ENGINE VARIABLE IMPACT ANALYSIS OF FUEL USE AND EMISSIONS FOR HEAVY DUTY DIESEL MAINTENANCE EQUIPMENT

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Heavy Duty Diesel Equipment Emissions

6 Billion Gallons of Diesel Fuel

2 Million Items of Nonroad Equipment

NO_x = 657,000 tons

PM = 63,000 tons

CO = 1,100,000 tons

CO_2= 67,000,000 tons

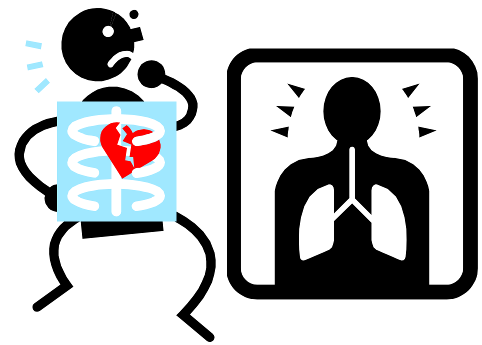
HC Precursor to Ground Level Ozone

Diesel Emissions Impacts

HEALTH

Allergies

Asthma



Heart/Lung Issues

ENVIRONMENT

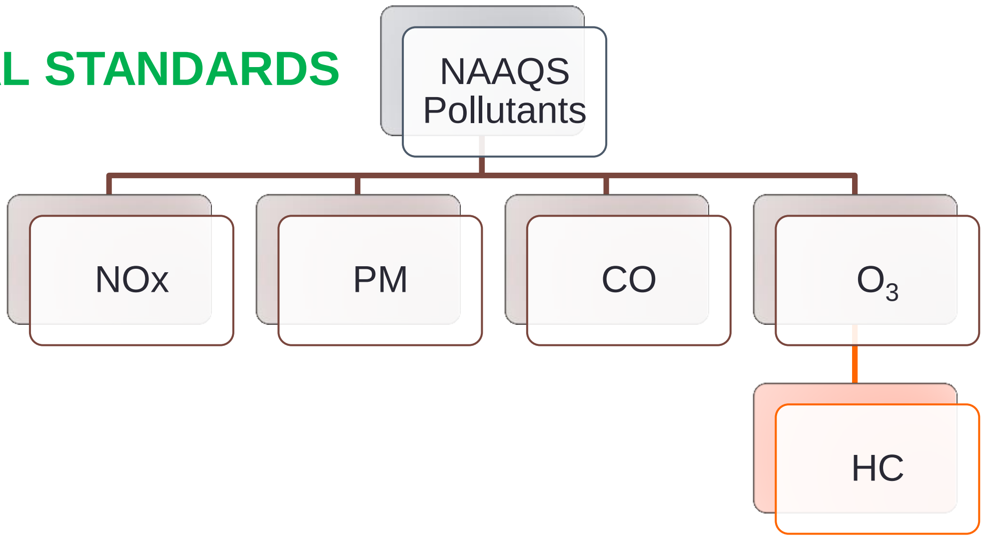
Smog

Acid Rain

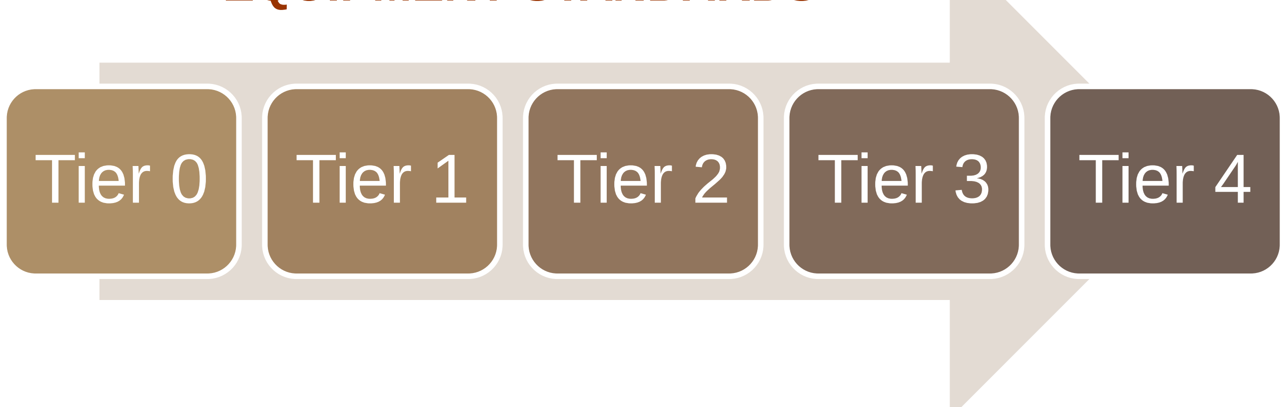
