MOVES

Motor Vehicle Emission Simulator

Update to running exhaust criteria pollutant emission rates for model year 2010+ heavy-duty diesel vehicles

Gurdas S. Sandhu and Darrell Sonntag

FACA MOVES Review Work Group | December 7, 2016 | Ann Arbor, MI

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Outline

1. Motivation and Proposed Updates
2. Manufacturer-run heavy-duty in-use testing (HDIUT) - Overview and Data Description
3. Analysis Methodology – Emission Rates and Production Volume
4. Preliminary Results – OpMode Avg. and Cycle Total Emissions
5. Emerging Questions

Motivation
MOVES2014a NO_x Data Sources

		Regulatory Class			
Data Source	MYG	HHD	MHD	LHD	BUS
ROVER and Consent Decree Testing	1991-1997	19	-	-	2
	1998	12	-	-	-
	1999-2002	78	30	-	25
	2003-2006	91	32	-	19
HDIU	2003-2006	40	25	15	-
	2007-2009	68	71	24	-
Houston Drayage	1991-1997	8	-	-	-
	1998	1	-	-	-
	1999-2002	10	-	-	-
	2003-2006	8	-	-	-

HDIU: Heavy-duty in-use

Table 2-2 (pg 16) , *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES2014*, EPA-420-R-15-015a, November 2015
https://www3.epa.gov/otaq/models/moves/documents/420r15015a.pdf

Proposed updates

- Update running emission rates for MY 2010+ heavy-duty vehicles.
  - Update NO_x, CO, and HC
  - Update energy use (which affects CO_2 emissions)
  - Currently do not plan to update PM due to limited data

Heavy-duty In-use Testing (HDIUT)*

- Each year, US EPA selects a few engine families with production volume ≥ 1,500 units
- Engine manufacturer contacts customers to recruit vehicles operating in the real-world that have the selected engine family
  - Typically, five vehicles are tested for each engine family
  - Vehicles have good maintenance history and no malfunction indicators on
  - Vehicle mileage within the Useful Life
    - 110K, 185K, 435K miles for light-/medium-/heavy- heavy-duty, respectively
- Engine manufacturer conducts emissions measurements and submits 1 Hz data to EPA
  - Vehicles are tested "in-use" – that is, doing normal work and operated by regular driver
  - Measurements made with instruments certified per 40 CFR 1065

* 40 CFR Part 86 Subpart T: Manufacturer-Run In-Use Testing Program for Heavy-Duty Diesel Engines.

Data Overview

- Service Class: Light-/Medium-/Heavy-Heavy-Duty Diesel (LHDD, MHDD, HHDD) and Urban Bus (URBU)
- MY 2010-2013 engine families
- Over 30 unique engine families
- Over 230 vehicles
- Over 6 million seconds of data
- Current work involves updating emission rates using HDIUT data from engines selected for testing in CY 2010-2014. Data for engines selected in 2015 is expected by January 2017 and the plan is to include it in the update.

