Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Nonroad Construction Equipment

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Objectives

The objectives of this study are to:

- Measure real-world duty cycles for specific types of nonroad construction vehicles;
- Characterize the in-use emissions and energy use of nonroad construction vehicles and equipment;
- Develop vehicle-specific micro-scale models of fuel use and emissions; and
- Assess the variations of fuel use and emissions among different duty cycles.

US National Total Emissions of Onroad, Nonroad, and Nonroad Construction Vehicle in 2002

Sources \ Pollutants	NO_x	PM	CO	HC
Total Onroad Vehicles	7,365	204	62,161	4,543
Total Nonroad Vehicles	4,086	311	24,450	2,688
Nonroad Construction Vehicles	770	73	1,120	135

(Unit: thousand tons)

18.9% 23.5%

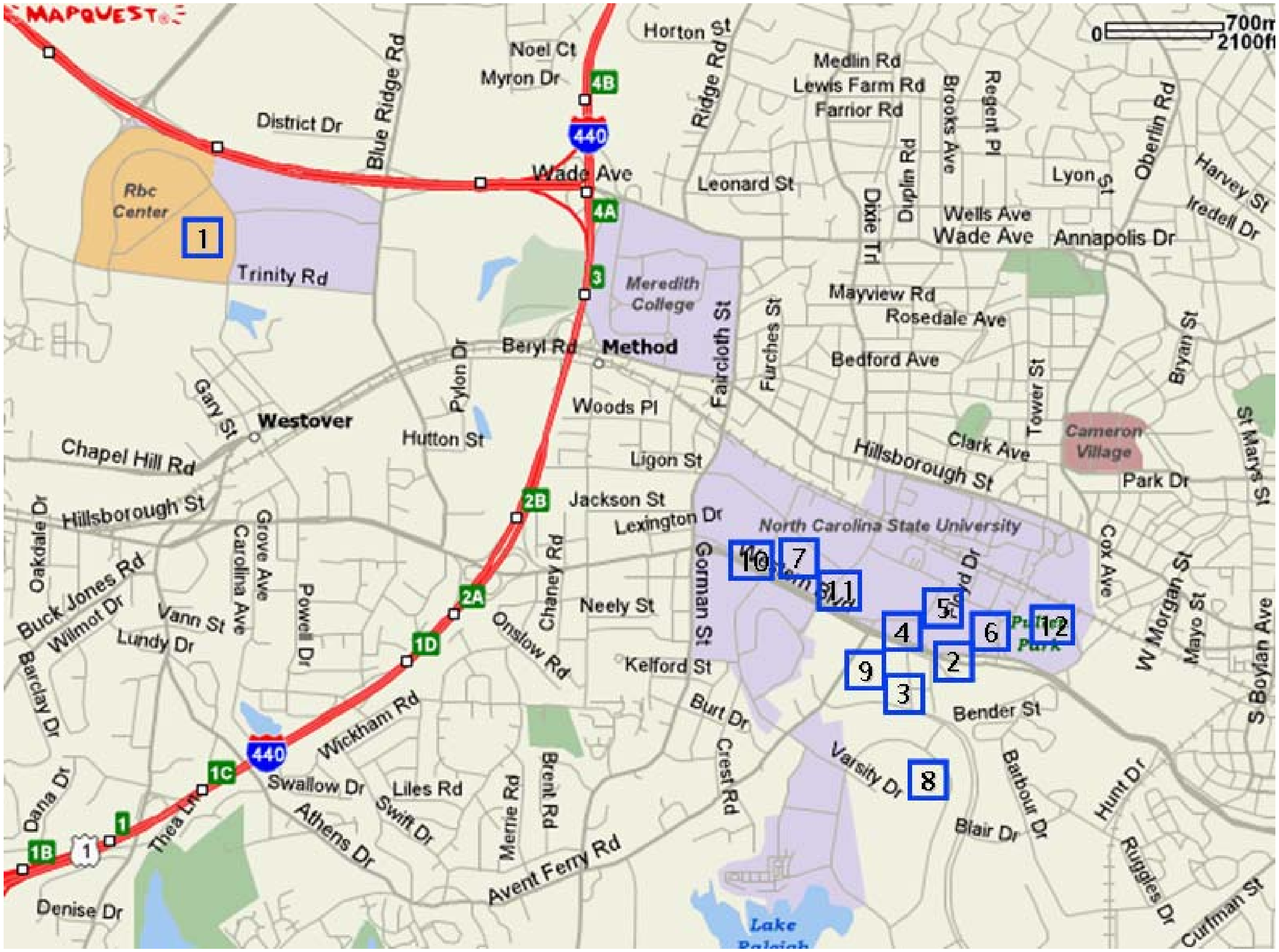
Methodology

- Study Design
- Instrumentation
- Data Collection Procedure
- Data Screening and Quality Assurance
- Exploratory Analysis of Empirical Data
- Development of Physically-Based Regression Models
- Comparison of Real-World Duty Cycles

General Overview of Study Design

- Study Location
  - Near NCSU campus
- Vehicle Selection
  - Prioritized based on EPA’s NONROAD model
- Vehicle Activities
  - Such as moving and pushing by dozers
- Data Collection Scheduling
  - Cooperation must be obtained from the owner
- Driver/Operator
  - Based on contractor driver schedule

