0.3 vol-% for CO_2), data are excluded.

- **Inter-analyzer discrepancy (IAD)** is the absolute value of the difference in measured pollutant concentration for a given pollutant between $A_n$alyzer A and Analyzer B. The IAD is compared to the maximum acceptable difference (MAD) between the readings of both analyzers to determine if further examination of the data is needed. The MAD for each pollutant is determined by the level of precision of each sensor. Table C-1 provides the levels of precision for each pollutant, as reported by the sensor manufacturer (*7*). For example, the precision of the NO sensor is reported as ± 25 ppm for the NO measurement in the concentration range 0 to 4,000 ppm. This implies that the concentration of NO in one second of data collection can be reported 25 ppm higher than the true concentration from one analyzer, while the other analyzer provides 25 ppm less than the true concentration. Thus, the typical maximum allowable difference between the two analyzers' readings for NO will be 50 ppm. Therefore, a MAD value of 50 ppm is assumed for NO. If the IAD for NO is less than the MAD of 50 ppm, then an average of NOx analyzer concentrations is used to estimate emission rates. However, if the difference between the analyzers is greater than the MAD, further investigation is needed to determine if an error has occurred. The MAD values for HC, CO, and CO2 emissions are shown in Table C-1.

- If IAD is larger than the maximum acceptable difference (MAD), data is corrected or deleted.
    - If IAD > MAD, and concentration values from both analyzers are greater than the detection limits for all pollutants over 15 consecutive seconds, data are further investigated. If one bench is suspected of being in error, only data from the other bench is used. Otherwise, data are not used from either bench.
    - If IAD > MAD, and concentration values from one analyzer for one or more pollutants is lower than the detection limits, the values from the analyzer which is greater than detection limits is used.
    - If IAD > MAD, and concentration values from both analyzers are lower than the detection limits, the average value is used.
- **Negative value**: Because of random measurement errors, on occasion some of the measured concentrations will have negative values that are not statistically different from zero or a small positive value (*8*). Since diesel engines typically have low HC emissions, it is frequently the case that HC emission measurements are very low and not substantially different from zero. Negative values of emissions estimates were assumed to be zero and were replaced with a numerical value of zero. The levels of detection limits are used to infer as acceptable negative value (ANV) that is assessed

to be not significantly different from zero because of measurement imprecision. Detection limits for HC and CO are 15 ppm and 0.018%, respectively. If a negative value is larger in magnitude than ANV, this value is deleted because the negative value is significantly different from zero.

Loss of Power to Instrument. A loss of power to the instrument results in a complete loss of data collection during the time period when power was not available. However, the system saves data up to the point at which the power loss occurs. A typical cause of power loss for manual transmission vehicles is stalling of the engine due to a problem shifting. Such problems typically occur when going from idle into first gear, or for the lower gears. After a loss of power, the instrument needs to be rebooted, which takes approximately five to ten minutes. During the power loss and rebooting, no data can be collected.

NCSU has developed a series of Macros in Visual Basic, in conjunction with MS Excel. Raw data from the Montana system is processed via these macros to identify data quality problems. Where possible, such problems are corrected. If correction is not possible, then the errant data are omitted from the final database used for analysis. More detail on the Macros is available elsewhere (*9*).

C7. Vehicle specific power distributions for each route

This section describes a vehicle duty cycle quantified based on the cumulative frequency distribution (CDF) of vehicle specific power (VSP) for each driving cycle. Routes 1 and 2 were measured for the observed PHSB and CDSB trips, respectively. The Highway cycle is based on the highway portion of Route 1. The Arterial cycle is based on the arterial portion of Route 2. The Local cycle is based on the local portion of Route 2. Figure C-4 shows the VSP distribution for each cycle.

Generally, average VSP for the Highway cycle is higher than for the Arterial cycle and has a narrower range of VSP. For example, the average VSP for Routes 1 and 2 are 1.9 and 1.4 kW/ton, respectively. The 95 percent ranges of VSP for Routes 1 and 2 are from –13 to 14 kW/ton and from – 15 to 16 kW/ton, respectively. Since Route 1 includes more highway segments than Route 2, the fluctuation of vehicle speed is lower than Route 2.

The average VSP for the Highway, Arterial, and Local cycles are approximately 3.4, 2.0, and 0.9 kW/ton, respectively. The Highway cycle has a relatively narrow 95 percent range of VSP from –5 to 12 kW/ton because the school bus was driven at relatively constant speed on the highway. The 95 percent range for the Arterial cycle is from –18 to 20 kW/ton. The Arterial cycle has wider range of VSP than others due to significant fluctuation of vehicle speed. The Local cycle has the 95 percent range of VSP from – 11 to 14 kW/ton.