Global Warming

EPA Diesel Emissions Regulations

ENVIRONMENTAL STANDARDS

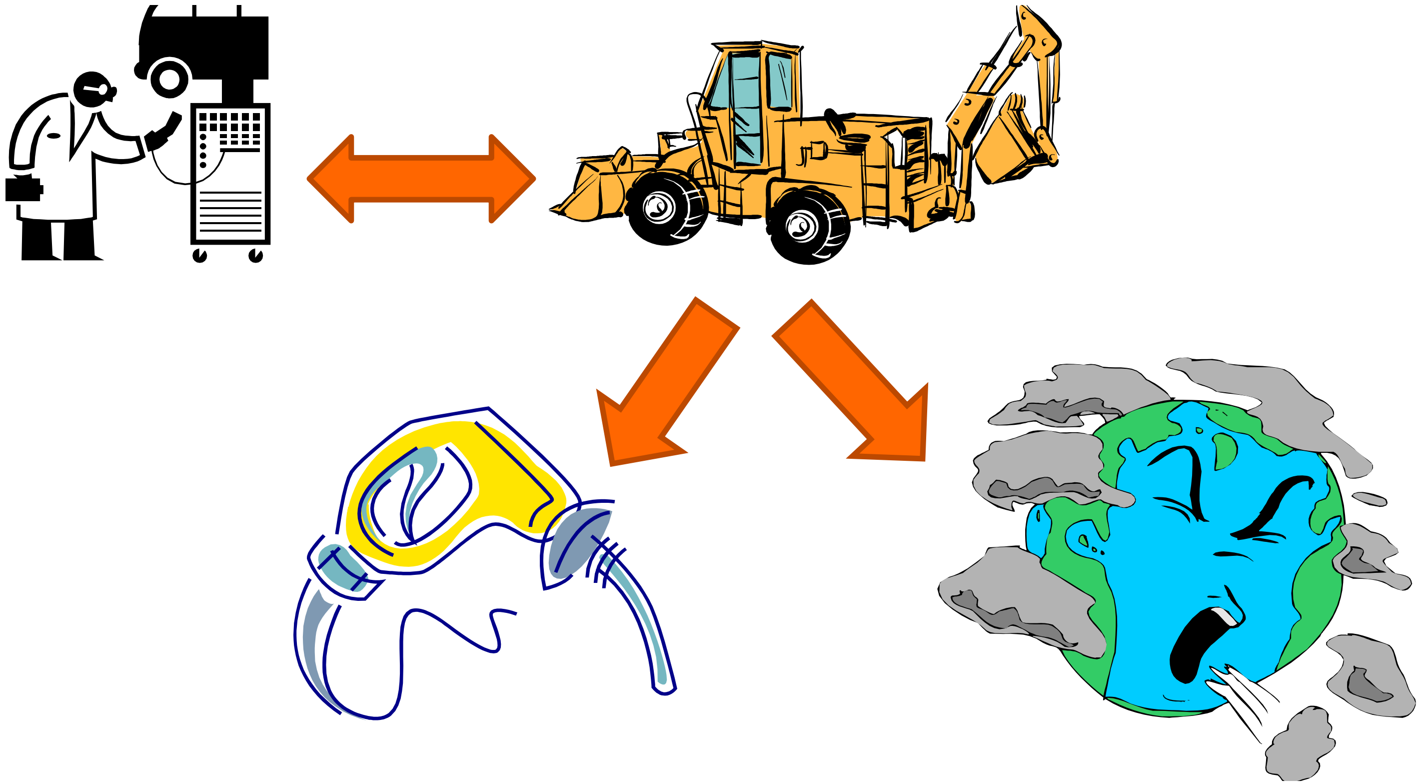


EQUIPMENT STANDARDS



Research Question

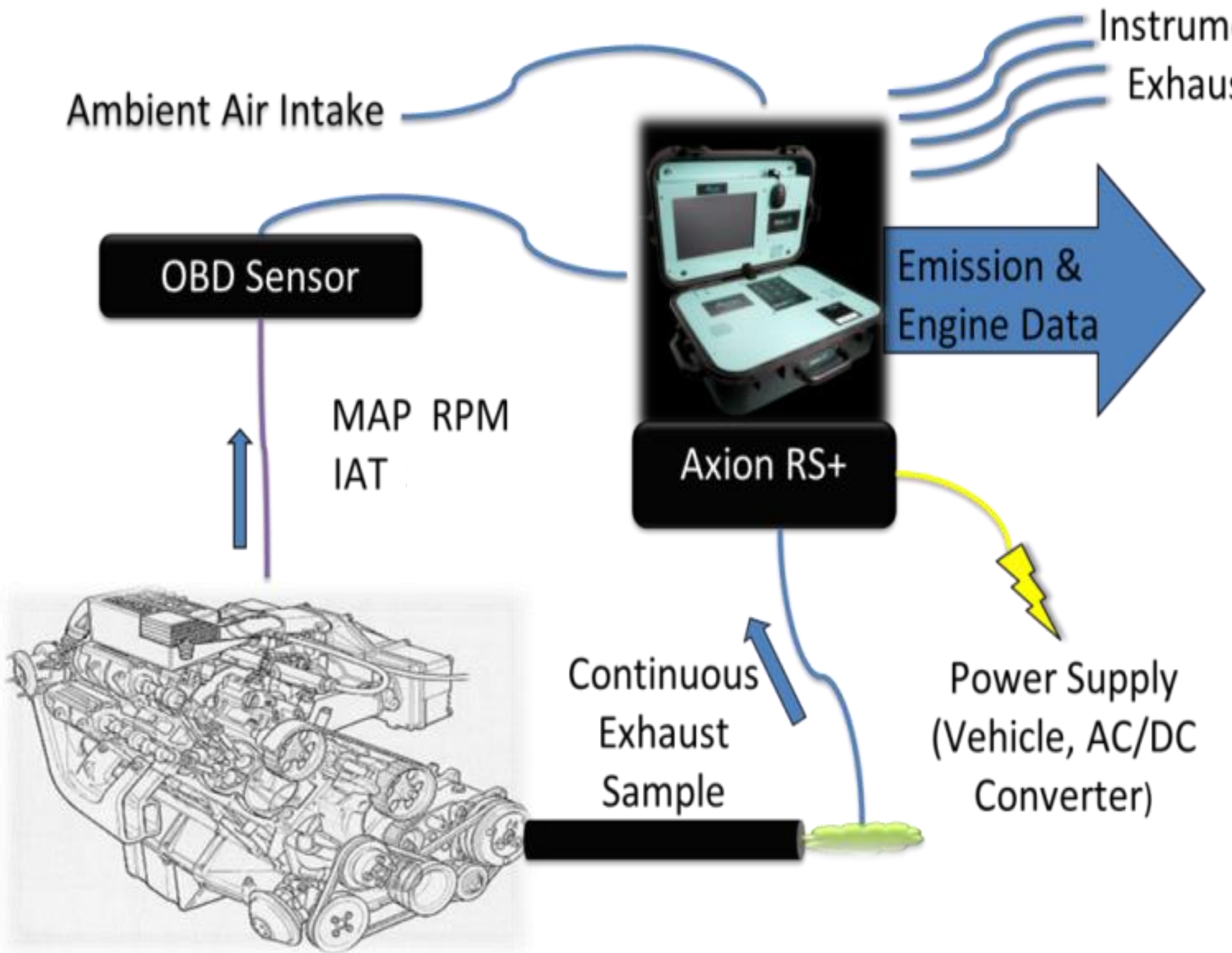
Which engine variables have the greatest impact on fuel use and pollutant emission rates for HDD equipment?