Locations of Construction Sites



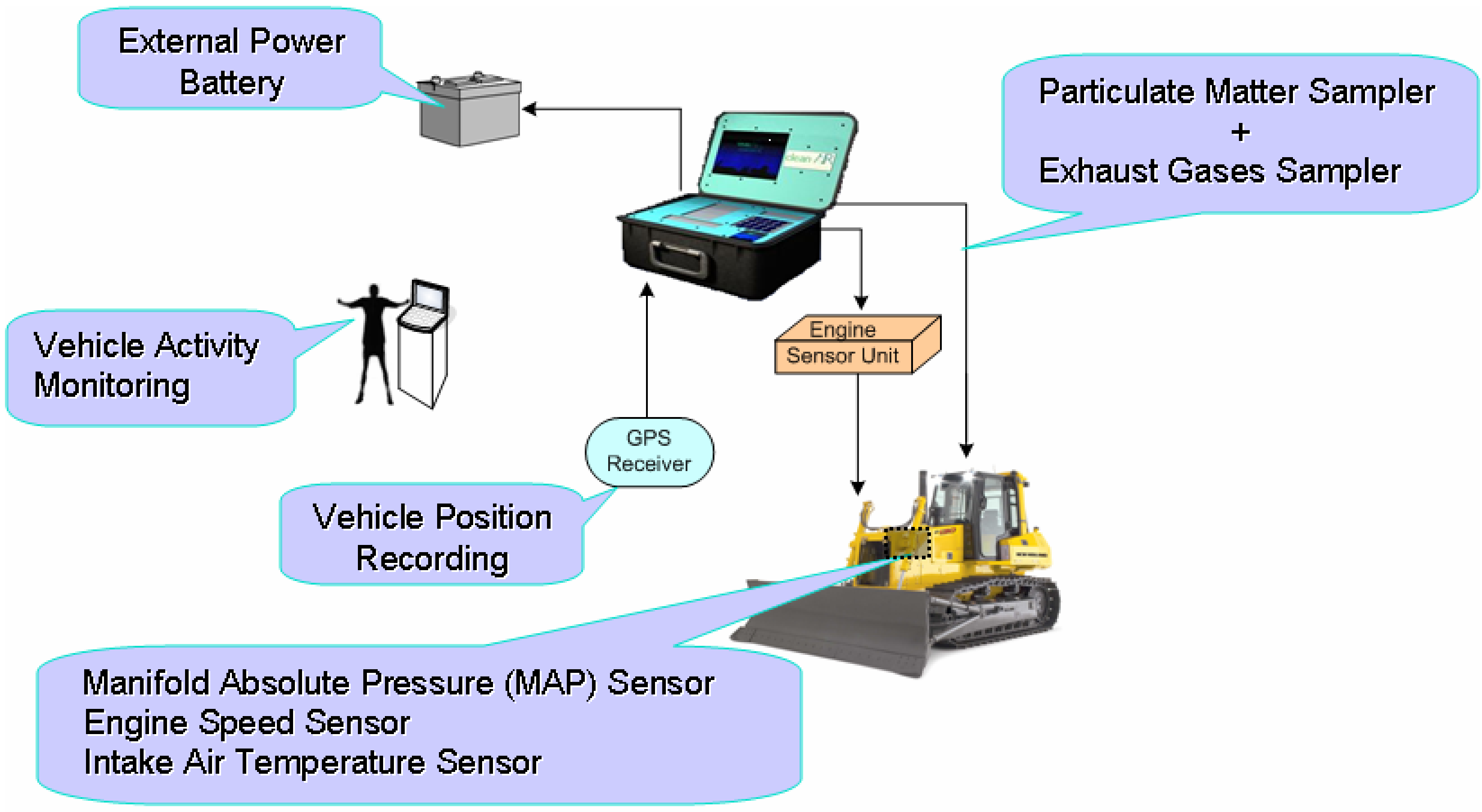
Portable Emission Measurement System

- OEM-2100 Montana System
  - Clean Air Technologies International, Inc.
  - Carry-on Luggage shape
  - Weight: 35 *lbs.*
  - 13.8 *volt* with 5~18 *amps.*
  - 2 gas analyzers
  - Global Positioning System (GPS)

- Gas Analyzer
  - NO and O_2 from electro-chemical sensors
  - HC, CO, and CO_2 from non-dispersive infrared (NDIR)

- Global Positioning System (GPS)
  - GPS system measures vehicle location

Real-World Field Measurement



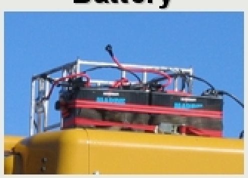
Procedure for Installation of the Portable Emission Measurement System and Field Measurement

