DEVELOPMENT OF A FUEL CONSUMPTION AND EMISSIONS TAXONOMY FOR NONROAD DIESEL EQUIPMENT (16-6242)

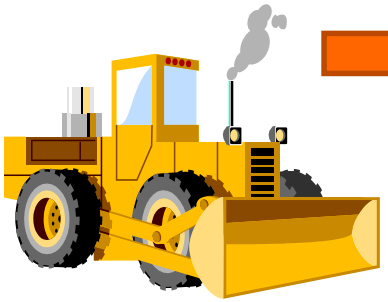
Phil Lewis, PhD, PE
Oklahoma State University

Heni Fitriani, PhD
University of Sriwijaya (Indonesia)

Yongwei Shan, PhD
Oklahoma State University

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

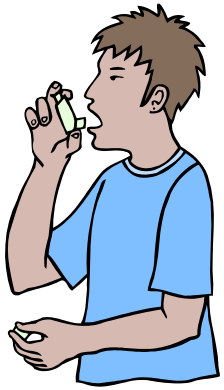
CO_2= 67,000,000 tons

HC Precursor to Ground Level Ozone

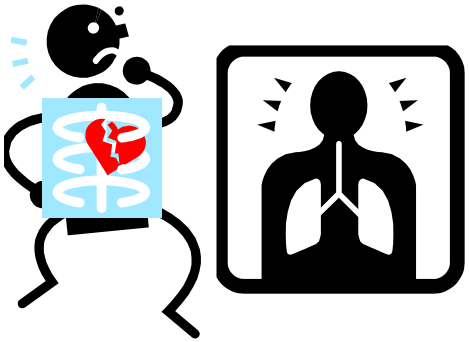
Diesel Emissions Impacts

HEALTH

Allergies



Asthma



Heart/Lung Issues

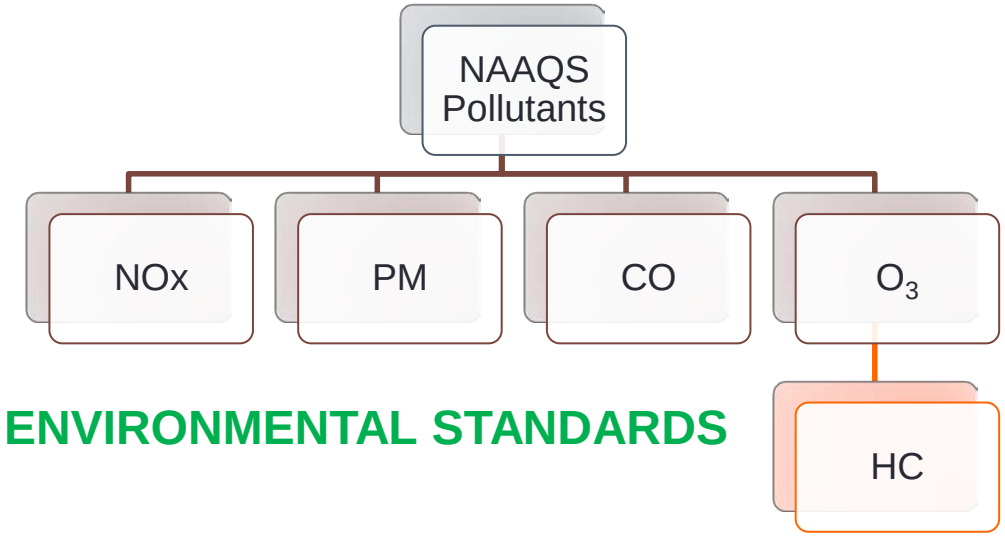
ENVIRONMENT

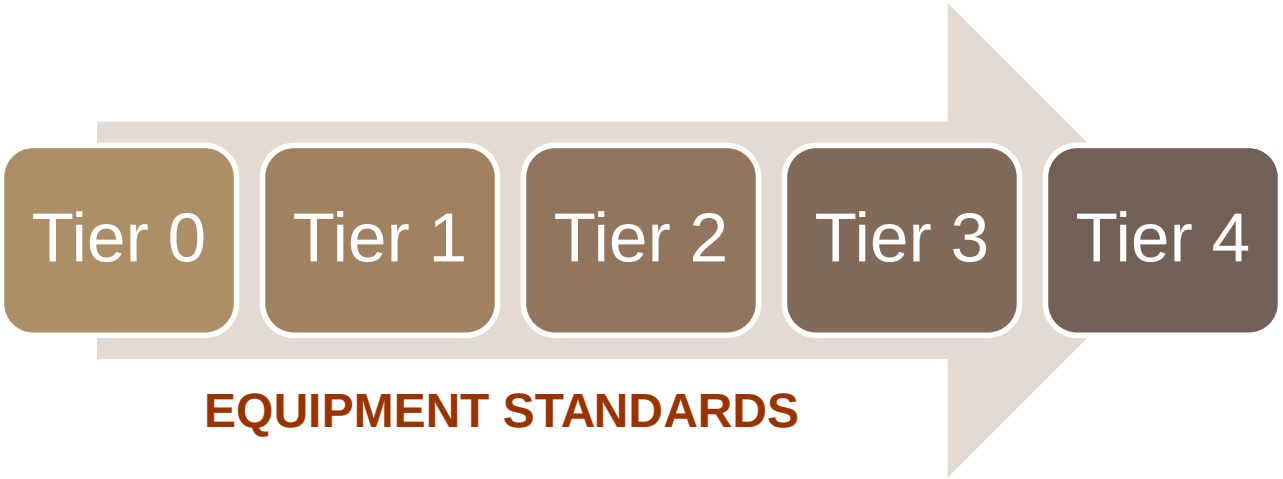
Smog

Acid Rain

Global Warming

EPA Diesel Emissions Regulations





Current Events

World Meteorological Organization
Weather · Climate · Water

GLOBAL ATMOSPHERE WATCH

WMO GREENHOUSE GAS BULLETIN

The State of Greenhouse Gases in the Atmosphere
Based on Global Observations through 2014

