ABSTRACT

ABOLHASANI, SAEED. Assessment of On-Board Emissions and Energy Use of Nonroad Construction Vehicles. (Under the direction of Dr. H. Christopher Frey.)

In the past decade, nonroad engine emissions have increasingly become the focus of regulatory actions and air quality improvement strategies. The U.S. Environmental Protection Agency is undertaking an effort to develop a new set of modeling tools for estimation of emissions produced by nonroad vehicles. A critical element of the new models is the use of data gathered using on-board emissions measurement systems. Recent developments in on-board instrumentation enable measurement of vehicle activity and emissions under real- world conditions as opposed to laboratory tests.

The primary purpose of this thesis is to develop methodologies for on-board vehicle activity and emissions data collection, screening, and analysis for construction vehicles. The method was applied to field data collection for three excavators. Analysis of on-board data provided insights regarding quantification of variability in vehicle emissions and fuel consumption data. The influence of vehicle activity patterns on the average emission and fuel consumption rates was characterized using engine manifold absolute pressure. A consistent finding is that NO and CO_2 emissions are highly correlated to fuel consumption, reflected in an average coefficient of determination of 0.96 between either of these emission rates and fuel consumption rate. Short-term episodes can produce a substantial portion of total emissions. For example, on average, 50% of the total NO emissions were associated with 28% of the time of vehicle operation, during which the average engine speed and manifold

absolute pressure were significantly higher than corresponding averages for the total data.

A secondary, but equally important, purpose was to demonstrate a conceptual analytical methodology for analyzing on-board emissions data from nonroad construction vehicles and develop conceptual models to predict emissions using on-board data. Several different modeling methods were explored, including stratification of the data into operating modes, supplementing the modal models with ordinary least square regression, and multiple least squares regression. The modal approach offers the advantages of being conceptually the simplest, reducing the influence of autocorrelation in the model, and offering substantial explanatory power. The relationship between predicted mode-specific average emissions and exhaust flow was found to be stable, similar, and consistent for all vehicles. On average, an improvement in coefficient of determination value from 0.85 to 0.93 was estimated for observed versus estimated NO_x emissions using combined-regression modal versus simple modal approach. Modal models can be used in a new set of modeling tools to estimate emissions produced by nonroad construction vehicles.

ASSESSMENT OF ON-BOARD EMISSIONS AND ENERGY USE OF NONROAD CONSTRUCTION VEHICLES

By

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To my beloved mother, wife, son, brothers, and sisters

BIOGRAPHY

Saeed Abolhasani was born on the 23rd of August, 1968 at Abhar, Iran. He got his Bachelor's Degree in Mechanical Engineering from Sharif University of Technology, Tehran, Iran in 1992. He worked in Air Quality Control Company, Tehran, Iran, from 1992 to 2003. He came to North Carolina State University for his Master's in Environmental Engineering in 2004. He was a research assistant in Dr. H. Christopher Frey's research group, and worked on assessment of on-board emissions and fuel use from nonroad construction vehicles at the Computational Laboratory for Energy, Air, and Risk (CLEAR). This thesis completes the requirements for this degree.

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PART I

INTRODUCTION

1.0 Introduction

Unlike emissions trends for on-road vehicles, emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and VOC (volatile organic compounds) from nonroad engines and vehicles increased steadily from 1940 to 1996.[1] In 2005, nonroad diesel construction vehicles were estimated to emit annual U.S. national totals of 657,000 tons of NO_x, 1,100,000 tons of CO, 63,000 tons of PM_{10}, and 94,000 tons of SO_2.[2]

In recent years, the U.S. Environmental Protection Agency (EPA) has set Tier 1 to Tier 4 emission standards for the engines used in most construction, agricultural, and industrial vehicles. The most stringent of these standards, Tier 4, are to be phased-in over the period of 2008-2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by about 50 and 90 percent, respectively, compared to the current emission standard of Tier 3.[3, 4] However, the existing vehicle fleet will emit pollutants at higher rates than Tiers 3 and 4.

National Research Council has recommended developing a mobile source emission modeling tool to accurately predicting NO_x and PM emissions from nonroad sources.[5] Emissions estimation modeling tools presently used at the regional, state, and national levels, such as EPA's NONROAD model, are based upon average emissions for a limited number of standard operating cycles measured in the laboratory across a number of nonroad engines.[6, 7]

The EPA is undertaking an effort to develop a new modeling tool, MOVES, for the estimation of emissions produced by nonroad sources, including construction vehicles.[8] The MOVES model has been designed to consider multiple pollutants, such as HC, CO, NO_x, and PM as well as greenhouse gases such as CO_2. A critical element of MOVES is the use of data gathered using on-board emissions measurement systems.[8]

There is a critical need to provide insight regarding the real-world episodic nature of energy use and emissions from construction vehicles by analyzing on-board emissions and fuel consumption. A hypothesis is that variability in in-use activity patterns leads to important variability in energy use and emissions that should be accounted for when developing an energy and emissions assessment framework. This insight will also help better understanding of the relationship between construction vehicle activity patterns and energy use and emissions.[8] Therefore, short-term episodes associated with higher emission rates that substantially affect the average emission and fuel use rates can be defined analyzing on-board data.

2.0 Objectives

The objectives of this study are to develop and apply a procedure for data collection and quality assurance of on-board in-use emissions and fuel consumption data from construction vehicles, and to develop conceptual modal models incorporating portable emissions measurement system (PEMS) data for emissions prediction purposes. These objectives serve as an aid in identifying the feasibility of on-board data collection from construction vehicles, challenges involved, and the level of accuracy of prediction emissions employing a modeling approach.

All vehicles in this study are powered by diesel engines. Diesel engines greatly contribute to national total emissions of both NO_x and PM. For example, approximately 30 percent of the total notional NO_x from transportation was produced by diesel engines in 2002.[9] NO_x is comprised of 90 to 95% nitric oxide (NO) and 5 to 10% nitrogen dioxide (NO_2). Nitric oxide is formed mainly from higher combustion temperatures in engine and

NO_2 forms from NO. Particulate matter is composed of soot (i.e. carbonaceous solid matter similar to carbon black). Soot is formed in the cylinder, from heavy hydrocarbons in the gas phase which condense in the oxygen deficient region in the fuel rich core of the fuel sprays. The main strategies to reduce soot emissions aim to increase the air and fuel mixing rate.[10]

The efforts and analyses of this thesis are targeted to answer several key questions that address the overall objectives of the research. The answers to these questions are discussed in Part V:

- What are Advantages of Using Real-World Emissions Data to Estimate Emission Rates from Nonroad Construction Vehicles/Equipment?
- What are the Main Categories of Construction Vehicles and Equipment Contributing to Air Quality Problems?
- How should Emissions be Estimated Based on Engine Data?
- What are Key Considerations in Data Quality Assurance?
- How Can Emissions be Estimated Using Modal Modeling Approaches?
- Do Average Emission Rates Change with Change of Mode of Activity?

3.0 Overview of Research

This study was designed to: (1) identify and collect on-board in-use emissions and fuel consumption data measured by other sources; (2) design a field data collection study to fill on-board data gaps; (3) conduct field studies to collect data; and (4) develop modal models to predict emissions from construction vehicles.

The EPA, West Virginia University (WVU), and Clean Air Technologies International, Inc. (CATI), have separately conducted different on-board in-use measurements to characterize emissions from construction vehicles.[11, 12, 13] However, not all of these data were quality assured or publicly available. Quality assured data for nine of the vehicles tested using a portable emission measurement system were provided by EPA and are used in this work. The data include engine speed, exhaust flow rate, and ambient conditions. Because there were no data regarding vehicles activity such as lateral movement of the vehicle chassis, it was not possible to investigate the relationship between vehicles activity patterns and emissions and fuel consumption. Thus, the data obtained from EPA to support this research was not sufficient.

For the purpose of identifying and filling key gaps in the available in-use data, a field data collection study was designed. The experience gained during fieldwork, data processing, and data analysis led to development of new data collection and quality assurance and analysis procedures.

4.0 Organization

Part II discusses the contribution of nonroad construction vehicles and equipment to air pollution. Furthermore, the choice of vehicle types for field data collection is addressed. Key issues include identifying target pollutants with respect to air quality control strategies and emissions standards, and ranking the construction vehicle types based on their contributions to the total U.S. national emissions in 2005. To estimate emissions from each vehicle type, EPA's NONROAD model is used.

Part III is a paper and discuses feasibility of predicting emissions from nonroad construction vehicles using modal models. On-board in-use data for nine construction vehicles were supplied by EPA for modeling efforts. A procedure was developed in this work for exploratory analysis of PEMS data. Several modeling methods were explored, including dividing the data into modes, supplementing the modal models with ordinary least squares regression, and multiple least squares regression.

The manuscript given in Part IV focuses on conceptual development of procedures for data collection, quality assurance, and analysis of on-board emissions from nonroad construction vehicles. Excavators are discussed as a case study because they are one of the major types of vehicles most commonly used in construction. This work illustrates the relationship between vehicle activity patterns and energy use and emissions.

Part V provides the conclusion and recommendations based on the analyses provided in Parts III and IV in order to answer the questions raised in Section 2. Appendix A provides a glossary of technical terms to assist the reader. Appendix B provides detailed information about the procedure of data screening and quality assurance of on-board emissions data from nonroad construction vehicles. Appendix C provides a detailed description of the computer programs developed for the screening and quality assurance of on-board emissions data. Each part of this thesis has its own list of references cited.

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PART II

CONTRIBUTION OF NONROAD CONSTRUCTION VEHICLES TO AIR POLLUTION

1.0 Introduction

The objective this chapter is to present a methodology for selecting nonroad construction vehicles for emissions assessment with respect to their contribution to air pollution. It is not possible or necessary to include all possible types of nonroad construction vehicles in an emissions assessment effort. To identify the contribution of construction vehicles to air pollution, the EPA's NONROAD2004 emission inventory model was used. The NONROAD model estimates air pollution from more than 80 types of compression ignition (CI) and spark ignition (SI) nonroad sources. Furthermore, the NONROAD model provides a flexible tool that can be applied to a wide variety of air quality modeling and planning functions. Using information on construction vehicles populations, annual activity/use, fuel type, and emission factors, the NONROAD model estimates mass emissions of hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxides (CO_2), and particulate matters (PM_{10} and $PM_{2.5}$) for the nation, specific states and counties for past and future years.[1]

The NONROAD model tracks engines rather than vehicles because present and future nonroad emission regulations focus on the engine instead of vehicle. The EPA anticipates that future nonroad emission regulations would also focus on engines.[2] Engine populations are divided into 5 fuel types: diesel, gasoline 2-stroke, gasoline 4-stroke, compressed natural gas (CNG), and liquefied petroleum gas (LPG). The engine populations are divided into different power level categories by taking into account application and fuel type. The construction vehicles/equipment are categorized in 15 power level categories.[1]

The NONROAD model uses a default base year population as a starting point to estimate future and past year engine population. The base year for construction vehicles and equipment is 2000 and is the most recent year for which population data are available. Each combination of application and fuel is assigned a unique "Source Classification Code" (SCC), which is a ten digit number. Diesel construction vehicles and stationary equipment are assigned the SCC numbers of "2270002000" and "2270006000," respectively. The last two digits differ based upon vehicles types. For example, diesel excavators and generator sets are assigned SCC of "2270002036" and "2270006005," respectively.[2, 3]

In the NONROAD model, construction vehicles are classified into 25 categories with respect to applications. Table 1 summarizes these classifications with respect to SCC. Construction equipment are classified into 6 categories, as shown in Table 2.

The NONROAD model was accessed through EPA's website. This model can be down loaded and installed on a personal computer. An option file is needed as input which includes a scenario for a case study. For example, the user defines in an option file the region, period, source, and fuel for which emissions estimated. Once the user setup an option file, the graphical interface allows the user to easily submit the option file to the core model to run. The core model of NONROAD, written in Fortran, contains all of the algorithms used by the model for calculating emissions estimates.[4]

In order to estimate annual mass emissions released by each type of construction vehicle and/or equipment in 2005, the NONROAD model was run based on the following scenario:[5]

- Region: US total
- Period: Annual
- Year: 2005

- Source/Segment: Construction
- Fuel : Diesel

Table 1. Construction Vehicle Classifications

	SCC[1]	Vehicle Description
1	2270002003	Pavers
2	2270002006	Tampers/Rammers
3	2270002009	Plate Compactors
4	2270002015	Rollers
5	2270002018	Scrapers
6	2270002021	Paving Equipment
7	2270002024	Surfacing Equipment
8	2270002027	Signal Boards/Light Plants
9	2270002030	Trenchers
10	2270002033	Bore/Drill Rigs
11	2270002036	Excavators
12	2270002039	Concrete/Industrial Saws
13	2270002042	Cement & Mortar Mixers
14	2270002045	Cranes
15	2270002048	Graders
16	2270002051	Off-highway Trucks
17	2270002054	Crushing/Proc. Equipment
18	2270002057	Rough Terrain Forklifts
19	2270002060	Rubber Tire Loaders
20	2270002066	Tractor/Loader/Backhoes
21	2270002069	Crawler Tractor/Dozer
22	2270002072	Skid Steer Loader
23	2270002075	Off-highway Tractors
24	2270002078	Dumpers/Tenders
25	2270002081	Other Construction Equipment

1) SCC: Source Classification Code

Table 2. Construction Equipment Classification

	SCC[1]	Equipment Description
1	2270006005	Generator Sets
2	2270006010	Pumps
3	2270006015	Air Compressors
4	2270006020	Gas Compressors
5	2270006025	Welders
6	2270006030	Pressure Washers

1) SCC: Source Classification Code

2.0 Ranking of the Importance of Construction Vehicle Categories

The objective of this section is to explain how target pollutants were selected and how construction vehicle and equipment subgroups were ranked with respect to their contributions to total national emissions of the target pollutants. The EPA is adopting requirements to reduce emissions, especially NO_x, CO, and PM_{10} from nonroad diesel engines.[6] Thus, these three pollutants are considered as target pollutants.

The NONROAD model was run for scenario explained in Section 1. The selected output from the model was source-based emissions reporting for NO_x, CO, and PM_{10}. This type of reporting provides information on mass of emissions produced by each type of construction vehicle and equipment in 2005. Vehicle and equipment types were ranked taking into account the contribution of each type to total emissions of each of the target pollutants. The following ranking scenarios were considered:

- Scenario 1 : NO_x Emissions
- Scenario 2: CO Emissions
- Scenario 3: PM_{10} Emissions

The results of the rankings are presented and discussed in the following sections.

2.1 Ranking Based on NO_x Emissions

According to the NONROAD model output, construction vehicles and equipment contributed an estimated 778,600 tons of NO_x in 2005 nationally in the U.S. Table 3 summarizes the ranking results for 31 types of construction vehicles and equipment. The types of equipment are shown in bold face. Rubber tire loaders are ranked first because they have the highest contribution to the total U.S. NO_x emissions. The first seven types are responsible for approximately 70% of NO_x emissions. The first six types are vehicles and the seventh type is "Generator Sets," which is from the construction equipment category.

2.2 Ranking Based on CO Emissions

Construction vehicles contributed 418,600 tons of CO emissions in 2005 nationally in the U.S. Table 4 summarizes results of ranking based on CO missions. Tractors/Loaders/Backhoes are ranked first because they contributed the highest percentage of national CO emissions. The first seven types of this table are the same as the first seven types shown in Table 3, but these are in a different sequence. Similarly, generator sets are ranked seventh. Furthermore, the contribution to total national CO emissions is about 70% for the first seven types.

Table 3. Ranking of Construction Vehicles and Equipment Based on Their Contributions to National NO_x Emissions[1]

SCC	Vehicle/Equipment	NO_x[2] ton/yr	Contribution %	Cumulative %	Rank
2270002060	Rubber Tire Loaders	112516	14.45	14.45	1
2270002069	Crawler Tractor/Dozers	97255	12.49	26.94	2
2270002036	Excavators	88816	11.41	38.35	3
2270002051	Off-highway Trucks	85892	11.03	49.38	4
2270002066	Tractors/Loaders/Backhoes	71395	9.17	58.55	5
2270002072	Skid Steer Loaders	48241	6.20	64.75	6
2270006005	**Generator Sets**[3]	**36789**	**4.73**	**69.47**	**7**
2270002057	Rough Terrain Forklifts	30161	3.87	73.35	8
2270002018	Scrapers	26443	3.40	76.74	9
2270002045	Cranes	24871	3.19	79.94	10
2270002015	Rollers	22827	2.93	82.87	11
2270002048	Graders	22362	2.87	85.74	12
2270006015	**Air Compressors**	**20750**	**2.67**	**88.41**	**13**
2270002033	Bore/Drill Rigs	14125	1.81	90.22	14
2270002075	Off-Highway Tractors	12124	1.56	91.78	15
2270002081	Other Construction Equipment	11877	1.53	93.30	16
2270002030	Trenchers	10993	1.41	94.72	17
2270006025	**Welders**	**10675**	**1.37**	**96.09**	**18**
2270002003	Pavers	9016	1.16	97.24	19
2270006010	**Pumps**	**8622**	**1.11**	**98.35**	**20**
2270002054	Crushing/Proc. Equipment	4435	0.57	98.92	21
2270002027	Signal Boards/Light Plants	2821	0.36	99.28	22
2270002021	Paving Equipment	1460	0.19	99.47	23
2270006030	**Pressure Washers**	**1273**	**0.16**	**99.64**	**24**
2270002024	Surfacing Equipment	1017	0.13	99.77	25
2270002039	Concrete/Industrial Saws	734	0.09	99.86	26
2270002042	Cement & Mortar Mixers	571	0.07	99.93	27
2270002009	Plate Compactors	322	0.04	99.97	28
2270002078	Dumpers/Tenders	160	0.02	100.00	29
2270002006	Tampers/Rammers	21	0.00	100.00	30
2270006020	**Gas Compressors**	**2**	**0.00**	**100.00**	**31**
	Total	778565	100		

1) Data source: result of running the NONROAD model in Section 1
2) Estimations are on a U.S. national basis
3) Bold items are construction equipment

Table 4. Ranking of Construction Vehicles and Equipment Based on Their Contributions to National CO Emissions[1]

SCC	Vehicle/Equipment	CO[2] ton/yr	Contribution %	Cumulative %	Rank
2270002066	Tractors/Loaders/Backhoes	66774	15.95	15.95	1
2270002072	Skid Steer Loaders	60537	14.46	30.41	2
2270002060	Rubber Tire Loaders	48029	11.47	41.89	3
2270002069	Crawler Tractor/Dozers	39026	9.32	51.21	4
2270002036	Excavators	31110	7.43	58.64	5
2270002051	Off-highway Trucks	30516	7.29	65.93	6
2270006005	**Generator Sets[3]**	**21148**	**5.05**	**70.99**	**7**
2270002057	Rough Terrain Forklifts	19151	4.58	75.56	8
2270006025	**Welders**	**15755**	**3.76**	**79.33**	**9**
2270002015	Rollers	12071	2.88	82.21	10
2270002018	Scrapers	11206	2.68	84.89	11
2270006015	**Air Compressors**	**9267**	**2.21**	**87.10**	**12**
2270002030	Trenchers	7687	1.84	88.94	13
2270002048	Graders	6940	1.66	90.60	14
2270002045	Cranes	6334	1.51	92.11	15
2270002081	Other Construction Equipment	6211	1.48	93.59	16
2270002075	Off-Highway Tractors	6036	1.44	95.04	17
2270002033	Bore/Drill Rigs	5555	1.33	96.36	18
2270006010	**Pumps**	**4677**	**1.12**	**97.48**	**19**
2270002003	Pavers	3954	0.94	98.42	20
2270002027	Signal Boards/Light Plants	1671	0.40	98.82	21
2270002054	Crushing/Proc. Equipment	1498	0.36	99.18	22
2270002021	Paving Equipment	803	0.19	99.37	23
2270006030	**Pressure Washers**	**742**	**0.18**	**99.55**	**24**
2270002024	Surfacing Equipment	640	0.15	99.70	25
2270002039	Concrete/Industrial Saws	582	0.14	99.84	26
2270002042	Cement & Mortar Mixers	269	0.06	99.91	27
2270002009	Plate Compactors	198	0.05	99.95	28
2270002078	Dumpers/Tenders	166	0.04	99.99	29
2270002006	Tampers/Rammers	13	0.00	100.00	30
2270006020	**Gas Compressors**	**1**	**0.00**	**100.00**	**31**
	Total	418565	100		

1) Data source: result of running the NONROAD model in Section 1
2) Estimations are on a U.S. national basis
3) Bold items are construction equipment

2.3 Ranking Based on PM_{10} Emissions

The third ranking scenario is based on national PM_{10} emissions. Construction vehicles and equipment emitted less mass of PM_{10} than CO and NO_x pollutants in 2005. Table 5 summarizes the ranking results for PM_{10}. Tractors/Loaders/Backhoes contributed 15% of the total national PM_{10} emissions and were ranked first. The top seven categories contributed 70% of total estimated national PM_{10} emissions from nonroad vehicles and equipment. The top six types are vehicles and the seventh are Generator Sets.

Table 5. Ranking of Construction Vehicles and Equipment Based on Their Contributions to National PM_{10} Emissions[1]

SCC	Vehicle/Equipment	PM_{10}[2] ton/yr	Contribution %	Cumulative %	Rank
2270002066	Tractors/Loaders/Backhoes	11273	15.07	15.07	1
2270002072	Skid Steer Loaders	10184	13.62	28.69	2
2270002060	Rubber Tire Loaders	8339	11.15	39.84	3
2270002069	Crawler Tractor/Dozers	6803	9.10	48.93	4
2270002036	Excavators	6460	8.64	57.57	5
2270002051	Off-highway Trucks	4895	6.55	64.12	6
2270006005	**Generator Sets**[3]	**4484**	**6.00**	**70.11**	**7**
2270002057	Rough Terrain Forklifts	3443	4.60	74.72	8
2270006025	**Welders**	**2516**	**3.36**	**78.08**	**9**
2270002015	Rollers	2217	2.96	81.04	10
2270006015	**Air Compressors**	**2036**	**2.72**	**83.77**	**11**
2270002018	Scrapers	1745	2.33	86.10	12
2270002048	Graders	1550	2.07	88.17	13
2270002045	Cranes	1427	1.91	90.08	14
2270002030	Trenchers	1353	1.81	91.89	15
2270002033	Bore/Drill Rigs	1172	1.57	93.46	16
2270006010	**Pumps**	**1012**	**1.35**	**94.81**	**17**
2270002081	Other Construction Equipment	972	1.30	96.11	18
2270002075	Off-Highway Tractors	872	1.17	97.27	19
2270002003	Pavers	781	1.04	98.32	20
2270002027	Signal Boards/Light Plants	323	0.43	98.75	21
2270002054	Crushing/Proc. Equipment	303	0.41	99.15	22
2270006030	**Pressure Washers**	**151**	**0.20**	**99.36**	**23**
2270002021	Paving Equipment	142	0.19	99.55	24
2270002024	Surfacing Equipment	103	0.14	99.69	25
2270002039	Concrete/Industrial Saws	102	0.14	99.82	26
2270002042	Cement & Mortar Mixers	57	0.08	99.90	27
2270002009	Plate Compactors	38	0.05	99.95	28
2270002078	Dumpers/Tenders	33	0.04	99.99	29
2270002006	Tampers/Rammers	2	0.00	100.00	30
2270006020	**Gas Compressors**	**0**	**0.00**	**100.00**	**31**
	Total	74789	100		

1) Data source: result of running the NONROAD model in Section 1
2) Estimations are on a U.S. national basis
3) Bold items are construction equipment

3.0 Conclusions

Tables 3 to 5 indicate that seven types of vehicles and equipment contribute approximately 70% of the estimated U.S. national emissions of each of three target pollutants. These types include:

- Rubber Tire Loaders
- Crawler Tractor/Dozers
- Excavators
- Off-highway Trucks
- Tractors/Loaders/Backhoes
- Skid Steer Loaders
- Generator Sets

Tractors/Loaders/Backhoes, Skid Steer Loader, and Rubber Tire Loaders are ranked 1, 2, and 3, respectively, for both CO and PM_{10} emissions. However, the three groups that are most important with respect to NO_x emissions are Rubber Tire Loaders, Crawler/Tractors, and Excavators. Since NO_x is typically the pollutant of greatest concern because it is emitted in relatively high quantities from diesel engines and is a precursor to tropospheric ozone, the priority emphasise for field data collection efforts is on these types of vehicles.

Of course, access to vehicles for on-board emissions data collection involves some difficulties and depends on cooperation from contractors that own and operate such vehicles. The key finding is that most of the emissions of specific pollutants can be attributed to a relatively small number of vehicle or equipment categories. This enables data collection priorities to be established.

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PART III

DEVELOPMENT OF MODAL MODELS TO ESTIMATE NONROAD CONSTRUCTION VEHICLE EMISSIONS BASED UPON ON-BOARD ENGINE AND EMISSIONS DATA

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Abstract

This paper explores a number of key issues pertaining to the methodology for analyzing on-board emissions data and developing modal models based on case study examples for nine selected nonroad construction vehicles. Data for these vehicles were obtained from the U.S. Environmental Protection Agency. Several different modeling methods were explored, including stratification of the data into operating modes, supplementing the modal models with ordinary least square regression, and multiple least square regression. By comparison, the modal approach offers the advantages of being conceptually the simplest, reducing the influence of autocorrelation in the model, and offering substantial explanatory power. From modal models regardless of vehicle type, it was found that relationship between predicted mode-specific average emissions and exhaust flow is very stable, similar, and consistent for all vehicles and the difference in average emissions rates is because of difference in duty cycles and activity patterns during the data collection. On average, an improvement in coefficient of determination value from 0.85 to 0.93 was estimated for observed versus estimated NO_x emissions using combined-regression modal versus simple modal approach. The significance of improvement in explanatory power of combined- regression modal model is influenced by duty cycles and activity patterns of vehicles that may result in less variability in emissions. Modal models can be used in new set of modeling tools to estimate emissions produced by nonroad construction vehicles. Those new models are ensured to be based upon on-board second-by-second in-use activity and emissions data.

Key words: nonroad; construction; modal model; regression; on-board; emissions

1.0 Introduction

The objectives of this paper are to: (1) demonstrate a conceptual analytical methodology for analyzing on-board emissions data from nonroad construction vehicles; (2) develop conceptual models to predict emissions using second-by-second emissions and engine data; (3) develop recommendations regarding other emissions and engine data that should be used in developing modal models; and (4) develop recommendations for future construction vehicle on-board emissions testing strategies.

In 2005, nonroad construction vehicles were estimated to emit U.S. national annual totals of 657,000 tons of NO_x, 1,100,000 tons of CO, 63,000 tons of PM_{10}, and 94,000 tons of SO_2.[1] Emissions for nonroad vehicles are currently estimated using the NONROAD emission factor and inventory model.[2] The NONROAD model is based on average emission rates obtained from steady-state modal engine dynamometer tests.[3, 4] The NONROAD model is intended to produce "macro-scale" estimates of emissions that are appropriate at a regional or larger scale. However, a key question is whether steady state modal test cycles are representative of real world data.

Although the Engine Manufacturers Association and the U.S. Environmental Protection Agency (EPA) have jointly developed several transient engine dynamometer test cycles for an agricultural tractor, a crawler dozer, and a backhoe loader,[5, 6] such tests are not part of the basis of the NONROAD model. It is hypothesized that fuel use and emissions are sensitive to duty cycles, and that a particular type of construction vehicle may be used for a variety of tasks. Thus there may be a variety of possible duty cycles.

In recent years, the U.S. Environmental Protection Agency (EPA) has set Tier 1 to Tier 4 emission standards for the engines used in most construction, agricultural, and industrial vehicles. Tier 1, 2 and 3 are phased-in from 1996 to 2000, 2001 to 2006, and 2006 to 2008, respectively. The most stringent of these standards, Tier 4, are to be phased-in during 2008 to 2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by about 50 and 90 percent, respectively, compared to the current Tier 3 emission standard.[7, 8] However, the existing vehicle fleet will emit pollutants at higher average rates than Tier 3 and Tier 4 for some time to come. This is because there will be a transition period as older vehicles are retired. Therefore, in order to characterize in-use emissions of the existing fleet, it is useful to measure emissions for vehicles that were built under a variety of emission standards.

The National Research Council has recommended development of a modeling tool to accurately predicting emissions from nonroad emission sources, particularly for NO_x and PM emissions.[9] In response, EPA is developing MOVES, which is intended to estimate emissions for both on-road and nonroad mobile sources, including construction vehicles. The design of MOVES includes multiple pollutants, such as HC, CO, NO_x, PM, and greenhouse gases such as CO_2, a variety of mobile sources, and emissions estimates at the levels of resolution needed for diverse emissions inventory applications.[10] With respect to the latter, MOVES will employ a modal approach based on second-by-second dynamometer and in-use measurements. Such data can be used to support mesoscale emissions estimates, such as for a transportation corridor or small geographic area, and potentially could be used for microscale applications, such as at a particular intersection or job site. MOVES is intended to be empirically-based to the extent possible, in order to avoid imposing modeling assumptions and to enable a user to weight the modes to represent any arbitrary duty cycle.

In contrast, the existing onroad model, MOBILE6, and NONROAD are based on embedded assumptions regarding duty cycles that cannot be changed by the user.

A critical element of MOVES is the use of data gathered using portable on-board emissions measurement systems (PEMS).[10] PEMS have been developed over the past decade to the point where commercially available systems can be used to collect data on a wide variety of on-road and non-road vehicles.[11-13] PEMS provide a capability to simultaneously measure real-world duty cycles and the corresponding emissions. Therefore, PEMS data can be used to develop empirically-based representative estimates of emissions.

Potential methods for using PEMS data to generate nonroad emission rates for MOVES were evaluated by the University of California at Riverside (UCR), Environ Corporation, and North Carolina State University (NCSU) based on a few hours of PEMS data for each of three nonroad vehicles.[3] UCR pursued a database approach, deriving separate emissions for macroscale, mesoscale, and microscale based on a database lookup of individual nonroad vehicle and duty cycle results. Environ's basic approach was to divide the second-by-second nonroad PEMS data into a series of microtrips. NCSU pursued a modal binning approach in which nonroad vehicle operational modes were defined based on changes in engine speed and exhaust flow and refined the estimates within each mode using regression analysis. Stratification of the data into modes was a feasible approach that reduced the influence of autocorrelation.

In comparison to engine dynamometer tests, there is relatively little PEMS data for nonroad construction vehicles. Clean Air Technologies International (CATI), Inc., conducted measurements using their Montana system PEMS at the World Trade Center site for a Caterpillar loader, a large Caterpillar excavator, a small Komatsu excavator, and a crane for the purpose of evaluating the benefits of ultra-low sulfur and diesel particulate filter technologies.[14] West Virginia University (WVU) collected PEMS data for a street sweeper, a rubber-tire loader, and an excavator to generate transient test cycles that could be used to simulate real-world operating conditions for exhaust emissions research.[15] EPA used a specialized PEMS, the Simple Portable On-Board Test (SPOT) instrument, to collect engine and exhaust data for 50 construction vehicles in 2002 to evaluate potential methods for using on-board emissions data to generate emissions rates for MOVES.[3, 16] However, not all of these data are quality assured or publicly available.

The main goal here is to further evaluate, based on a larger set of vehicles, nonroad vehicle modal emissions estimation approaches.

2.0 Methodology

The key methodological elements for development of modal models to estimate nonroad vehicle emissions using PEMS data include: (1) database formation; (2) exploratory analysis; and (3) model development.

2.1 Source of Data

EPA provided quality assured data for nine nonroad vehicles that were measured in the field using the SPOT instrument. The vehicles include five dozers, an excavator, a front end loader, and two off-highway trucks. Summary information about the test vehicles is given in Table 1. The vehicles were tested in their normal operations, and thus the data provide insights regarding real-world duty cycles. A duty cycle refers to the sequential tasks that are performed by a construction vehicle to produce a unit of output. For example, an excavator may use its attachment (i.e. bucket) to repeatedly dig the ground in order to excavate or a hole, while a dozer may use its blade to push dirt from one location to another or in order to smooth a surface. However, a given type of vehicle can be used for more than one type of duty cycle. Thus, there may not be a unique type of duty cycle associated with a particular type of vehicle. A duty cycle can be subdivided into modes, such as idling, lateral movement of the vehicle chassis, movement of a bucket or blade, and so on. A particular duty cycle can be represented as a weighted combination of specific modes. Alternatively, modes can be defined based on measures of engine performance, and such modes can be weighted to comprise a duty cycle. Table 1 provides a highly aggregated estimation of modal activity with respect to the percentage of time in engine idle versus non-idle. There was no information collected and reported regarding the tasks performed by the nine vehicles.

The SPOT system was designed for use with nonroad vehicles and for non-attended operation of up to one week.[3, 16] SPOT collects data for: engine speed (RPM): exhaust flow rate (scfm): pollutant concentrations for NO_x (ppm) and CO_2 (vol%): and ambient conditions including relative humidity (%), temperature (^{0}C), and pressure (kPa). Other variables that might be useful for modeling purposes, such as manifold absolute pressure (MAP), and throttle position, are not collected by the SPOT system. Engine speed and MAP are indicators of engine load.[17] Exhaust flow is proportional to engine load in that it depends on manifold absolute pressure and engine RPM. Thus, exhaust flow is a surrogate indicator of engine load. Engine and ambient variables measured by SPOT are used here as potential explanatory variables for analysis and modeling.

2.2 Database Formation

Engine and emissions data were reviewed for all nine individual vehicle databases to determine whether any errors or problems exist in the data, correct such errors or problems where possible, and remove invalid data if errors or problems cannot be corrected.

For example, engine speed was evaluated. The engine speed for a diesel engine typically varies from at least 500 RPM to not more than 4,000 RPM.[18] If the measured engine speed exceeds this range, then an error is suspected. Engine speed was found to be zero for 23 to 50 seconds (out of approximately 27,000 seconds per vehicle, on average) for Dozers 20, 49, and 50, and Front-end loader 44. Such data indicate either no engine operation or missing engine data and were excluded from the databases.[19]

No errors of zero exhaust flow were found. Furthermore, all NO_x and CO_2 concentrations had values greater than zero, as expected.

The vehicle data files were inspected to verify synchronization of engine and emissions data. For this purpose, engine speed and CO_2 concentrations were compared. A change in engine speed results in a change in fuel consumption and CO_2. For each vehicle, segments of second-by-second data were selected in which engine speed changed by more than 200 RPM in one second and for more than 500 RPM for an event that may have lasted a few seconds. Temporal trends of engine speed and CO_2 were compared to each other to indicate the time difference between the corresponding initial rises (or initial decrease) in engine speed versus CO_2 concentrations. No synchronization problems were observed for any vehicle.

After completion of the quality assurance checks a new database was created for each vehicle for use in analysis.

2.3 Exploratory Analysis

An exploratory analysis was conducted to quantify variability of emissions with respect to engine operation and ambient conditions. The exploratory analysis included data visualization and development of summary statistics.

For data visualization purposes, scatter plots for both NO_x and CO_2 emissions were generated with respect to each explanatory variable for each of the nine vehicles. In order to simplify the analysis and enable comparisons between vehicles, the emission rates of NO_x and CO_2, and the exhaust flow and engine speed were normalized with respect to the maximum values of each quantity for each construction vehicle. Summary statistics for emissions and explanatory variables were developed for each data file including mean, mean confidence interval, standard deviation, 2.5 percentile, and 97.5 percentile

In order to compare PEMS data with current methods for emissions estimation, the average NO_x emission rates of the test vehicles was compared to estimates from the NONROAD model for similar engine sizes. The NONROAD model reports emission factors in units of g/bhp-hr. In order to compare to the SPOT data, the NONROAD model emission factors were converted to a gram per gallon of fuel consumption basis using average brake-specific fuel consumption (BSFC) rate of 0.367 lb/hp-hr estimated by EPA for engine horsepower levels of > 100 hp.[2]

2.4 Model Development

Both modal and regression-based approaches, as well as a combination of both, are explored here. For regression-based approaches using least squares, the data should be comprised of statistically independent samples. However, vehicle activity and emissions data are typically autocorrelated, because the activity and emissions in the current second have some dependency on what happened in the previous few seconds. Therefore, prior to developing a statistical model, autocorrelation should be assessed. If the data have autocorrelation, then statistical analysis needs to be performed appropriately. For example, ordinary least squares regression should be used only if the residuals are uncorrelated with each other.[20, 21] The PEMS data for all nine construction vehicles were checked for autocorrelation using SAS software.

For autocorrelated data, a key question is whether a time series approach might be appropriate for making predictions for individual vehicle based upon continuous time series of data. A time series approach is not expected to be practical because they require one continue series of data, whereas available data are typically for many individual segments (e.g., measurements made on different days for the same vehicle).[19]

An alternative to using time series models is to stratify the data into modes. The process of stratifying the data is a technique for reducing the influence of autocorrelation in the data.[3] Using this approach, modal models were developed with respect to the explanatory variable that is most highly associated with changes in average NO_x and CO_2 emissions.

To explore whether the explanatory power of a modal model can be improved, the modal approach was combined with ordinary least square (OLS) regression for data within each mode. These are referred to as Combined Modal-Regression (CMR) models For each mode, a linear regression with intercept "b" and slope "m" was fit to the data to further explain the variability in NO_x and CO_2 emissions as a function of a supplemental explanatory variable.

Finally, for comparison purposes only, a multiple OLS regression approach was explored. It is recognized that this approach will not be appropriate from a strictly statistical perspective when data are autocorrelated and there is a lack of stratification to reduce autocorrelation effects. However, an objective was to compare the multiple OLS regression approach with the modal approaches to determine if reducing autocorrelation effects by stratification of the data may increase the explanatory power of the model substantially compared to an approach that does not properly account for autocorrelation (i.e. multiple OLS regression).

3.0 Results

The key results include: (1) exploratory analysis of each data files; (2) assessment of autocorrelation in data; (3) development of the alternative models; (4) comparison of the models; and (5) comparison of the vehicle duty cycles with respect to average emission rates.

3.1 Exploratory Analysis

The average NO_x emission rate varies from 0.023 to 0.30 g/sec, or by more than an order of magnitude, among the nine vehicles, and by slightly less than an order of magnitude for CO_2 emission rate, as shown in Table 2. Thus, there is substantial inter-vehicle variability in emission rates. The data set includes several vehicles with the same make and model of engine. For example, vehicles 20 and 45 both have 10.5 liter Caterpillar 3306 engines. However, their average emission rates differ by factors of approximately five and two for NO_x and CO_2, respectively. There are four vehicles, numbers 34, 39, 49, and 50, that have 14.6 liter Caterpillar 3406 engines. There is substantial variability among these vehicles also. Some of this variability may be attributable to the duty cycle. For example, the average emission rates for a given type of engine tend to be proportional to the average exhaust flow, which is a surrogate for engine load and is influenced by the duty cycle. Thus, differences in average emissions between vehicles that have the same type of engine are likely to be a result of differences in duty cycles. These differences are further explored later.

The key explanatory variables associated with variability in emissions were identified based on pair-wise assessment of the portion of variability in emission rate attributable to an individual explanatory variability, as summarized in Table 3. For all vehicles, NO_x and CO_2 emissions are a strong function of exhaust flow rate as indicated by R^2 values ranging from 0.88 to 0.97 depending on the vehicle and pollutant. The high R^2 values indicated that there is an approximately linear trend in average NO_x and CO_2 emissions for a given exhaust flow and normalized exhaust flow rate. However, there is also substantial variability in NO_x and CO_2 emissions for any single point estimate for normalized exhaust flow. The normalized emissions are also highly associated with normalized engine speed, as indicated by R^2 values of 0.72 to 0.91. There appears to be a weak relationship between emissions and relative humidity, ambient temperature, and barometric pressure, as indicated by R^2 values of less than 0.16. Ambient temperature and relative humidity were highly correlated with each other for all data files. Based on these results, exhaust flow is identified as the single most important explanatory variable with respect to emission rates.

A comparison of average emission rates from the field data versus estimates from the NONROAD model are given in Table 1. The NONROAD estimates are tailored to the model year, type of vehicle, and engine size. All of the average emissions rates estimated from PEMS data are significantly lower than the estimates obtained from NONROAD. For many cases (i.e. vehicles 20, 34, 49, 50, and 44) the two average values are of the same order of magnitude but differ by approximately 25 percent. For other cases, the PEMS average is approximately half or less of the NONROAD estimate. For vehicles 49 and 50, the same average values are reported by NONROAD since the same engine emissions standard (i.e. Base) and conversion factors (i.e. transient adjustment and deterioration factors) are used for these types of vehicles and model years of engines. The differences may be, at least in part, because of differences in real-world duty cycles versus engine dynamometer test cycles. For example, the engine data in NONROAD is based on the 8-mode steady-state modal test cycle, which includes 15 percent of test time in idling.[22] For 6 of the 9 vehicles, the percent of time in idle ranged from 19 to 73 percent. However, the proportion of time in idle is not a sufficient explanation for the lower average in-use emissions compared to the NONROAD model predictions, since some of the field data involved less time in idle but nonetheless had lower average emission rates than the model predicts. Other aspects of the duty cycle, such as the distribution of engine load at non-idle, may be more important.

The NONROAD model uses adjustment factors for deterioration and transient aspects of duty cycles. These factors are estimated as average values for different categories of engine horsepower levels and vehicles, but may not accurately reflect the conditions for a specific vehicle.[3]

3.2 Autocorrelation

Assessment of autocorrelation was performed for both NO_x and CO_2 emissions for all nine databases. Correlations were estimated between emissions values at time t and $t+k$, which represent a time lag of k. In order to determine whether autocorrelations are significantly different from zero, 95 percent confidence intervals were estimated. If the 95 percent probability range of uncertainty in the autocorrelations encloses zero, then they are not statistically different from zero.[21] The data were found to include statistically significant autocorrelations for all vehicles. The number of time lags in which autocorrelations were significant ranged up to 6 to 10 for NO_x and from 7 to 10 for CO_2 emissions, depending on the vehicle. For example for NO_x, the autocorrelation ranged from 0.67 to 0.96 at lag 1, 0.35 to 0.87 at lag 3, and 0.31 to 0.78 at lag 5, among the vehicles. The existence of significant autocorrelation motivates the need to stratify the data in order to reduce the influence of autocorrelation on emissions estimates.

3.3 Modal Models

The data were stratified with respect to exhaust flow as the basis for developing a modal model. In deciding upon the endpoints of each mode, consideration was given to several factors. First, a decision was made to define 10 modes for each vehicle. Second, each mode was selected to account for approximately 10 percent of the total NO_x emissions. Third, the average emission rate for each mode should be significantly different than the adjacent mode; otherwise, there is no need to maintain separate modes. Fourth, the coefficient of variation (CV) of each mode, which represents the standard deviation of the NO_x or CO_2 emissions divided by the mean NO_x or CO_2 emissions within a mode, respectively, should be as small as possible. Because CO_2 and NO_x are highly correlated with each other, as indicated by correlations of 0.91 to 0.97 among the vehicles, the same modes were used for both pollutants.