C8. Manifold absolute pressure distributions for each route

In order to estimate fuel use and emission rates, the frequency distributions of MAP were estimated based on VSP duty cycles for each route. The MAP mode was estimated for each second of the duty cycle based on the relationship between VSP and MAP as given in Figure C-2 of the main paper. Figure C-5 shows estimated frequency distribution of MAP for PHSB and CDSB for each route.

Since the PHSB has an electric motor that supplements the engine, the engine load for PHSB is generally lower than that for the CDSB. For example, the PHSB has a lower proportion of high MAP modes and a higher proportion of low MAP modes compared to the CDSB.

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Table C-1. Measurement Precision and Maximum Acceptable Difference Estimation for Inter-Analyzer Discrepancies (IAD).

Gases	Precision[a]	Maximum Acceptable Difference (MAD)
NO	± 25 ppm	50 ppm
HC	± 4 ppm	28 ppm[b]
CO	± 0.02 vol-%	0.04 vol-%
CO_2	± 0.3 vol-%	0.06 vol-%

Note: [a] Precision of each pollutant provided from manufacturer (*7*). [b] The measured concentration values can change with respect to vibration, particularly for the lower wavelengths of HC detection (*7*). For this reason, a MAD of 28 ppm of MAD is assumed for HC (*9*).

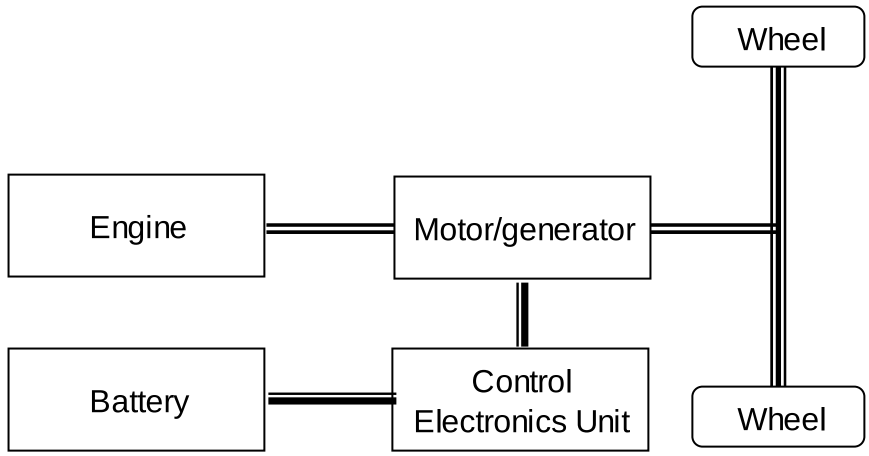

Figure C-1. Power Flow for Parallel Plug-In Hybrid Electric Vehicle.

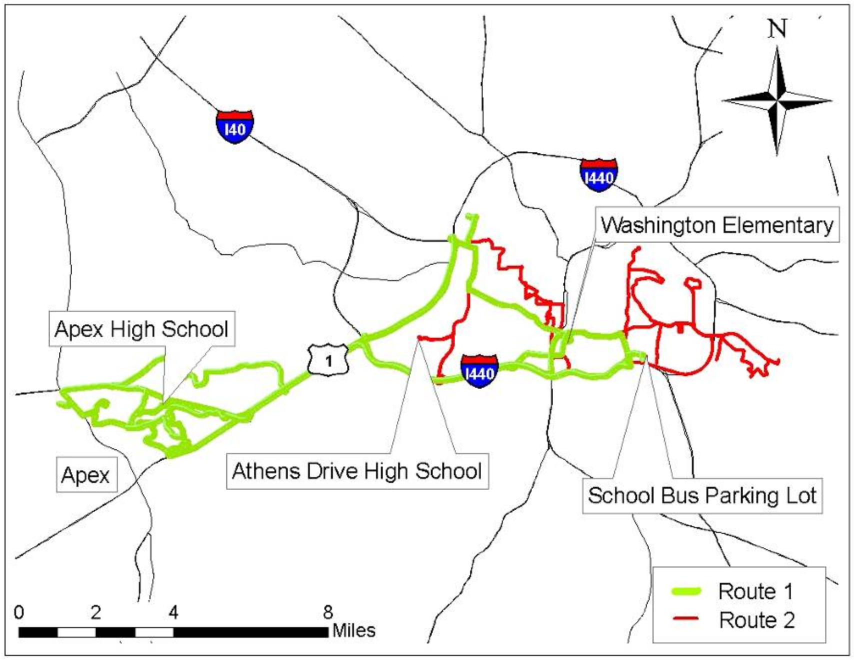

Figure C-2. Real-World Driving Cycles for a Plug-In Diesel-Electric Hybrid School Bus (PHSB) and Conventional Diesel School Bus (CDSB) measured in Raleigh and Apex Area, North Carolina. Note: Route 1 was driven by the PHSB. Route 2 was driven by the CDSB.