Claims global averages of CO_2 in the atmosphere reached new highs in 2014

Volkswagen: The scandal explained

By Russell Hotten
Business reporter, BBC News

10 December 2015 | Business

Used “defeat devices” to falsify emissions data

EPA Strengthens Ozone Standards

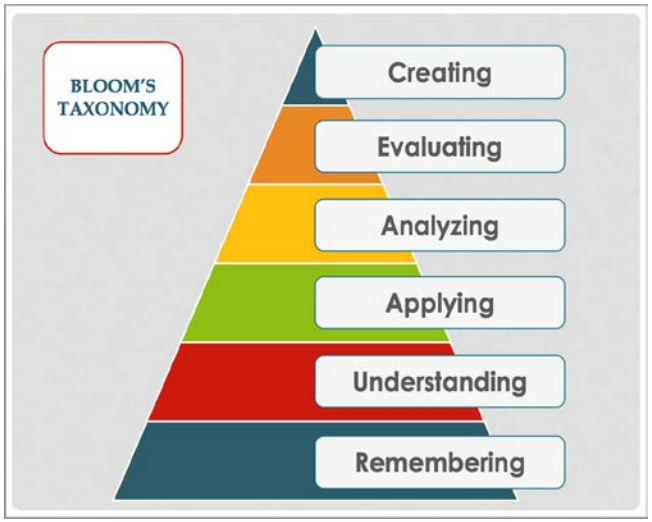
Oct 01, 2015

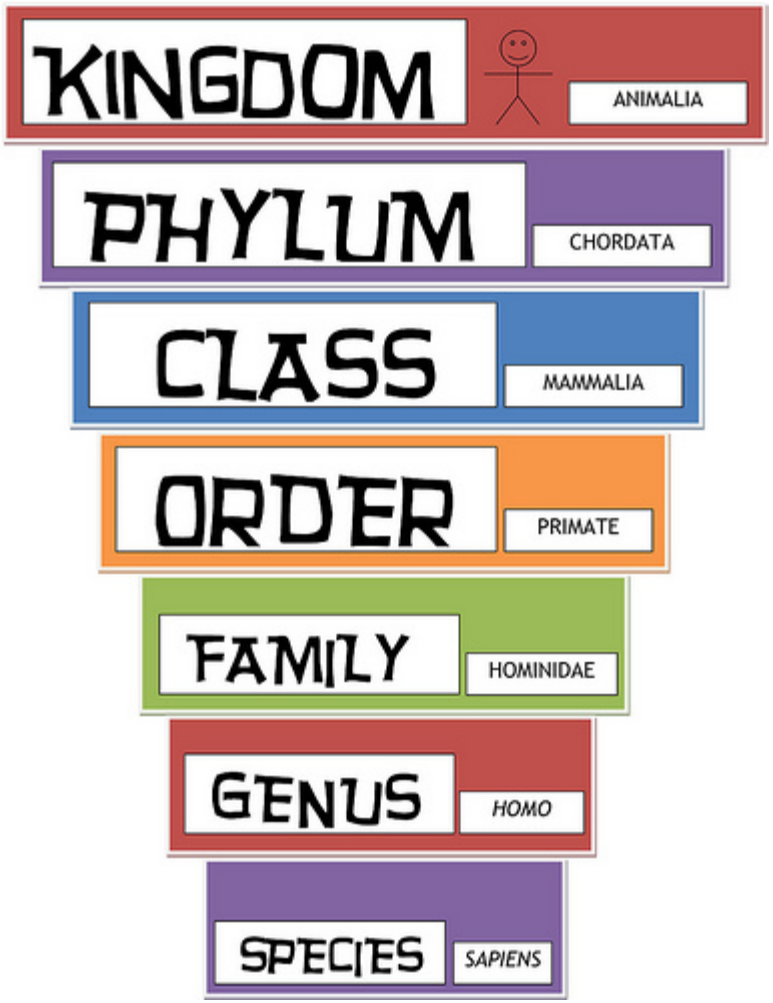
Ground-level ozone 75 ppb -> 70 ppb

Management

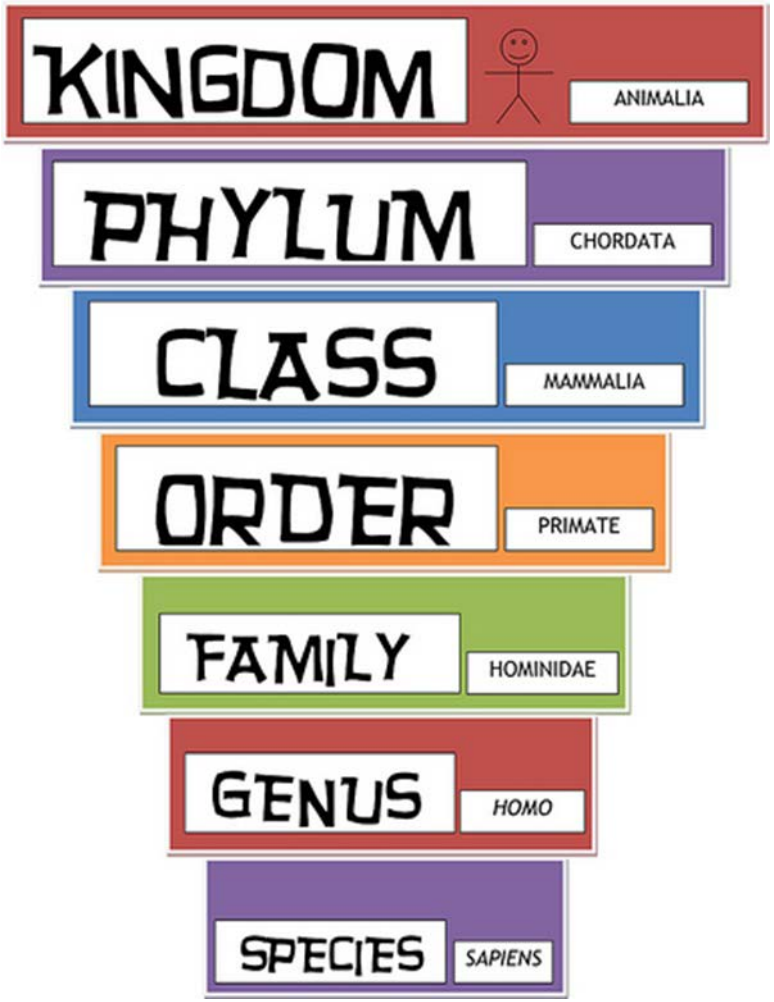
Taxonomy

The process or system of describing the way in which different things are related by putting them in groups