The average NO_x and CO_2 emission rates in each mode were found to increase monotonically from modes 1 to 10 for all vehicles. A typical case is shown in Table 4. The CV tends to decrease, in most cases, as the average emission rate increases. On a relative basis, the 95 percent confidence intervals on the mean emission rates in each mode are typically less than 2 percent of the mean values. Some modes such as Modes 9 and 10, account for periods of high emission rates in which 10% of the total NO_x emission are observed in smaller fractions of data collection time.

The explanatory power of the modal models was evaluated by assessing their goodness of fit, as illustrated for one vehicle in Figure 1(a). The modal model produces 10 discrete values of emissions rate, corresponding to observed second-by-second data that vary continuously. In order to indicate the proportional density of the observed data, a box and whiskers plot is used instead of a scatter plot.[23] As expected, the empirical modal model produces average emissions estimates that agree with average observed emission rates in each mode. However, more significantly, the overall R^2 values for these models are on the order of 0.8 for the example in Figure 1 (a), and vary from 0.76 to 0.96 depending on the vehicle and pollutant. A hypothesis was tested that mean emission rates for a given pollutant and vehicle are not statistically significantly different when comparing modes. With a 95 percent confidence, this hypothesis was rejected for all pairwise comparisons of modes for a given vehicle.

Figures 2(a) and 2(b) represent the average normalized emission rates versus the average normalized exhaust flow rate for each mode for all the vehicles. For most of the cases, an inter-vehicle similarity and consistency is observed in which the average emission rates monotonically increase as exhaust flow increases. The trend for Excavator 41 is slightly different than for the other vehicles because there is a substantial increase in engine speed and exhaust flow rate when the excavator starts using the attachment (i.e. bucket). Although the generic relationship between the average emission rates and exhaust flow are similar, the magnitudes of the average emissions rates estimated from modal models are different for each vehicle.

3.4 Combined Modal-Regression Models

Although the modal models for each vehicle offer a significant degree of explanatory power, an effort was made to determine if these models could be substantially improved by incorporating functional relationships between emissions and one or more explanatory variables within the data for each mode. A simple approach to doing this was explored based upon the use of ordinary least squares (OLS) regression for one explanatory variable at a time for the data in each mode. For this purpose, a linear regression model was fit to estimate variability in each of NO_x and CO_2 emissions within a given mode for a given vehicle as a function of either exhaust flow, engine speed, ambient temperature, barometric pressure, or relative humidity.

As an example, Table 5 summarizes the mode-specific OLS regression results for NO_x and CO_2 for Excavator 41. The average R^2 values for engine speed, ambient temperature, barometric pressure, and relative humidity are 0.34, 0.10, 0.04, and 0.10, for NO_x, and 0.51, 0.11, 0.02, and 0.12 for CO_2, respectively. Based upon a review of results for all nine vehicles and with the purpose of simplifying the model development process, a judgment was made to select engine speed as the supplemental explanatory variable because it has useful explanatory power as reflected in R^2 values of 0.30-0.87 in most of the cases.

3.5 Multiple OLS Regression Models

The application of multiple OLS regression to the autocorrelated nonroad data sets is intended mainly for comparative purposes in order to help identify or understand the potential benefits of the modal approaches, but is not recommended as an approach to use in future model development. The results of the multiple OLS regressions are summarized in

Table 6 for all nonroad vehicles. The R^2 values vary from 0.91 to 0.94 for NO_x emissions and from 0.93 to 0.97 for CO_2 emissions, among the nine vehicles.

3.6 Comparison of the Models

The performance of the modal, CMR, and multiple OLS approaches were evaluated using parity plots of observed emissions versus predicted NO_x and CO_2 emissions, as shown in Figures 1 (a), (b), and (c) for Dozer 45 as a typical case. For all of the nonroad vehicles, the trend lines found in the parity plots had a slope identically equal to one indicating that on average the models are accurate in predicting emissions.

A summary of the R^2 values for all nonroad vehicles with respect to the three alternative models is given in Table 7. All three of the alternative models are found to provide explanatory capability for variability in CO_2 emissions more so than for NO_x emissions. The R^2 values for the CMR models are similar for all nine vehicles. There is a substantial increase in explanatory power of the CMR models compared to the modal models for some of the test vehicles, such as Dozers 20, 45, 49, and 50. In other cases, the R^2 values for the modal models are so high (e.g., 0.93 to 0.95 for Dozer 34) that substantial improvement is not possible

The multiple OLS approach has a slightly lower R^2 value than the CMR approach, in most cases. However, the CMR and multiple OLS approaches both have very high R^2 values, typically 0.91 or higher for NO_x and 0.93 and greater for CO_2. Because the CMR models involve stratification of data that reduces the influence of autocorrelation, they are preferred over the multiple OLS models.

3.7 Comparison of Duty Cycles

Modal models can be used to explain differences in the estimated average emission rates with respect to differences in duty cycles. Duty cycles are represented as distributions of time spent in each mode for a given vehicle as summarized in Table 8. The time spent in a given mode differs from one vehicle to another. However, the average emissions for any duty cycle can be estimated for a given vehicle by appropriate weighting of the modes. A comparison of estimated average emissions for different duty cycles provides insight into the importance of duty cycle as a determinant of emissions.

For each of the 9 vehicles, the weighted average emissions were estimated for 9 duty cycles. Each duty cycle is based on the modal fraction of time observed for a particular vehicle. For example, for Dozer 20, 18.7 percent of time was spent in Mode 1, as shown in Table 5. The average normalized NO_x emission rate for Dozer 20 based on its duty cycle is 0.65, as shown in Table 9. However, if the duty cycle experienced by Dozer 34 (as shown in Table 4) is used to weight the modal emission rates for Dozer 20, the resulting average normalized emission rate is 0.44 (as shown in Table 6). Thus, the column for Dozer 20 in Table 6 indicates the variability in average emission rate associated with differences in duty cycles. The inter-cycle variability in average normalized NO_x emissions rate for Dozer 20 is from 0.26 to 0.65.

Of course, not all duty cycles are appropriate to all types of vehicles. However, it is possible for a given make and model of engine to be used in different types of vehicles. For example, the Caterpillar 3406 engine is used in both dozers and a front end loader (see Table 1). The modal emissions data are representative of the engine, and can be weighted to represent activity for a given type of vehicle and duty cycle. For example, vehicles 34, 44, 49, and 50 have the same basic model of engine. For a given duty cycle, the average normalized emission rates among these four vehicles are within 6 to 20 percent of each other, whereas for a given vehicle the average emissions vary by nearly a factor of three when comparing duty cycles. Thus, the inter-engine variability for a given make and model of engine is much less than the inter-cycle variability. Similarly, vehicles 20 and 45 have the same make and model of engine and nearly identical average emissions rates for each mode, as do vehicles 38 and 39.

The bulldozer cycles generally have higher average emissions than the cycles observed for the other vehicles. On average, the five bulldozer cycles have emissions 147 percent higher than for the one front-end loader cycle, 99 percent higher than for the one excavator cycle, and 144 percent higher than for the two off-highway truck cycles. The average variability among the five bulldozer cycles was a 57 percent increase when comparing the cycle with highest emissions to that with the lowest emissions. Thus, the variability in cycles between different types of vehicles is greater than the variability within the bulldozer category.

4.0 Conclusions

The development of modal-based models of nonroad vehicle duty cycles and emissions enables key representative insights regarding the effect of alternative duty cycles, types of vehicles, and engines on real-world emissions. .

Modal models offer the advantages of stratifying the data to reduce the influence of autocorrelation, being conceptually simple, and having substantial explanatory power. Combined Modal-Regression (CMR) models produced an improvement in explanatory power in some cases, compared to a simple modal model. A naïve application of multiple ordinary least squares regression produces R^2 values typically not better than achieved with the CMR approach, and is not recommended because of autocorrelation in the data.

The relationship between average normalized emissions and exhaust flow was found to be stable, consistent, and similar among the vehicles. The consistency of these finding suggests that it is possible to characterize the emissions profile of an engine with a limited amount (e.g., perhaps several hours) of real world data. In order to estimate modal emissions rates. The modal emissions can be reweighted as needed to estimate emissions for a variety of duty cycles.

Differences in duty cycles can lead to substantial differences in average emission rates for a given type of vehicle, such as bulldozers, and when comparing different types of vehicles, such as bulldozers and off-highway trucks. The average emissions varied by a factor of two or more for many of the pairwise comparisons of duty cycles afforded by the available data. These large differences strongly motivate the need for future work to more fully characterize representative duty cycles for nonroad vehicles.

A key difficulty in this work was that potential explanatory variables available for exploratory analysis and modeling were limited to engine data and ambient conditions. To better characterize duty cycles, future data collection should include information regarding the vehicle task and components of the duty cycle, such as lateral movement of the vehicle, and usage of vehicle accessories and attachments such as blades and buckets. Furthermore, data regarding the extent of the vehicle task, such as volume of dirt excavated, could be the basis for development of activity-specific emission factors (e.g., mass of pollutant emitted per cubic yard of material excavated).

An on-board data collection procedure for nonroad construction vehicles needs to be developed to appropriately document the pattern of the vehicle, obtain data for variables that either directly or indirectly quantify engine load, and obtain data for a wider range of pollutants of interest for diesel-fueled nonroad vehicles, such as particulate matter. The use of PEMS and modal emissions modeling approaches is recommended. The study design for PEMS data collection should account for key sources of variability that affect emissions, such as engine make and model, model year, type of vehicle, and duty cycle (which in turn implies the need to collect data for different job sites and tasks). Field studies should be designed and conducted for a variety of purposes, such as characterization of emission factors and inventories, comparison of vehicle technologies, and evaluation of operational strategies for performing a given task, among others. The long-term development of real-world data will enable more accurate quantification of emissions and, therefore, improved efficacy of air quality management strategies.

5.0 Implications

There is a growing need to measure and analyze real world, in-use data for nonroad construction vehicles and equipment in order to develop more accurate emission inventories for such sources. An empirically-based modal modeling approach using data from portable emission measurement systems is shown to be highly flexible and provides key insights regarding the importance of inter-cycle and inter-vehicle variability. The use of empirical data from portable emissions measurement systems and modal models is recommended as a means to improve the accuracy of emission factors and inventories, which in turn will improve the ability to predict and management emissions from nonroad sources.

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Table 1. Characteristics and Activity Patterns of Selected Nonroad Construction Vehicles and Comparison of Their Derived versus Estimated Average NO_x Emission Rates

EPA ID No.	Chassis				Engine				Vehicle Activity Pattern[3]		Average NO_x Emission Rates (g/gal)	
	Type	Make	Model	Model Year	Volume (L)	Model	Horse power (hp)	Cylin-ders	Idling %	Non-Idling %	PEMS[1]	NMD[2]
20	Dozer	CAT	D7G	1985	10.5	3306	200	6	6.3	93.7	168	203
34	Dozer	CAT	D8N	1990	14.6	3406	285	6	13.9	86.1	86	128
45	Dozer	CAT	D6H	1995	10.5	3306	200	6	2.8	97.2	61	126
49	Dozer	CAT	D8N	1987	14.6	3406	285	6	24.0	76.0	103	129
50	Dozer	CAT	D8N	1988	14.6	3406	285	6	18.7	81.3	92	129
41	Excavator	CAT	225D	1989	10.5	3056	165	8	27.4	72.6	65	126
38	Off-highway Truck	Volvo	A35D	2001	12	D12C	375	6	73.0	27.0	57	125
39	Off-highway Truck	Volvo	A35D	2001	12	D12C	375	6	70.3	29.7	49	125
44	Front-end Loader	CAT	980C	1983	14.6	3406	285	6	46.7	53.3	170	235

1: Average NO_x emission rate estimated from PEMS data
2: Average NO_x emission rate derived from the EPA's NONROAD model database
3: Vehicle activity pattern represents percent of time that vehicle has been operated in idling and non-idling modes.

Table 2. Summary of In-Use Measurement Data for Nine Nonroad Vehicles

		Dozer					Excavator	Off-highway Truck		Front Loader
Vehicle ID		**20**	**34**	**45**	**49**	**50**	**41**	**38**	**39**	**44**
Relative Humidity (%)	Mean	46.7	86.6	55.0	43.0	46.9	21.9	31.8	42.5	32.6
	Mean CI[1]	0.117	0.152	0.089	0.177	0.254	0.196	0.061	0.117	0.231
	SD[2]	10.6	13.6	8.14	16.1	22.8	17.1	5.52	10.6	14.4
	2.5% Pr[3]	34.2	65.4	40.5	26.3	26.3	12.3	24.9	29.1	24.1
	97.5% Pr	64.7	102	67.8	80.5	95.7	83.7	44.8	59.3	81.8
Ambient Temperature (^0C)	Mean	8.01	10.8	31.2	34.0	37.1	27.1	26.9	23.7	28.1
	Mean CI	0.032	0.046	0.028	0.060	0.076	0.071	0.030	0.037	0.032
	SD	2.92	4.08	2.54	5.45	6.76	6.37	2.69	3.37	1.99
	2.5% Pr	2.70	1.10	27.4	21.8	22.9	6.63	21.8	16.2	22.4
	97.5% Pr	11.6	16.1	35.9	40.3	44.1	33.7	32.5	28.6	29.8
Barometric Pressure (kPa)	Mean	99.8	100	97.9	104	100	100	98.3	98.9	104
	Mean CI	0.001	0.001	0.001	0.023	0.002	0.001	0.002	0.003	0.003
	SD	0.101	0.099	0.064	2.09	0.144	0.087	0.142	0.237	0.207
	2.5% Pr	99.7	100	97.8	97.6	99.9	100	98.1	98.6	104
	97.5% Pr	100	100	98.0	109	100	100	98.6	99.3	105
Engine Speed (RPM)	Mean	2003	1877	1799	1559	1751	1272	1027	1078	1071
	Mean CI	4.03	7.97	2.54	6.25	5.47	4.98	5.08	5.64	7.54
	SD	368	715	232	570	492	451	463	515	471
	2.5% Pr	650	613	1161	521	706	719	760	760	536
	97.5% Pr	2183	2611	1982	2069	2092	1991	2155	2257	2039
Exhaust Flow (scfm)	Mean	418	200	130	169	265	72.0	67.0	101	93.0
	Mean CI	1.12	1.15	0.286	0.933	1.21	0.335	0.653	1.03	0.648
	SD	101	103	26.1	85.1	109	30.2	59.5	94.3	40.5
	2.5% Pr	85.9	54.1	62.9	25.0	50.2	35.3	30.2	40.3	40.5
	97.5% Pr	510	337	152	268	385	141	230	347	208
NO_x (g/sec)	Mean	0.304	0.151	0.064	0.144	0.216	0.023	0.028	0.038	0.029
	Mean CI	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.000
	SD	0.093	0.067	0.19	0.088	0.090	0.017	0.027	0.040	0.020
	2.5% Pr	0.040	0.018	0.016	0.013	0.021	0.009	0.012	0.014	0.007
	97.5% Pr	0.426	0.218	0.089	0.272	0.318	0.073	0.109	0.153	0.084
CO_2 (g/sec)	Mean	18.2	11.52	7.64	10.1	15.6	2.55	3.50	5.53	4.17
	Mean CI	0.068	0.064	0.025	0.066	0.079	0.023	0.053	0.085	0.052
	SD	6.18	5.78	2.29	6.02	7.11	2.09	4.85	7.77	3.24
	2.5% Pr	0.617	1.07	1.54	0.638	1.28	0.718	0.766	0.987	0.997
	97.5% Pr	26.5	18.7	10.2	18.2	24.4	7.89	17.3	26.2	13.6
Seconds of data (sec)		31976	30951	31894	31918	31079	31306	31920	31915	15005

(1) Mean Confidence Interval in the magnitude of the 2.5th percentile to the 97.5th percentile
(2) Standard Deviation
(3) 2.5th Percentile of variability in the observed data on a second-by-second basis
(4) 97.5th Percentile of variability in the observed data on a second-by-second basis

Table 3. Coefficients of Determination (R^2) from Ordinary Least Squares Regression of Normalized NO_x and CO_2 Emissions versus Individual Explanatory Variables

Type of Vehicle		**Coefficient of Determination R^2**								
		Dozer					**Excavator**	**Off-highway Truck**		**Front Loader**
Vehicle ID Number		**20**	**34**	**45**	**49**	**50**	**41**	**38**	**39**	**44**
Normalized Exhaust Flow	**NO_x**	0.88	0.92	0.85	0.91	0.92	0.90	0.92	0.92	0.93
	CO_2	0.91	0.95	0.93	0.97	0.97	0.95	0.97	0.96	0.92
Normalized Engine Speed	**NO_x**	0.82	0.76	0.85	0.72	0.90	0.85	0.79	0.76	0.78
	CO_2	0.90	0.75	0.85	0.87	0.91	0.82	0.87	0.87	0.87
Temperature (^{0}C)	**NO_x**	0.01	0.00	0.01	0.03	0.00	0.15	0.00	0.00	0.00
	CO_2	0.02	0.00	0.00	0.02	0.00	0.15	0.00	0.00	0.00
Barometric Pressure(kPa)	**NO_x**	0.02	0.01	0.00	0.02	0.01	0.00	0.01	0.00	0.03
	CO_2	0.02	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.03
Relative Humidity(%)	**NO_x**	0.02	0.00	0.01	0.03	0.00	0.15	0.00	0.00	0.00
	CO_2	0.02	0.00	0.00	0.03	0.00	0.16	0.00	0.00	0.00

Note: Each OLS regression has only one explanatory variable. For example, for Dozer 20, the R^2 of 0.88 is related to the OLS regression of normalized NO_x and normalized exhaust flow rate.

Table 4. Summary of Modal NO_x and CO_2 Emission Model for Dozer 50

Mode No.	Normalized Exhaust Flow	Fraction of time (%)	NO_x Emissions per Mode (%)	Normalized NO_x Emission Rate			Normalized CO_2 Emission Rate		
				Average	CV[1]	Mean CI[2]	Average	CV	Mean CI
1	0.104-0.624	28.7	10	0.172	0.286	0.003	0.169	0.191	0.004
2	0.625-0.703	10.3	10	0.486	0.141	0.002	0.508	0.098	0.001
3	0.704-0.731	9.1	10	0.534	0.112	0.002	0.552	0.077	0.001
4	0.732-0.756	8.6	10	0.573	0.108	0.002	0.587	0.069	0.001
5	0.757-0.780	8.2	10	0.603	0.108	0.002	0.618	0.063	0.002
6	0.781-0.803	7.7	10	0.639	0.107	0.003	0.650	0.063	0.002
7	0.804-0.827	7.4	10	0.669	0.105	0.004	0.682	0.063	0.002
8	0.828-0.853	7.1	10	0.701	0.105	0.005	0.717	0.062	0.003
9	0.854-0.886	6.6	10	0.739	0.104	0.006	0.758	0.062	0.003
10	0.887-1.00	6.3	10	0.791	0.104	0.006	0.820	0.061	0.004

1) CV: Coefficient of Variation (standard deviation divided by the mean)
2) CI: Confidence Interval (1/2 range of 95% confidence interval)

Table 5. Summary of Ordinary Least Square Regression Equations for Normalized NO_x and CO_2 Emission Rates versus Individual Explanatory Variables for Each Mode for Excavator 41

Mode		Normalized Engine Speed			Normalized Exhaust Flow			Ambient Temperature (^0C)			Barometric Pressure (kPa)			Relative Humidity (%)		
		m	b	R^2	m	b	R^2	m	b	R^2	m	b	R^2	m	b	R^2
1	NO_x	0.60	-0.10	0.31	0.54	0.02	0.73	0.00	0.14	0.35	0.02	-2.3	0.19	0.00	0.09	0.23
	CO_2	0.40	-0.06	0.27	0.39	-0.01	0.74	0.00	0.10	0.32	0.01	-1.0	0.07	0.00	0.06	0.22
2	NO_x	0.150	0.07	0.37	0.24	0.05	0.60	0.00	0.10	0.16	0.01	-0.8	0.01	0.00	0.15	0.22
	CO_2	0.28	-0.01	0.74	0.39	-0.02	0.87	0.00	0.06	0.28	-0.01	1.43	0.01	0.00	0.13	0.37
3	NO_x	0.45	-0.08	0.32	0.99	-0.2	0.48	-0.01	0.34	0.17	0.12	-12	0.06	0.01	0.04	0.23
	CO_2	0.60	-0.17	0.55	1.2	-0.32	0.70	-0.01	0.31	0.14	0.09	-8.9	0.03	0.01	0.03	0.21
4	NO_x	-0.76	0.83	0.17	-0.09	0.28	0.00	0.00	0.19	0.06	0.09	-8.3	0.01	0.00	0.25	0.06
	CO_2	-0.52	0.68	0.11	0.30	0.12	0.02	0.00	0.26	0.02	0.01	-0.2	0.00	0.00	0.29	0.02
5	NO_x	-2.4	2.2	0.30	5.5	-2.9	0.21	0.00	0.19	0.18	0.26	-26	0.09	0.00	0.34	0.20
	CO_2	-3.0	2.78	0.51	5.3	-2.79	0.21	0.00	0.27	0.13	0.22	-21	0.06	0.00	0.39	0.14
6	NO_x	-2.4	2.3	0.46	3.3	-1.6	0.04	-0.01	0.71	0.04	0.13	-12	0.01	0.00	0.31	0.02
	CO_2	-2.9	2.80	0.75	3.8	-1.88	0.05	-0.01	0.75	0.04	0.14	-13	0.01	0.00	0.36	0.02
7	NO_x	-0.24	-2.4	0.42	4.4	-2.3	0.08	-0.01	0.63	0.01	0.17	-16	0.02	0.00	0.38	0.02
	CO_2	-2.8	2.76	0.64	4.7	-2.45	0.11	0.00	0.66	0.01	0.13	-12	0.01	0.00	0.44	0.02
8	NO_x	-0.47	0.91	0.18	-0.11	0.58	0.00	0.00	0.40	0.03	0.00	0.07	0.00	0.00	0.53	0.03
	CO_2	-0.73	1.19	0.37	-0.4	0.84	0.05	0.01	0.36	0.08	-0.06	6.7	0.02	0.00	0.61	0.09
9	NO_x	-1.2	1.8	0.06	2.0	-1.0	0.37	0.00	0.66	0.00	-0.06	6.5	0.00	0.06	6.54	0.00
	CO_2	-3.9	4.43	0.54	1.6	-0.71	0.19	0.00	0.57	0.07	0.24	-23	0.02	0.00	0.72	0.08
10	NO_x	-3.9	4.6	0.28	2.3	-1.2	0.64	0.00	0.85	0.00	-0.08	9.3	0.00	0.00	0.85	0.00
	CO_2	-6.6	7.23	0.64	2.5	-1.45	0.61	0.00	0.82	0.01	0.04	-3.3	0.00	0.00	0.90	0.01

Note: the m, b, and R^2 are slope, intercept, and coefficient of determination of the regressions. The m values of regressions for normalized engine speed and normalized exhaust flow rate are dimensionless and for ambient temperature, barometric pressure, and relative humidity, are in $(^0C)^{-1}$, $(kPa)^{-1}$, $(\%)^{-1}$. All b values in Table 6 are dimensionless.

Table 6. Summary of Parameter Estimates for Multiple OLS Regression Equations for Normalized NO_x and CO_2 Emission Rates as a Function of Four Explanatory Variables for each of Nine Nonroad Vehicles

Vehicle \ Parameter		Intercept		Ambient Temperature (^0C)		Barometric Pressure (kPa)		Normalized Engine Speed		Normalized Exhaust Flow		R^2	
		NO_x	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x	CO_2
Dozer	20	13	1.7	-0.002	0.002	-0.13	-0.02	-0.52	-0.56	1.4	1.5	0.92	0.96
	34	1.7	4.2	-0.004	0.007	-0.02	-0.04	0.02	0.01	0.81	0.87	0.91	0.94
	45	-6.2	-5.0	0.005	0.002	0.06	0.05	-0.43	-0.27	1.3	1.4	0.93	0.94
	49	0.04	0.53	0.002	0.000	-0.01	-0.01	-0.10	-0.14	1.0	1.0	0.91	0.97
	50	6.0	6.2	0.003	0.001	-0.06	-0.06	-0.25	-0.25	1.1	1.1	0.91	0.94
Excavator	41	-13	-15	0.002	0.004	0.13	0.14	-1.3	-0.95	2.4	2.1	0.92	0.93
Off-highway Truck	38	-3.1	-0.73	0.001	0.001	0.03	0.01	-0.26	-0.18	0.91	1.1	0.94	0.97
	39	-1.9	-0.03	-0.001	0.003	0.02	0.01	-0.22	-0.26	0.62	1.1	0.91	0.94
Loader	44	-0.86	-1.1	0.004	0.002	0.01	0.01	0.12	0.15	0.88	0.88	0.91	0.94

Table 7. R^2 Values for the Scatter Plots of Predicted versus Observed Emissions Values for NO_x and CO_2 Emissions of Nine Selected Vehicles for Three Alternative Modeling Approaches

Vehicle		Modal Model		Combined Modal-Regression Model		Multiple OLS Regression	
		NO_x	CO_2	NO_x	CO_2	NO_x	CO_2
Dozer	20	0.76	0.80	0.92	0.96	0.92	0.96
	34	0.93	0.95	0.94	0.97	0.91	0.94
	45	0.79	0.85	0.94	0.95	0.93	0.94
	49	0.86	0.90	0.91	0.97	0.91	0.97
	50	0.83	0.86	0.92	0.96	0.91	0.94
Excavator	41	0.91	0.93	0.94	0.96	0.92	0.93
Off-highway Truck	38	0.92	0.96	0.93	0.97	0.94	0.97
	39	0.90	0.95	0.91	0.97	0.91	0.94
Loader	44	0.86	0.92	0.92	0.94	0.91	0.94

Table 8. Summary of Mode-Specific Average Normalized NO_x Emission Rates and Vehicles Activity Patterns on a Fraction of Time Spent in each Mode Basis for each Nine Vehicles

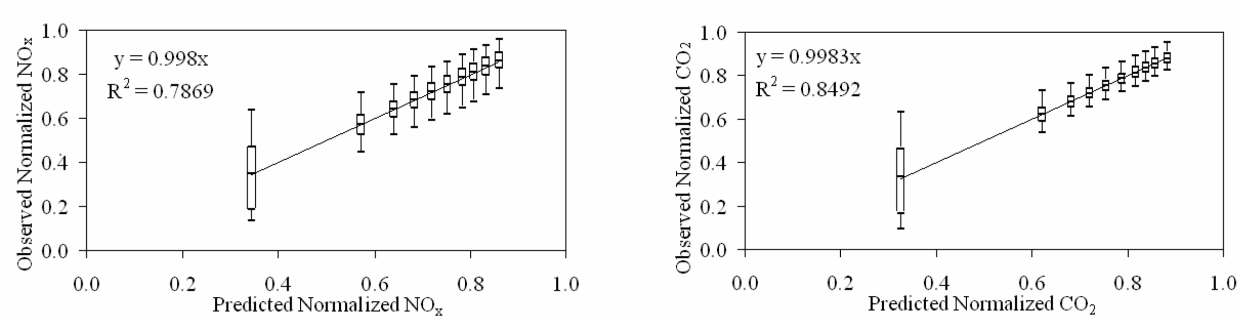
Mode	Dozer										Excavator		Off-highway Truck				Front-end Loader	
	20		34		45		49		50		41		38		39		44	
	NO_x[1]	FT[2] %	NO_x	FT %	NO_x	FT %	NO_x	FT %	NO_x	FT %	NO_x	FT %	NO_x	FT %	NO_x	FT %	NO_x	FT %
1	0.35	18.7	0.09	38.1	0.34	19.0	0.14	35.9	0.17	28.7	0.11	22.9	0.08	23.3	0.07	27.9	0.09	23.6
2	0.56	11.8	0.32	10.9	0.57	11.4	0.46	9.65	0.49	10.4	0.13	19.0	0.09	17.8	0.08	18.6	0.12	18.4
3	0.61	10.2	0.43	8.20	0.64	10.3	0.58	16.3	0.53	9.05	0.15	15.6	0.09	17.8	0.09	20.3	0.17	12.5
4	0.65	10.1	0.48	7.36	0.68	9.50	0.66	7.11	0.57	8.62	0.23	10.8	0.11	15.1	0.16	10.7	0.22	9.82
5	0.69	9.38	0.51	7.01	0.72	9.42	0.71	7.11	0.60	8.21	0.30	8.13	0.19	8.34	0.28	6.17	0.25	8.66
6	0.74	9.00	0.54	6.62	0.75	8.63	0.75	6.47	0.64	7.65	0.37	6.70	0.30	5.39	0.38	4.56	0.28	7.49
7	0.78	8.08	0.57	5.99	0.78	8.13	0.79	4.29	0.67	7.40	0.44	5.44	0.43	3.86	0.49	3.47	0.33	6.53
8	0.82	8.02	0.61	5.80	0.81	8.10	0.81	1.85	0.70	7.09	0.50	4.79	0.52	3.12	0.57	3.08	0.40	5.40
9	0.85	7.71	0.65	5.33	0.83	8.04	0.83	5.56	0.74	6.62	0.64	3.82	0.58	2.78	0.62	2.86	0.47	4.55
10	0.88	7.01	0.75	4.69	0.86	7.48	0.87	5.31	0.79	6.26	0.85	2.82	0.65	2.51	0.71	2.36	0.70	3.05

1) NO_x: Average normalized NO_x emission rate in each mode
2) FT: Fraction of time that a test vehicle has been operated in each mode during data collection

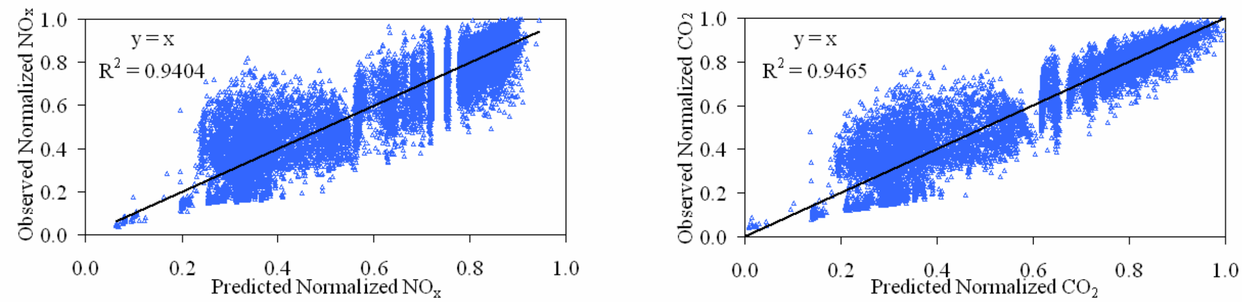
Table 9. Average Normalized NO_x Emission Estimated for Each Vehicle based upon Different Duty Cycles

Duty Cycle of Vehicle[1]	Dozer					Excavator	Off-highway Truck		Front-end Loader
	20	34	45	49	50	41	38	39	44
Dozer 20	0.65	0.57	0.64	0.57	0.61	0.60	0.59	0.57	0.61
Dozer 34	0.44	0.35	0.44	0.35	0.40	0.39	0.38	0.35	0.39
Dozer 45	0.65	0.57	0.65	0.57	0.61	0.61	0.60	0.58	0.62
Dozer 49	0.59	0.48	0.59	0.48	0.54	0.53	0.52	0.49	0.54
Dozer 50	0.54	0.45	0.53	0.45	0.49	0.49	0.48	0.46	0.50
Excavator 41	0.32	0.26	0.32	0.25	0.29	0.25	0.23	0.21	0.26
Off-highway Truck 38	0.26	0.21	0.26	0.19	0.24	0.19	0.17	0.15	0.20
Off-highway Truck 39	0.29	0.23	0.29	0.21	0.26	0.21	0.19	0.17	0.23
Front-end Loader 44	0.26	0.22	0.26	0.21	0.24	0.21	0.20	0.19	0.22

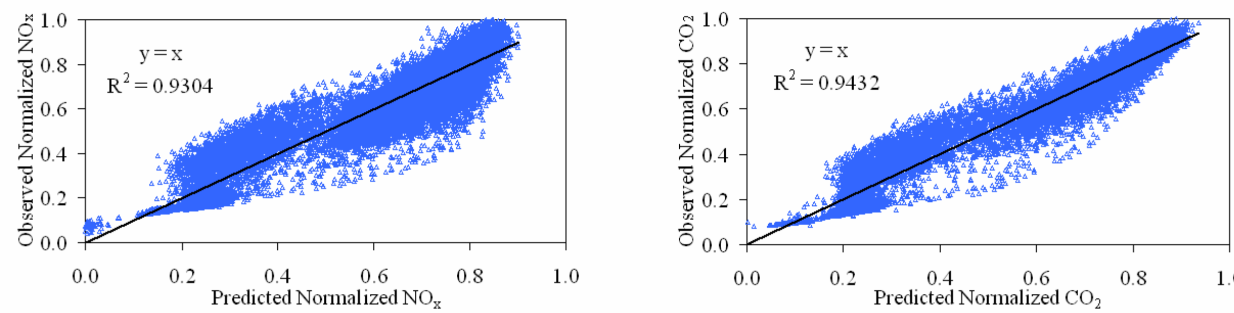
1) Duty cycle for each vehicle is characterized based upon percentage of time spent in each exhaust flow rate specific-mode



(a) Parity Plots for Exhaust Flow Modal Model

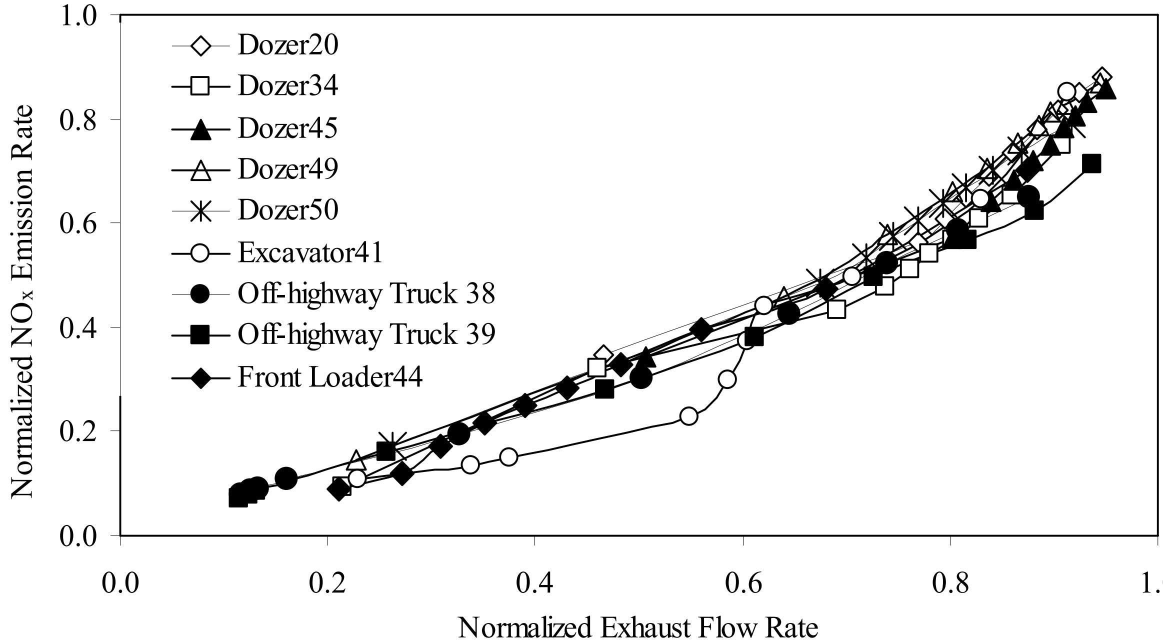


(b) Parity Plots for Combined Modal-Regression Model

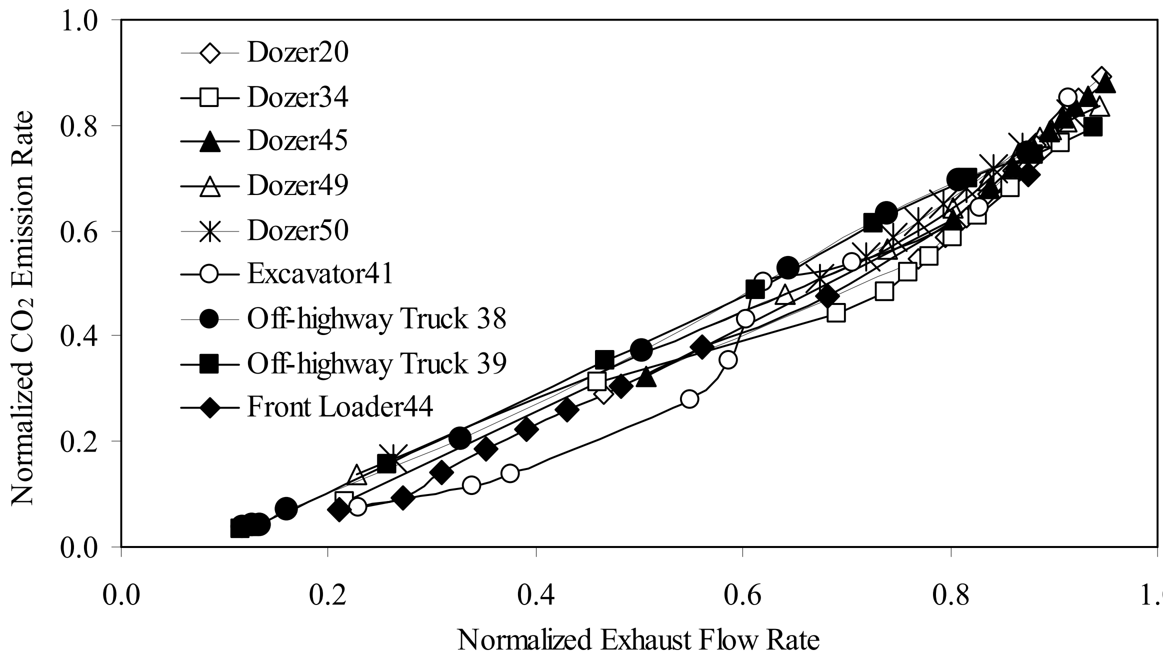


(c) Parity Plots for Multiple OLS Regression Model

Figure 1. Comparison of Second-by-Second Observations for Three Alternative Models for NO_x and CO_2 Emissions from Dozer 45



Average Normalized NO_x Emission Rates versus Average Exhaust Flow Rates



(b) Average Normalized CO_2 Emission Rates versus Average Exhaust Flow Rates

Figure 2. Average of Normalized Emission Rates for each Vehicle and Mode versus Normalized Exhaust Flow Rate.

Development of Modal Models to Predict Nonroad Construction Vehicles Emissions Using On-Board Engine and Emissions Data

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Supporting Information

This supporting information (SI) contains figures and tables pertaining to analyses that were not shown in the paper. Materials presented here include: (1) summary of multiple OLS regression equations for normalized NO_x and CO_2 emission rates for all test vehicles; (2) summary of autocorrelation assessment for all vehicles with respect to NO_x emission rates; (3) summary of autocorrelation assessment for all vehicles with respect to CO_2 emission rates; (4) results of pairwise *t* tests for Dozer 20 to evaluate statistical significance of difference in average modal rates for NO_x and CO_2 emissions; (5) average NO_x and CO_2 emission rates estimated for idling and non-idling modes of operation; (6) summary of ordinary least square equations for normalized NO_x versus normalized CO_2 for each of nine vehicles; (7) comparisons of time series data for engine speed and CO_2 volume percent in order to verify synchronization of engine and analyzer data; (8) scatter plots of normalized second-by-second NO_x and CO_2 emissions versus candidate explanatory variables for Dozer 34, with trend lines indicated; and (9) average normalized CO_2 emission estimated for each vehicle based upon different duty cycles.