Case Study Fleet

Equipment	Horsepower (HP)	Displacement (Liters)	Model Year	Engine Tier	Data (s)
Backhoe 1	88	4.0	2004	2	8,780
Backhoe 2	88	4.2	1999	1	13,407
Backhoe 3	88	4.2	2000	1	9,853
Backhoe 4	97	3.9	2004	2	6,406
Backhoe 5	97	4.5	2004	2	5,379
Motor Grader 1	195	8.3	2001	1	16,293
Motor Grader 2	195	7.1	2004	2	10,767
Motor Grader 3	195	8.3	2001	1	5,590
Motor Grader 4	167	8.3	1990	0	10,040
Motor Grader 5	160	8.3	1993	0	9,788
Motor Grader 6	198	7.2	2007	3	7,757
Wheel Loader 1	149	5.9	2004	2	15,226
Wheel Loader 2	130	5.9	2002	1	19,064
Wheel Loader 3	130	5.9	2002	1	3,404
Wheel Loader 4	126	5.9	2002	1	6,718
Wheel Loader 5	133	6.0	2005	2	11,827

Equipment Data Collection



NO_x, PM, HC, CO, & CO_2

IAT, MAP, RPM

Analytical Methodology

Multiple Linear Regression

$$Y_{1\text{-}6} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

where:

$Y_{1\text{-}6}$ = Fuel Use, NO_x, HC, CO, CO_2, or PM (grams per second)

X_1 = Manifold Absolute Pressure (kilopascal)

X_2 = Engine Speed (RPM)

X_3 = Intake Air Temperature (Celsius degrees)

β_0, β_1, β_2, β_3 = Coefficients of linear relationship

Variable Impact Analysis

- The purpose of variable impact analysis (VIA) is to measure the sensitivity of prediction models to changes in independent variables
- Every independent variable is assigned a relative variable impact value; these are percent values and sum to 100%
- The lower the percent value for a given variable, the less impact the variable has on the predictions
- VIA is used to determine the relative impact of RPM, MAP, and IAT on predicting fuel use and emission rates of NO_x, HC, CO, CO_2, and PM

Summary Statistics Backhoes

Equipment	MAP (kPa)	RPM (rpm)	IAT (C)	Fuel (g/s)	NO_x (g/s)	HC (g/s)	CO (g/s)	CO_2 (g/s)	PM (g/s)
Backhoe 1	104	905	20	0.43	0.02	0.000	0.000	1.3	0.02
Backhoe 2	101	1,256	26	0.93	0.03	0.003	0.009	2.9	0.30
Backhoe 3	104	1,225	56	0.74	0.02	0.002	0.004	2.3	0.35
Backhoe 4	112	1,119	51	0.41	0.02	0.002	0.001	1.3	0.09
Backhoe 5	111	1,095	47	0.42	0.02	0.002	0.003	1.3	0.11
Average	***106***	***1,120***	***40***	***0.58***	***0.02***	***0.002***	***0.003***	***1.8***	***0.17***

Summary Statistics Motor Graders

Equipment	MAP (kPa)	RPM (rpm)	IAT (C)	Fuel (g/s)	NO_x (g/s)	HC (g/s)	CO (g/s)	CO_2 (g/s)	PM (g/s)
Motor Grader 1	174	1,789	30	4.8	0.18	0.015	0.02	15	1.40
Motor Grader 2	115	1,167	45	1.5	0.05	0.014	0.01	4.7	0.27
Motor Grader 3	149	1,746	41	2.2	0.08	0.042	0.01	7.0	0.78
Motor Grader 4	113	1,827	0	2.5	0.16	0.032	0.04	8.0	0.63
Motor Grader 5	120	1,405	12	2.3	0.12	0.014	0.05	9.9	0.53
Motor Grader 6	169	1,839	60	2.2	0.04	0.010	0.01	10	0.51
Average	***140***	***1,628***	***31***	***2.6***	***0.11***	***0.021***	***0.02***	***9.1***	***0.68***