Equipment Taxonomy

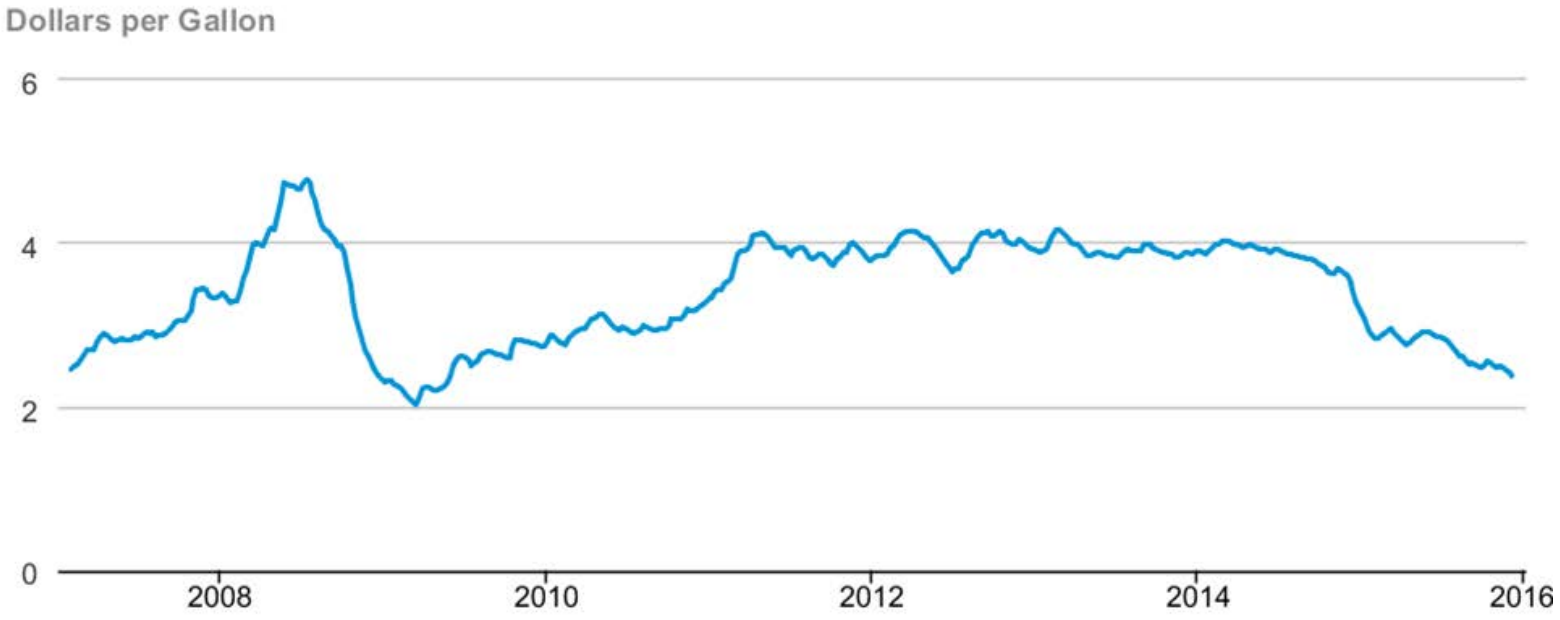


- FOSSIL FUEL VEHICLES
- DIESEL VEHICLES
- HEAVY DUTY EQUIPMENT
- NONROAD EQUIPMENT
- CONSTRUCTION EQUIPMENT
- TRACK-TYPE TRACTORS
- DOZERS

Diesel Fuel

Diesel fuel is the lifeblood of the equipment

It is expensive and its price is hard to predict



Weekly U.S. No. 2 Diesel Ultra Low Sulfur Retail Prices
(Source: U.S. Energy Information Administration, 2015)

Estimating Fuel Use

We can't predict fuel prices but we can estimate quantity

- Fuel Efficiency
  - Unit of work per unit of fuel (tons/gallon) – like *mpg* for cars
  - Hard to compute – most equipment fleet managers don't bother
- Fuel Burn Rate (or *Fuel Use* or *Fuel Consumption*)
  - Most accurately measured in field, but time consuming
  - $FC = FF \times HP \times LF$ (1)

FC = hourly fuel consumption rate (gal/h)
FF = fuel factor (gal/hp-h)
HP = engine rated horsepower (hp)
LF = engine load factor (%)

Estimating Fuel Use

*Equipment Handbooks provide **some** guidance for FF*

BACKHOE LOADERS

Model	Low		Medium		High	
	liter	U.S. gal	liter	U.S. gal	liter	U.S. gal
416E (Tier 2) 56 kW/75 hp	1.9-7.9	0.5-2.1	7.9-12.1	2.1-3.2	12.1-14.4	3.2-3.8
416E (Tier 2) 68.5 kW/92 hp	2.6-11.7	0.7-3.1	11.7-16.7	3.1-4.4	16.7-18.9	4.4-5.0
416F (Tier 4 Interim) 70 kW/94 hp	2.6-12.4	0.7-3.3	12.4-17.4	3.3-4.6	17.4-19.0	4.6-5.0
420F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
420F (Tier 4 Interim) 74.5 kW/100 hp	2.9-13.6	0.8-3.6	13.6-18.9	3.6-5.0	18.9-19.7	5.0-5.2
422F (Tier 2) 56.5 kW/75 hp	1.9-7.9	0.5-2.1	7.9-12.1	2.1-3.2	12.1-14.4	3.2-3.8
422F (Tier 2) 68.5 kW/92 hp	2.6-11.7	0.7-3.1	11.7-16.7	3.1-4.4	16.7-18.9	4.4-5.0