STEP 1

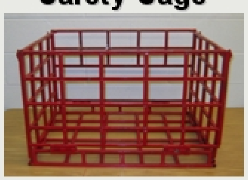
Pre-Installation

Sensor Unit

External Battery



Main Unit Safety Cage



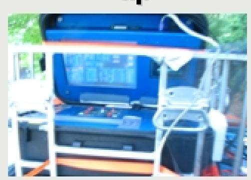
STEP 2

Installation

Gas & PM Samplers

Vehicle Activity Monitors

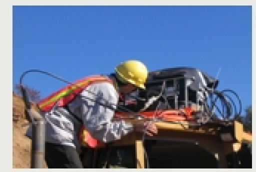
System Warm-up



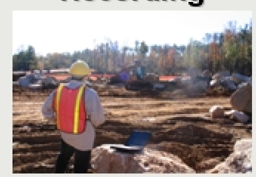
STEP 3

Data Collection

Periodic System Check



Laptop-Activity Recording

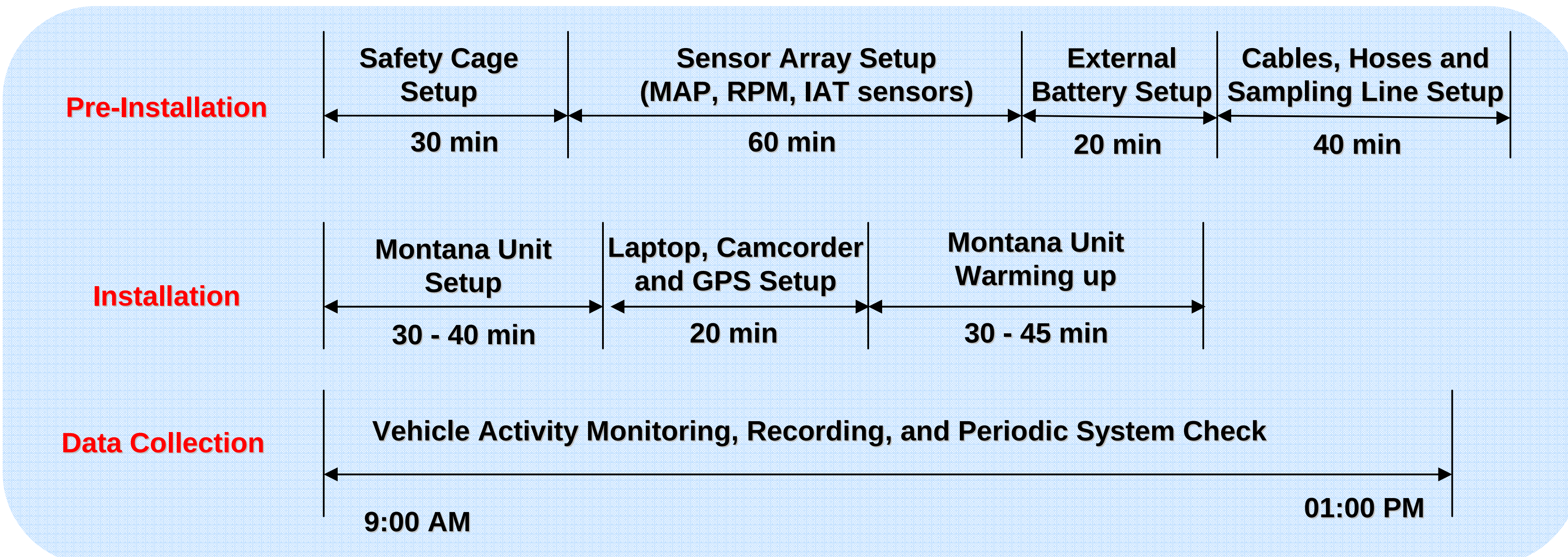


Video-Activity Recording

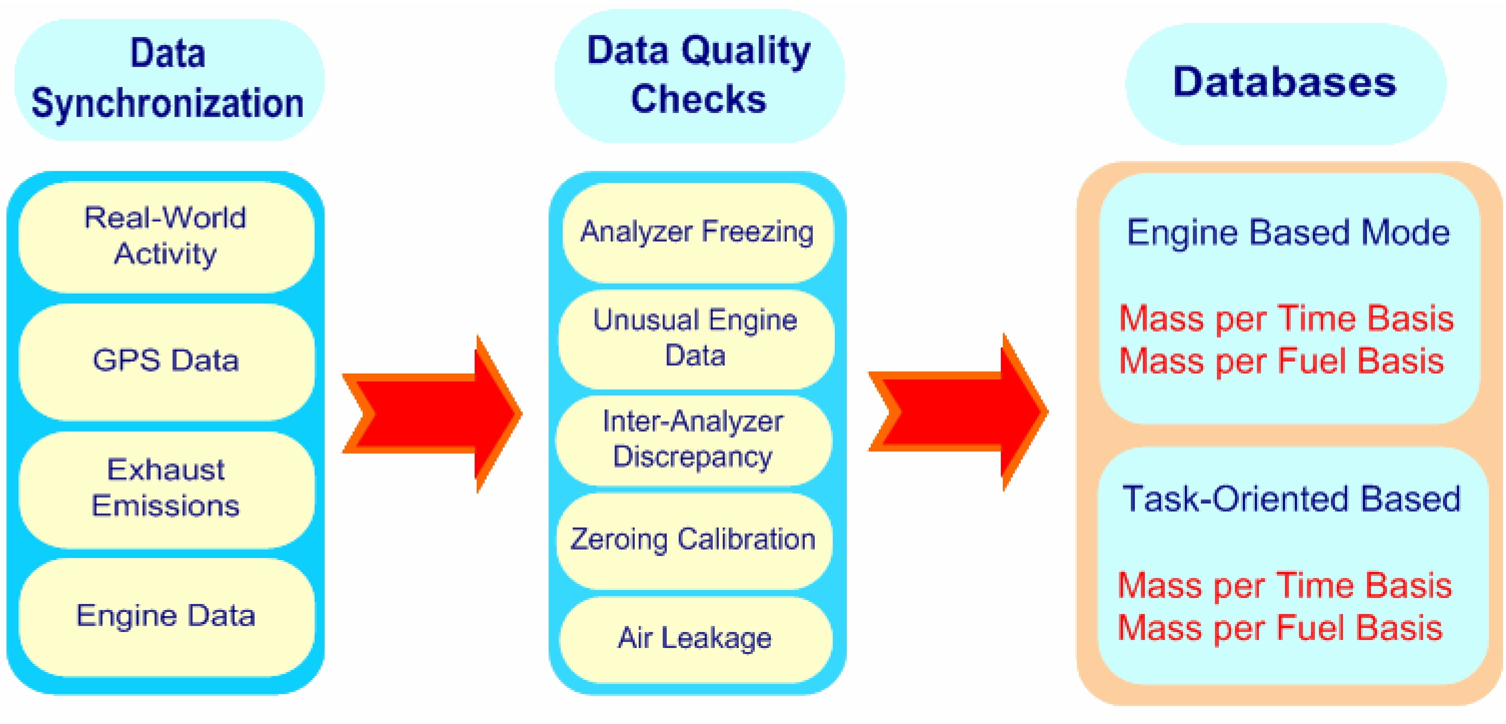
Foam Padding and Cover for the PEMS

Typical Time Period for Testing Procedures

STEP 1	Pre-installation : 2 hours 30 minutes
STEP 2	Installation : 1 hour 30 minutes
STEP 3	Data Collection : 4 hours