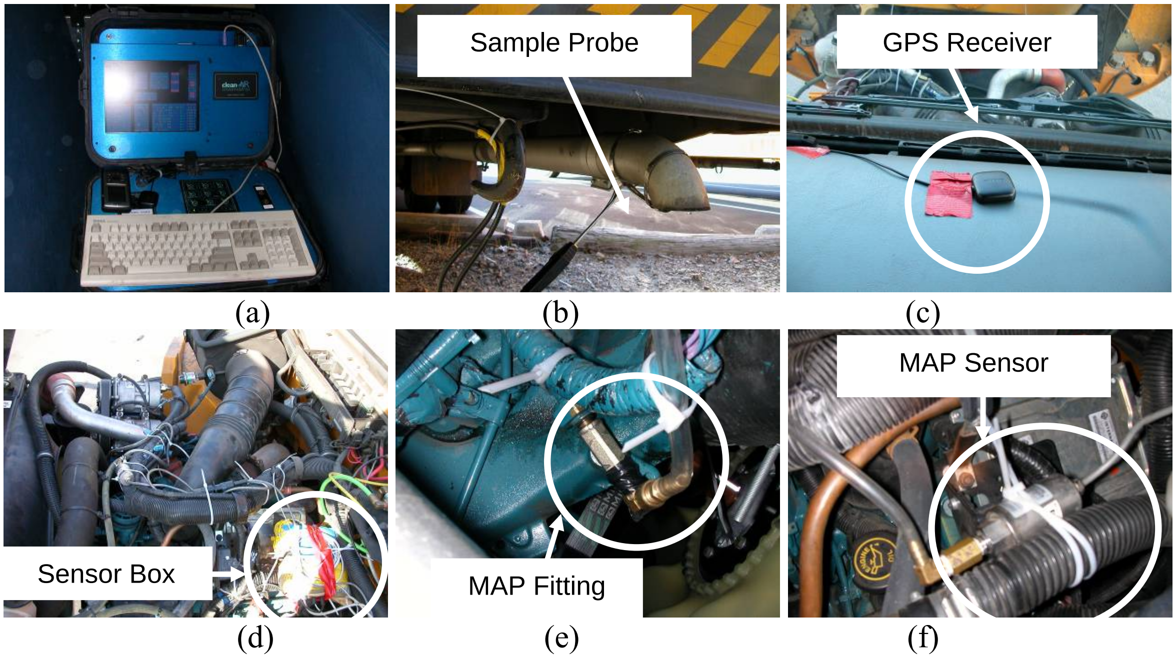

Figure C-3. Installation of the Portable Emissions Measurement System (PEMS). (a) the portable unit on a bus seat (front-view); (b) sampling exhaust gases using a probe secured with a hose clam; (c) GPS receiver on the dashboard; (d) sensor box; (e) Manifold Absolute Pressure (MAP) Fitting; and (f) Manifold Absolute Pressure (MAP) Sensor

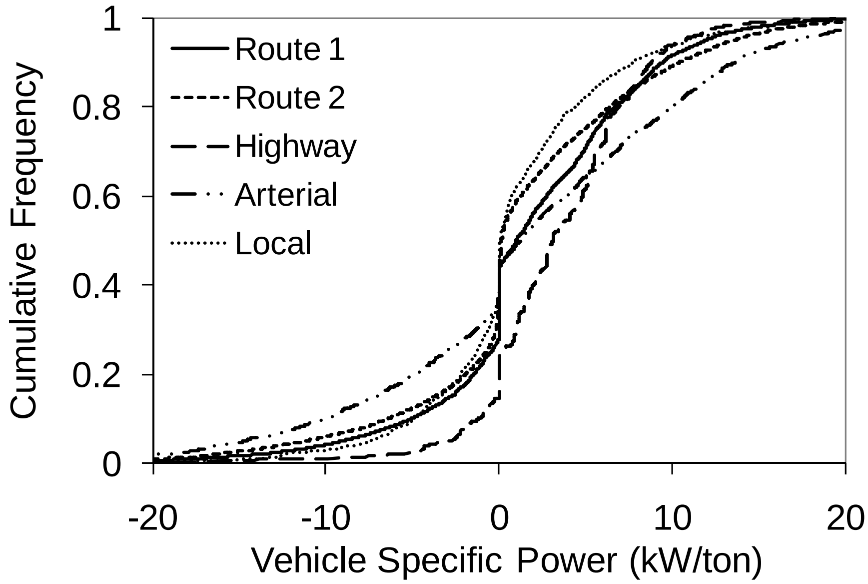

Figure C-4. Vehicle Specific Power Distributions for each Route. Note: Routes 1 and 2 are actual school bus routes for the hybrid bus and control bus, respectively. Highway cycle is based on the highway portion of Route 1. Arterial and Local cycles are based on the arterial and local portions of Route 2, respectively.