Table S1. Summary of Multiple OLS Regression Equations for Normalized NO_x and CO_2 Emission Rates for all Vehicles

Vehicle			Normalized Exhaust Flow			Normalized Engine Speed			Ambient Temperature (^{0}C)			Barometric Pressure (kPa)			Relative Humidity (%)		
			m	b	R^2	m	b	R^2	m	b	R^2	m	b	R^2	m	b	R^2
Dozer	20	NO_x	0.98	-0.12	0.88	0.91	-0.17	0.82	0.01	0.58	0.01	-0.28	28	0.02	0.00	0.76	0.02
		CO_2	0.93	-0.21	0.91	0.95	-0.27	0.90	0.01	0.54	0.02	-0.27	27	0.02	0.00	0.76	0.02
	34	NO_x	0.87	-0.09	0.92	0.86	-18	0.76	0.00	0.34	0.00	0.21	-20	0.01	0.00	0.25	0.00
		CO_2	0.89	-0.10	0.95	0.87	-0.19	0.75	0.00	0.33	0.00	0.16	-16	0.00	0.00	0.28	0.00
	45	NO_x	1.10	-0.22	0.85	0.87	-0.34	0.85	0.00	0.45	0.01	-0.15	15	0.00	0.00	0.76	0.01
		CO_2	1.00	-0.30	0.93	0.90	-0.49	0.85	0.00	0.56	0.00	-0.15	16	0.00	0.00	0.74	0.00
	49	NO_x	0.93	-0.07	0.91	0.83	-0.19	0.72	0.01	0.19	0.03	-0.02	2.3	0.02	0.00	0.62	0.03
		CO_2	0.92	-0.08	0.97	0.92	-0.20	0.87	0.00	0.21	0.02	-0.02	2.6	0.02	0.00	0.59	0.03
	50	NO_x	0.89	-0.06	0.92	0.91	-0.25	0.90	0.00	0.45	0.00	0.17	-16	0.01	0.00	0.51	0.00
		CO_2	0.93	-0.08	0.97	0.94	-0.27	0.91	0.00	0.52	0.00	0.16	-15	0.01	0.00	0.39	0.00
Excavator	41	NO_x	0.89	-0.15	0.90	0.81	-0.17	0.85	-0.01	0.54	0.15	0.00	0.27	0.00	0.00	0.15	0.15
		CO_2	1.00	-0.21	0.95	0.84	-0.25	0.82	-0.01	0.59	0.15	-0.30	2.9	0.00	0.00	0.15	0.16
Off-highway Truck	38	NO_x	0.92	0.00	0.92	0.89	-0.13	0.79	0.00	0.25	0.00	0.08	-7.5	0.01	0.00	0.16	0.00
		CO_2	0.93	-0.08	0.97	0.96	-0.25	0.87	0.00	0.26	0.00	0.07	-6.7	0.00	0.00	0.13	0.00
	39	NO_x	0.70	-0.10	0.92	0.81	-0.14	0.76	0.00	0.15	0.00	0.05	-4.9	0.00	0.00	0.22	0.00
		CO_2	0.94	-0.80	0.96	0.97	-0.26	0.87	0.00	0.09	0.00	0.02	-1.9	0.00	0.00	0.22	0.00
Front Loader	44	NO_x	0.93	-0.10	0.93	0.88	-0.07	0.78	0.00	0.14	0.00	-0.12	12	0.03	0.00	0.21	0.00
		CO_2	0.91	-0.14	0.92	0.81	-0.10	0.87	0.00	0.17	0.00	-0.12	12	0.00	0.00	0.18	0.00

Table S2. Summary of Autocorrelation Assessment for all Vehicles with Respect to NO_x Emission Rates

Vehicle			Time Lags with Statistically Significant Autocorrelation									
			1	2	3	4	5	6	7	8	9	10
Dozer 20	NO_x	Correlation[1]	0.737	0.490	0.487	0.517	0.515	0.511	0.502	0.487	0.476	0.469
		Standard Error	0.006	0.007	0.007	0.008	0.008	0.008	0.007	0.007	0.007	0.006
Dozer 34	NO_x	Correlation	0.843	0.607	0.491	0.455	0.426	0.386	0.347	0.320	0.301	0.285
		Standard Error	0.006	0.009	0.011	0.011	0.011	0.009	0.006	0.005	0.005	0.003
Dozer 45	NO_x	Correlation	0.817	0.635	0.585	0.579	0.558	0.524				
		Standard Error	0.005	0.007	0.008	0.007	0.007	0.006				
Dozer 49	NO_x	Correlation	0.901	0.732	0.571	0.446	0.356	0.294	0.250	0.222		
		Standard Error	0.005	0.006	0.006	0.007	0.009	0.009	0.009	0.006		
Dozer 50	NO_x	Correlation	0.905	0.787	0.687	0.612	0.550	0.497	0.451	0.415	0.388	0.365
		Standard Error	0.005	0.006	0.004	0.004	0.005	0.005	0.006	0.006	0.005	0.003
Excavator 41	NO_x	Correlation	0.893	0.769	0.697	0.654	0.618	0.581	0.548	0.519	0.493	
		Standard Error	0.003	0.005	0.005	0.005	0.004	0.003	0.002	0.002	0.003	
Off-Highway Truck 38	NO_x	Correlation	0.673	0.424	0.349	0.329	0.310	0.292	0.274	0.254	0.231	
		Standard Error	0.006	0.007	0.006	0.006	0.006	0.006	0.006	0.006	0.005	
Off-Highway Truck 39	NO_x	Correlation	0.684	0.429	0.369	0.351	0.343	0.322	0.297	0.273	0.253	
		Standard Error	0.005	0.006	0.005	0.005	0.006	0.005	0.005	0.004	0.004	
Front Loader 44	NO_x	Correlation	0.957	0.909	0.866	0.830	0.798	0.766	0.735	0.704	0.671	0.642
		Standard Error	0.007	0.009	0.008	0.007	0.007	0.006	0.006	0.007	0.008	0.007

1) Correlations were estimated between emission values at time t and $t+k$, which represent a time lag of k.

Table S3. Summary of Autocorrelation Assessment for all Vehicles with Respect to CO_2 Emission Rates

Vehicle			Time Lags with Statistically Significant Autocorrelation									
			1	2	3	4	5	6	7	8	9	10
Dozer 20	CO_2	Correlation[1]	0.459	0.224	0.362	0.377	0.351	0.339	0.327	0.305	0.300	0.297
		Standard Error	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.006
Dozer 34	CO_2	Correlation	0.369	0.131	0.262	0.287	0.239	0.182	0.151	0.131	0.128	0.120
		Standard Error	0.005	0.005	0.006	0.006	0.006	0.006	0.005	0.005	0.006	0.005
Dozer 45	CO_2	Correlation	0.608	0.377	0.432	0.443	0.399	0.359	0.325			
		Standard Error	0.005	0.006	0.006	0.007	0.006	0.006	0.005			
Dozer 49	CO_2	Correlation	0.696	0.502	0.471	0.464	0.441	0.407	0.370	0.339		
		Standard Error	0.005	0.006	0.006	0.006	0.006	0.005	0.005	0.004		
Dozer 50	CO_2	Correlation	0.974	0.958	0.948	0.942	0.936	0.934	0.932	0.925	0.922	0.918
		Standard Error	0.005	0.006	0.006	0.006	0.007	0.007	0.006	0.006	0.006	0.005
Excavator 41	CO_2	Correlation	0.747	0.584	0.522	0.502	0.483	0.463	0.448	0.437	0.427	0.422
		Standard Error	0.003	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.003
Off-Highway Truck 38	CO_2	Correlation	0.402	0.190	0.205	0.215	0.184	0.514	0.129			
		Standard Error	0.005	0.006	0.006	0.006	0.006	0.006	0.005			
Off-Highway Truck 39	CO_2	Correlation	0.300	0.117	0.132	0.111	0.120	0.115	0.097	0.072		
		Standard Error	0.005	0.005	0.006	0.005	0.006	0.005	0.005	0.005		
Front Loader 44	CO_2	Correlation	0.844	0.658	0.549	0.483	0.432	0.391	0.356	0.324	0.301	0.285
		Standard Error	0.007	0.011	0.008	0.007	0.006	0.005	0.005	0.005	0.005	0.004

1) Correlations were estimated between emission values at time t and $t+k$, which represent a time lag of k.

Table S4. Results of Pairwise *t* Tests[1] for Dozer 20[2] to Evaluate Statistical Significance of Differences in Average Modal Rates for NO_x and CO_2 Emissions

Mode	**Seconds of Data in Each mode (n)**	**Emissions**											
		Normalized NO_x						**Normalized CO_2**					
		Average	SD[3]	Pairwise *t* Test				Average	SD	Pairwise *t* Test			
				Modes[5]	*t*-test	*t*-Statistics	$\mu_i=\mu_j$[4]			Modes	*t*-test	*t*-Statistics	$\mu_i=\mu_j$
1	5983	0.347	0.21	1-2	76.2	1.96	reject	0.289	0.21	1-2	91.9	1.96	reject
2	3764	0.563	0.06	2-3	37.9	1.96	reject	0.545	0.04	2-3	51.8	1.96	reject
3	3275	0.610	0.04	3-4	38.9	1.96	reject	0.588	0.03	3-4	52.5	1.96	reject
4	3238	0.650	0.04	4-5	39.8	1.96	reject	0.626	0.03	4-5	54.0	1.96	reject
5	2983	0.692	0.04	5-6	38.6	1.96	reject	0.668	0.03	5-6	52.0	1.96	reject
6	2878	0.736	0.04	6-7	36.6	1.96	reject	0.713	0.03	6-7	55.3	1.96	reject
7	2583	0.778	0.04	7-8	34.2	1.96	reject	0.762	0.03	7-8	51.1	1.96	reject
8	2565	0.818	0.04	8-9	29.1	1.96	reject	0.808	0.03	8-9	48.7	1.96	reject
9	2464	0.851	0.04	9-10	26.1	1.96	reject	0.850	0.03	9-10	49.5	1.96	reject
10	2243	0.881	0.04					0.892	0.02				

1) t-Test has been conducted on a confidence level of 95%
2) As an example the results for Dozer 20 in given in this table.
3) SD: Standard Deviation
4) $\mu_i=\mu_j$: result of testing the hypothesis the modal averages are significantly the same
5) The modes for which significance of differences in modal averages were evaluated

Table S5. Average NO_x and CO_2 Emission Rates Estimated for Idling and Non-Idling Modes of Operation

Vehicle	Average Emission Rate (g/s)							
	NO_x				CO_2			
	Idling		Non-Idling		Idling		Non-Idling	
	Mean	Mean CI[1]	Mean	Mean CI	Mean	Mean CI	Mean	Mean CI
Dozer 20	0.044	0.001	0.321	0.003	0.767	0.003	19.3	0.092
Dozer 34	0.019	0.001	0.113	0.003	1.22	0.004	9.70	0.043
Dozer 45	0.018	0.001	0.065	0.001	1.60	0.004	7.82	0.035
Dozer 49	0.023	0.000	0.182	0.001	1.37	0.003	12.8	0.076
Dozer 50	0.028	0.000	0.221	0.002	1.90	0.005	17.6	0.080
Excavator 41	0.010	0.000	0.027	0.000	0.818	0.003	3.20	0.023
Off-Highway Truck 38	0.014	0.001	0.061	0.001	1.05	0.004	10.1	0.052
Off-Highway Truck 39	0.017	0.001	0.084	0.001	1.29	0.004	15.5	0.061
Front-end Loader 44	0.014	0.001	0.041	0.001	1.86	0.004	6.19	0.031

1) CI: Confidence Interval (1/2 range of 95% confidence interval)

Table S6. Summary of Ordinary Least Square Equations for Normalized NO_x versus Normalized CO_2 for each of Nine Vehicles

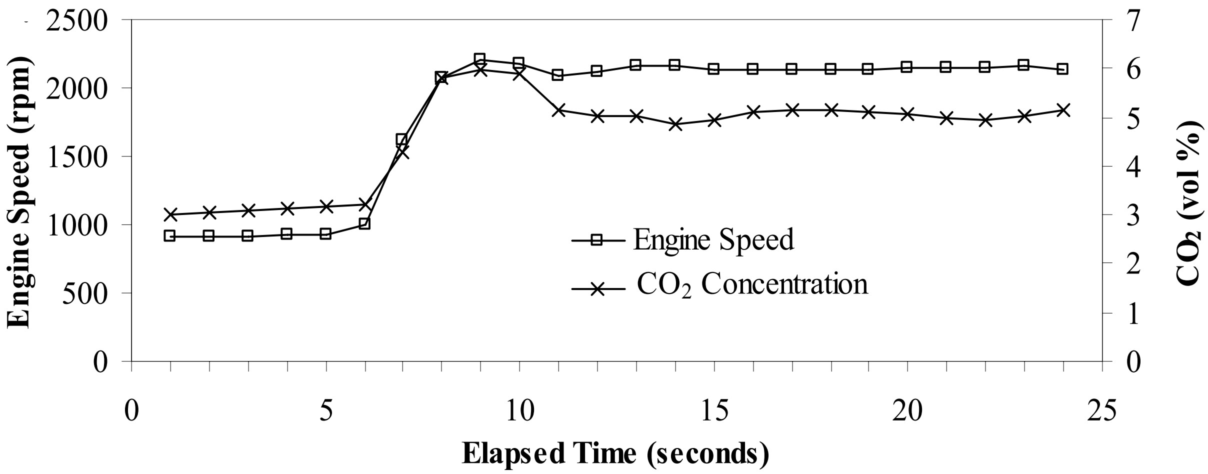
Vehicle		Parameter Estimates and R^2 Values		
		m	**b**	**R^2**
Dozer	**20**	0.91	0.08	0.96
	34	0.94	0.02	0.93
	45	0.92	0.03	0.94
	49	0.99	0.01	0.91
	50	0.97	0.01	0.97
Excavator	**41**	0.91	0.02	0.91
Off-highway Truck	**38**	0.94	0.05	0.95
	39	0.94	0.04	0.92
Front-end Loader	**44**	0.93	0.01	0.92

Note: the m, b, and R^2 are slope, intercept, and coefficient of determination of the regressions. The m and b values of regressions are dimensionless.

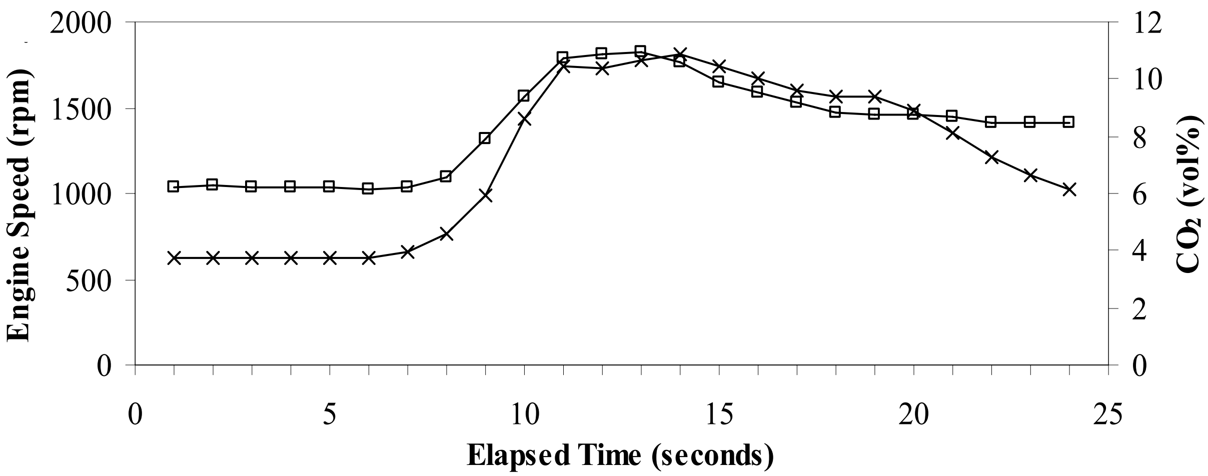
Table S7. Average Normalized CO_2 Emission Estimated for each Vehicle based upon Different Duty Cycles

Duty Cycle of Vehicle[1]	Dozer					Excavator	Off-highway Truck		Front-end Loader
	20	34	45	49	50	41	38	39	44
Dozer 20	0.62	0.54	0.62	0.54	0.58	0.58	0.56	0.54	0.58
Dozer 34	0.45	0.36	0.44	0.36	0.40	0.39	0.38	0.36	0.40
Dozer 45	0.68	0.59	0.67	0.59	0.63	0.64	0.63	0.60	0.64
Dozer 49	0.58	0.47	0.58	0.47	0.53	0.53	0.51	0.48	0.53
Dozer 50	0.55	0.46	0.55	0.46	0.50	0.51	0.50	0.47	0.51
Excavator 41	0.34	0.27	0.33	0.25	0.30	0.26	0.24	0.21	0.27
Off-highway Truck 38	0.28	0.21	0.28	0.18	0.25	0.18	0.15	0.14	0.20
Off-highway Truck 39	0.33	0.24	0.32	0.21	0.29	0.22	0.19	0.16	0.24
Front-end Loader 44	0.24	0.20	0.24	0.19	0.22	0.19	0.18	0.16	0.19

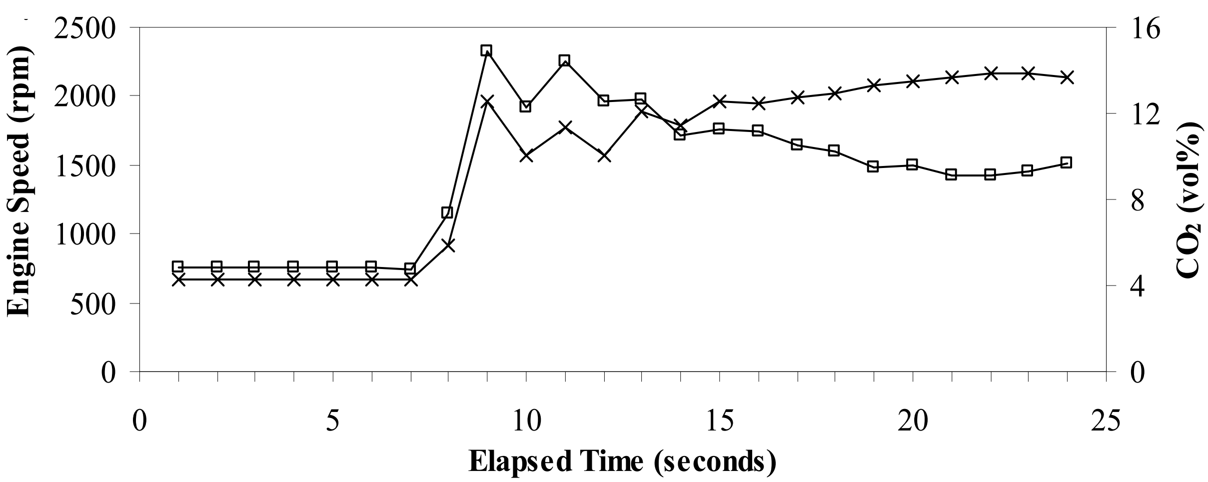
1) Duty cycle for each vehicle was characterized based upon percentage of time spent in each exhaust flow rate specific-modes



(a) Synchronization Check for Dozer 20

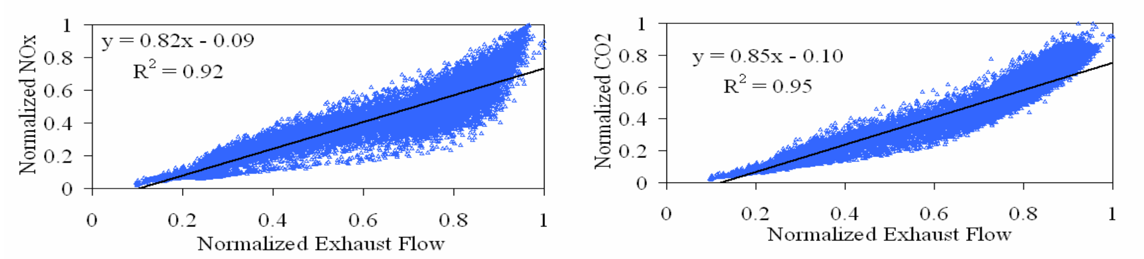


(b) Synchronization Check for Dozer 45

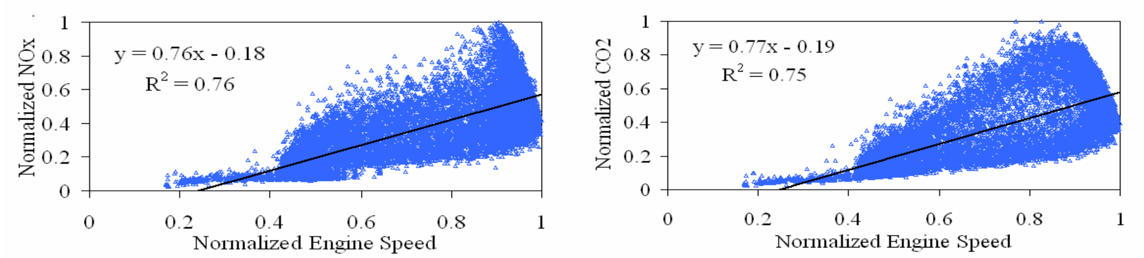


(c) Synchronization Check for Off-highway Truck 38

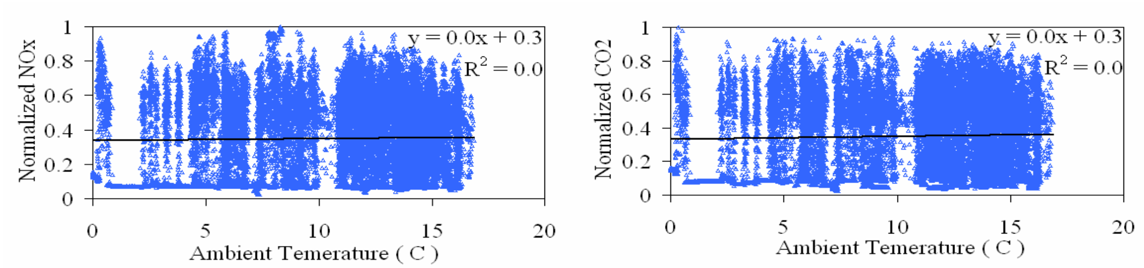
Figure S1. Comparisons of Time Series Data for Engine Speed and CO_2 Volume Percent in order to Verify Synchronization of Engine and Analyzer Data



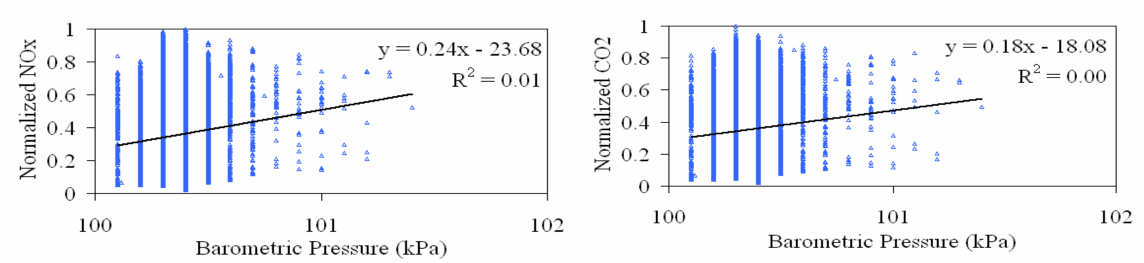
(a) Normalized NO_x and CO_2 vs. Normalized Exhaust Flow



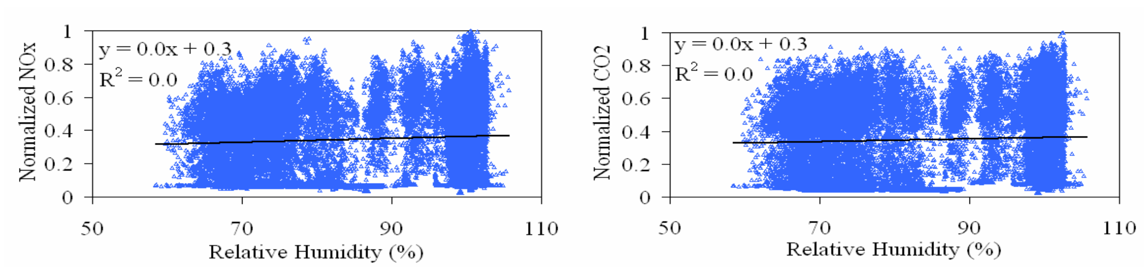
(b) Normalized NO_x and CO_2 vs. Normalized Engine Speed



(c) Normalized NO_x and CO_2 vs. Ambient Temperature



(d) Normalized NO_x and CO_2 vs. Barometric Pressure



(e) Normalized NO_x and CO_2 vs. Relative Humidity

Figure S2. Scatter Plots of Normalized Second-by-Second NO_x and CO_2 Emissions versus Candidate Explanatory Variables for Dozer 34, With Trend Lines Indicated

PART IV

PROCEDURE FOR REAL-WORLD EMISSION DATA COLLECTION FROM NONROAD CONSTRUCTION VEHICLES: A CASE STUDY FOR EXCAVATORS

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Abstract

A study design was developed and demonstrated for deployment of portable on-board emission measurement systems for excavators as most commonly used vehicles in construction activities. Data collection, screening, processing, and analyzing protocols were developed to assure data quality and to provide insights regarding quantification of variability in vehicle emissions and fuel consumption data. Provisions to avoid disruption of the normal operation of the test vehicle and for security of the portable emission measurement system are the most important factors in data collection. There were several identified sources of data quality problems, with the most frequent cause associated with a 7 percent occurrence rate. The frequency of occurrence can be reduced by periodically cleaning the nondispersive infrared unit of the analyzer. On average 50% of the total NO emissions was associated with 28% of the time of operation, during which the average engine speed and manifold absolute pressure were significantly higher than corresponding averages for all data. That average emission rates during non-idle modes (i.e. moving and using bucket), are on average 7 times greater than the idle mode. Fuel-based emission factors were found to be much less variability to operating conditions than time-based factors. This study characterizes the influence of engine duty cycle on the average fuel consumption and emissions rates using engine manifold absolute pressure. Differences in normalized average rates were found to be influenced more by inter-cycle differences than inter-vehicle differences. This study demonstrates the importance of accounting for inter-cycle variability in real-world in-use emissions to develop more accurate emission inventories. Fuel-based emission factors are recommended as a basis for future inventory development.

Keywords: On-board, Emissions, Excavators, Construction, Nonroad

1.0 Introduction

In the past decade, nonroad engine emissions have increasingly become the focus of regulatory action and air quality improvement strategies.[1] Nonroad sources consist of ten major categories as defined by the U.S. Environmental Protection Agency (EPA),[2] such as: construction, farm, and industrial (CFI); lawn/garden; recreational; marine; locomotives; aviation, and others. According to 2002 emission inventory estimates, CFI sources contribute approximately 92 percent of the total NO_x emissions from nonroad diesel sources and almost 10 percent of the total national NO_x emissions from transportation.[1]

Most emissions tests of CFI equipment have been done using steady-state engine dynamometer test cycles that involve operating the engine at one or more settings of constant load and engine speed.[3-9] EPA's NONROAD model, which is widely used for development of emissions inventories, is based on such data for a limited number of such cycles measured in the laboratory for nonroad engines of different sizes.[10, 11] Adjustment factors are applied to the test cycle data to represent emissions for various "applications" that are intended to represent specific types of equipment, such as bulldozers, front-end loaders, excavators, and so on. However, the empirical basis for such adjustments is limited to non-existent.

An alternative method for measuring emissions is to collect data in the field during actual operations. Formerly, on-board emission measurements was prohibitively expensive, with several past efforts involving the use of bulky and expensive laboratory grade instrumentation that was permanently mounted inside a vehicle (e.g., inside a 53 foot truck trailer).[12-16] However, recently, lower-cost portable instruments have been developed. For example, the EPA supported development of portable emissions measurement systems (PEMS) for both light and heavy duty vehicles, including nonroad equipment.[17-19]

Commercial PEMS are available for both light duty and heavy duty vehicle applications, for either gasoline or diesel vehicles.[20-24]

There is a lack of real world data for construction equipment. Limited data have been collected by Clean Air Technologies International (CATI), Inc. at the World Trade Center site for a loader, a large Caterpillar excavator, a small Komatsu excavator, and a crane for the purpose of evaluating the benefits of ultra-low sulfur and diesel particulate filter technologies.[25] West Virginia University (WVU) collected PEMS data for a street sweeper, a rubber-tire loader, and an excavator to generate transient test cycles that could be used to simulate real-world operating conditions for exhaust emissions research.[26] EPA used a specialized PEMS, the Simple Portable On-Board Test (SPOT) instrument, to collect engine and exhaust data for 50 construction vehicles in 2002.[27, 28] However, not all of these data are quality assured or publicly available.

A key question whether duty cycles vary for a given type of vehicle such that lead to significant differences in average emissions for that type of vehicle. Duty cycle refers the sequence of tasks which is repeated to produce a unit of output. A unit of output can be cubic yards of dirt removed or dumped per use of the bucket. A hypothesis is that variability in in-use duty cycles leads to important variability in energy use and emissions that should be accounted for when developing an energy and emissions assessment framework. There is a critical need to analyze real-world on-board data to understand the relationship between construction equipment duty cycles with respect to energy use and emissions.[12]

The main focus of this paper is on excavators which are commonly used equipment in construction activities.[29]

The objectives of this study are to: (1) document a procedure for collecting real-world emissions and fuel use data from excavators; (2) develop a procedure for data quality assurance; (3) demonstrate a conceptual analytical methodology for analyzing on-board data; (4) demonstrate the episodic nature of vehicles activity and emissions data and the influence of vehicle duty cycle on the average emission rates; (5) develop recommendations for future construction vehicle on-board emissions testing strategies.

2.0 The Role of Excavators in Construction and Their Emissions

Based on results obtained using EPA's NONROAD model, excavators contributed 11 percent of NO_x, 7.4 percent of CO, and 8.6 percent of PM_{10} emissions produced by construction equipment in 2005.[30] In 2005, there were an estimated 139,000 diesel excavators, according to the NONROAD model's engine population estimates. Excavators are powered by diesel engines raging from 17 to 2,000 hp; however, 87 percent of all excavators are in the range of 50 to 600 hp.[31]

Excavators consist of three major components: (1) a carrier which provides mobility and stability for the equipment; (2) a revolving deck which contains the power and control units; and (3) a front end attachment which serves various operational functions, known as the "bucket." The bucket can be used to dig the ground, but also to lift and transport heavy objects such as rip raps, or equipment such as generators or mixers, typically using chains or belts attached to a hook on the underside of the bucket. Excavators are classified as either track- or wheel-type. Unless the application calls for significant travel to, from, and around the construction site, a track-type of excavator is preferred.[32, 33]

Various factors that affect the emissions produced by such engines include the vehicle weight, duty cycle and the terrain traveled (which, in turn, affects engine power demand), age, and ambient conditions. In addition, engine controls such as injection timing strategies can have significant effects on measured emissions.[34, 35] In recent years, EPA has set Tier 1 to Tier 4 emission standards for the engines used in most construction vehicles. Tiers 1 to 3 are phased-in from 1996 to 2006 and are met through advanced engine design with no use of exhaust gas aftertreatment. The most stringent of these standards, Tier 4, are to be phased-in during 2008 to 2015. The Tier 4 standards require that emissions of PM and NO_x be further reduced by about 50 and 90 percent, respectively, compared to the current Tier 3 emission standard. Compliance with the Tier 4 standards is expected to require the use of aftertreatment control technologies.[36, 37]

3.0 Comparison of Emissions Measurement Methods

Current approaches for estimating construction equipment emissions are based upon testing only the engine, not the entire chassis, on an engine dynamometer and estimating average emissions for a weighted combination of steady-state modes.[38, 39] A mode involves operation of the engine at a specified constant engine speed and/or load. The most common tests procedures, such as the 8-, 13-, and 21-mode tests, involve multiple modes. EPA has primarily used data from the 8-mode test known as ISO-C1 as the basis for the NONROAD model. For this test procedure, the engine is run at rated RPM for three levels of torque (100, 75, and 50 percent of maximum torque), at an intermediate RPM level for the same three percentages of maximum torque, and twice at idle.[38]

To improve the representativeness of engine dynamometer tests, EPA and the Engine Manufacturers Association (EMA) have jointly developed some non-regulatory transient test cycles for agricultural tractors, backhoe loaders, crawlers tractors, excavators, arc welders, skid steer loaders, and wheeled loaders.[11, 40] However, these cycles are not yet used as the basis for the NONROAD model and there are no reported plans to use such cycles.

On-board emission measurement enables data collection under real-world in-use conditions at a job site.[41, 42] In-use data collection captures the effects of the chassis (e.g., vehicle weight) and actual duty cycle. However, because in-use measurement is essentially an observational, rather than controlled, measurement, there can be more variability in results from one test to another.

4.0 Methodology

The methodology includes: (1) study design; (2) instrumentation; (3) installation of instrumentation; (4) field data collection; (5) data quality assurance; and (6) data analysis.

4.1 Study Design

The design of an on-board in-use data collection for excavators is subject to controllable and uncontrollable factors. The controllable factors include scheduling and, in principal, also include the choice of vehicle, duty cycle, and site. However, the latter factors required cooperation from vehicle operators. Access to a vehicle, its duty cycle, and the site of data collection depended on the work schedule of the contractor and their willingness to allow their vehicle to be instrumented and observed. Uncontrollable factors include ambient conditions and operator behavior. The data were collected during normal duty cycles.

The characteristics of the three excavators that were tested are given in Table 1. These excavators range from 93 to 254 hp, corresponding to NONROAD model engine size categories of 76 to 100 hp, 101 to 175 hp, and 176 to 300 hp. These three categories represent 77 percent of the estimated number of excavators in the U.S. Although the engines have different model years, they were all produced under the same Tier 1 emission standard.[39]

Data were collected at two sites and each site included flat and hilly terrain. The soil at both sites was mostly muddy. All three excavators performed similar tasks, including excavating dirt and lifting heavy objects. Excavator 1 was used to transport foundation casting frame over the site and excavate the elements of foundation. Excavator 2 was used to install constructed riffles which are stone structures used as velocity dissipaters in stream beds to help prevent erosion and scour of embankments. Excavator 3 was used for loading dump trucks at two locations over the site.

4.2 Portable Emission Measurement System

The PEMS used here is the Montana Universal System manufactured by CATI.[24, 43, 44] As illustrated in Figure 1, the system is comprised of two identical five-gas analyzers, a particulate matter (PM) measurement device, an engine diagnostic scanner or sensor array, a global positioning system (GPS), and an on-board computer. All data are recorded on a second-by-second basis.

Each of five-gas analyzers measures concentrations of HC, CO, and CO_2 using nondispersive infrared (NDIR), and NO and oxygen (O_2) using electrochemical sensors. PM concentrations are estimated based on light scattering, and thus are approximately comparable to an opacity type of measurement.

Although many newer model construction vehicles have an electronic control unit with an engine diagnostic link, unlike light duty gasoline vehicles these interfaces are not standardized. The software needed to decode ECU data, when available, is proprietary. The sensor array can be used with any make or model of vehicle and therefore provided flexibility. The sensor array includes sensors that are temporarily installed on an engine for measuring engine speed (ES), intake air temperature (IAT), and manifold absolute pressure (MAP).

Based on the engine data, exhaust concentration data for CO_2, engine displacement, and an estimate of the engine volumetric efficiency, the mass exhaust flow rate is calculated on a second-by-second basis.[44]

The system operates on 13 volts DC power. To avoid imposing a power load on the vehicle, two batteries independent of the vehicle were used as a power supply.

CATI conducted studies to compare the PEMS with dynamometer measurements at the New York Department of Environmental Conservation (NYDEC) and EPA's National Fuel and Vehicle Emissions Laboratory in Ann Arbor.[25] The coefficient of determination (R^2) values for comparisons of cycle total emissions for the Montana system versus the dynamometer were in a range of 0.90 to 0.99, which indicates good precision. Furthermore, the slopes of the parity plots of cycle total emissions for a given pollutant were not significantly different from one for CO_2, CO, and NO, indicating good accuracy. For HC, it is well known that NDIR responds accurately to short chain alkenes but has less than full response for other types of compounds (e.g., alkenes, aromatics, and others).[45] Therefore, the total response of the HC measurement is typically approximately 50 percent of the total actual HC levels in the exhaust.

The fuel consumption levels reported by the Montana system have been verified based on measurements for 12 dump trucks that were tested for one day each on petroleum diesel fuel and one day each on B20 biodiesel fuel.[46] When comparing the measured to actual fuel consumption for each of the 24 days of testing, the R^2 was 0.999 and the slope of the parity plot was 0.996. Thus, the fuel consumption data are deemed to be of good precision and accuracy.

The Montana system was calibrated before each test using a span gas mixture containing 200 ppm propane (C_3H_8), 0.5 *vol*-% carbon monoxide (CO), 6.0 *vol*-% carbon dioxide (CO_2) and 300 ppm nitric oxide (NO), which is recommended by CATI for diesel engines. A detailed information regarding the calibration procedure is given elsewhere.[24] the Montana system performs zero calibration automatically every 10 minutes.

4.3 Installation of the Portable Emission Measurement System

A procedure for field data collection was developed taking into account four key factors: (1) applicability to any vehicle and site; (2) avoidance of disruption of the normal operation of the vehicle; and (3) placement of the PEMS so as to avoid limiting the operational performance of the vehicle; and (4) installation of the PEMS system so as to avoid damage to it during data collection.

Based on these considerations, the field data collection procedure was divided into three steps of pre-installation, installation, and data collection. The separation of installation into two steps minimizes disruption of the operator's work schedule. The PEMS components that are time consuming to install are "pre-installed" on the vehicle during off-hours the afternoon or evening before data collection. The final "installation" occurs early the morning of data collection for the more expensive and sensitive system components. The two-step installation procedure also allows time to carefully place the PEMS so as to avoid limiting vehicle operation and damage to the PEMS. A checklist of pre-installation and installation steps was developed and followed in order to have consistent and complete installations for any vehicle.

Pre-installation includes placement of the engine sensors, sensor unit, exhaust sampling probes and hoses, external batteries, and a safety cage. The latter was fabricated by NCSU for the purpose of protecting the main unit of the Montana system from damage. Installation includes securing the main unit of the Montana system inside the safety cage, mounting the GPS system on the chassis, connecting cables routed from the sensors and hoses from the tailpipe to the main unit of the Montana system.

Placement of the engine speed and MAP sensors was the most challenging aspect of pre-installation. The ES sensor must be secured to a stationary metal object that allows an unobstructed view of reflective tape attached to the flat section of the harmonic balancer. The MAP sensor must be connected to an existing boost pressure port located between the turbocharger and the engine intake manifold. Properly functioning of the sensors was verified during pre-installation by temporarily connecting them to the Montana system main unit. Exhaust sample probes are secured to the tailpipe using radiator pipe clamps. Cables and hoses are routed to the location of the safety cage using plastic ties placed at strategic points along their path, so that they do not come loose during vehicle operation.

The safety cage is secured to the roof or hood of the vehicle using heavy duty adjustable cargo straps. For Excavator 1, the safety cage was mounted on cab roof. For Excavators 2 and 3, the cage was mounted on a flat area of the engine hood. Prior to installation of the main unit, rubber and foam pads were placed in the safety cage to as to reduce transmission of vibration from the vehicle. Furthermore, the main unit was shielded from direct sunlight by a tarp secured over the top of the cage.

The main unit was warmed up for 30 to 45 minutes prior to data collection. Installation was scheduled to be finished before the excavator was needed for its normal duty cycle. On average, pre-installation required two people and took approximately 2.5 hours, while installation also required two people and took approximately 1.5 hours.

4.4 Field Data Collection

Data collection is comprised of two main activities. The first is monitoring the operation of the PEMS and the second is recording additional data regarding site conditions and vehicle modes of operation.

During data collection, the status of the PEMS is periodically monitored by checking the screen of the main unit during operator work breaks. The objectives of this action are to make sure that the sensor array is properly communicating with the computer of the Montana system and both analyzers are properly measuring exhaust gas.

Site conditions are recorded on a standard form. An example of the vehicle activity at the site is recorded for approximately 15 minutes using a camcorder so that there is a visual record of the site conditions and the typical vehicle activity. A research assistant who is observing the vehicle from a safe distance records the timing of specific modes of operation using a laptop computer. The modes of operation, also referred to as task-oriented modes, are activities that the equipment routinely performs to accomplish a specific task. For the excavators tested, the task-oriented modes including idling, moving, and using the bucket. Moving refers to lateral transport of the excavator from one location to another at the site.

Using the bucket refers to any activity in which the bucket was lowered, filled, raised, or emptied. The bucket is also used to lift heavy equipment and objects.

4.5 Data Quality Assurance

The goal of quality assurance is to develop a database that contains valid data. The procedure includes identification of whether any errors or problems exist in the data, correcting such errors or problems where possible, and removing invalid data if errors or problems cannot be corrected.

The types of errors or problems that may be encountered include data flagged as "invalid" by the Montana system, missing MAP values, unusual engine speed, unusual intake air temperature, inter-analyzer discrepancy, zero calibration procedure of the Montana system, negative values of pollutant concentrations, leakage in exhaust gas sampling system, gas analyzer freezing, and synchronization of engine and emissions data. "Freezing" refers to a situation in which there is no reported change in emission concentrations for a period of several seconds while engine data are changing. Criteria for detecting and correcting errors associated with missing MAP values, unusual IAT, and synchronization of engine and emissions data are briefly explained. For the other errors and problems, procedures developed previously were used.[43, 46, 47]

On occasion, communication between the sensor array and Montana system might be lost leading to loss of MAP data. In this case, an error code of "-34" is presented in the data file. Typically, when an value is missing, other measured data including engine RPM and pollutant concentrations are valid at the time. Missing MAP data are estimated when the absolute relative difference (ARD) between MAP values that occur before and after missing values is less than 5 percent. After estimating missing MAP values, emission rates are recalculated. The missing MAP error was for 3.9 percent of the 23,893 seconds of data for Excavator 3. However, this error was not observed for Excavators 1 and 2.

Intake air temperature should be greater than ambient temperature ant typically changes gradually over time. It was found from previous field data collection that when absolute difference of IAT values between two consecutive seconds is greater than 1, there may be some problems with IAT sensor. IAT was checked for all seconds of data and no unusual values or rapid changes were found for any excavator.

Synchronization of engine and emissions data is evaluated after other quality checks are completed. For this purpose, segments of second-by-second data are selected in which engine speed changes by greater than 200 RPM in one second and by greater than 500 RPM for a short-term event that may occur over several seconds. Temporal trends of CO_2 and CO concentrations are compared to the change in engine RPM. Based on analysis of time traces, the concentrations of CO_2 and CO were found to be more responsive to changes in engine speed than for other pollutants. The time difference between the corresponding initial rise (or initial decrease) in engine speed versus CO_2 concentration, CO concentration, or both, is referred to as "synchronization time (T_{synch})." If T_{synch} is not zero, then the engine data must be shifted earlier or later compared to gas analyzer data and the second-by-second emission rates must be recalculated using the proper pairing of engine and concentration data. For each of the test excavators, the raw emissions data reported by the PEMS were found to be one second earlier than engine data. This error was corrected for all data files.

A screened and quality assured data file includes: (a) time stamps for each second; (b) measured values of engine RPM, IAT, MAP, and pollutant concentrations; (c) estimated rates of intake air mass flow, exhaust gas mass flow, fuel consumption, and emissions; (d)

GPS data; and (e) modes of operation recorded separately and combined with the PEMS data file.

5.0 Results

Data analysis included: (1) comparing emissions rates of the excavators with similar emissions estimates based on the NONROAD model; (2) exploratory analysis of emissions with respect to engine variables; (3) characterizing the episodic nature of microscale events (e.g. short-term events such as use of the bucket) during real-world operation; (4) quantifying variability in emissions and fuel consumption rates with respect to variability in duty cycles.

5.1 Comparison of On-Board Emissions with the Engine-Dynamometer Results

The average emission rates obtained from measurements using PEMS are compared to estimates obtained using the NONROAD model in order to assess similarities and for benchmarking purposes. [39] The comparisons were done on a mass of pollutant per unit of fuel consumed basis. Because the NONROAD models reports emission factors in units of g/bhp-hr, a brake-specific fuel consumption (BSFC) rate of 0.367 g/bhp-hr was used for conversion.[39] To correspond as closely as possible to the tested excavators, NONROAD model results were obtained for excavators for specific model years and engine size ranges. The results of the comparison are given in Table 2.

The average emission rates for NO based on the PEMS measurements ranged from 87.4 to 123 g/gallon versus values of approximately 97.6 to 106 g/gallon from the NONROAD model. These numbers agree well in terms of magnitude and also imply substantial similarity in fuel-based NO emission rates for different vehicles. The PEMS data are based on NO whereas the NONROAD estimates include both NO and NO_2. The substantial agreement is not surprising since for diesel vehicles without post-combustion controls, total NO_x is typically approximately 90 to 95 percent NO, with the balance NO_2.[48]

For Excavators 1 and 3, the magnitudes of the average HC emission rates agree well for both the PEMS and NONROAD-based estimates. The difference in the average emission rate for Excavator 2 is approximately 24 percent.

The average CO emission rates are consistently higher based on the NONROAD models estimates than for the PEMS data. The average difference is 18 percent.