Fuel Use and Emissions Database Development

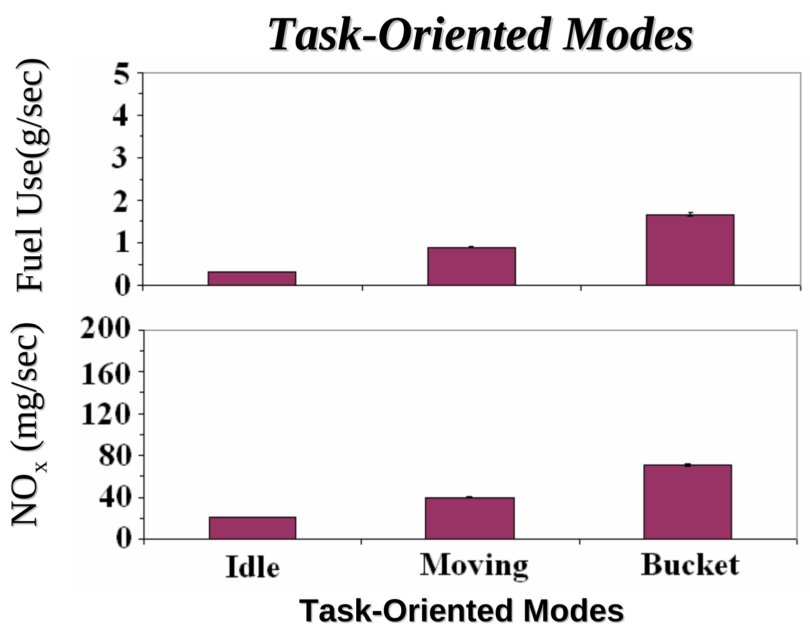


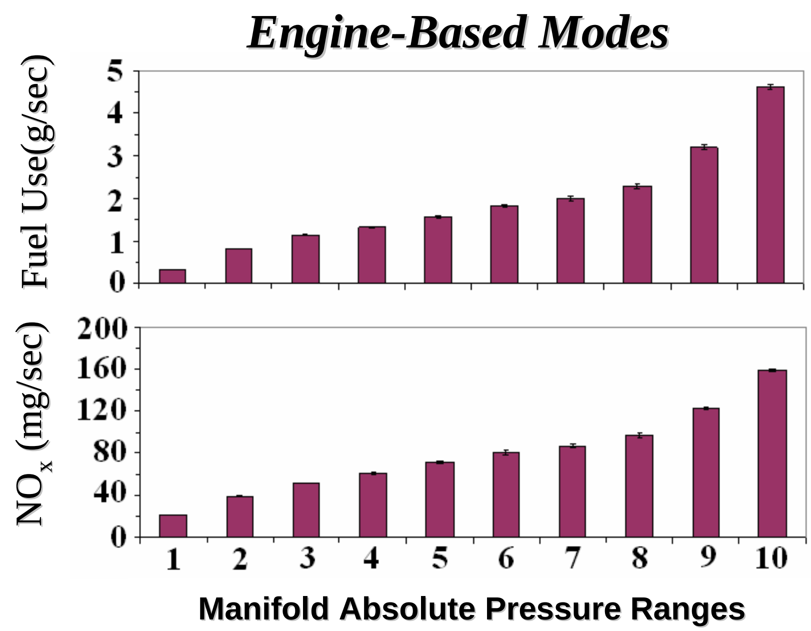
Exploratory Analysis of Empirical Data

Estimation of Modal Emission Rates

- Task-Based Modes
  - Activity-based real-world duty cycle
  - Record in the field with laptop computer
- Engine-Based Modes
  - Sorted the data by manifold absolute pressure (MAP)
  - Divide the data into MAP strata so that each strata represents 10% of total duty cycle NO_x emissions

Time-Based Modal Emission Factors for a Front-End Loader





Task-Oriented Based Modes

Idle: Idling
Moving: Moving without using bucket
Scoop: Moving while using bucket

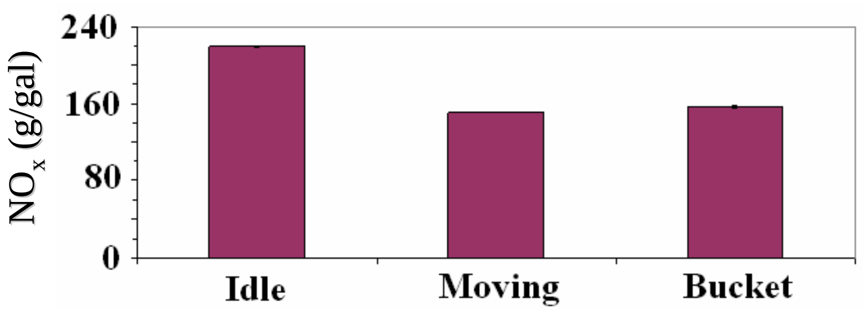
Engine Based Mode [MAP (kPa)]