428F (Tier 2) 70 kW/94 hp	2.6-11.0	0.7-2.9	11.0-16.7	2.9-4.4	16.7-19.3	4.4-5.1
428F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
428F (Stage 3a) 70 kW/94 hp	2.6-11.0	0.7-2.9	11.0-16.7	2.9-4.4	16.7-19.3	4.4-5.1
428F (Stage 3a) 74.5 kW/100 hp	2.6-11.4	0.7-3.0	11.4-17.0	3.0-4.5	17.0-20.8	4.5-5.5
428F (Stage 3b) 70 kW/94 hp	2.6-12.4	0.7-3.3	12.4-17.4	3.3-4.6	17.4-19.0	4.6-5.0
428F (Stage 3b) 74.5 kW/100 hp	2.9-13.6	0.8-3.6	13.6-18.9	3.6-5.0	18.9-19.7	5.0-5.2
430F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
430F (Tier 4 Interim) 86 kW/115 hp	3.1-14.8	0.8-3.9	14.8-20.9	3.9-5.5	20.9-22.8	5.5-6.0
432F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
432F (Stage 3a) 74.5 kW/100 hp	2.6-11.4	0.7-3.0	11.4-17.0	3.0-4.5	17.0-20.8	4.5-5.5
432F (Stage 3b) 82 kW/110 hp	2.9-13.7	0.8-3.6	13.7-19.0	3.6-5.0	19.0-21.9	5.0-5.8
434F (Tier 2) 68.5 kW/92 hp	2.6-11.7	0.7-3.1	11.7-16.7	3.1-4.4	16.7-18.9	4.4-5.0
434F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
434F (Stage 3a) 70 kW/94 hp	2.6-11.0	0.7-2.9	11.0-16.7	2.9-4.4	16.7-19.3	4.4-5.1
434F (Stage 3a) 74.5 kW/100 hp	2.6-11.4	0.7-3.0	11.4-17.0	3.0-4.5	17.0-20.8	4.5-5.5
434F (Stage 3b) 74.5 kW/100 hp	2.9-13.6	0.8-3.6	13.6-18.9	3.6-5.0	18.9-19.7	5.0-5.2
444F (Tier 2) 74.5 kW/100 hp	2.6-11.7	0.7-3.1	11.7-17.4	3.1-4.6	17.4-20.1	4.6-5.3
444F (Stage 3a) 74.5 kW/100 hp	2.6-11.4	0.7-3.0	11.4-17.0	3.0-4.5	17.0-20.8	4.5-5.5
444F (Stage 3b) 82 kW/110 hp	2.9-13.7	0.8-3.6	13.7-19.0	3.6-5.0	19.0-21.9	5.0-5.8
450E (Tier 3) 102 kW/137 hp	3.1-13.6	0.8-3.6	13.6-21.9	3.6-5.8	21.9-26.1	5.8-6.9
450F (Tier 4 Interim) 106 kW/142 hp	3.3-16.2	0.9-4.3	16.2-23.1	4.3-6.1	23.1-27.1	6.1-7.2