The comparison of opacity values from the PEMS measurement with the NONROAD estimates indicates that the light-scattering based method may not be responding adequately to the full loading of particles that may be in the exhaust. The PEMS-based averages are within an order-of-magnitude of the estimates from the NONROAD model, but the latter are consistently larger than the former. Thus, the opacity data from the PEMS are not likely to be useful for estimating the magnitude of total PM emissions, but might nonetheless be useful for assessing relative differences among vehicles (or among modes for a given vehicle).

5.2 Exploratory Analysis

Exploratory analysis was conducted to quantify the intra-vehicle variability of emissions and identify trends with respect to engine variables. The strength of the linear relationship between either fuel use or emission rates to each explanatory variable is reported in Table 3. Emission and fuel use rates have higher linear association with MAP compared to the other engine variables. This indicates that MAP has potential to be used for modal analysis of emissions with respect to engine variables. Emission rates appear to have weak to moderate linear relationship with engine speed. There is relatively weak relationship between emissions rates and IAT. Engine speed had high correlation with MAP based on R^2 values ranging from 0.67 to 0.75 among the excavators.

Trends were identified to verify the relationship between each of the emissions and fuel consumption rates. There was a perfect linear relationship between fuel consumption and CO_2 emission rates reflected in R^2 value of 1 for all excavators. A strong correlation between NO emission rates and fuel use was found with R^2 values ranging from 0.91 to 0.97. There appear to be weak relationship between HC, CO, and PM emission rates with respect to fuel consumption rate with the average R^2 value 0.14.

5.3 Microscale Activity and Emissions

To characterize episodic nature of microscale event and gain insight into the temporal variation in vehicle activity, fuel use, and emissions, an example for Excavator 1 of a time trace of engine speed, MAP, fuel use rate, and emission rates for selected pollutants is given in Figure 2.

For the example, the excavator performs two cycles of operation that include idle, moving, and use of the bucket. The temporal profiles of engine speed are similar each time the bucket is used, which occurs between 0 and 3.5 elapsed minutes and between 7.5 and 11 elapsed minutes. During these times, engine speed varies between approximately 960 to 2150 RPM. Likewise, the engine speed profile is similar for the two time periods when the excavator is moving.

Most of the large peaks in fuel consumption and emissions rates, on a mass per time basis coincide with peaks in engine speed and MAP. The fuel use rate, and the CO_2, NO, and CO emission rates, appear to be more responsive to variation of engine speed and MAP than for the other emission rates. The emissions of CO and HC are low compared with the CO_2

emissions. On average, 99.8% of the carbon in the fuel is emitted as CO_2. Therefore, CO_2 emissions are a good surrogate for fuel consumption.

For NO emissions, 50% of the total NO emissions were produced in 29, 23, and 32 percent of the total time for Excavators 1, 2, and 3, respectively. The average engine speed and MAP values for these episodes were higher compared to the average values for the total data. Thus, short-term episodes can substantially affect average emissions.

5.4 Task-Oriented Modes

PEMS data were analyzed with respect to task-oriented modes. The purpose of this analysis is to explore variability in emissions with respect to variability in modes of operation.

For excavators, idling is comprised of four sub-modes that include low idle, high idle, and two transients, as illustrated in Figure 3 for Excavator 2. In low idle, the engine runs at 900 RPM or less. Prior to when the operator is ready to start using the bucket, the operator uses the engine speed control unit to manually increase the engine idle speed to a high idle. The two types of idles, as well as the transitions between low and high idle, and between high idle and use of the bucket, are assessed individually with respect to their effect on fuel use and emissions.

A comparison of the average modal rates for fuel consumption and each of five pollutants is shown in Figure 4. Typically, for a given quantity, the rate for low idle is the lowest. High idle has a higher rate than low idle. The transient (1) mode has comparable or higher rates than high idle in most cases. The transient (2) mode is highly variable among the vehicles. For Excavator 1, transient (2) has average rates comparable to the other idling modes, whereas for Excavator 2 and, especially, Excavator 3, these rates are typically significantly higher. The using bucket and moving modes tend to have similar average rates for a given quantity and vehicle. In most cases, the using bucket and moving modes have higher average rates than the transient (2) mode. Overall, it appears that there is not much benefit to separately quantifying the using bucket and moving modes, because their rates are similar. Thus, these two modes can be combined into one "non-idle" mode. .

The task-oriented modes were also analyzed on the basis of mass of emissions per gallons of fuel consumed. NO and HC emission rates per gallon of fuel consumed are highest for idling for all the excavators and are approximately similar when comparing the using bucket and moving modes.

To evaluate the relative importance of each of the operation modes, the distributions by mode of total time, fuel consumption, and emissions are given in Figure 5. On average, all idle and transient modes account for 50% of time, but only 18% of fuel consumption. The distribution of pollutants by mode is approximately similar to that of the distribution of fuel use, except for HC and CO for which there is typically a larger proportional contribution from the idling modes.

5.5 Engine-Based Modes

As an alternative to the task-oriented modal analysis described above, an engine-based modal analysis was also performed. One purpose of this analysis is to determine whether there are consistent trends in the relationship of fuel consumption or emissions rates versus engine activity. Because these rates were found to be highly correlated with MAP, modes were defined based on MAP ranges. The specific MAP ranges for a given mode differ from one vehicle to the next.

Because NO is one of the pollutants of greatest concern from diesel-fueled vehicles, the modes were defined to account for equal shares of the total NO emissions, and a choice was made to stratify the data into ten modes. Figure 6 presents an example of results of average modal rates for fuel consumption and emissions on a mass per time basis, and for emission rates on a fuel basis. With only minor exceptions for HC and CO, the modal mass per time rates increase monotonically with MAP, and the lowest rates are associated with engine idling in the lowest MAP range.

In contrast, the emissions per gallon of fuel consumed are highest at idle for NO, HC, and CO. For higher values of MAP, the fuel-based emission rates of these pollutants are approximately constant. The results for opacity follow a different trend, with lower values at idle and higher values as MAP increases. However, overall, these results suggest that fuel-based emission factors could be developed for idle versus non-idle modes and that such factors would have less variability as a function of engine operating conditions than mass per time-based estimates.

To enable comparisons between vehicles in the next section, all MAP, emission rates, and fuel consumption rate values were normalized. For a given vehicle, all of the second-by-second data for each of these quantities was divided by the largest observed value. As an example, the average normalized modal MAP and NO emission rate are shown in Table 4 for each of the three excavators, along with the fraction of total time spent in each mode. The average normalized modal NO emissions are similar for all three excavators for Modes 1, 8, 9, and 10, but differ substantially for the other modes, especially when comparing Excavator 1 to either of the other two excavators. Concurrently, the modal average normalized MAP values are larger for Excavator 1 for Modes 2 through 7 than for the other two excavators. The overall average normalized NO emission rate is 0.47, 0.35, and 0.33 for Excavators 1, 2, and 3, respectively. These differences are the combined effect of the individual duty cycles of each vehicle and their respective modal emission rates.

5.6 Duty Cycle

The individual effect of the duty cycle on average emission rate is evaluated here. The excavators performed repetitive operations within the confines of the construction sites. A unit of output for Excavators 1 and 3 was cubic yards of dirt removed or dumped and for Excavator 2 was the cubic yard of rip rap installed per use of the bucket. A duty cycle can be subdivided into either task-oriented or engine-based modes.

To illustrate the spatial aspects of duty cycles, maps of excavator locations for each second of operation for two examples are shown in Figure 7 based on GPS data. Excavator 1 traveled more extensively around the site than did Excavator 2.

The duty cycles are compared in terms of the cumulative distribution function of second-by-second MAP values for the engines of each of the three excavators, as shown in Figure 8. MAP fluctuates with the throttle position and the engine load.[48] Excavator 1 spent a higher proportion of time in the non-idle modes (see Figure 5) than the other two, and thus has a higher average MAP than the other excavators. In contrast, Excavators 2 and 3 have duty cycles that are similar to each other, particularly for the non-idle modes, as indicated by similar distributions of MAP for values greater than 115 kPa.

In order to evaluate the effect of duty cycle on average emission rate for a given vehicle, three duty cycles were compared for each of the three excavators. The duty cycles are characterized based on the CDFs of normalized MAP observed on a given day of data collection with a given vehicle. For a given duty cycle (e.g., from Site 1 on January 19, 2005), the percentage of time in each mode was estimated for each of the three vehicles separately, using their respective normalized modal MAP cut-off values. The average emission rate for the cycle was estimated based upon the time-weighted average of the normalized modal emission rates. The results are given in Table 5.

For a given vehicle, the average normalized fuel use and emission rates vary substantially when comparing Engine Duty Cycles 1 and 2, with the exception of CO. For example, the normalized average fuel consumption rate for Excavator 1 is 0.44 and 0.31 for these two cycles, respectively. On average, there is 24 percent reduction (except for CO) in normalized emissions and fuel consumption rates when comparing these two cycles. However, Engine Duty Cycles 2 and 3 are similar to each other, and the average normalized rates for a given vehicle and quantity differ by less than 0.03 in most cases when comparing these two cycles. On average, there is 5 percent increase (except for CO) in normalized emissions and fuel use rates when comparing these two cycles.

For a given duty cycle, the average normalized rates are similar when comparing different vehicles. For example, the average normalized NO emission rate has a range of only 0.46 to 0.47. The normalized inter-vehicle differences for a given duty cycle and quantity are less than or equal to 0.04 in all cases, corresponding to relative differences of approximately 10 percent.

Overall, for the examples given here, there are larger differences in normalized average emission rates because of inter-cycle differences than because of inter-vehicle differences.

6.0 Conclusion

For implication of the procedure developed for real-world data collection, it was found that two factors of disruption of the normal operation of the vehicle and security of the PEMS system are the most important factors that can significantly affect quality of data collection. Disruption of the vehicle decreases cooperation from the vehicle operator and not securely enough installation of the PEMS results in loss of qualified data.

A high proportion (i.e. 91%) of measurement attempts resulted in valid vehicle activity and emission files for Excavators 2 and 3. However, for Excavator 1, this proportion was 82.5% because of serious vibration resulted in several time loss of power to the Montana system. For all excavators, inter-analyzer discrepancy and analyzer freezing were the most frequent errors observed. To reduce the effects of these errors, the NDIR of both analyzers must be cleaned before the test and attempt to reduce vibration transferred to the Montana system using more foam pads around the system.

Comparison of the average emission rates estimated from PEMS data and the NONROAD model with benchmarking purposes indicated that the estimates agree well in terms of magnitude for NO, HC, and CO emissions.

It was understood from exploratory analysis that among the engine data, available in this work, MAP is a potential explanatory variable highly associated with emissions and fuel consumption rates. Therefore, because MAP is a good indicator of engine load, it is an appropriate variable to be used for characterizing and evaluating effects of duty cycle on emission and fuel use rates.

Conceptual analysis of time traces indicated the episodic nature of fuel consumption and emissions from the excavators. It was found that real-world on-board data enables defining short term events associated with higher emission and fuel consumption rates. For example, it was found that on average 50% of the total NO emission from test excavators is produced in 28% of the total operation time during data collection.

Task-oriented modes analysis rejected the hypothesis that there is a significant difference between modes of using bucket and moving. Similarity is emission and fuel consumption rates for these two modes led to considering these modes as an individual mode for any future work.

Overall, analysis of engine-based modes per gallon of fuel consumed indicated less variability in emissions as a function of engine operating conditions compared to mass per time-based estimates. This implies that performing emission inventory estimates on a mass per fuel use basis leads to less variability in estimations compare to when estimates are performed based on mass per time.

Comparison of emissions and fuel use estimated based upon the engine duty cycles developed for each of the test vehicles indicated that similarity in duty cycle results in similar average emissions and fuel use rates. It was found that differences in normalized average emission rates are because of inter-cycle differences than because of inter-vehicle differences.

7.0 Implications

There is a critical need to gather on-board emissions and activity data from construction vehicles to use in new generation emission modeling tools. An empirically-based on-board data collection procedure is demonstrated to be applicable to any given construction site and vehicle. Therefore, key insights regarding conceptual analysis of data are provided. The use of on-board emission data is recommended with the purpose of improving the accuracy of emission factors and inventories.

8.0 Acknowledgments

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Table 1. Characteristics, Emission Test, and Construction Site Information for the Selected Excavators

	Excavator		
	(1)	(2)	(3)
Chassis			
Size	Small	Medium	Large
Manufacturer	Kobelco	Caterpillar	Komutsu
Model	SK130	320C	PC300-7
Year	1998	2002	2001
Engine			
Rated Horsepower (hp)	93	138	254
RPM at Rated hp (rpm)	2200	1900	1900
Displacement (L)	3.9	6.37	8.27
Number of Cylinders	4	6	6
Fuel Type	Diesel	Diesel	Diesel
Emission Standard	Tier 1	Tier 1	Tier 1
Construction Site			
Location	Site 1: NCSU Campus, Western Blvd.	Site 2: NCSU Campus, Cates Avenue	Site 2: NCSU Campus, Cates Avenue
Terrain	Flat/Hill[1]	Flat/Hill	Flat/Hill
Soil Condition	Muddy	Muddy/Rock	Muddy
Activity	Carrying heavy objects/Digging	Moving rip raps/Digging	Carrying heavy objects/ Digging
Data collection Summary			
Date of Data Collection	January 16, 2006	November 2, 2005	August 24-26, 2005
Seconds of Data[2] (sec)	22,515	23,593	53,487
Ambient Temperature (^{0}F)	31-62	40-68	65-85
Relative Humidity (%)	20-72	26-96	46-94

[1] The site area includes both terrains of hill and flat.
[2] These data are raw data.

Table 2. Comparison of Average Normalized Emission Rates Estimated for the Excavators Using On-Board Data with Estimates of EPA's NONROAD Model

Vehicle	Emission Estimation Method	Pollutants			
		NO (g/gal)	HC (g/gal)	CO (g/gal)	Opacity (g/gal)
Excavator 1	**PEMS[1]**	110	10.2	14.1	0.792
	NONROAD[2]	97.6	9.09	17.3	8.11
Excavator 2	**PEMS**	87.4	8.99	15.3	0.830
	NONROAD	106	6.78	19.2	5.53
Excavator 3	**PEMS**	123	6.64	13.2	1.12
	NONROAD	105	6.01	14.2	5.09

[1] PEMS: the average emission rates estimated by data measured by the Montana system.
[2] NONROAD: the average emission rates estimated using the NONROAD model. Because the NONROAD models reports emission factors in units of g/bhp-hr, a brake-specific fuel consumption (BSFC) rate of 0.367 g/bhp-hr was used for conversion. To correspond as closely as possible to the tested excavators, NONROAD model results were obtained for excavators for specific model years and engine size ranges.

Table 3. Coefficient of Determination (R^2) Ordinary Least Square Regression of Second-by-Second Emission and Fuel Consumption Rates versus Individual Engine Variables [a]

		Coefficient of Determination R^2		
		MAP [b]	**Engine Speed** [c]	**IAT** [d]
Excavator 1	**NO (g/s)**	0.62	0.55	0.16
	HC (g/s)	0.16	0.17	0.11
	CO (g/s)	0.20	0.50	0.06
	CO_2 (g/s)	0.61	0.58	0.13
	Opacity [e] (g/s)	0.20	0.18	0.13
	Fuel (g/s)	0.61	0.58	0.13
Excavator 2	**NO (g/s)**	0.52	0.57	0.20
	HC (g/s)	0.31	0.36	0.10
	CO (g/s)	0.20	0.31	0.08
	CO_2 (g/s)	0.49	0.50	0.16
	Opacity (g/s)	0.39	0.32	0.10
	Fuel (g/s)	0.49	0.39	0.16
Excavator 3	**NO (g/s)**	0.46	0.31	0.19
	HC (g/s)	0.43	0.52	0.30
	CO (g/s)	0.49	0.68	0.30
	CO_2 (g/s)	0.48	0.37	0.18
	Opacity (g/s)	0.57	0.33	0.15
	Fuel (g/s)	0.49	0.37	0.18

[a] All of these numbers are statistically significant at a 0.05 significance level.

[b] MAP: Manifold Absolute Pressure (kPa)

[c] Engine Speed: Revolutions per Minute (RPM)

[d] IAT : Intake Air Temperature (^{0}C)

[e] The term "opacity" is used here rather than Particulate Matter because PM are detected using a light-scattering method, which is a semi-quantitative approach for characterizing the particle loading in the exhaust.

Table 4. Modal Values of Average Normalized NO Emissions, Average Manifold Absolute Pressure, and Fraction of Time for each Excavator.[1]

Mo-de	Excavator								
	1			2			3		
	Average Normalized MAP[2]	Average Normalized NO	Fraction of time %	Average Normalized MAP	Average Normalized NO	Fraction of time %	Average Normalized MAP	Average Normalized NO	Fraction of time %
1	0.45	0.14	35	0.48	0.14	30	0.43	0.11	34
2	0.64	0.44	10	0.49	0.18	20	0.49	0.19	16
3	0.70	0.57	9	0.52	0.25	12	0.54	0.31	10
4	0.73	0.62	9	0.63	0.48	7	0.57	0.39	9
5	0.76	0.65	6	0.68	0.56	6	0.61	0.46	7
6	0.78	0.68	7	0.73	0.61	6	0.65	0.53	6
7	0.81	0.72	6	0.78	0.66	5	0.69	0.61	5
8	0.84	0.75	6	0.83	0.72	5	0.74	0.70	5
9	0.87	0.80	6	0.89	0.78	5	0.79	0.80	4
10	0.92	0.86	5	0.95	0.84	4	0.86	0.88	4

[1] For a given excavator and quantity (e.g., NO emission rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.
[2] MAP: Manifold absolute pressure

Table 5. Comparison of Average Normalized Emissions and Fuel Use Rates of Three Excavators with Respect to Engine Duty Cycles

Engine Duty Cycle[1]	Quantity	Average Estimated Fuel Use and Emission Rates by Excavator[2]		
		1	2	3
Site 1, January 16, 2006	Fuel Use	0.44	0.43	0.42
	CO_2	0.44	0.43	0.42
	NO	0.47	0.47	0.46
	HC	0.55	0.56	0.55
	CO	0.63	0.66	0.64
	Opacity	0.35	0.34	0.33
Site 2, November 2, 2005	Fuel Use	0.31	0.28	0.28
	CO_2	0.34	0.30	0.31
	NO	0.38	0.35	0.35
	HC	0.47	0.45	0.45
	CO	0.63	0.62	0.62
	Opacity	0.23	0.20	0.20
Site 3, August 24-26, 2005	Fuel Use	0.32	0.30	0.30
	CO_2	0.32	0.30	0.29
	NO	0.36	0.33	0.33
	HC	0.48	0.49	0.48
	CO	0.53	0.54	0.53
	Opacity	0.29	0.27	0.26

1 The engine duty cycle from a given excavator is estimated based upon the cumulative distribution function (CDF) of normalized exhaust flow based upon field data.

2 The average normalized fuel use or emission rate is estimated based on the CDF of exhaust flow for a given engine duty cycle, from which the fraction of time in each mode for a given excavator was estimated. The average normalized fuel use or emission rate is a time-weighted modal average.

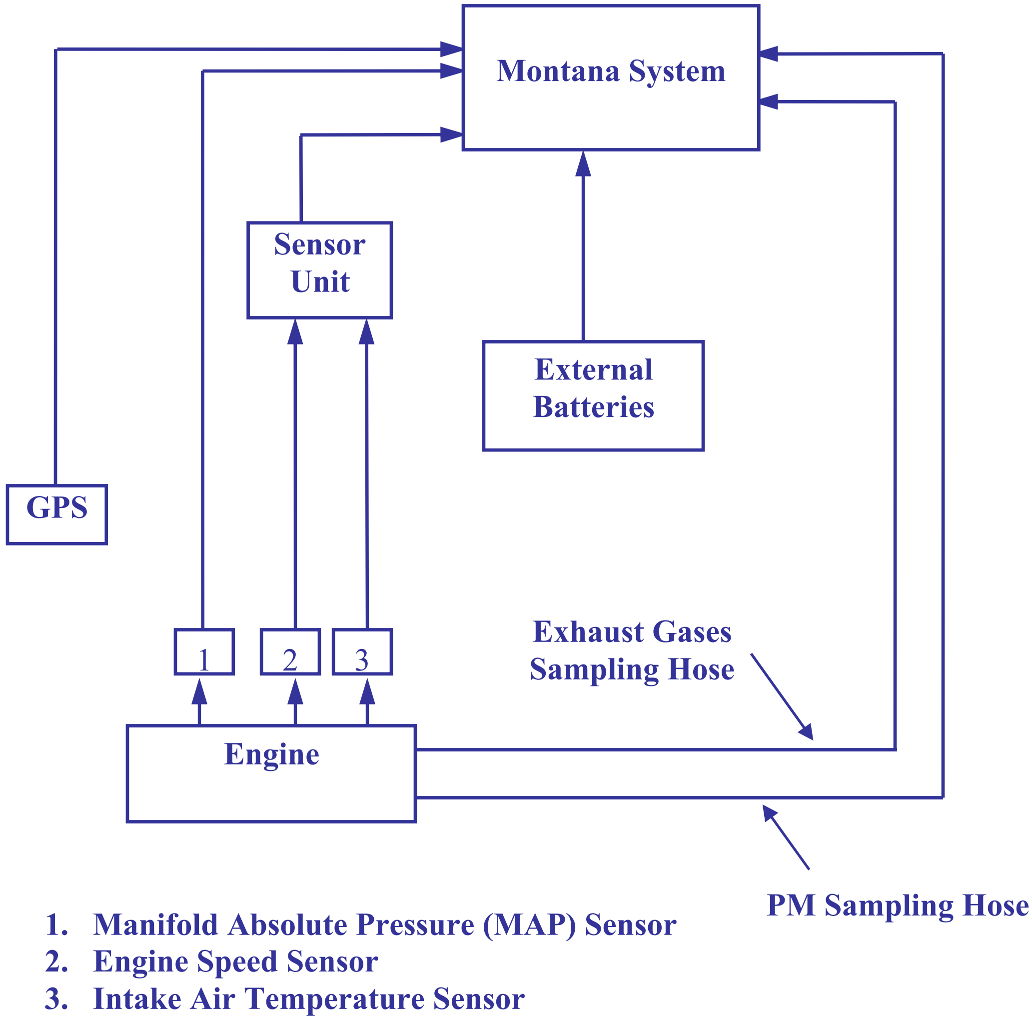


Figure 1. Conceptual Diagram for Installation of the Portable Emission Measurement System (PEMS) on Nonroad Construction Vehicles

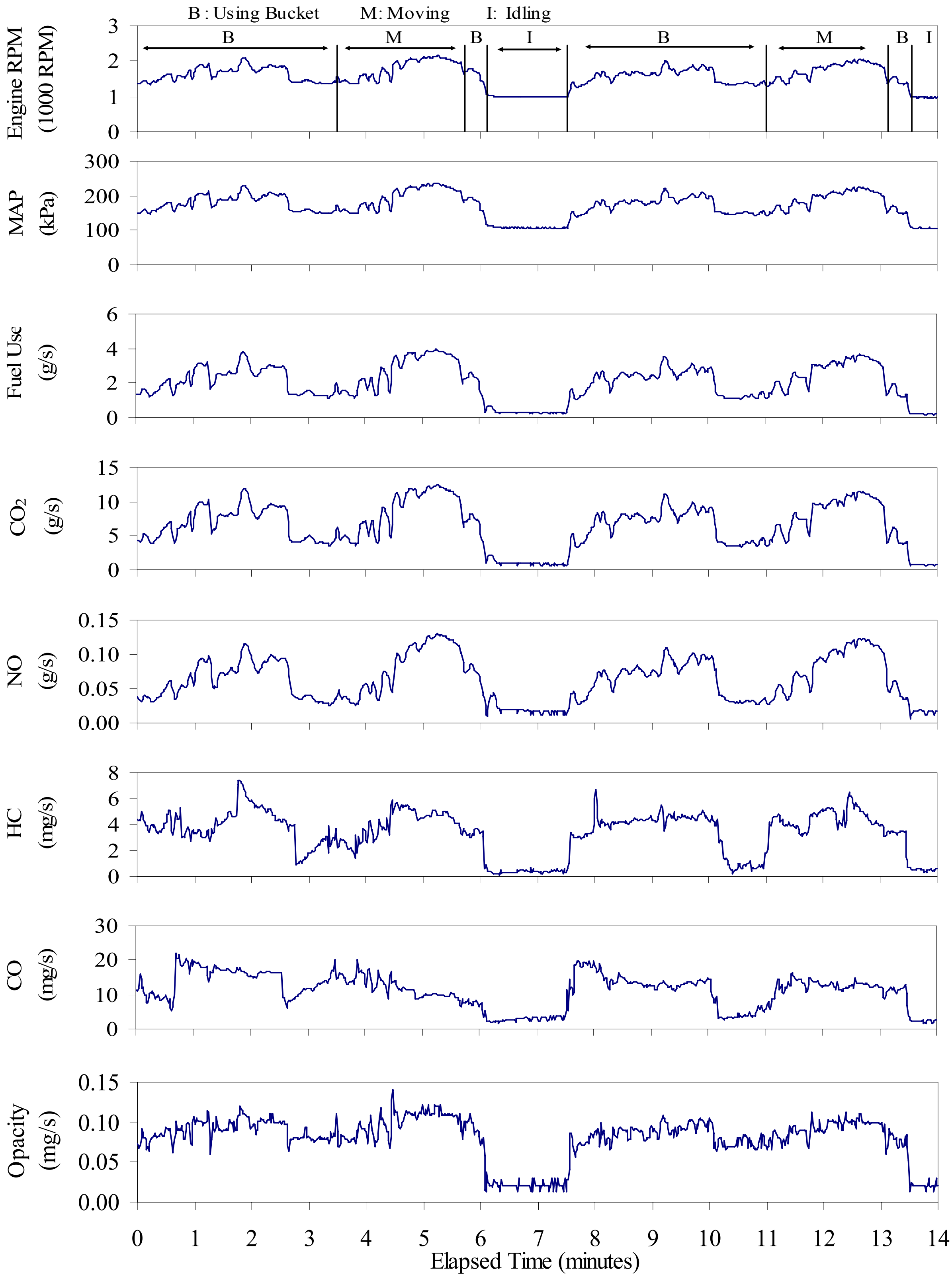


Figure 2. Example Time Traces of Engine Data, Fuel Consumption Rate, and Emission Rates for Excavator 1 Tested on January 16, 2006

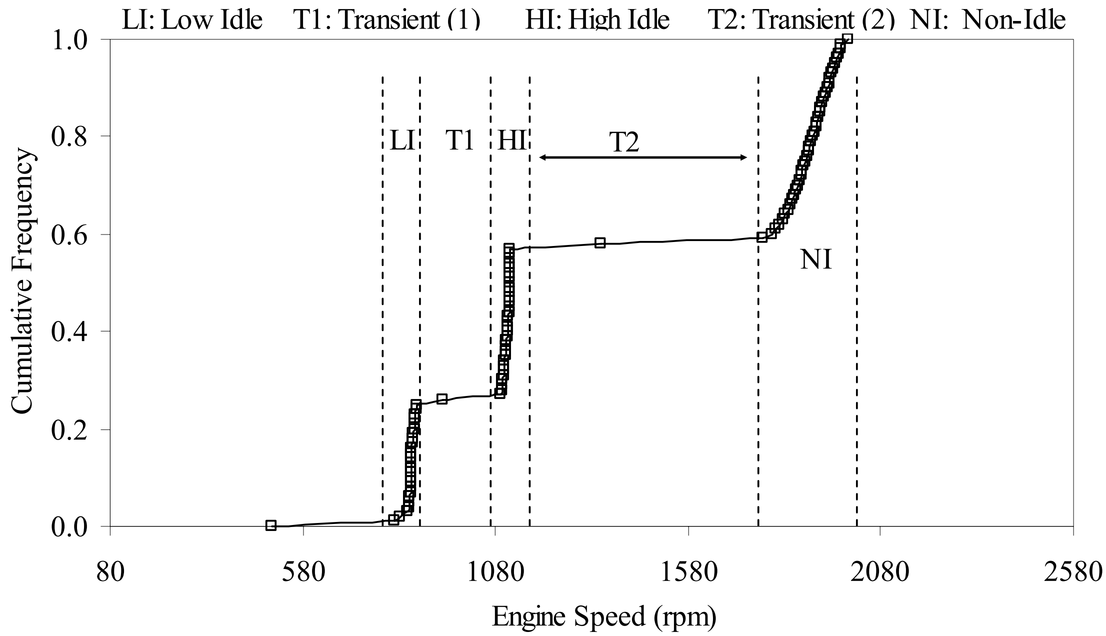


Figure 3. Cumulative Distribution Function of the Frequency of Engine Speed Data for Excavator 2, with Modes of Operation Indicated.

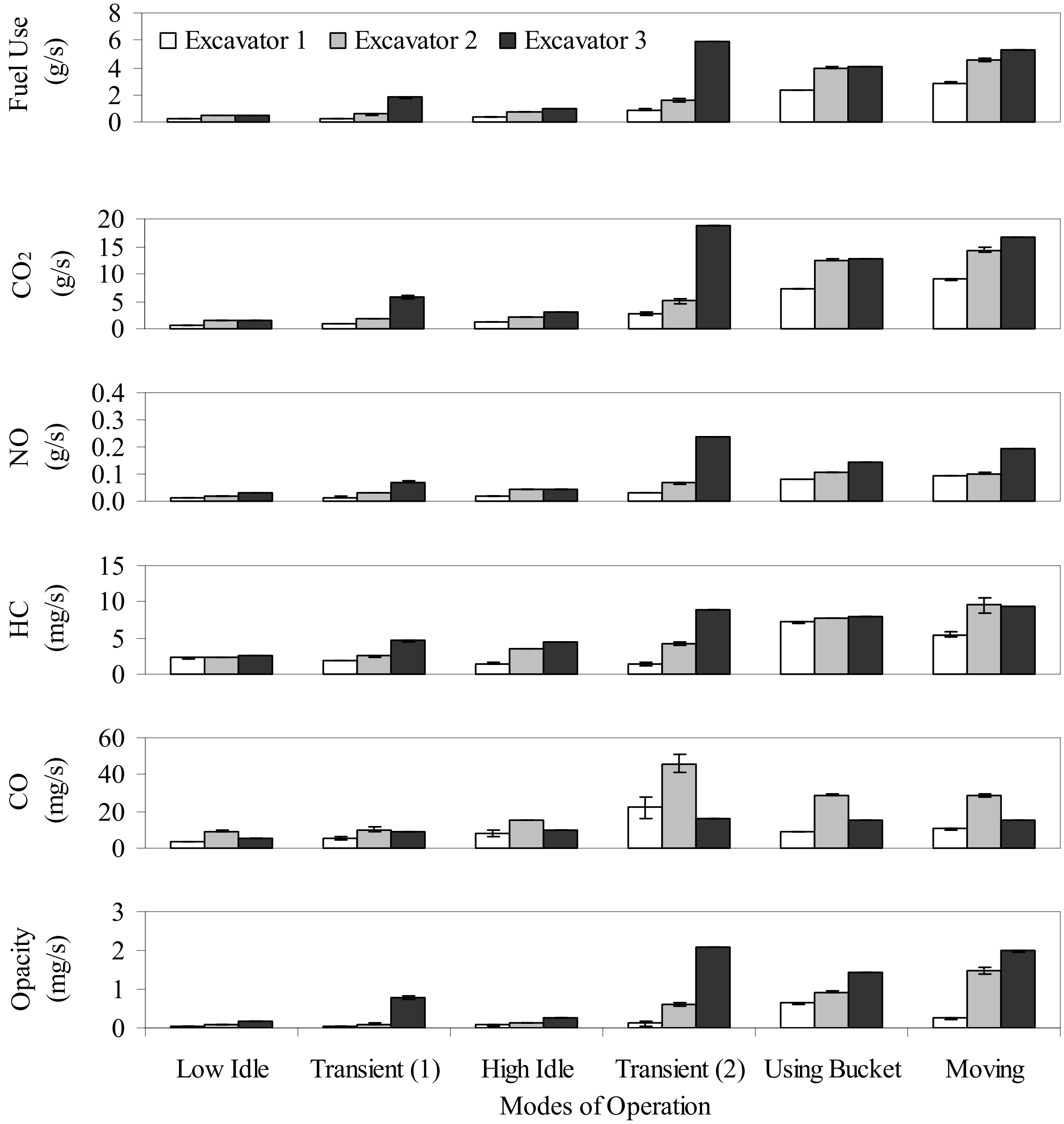
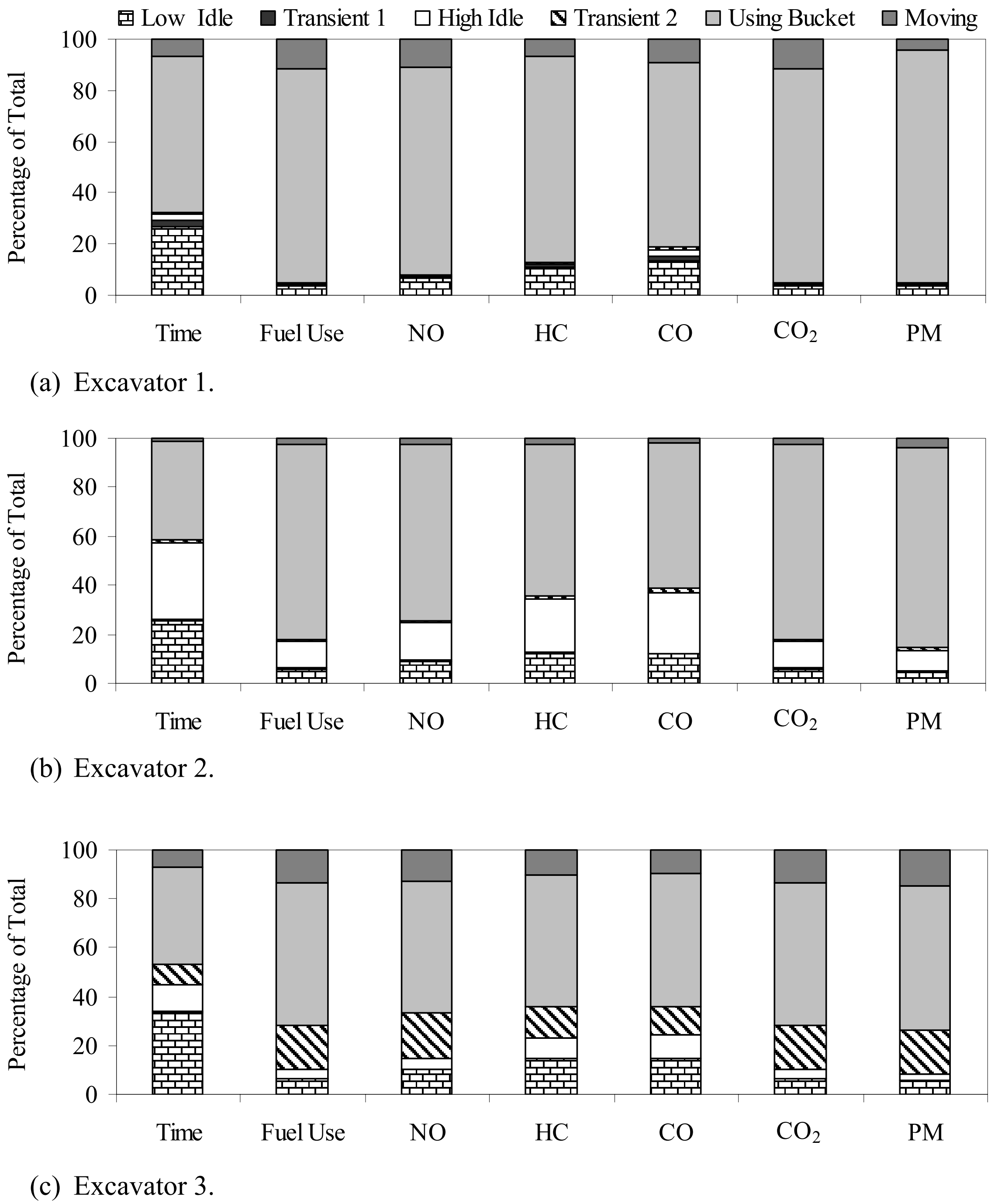


Figure 4. Comparison of Average Mass per Time Fuel Use and Emission Rates Along with 95 Percent Confidence Interval for Mean Values for Task-Oriented Modes



(a) Excavator 1.

(b) Excavator 2.

(c) Excavator 3.

Figure 5. Distribution of Task-Oriented Modes with Respect to Total Operation Time, Fuel Use, and Emissions for the Test Excavators

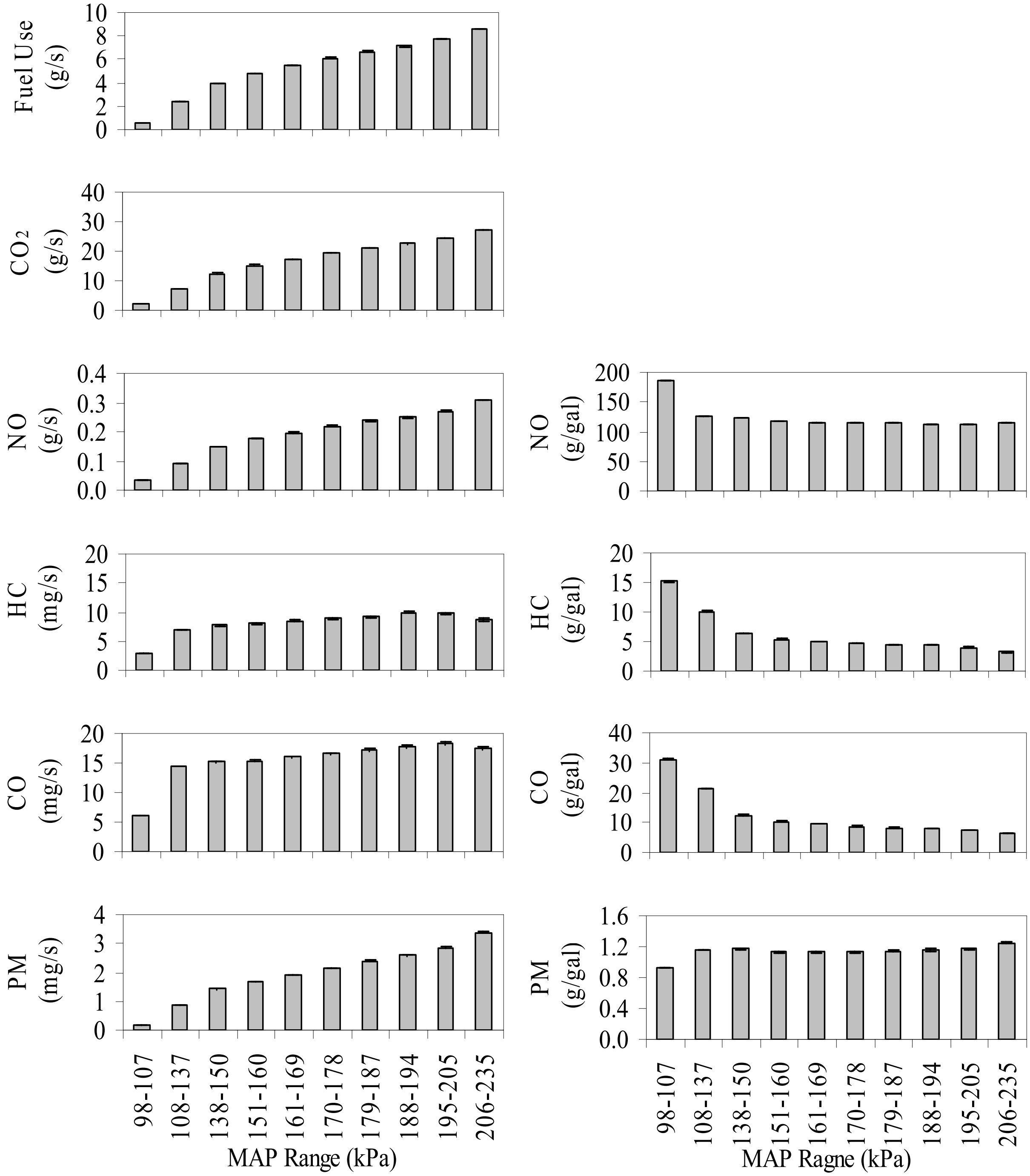
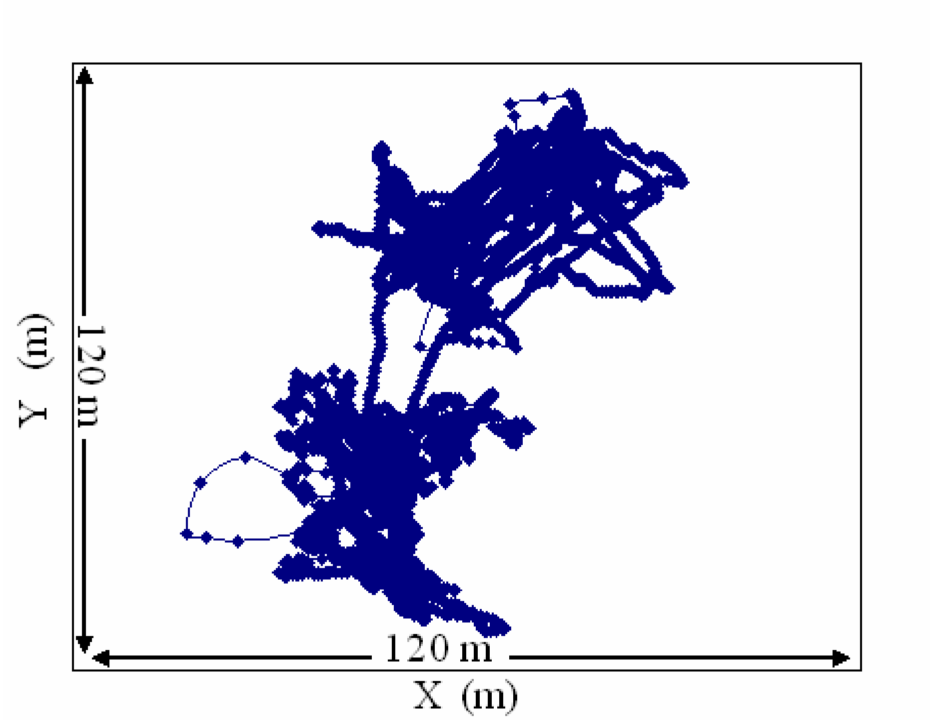
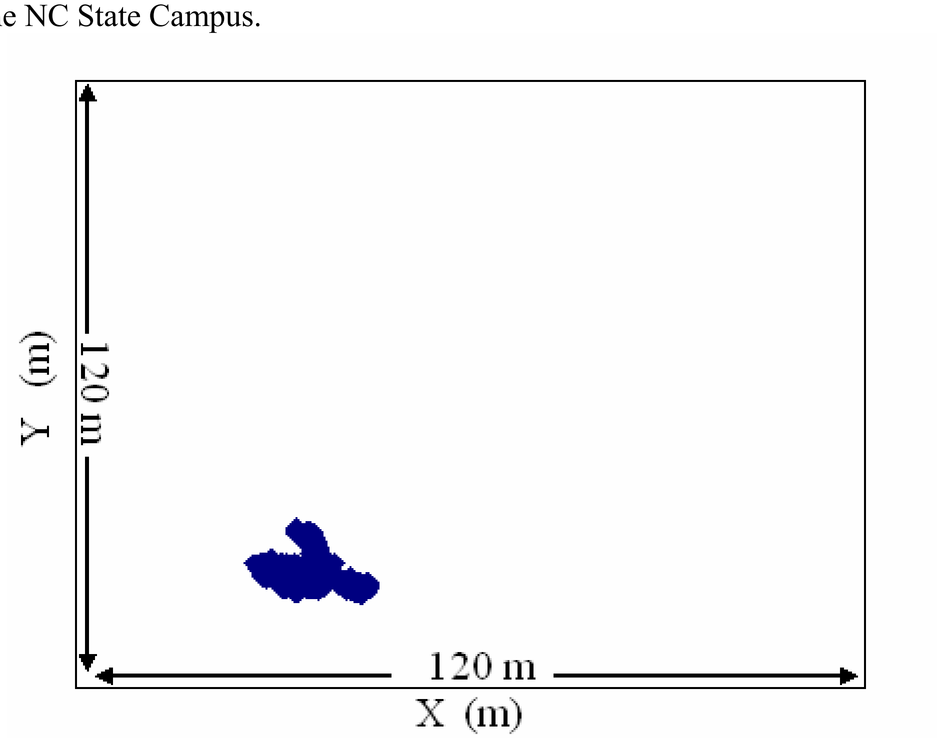


Figure 6. Average Modal Fuel Consumption and Mass Emission Rates and Average Emissions per Gallon of Fuel Consumed for Engine-Based Modes for Excavator 3.