1: 100-106 **4**:123-127 **7**: 141-147
2: 107-116 **5**:128-134 **8**: 148-158
3: 117-122 **6**:135-140 **9**: 159-193
10: 194-228

Each mode accounts for 10 percent of total NO emissions

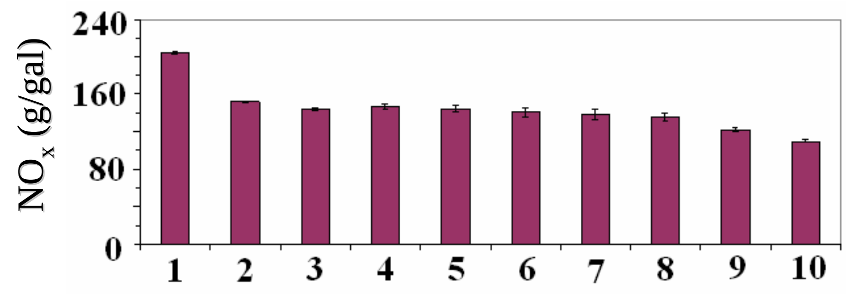
Fuel-Based Modal Emission Factors for a Front-End Loader

Task-Oriented Modes



Task-Oriented Modes

Engine-Based Modes



Manifold Absolute Pressure Ranges

Task-Oriented Based Modes

Idle: Idling
Moving: Moving without using bucket
Scoop: Moving while using bucket

Engine Based Mode [MAP (kPa)]

1: 100-106 **4**:123-127 **7**: 141-147
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Each mode accounts for 10 percent of total NO emissions

Summary of Modal Models

- For non-idle modal models, fuel-based emission factors typically have less variability compared to time-based emission factors.
- Manifold absolute pressure (MAP) is a good explanatory variable for statistical emission models

Ordinary Least Squares Regression

$$\overline{Y}_i^{\Delta t} = \alpha_i + \beta_i \times \overline{MAP}^{\Delta t}$$

Where,

$\overline{Y}_i^{\Delta t}$ = Average mass emission rate (g/sec) for specie *i* (fuel use, HC, CO, CO_2 and Opacity) for consecutive averaging time of 12 seconds

α_i, β_i = Coefficients for specie *i* (fuel use, HC, CO, CO_2, and Opacity)

$\overline{MAP}^{\Delta t}$ = Average manifold absolute pressure (kPa) for consecutive averaging time of 12 seconds

NOTE: Consecutive averaging time of 12 seconds is used to reduce the influence of instrument response time and autocorrelation.

Ordinary Least Squares Regression

$$\overline{Y}_{NO}^{\Delta t} = \frac{a_{NO}}{\left(\overline{MAP}^{\Delta t}\right)^{0.5}} \exp\left(\frac{b_{NO}}{\overline{MAP}^{\Delta t}}\right)$$

Where,

$\overline{Y}_{NO}^{\Delta t}$ = Average mass emission rate (g/sec) for NO for consecutive averaging time of 12 seconds

a_{NO}, b_{NO} = Coefficients for NO

$\overline{MAP}^{\Delta t}$ = Average manifold absolute pressure (kPa) for consecutive averaging time of 12 seconds

Steps for Developing Calibration and Validation Datasets

STEP 1: Identify time series "segments." Each segment represents one complete duty cycle.

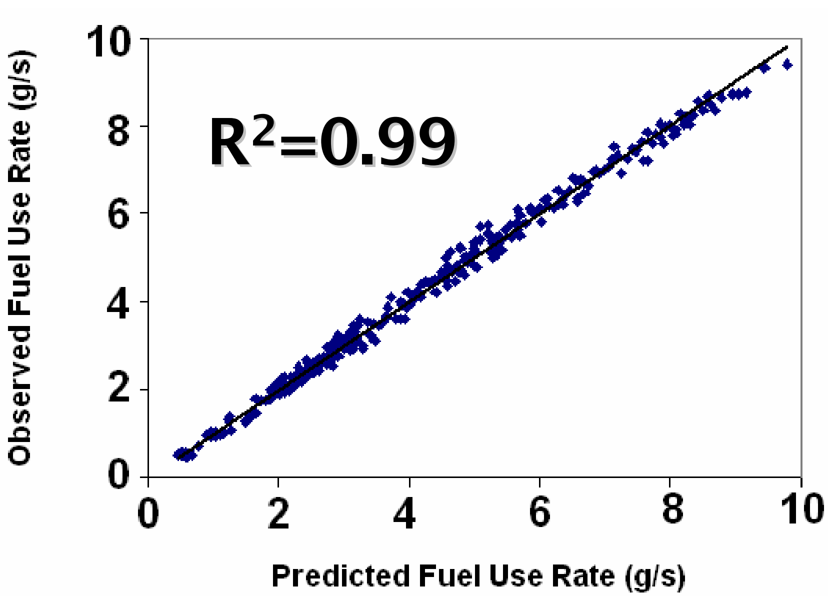
STEP 2: Randomly assign the time series segments to the calibration dataset (75% of total data) or validation dataset (25% of total data).