Estimating Fuel Use

Also need an estimate for LF

Backhoe Loaders
Typical Application Description
(relative to work application)

Low	Light duty utility applications with intermittent cycles in light to medium soil. Trenching depths less than 1.83 m **(6 feet)**.
Medium	General utility applications with regular cycles in medium to heavy soil. Dig depths to 3.05 m **(10 feet)**. Occasional use of constant flow implements.
High	Production applications or digging in rock. Dig depths over 3.05 m **(10 feet)**. Long cycle times or regular use of constant flow implements.

Load Factor Guide
(average engine load factor based on application description for each range)

Low	20%-40%
Medium	40%-65%
High	65%-80%

Example

Extremely high variability in estimates of FF and LF

Example 420 F Backhoe (100 HP)

- FF ranges from 0.7 to 3.1 gal/h for Low Application
- LF ranges from 20% to 40%
  - Therefore, FC ranges from 0.14 to 1.24 gal/h (785% Difference)
  - That's only if we get the Application right

Maybe we should just use an average FF

Most textbooks use FF = 0.04 gal/hp-h

None of this helps with estimating emissions

Objectives

1. Evaluate the efficacy of *FF = 0.04 gal/hp-h* using real world, in-use equipment data;
2. Conduct an engine modal analysis of equipment data to determine the distribution of time, fuel use, and emissions over the full range of equipment engine loads;
3. Compute weighted average fuel use and emissions rates based on the amount of time spent in each engine mode; and
4. Develop a taxonomy of fuel use and emissions rates based on equipment type and EPA engine tier technology type.

Methodology

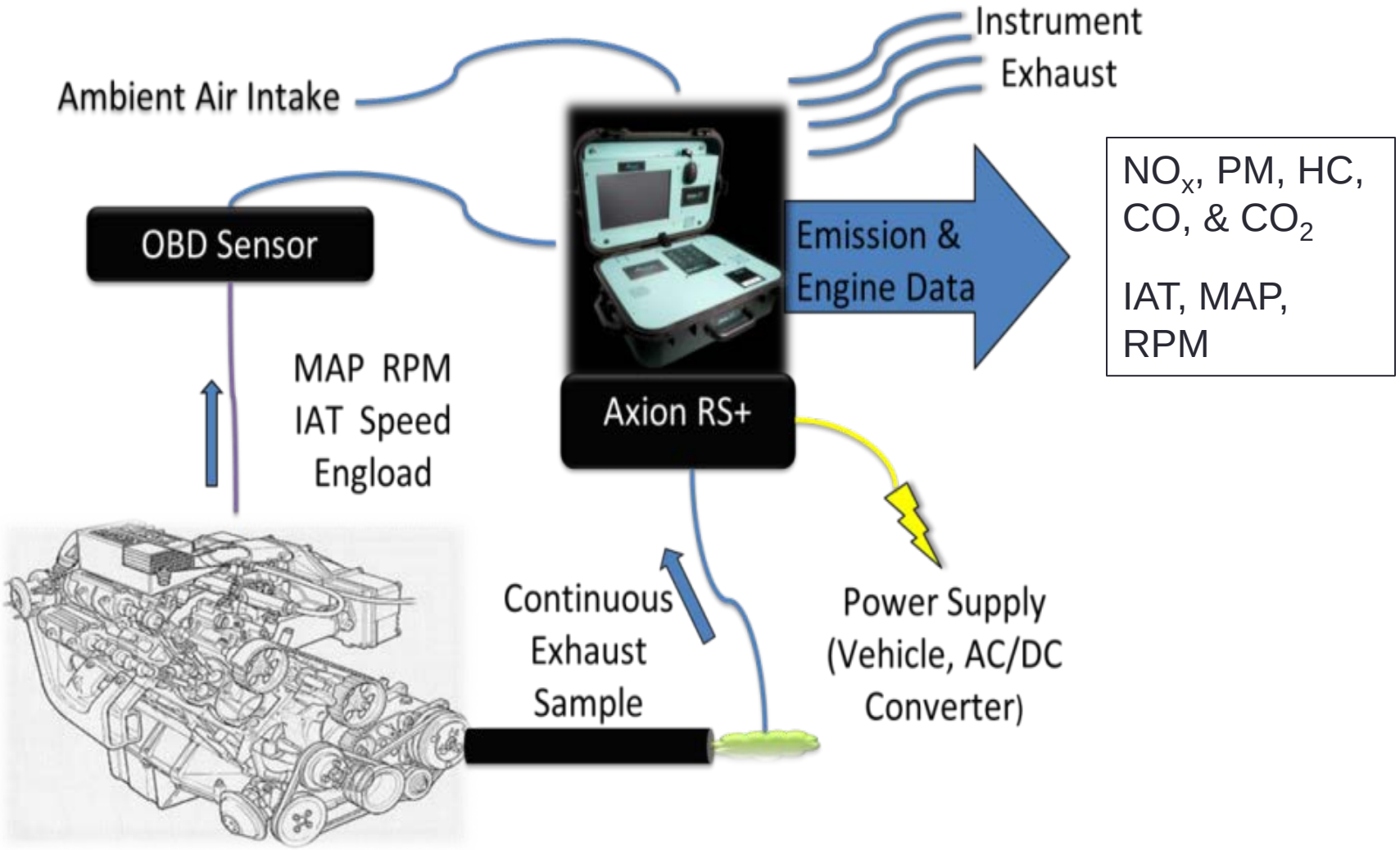
Collect real world fuel use and emissions data from HDD equipment in the field