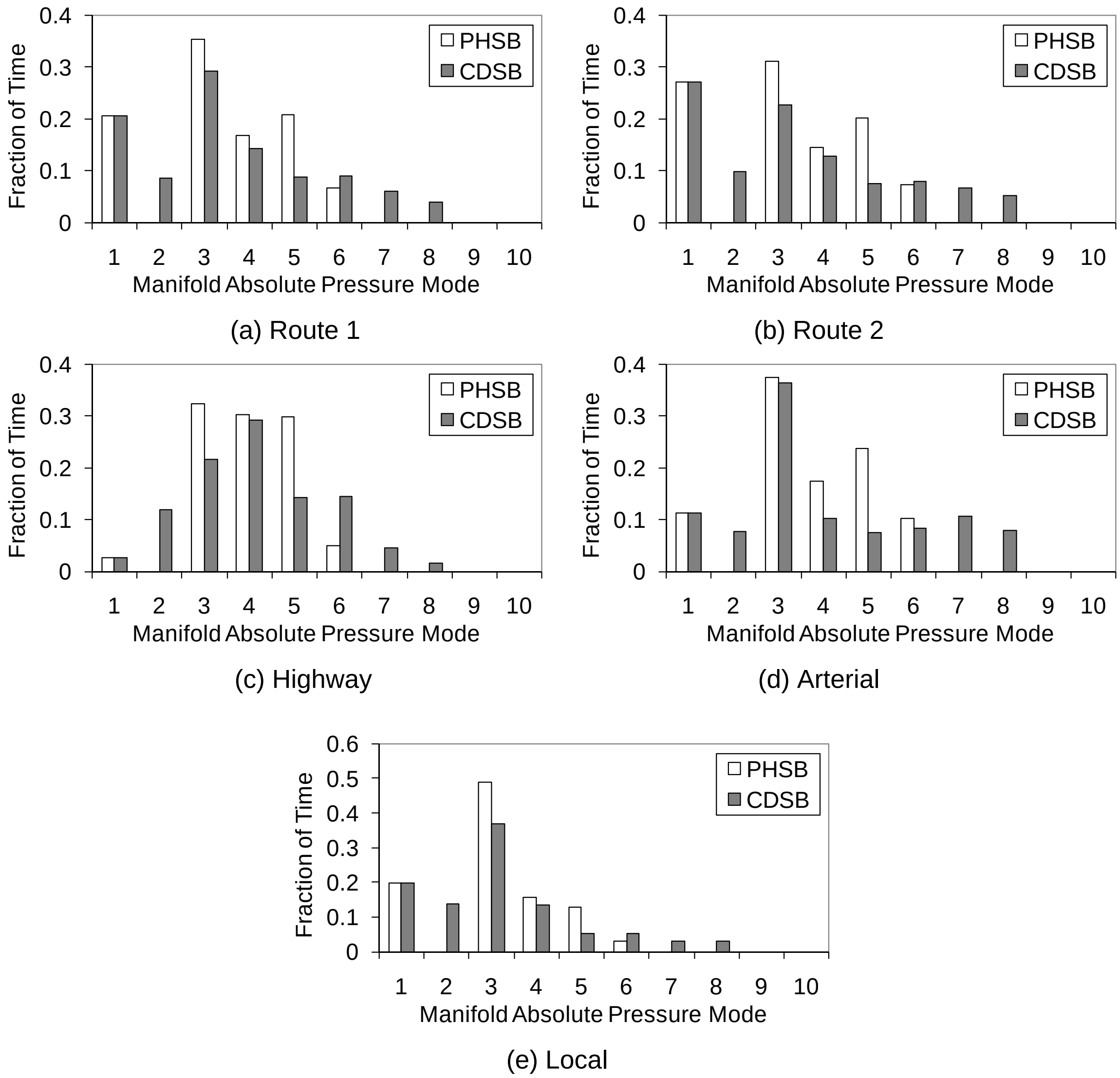

Figure C-5. Estimated manifold absolute pressure (MAP) distributions for each route based on relationship for measured MAP versus vehicle specific power. Note: PHSB = Plug-in Hybrid School Bus. CDSB = Conventional Diesel School Bus. Routes 1 and 2 are actual school bus routes for the hybrid bus and control bus, respectively. Highway cycle is based on the highway portion of Route 1. Arterial and Local cycles are based on the arterial and local portions of Route 2, respectively.