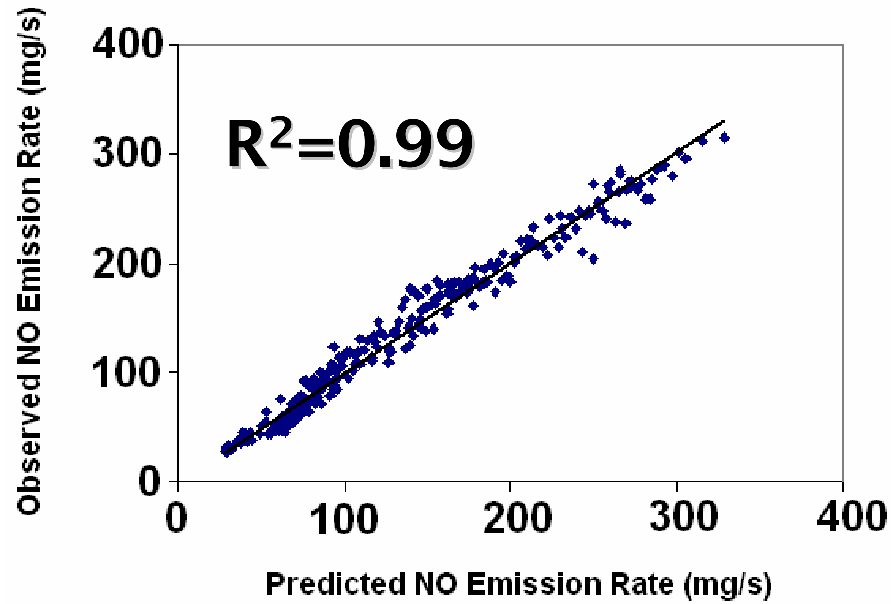
STEP 3: Compare the mean and standard deviation of manifold absolute pressure (MAP) and emissions for the calibration and validation datasets.

STEP 4: If the distributions of these two datasets are similar, the calibration and validation datasets are ready. If not, go back to STEP 2 and re-assign the segments.

Parity Plots of Observed Fuel Use and Emissions versus Predicted Values

Example of Excavator 1





Note: This is for validation data. The slope for all of the parity plots was 1.0

Coefficient of Determination of Time-Based Regression Models for Fuel Use and Emission Rates (Validation Dataset)

R^2	Fuel	CO_2	NO_x	HC	CO	Opacity
Dozer 1	1.00	1.00	0.99	0.63	0.91	0.95
Dozer 2	0.97	0.97	0.92	0.89	0.21	0.76
Dozer 3	0.97	0.97	0.92	0.56	0.07	0.62
Excavator 1	0.99	0.99	0.99	0.72	0.66	0.92
Excavator 2	0.99	0.99	0.96	0.80	0.45	0.92
Excavator 3	0.97	0.97	0.94	0.42	0.13	0.75
Off-Highway Truck	0.95	0.95	0.82	0.78	0.44	0.90
Backhoe 1	0.91	0.91	0.86	0.27	0.002	0.84
Backhoe 2	0.95	0.95	0.77	0.08	0.25	0.33
Front-End Loader	0.90	0.90	0.79	0.79	0.60	0.85
Skid Steer Loader	0.95	0.95	0.91	0.80	0.80	0.76
Average R^2	**0.96**	**0.96**	**0.88**	**0.61**	**0.41**	**0.78**

Summary of the Regression Models

- The R^2 for fuel use, CO_2, and NO_x emission rates are high for all vehicles.
- The statistical regression models perform well.

Definitions of Duty Cycles

Duty Cycle 1:	Material Handling using a front-end loader
Duty Cycle 2:	Clearing land using a bulldozer
Duty Cycle 3:	Spreading materials using a bulldozer (Dozer 2)
Duty Cycle 4:	Spreading materials using a bulldozer (Dozer 3)
Duty Cycle 5:	Tree/Stump removal using an excavator
Duty Cycle 6:	Moving objects using an excavator
Duty Cycle 7:	Mass excavation using an excavator
Duty Cycle 8:	Material hauling using an off-highway truck
Duty Cycle 9:	Load a dump truck using a backhoe
Duty Cycle 10:	Mass excavation using a backhoe
Duty Cycle 11:	Material handling using a skid steer loader
Duty Cycle 12:	Power generation using a generator
Duty Cycle 13:	ISO-C1 engine dynamometer test cycle

Vehicle or Equipment Information

ID No.	Description	Year	Disp.[a]	Cyl.[b]	HP[c]	Engine Tier
1	Front-end Loader	2004	6.0	6	149	Tier 2
2	Dozer 1	1988	5.0	6	80	Tier 0
3	Dozer 2	2004	3.9	4	85	Tier 2
4	Dozer 3	2003	5.0	6	90	Tier 1
5	Excavator 1	2001	8.3	6	254	Tier 1
6	Excavator 2	2003	6.4	6	138	Tier 2
7	Excavator 3	2002	3.9	4	93	Tier 1
8	Off-Highway Truck	2005	9.6	6	306	Tier 2
9	Backhoe 1	2001	4.0	4	88	Tier 1
10	Backhoe 2	1999	4.5	4	88	Tier 1
11	Skid Steer Loader	2003	2.0	4	44	Tier 1
12	Generator	2002	4.5	4	108	Tier 1

[a] Engine Displacement (liters) [b] Number of cylinders [c] Rated Engine Horsepower