Conduct an engine modal analysis to categorize the fuel consumption and emissions data according to engine load

Calculate weighted average fuel use and emissions rates based on the results of the engine modal analysis

Develop a taxonomy of fuel use and emissions rates based on the modal weighted averages

Data Collection



Engine Modal Analysis

$$MAP_{norm} = \frac{MAP - Min\ MAP}{Max\ MAP - Min\ MAP}\ x\ 100 \qquad (2)$$

where:
- MAP_{norm} = normalized MAP value (%)
- MAP = instantaneous MAP measurement from PEMS (kilopascals)
- $Min\ MAP$ = minimum MAP measurement from PEMS (kilopascals)
- $Max\ MAP$ = maximum MAP measurement from PEMS (kilopascals)

$$Ho: \mu = 0.04\ gal/hp\text{-}h \qquad Ha: \mu \neq 0.04\ gal/hp\text{-}h \qquad (3)$$

Fuel Use & Emissions Rates

$$FC = \sum_{i=1}^{10} Ti \; x \; Fi \qquad (4)$$

where: FC = weighted average fuel consumption rate (gal/hp-h)
Ti = time spent in mode i (%)
Fi = fuel consumption rate in mode i (gal/hp-h)

$$ERj = \sum_{i=1}^{10} Ti \; x \; Eij \qquad (5)$$

where: ERj = weighted average emission rate for pollutant j (g/hp-h)
Ti = time spent in mode i (%)
Eij = emission rate in mode i for pollutant j (g/hp-h)

$$ER'j = \frac{ERj}{FC} \qquad (6)$$

where: $ER'j$ = mass per fuel used weighted average emission rate for pollutant j (g/gal)