(a) Excavator 1 Transported Foundation Casting Frames at a Site near Western Blvd on the NC State Campus.



(b) Excavator 2 Installed Constructed Riffles at a Site near Cates Ave. on the NC State Campus.

Figure 7. Examples of Spatial Patterns Associated with Duty Cycles of Excavator 1 at Site 1 and Excavator 2 at Site 2, Based on Geographic Position System (GPS) Data.

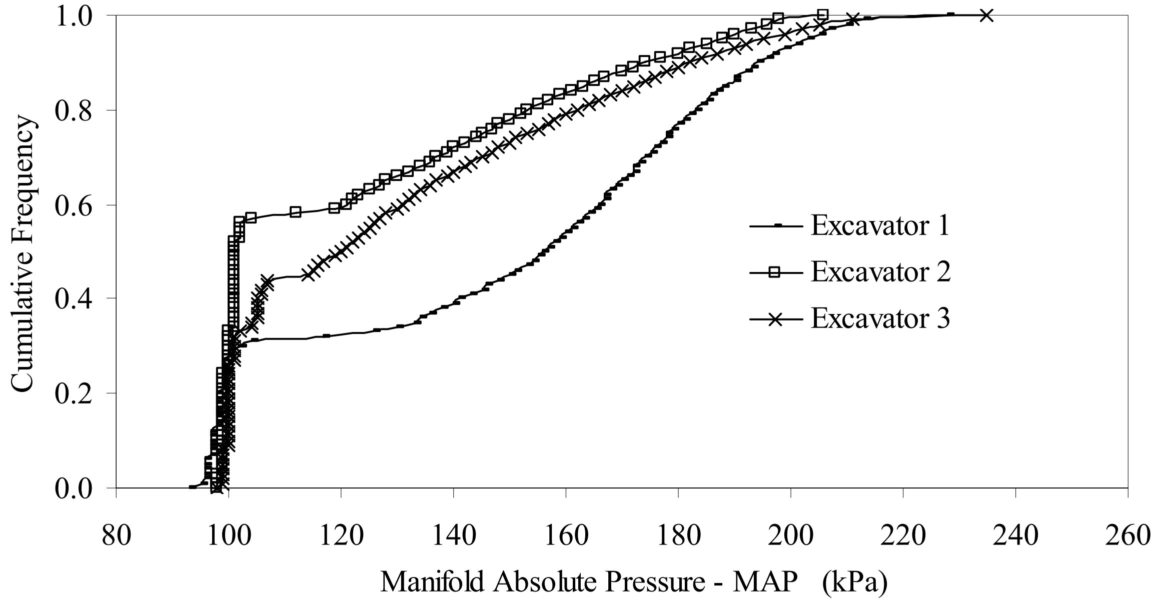


Figure 8. Cumulative Distribution Function of the Frequency of Manifold Absolute Pressure Data for the Three Excavators and Concordance with Idle versus Non-Idle Modes of Operation.

Real-World Emission Data Collection from Nonroad Construction Vehicles: A Case Study for Excavators

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Supporting Information

This supporting information (SI) contains figures and tables pertaining to analyses that were not shown in the paper. Materials presented here include: (1) normalized average emissions and fuel consumption estimated for test excavators; (2) correlation between fuel consumption and CO_2 emission rates for the test excavators; (3) correlation between fuel consumption rate and engine speed for the test excavators; (4) correlation between NO emission rates and fuel consumption, CO_2 emissions, and engine speed for Excavator 1 tested on January 16, 2006; (5) correlation between HC emission rates and fuel consumption rate, CO_2 emission rates, NO emission rates, and engine speed for Excavator 1 tested on January 16, 2006; (6) correlation between CO emission rates and fuel consumption rate, CO_2 emission rates, NO emission rates, and engine speed for Excavator 1 tested on January 16, 2006; (7) correlation between particulate matter emission rates and fuel consumption rate, CO_2 emission rates, NO emission rates, and engine speed for Excavator 1 tested on January 16, 2006; (8) correlation between engine speed and manifold absolute pressure for test excavators; (9) average normalized fuel consumption, average manifold absolute pressure, and fraction of time in each mode for the test excavators; (10) average normalized CO_2 emissions, average manifold absolute pressure, and fraction of time in each mode for the test excavators; (11) average normalized HC emissions, average manifold absolute pressure, and fraction of time in each mode for the test excavators; (12) average normalized CO emissions, average manifold absolute pressure, and fraction of time in each mode for the test excavators; (13) average normalized PM emissions, average manifold absolute pressure, and fraction of time in each mode for the test excavators.

Table S1. Normalized[1] Average Emissions and Fuel Consumption Rates Estimated for Test Excavators

Vehicle	Normalized Average Emissions					Normalized Average Fuel Use	Normalized Average Engine Parameters		
	NO	HC	CO	CO_2	PM		Engine Speed	IAT[2]	MAP3
Excavator 1	0.40	0.32	0.13	0.38	0.13	0.38	0.76	0.76	0.66
Excavator 2	0.12	0.06	0.09	0.30	0.10	0.30	0.68	0.76	0.57
Excavator 3	0.25	0.14	0.06	0.25	0.08	0.25	0.67	0.79	0.55

[1] The data were normalized with respect to maximum values for each pollutant and fuel consumption

[2] IAT: Intake air temperature

[3] MAP: Manifold absolute pressure

Table S2. Modal Values of Average Normalized Fuel Use Rate, Average Manifold Absolute Pressure, and Fraction of Time for each Excavator.[1]

Mode	Excavator								
	1			2			3		
	Average Normalized MAP[2]	Average Normalized Fuel use	Fraction of time %	Average Normalized Fuel use	Average Normalized MAP	Fraction of time %	Average Normalized MAP	Average Normalized Fuel use	Fraction of time %
1	0.45	0.10	35	0.08	0.48	30	0.43	0.06	34
2	0.64	0.42	10	0.10	0.49	20	0.49	0.17	16
3	0.70	0.52	9	0.15	0.52	12	0.54	0.27	10
4	0.73	0.57	9	0.37	0.63	7	0.57	0.34	9
5	0.76	0.61	6	0.47	0.68	6	0.61	0.42	7
6	0.78	0.65	7	0.53	0.73	6	0.65	0.51	6
7	0.81	0.69	6	0.60	0.78	5	0.69	0.59	5
8	0.84	0.73	6	0.66	0.83	5	0.74	0.68	5
9	0.87	0.79	6	0.75	0.89	5	0.79	0.76	4
10	0.92	0.87	5	0.82	0.95	4	0.86	0.88	4

[1] For a given excavator and quantity (e.g., Fuel use rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.

[2] MAP: Manifold absolute pressure

Table S3. Modal Values of Average Normalized CO_2 Emissions Rate, Average Manifold Absolute Pressure, and Fraction of Time for Each Excavator.[1]

Mode	Excavator								
	1			2			3		
	Average Normalized MAP[2]	Average Normalized CO_2	Fraction of time %	Average Normalized MAP	Average Normalized CO_2	Fraction of time %	Average Normalized MAP	Average Normalized CO_2	Fraction of time %
1	0.45	0.09	35	0.48	0.08	30	0.43	0.06	34
2	0.64	0.42	10	0.49	0.11	20	0.49	0.17	16
3	0.70	0.51	9	0.52	0.16	12	0.54	0.27	10
4	0.73	0.57	9	0.63	0.41	7	0.57	0.34	9
5	0.76	0.61	6	0.68	0.51	6	0.61	0.42	7
6	0.78	0.64	7	0.73	0.58	6	0.65	0.50	6
7	0.81	0.69	6	0.78	0.65	5	0.69	0.59	5
8	0.84	0.72	6	0.83	0.73	5	0.74	0.67	5
9	0.87	0.79	6	0.89	0.82	5	0.79	0.76	4
10	0.92	0.86	5	0.95	0.90	4	0.86	0.87	4

[1] For a given excavator and quantity (e.g., CO_2 emission rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.

[2] MAP: Manifold absolute pressure

Table S4. Modal Values of Average Normalized HC Emissions Rate, Average Manifold Absolute Pressure, and Fraction of Time for Each Excavator.[1]

Mode	Excavator								
	1			2			3		
	Average Normalized MAP[2]	Average Normalized HC	Fraction of time %	Average Normalized MAP	Average Normalized HC	Fraction of time %	Average Normalized MAP	Average Normalized HC	Fraction of time %
1	0.45	0.27	35	0.48	0.24	30	0.43	0.20	34
2	0.64	0.63	10	0.49	0.32	20	0.49	0.46	16
3	0.70	0.62	9	0.52	0.35	12	0.54	0.58	10
4	0.73	0.66	9	0.63	0.60	7	0.57	0.60	9
5	0.76	0.68	6	0.68	0.65	6	0.61	0.63	7
6	0.78	0.70	7	0.73	0.67	6	0.65	0.66	6
7	0.81	0.76	6	0.78	0.74	5	0.69	0.70	5
8	0.84	0.74	6	0.83	0.77	5	0.74	0.73	5
9	0.87	0.81	6	0.89	0.83	5	0.79	0.78	4
10	0.92	0.86	5	0.95	0.85	4	0.86	0.87	4

[1] For a given excavator and quantity (e.g., HC emission rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.

[2] MAP: Manifold absolute pressure

Table S5. Modal Values of Average Normalized CO Emissions Rate, Average Manifold Absolute Pressure, and Fraction of Time for Each Excavator.[1]

Mode	Excavator								
	1			2			3		
	Average Normalized MAP[2]	Average Normalized CO	Fraction of time %	Average Normalized MAP	Average Normalized CO	Fraction of time %	Average Normalized MAP	Average Normalized CO	Fraction of time %
1	0.45	0.48	35	0.48	0.33	30	0.43	0.23	34
2	0.64	0.86	10	0.49	0.46	20	0.49	0.57	16
3	0.70	0.68	9	0.52	0.73	12	0.54	0.64	10
4	0.73	0.66	9	0.63	1.04	7	0.57	0.66	9
5	0.76	0.64	6	0.68	0.89	6	0.61	0.69	7
6	0.78	0.63	7	0.73	0.84	6	0.65	0.71	6
7	0.81	0.66	6	0.78	0.85	5	0.69	0.74	5
8	0.84	0.69	6	0.83	0.84	5	0.74	0.76	5
9	0.87	0.76	6	0.89	0.89	5	0.79	0.79	4
10	0.92	0.83	5	0.95	0.88	4	0.86	0.88	4

[1] For a given excavator and quantity (e.g., CO emission rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.

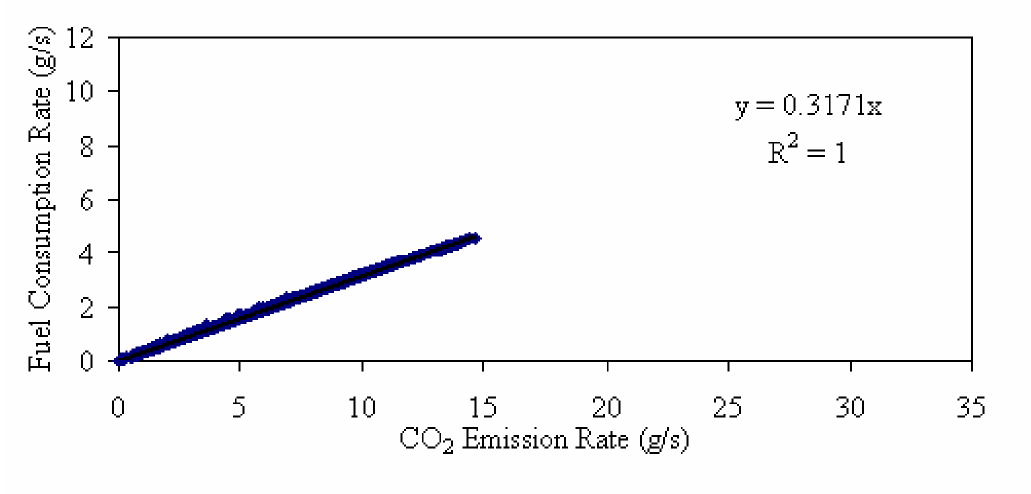
[2] MAP: Manifold absolute pressure

Table S6. Modal Values of Average Normalized Opacity Rate, Average Manifold Absolute Pressure, and Fraction of Time for Each Excavator.[1]

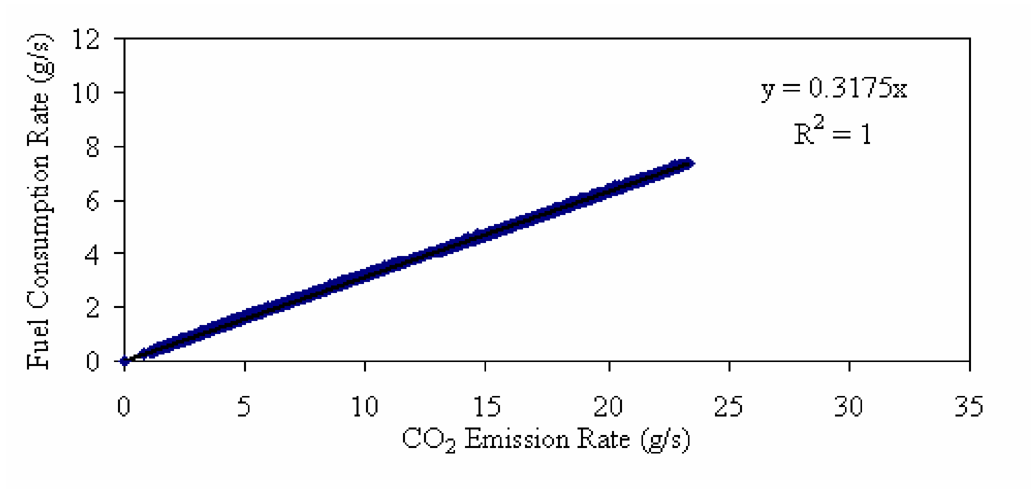
Mode	Excavator 1			Excavator 2			Excavator 3		
	Average Normalized MAP[2]	Average Normalized Opacity	Fraction of time %	Average Normalized MAP	Average Normalized Opacity	Fraction of time %	Average Normalized MAP	Average Normalized Opacity	Fraction of time %
1	0.45	0.07	35	0.48	0.04	30	0.43	0.05	34
2	0.64	0.32	10	0.49	0.05	20	0.49	0.14	16
3	0.70	0.35	9	0.52	0.09	12	0.54	0.25	10
4	0.73	0.40	9	0.63	0.20	7	0.57	0.31	9
5	0.76	0.48	6	0.68	0.27	6	0.61	0.38	7
6	0.78	0.49	7	0.73	0.35	6	0.65	0.46	6
7	0.81	0.55	6	0.78	0.44	5	0.69	0.53	5
8	0.84	0.63	6	0.83	0.55	5	0.74	0.61	5
9	0.87	0.72	6	0.89	0.70	5	0.79	0.71	4
10	0.92	0.85	5	0.95	0.86	4	0.86	0.88	4

[1] For a given excavator and quantity (e.g., Opacity rate and MAP for Excavator 1), the values were normalized by identifying the maximum value that occurred and dividing all second-by-second values by the maximum.

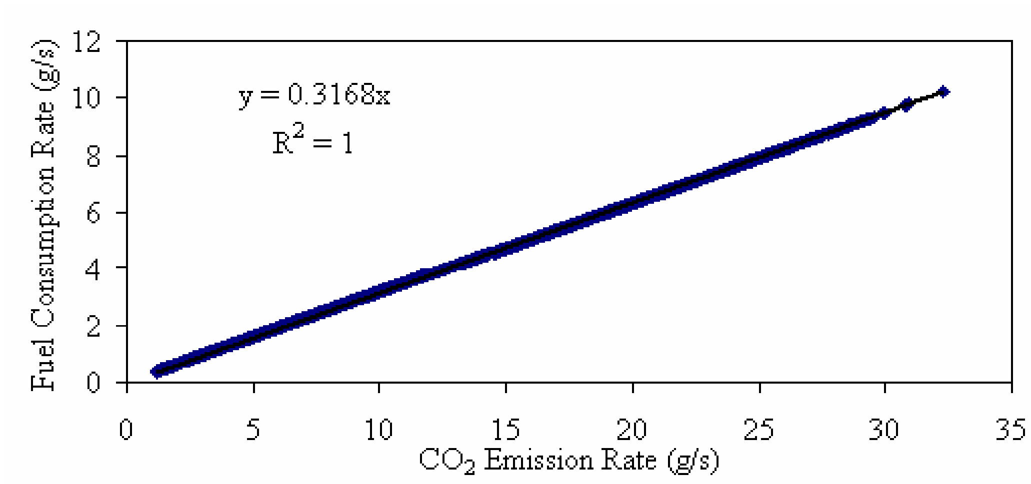
[2] MAP: Manifold absolute pressure



a) Excavator 1

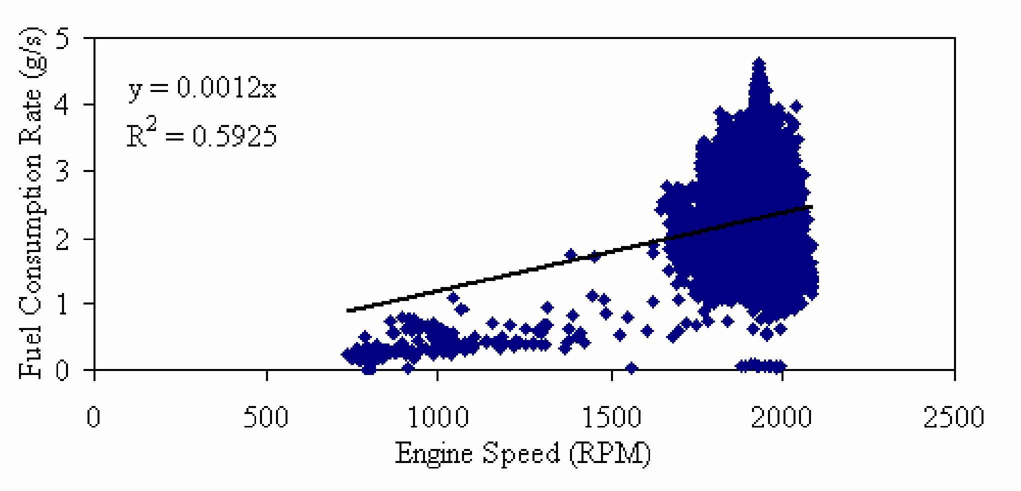


b) Excavator 2

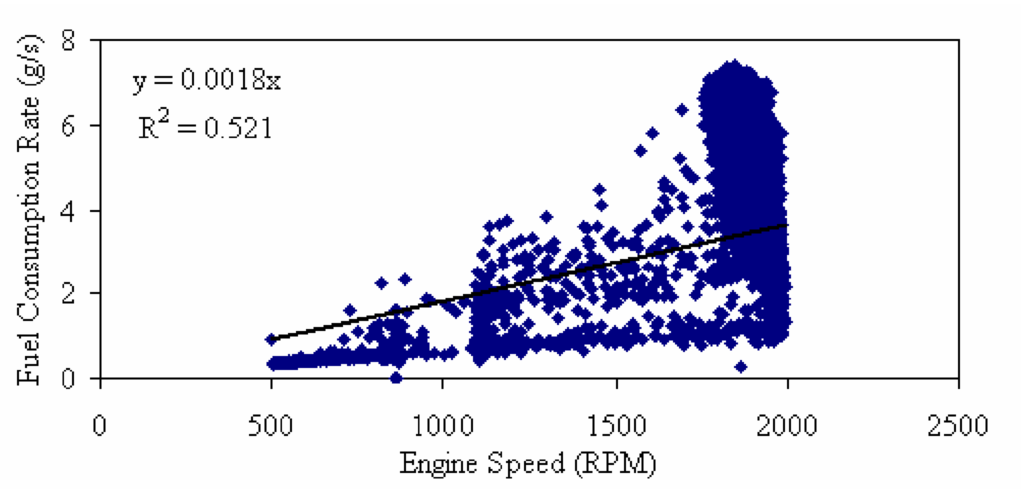


c) Excavator 3

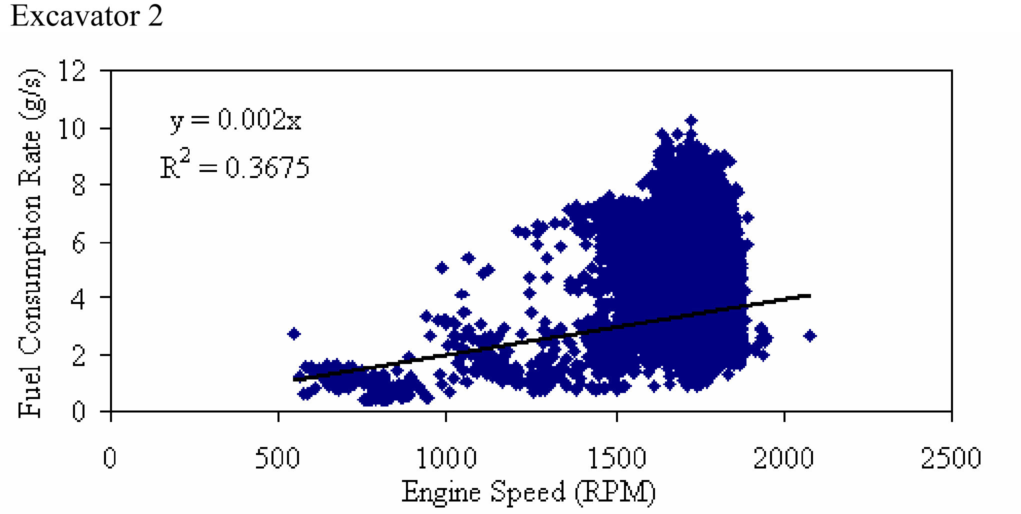
Figure S1. Correlation between Fuel Consumption and CO_2 Emission Rates for the Test Excavators



a) Excavator 1



b) Excavator 2



c) Excavator 3

Figure S2. Correlation between Fuel Consumption Rate and Engine Speed for the Excavators

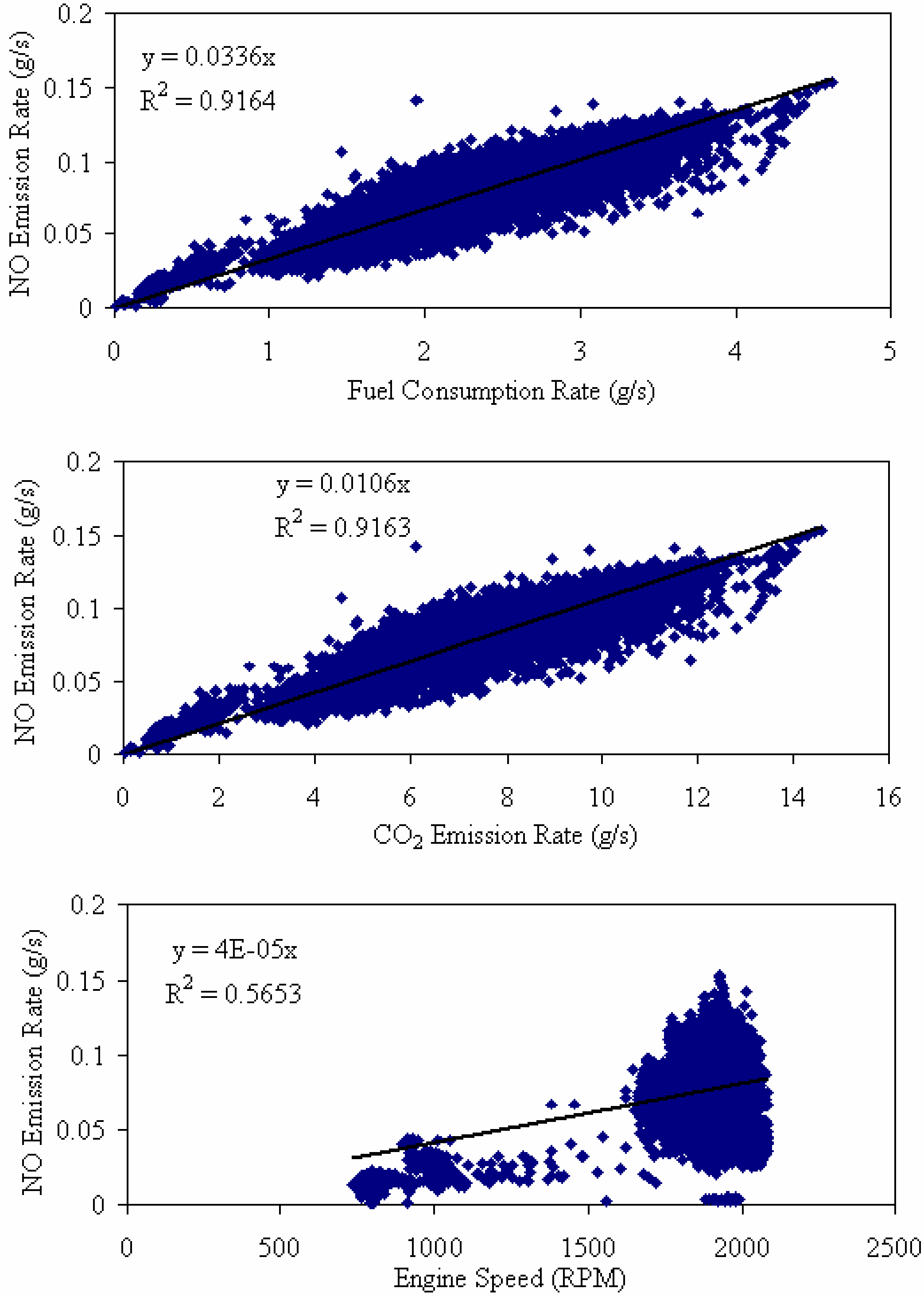


Figure S3. Correlation between NO Emission Rate and Fuel Consumption Rate, CO_2 Emission Rate, and Engine Speed for Excavator 1

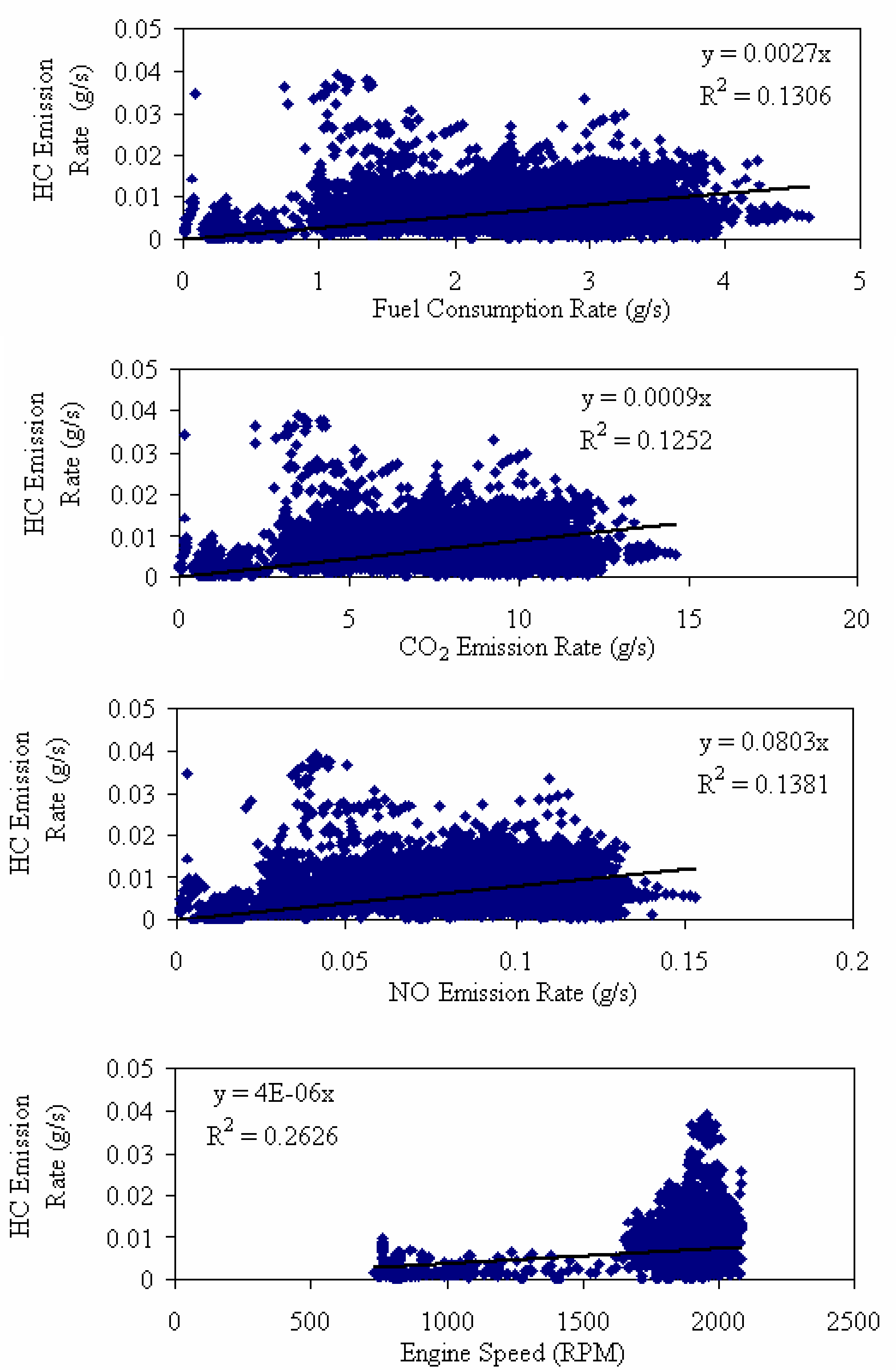


Figure S4. Correlation between HC Emission Rate and Fuel Consumption Rate, CO_2 Emission Rates, NO Emission Rates, and Engine Speed for Excavator 1

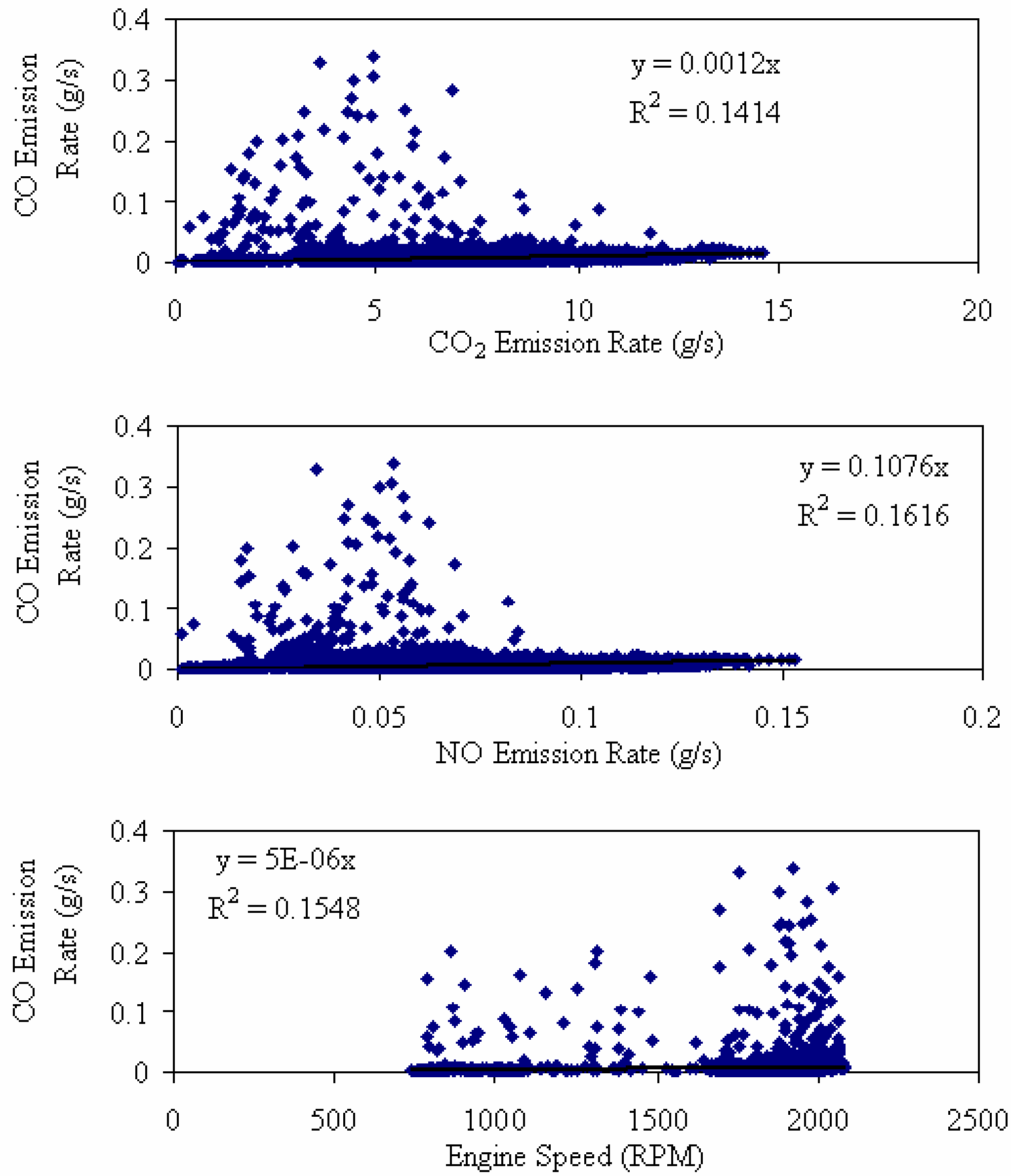


Figure S5. Correlation between CO Emission Rate and Fuel Consumption Rate, CO_2 Emission Rates, NO Emission Rates, and Engine Speed for Excavator 1

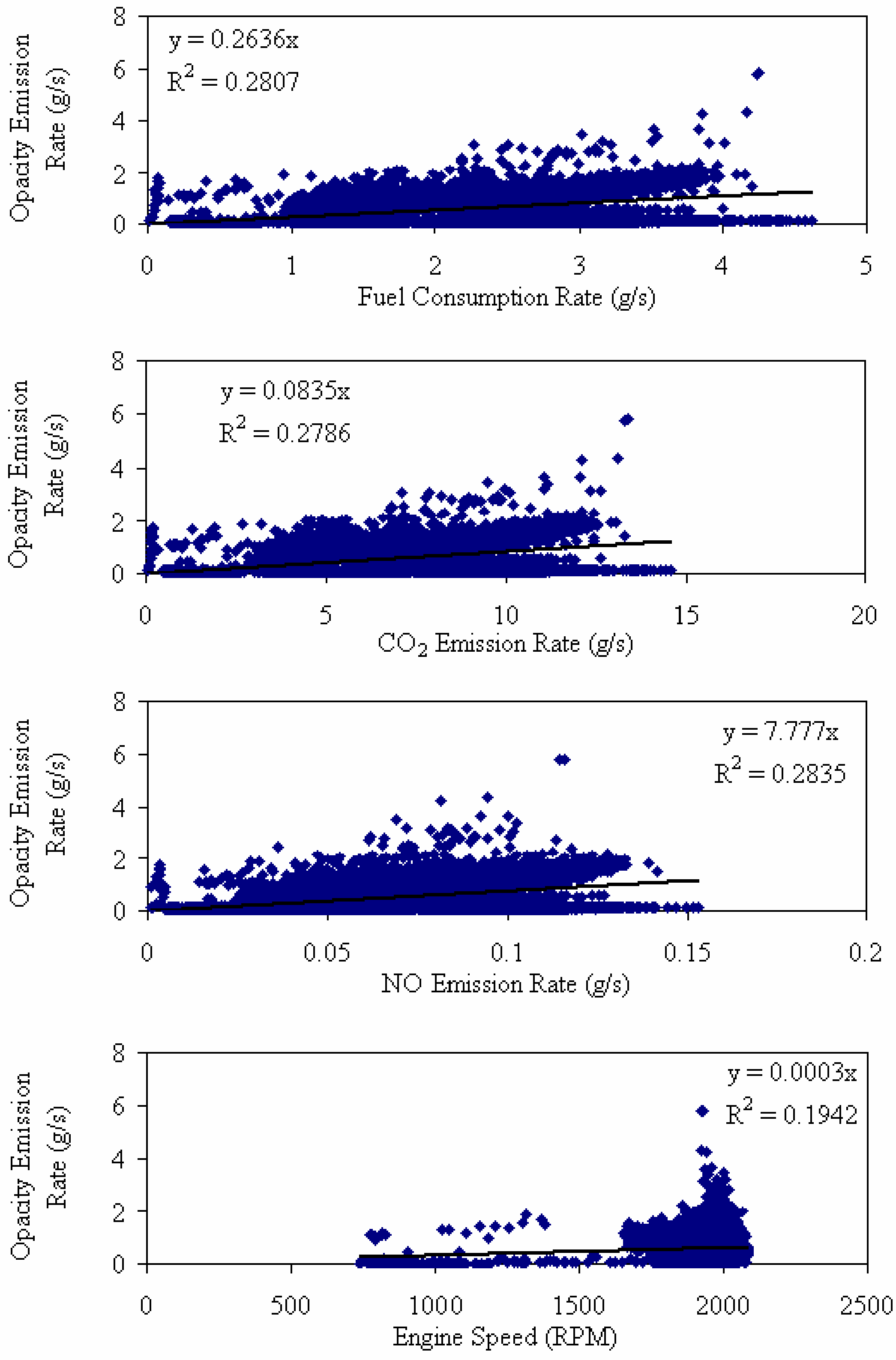
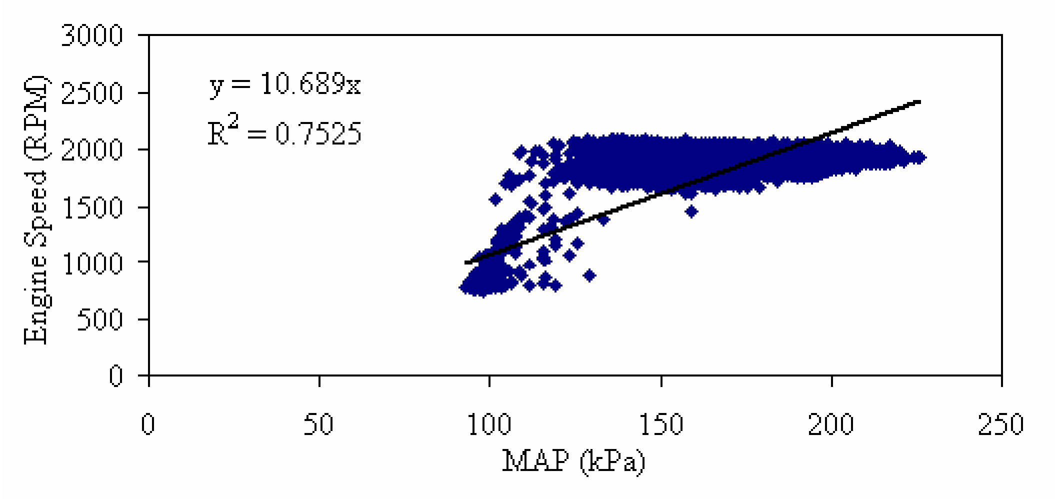
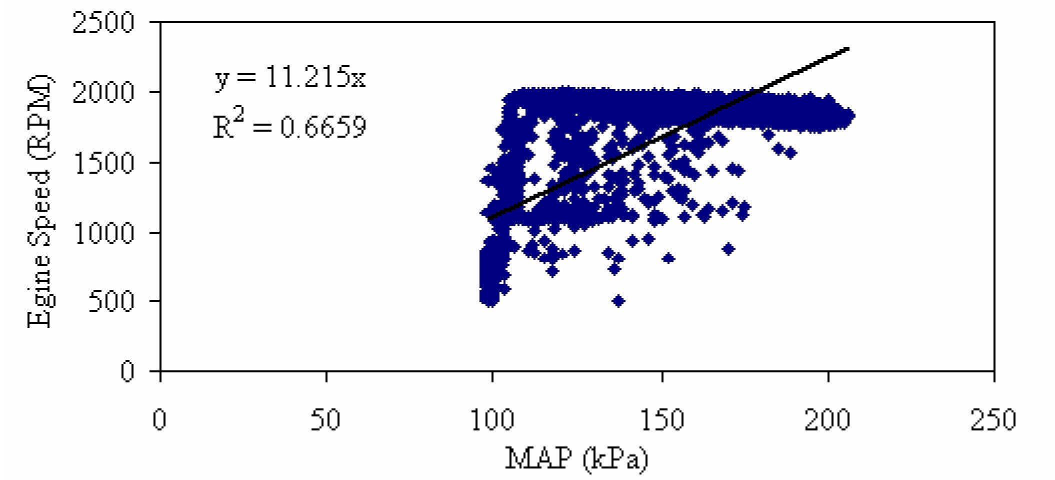


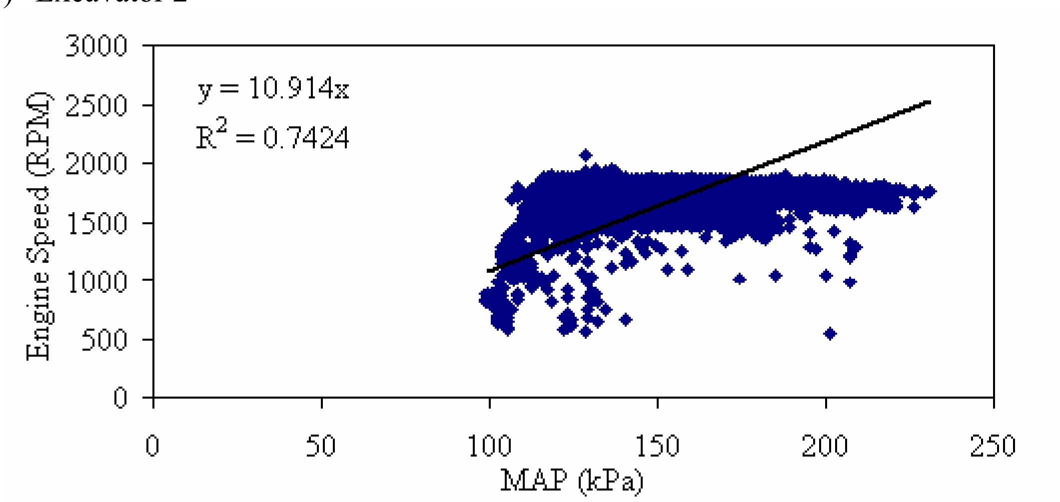
Figure S6. Correlation between Opacity Rates and Fuel Consumption Rate, CO_2 Emission Rates, NO Emission Rates, and Engine Speed for Excavator



a) Excavator 1



b) Excavator 2



c) Excavator 3

Figure S7. Correlation between Engine Speed and Manifold Absolute Pressure for Test Excavators

PART V

CONCLUSIONS AND RECOMMENDATIONS

1.0 Conclusions

In this part, conclusions are presented. Key questions that are raised in Section 2 of Part I are addressed. Suggestions for future research directions are provided.