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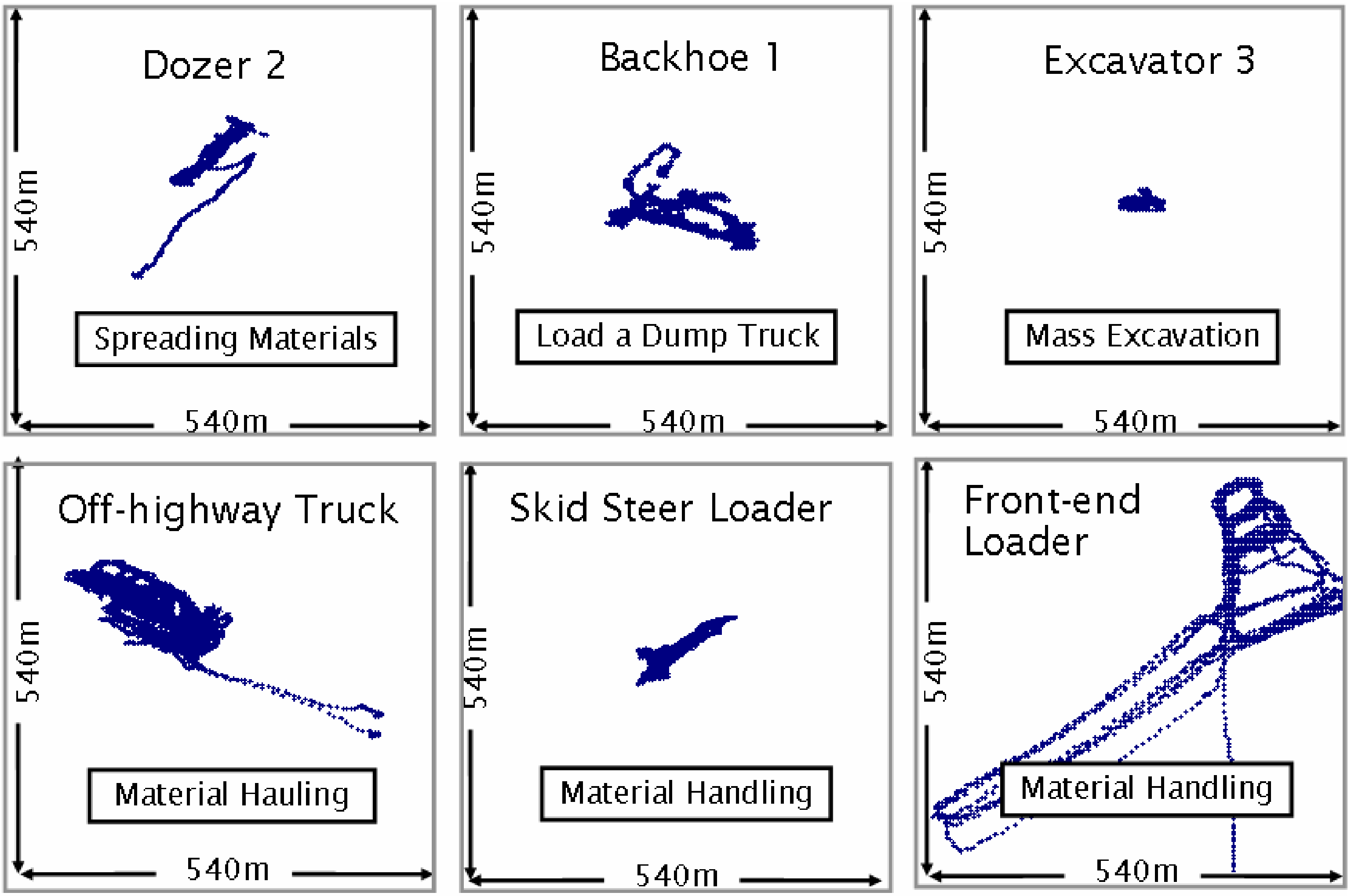
Maps of Typical Work Duty



Inter-Engine and Inter-Cycle Variations of Fuel Use Rates (gallon/hour)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1		Dozers										
DC2		**2.5**	**1.8**	**3.6**								
DC3		**2.2**	**1.6**	**3.3**								
DC4		**1.6**	**1.2**	**2.5**								
DC5												
DC6												
DC7												
DC8												
DC9												
DC10												
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of Fuel Use Rates (gallon/hour)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1			Dozers									
DC2		**2.5**	**1.8**	**3.6**								
DC3		**2.2**	**1.6**	**3.3**								
DC4		**1.6**	**1.2**	**2.5**		Excavators						
DC5					**4.1**	**3.3**	**1.6**					
DC6					**4.6**	**3.7**	**1.8**					
DC7					**6.0**	**4.8**	**2.4**					
DC8												
DC9												
DC10												
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of Fuel Use Rates (gallon/hour)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1			Dozers									
DC2		2.5	1.8	3.6								
DC3		2.2	1.6	3.3								
DC4		1.6	1.2	2.5		Excavators						
DC5					4.1	3.3	1.6					
DC6					4.6	3.7	1.8					
DC7					6.0	4.8	2.4					
DC8									Backhoes			
DC9									0.9	1.1		
DC10									1.2	1.5		
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of Fuel Use Rates (gallon/hour)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	2.0	1.5	1.1	2.3	3.2	2.6	1.2	3.5	1.1	1.5	0.6	
DC2	3.1	2.5	1.8	3.6	5.1	4.1	2.0	5.3	1.8	2.4	0.8	
DC3	2.7	2.2	1.6	3.3	4.5	3.6	1.8	4.8	1.6	2.2	0.7	
DC4	2.2	1.6	1.2	2.5	3.4	2.8	1.4	3.7	1.2	1.6	0.6	
DC5	2.5	1.9	1.5	2.9	4.1	3.3	1.6	4.4	1.5	1.9	0.7	
DC6	2.8	2.3	1.6	3.3	4.6	3.7	1.8	4.9	1.6	2.2	0.7	
DC7	3.5	2.9	2.0	4.3	6.0	4.8	2.4	6.2	2.0	2.8	0.9	
DC8	1.7	1.0	0.9	1.7	2.4	2.0	0.9	2.7	0.9	1.1	0.5	
DC9	1.7	1.0	0.9	1.7	2.4	2.0	0.9	2.7	0.9	1.1	0.5	
DC10	2.2	1.5	1.2	2.4	3.3	2.7	1.2	3.6	1.2	1.5	0.6	
DC11	4.6	4.2	2.8	5.9	8.4	6.5	3.3	8.5	2.7	3.8	1.1	
DC12	0.8	1.0	0.5	1.1	0.8	1.0	0.5	1.1	0.5	1.2	0.2	0.8
DC13	4.0	3.5	2.4	5.0	7.0	5.4	2.7	7.1	2.4	3.3	1.0	

Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (mg/sec)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1												
DC2		**103**	**51**	**153**								
DC3		**92**	**44**	**130**								
DC4		**67**	**38**	**105**								
DC5												
DC6												
DC7												
DC8												
DC9												
DC10												
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (mg/sec)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1												
DC2		103	51	153								
DC3		92	44	130								
DC4		67	38	105								
DC5					112	75	47					
DC6					132	79	54					
DC7					170	98	69					
DC8												
DC9												
DC10												
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (mg/sec)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1												
DC2		103	51	153								
DC3		92	44	130								
DC4		67	38	105								
DC5					112	75	47					
DC6					132	79	54					
DC7					170	98	69					
DC8												
DC9									32	22		
DC10									52	41		
DC11												
DC12												
DC13												

Inter-Engine and Inter-Cycle Variations of NO_x Emission Rates (mg/sec)

Duty Cycle	Engine											
	1	2	3	4	5	6	7	8	9	10	11	12
DC1	52	64	33	89	89	60	38	110	42	33	14	
DC2	76	103	51	153	139	89	58	163	67	60	20	
DC3	68	92	44	130	125	80	52	147	57	49	18	
DC4	57	67	38	105	93	65	39	122	52	42	15	
DC5	65	82	43	123	112	75	47	138	57	49	17	
DC6	67	97	41	120	132	79	54	143	49	42	18	
DC7	81	127	50	154	170	98	69	175	58	52	22	
DC8	42	52	24	64	73	48	31	88	29	21	11	
DC9	43	49	25	65	69	48	29	89	32	22	11	
DC10	56	63	37	102	88	63	38	119	52	41	14	
DC11	94	172	53	148	239	117	95	208	47	35	25	
DC12	22	45	12	41	33	29	19	46	15	34	8	26
DC13	83	144	47	134	202	101	80	181	46	38	22	

Conclusions

- The procedures described in this paper are applicable to any construction site and type of nonroad construction equipment.
- Inter-cycle and inter-engine variations of fuel use and emissions are significant.
- Real-world in-use measurements should be a basis for developing duty cycle correction factors in models such as NONROAD.

Acknowledgements

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Disclaimer

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Benchmarking Weighted Average Emission Rates with NONROAD Model

Equipment	Duty Cycle	NO_x (g/gal)		HC (g/gal)		CO (g/gal)	
		Cycle	NONROAD Model	Cycle	NONROAD Model	Cycle	NONROAD Model
Front-End Loader	DC1	92	81	11.3	6.8	38.9	25.5
Dozer 1	DC2	149	114	7.1	18	27.5	92.4
	DC3	154		7.7		30.1	
	DC4	152		9.3		34.1	
Dozer 2	DC2	101	81	16.3	6.2	17.9	40.7
	DC3	100		17.0		18.2	
	DC4	110		17.6		23.1	
Dozer 3	DC2	152	92	7.9	9.5	25.8	62.7
	DC3	143		8.0		28.5	
	DC4	152		9.0		37.6	

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Benchmarking Weighted Average Emission Rates with NONROAD Model

Equipment	Duty Cycle	NO_x (g/gal)		HC (g/gal)		CO (g/gal)	
		Cycle	NONROAD Model	Cycle	NONROAD Model	Cycle	NONROAD Model
Excavator 1	DC5	99	102	5.2	6.2	11.5	22.0
	DC6	102		4.9		10.9	
	DC7	102		4.6		10.2	
Excavator 2	DC5	82	81	9.6	6.8	29.6	25.5
	DC6	76		9.3		27.9	
	DC7	74		8.9		25.0	
Excavator 3	DC5	107	92	10.4	9.5	18.2	62.1
	DC6	107		9.7		15.9	
	DC7	104		8.8		13.6	

Benchmarking Weighted Average Emission Rates with NONROAD Model

Equipment	Duty Cycle	NO_x (g/gal)		HC (g/gal)		CO (g/gal)	
		Cycle	NONROAD Model	Cycle	NONROAD Model	Cycle	NONROAD Model
Off-Highway Truck	DC8	117	82	9.0	6.2	53.0	21.9
Backhoe 1	DC9	127	91	16.3	17.7	27.8	40.6
	DC10	150		13.3		20.2	
Backhoe 2	DC9	70	95	6.4	19.1	35.0	43.7
	DC10	100		5.4		31.8	
Skid Steer Loader	DC11	80	89	12.7	14.6	15.9	71.6
Generator	DC12	118	98	11.4	9.1	68.1	41.4