Summary Statistics Wheel Loaders

Equipment	MAP (kPa)	RPM (rpm)	IAT (C)	Fuel (g/s)	NO_x (g/s)	HC (g/s)	CO (g/s)	CO_2 (g/s)	PM (g/s)
Wheel Loader 1	122	1,217	30	1.5	0.05	0.012	0.02	4.8	0.42
Wheel Loader 2	118	1,373	21	1.4	0.05	0.002	0.01	4.3	0.41
Wheel Loader 3	119	1,192	19	0.8	0.04	0.002	0.05	2.6	0.12
Wheel Loader 4	126	1,392	18	1.0	0.04	0.004	0.00	3.2	0.31
Wheel Loader 5	105	1,072	33	0.7	0.22	0.002	0.01	2.2	0.13
Average	***118***	***1,249***	***24***	***1.1***	***0.08***	***0.004***	***0.02***	***3.4***	***0.28***

MLR R^2 Values

Equipment	Fuel Use	NO_x	HC	CO	CO_2	PM
Backhoe 1	0.91	0.76	0.42	0.67	0.90	0.11
Backhoe 2	0.92	0.85	0.15	0.18	0.92	0.32
Backhoe 3	0.96	0.87	0.71	0.24	0.96	0.50
Backhoe 4	0.94	0.87	0.78	0.65	0.94	0.89
Backhoe 5	0.91	0.88	0.57	0.62	0.91	0.88
Average	***0.93***	***0.85***	***0.53***	***0.47***	***0.93***	***0.54***
Motor Grader 1	0.78	0.62	0.36	0.31	0.78	0.83
Motor Grader 2	0.97	0.84	0.41	0.12	0.96	0.72
Motor Grader 3	0.92	0.79	0.58	0.17	0.92	0.92
Motor Grader 4	0.90	0.75	0.25	0.13	0.90	0.71
Motor Grader 5	0.98	0.89	0.58	0.13	0.98	0.83
Motor Grader 6	0.92	0.45	0.60	0.12	0.92	0.90
Average	***0.91***	***0.72***	***0.46***	***0.16***	***0.91***	***0.81***
Wheel Loader 1	0.86	0.71	0.80	0.49	0.86	0.85
Wheel Loader 2	0.96	0.90	0.78	0.13	0.96	0.87
Wheel Loader 3	0.90	0.84	0.78	0.39	0.89	0.87
Wheel Loader 4	0.91	0.84	0.25	0.47	0.91	0.79
Wheel Loader 5	0.96	0.89	0.51	0.52	0.96	0.87
Average	***0.92***	***0.89***	***0.62***	***0.40***	***0.92***	***0.85***
Overall Average	***0.92***	***0.80***	***0.54***	***0.33***	***0.91***	***0.72***

Variable Impact Analysis

Equipment	Variable	Fuel Use	NO_x	HC	CO	CO_2	PM
Backhoes (n = 5)	MAP	51	34	26	26	48	34
	RPM	35	53	55	46	42	41
	IAT	14	13	19	28	10	25
	Total	*100*	*100*	*100*	*100*	*100*	*100*
Motor Graders (n = 6)	MAP	69	56	34	53	67	62
	RPM	25	29	37	28	25	25
	IAT	6	15	29	19	8	13
	Total	*100*	*100*	*100*	*100*	*100*	*100*
Wheel Loaders (n = 5)	MAP	53	54	23	43	54	58
	RPM	38	33	57	31	38	28
	IAT	9	13	20	26	8	14
	Total	*100*	*100*	*100*	*100*	*100*	*100*
Overall (n = 16)	MAP	58	48	28	41	56	51
	RPM	33	38	50	35	35	31
	IAT	9	14	22	24	9	18
	Total	*100*	*100*	*100*	*100*	*100*	*100*