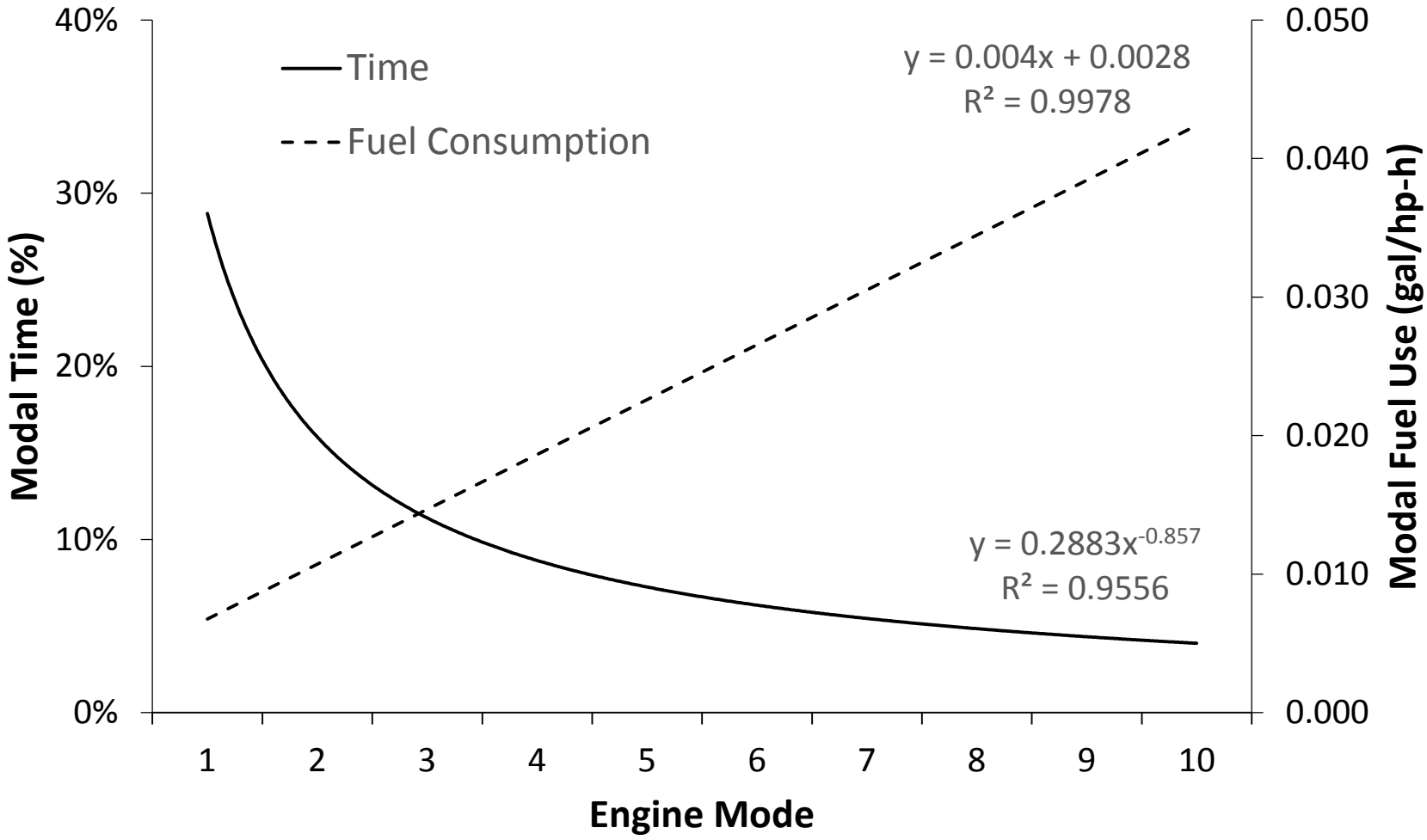
Data Collection Results

Equipment	Horsepower (HP)	Displacement (L)	Model Year	Engine Tier
Backhoe 1	88	4.0	2004	2
Backhoe 2	88	4.2	1999	1
Backhoe 3	88	4.2	2000	1
Backhoe 4	97	3.9	2004	2
Backhoe 5	99	4.5	1999	1
Backhoe 6	97	4.5	2004	2
Bulldozer 1	89	5.0	1988	0
Bulldozer 2	95	3.9	2002	1
Bulldozer 3	90	5.0	2003	1
Bulldozer 4	175	10.5	1998	1
Bulldozer 5	285	14.2	1995	0
Bulldozer 6	99	4.2	2005	2
Excavator 1	254	8.3	2001	1
Excavator 2	138	6.4	2003	2
Excavator 3	93	3.9	1998	1
Motor Grader 1	195	8.3	2001	1
Motor Grader 2	195	7.1	2004	2
Motor Grader 3	195	8.3	2001	1
Motor Grader 4	167	8.3	1990	0
Motor Grader 5	160	8.3	1993	0
Off-Road Truck 1	306	9.6	2005	2
Off-Road Truck 2	285	10.3	1998	1
Off-Road Truck 3	285	10.3	1998	1
Track Loader 1	121	7.2	1998	1
Track Loader 2	70	4.5	1997	0
Track Loader 3	127	7.2	2006	2
Wheel Loader 1	149	5.9	2004	2
Wheel Loader 2	130	5.9	2002	1
Wheel Loader 3	130	5.9	2002	1
Wheel Loader 4	126	5.9	2002	1
Wheel Loader 5	133	6.0	2005	2

Engine Modal Analysis

Modal Fuel Consumption Rates, *Fi* (gal/hp-h)								
Mode	**BH**	**BD**	**EX**	**MG**	**OT**	**TL**	**WL**	***Average***
1	0.004	0.006	0.010	0.003	0.004	0.010	0.005	*0.006*
2	0.008	0.013	0.013	0.009	0.012	0.013	0.009	*0.011*
3	0.011	0.019	0.015	0.013	0.017	0.017	0.012	*0.015*
4	0.014	0.024	0.018	0.016	0.021	0.028	0.016	*0.019*
5	0.016	0.028	0.021	0.020	0.025	0.032	0.018	*0.023*
6	0.019	0.032	0.023	0.024	0.029	0.035	0.021	*0.026*
7	0.021	0.037	0.026	0.028	0.032	0.040	0.024	*0.030*
8	0.024	0.042	0.028	0.032	0.035	0.048	0.028	*0.034*
9	0.027	0.047	0.031	0.037	0.040	0.056	0.032	*0.039*
10	0.030	0.050	0.033	0.042	0.043	0.063	0.039	*0.043*
Modal Time, *Ti* (%)								
Mode	**BH**	**BD**	**EX**	**MG**	**OT**	**TL**	**WL**	***Average***
1	29%	25%	31%	24%	72%	27%	40%	*35%*
2	26%	15%	5%	7%	10%	5%	20%	*13%*
3	24%	16%	8%	10%	5%	4%	12%	*11%*
4	10%	9%	8%	11%	3%	4%	8%	*8%*
5	3%	7%	10%	10%	2%	8%	6%	*6%*
6	2%	7%	11%	12%	2%	13%	4%	*7%*
7	1%	5%	10%	12%	2%	9%	3%	*6%*
8	2%	4%	9%	6%	2%	8%	3%	*5%*
9	2%	7%	6%	5%	1%	9%	2%	*5%*
10	1%	6%	2%	4%	1%	14%	1%	*4%*