1.1 Main Categories of Construction Vehicles Contributing to Air Quality Problems

Top seven vehicles and equipment types were found to contribute approximately 70 percent of estimated U.S. national total nonroad construction vehicle and equipment emissions in the U.S. Thus, these seven types are recommended as priorities for field data collection. These seven types include Rubber Tire Loaders, Crawler Tractor/Dozers, Excavators, Off-Highway Trucks, Tractors/Loaders/Backhoes, Skid Steer Loaders, and Generator Sets.

1.2 Advantages of Using Real-World Data to Assess Emissions and Fuel Consumption

Advantages of using real-world in-use data to estimate emissions from construction vehicles were demonstrated in Parts III and IV. Currently available emissions modeling tools have been focused on the estimation of emissions based on average operating characteristics over broad geographical areas such as MOBILE, PART, MOBTOX, and NONROAD. For example, NONROAD model's estimations are based upon average estimates of emissions for a limited number of standard operating cycles measured in the laboratory across a number of nonroad engines. However, standardized test cycles cannot be representative of all real-world activity patterns.

Real-world in-use data provides the opportunity to quantify the episodic nature of emissions and fuel use and critically account for variability in activity patterns as well as variability in energy use and emissions. There is a critical need to analyze on-board emissions and energy use data to understand the relationship between construction equipment activity patterns with respect to energy use and emissions, particularly at the microscale. New emissions models are expected to use on-board second-by-second emissions data for emissions estimation purposes. Real-world emissions data can be used to support a variety of research objectives in which emissions and fuel use patterns in short-term events are the focus of studies.

This was verified that short-term episodes can substantially affect average emissions. As demonstrated in PART IV, it was found that on average 50% of the total NO emissions were associated with 28% of the time of vehicles operation in which the average engine speed and manifold absolute pressure were significantly higher than corresponding averages for the total data. There is a serious concern that existing models calibrated with laboratory data are not sufficiently accurate to estimate local emissions. The concern is heightened as the desired geographic scale and temporal averaging time of the predictions is decreased. Of course, microscale data for a specific construction project can always be aggregated to produce macroscale estimates. However, data collected at only the macroscale cannot be disaggregated to the microscale.

1.3 Modal Modeling Approaches

Part III focused on developing conceptual modal models to estimate emission from construction vehicles using on-board emissions data. The modal models offer the advantages of being conceptually simple and identifying substantial explanatory power in estimating modal average emissions rates. Because the total emissions from the vehicles are influenced more by periods of high emission rate than by periods of low emission rate, it is desirable for the modal model to offer the most precision in estimating the highest emission rate, which this one does for both pollutants.

The modal approach offers the advantages of being conceptually the simplest, of dividing the time series into segments that reduces the influence of autocorrelation, and of offering substantial explanatory power, as reflected in R^2 values of observed versus estimated emissions.

There is a substantial increase in explanatory power of the combined modal-regression modal models for some of the test vehicles. In other cases, the R^2 values for the modal models are so high (e.g. 0.93 to 0.95) that substantial improvement is not possible

1.4 Duty Cycles and Activity Patterns

It was demonstrated in this work that emissions and fuel consumption rates change with respect to modes of activity. From analysis of time traces, it was found that most of the large peaks in emissions and fuel consumption rates, on a mass per time basis, tend to coincide with higher engine speed and MAP peaks. The emissions of NO and CO_2, and fuel use rates appear to be more responsive to variation of engine speed rather than the other emissions. The emission rates and fuel use during idling are low compared to the other operational modes. The emission rate for HC responds in a manner almost qualitatively the same as that for CO. The CO_2 emissions and fuel consumption traces are similar to each other. Because the emissions of CO and HC are low compared with the CO_2 emissions, it is estimated that more than 99.8% of the carbon in the fuel is emitted as CO_2. Therefore, CO_2 emissions are a good surrogate for fuel consumption.

The influence duty cycles and activity patterns on average emission rates were verified in PARTS III and IV. In PART III, it was shown that a modal model can be used to explain the effects of duty cycles on average emissions. The relationship between mode-specific average normalized emissions and exhaust flow was found to be very stable, consistent, and similar among the vehicles. The normalized average NO_x and CO_2 emissions increase as normalized exhaust flow increases. This means that inter-vehicle differences in emissions are because of differences in activity patterns reflected in the fraction of time spent in each mode or duty cycles reflected in the modal average exhaust flow rates.

In PART IV, from analysis of time traces, it was found that most of the large peaks in emissions and fuel consumption rates, on a mass per time basis, tend to coincide with higher MAP peaks that occur during the moving and using bucket modes. Therefore, there was higher correlation between emissions and MAP compared to the other engine variables. It was concluded that MAP has the potential to explain the effect of activity patterns on the average emission and fuel consumption rates. For the vehicles that are operated longer in MAP values close to the maximum MAP of the vehicle, it is expected to observe higher emission and fuel consumption rates.

1.5 Key Considerations in Data Quality Assurance

Several sources of error were defined in conjunction with the gas analyzers including effects of zero calibration of pollutants concentrations, inter-analyzer discrepancies, and synchronization of engine and emissions data. A high proportion (i.e. 91%) of measurement attempts resulted in valid vehicle activity and emission files for Excavators 2 and 3. However, for Excavator 1, this proportion is 82.5% because of serious vibration resulted in several time losing power to the Montana system. For all excavators, analyzer freezing and inter-analyzer discrepancy were the most frequent errors occurred. To reduce the effects of these errors, the NDIR of both analyzers must be cleaned before the test and attempt to reduce vibration transferred to the Montana system using more foam pads around the system.

2.0 Recommendation for Future Work

Key recommendations of this study are:

1. An on-board study is more complicated than that for a laboratory study since it is partly observational and partly controlled. Of course, a careful study and experimental design is required with respect to the study objectives. Key factors that should be considered in future studies are vehicle selection, access to vehicles, security of the PEMS, ambient conditions, site characteristics, data quality assurance, and sample size.
2. An on-board data collection procedure for nonroad construction vehicles needs to be developed to include duty cycle and activity pattern of the vehicle in the emissions database. This data is helpful to explain relationship between exhaust flow rate and vehicle activity patterns.
3. For developing modal models, data should be collected for multiple operators, multiple days, or for multiple applications of the vehicles to different tasks, to include variables such as operator's operating pattern and different vehicle duty cycles that affect variability in emissions data. In order to develop more useful emission models, data about the other emissions such as CO, HC, and PM are essential needs.
4. In on-board emissions measurement, there is a critical need to characterize engine load by developing an appropriate surrogate for that to provide a better understanding of emission patterns in regard to engine behavior.
5. For emission inventory purposes using on-board in-use data, emissions and fuel use should be estimated per unit of vehicle activity. For example, it is possible to design a study in order to estimate the average emissions and fuel consumption rates per cubic yard of dirt excavated by excavators.

6. In this work, a computer program was written and setup on a laptop computer to be used by an at site observer to manually record the modal activities including using bucket, moving, and idling. In future work, it might be possible to record modes of activity using sensors attached to the test vehicle. Use of this approach will result in accurate collection of modes of activity data.

APPENDIX A

GLOSSARY OF TECHNICAL TERMS

Autocorrelation Autocorrelation is the correlation (relationship) between members of a time series of observations, such as second-by-second emission concentrations.

Binning Process A summarization technique in which emission values are binned into predefined intervals. Binning leads to loss of one-to-one correspondence between emissions and exhaust flow rates and reduces influence of autocorrelation in time series data.

Bucket An attachment to excavators which is used for accomplishing a task such as excavating or carrying heavy objects.

CFI Construction, Far, and Industrial equipment. A group of equipment categorized by the EPA as one of nonroad air pollution sources.

Coefficient of Determination (R^2) A statistic that is widely used as a goodness-of-fit measure for regression analysis. R^2 represents the fraction of variation in a variable such as estimated emission rates that can be explained by the fitted regression model.

Confidence Interval The computed interval with a given probability (i.e., 95%) that the true value of the statistic, such as a mean, proportion, or rate, is contained within the interval.

Estimation An indication of the value of an unknown quantity based on observed data.

Exploratory Analysis An approach for data analysis that employs a variety of techniques such as maximize insight into a data set, extract important variables, and test underlying assumptions.

GPS Global Positioning System. A satellite-based navigation system made up of a network of 24 satellites placed into orbit by the U.S. Department of Defense.

Monotonic Relationship A relationship that occurs when there is an association between two variables that is either consistently increasing or consistently decreasing.

Monte Carlo Simulation a method of generating random values from a known distribution for the purposes of numerical experimentation.

NDIR Nondispersive infrared. NDIR is a technique of measuring HC, CO, and CO_2 emission concentrations.

NONROAD2004 A model developed by the EPA for estimation of emissions from nonroad air pollution sources. This model is an emission inventory model.

PEMS Portable Emission Measurement System. PEMS is a system which is used on-board emissions measurement from vehicles.

Scatter Plot A figure in which individual data points are plotted in two-dimensional space.

Scenario A set of facts, assumptions, and inferences about a problem of interest that helps an analyst in evaluating, estimating, or quantifying the problem of interest.

Screening A procedure of inspecting data in order to define any kinds of error

Statistical Significance The satisfaction of a statistical criterion determined by a priori specification of an acceptable probability of wrongly rejecting a true hypothesis (i.e. usually 0.05 percent).

Variability Heterogeneity of values over time, space, or different members of a population. Variability is a property of nature.

APPENDIX B

PROCEDURE FOR DATA SCREENING AND QUALITY ASSURANCE OF ON-BOARD EMISSIONS DATA FROM NONROAD CONSTRUCTION VEHICLES

B.1 Introduction

Data screening and quality assurance are procedures for reviewing data collected in the field, determining whether any errors or problems exist in the data, correcting such errors or problems where possible, and removing invalid data if errors or problems cannot be corrected. The goal of data screening and quality assurance is to produce a database that contains valid data. The procedures developed in this thesis for data screening and quality assurance are discussed in this appendix.

From previous work, a number of possible errors and problems have been identified.[1, 2] In the previous work, engine data were collected via the electronic data link of the vehicle, such as the on-board diagnostic link of light duty gasoline vehicles and the engine control module link of heavy duty vehicles. However, in the current study, engine data are obtained using a sensor array. Thus, the data screening and quality assurance procedures required modification for this work to account for problems and errors that can occur in conjunction with the sensor array.

In the following two sections, problems and errors associated with the sensor array and the gas analyzer are identified and procedures for dealing with them are detailed.

B.2 Errors and Problems Associated with Sensor Array

The sensor array is comprised of engine speed, manifold absolute pressure, and intake air temperature, sensors. This section identifies the possible problems and errors associated with the engine speed and manifold absolute pressure sensors, as well as detailed procedures for avoiding or dealing with such problems and errors. Errors associated with intake air temperature sensor are not discussed in this appendix.

B.2.1 Engine Speed

Engine speed is the number of revolutions per minute (RPM) at which the engine crankshaft turns whether the vehicle is stationary or in motion. The engine speed for a diesel engine typically varies from at least 500 RPM to not more than 4,000 RPM.[3] If the measured engine speed exceeds this range, then an error is suspected. This type of error is rarely observed in data.

B.2.1.1 Criteria for Detecting and Removing Unusual Engine Speed

The criterion for detecting an unusual engine speed in a dataset is.

$$ES_t \leq 500 \text{ RPM} \quad \text{or} \quad ES_t \geq 4{,}000 \text{ RPM} \qquad (1)$$

where,

ES_t = Engine Speed at time t; RPM

If the observed engine speed exceeds the acceptable range, then all emission rate data for that specific second need to be removed from the dataset. This is because engine RPM is used to estimate the exhaust flow rate, which in turn is used to convert the pollutant concentration data into a mass emission rate.

B.2.2 Manifold Absolute Pressure

Manifold absolute pressure (MAP) is used to estimate the intake air and exhaust flow rate for the engine, the latter of which is used to estimate mass emission rates. On occasion, communication between the sensor array and the Montana system might be lost, leading to loss of MAP data. For example, MAP errors were observed in 927 out of 23,893 seconds, or

3.88 percent, of data for an excavator that was tested on August 25, 2005. Typically, missing values occurred for 3 or fewer consecutive seconds of data. The problem of missing MAP data was observed in two days of data collection and the reason for missing MAP data was the vibration of connection cable of MAP sensor due to operation of construction vehicles. The problem was solved for the further experiments.

B.2.2.1 Criteria for Detecting Missing MAP

Missing values are represented in the Montana system by a data missing code of "-34" for each second in which a missing value occurs. Therefore, the criterion for identifying missing MAP data is:

$$MAP_t = -34 \tag{2}$$

where,

MAP_t = Manifold Absolute Pressure at time t; kPa

Typically, other measured data including engine and emissions data are valid at the time when a missing MAP value occurs. Therefore, it is desirable to replace missing values with an estimate of MAP in situations where such estimates can be done with confidence. In turn, emissions rates can be estimated based on the valid values of the other measured variables and the estimate of MAP.

B.2.2.2 Criteria for Evaluating MAP

The procedure for evaluating missing MAP data involves several steps. The first step is to calculate the absolute relative difference (ARD) between MAP values that occur before and after missing values. In the second step, the magnitude of ARD is evaluated to determine whether corrective action is possible. If the ARD is less than or equal to a threshold value, then the missing values are replaced with estimates. If the ARD is too large, then the estimation process is deemed to be unreliable and no emission estimates should be made or used during the seconds for which the missing MAP data occur.

The ARD is calculated based on the two seconds of observed MAP data that occur before the missing value(s), and the two seconds of MAP data that occur immediately following the missing value(s). This procedure is applied when missing values occur for 1, 2, or 3 consecutive seconds:

$$\mathrm{ARD} = \left| \frac{(MAP_{t+i} + MAP_{t+i+1}) - (MAP_{t-1} + MAP_{t-2})}{(MAP_{t-1} + MAP_{t-2})} \right| \times 100 \qquad (3)$$

where,

ARD	=	Absolute value of Relative Difference
t	=	time at which the first missing MAP is observed
i	=	number of MAP errors that occur consecutively, i =1, 2, 3
MAP_{t+I}	=	MAP value at time $t+i$ immediately after missing value(s); kPa
MAP_{t+i+1}	=	MAP value at time $t+i+1$ after missing value(s); kPa
MAP_{t-1}	=	MAP value at time $t-1$ immediately before missing value(s); kPa
MAP_{t-2}	=	MAP value at time $t-2$ before missing value(s); kPa

The emission rates estimated by the Montana system are approximately a linear function of MAP. For example, if the MAP estimate varies by plus or minus 5 percent, while all other measured variables are held constant, then the emission estimate (g/sec) will vary by -5 to +5 percent. In order to prevent the error associated with estimation of missing MAP values to exceed this range of variation for the emission estimates, the following criteria were established:

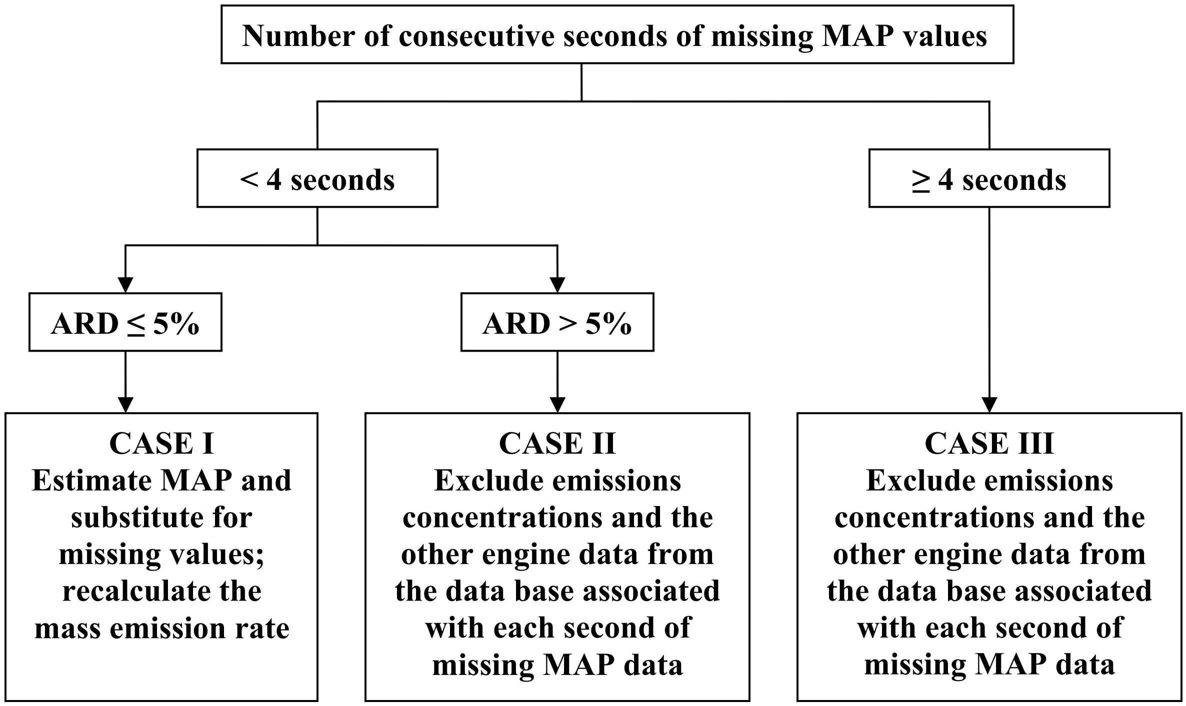
Case I: If ARD $\leq$ 5%, then the missing MAP values are replaced with the following estimate(s) for each second in which missing values occur:

$$\frac{MAP_{t+i} + MAP_{t+i+1} + MAP_{t-1} + MAP_{t-2}}{4}$$

Case II: If ARD > 5%, then the missing MAP values are not replaced. Instead, MAP and all mass emission rate (g/sec) estimates that are based on MAP are deleted from the database for each second in which the missing values occur.

Case III: Four or more seconds of missing data occur, in which case the estimation procedure is deemed to be unreliable. In this case, MAP and all emission concentrations and the other engine data MAP are deleted from the database for each second in which the four or more missing values occur.

If the observed MAP is the same in the two seconds immediately before and after the missing values, then Case I simplifies to replacement of the missing values with these observed values. Figure B.1 summarizes the procedure for identifying and estimating missing MAP values.



ARD: Absolute relative difference (ARD) between MAP values that occur before and after missing values

Figure B.1. Criteria for Detection of Missing Manifold Absolute Pressure (MAP) Data and for Estimation of Missing Values.

B.2.2.4 Application of Estimating MAP Values to Real Data

The objective of this section is to illustrate the application of the criteria for identifying and estimating MAP values in a data file obtained from an excavator tested on August 25th, 2005. A Visual Basic Program was written to check data files in order to identify missing MAP data and to estimate MAP when the criteria for the number of consecutive seconds of missing data, and the ARD, were satisfied. After estimation of missing MAP data, the Visual Basic Program estimates mass emission rates per time using engine speed, intake air temperature, MAP, and emissions concentrations. The details of the procedure for estimating mass emission rate are given in elsewhere.[4]

To illustrate the application of the procedure for identifying and estimating missing MAP values, examples are shown in Table B.1. The first example illustrates a case in which the MAP values before and after missing data are constant, for which ARD is zero percent. Therefore, the estimates of the missing value(s) are identical to the observed values immediately before and after the occurrence of missing data. In the second example, the ARD is less than 5 percent. In this example, the missing values are estimated. In the third example, the ARD is greater than 5 percent, in which case the mass emission rates for each second in which MAP is missing cannot be calculated reliably and thus must be deleted from the database.

B.3 Errors and Problems Associated with Gas Analyzer

The objective of this section is to explain how the errors associated with the gas analyzer are considered for data quality assurance. The most common errors indicated in this study and previous works in North Carolina State University (NCSU) regarding gas analyzer are: inter-analyzer discrepancy between readings of analyzer, zeroing procedure of analyzer, gas analyzer freezing, and negative emissions values. In this appendix, the procedures developed in this thesis for screening and correcting errors associated with zeroing effects and synchronization of engine and emissions data are discussed. More detail about the other error detecting and correcting criteria is given elsewhere.[4] The procedures for screening, detecting, and correcting zeroing effects and synchronization problems will be described in the following sections.

Table B.1. Examples of the Application of Criteria for Identifying and Estimating Missing MAP Values Based on Field Data for an Excavator Tested on August 25th, 2005

Case	Time (sec)	Observed MAP (kPa)	Absolute Value of Relative Difference (ARD) Between MAP Data Before and After Missing Values (%)	Estimated MAP (kPa)
I	30,182	99	$\left\lvert\frac{(99+99)-(99+99)}{(99+99)}\right\rvert\times 100 = 0\%$	99
	30,183	99		99
	30,184	***-34***		***99***
	30,185	***-34***		***99***
	30,186	99		99
	30,187	99		99
	42,154	161	$\left\lvert\frac{(157+157)-(159+161)}{(159+161)}\right\rvert\times 100 = 1.9\%$	161
	42,155	159		159
	42,156	***-34***		***158.5***
	42,157	***-34***		***158.5***
	42,158	157		157
	42,159	157		157
II	28,504	159	$\left\lvert\frac{(160+160)-(202+159}{(202+159)}\right\rvert\times 100 = 11.4\%$	159
	28,505	202		202
	28,506	***-34***		-*
	28,507	***-34***		-*
	28,508	160		160
	28,509	160		160
III	This case was not observed in the datasets			

* Emission concentrations and the other engine data are removed from the data set.

B.3.1 Zeroing Procedures of PEMS Instrument

The Montana system includes two identical but separate analyzers referred as Analyzer "A" and "B". Each of the analyzers perform periodic zero calibration with ambient air in every 10 minutes. The mechanism of starting and ending periodic zeroing is potentially a source of error in measurement.

The Montana system takes an average of readings from both analyzers in order to estimate emissions and fuel use rates except when one of the analyzers is performing periodic zero calibration. In this case, the Montana system takes readings from the analyzer for which zeroing procedure is not in progress. When zeroing begins a solenoid valve switches from intake of exhaust gas to intake of ambient air. An example of such a valve is shown in Figure B.2. When the zeroing procedure ends, the solenoid valve switches again and the analyzer intakes emissions from the tailpipe. There is a period of transition while this switching occurs. The sensors of oxygen, NO, HC, CO, and CO_2 need several seconds to respond the switching of gases. To allow adequate time for a complete discharge of the previous gas from the analyzer, a time delay of 10 seconds is assumed. Thus, for 10 seconds before starting periodic zero calibration procedure and 10 seconds after ending the procedure, emissions rates are estimated using the data from the analyzer at which the zeroing procedure is not in progress.

B.3.1.1 Criteria of Detecting and Correcting Zeroing Effects

The criteria of detecting and correcting zeroing effects in a database are composed of two steps. In the first step, the periods in which zeroing may affect emissions data are indicated in a given database. A Visual Basic Program was written with this purpose by NCSU team. Computer of the Montana system separately records operating status of each of the analyzers in a second-by-second basis. In an output emission data file given by the Montana system, the code of "3,000,000" represents that an analyzer is properly measuring exhaust gases and the code of "19,000,000" shows periodic zero calibration. These codes are used to detect periods associated with zeroing effects. Both analyzers have been programmed to have no zero calibration at the same time. The Visual Basic Program screens a given database and indicates emissions records in 10 seconds before and after of each zeroing period. In the second step, mass emission and fuel consumption rates are recalculated using NO, HC, CO, CO_2, and O_2 concentrations from the analyzer that is not performing zero calibration. The analytical procedure of recalculating emission rates is given elsewhere.[4]

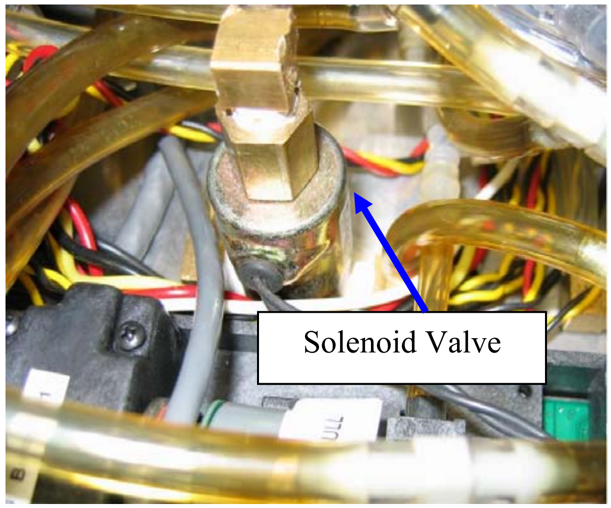


Figure B.2. The Solenoid Valve inside the Montana System

B.3.1.2 Examples of Dealing with Data Affected by Zeroing

Table B.2 shows an actual example indicating start and end point of zeroing procedure for Analyzer A. In Table B.2, zeroing in Analyzer A starts at time of 39,635 seconds and ends at 39,669. Codes of "3,000,000" or "19,000,000" indicate that analyzer is measuring emissions properly or zeroing, respectively.

B.3.2 Synchronization of Engine and Emissions Data

A possible concern with on-board emission measurements from construction vehicles is the synchronization of the data streams from the engine sensor array and the gas analyzers. The objective of this section is to develop a procedure for identifying and correcting synchronization problems.

Table B.2. Criteria of Indicating Start and End of Zeroing Procedure

Time (sec)	Analyzer Status Code		
	Analyzer A	Analyzer B	
39,623 39,624	3,000,000 3,000,000	3,000,000 3,000,000	Measuring Emissions from the exhaust
39,625 . . 39,633 39,634	3,000,000 . . 3,000,000 3,000,000	3,000,000 . . 3,000,000 3,000,000	*Assuming zeroing period in Analyzer A*
39,635* 39,636 . . 39,668 ***39,669****	***19,000,000*** 19,000,000 . . 19,000,000 ***19,000,000***	***3,000,000*** 3,000,000 . . 3,000,000 ***3,000,000***	*Actual Zeroing in Analyzer A*
39,670 39,671 . . 39,679	3,000,000 3,000,000 . . 3,000,000	3,000,000 3,000,000 . . 3,000,000	*Assuming zeroing period in Analyzer A*
39,680 39,681	3,000,000 3,000,000	3,000,000 3,000,000	Measuring Emissions from the exhaust

It takes time to sample and analyze exhaust gas concentrations. The typical time for exhaust gas samples to be drawn from the exhaust system and analyzed by the analyzers is estimated to be 12 seconds based on the default value assumed by Clean Air Technologies International, Inc. (CATI) for the Montana system. The delay time is the sum of three time periods.

The first applies to the exhaust gas travel time from the engine to the end of the tailpipe where samples are drawn from the exhaust system. The second applies to the travel time from the inlet of the sampling hose to the analyzers, inside the main unit of the Montana system. The third part of delay time applies to the time taken by the analyzers to analyze exhaust gas samples.

The total delay time is:

$$T_{DL} = T_{EX} + T_{SH} + T_{SR} \tag{4}$$

where,

T_{DL} = The Montana system's default total delay time value which is 12 seconds.

T_{EX} = Travel time in the exhaust system which is typically 1-2 seconds as estimated in Section B.3.2.2

T_{SH} = Travel time in the sampling hoses which is typically 2 seconds. The procedure of estimating T_{SH} is given below.

T_{SR} = Pollutants measurement time by the sensors which is typically 8 seconds and is estimated from subtraction of T_{SH} and T_{EX} from T_{DL}.

The T_{SH} is estimated 2 seconds based on the length, cross area, and volumetric flow rate of exhaust gas sample in the sampling hose as follows:

$$T_{SH} = \frac{L_{SH} \times A_{SH}}{Q_{SH}} \tag{5}$$

where,

L_{SH} = the length of sample hose, which is 6.1 m, as given in the Montana system's manual.

A_{SH} = the cross sectional area of the sample hoes, which is 4.6×10^{-5} m^2 measured by NCSU.

Q_{SH} = volumetric flow rate of the exhaust gas flow in the sampling hose which corresponds to the sampling flow of the pumps of 1.4×10^{-4} m^3/sec, given in the Montana system's manual.

For any emission test using the Montana system, T_{SH} and T_{SR} are constant because there is no change in sampling hose length and samples are drawn from the exhaust system at a constant rate and analyzed in the same amount of time. However, T_{EX} may vary depending on the exhaust flow rate and size of the tailpipe, including its length and diameter. Since onroad and nonroad construction vehicles have different exhaust flow and the tailpipe length and diameters, there is a possibility that T_{EX} and, therefore, synchronization of engine and concentration data, might be different for nonroad vehicles compared to onroad vehicles.

B.3.2.1 Variability of T_{EX} for Nonroad and Onroad Vehicles

The objective of this section is to estimate T_{EX} for onroad and nonroad vehicles to show whether modification of T_{DL}, shown in Equation (4), is necessary when testing nonroad vehicles. Using the ideal gas law, the relationship between the exhaust flow parameters is described as:

$$P_e V_e = n_e R T_e \tag{6}$$

where,

P_e = Pressure in exhaust flow (atm)

V_e = Volume of exhaust flow (m^3)

n_e = Number of moles of exhaust flow (mole)

R = Universal gas constant (0.082058×10^{-3} m^3-atm/mol-K)

T_e = Exhaust temperature (K)

To calculate the gas volume and the number of moles per unit time (i.e. volumetric and molar flow rate), both sides of Equation (6) are divided by $T_{EX:}$

$$P_e\left(\frac{V_e}{T_{EX}}\right)=\left(\frac{n_e}{T_{EX}}\right)RT_e \tag{7}$$

Assuming a cylindrical shape for the tailpipe of nonroad construction vehicles with a length of "L" and a diameter of "D," the volume of the tailpipe is calculated:

$$V_e=\frac{\pi D^2 L}{4} \tag{8}$$

The molar flow rate of exhaust gas is:

$$M_e=\frac{n_e}{T_{EX}} \tag{9}$$

The analytical procedure for calculating M_e is given elswhere.[4] From Equations (7), (8), and (9) we have:

$$T_{EX}=\frac{\pi D^2 LP_e}{4RT_e M_e} \tag{10}$$

P_e is assumed to be 1 atm. For the purpose of estimating variability of T_{EX} for nonroad vehicles, a Monte Carlo simulation approach was applied to Equation (10) assuming distributions for the equation inputs as shown in Table B.3. Monte Carlo simulation is a method of generating random values from a known distribution for the purposes of numerical experimentation. This is accomplished by generating pseudo random numbers for the input variables of Equation (10) and estimating possible outcomes of T_{EX}. A computer program written in MATLAB was used for this purpose.

Table B.3. Distribution of Variables in Equation (10) for Nonroad Vehicles

Variable	Mean	Standard Deviation	Assumed Distribution	Source of Data
D [m]	0.11	0.03	Normal	Analytical Engineering, Inc.
L [m]	0.90	0.45	Normal	Caterpillar Performance Handbook[1]
T_e [K]	520	68	Normal	Data supplied by EPA as "SPOT" data[2]
M_e [mol/s]	2.73	1.75	Normal	Emission tests done by NCSU[3]

1 : The length of tailpipe was obtained for backhoes, dozers, excavators, and front end loaders.
2 : The data is for five different dozers, two haulers, an excavator, a front end loader supplied by the EPA.
3 : The data is for a Caterpillar Excavator tested by NCSU on November 2, 2005.

The mean and standard deviation of D were estimated using the dimensions reported by Analytical Engineering, Inc. for different types of construction vehicles.[5] The mean and standard deviation of L were estimated using the dimensions given for different models of backhoes, dozers, excavators, and front end loaders in the Caterpillar Performance Handbook.[3] The mean and standard deviation of T_e was estimated using exhaust temperature data from five different types of dozers, two haulers, an excavator, a front end loader tested by the EPA.[5] The mean and standard deviation of M_e was estimated using data from three different sizes of excavators, a front end loader, a backhoe, and a dozer tested by NCSU. A summary information for the tested vehicles is shown in Table B.4.

Table B.4. Summary Information for Six Different Types of Nonroad Vehicles

Vehicle	**Make**	**Model**	**Model Year**	**Engine size (L)**	**Engine Horsepower (hp)**	**Date Tested**	**T_{synch} (sec)**	**T_{synch} (+,-)[1]**
Front-end Loader	CAT	930G	2004	6	149	1/27/2006	1	+
Backhoe	CAT	420D	2004	4	85	12/20/2005	2	+
Excavator	Komatsu	PC300	2001	8.27	245	8/24/2005	1-2	+
Dozer	CAT	D5G	2003	6	90	11/17/2005	1	+
Excavator	CAT	320C	2002	6.37	138	11/02/2005	1-2	+
Excavator	Kobelco	SK130	1998	3.9	93	1/16/2006	1	+

1 : Positive T_{synch} is positive when the emissions data respond before the engine data and is negative (-) otherwise

Results of the Monte Carlo simulation of T_{EX} for nonroad vehicles are shown in Figure B.3. The 2.5 percentile, average, and 97.5 percentile of T_{EX} are estimated to be 9, 25, and 456 milliseconds, respectively. The variation of T_{EX} estimated for nonroad vehicles is less than the temporal measurement resolution of the Montana system of one second. Thus, variation in all input variables of Equation (10) will not significantly affect T_{EX} and proportionally T_{DL} values for a given vehicle.

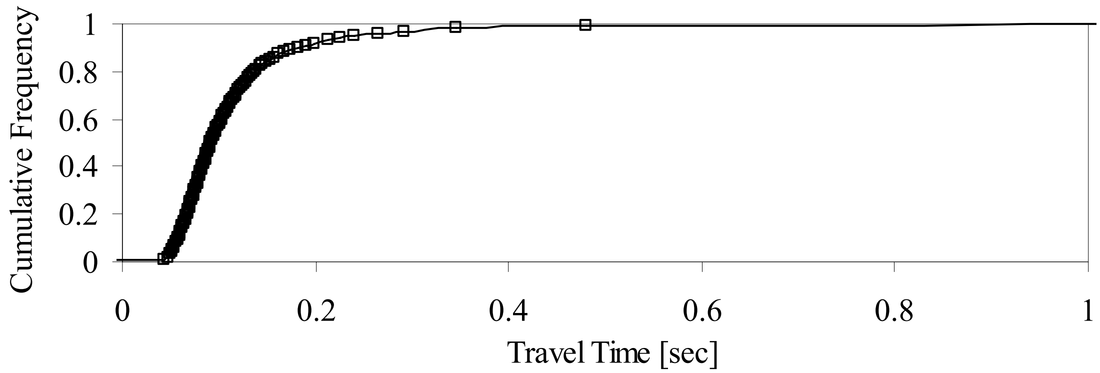


Figure B.3. Variation of T_{EX} Travel Time for Nonroad Vehicles

Table B.5. Distribution of Variables in Equation (10) for On-Road Vehicles

Variables	Mean	Standard Deviation	Assumed Distribution	Source of Data
D [m]	0.05	0.02	Normal	Websites of tailpipe suppliers[1]
L [m]	4.8	0.35	Normal	Given in Table B.6
T_e [K]	350	70.3	Normal	Data reported by Lee *et al.*[6]
Me [mol/s]	2.47	0.91	Normal	North Carolina State University[2]

1 : Data obtained from the websites of "Advanced Exhaust Tech I" and "Aliabad Exhaust."
2 : The emissions test performed by NCSU from a 2005 Chevrolet Cavalier with a 2.2 liter engine tested on October 4-22, 2004, and a 2005 Chevrolet Tahoe with a 5.3 liter engine tested on November 8-26, 2004.

To estimate variability of T_{EX} for onroad vehicles, distributions were assumed for the input variables of Equation (10) as shown in Table B.5. The mean and standard deviation of D were estimated using the product specifications given on the websites of different onroad vehicle tailpipe suppliers. The tailpipe diameter ranges between 4.4 cm and 7.6 cm depending on the size of the engine. To estimate the mean and standard deviation of L, it was assumed that the length of the exhaust system is equal to the length of the vehicle. Although the straight line distance between the engine and rear of the vehicle is shorter than the length of the vehicle, the tailpipe is not a straight line. Based on this assumption, the mean and standard deviation of L were estimated using lengths of different vehicles reported by the manufacturers in their websites as shown in Table B.6.

Table B.6. Length of Different Onroad Vehicles

Vehicle Type	Vehicle	Length (m)
Sedan Family	Buick Century	4.80
	Chevrolet Malibu	4.77
	Dodge Stratus	4.75
Sedan Large	Chrysler 300	4.80
	Ford Crown Victoria	4.99
	Toyota Avalon	5.00
Minivans	Dodge Caravan	5.10
	Honda Odyssey	5.11
	Toyota Sienna	5.08
Sport	Audi TT	4.04
	BMW M3	4.47
	Toyota Camry	4.80
SUV Small	Acura RDT	4.71
	Kia Sorento	4..67
	Toyota RAV4	4.60
SUV Midsized	Ford Edge	5.15
	GMC Envoy	4.87
	Lexus RX	4.73
SUV Large	Chevrolet Tahoe	5.13
	Nissan Armada	5.25
	Toyota Sequoia	5.18
Wagon	Wagon Station	4.24
	Volvo Station	4.71
	Dodge Caliber	4.42

Source: The over all length of the vehicles obtained from the website of Consumer Report

The mean and standard deviation of T_e was estimated from tailpipe temperature data measure by Lee *et al.* on a 1.8 liter spark ignition engine.[6] The mean and standard deviation of M_e was estimated from a combination of measurements performed by NCSU for a 2005 Chevrolet Cavalier with a 2.2 liter engine and a 2005 Chevrolet Tahoe with a 5.3 liter engine. The result of Monte Carlo simulation for onroad vehicles is compared to nonroad vehicles as shown in Figure B.4. The 2.5 percentile, average, and 97.5 percentile values of T_{EX} are estimated to be 0.13, 1.76, and 5.1 seconds, respectively. The difference between the average T_{EX} for onroad and nonroad vehicles, $T\Delta_{EX}$, is:

$$T\Delta_{EX} = T_{EX,\ onroad} - T_{EX,\ nonroad} = 1.76 \text{ sec} - 0.25 \text{ sec} = 1.51 \text{ sec} \tag{11}$$

where,

$T_{EX,\ onroad}$ = T_{EX} for onroad vehicles, 1.76 sec

$T_{EX,\ nonroad}$ = T_{EX} for nonroad vehicles, 0.25 sec

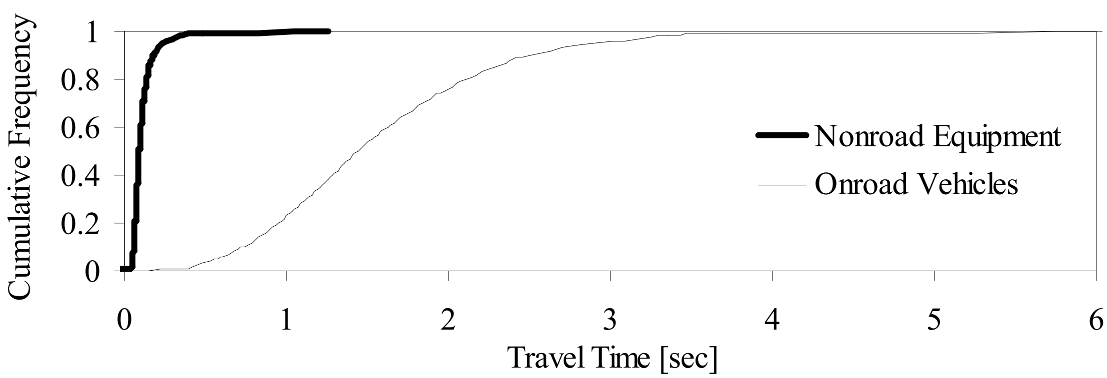


Figure B.4. Comparison of Variation T_{EX} Travel Time for Nonroad and Onroad Vehicles

The value of $T\Delta_{EX}$ is larger than to the temporal resolution of the Montana system. Thus, the hypothesis that there might be a significant difference between T_{EX} for onroad and nonroad vehicles is verified because the difference is higher than the temporal resolution of the system. Furthermore, the T_{DL} for nonroad and onroad vehicles will be significantly different compared to the temporal resolution of the Montana system.

B.3.2.2 Criteria for Detecting Synchronization Effects

The objective of this section is to verify synchronization problems in data measured by the Montana system from different types of construction vehicles and to develop a procedure for correcting these effects.

In order to identify the synchronization effects, a detailed review of engine and exhaust data was performed for six different types of construction vehicles, given the vehicles summary information in Table B.4. Examples of small time series of data were selected and analyzed in order to assure synchronization. These data were selected taking into account the following considerations:

- Need for short time series of consecutive seconds of data with no gaps.
- No errors such as freezing, discrepancy, or zeroing effects were observed in the data.
- Engine data had a substantial change such as a change in engine speed of greater than 200 RPM in one second and for a total of 500 RPM or more over one or more seconds.
- Emission concentrations including NO (ppm), HC (ppm), CO (vol%), CO_2 (vol%), were used for the synchronization analysis instead of mass emission rates because concentrations are directly measured at the tailpipe. Oxygen concentrations were not included in the analysis.