Simple Linear Regression Models

$$MAP_{norm} = \frac{MAP_i - MAP_{min}}{MAP_{max} - MAP_{min}}$$

where:

MAP_{norm} = Normalized MAP (%)

MAP_i = MAP value at time *i* (kilopascal)

MAP_{min} = Minimum MAP value (kilopascal)

MAP_{max} = Maximum MAP value (kilopascal)

$$Y_{1\text{-}6} = mX + b$$

where:

$Y_{1\text{-}6}$ = Fuel use or emission rate of NO_x, HC, CO, CO_2, or PM

m = slope of the regression line

X = Engine load (%) (or MAP_{norm})

b = y-intercept

SLR R^2 Values

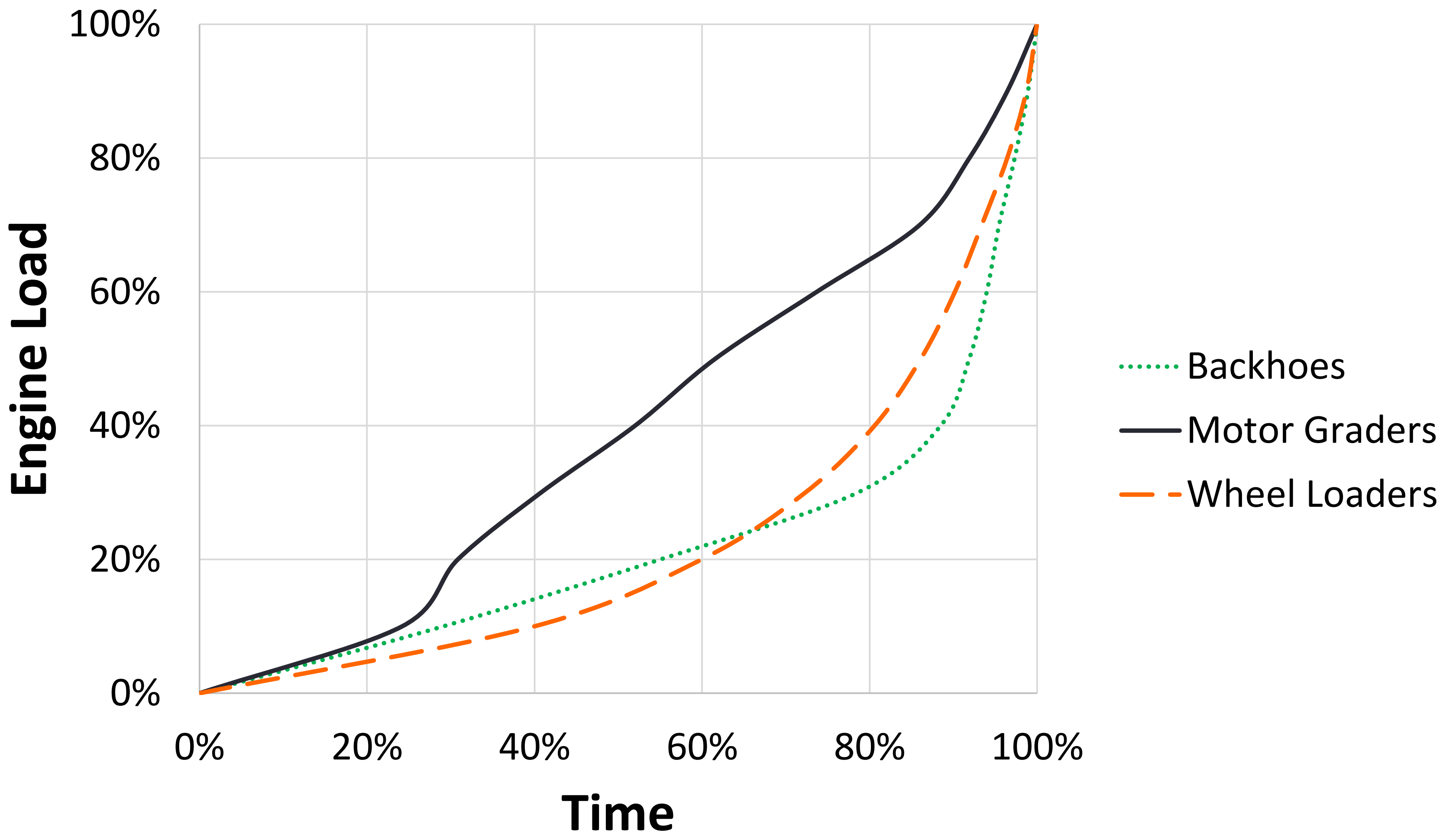
Equipment	Fuel Use	NO_x	HC	CO	CO_2	PM
Backhoe 1	0.86	0.62	0.17	0.01	0.86	0.06
Backhoe 2	0.83	0.62	0.05	0.14	0.83	0.28
Backhoe 3	0.96	0.78	0.67	0.25	0.96	0.37
Backhoe 4	0.89	0.79	0.66	0.62	0.89	0.89
Backhoe 5	0.77	0.75	0.4	0.5	0.77	0.85
Average	***0.86***	***0.71***	***0.39***	***0.30***	***0.86***	***0.49***
Motor Grader 1	0.76	0.60	0.19	0.26	0.76	0.81
Motor Grader 2	0.95	0.79	0.24	0.12	0.96	0.67
Motor Grader 3	0.92	0.75	0.51	0.17	0.92	0.91
Motor Grader 4	0.88	0.74	0.18	0.10	0.88	0.69
Motor Grader 5	0.98	0.89	0.49	0.08	0.98	0.82
Motor Grader 6	0.92	0.44	0.07	0.06	0.92	0.85
Average	***0.90***	***0.70***	***0.28***	***0.13***	***0.90***	***0.79***
Wheel Loader 1	0.84	0.67	0.74	0.47	0.84	0.81
Wheel Loader 2	0.94	0.87	0.74	0.01	0.94	0.84
Wheel Loader 3	0.89	0.82	0.69	0.34	0.89	0.84
Wheel Loader 4	0.85	0.78	0.13	0.31	0.85	0.75
Wheel Loader 5	0.95	0.88	0.43	0.50	0.95	0.85
Average	***0.89***	***0.81***	***0.54***	***0.33***	***0.89***	***0.82***
Overall Average	***0.89***	***0.74***	***0.40***	***0.25***	***0.89***	***0.71***