Modal Fuel Use vs. Modal Time



Sample Calculations

Mode	*Ti* (%)	*Fi* (gal/hp-h)	*Ti* × *Fi* (gal/hp-h)	*Ei* (g/hp-h)	*Ti* × *Ei* (g/hp-h)
1	29%	0.005	0.0015	1.1	0.3
2	26%	0.013	0.0034	2.4	0.6
3	24%	0.019	0.0045	3.3	0.8
4	10%	0.026	0.0026	4.4	0.4
5	3%	0.030	0.0010	4.9	0.2
6	2%	0.034	0.0007	5.3	0.1
7	1%	0.039	0.0006	5.9	0.1
8	2%	0.046	0.0009	7.6	0.1
9	2%	0.053	0.0008	9.3	0.1
10	1%	0.060	0.0007	10.9	0.1
Weighted Average			**0.017**		**2.9**

Mass Per Time Taxonomy

Variable	Tier	BH	BD	EX	MG	OT	TL	WL	*Average*
FC (gal/hp-h)	**Tier 0**	0.017	0.024	0.025	0.026	0.011	0.031	0.017	*0.022*
	Tier 1	0.013	0.018	0.019	0.020	0.009	0.023	0.013	*0.016*
	Tier 2	0.012	0.015	0.016	0.016	0.009	0.018	0.012	*0.014*
NO_x (g/hp-h)	**Tier 0**	2.9	4.1	4.2	4.3	1.9	5.2	2.9	*3.6*
	Tier 1	1.7	2.2	2.3	2.4	1.2	2.7	1.7	*2.0*
	Tier 2	1.2	1.5	1.5	1.5	1.0	1.7	1.2	*1.4*
HC (g/hp-h)	**Tier 0**	0.25	0.3	0.31	0.32	0.18	0.34	0.25	*0.28*
	Tier 1	0.17	0.2	0.21	0.22	0.13	0.23	0.17	*0.19*
	Tier 2	0.15	0.16	0.16	0.17	0.12	0.17	0.14	*0.15*
CO (g/hp-h)	**Tier 0**	0.68	0.71	0.69	0.73	0.49	0.72	0.64	*0.67*
	Tier 1	0.43	0.59	0.61	0.61	0.33	0.75	0.44	*0.54*
	Tier 2	0.39	0.44	0.44	0.46	0.29	0.49	0.38	*0.41*
CO_2 (g/hp-h)	**Tier 0**	175	251	264	275	116	325	178	*226*
	Tier 1	136	192	203	212	95	247	139	*175*
	Tier 2	127	162	167	172	99	195	128	*150*
PM (g/hp-h)	**Tier 0**	0.017	0.024	0.026	0.027	0.011	0.031	0.017	*0.022*
	Tier 1	0.014	0.020	0.021	0.022	0.010	0.027	0.014	*0.018*
	Tier 2	0.009	0.012	0.012	0.013	0.007	0.015	0.009	*0.011*

Mass Per Fuel Used Taxonomy

Variable	Tier	BH	BD	EX	MG	OT	TL	WL	*Average*
NO_x (g/gal)	**Tier 0**	171	171	168	165	173	168	171	*169*
	Tier 1	131	122	121	120	133	117	131	*125*
	Tier 2	100	100	94	94	111	94	100	*99*
HC (g/gal)	**Tier 0**	15	13	12	12	16	11	15	*13*
	Tier 1	13	11	11	11	14	10	13	*12*
	Tier 2	13	11	10	11	13	9	12	*11*
CO (g/gal)	**Tier 0**	40	30	28	28	45	23	38	*33*
	Tier 1	33	33	32	31	37	33	34	*33*
	Tier 2	33	29	28	29	32	27	32	*30*
CO_2 (g/gal)	**Tier 0**	10,300	10,500	10,600	10,600	10,500	10,500	10,500	*10,500*
	Tier 1	10,500	10,700	10,700	10,600	10,600	10,700	10,700	*10,600*
	Tier 2	10,600	10,800	10,400	10,700	11,000	10,800	10,700	*10,700*
PM (g/gal)	**Tier 0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	*1.0*
	Tier 1	1.1	1.1	1.1	1.1	1.1	1.2	1.1	*1.1*
	Tier 2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	*0.8*

Conclusions

- *FF = 0.04 gal/hp-h* is a valid estimate for fuel factor in the absence of more refined data
- Modal time has an inverse relationship with modal fuel use
- Weighted average fuel use and emissions rates account for variability in engine load in equipment application so they do not need to be adjusted for engine load
- The taxonomy of fuel use and emissions rates is a valid and reliable guide for estimating the energy and environmental impacts of HDD equipment