For the selected data, the following comparison and inference were made:

- Temporal trends of NO, HC, CO, and CO_2 concentrations were compared to the temporal trends of engine speed and MAP data, in order to identify which gas concentration is the best indicator of variation in engine data, for the selected seconds of the data.

- Two pollutants were selected as primary and secondary indicators of synchronization to engine data in order to confirm or better detect substantial changes in engine data.
- The time difference between the initial rise (or initial decrease) for a peak in engine versus exhaust data is referred to as "synchronization time," T_{synch}.
- Engine data are shifted in time to properly align with the emissions concentration data after estimating T_{synch}. Emission rates must be recalculated by applying the analytical recalculation procedure.[4]

For each reviewed data file, only two or three segments of data that met the requirements given above were found for the analysis. For example, among the data obtained from a dozer tested on December 22, 2005, only two segments of data were found to be useful for synchronization checks. For illustration purposes, the two data segments are shown in Figures B.5 and B.6, respectively.

In Figure B.5, engine speed increases by 784 RPM from elapsed seconds 3 to 5 and again by 376 RPM from elapsed seconds 13 to 14. Although MAP also increases at these times, the relative change in MAP is much smaller than the relative change in engine speed. However, the concentration data begin to rise approximately one second before the engine data. For example,

the concentrations of NO, CO, and CO_2 begin to rise between elapsed seconds 2 and 3, approximately one second before the corresponding increase in engine speed and MAP.

Similarly, the concentrations of CO and CO_2 begin to rise between elapsed seconds 12 and 13, approximately one second before the corresponding change in engine data. Figure B.6 illustrates a situation in which engine speed increases by 1331 RPM from elapsed seconds 4 to 8. The relative change in MAP is very similar to relative change in engine speed at these times. Similar to Figure B.5, the concentration data begin to rise approximately one second before the engine data. For example, the concentrations of NO, CO, and CO_2 begin to rise between elapsed seconds 3 and 4.

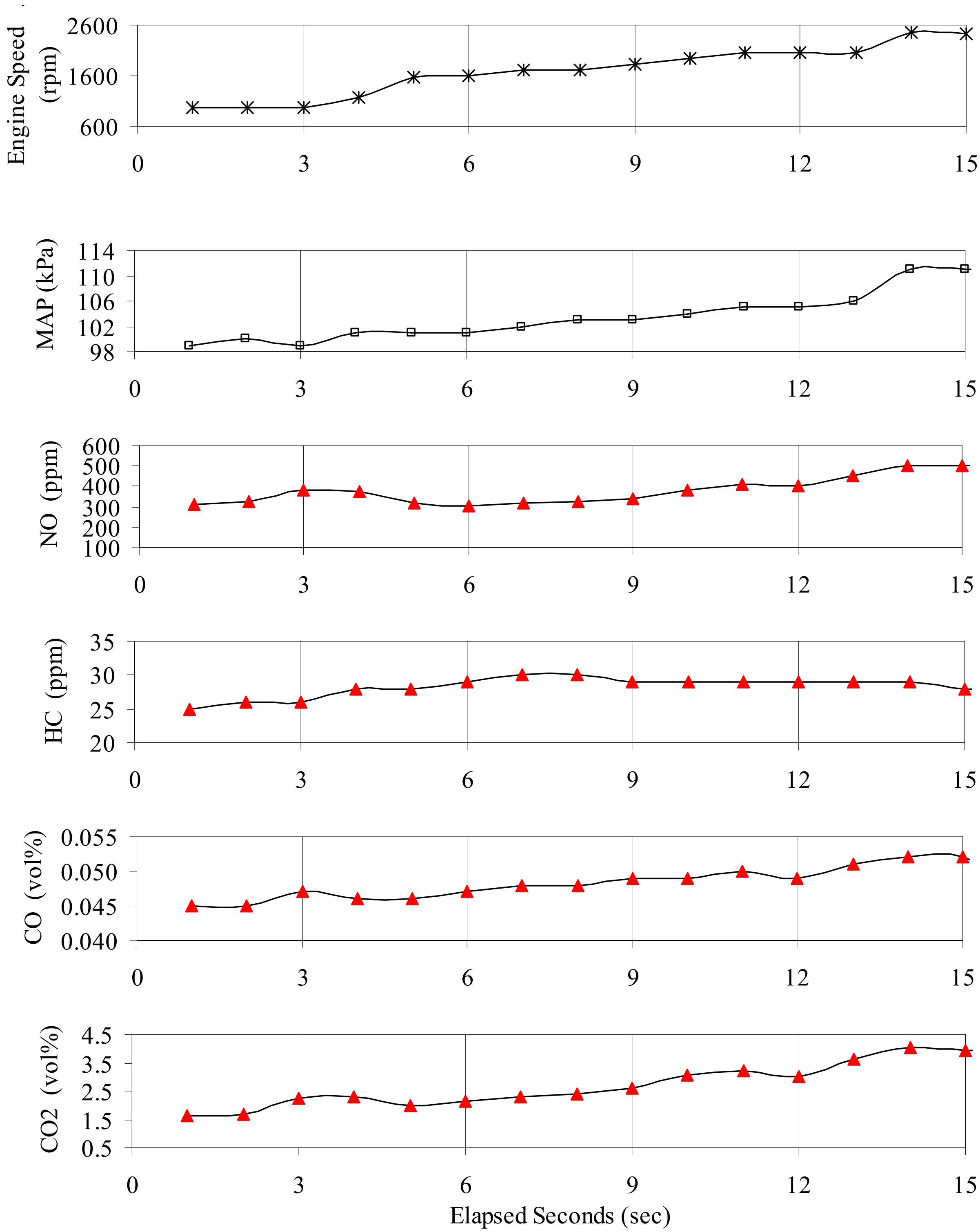


Figure B.5. Comparison of Engine Data and Exhaust Concentration for a Dozer tested on December 22, 2005: Data Segment (1)

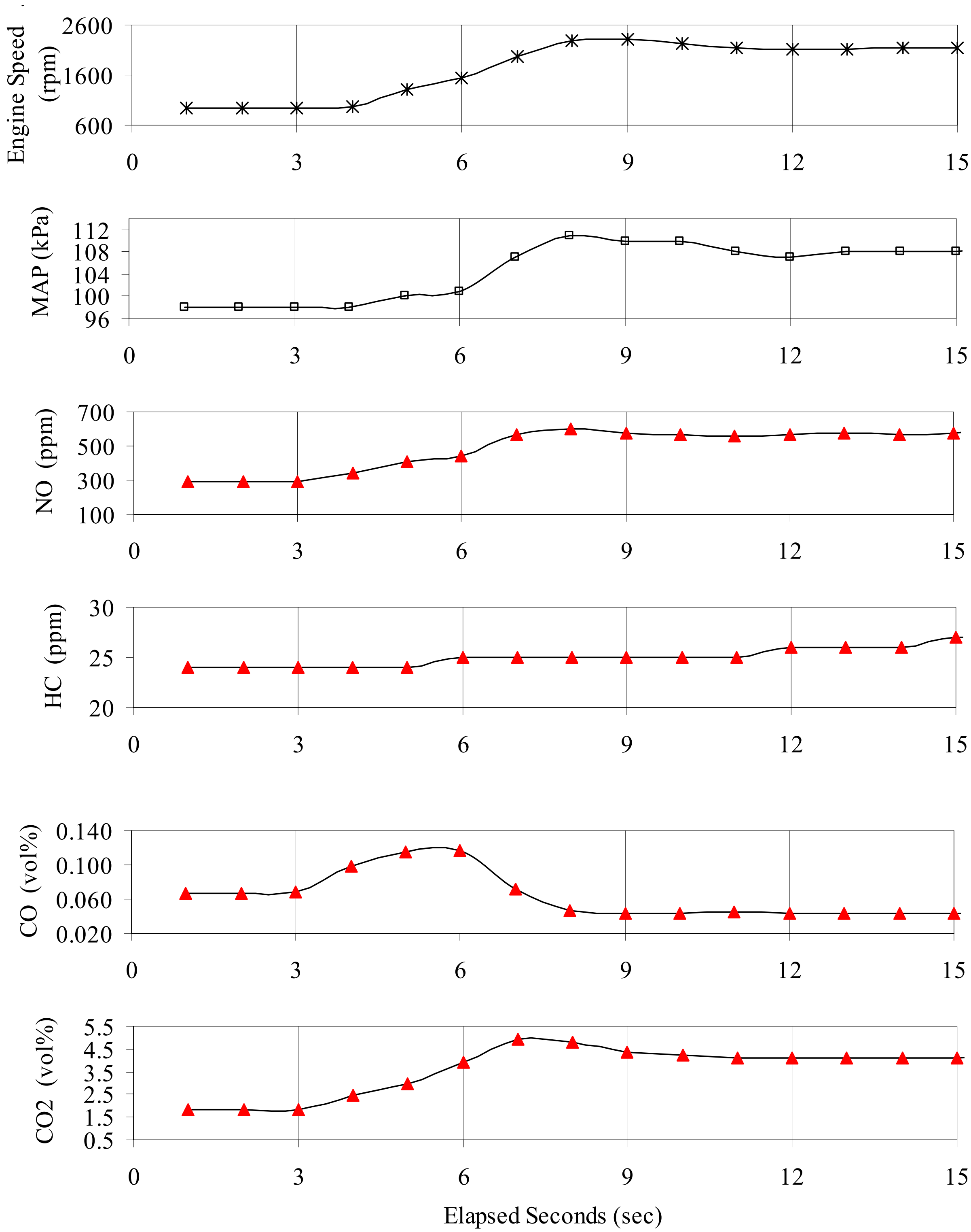


Figure B.6. Comparison of Engine Data and Exhaust Concentration for a Dozer tested on December 22, 2005: Data Segment (2)

Since the Montana system is comprised of two identical analyzers, another possible concern is synchronization of emissions concentrations from the two analyzers, which is referred to as inter-analyzer synchronization. The possibility of inter-analyzer differences in synchronization was investigated for all data files obtained from the vehicles shown in Table B.4. There was no inter-analyzer synchronization problem observed in any of the datasets. Figure B.7 illustrates inter-analyzer synchronization for the data shown in Figure B.6. The graphs for the pollutants of NO, HC, CO, and CO_2 include data obtained from Analyzers A and B of the Montana system. The concentrations of NO, CO, and CO_2 for both analyzers begin to rise in elapsed seconds 3 and 4.

Synchronization of pollutants measured by nondispersive infrared (NDIR) such as CO and CO_2, were checked in comparison to NO, which is measured by an electrochemical sensor. There was no synchronization problem observed between pollutants measured by the NDIR or electrochemical sensor in any of the datasets. As an example of this verification, Figure B.5 illustrate that in elapsed second 2 the concentrations of NO, CO, and CO_2 begin to rise at the same time. Similarly, the concentrations of NO, CO and CO_2 begin to rise in elapse time second 3 in Figures B.6 and B.7.

For illustrative purposes, Figure B.8 conceptually represents T_{synch} for the dozer tested on December 22, 2005. Figure B.8 is based on data given in Figure B.6. The concentration of CO_2 begins to rise one second before engine speed. The difference in time for these observations is a synchronization discrepancy and is referred to as T_{synch}. A similar discrepancy is seen in the difference in times of the peak values that occur in elapsed second 7 for CO_2 and elapsed second 8 for engine speed. A decision was made to consider T_{synch} positive when the emissions data respond before the engine data and negative otherwise.

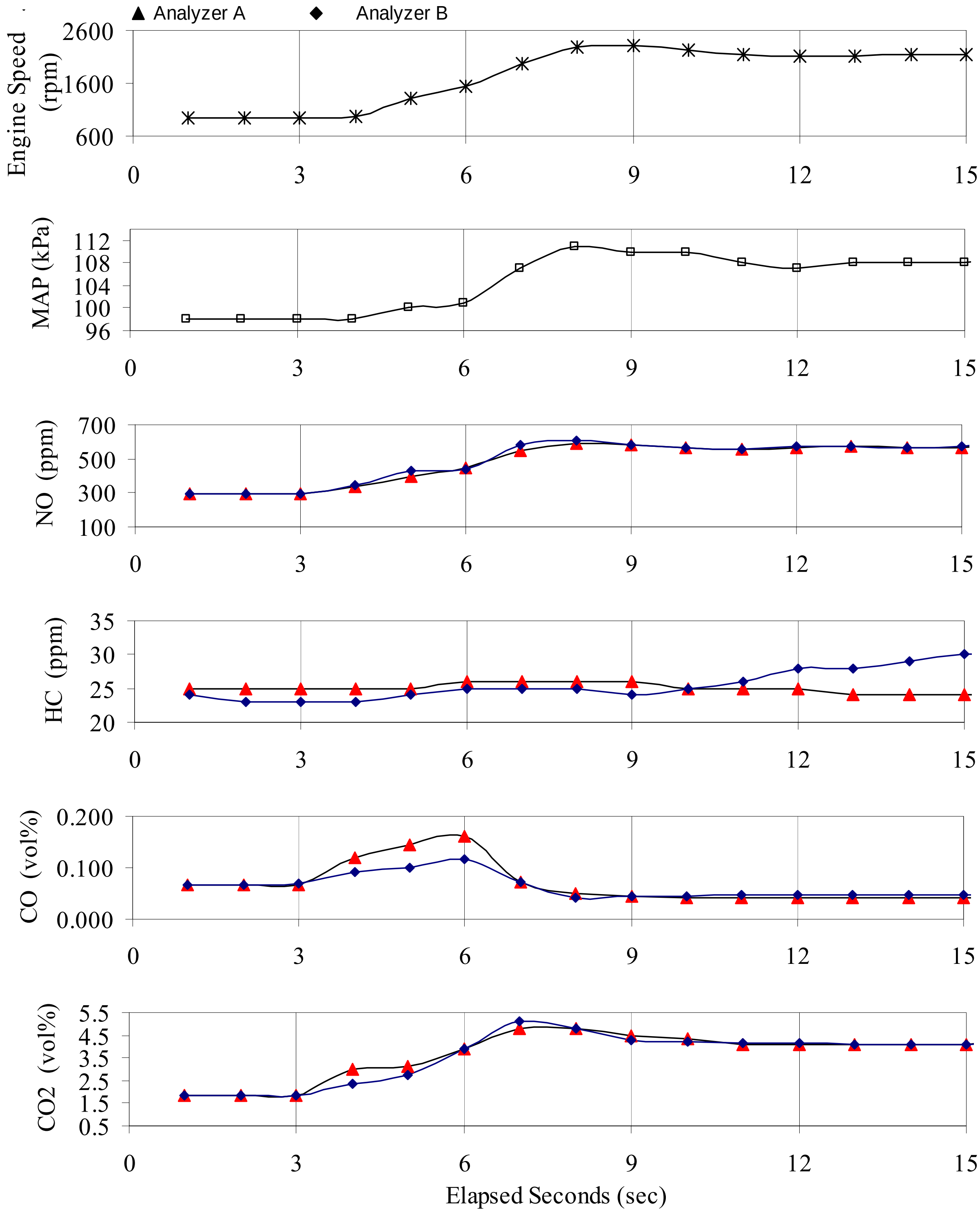


Figure B.7. Interanalyzer Synchronization Check Performed for a Dozer Tested on December 22, 2005

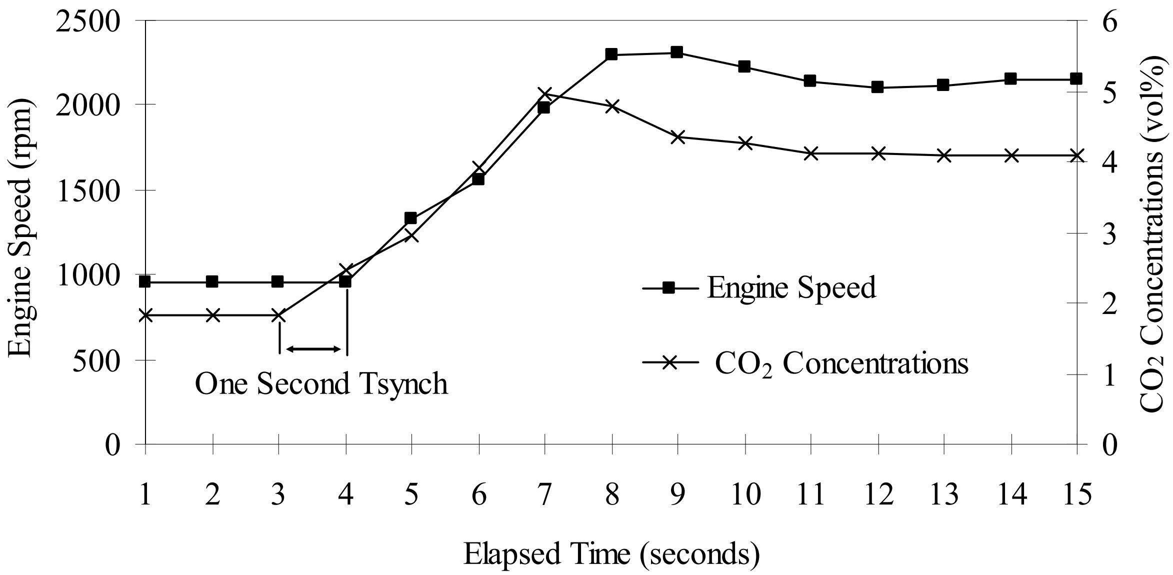


Figure B.8. Synchronization Time, T_{synch}, Estimated for a Dozer Tested on December 22, 2005

The results of synchronization analysis performed for an additional five construction vehicles tested by NCSU are represented in Table B.4. The synchronization time for all of the vehicles varies between 1 and 2 seconds. Therefore, all of the T_{synch} values are positive which means the emissions data respond before the engine data.

B.3.2.3 Criteria for Correcting Synchronization Effects

Based upon a detailed review of results for all six tested vehicles, a judgment was made to use the following procedure for synchronization check of engine and exhaust data:

- Engine speed is used as an indicator of synchronization among engine data because substantial absolute changes are observed in engine speed more so than for MAP and/or intake air temperature data.
- Among the gas concentration measurements, CO_2 concentrations offer the advantage of typically being the most responsive to variation of engine speed compared to the

other gas concentrations. The reason is because a change in engine speed is directly associated with a change in fuel consumption and CO_2.

- CO concentrations are selected as a secondary indicator because they are more responsive than NO and HC to variation in engine speed.

Table B.4 illustrates synchronization time observed for six pieces of tested vehicles. For all of these, a rise in CO_2 and/or CO concentrations was observed earlier than engine speed. As shown in Table B.4, the T_{synch} time for these vehicles varies from one to two seconds. In order to properly synchronize the engine and exhaust data, the engine data should be paired with exhaust data that are reported in the previous one or two seconds, and the emission rates must be recalculated. It is assumed that "synchronization time" observed in real data is related to the difference between T_{EX} for onroad and nonroad vehicles. The Montana system has a default value for T_{DL} of 12 seconds which may be appropriate for onroad vehicles. For nonroad vehicles, a more appropriate typical value of T_{DL} is expected to be 10 or 11 seconds. In order to minimize or eliminate synchronization effects in real world data from nonroad vehicles, two actions need to be taken before and after data collection. These are estimating a new delay time, $T_{DL,\ new}$, before data collection and verifying and if necessary correcting synchronization effects after data collection. They are explained in the flowing sections.

<u>B.3.2.3.1 Minimizing Synchronization Effects before Data Collection</u>

Before doing data collection, it is necessary to estimate the new delay time, $T_{DL,\ new}$, for a vehicle test using the Montana system's default delay time, the estimated $T\Delta_{EX}$ given in Equation (11), and an estimate of T_{EX} with the diameter and length of tailpipe for the test vehicle. The new delay time is estimated as:

$$T_{DL,\,new} = T_{DL,\,default} - T_{\Delta EX} + T_{EX,\,new}$$

(12)

where,

$T_{DL,\,new}$ = New delay time (sec)

$T_{DL,\,default}$ = Default delay time (sec); the Montana system's default value - 12 sec

$T_{EX,\,new}$ = New estimated exhaust gas travel time for the test vehicle (sec)

As noted early, $T_{DL,\,default}$ is 12 seconds and $T_{\Delta EX}$ is estimated 1.51 seconds. The new exhaust gas travel time, $T_{EX,\,new}$, is estimated from Equation (10) applying the new exhaust diameter (D) and length (L) values measured from test vehicle. Exhaust pressure is assumed to be 1 atm. The average exhaust temperature of 520 K from Table B.3 is used as a default value. The M_e is estimated based on engine displacement.[4] Thus, M_e is expected to be highly correlated with engine displacement. This correlation is reflected in a coefficient of determination (R^2) of 0.84 as shown in Figure B.9. The average molar flow rates were estimated from the second-by-second engine and emissions data obtained from the vehicles given in Table B.4. Thus, M_e is estimated as:

$$M_e = 0.4757 \times ED \qquad (13)$$

where,

ED = Engine displacement (L)

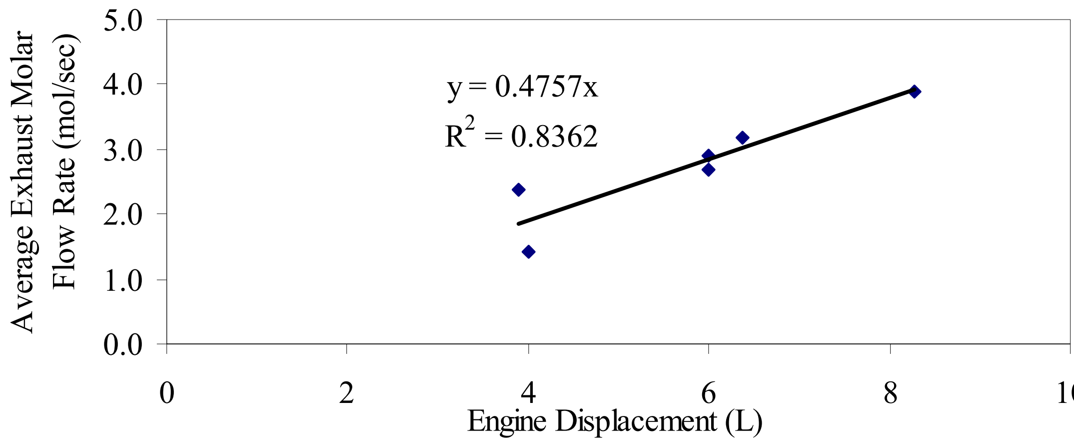


Figure B.9. Ordinary Least Square Regression of Exhaust Molar Flow Rate versus Engine Displacement.

Thus, the average $T_{EX, new}$ is estimated applying estimated values for D, L, T_e, and M_e to Equation (10). The $T_{DL, new}$ must be round to the nearest integer. After defining $T_{DL, new}$, it needs to be entered to the Montana system as a new delay value. Changing the delay default value must be done during the procedure of entering vehicle/engine information to the Montana system. As a part of this procedure, the Montana system asks the operator of the system to enter new delay time or accept the default value. The procedure of correcting delay time before data collection is shown in Figure B.10 as a flow diagram.

B.3.2.3.2 Minimizing Synchronization Effects after Data Collection

After data collection, it is necessary to verify, and if necessary correct, the synchronization of engine and exhaust data. The procedure explained in Section B.3.2.3 to identify segments of consecutive data for synchronization check is applied to check data after data collection. If there is a synchronization problem involved with the data, then T_{synch} must be estimated and the exhaust gas data must be shifted to properly synchronize with the engine data, as previously explained. Furthermore, if a correction is needed then the emission rates must be recalculated. The analytical procedure of recalculation is presented elsewhere.[4] The procedure for checking and correcting synchronization check is shown Figure B.11 as a flow diagram.

Measure diameter (D) and length (L) of the tailpipe for the test vehicle

↓

Estimate the average new exhaust gas travel time, $T_{EX,\,new}$ from:

$$M_e = 0.4757 \times ED$$

$$T_{EX,new} = \frac{\pi D^2 L P_e}{4 R T_e M_e}$$

Assuming exhaust parameters values of:

P_e = 1 atm
T_e = 520 K
M_e = Exhaust molar flow rate mol/s (calculated above)
ED = Engine Displacement (L) for the specific vehicle
R = 0.082058×10^{-3} m^3-atm/mol-K

↓

Estimate new delay time, $T_{DL,\,new}$, from:

$$T_{\Delta EX} = 1.41 \text{ sec}$$

$$T_{DL,\,new} = T_{DL,\,default} - T_{\Delta EX} + T_{EX,\,new}$$

$T_{DL,\,new}$ = New delay time (sec)
$T_{DL,\,default}$ = Default delay time 12 sec

↓

Round $T_{DL,\,new}$ to the nearest integer

↓

Enter $T_{DL,new}$ to the Montana system as a new default value while entering the test equipment information

FigureB.10. The Procedure for Estimating Delay Time for Entry into the Montana System before Testing Nonroad Vehicles.

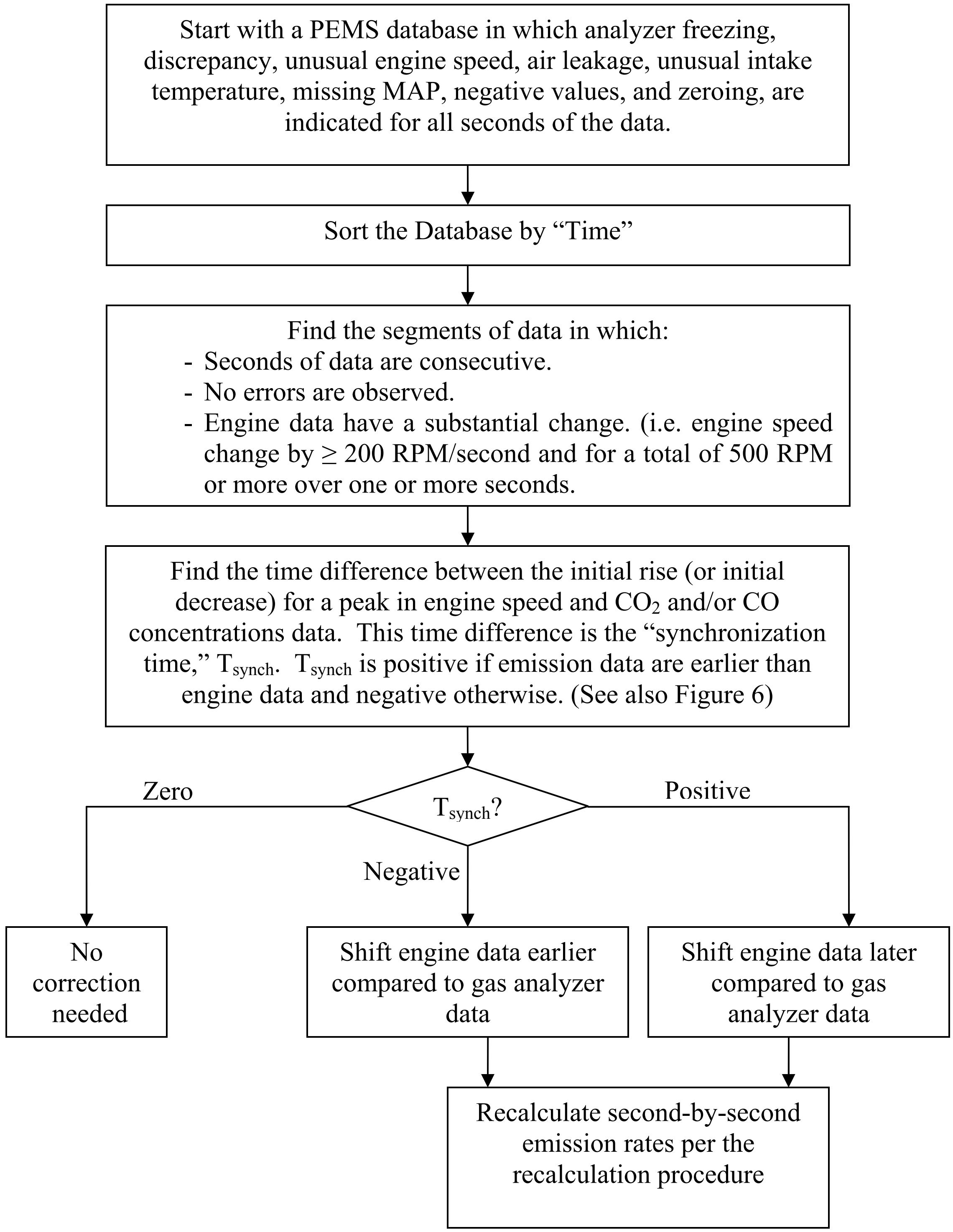


Figure B.11. The Procedure for Checking and Correcting Synchronization between Engine and Exhaust Data after Data Collection.

B.4 References

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6. Lee S., C. Bae, Y. Lee, T. Han, *Effects of Engine Operating Conditions on Catalytic Converter Temperature in an SI engine.* 2002, Korea Advanced Institute of Science and Technology, Hyundai-Motor Company.

APPENDIX C

DESCRIPTION OF THE COMPUTER PROGRAMS DEVELOPED FOR DATA SCREENING AND QUALITY ASSURANCE OF ON-BOARD EMISSIONS DATA

C.1 Introduction

The data screening and quality assurance procedure was conceptually explained in previous Appendix B. The objective of this section is to explain the algorithms of computer programs developed for quality checks and preliminary analyses of data. This document provides the user with an interface to communicate with inputs and outputs of the programs. All programs were written in Visual Basic which can be used as the macros incorporated with Microsoft Excel. As shown in Figure C.1, for a given raw data collected from nonroad construction vehicles, a quality assured database is developed in 19 steps in which 16 steps are performed running macros and 3 steps are performed manually. Therefore, the quality assured database is preliminarily analyzed in two steps consist of 6 macros. The steps developed in this study will be explained in the following sections. The steps that will not be explained include: (1) remove/correct negative emissions; (2) remove/correct gas analyzer freezing errors; (3) remove/correct inter-analyzer discrepancy errors; (4) remove unusual intake temperature; (5) remove data with invalid air fuel ratio.

C.2 Description of Raw Databases

A raw database downloaded from the Montana system is used as an input for developing a quality assured database. Table C.1 provides descriptions for the variable available in a raw database for data screening and quality assurance purposes. Since the Montana system is used for collecting data from onroad and nonroad vehicles, there are several fields of data for which no data is collected when measuring emissions from nonroad construction vehicles. These variables are shown in Table C.1. For example, there are no data collected for vehicles speed or acceleration thus in the database zero values are observed.

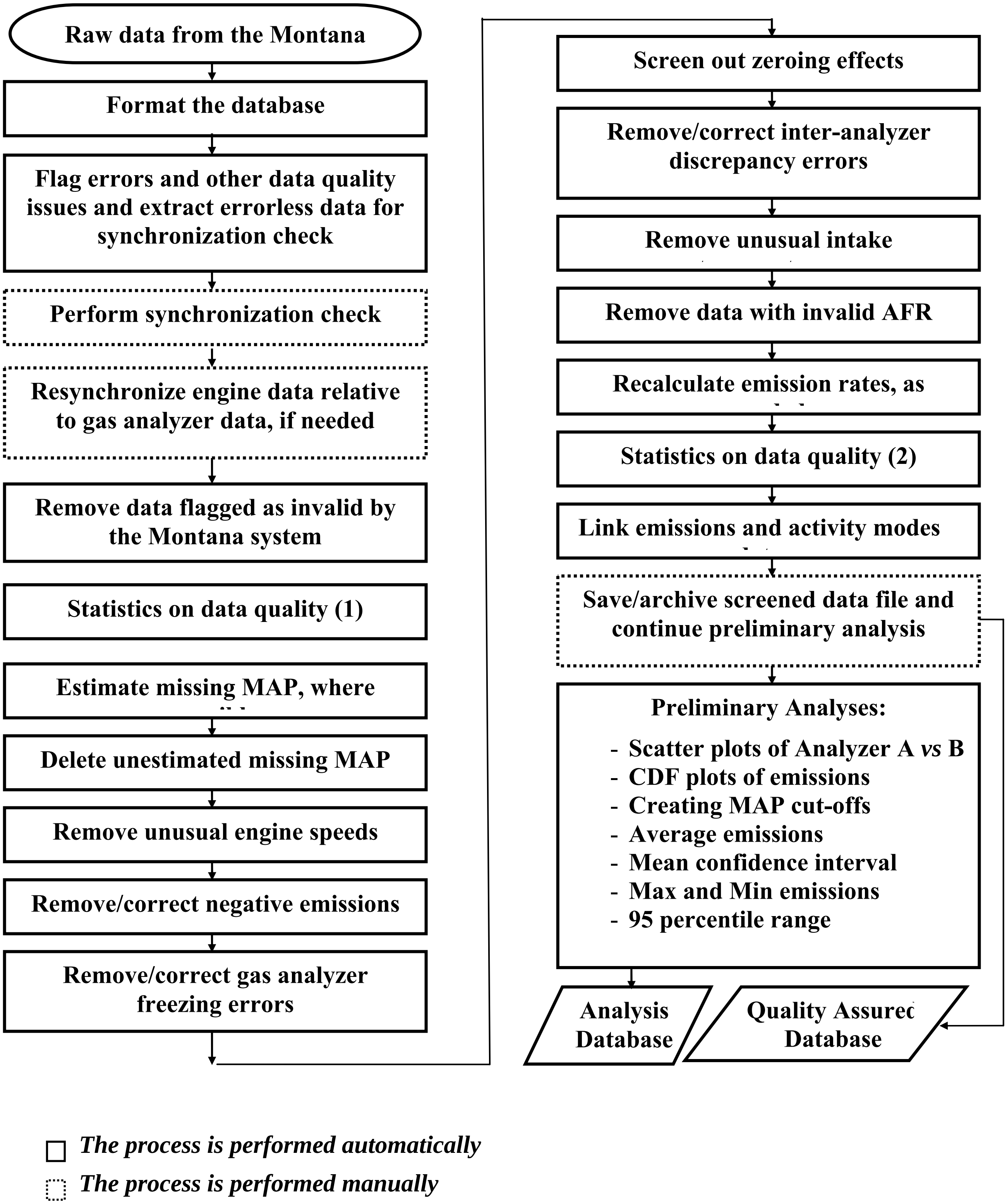


Figure C.1. Flow Diagram of Data Quality Assurance and Preliminary Analysis Macros

Table C.1. Description of Variables Available for Data Screening and Quality Assurance Checks in a Raw Database

No.	Variable	Variables Available for Screening	No.	Variable	Variables Available for Screening
1	time [s]	Recording time in second	30	HC[g/gal]	Estimated average HC rate
2	valid_g/gal	Validity of data	31	CO[g/gal]	Estimated average CO rate
3	Bag_No	Separating data into bags	32	CO_2[g/gal]	Estimated average CO_2 rate
4	Bag_distance[mi]	Not Available (NA)	33	PM[mg/gal]	Estimated average PM rate
5	Bag_time[s]	Duration of each bag	34	A_Valid	Validity of data of analyzer A
6	mph	NA	35	A_Stats	Operation status of analyzer A
7	accel[mph/gal]	NA	36	A_NO_x[ppm]	NO from analyzer A
8	SENSED_RPM	Engine speed	37	A_HC[ppm]	HC from analyzer A
9	SENSED_TEMP[C]	Intake air temperature	38	A_CO[%]	CO from analyzer A
10	SENSED_MAP[kPa]	Manifold absolute pressure	39	A_CO_2[%]	CO_2 from analyzer A
11	eng_rpm	The same as item 8	40	A_O_2[%]	O_2 from analyzer A
12	coolant[C]	NA	41	B_Valid	Validity of data of analyzer B
13	throttle[%]	NA	42	B_Stats	Operation status of analyzer B
14	MAP[kPa]	The same as item 10	43	B_NO_x[ppm]	NO from analyzer B
15	IAT[C]	The same as item 9	44	B_HC[ppm]	HC from analyzer B
16	torque[lbf]	NA	45	B_CO[%]	CO from analyzer B
17	intake_air[g/gal]	Mass flow of intake air	46	B_CO_2[%]	CO_2 from analyzer B
18	dry_exh[g/gal]	Mass flow of dry exhaust gas	47	B_O_2[%]	O_2 from analyzer B
19	total_exh_flow[scf]	Total mass flow of exhaust	49		NA – blank column
20	fuel[g/gal]	Estimated fuel flow rate	50	GPS_Fix	GPS Status
21	fuel[mpg]	NA	51	GPS_Satellites	Number of satellites
22	NO_x[ppm]	Average NO	52	GPS_time[seconds]	Recording time for GPS
23	HC[ppm]	Average HC	53	GPS_time[hh:mm:ss]	Recording time for GPS
24	CO[%]	Average CO	54	GPS_speed[mph]	NA
25	CO_2[%]	Average CO_2	55	grade[%]	Road grade
26	O2[%]	Average O_2	56	lon	Longitude
27	PM[%FS]	Particulate Matters in %FS	57	lat	Latitude
28	PM[mg/m^3]	Particulate Matters in mg/m^3	58	alt[ft]	Altitude
29	NO_x[g/gal]	Estimated average NO rate	59	bearing	NA

C.3 Getting Started

A Microsoft Excel file called "Data Quality Check and Analysis File (DQCAF)" is used for data quality assurance purposes. All macros have been incorporated in this file as 22 Visual Basic programs. From a raw database, all data needs to be copied and pasted in DQCAF. The list of the macros can be accessed clicking on "Tools" and then "Macros". Figure C.2 presents what is seen on the screen before running each of the macros.

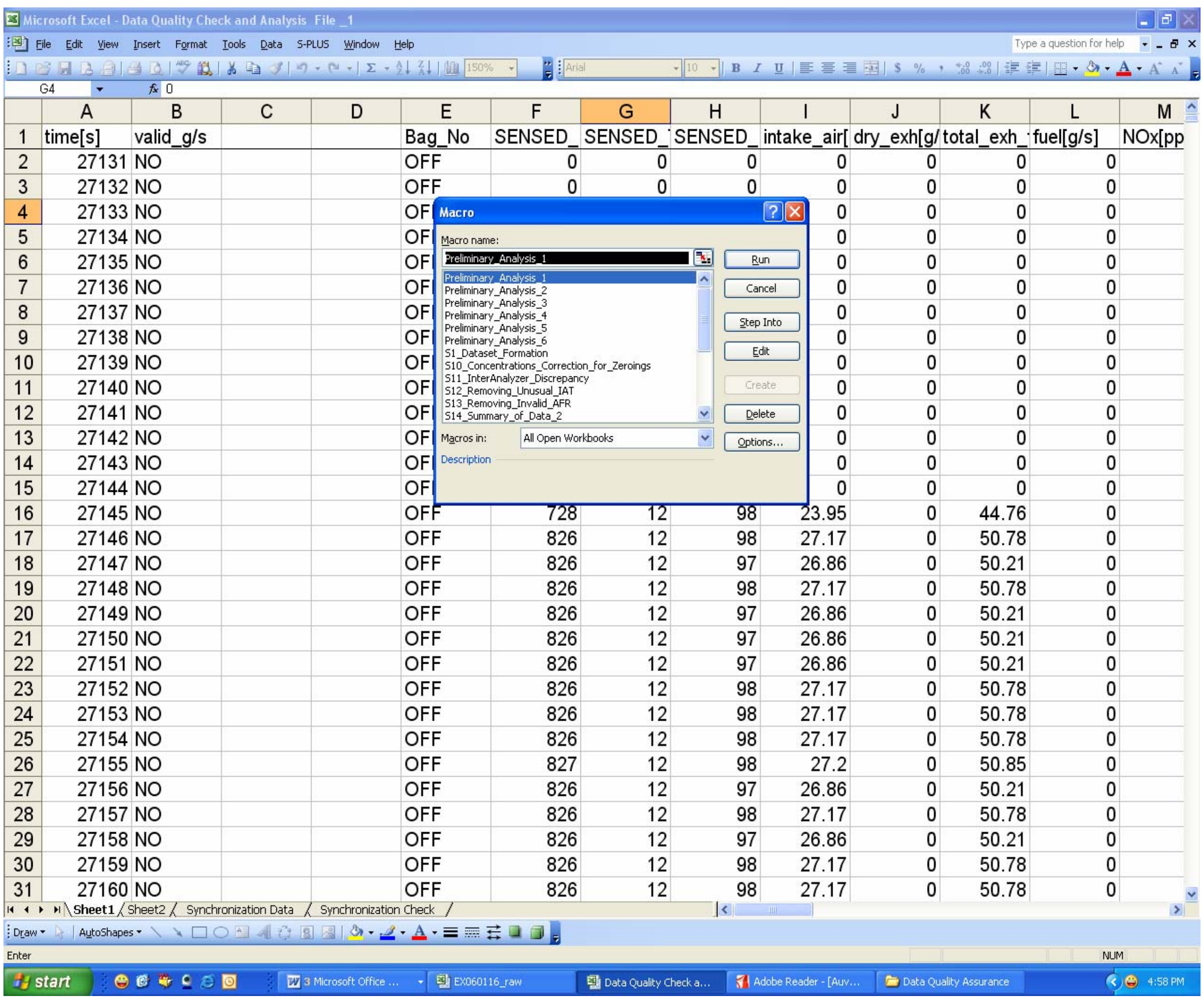


Figure C.2. List of the Macros on the Screen before each Run

C.4 Formatting the Database

Formatting a raw database is performed by the first macro referred to as "S1_Database_Formation." This program creates two columns after the column of "Bag_No." The new columns will be used for modes of activity and time in "hh:mm:ss" format. Furthermore, the program deletes columns of data for which there was no data collected or estimated by the Montana system. These columns are shown as item numbers of 4, 6, 7, 12, 13, 16, 21, 49, 54, 55, and 59 in Table C.1. The variables in the formatted database are shown in Table C.2. In addition, the macro excludes the Montana system's warm up time from the database. In order to perform this, the program will ask the user to enter the time in which recording modes of activity has been started. The user should have this time from another Excel file that contains recorded modes of activity data. Detailed information about this file is provided in Section 16. The user will be asked about entering the start time through a popped window on the screen. Figure C.3 presents what the user will see on the screen.