SLR Model Results

***Y* = *mX* + *b*, where *X* = Engine Load**

	Tier 0		Tier 1		Tier 2	
Y	**m**	**b**	**m**	**b**	**m**	**b**
Fuel Use (gal/h)	10	0.4	5.4	0.3	4.9	0.4
NO_x (lb/h)	3.8	0.2	1.2	0.2	0.9	0.9
HC (lb/h)	0.2	0.1	0.2	0.0	0.1	0.0
CO (lb/h)	0.2	0.2	0.1	0.0	0.1	0.0
CO_2 (lb/h)	225	8.0	120	6.0	110	8.0
PM (g/h)	8.8	0.3	5.3	0.3	3.3	0.2

Cumulative Frequency Diagram



Conclusions

- MAP, followed by RPM, has the greatest impact on mass per time rates of fuel use, NO_x, CO, CO_2, and PM;
- RPM, followed by MAP, has the greatest impact on mass per time rates of HC;
- IAT has the least impact on mass per time rates of fuel use, NO_x, HC, CO, CO_2, and PM;
- HC and CO are difficult to predict because of high variability in the data; and
- SLR models provide a practical and statistically defensible fuel use and emissions estimating tool for backhoes, motor graders, and wheel loaders.

Recommendations

- Other types of equipment should be included in the study;
- Other equipment variables, such as engine horsepower and gross vehicle weight, should be included in the study;
- Mass per fuel used emission rates may be used to estimate emissions inventories by fleet owners that keep meticulous fuel use records;
- Fuel use forecasts should help improve estimates of equipment operating costs as well as total highway maintenance activity costs; and
- Fleet managers, particularly those that oversee publicly owned fleets, should not overlook the environmental impacts of their equipment.