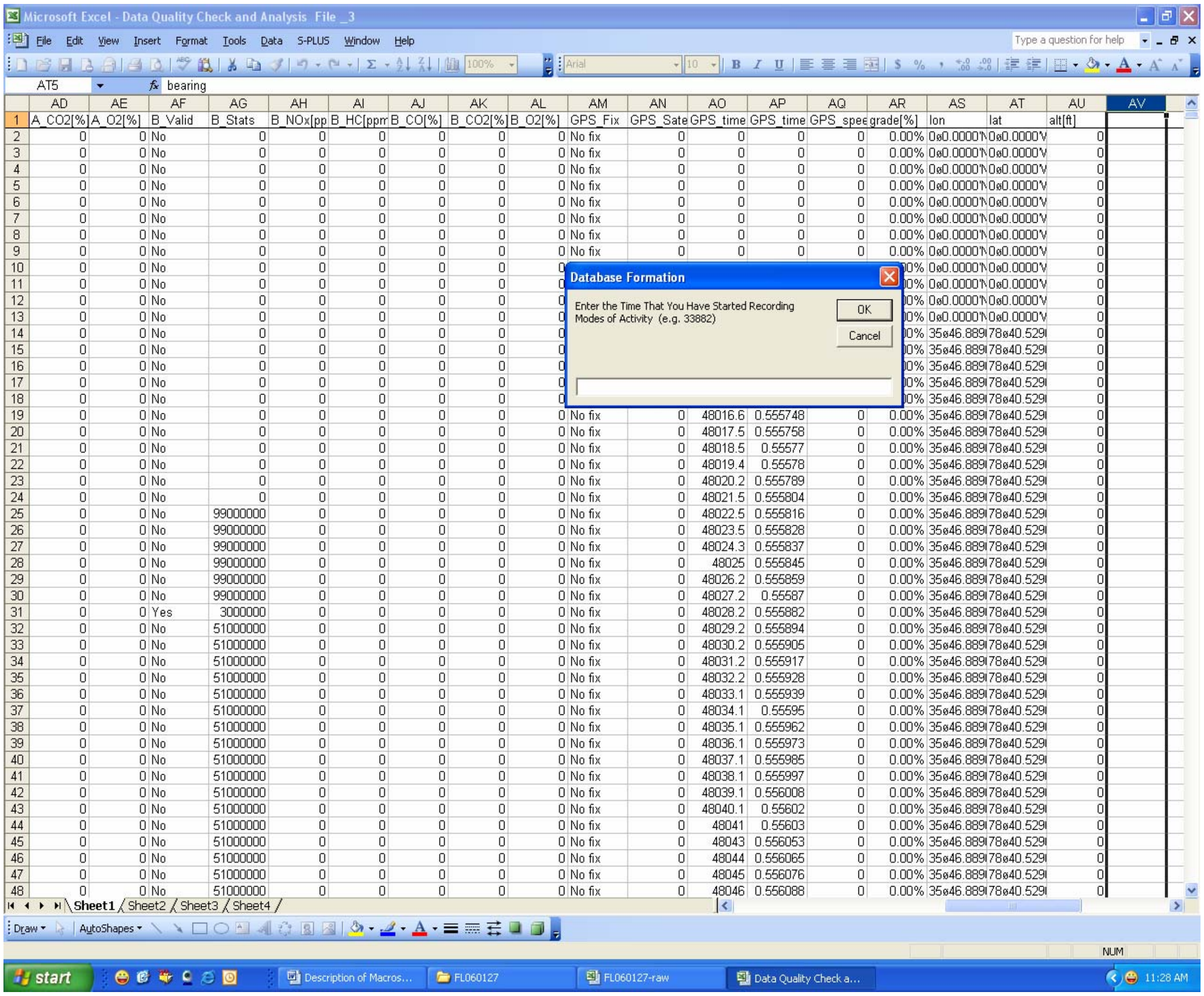


Figure C.3. The User Is Asked to Enter Starting Time of Modes of Activity Recording

C.5 Flagging Errors and Other Data Quality Issues

The objective of applying the second macro to the database is to flag errors and other data quality issues and extract errorless data for synchronization check. This macro is called "S2_Errors_Indication." Each second of data is screened and flagged if needed for the following errors:

- Missing manifold absolute pressure
- Unusual engine Speed
- Unusual intake air temperature

- Negative emissions values
- Gas analyzer freezing
- Zeroing effects
- Inter-analyzer discrepancy
- Effects of air leakage

Table C.2. Description of Variables Available for Data Screening after Formatting the Database

No.	Variable	Variables Available for Screening	No.	Variable	Variables Available for Screening
1	time[s]	Recording time in second	30	A_CO_2[%]	CO_2 from analyzer A
2	valid_g/gal	Validity of data	31	A_O_2[%]	O_2 from analyzer A
3		Blank for time (hh:mm:ss)	32	B_Valid	Validity of data of analyzer B
4		Blank for modes of activity	33	B_Stats	Operation status of analyzer B
5	Bag_No	Separating data into bags	34	B_NO_x[ppm]	NO from analyzer B
6	SENSED_RPM	Engine speed	35	B_HC[ppm]	HC from analyzer B
7	SENSED_TEMP[C]	Intake air temperature	36	B_CO[%]	CO from analyzer B
8	SENSED_MAP[kPa]	Manifold absolute pressure	37	B_CO_2[%]	CO_2 from analyzer B
9	intake_air[g/gal]	Mass flow of intake air	38	B_O_2[%]	O_2 from analyzer B
10	dry_exh[g/gal]	Mass flow of dry exhaust gas	39	GPS_Fix	NA – blank column
11	total_exh_flow[scf]	Total mass flow of exhaust	40	GPS_Satellites	GPS Status
12	fuel[g/gal]	Estimated fuel flow rate	41	GPS_time[seconds]	Number of satellites
13	NO_x[ppm]	Average NO	42	GPS_time[hh:mm:ss]	Recording time for GPS
14	HC[ppm]	Average HC	43	GPS_speed[mph]	Recording time for GPS
15	CO[%]	Average CO	44	grade[%]	Road grade
16	CO_2[%]	Average CO_2	45	lon	Longitude
17	O_2[%]	Average O_2	46	lat	Latitude
18	PM[%FS]	Particulate Matters in %FS	47	alt[ft]	Altitude
19	PM[mg/m^3]	Particulate Matters in mg/m^3			
20	NO_x[g/gal]	Estimated average NO rate			
21	HC[g/gal]	Estimated average HC rate			
22	CO[g/gal]	Estimated average CO rate			
23	CO_2[g/gal]	Estimated average CO_2 rate			
24	PM[mg/gal]	Estimated average PM rate			
25	A_Valid	Validity of data of analyzer A			
26	A_Stats	Operation status of analyzer A			
27	A_NO_x[ppm]	NO from analyzer A			
28	A_HC[ppm]	HC from analyzer A			
29	A_CO[%]	CO from analyzer A			

Definitions and criteria of detection of each of the errors have been explained in Appendix B. The following columns are created for flagging the errors in a database:

- Column 48 labeled as “Invalid” for flagging invalid data
- Column 49 labeled as “Missing MAP” for flagging missing MAP
- Column 50 labeled as “Un_RPM” for unusual engine speed
- Column 51 labeled as “Un_IAT” for unusual intake air temperature
- Column 52 labeled as “NVI” for negative emission values
- Column 53 labeled as “GAF_B” for gas analyzer freezing of Analyzer B
- Column 54 labeled as “GAF_A” for gas analyzer freezing of Analyzer A
- Column 55 labeled as “GAF_AB” for gas analyzer freezing of both analyzers
- Column 56 labeled as “ZE_A_be ” for zeroing effects of Analyzer A (before zeroing)
- Column 57 labeled as “ZE_A_af ” for zeroing effects of Analyzer A (after zeroing)
- Column 58 labeled as “ZE_B_be ” for zeroing effects of Analyzer B (before zeroing)
- Column 59 labeled as “ZE_B_be ” for zeroing effects of Analyzer B (after zeroing)
- Column 60 labeled as “Discpy” for inter-analyzer discrepancy
- Column 61 labeled as “AFR” for air leakage effects

The above errors are flagged by assigning a value of "1" to each column in corresponding row of data when an error is detected. After flagging the errors, the program will copy and paste the errorless seconds of data to "Sheet3." This data is used for synchronization check which will be explained in the following sections. Sheet 3 is renamed as "Synchronization Data" by this macro.

C.6 Performing Synchronization Check

As shown in Figure C.1, synchronization check is preformed manually. The instruction of performing this check is given in "Synchronization Check" sheet in DQCAF. According to this instruction, the user should screen the data in "Synchronization Data" sheet and copy and paste 15 consecutive seconds of data in which engine speed has a substantial change such as a change in engine speed of greater than 200 RPM in one second and for a total of 500 RPM or more over one or more seconds. Then, the user should check synchronization according to criteria given in Appendix B and define synchronization time of T_{synch}.

C.7 Resynchronizing Engine Data Relative to Gas Analyzer Data

After defining T_{synch}, synchronization of engine and emission data need to be corrected, if needed. The engine data need to be shifted earlier or later compared to emissions data as explained in Appendix B. The synchronization correction applies to data in Sheet 1 which contains all collected data. No emission rate recalculation applies to data in this section.

C.8 Removing Data Flagged as Invalid by the Montana System

A macro named "S3_Removing_Invalid_Data" is used to remove rows of data in which Column 48 (i.e. labeled as "Invalid") includes the value of 1. This column has been created by the macro of "S2_Errors_Indication" when indicating errors in the raw database. The data excluded in this section referred to as situations in which either the sensor array or sampling hoses have not been connected to the Montana system. Thus, engine data and/or pollutant concentrations are not detected in this situation.

C.9 Statistics on Data Quality (1)

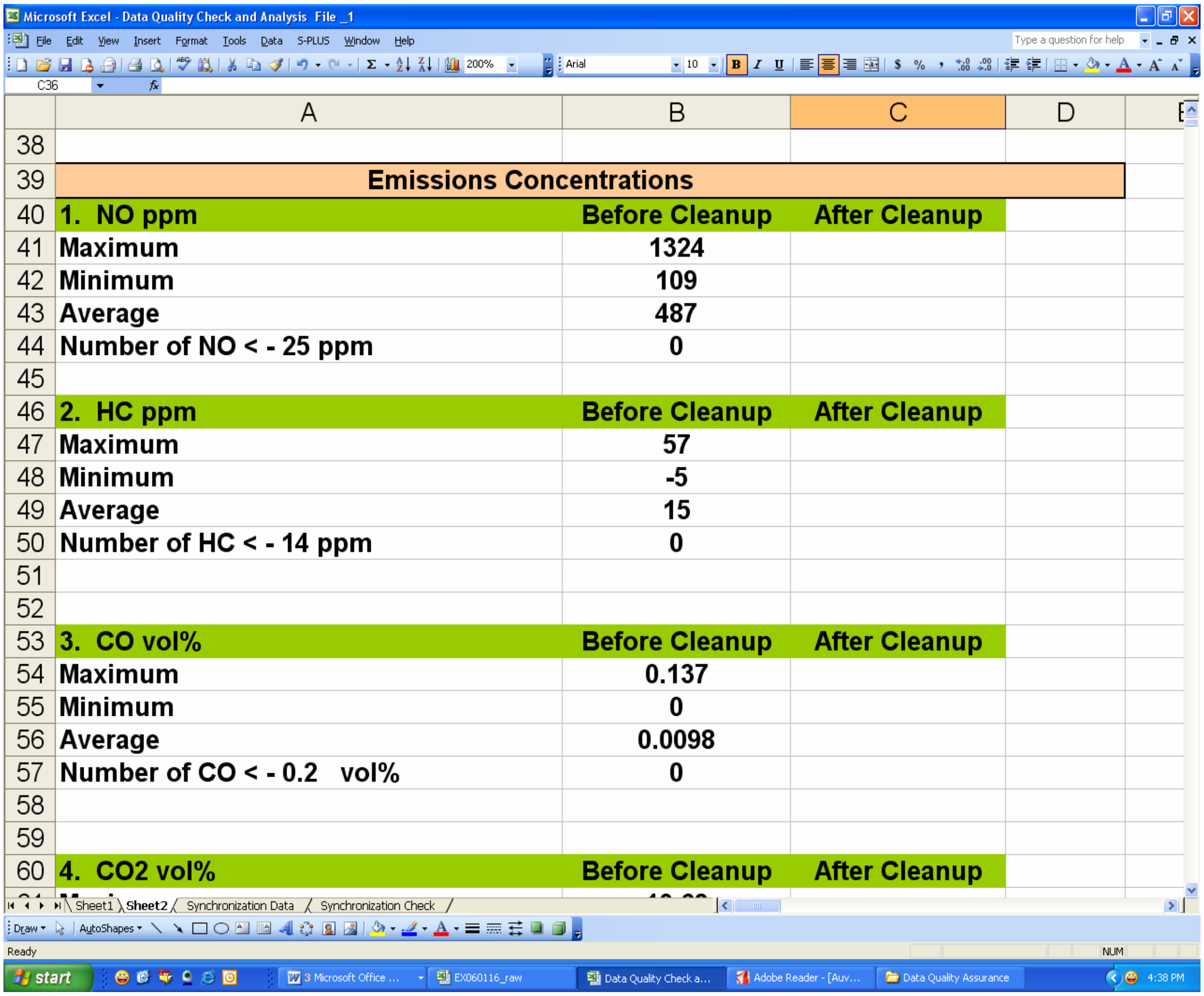
In this step, a macro called "S4_Summary_of_Data_1" provides a summary statistics of data for the user in Sheet 2 before excluding any data from the database. Figure C.4 illustrates what the user observes on the screen regarding to the summary statistics of data after running the macro. The summary statistics are given on the following criteria:

- o Time
- o Engine data
- o Emissions concentrations
- o Mass emissions rates
- o Operation of Analyzer A
- o Operation of Analyzer B

Time: the following items are reported regarding to time:

- Data collection start time (hh:mm:ss)

- Data collection end time (hh:mm:ss)
- Total data before screening (seconds)
- Data deleted because of invalid data (seconds)
- Data deleted because of missing MAP (seconds)
- Data deleted because of unusual engine speed (seconds)
- Data deleted because of unusual intake air temperature (seconds)
- Data deleted because of analyzer freezing (seconds)
- Data deleted because of inter-analyzer discrepancy freezing (seconds)
- Data deleted because of air leakage (seconds)
- Data deleted because of negative emission concentrations (seconds)
- Total data collection after screening (seconds)



	A	B	C
39	**Emissions Concentrations**		
40	**1. NO ppm**	**Before Cleanup**	**After Cleanup**
41	**Maximum**	**1324**	
42	**Minimum**	**109**	
43	**Average**	**487**	
44	**Number of NO < - 25 ppm**	**0**	
46	**2. HC ppm**	**Before Cleanup**	**After Cleanup**
47	**Maximum**	**57**	
48	**Minimum**	**-5**	
49	**Average**	**15**	
50	**Number of HC < - 14 ppm**	**0**	
53	**3. CO vol%**	**Before Cleanup**	**After Cleanup**
54	**Maximum**	**0.137**	
55	**Minimum**	**0**	
56	**Average**	**0.0098**	
57	**Number of CO < - 0.2 vol%**	**0**	
60	**4. CO2 vol%**	**Before Cleanup**	**After Cleanup**

Figure C.4. Summary Statistics of Data Shown on the Screen after Running the Macro

<u>Engine Data:</u> the following items are reported regarding to engine data:

- For Engine speed: maximum, minimum, zero engine speed, and number of unusual engine speeds.
- For IAT data: maximum, minimum, zero IAT, and number of unusual IAT
- For MAP data: maximum, minimum, zero MAP, and number of estimated MAP

Emissions Concentrations: maximum and minimum are reported for the concentrations of NO, HC, CO, CO_2, PM, and O_2. Therefore, the number of seconds in which concentrations are below the precision of the Montana system (i.e. NO<-25 ppm, HC<-14 ppm, CO<-0.02 vol%, CO_2<-0.30 vol%) are reported as well.

Mass Emission Rates: maximum, minimum, and average mass emission rates for NO, HC, CO, CO_2, and PM are reported.

Operation of Analyzers A and B: for each of the analyzers A and B, the number of seconds in which the analyzer has been operated normally or performed zero calibration are reported separately.

C.10 Estimating Missing Manifold Absolute Pressure

Missing MAP data will be estimated, where possible by the developed criteria in Appendix B. This step is performed by a macro called "S5_MAP_Estimations." There is no recalculation of emission rates performed in this section.

C.11 Removing Unestimated Missing Manifold Absolute Pressure

Missing MAP data that have not been estimated are removed from the database running the macro of "S6_Delete_Remaining_MAP." There is no recalculation of emission rates performed in this section. A row of data is excluded from the database in this step if MAP equals to "-34". There should not be observed any missing MAP after running this macro because part of missing values were estimated in previous section and the remaining unestimated values were deleted in this section. The reason that estimating and removing

MAP data are preformed in two steps is to give the user opportunity of screening out data to how MAP data were estimated and many missing data are remaining.

C.12 Removing Unusual Engine Speeds

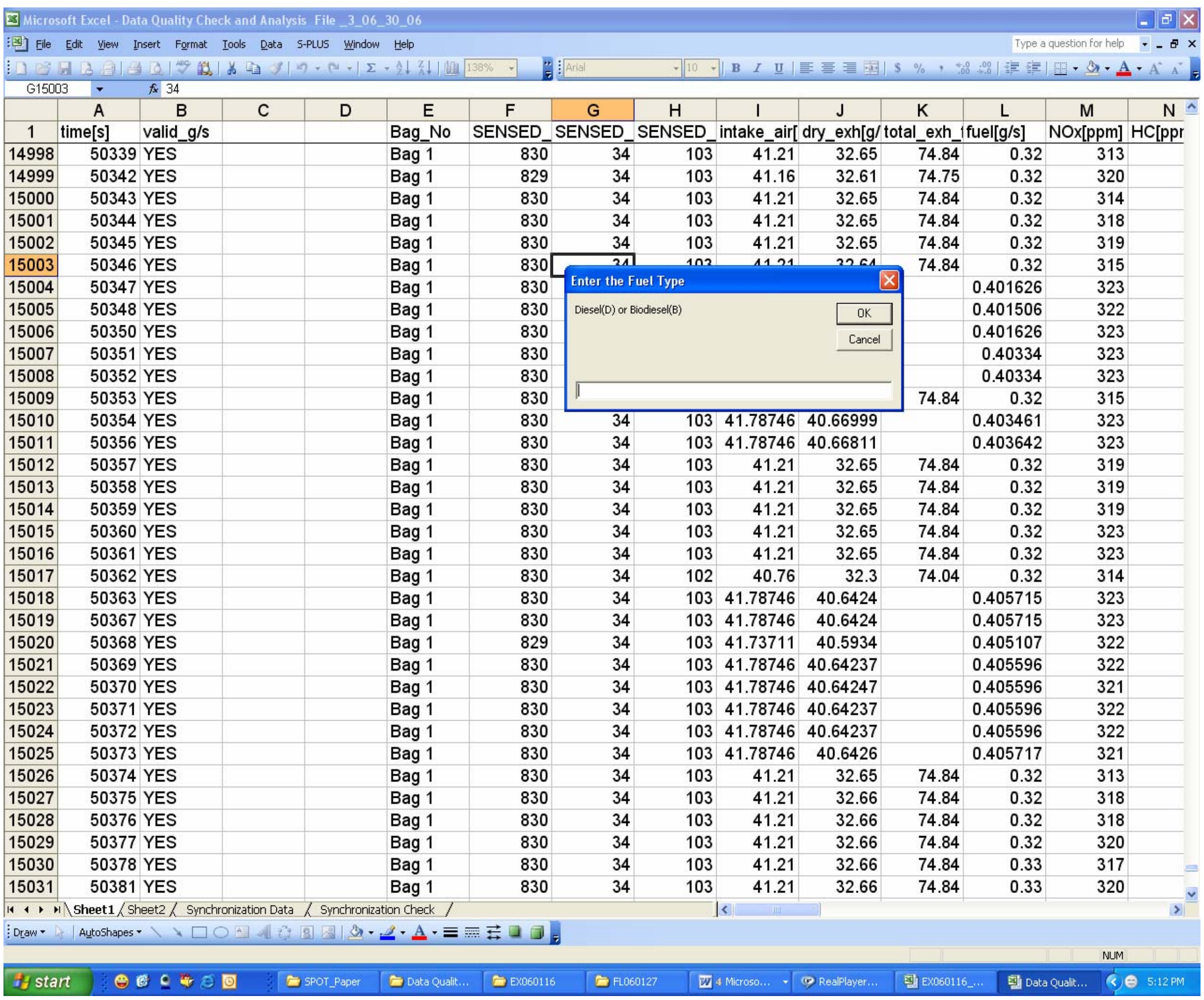
The macro of “S7_Removing_Unusual_RPM” deletes unusual engine speeds from the database. The program screens Column 50 labeled as “Un_RPM” and exclude the row of data from the database if the value of “1” appears in this column.

C.13 Screening Out Zeroing Effects

The macro of “S10_Concentrations_Correction_for_Zeroing” is used to correct the effects of zero calibration process on the fuel consumption and average emission rates. The macro has conceptually developed based on what was explained in Appendix B for correcting zero calibration effects. There is no recalculation performed running the macro in this step. The macro indicates 10 seconds before and after zeroing procedure for each of the analyzers from the flagged columns of 56, 57, 58, and 59 which are labeled by “ZE_A_be,” “ZE_A_af,” “ZE_B_be,” “ZE_B_af.” When Columns 56 or 57 contain the value of “1”, the macro copy and paste the concentrations in Columns 34 to 38 to Columns 13 to17, as shown in Table C.2. Therefore, when Columns 58 or 59 are 1 then Columns 27 to 31 will be copied and pasted to Columns 13 to17. Concentrations in Columns 13-17 will be used along with engine data in Columns 6 to 8 for recalculating fuel consumption and emission rates.

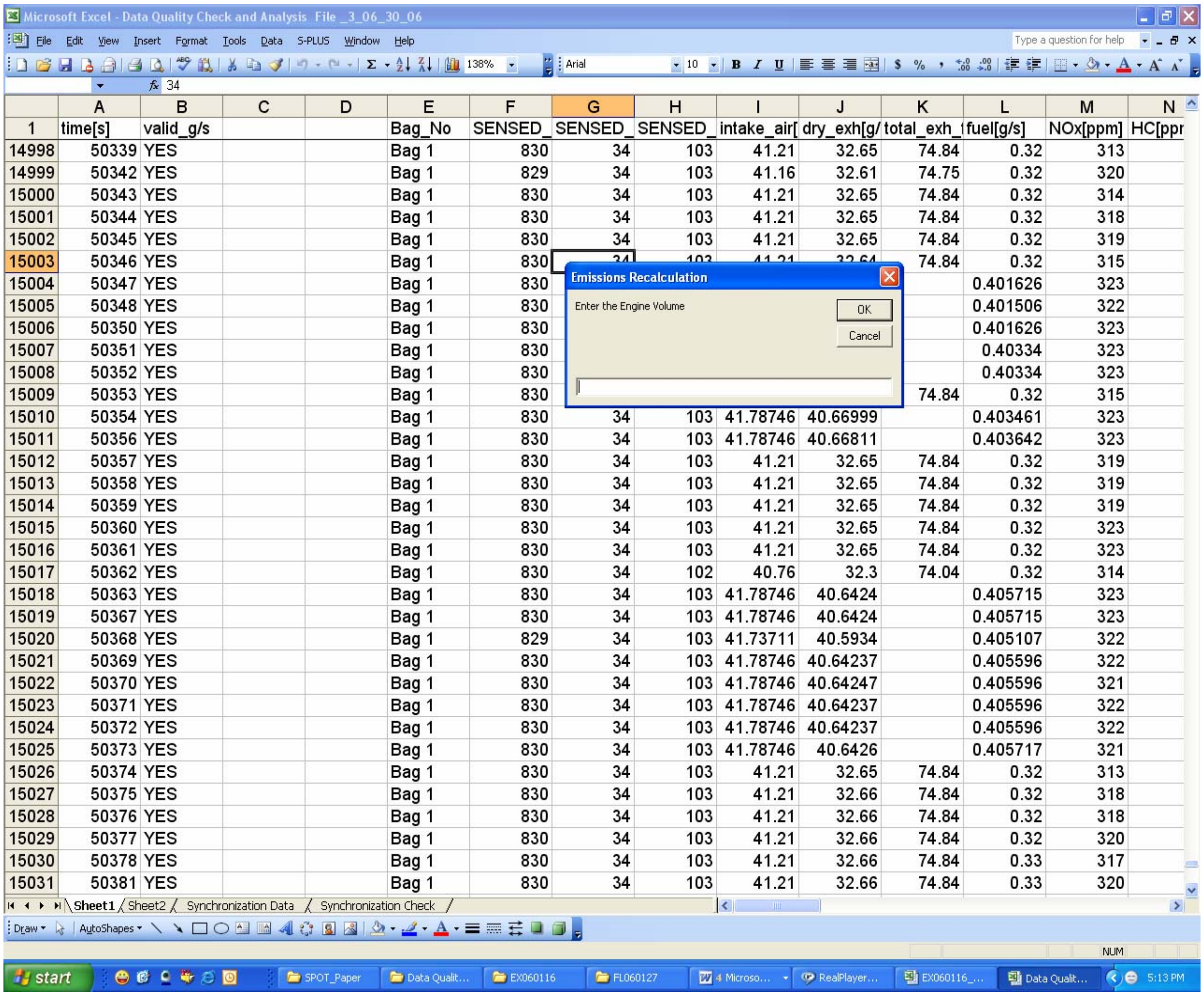
C.14 Recalculating Emission Rates

As mentioned previously, none of the above macros involve with the recalculation of mass fuel use and emission rates. The macro of "S14_Recalculations" is targeted to perform all fuel use and emission recalculations. At the beginning of running the macro, a window pops up and asks about the type of fuel. There are two options of D (i.e. diesel) and B (i.e. bio-diesel) for fuel type, as shown in Figure C.5. The next input variable is the engine displacement that is asked to be entered through another popped up window, as shown in Figure 6.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	time[s]	valid_g/s			Bag_No	SENSED_	SENSED_	SENSED_	intake_air[	dry_exh[g/	total_exh_	fuel[g/s]	NOx[ppm]	HC[ppr
14998	50339	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	313	
14999	50342	YES			Bag 1	829	34	103	41.16	32.61	74.75	0.32	320	
15000	50343	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	314	
15001	50344	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	318	
15002	50345	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15003	50346	YES			Bag 1	830					74.84	0.32	315	
15004	50347	YES			Bag 1	830						0.401626	323	
15005	50348	YES			Bag 1	830						0.401506	322	
15006	50350	YES			Bag 1	830						0.401626	323	
15007	50351	YES			Bag 1	830						0.40334	323	
15008	50352	YES			Bag 1	830						0.40334	323	
15009	50353	YES			Bag 1	830					74.84	0.32	315	
15010	50354	YES			Bag 1	830	34	103	41.78746	40.66999		0.403461	323	
15011	50356	YES			Bag 1	830	34	103	41.78746	40.66811		0.403642	323	
15012	50357	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15013	50358	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15014	50359	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15015	50360	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	323	
15016	50361	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	323	
15017	50362	YES			Bag 1	830	34	102	40.76	32.3	74.04	0.32	314	
15018	50363	YES			Bag 1	830	34	103	41.78746	40.6424		0.405715	323	
15019	50367	YES			Bag 1	830	34	103	41.78746	40.6424		0.405715	323	
15020	50368	YES			Bag 1	829	34	103	41.73711	40.5934		0.405107	322	
15021	50369	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15022	50370	YES			Bag 1	830	34	103	41.78746	40.64247		0.405596	321	
15023	50371	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15024	50372	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15025	50373	YES			Bag 1	830	34	103	41.78746	40.6426		0.405717	321	
15026	50374	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	313	
15027	50375	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	318	
15028	50376	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	318	
15029	50377	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	320	
15030	50378	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.33	317	
15031	50381	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.33	320	

Figure C.5. Defining the Fuel Type for the Macro



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	time[s]	valid_g/s			Bag_No	SENSED_	SENSED_	SENSED_	intake_air[	dry_exh[g/	total_exh_	fuel[g/s]	NOx[ppm]	HC[ppr
14998	50339	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	313	
14999	50342	YES			Bag 1	829	34	103	41.16	32.61	74.75	0.32	320	
15000	50343	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	314	
15001	50344	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	318	
15002	50345	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15003	50346	YES			Bag 1	830	34	103	41.21	32.64	74.84	0.32	315	
15004	50347	YES			Bag 1	830						0.401626	323	
15005	50348	YES			Bag 1	830						0.401506	322	
15006	50350	YES			Bag 1	830						0.401626	323	
15007	50351	YES			Bag 1	830						0.40334	323	
15008	50352	YES			Bag 1	830						0.40334	323	
15009	50353	YES			Bag 1	830					74.84	0.32	315	
15010	50354	YES			Bag 1	830	34	103	41.78746	40.66999		0.403461	323	
15011	50356	YES			Bag 1	830	34	103	41.78746	40.66811		0.403642	323	
15012	50357	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15013	50358	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15014	50359	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	319	
15015	50360	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	323	
15016	50361	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	323	
15017	50362	YES			Bag 1	830	34	102	40.76	32.3	74.04	0.32	314	
15018	50363	YES			Bag 1	830	34	103	41.78746	40.6424		0.405715	323	
15019	50367	YES			Bag 1	830	34	103	41.78746	40.6424		0.405715	323	
15020	50368	YES			Bag 1	829	34	103	41.73711	40.5934		0.405107	322	
15021	50369	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15022	50370	YES			Bag 1	830	34	103	41.78746	40.64247		0.405596	321	
15023	50371	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15024	50372	YES			Bag 1	830	34	103	41.78746	40.64237		0.405596	322	
15025	50373	YES			Bag 1	830	34	103	41.78746	40.6426		0.405717	321	
15026	50374	YES			Bag 1	830	34	103	41.21	32.65	74.84	0.32	313	
15027	50375	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	318	
15028	50376	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	318	
15029	50377	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.32	320	
15030	50378	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.33	317	
15031	50381	YES			Bag 1	830	34	103	41.21	32.66	74.84	0.33	320	

Figure C.6. Entering the Engine Displacement to the Macro

C.15 Statistics on Data Quality (2)

In this step, a macro called "S15_Summary_of_Data_2" provides a summary statistics of data for the user in Sheet 2 after screening data and performing quality assurance steps. The same procedure and information as explained in Section C.9, is provided by the macro in this step.

C.16 Linking Emissions and Modes of Activity Data

The macro called "S16_Time_Mode_Synchronization" links emissions data to modes of activity data. The following procedure needs to be followed in order to complete the process of linking emissions data to activity data:

1. Open the file in which modes of activity data has been collected. Mode of activity files normally labeled as "Time_mode". For example, for a backhoe it should be "Time_mode_Backhoe".
2. Run a macro in "Time_mode" file named "Detail_Time_Mode". This macro will provide the user with time and modes of activity in a second-by-second basis.
3. Copy Columns 5 and 6 which are labeled as "Time (sec)" and "Mode of Activity". Paste the copied columns in Columns 62 and 63 of DQCAF. In order to make sure data for linking emissions and activity data is available, a message window pops up to remind the user for completing the process of copying.
4. Make sure the value of cell (2, 62) is the same as cell (2, 1). If not, then delete pairs of time and mode in Columns 62 and 63 and shift the data in these columns up to have cell (2,62) = cell (2,1).
5. Run the macro of "S16_Time_Mode_Synchronization".

As a result of following the above procedure, Columns 3 and 4 in DQCAF will be filled with time in a "hh:mm:ss" format and modes of activity data, respectively. Sheet 1 will be renamed to "Data" and Sheet 2 to "Data Summary."

C.17 Saving/Archiving Data files and Continue Preliminary Analysis

The produce of performing the above steps is a quality assured database (QAD). This file is ready for any further analysis. However, before running the preliminary analysis macros, it is necessary to save the QAD. The user is reminded through a message window at the end of "S16_Time_Mode_Synchronization" macro to save the QAD. The QAD should be saved as "Screened" and "Analysis" files. "Screened" file will be archived for the future use and "Analysis" will be used for preliminary analysis. This step is performed manually as shown in Figure C.1.

C.18 Preliminary Analysis

The objective of performing preliminary analysis is to analyze data as quick as possible to provide the user with an overview on the quality of collected data. It was desirable to have one macro for preliminary analysis but it was not possible because the program became larger and longer than the program allowed by Excel to be as a macro. Thus, to avoid this problem, six macros were developed instead of one. Of course, breaking one macro into six provides the opportunity of checking the results partially between the two macros. It is recommended that the user close and open "Analysis" file one time before running preliminary analysis macros. The use should run the macros sequentially. The macros are:

- Preliminary_Analysis_1
- Preliminary_Analysis_2
- Preliminary_Analysis_3

- Preliminary_Analysis_4
- Preliminary_Analysis_5
- Preliminary_Analysis_6

The following sheets are created running “Preliminary_Analysis_1”:

- Summary (MAP) for saving the results of engine-emission based modes analysis
- MAP1 to MAP10 for 10 different MAP cutoffs which have been defined based on 10% of total NO in each cutoff.
- A_B Analyzers for comparing the data measure by Analyzer A and B

Products of running the preliminary analysis macros appeared in “Summary(MAP)” and “A_B Analyzers” sheets. These products are categorized in two groups: (1) preliminary engine-emission based modes analysis; (2) comparison of data measured by each of the analyzers.

According to engine-emission based modes analysis, data is sorted based on MAP values and binned with respect to MAP. This macro considers in total 10 bins for each vehicle and each bin accounts for approximately 10 percent of the total NO emission. For each of the ten MAP bins the followings are estimated and appeared in Summary(MAP) sheet:

1. Minimum and maximum MAP (kPa)
2. Number of data records (seconds)

3. The average fuel consumption rate (g/s)
4. The average emission rates of NO (g/s), HC (g/s), CO(g/s), CO_2(g/s), PM (g/s)
5. The 95 percentile range for NO (g/s), HC (mg/s), CO(mg/s), CO_2(g/s), PM (mg/s)
6. Minimum and maximum NO (g/s), HC (mg/s), CO(mg/s), CO_2(g/s), PM (mg/s)
7. The average emission rates of NO (g/gal),HC (g/gal),CO(g/gal),CO_2(g/gal),PM (g/gal)
8. The 95 percentile range for NO (g/gal), HC (g/gal), CO(g/gal), CO_2(g/gal), PM (g/gal)
9. Minimum and maximum NO (g/gal), HC (g/gal), CO(g/gal), CO_2(g/gal), PM (g/gal)
10. Distribution of time, fuel use, NO, HC, CO, CO_2, and PM among the bins

Therefore, the user is provided with the following graphs for data visualization purposes:

1. Bar charts of the average emissions and fuel use in each bin in a mass per time basis
2. Bar charts of the average emissions in each bin in a mass per gallon of fuel use basis
3. Distribution of time, fuel use, NO, HC, CO, CO_2, and PM among the bins

Figure C.7 presents an example of graphs that a user will observe on the screen in "Summary(MAP)" sheet.

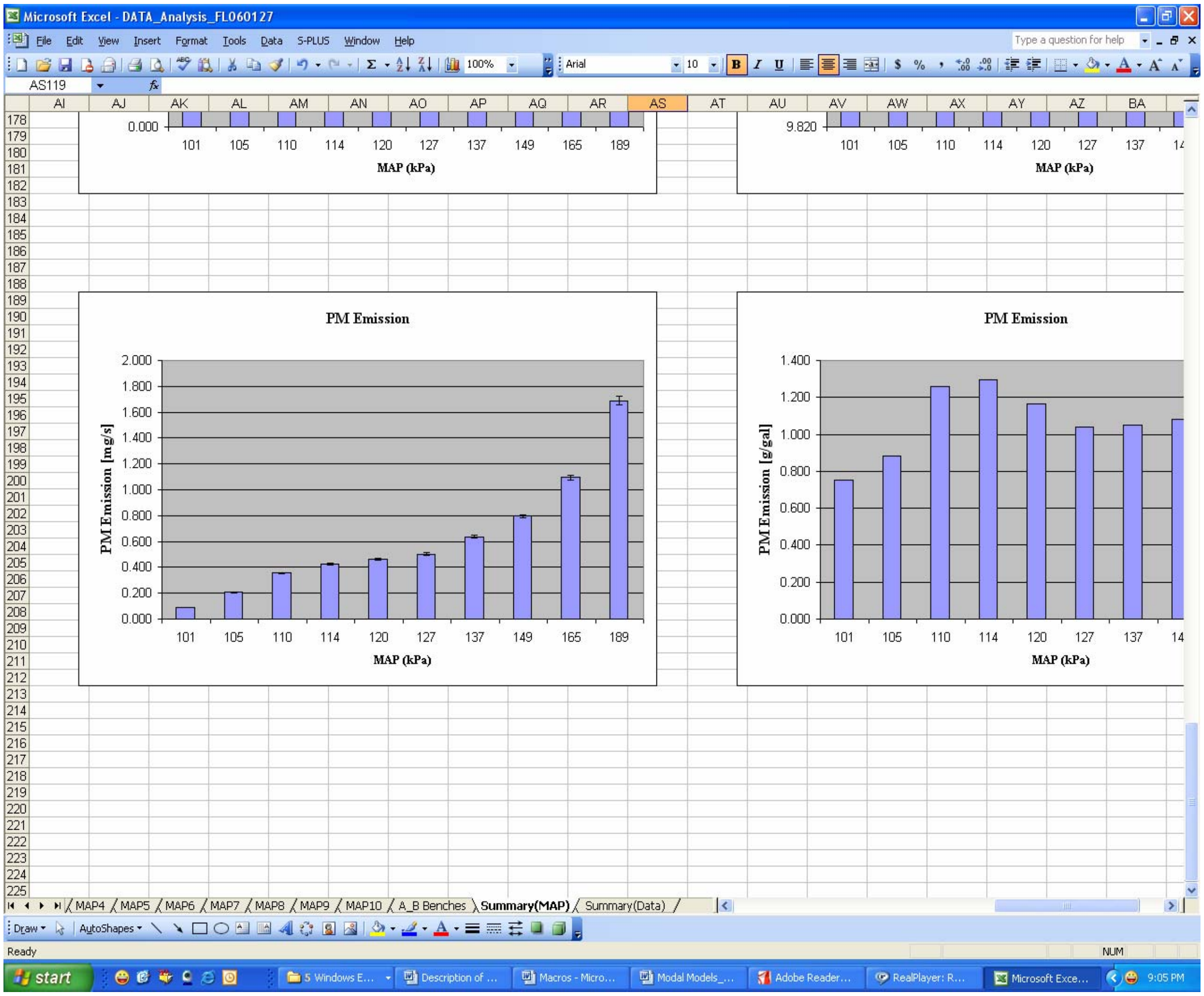


Figure C.7. An Example of Bar Chart Graphs Developed by the Macro Regarding Average Emission Rates in each Bin

To provide the use with an overview on the general status of the analyzers during data collection, the following graphs are developed in “A_B Analyzers” sheet:

1. NO concentrations of Analyzer A versus Analyzer B (ppm)
2. HC concentrations of Analyzer A versus Analyzer B (ppm)
3. CO concentrations of Analyzer A versus Analyzer B (vol%)
4. CO_2 concentrations of Analyzer A versus Analyzer B (vol%)
5. Cumulative frequency of average NO concentrations (ppm)

6. Cumulative frequency of average HC concentrations (ppm)

7. Cumulative frequency of average CO concentrations (vol%)

8. Cumulative frequency of average CO_2 concentrations (vol%)

An example graphs developed in "A_B Analyzers" sheet is shown in Figure C.8.

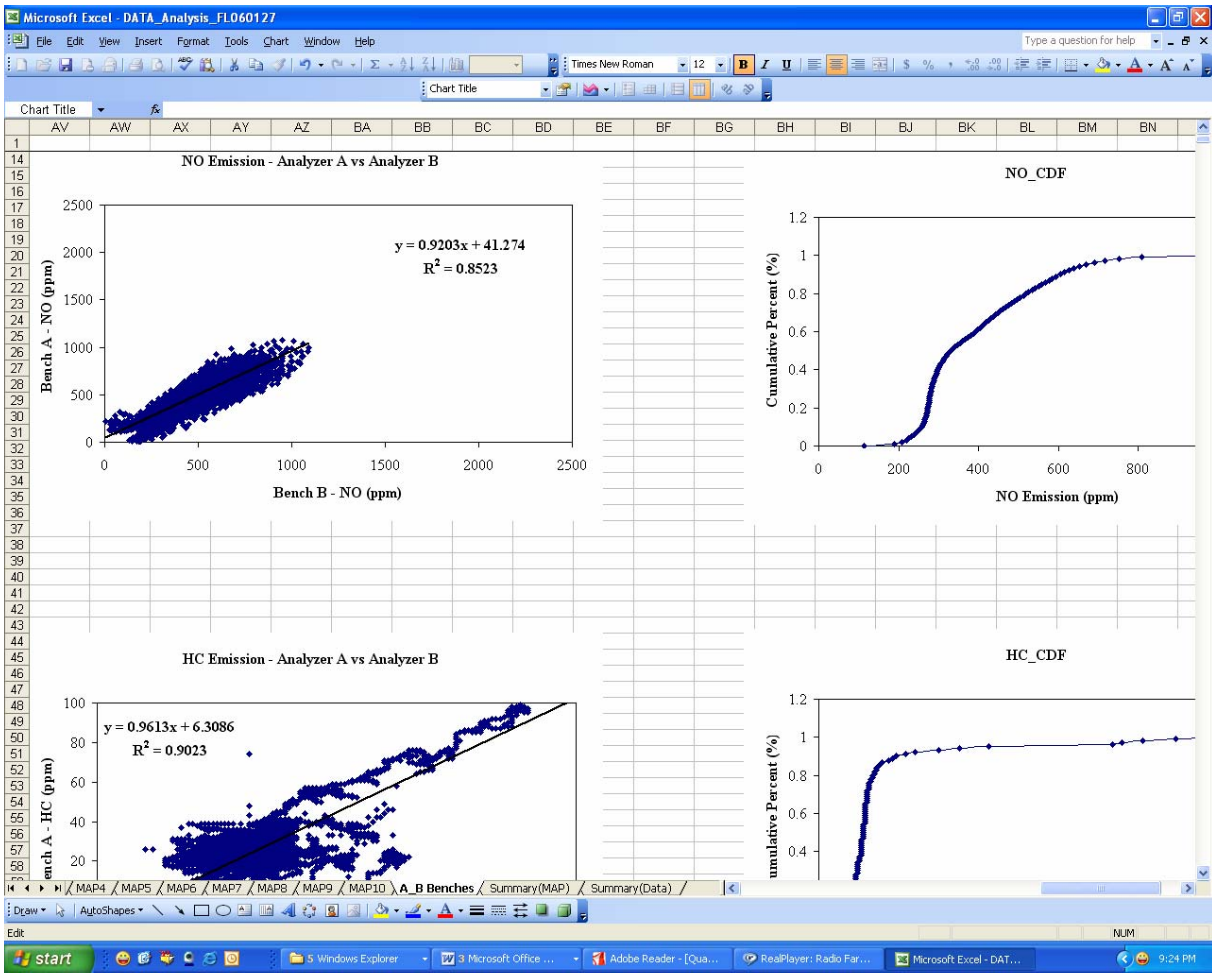


Figure C.8. An Example of Graphs Developed in "A_B Analyzers" Sheet