Subset of Heavy-heavy-duty Vehicles (GVWR>33K+ lbs) in HDIUT

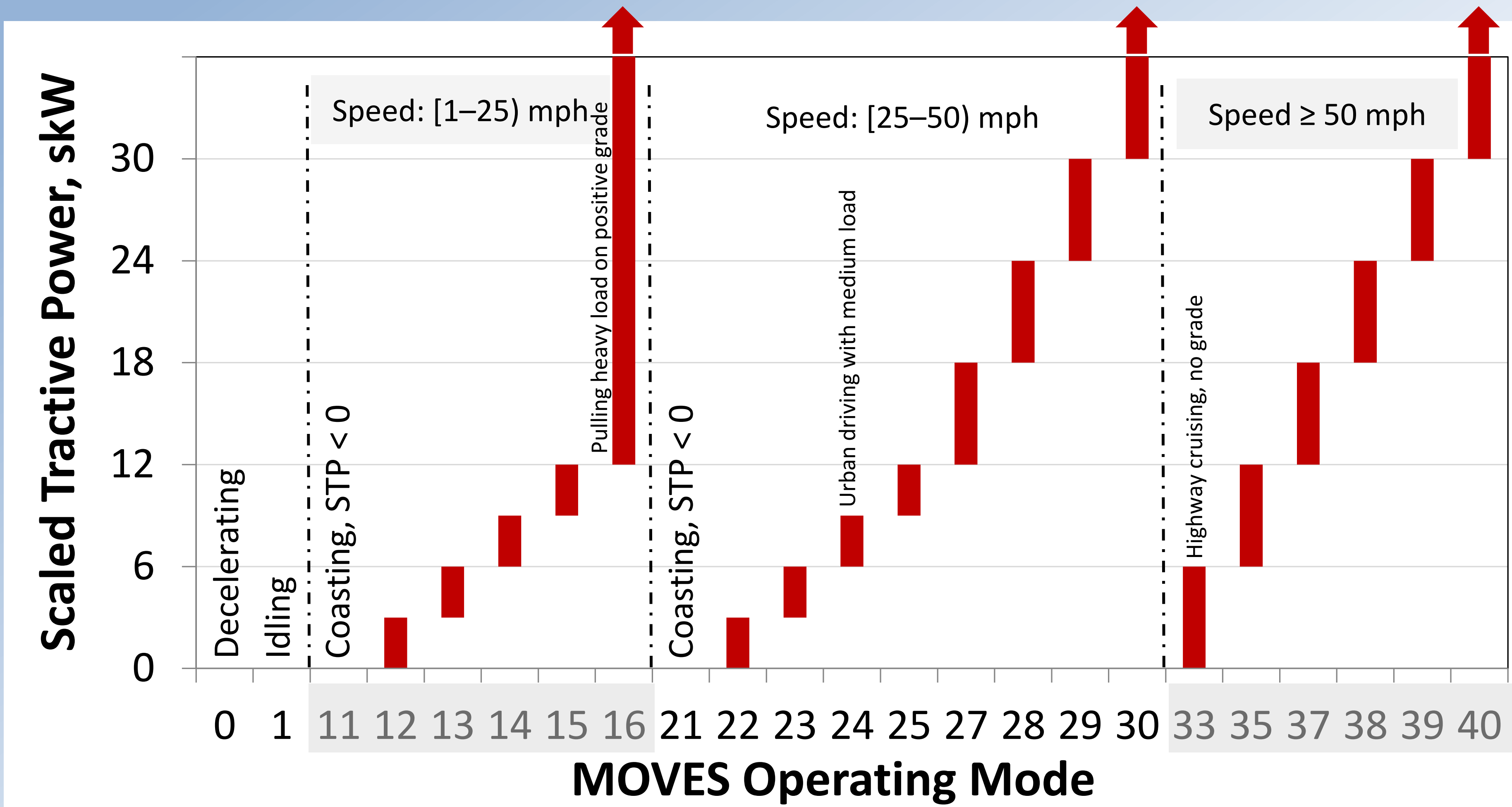
ID	Engine MY	Disp (L)	hp	Odo (10^3 mi)	Test Miles	Test Secs	Controls	Application
E1_T1	2010	15.0	475	246	266	23684	TC, CAC, EGR, DPF, SCR-U	Line Haul
E1_T3			475	268	330	30279		
E1_T4			475	261	153	27034		
E1_T5			475	324	258	39344		
E2_T1	2012	16.0	525	78	394	38039	TC, CAC, EGR, DPF, SCR-U, AMOX	Line Haul
E2_T2			575	127	253	31685		
E2_T3			525	153	322	39021		
E2_T4			525	107	317	33742		
E2_T5			525	166	393	36670		
E3_T1	2011	10.5	380	321	489	34241	TC, CAC, EGR, DPF	Delivery
E3_T2			400	205	190	23744		
E3_T3			380	206	325	34290		
E3_T4			400	131	191	35622		
E4_T1	2011	15.0	450	184	432	33474	TC, CAC, EGR, DPF	Delivery

TC: Turbocharger | CAC: Charge Air Cooler | EGR: Exhaust Gas Recirculation | DOC: Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter | SCR-U: Selective Catalytic Reduction using Urea | AMOX: Ammonia Oxidation Catalyst

Overview of Emission Rates Update Method

- Vehicle activity and emission rates are mapped onto an operating mode (OpMode) modal model.
- For each vehicle tested:
  - OpModes are assigned to each second of real-world emissions data based on estimated power demand at the wheel
  - Average the emissions from all seconds assigned the same OpMode
- Emission rates are estimated by service class (LHDD, MHDD, HHDD, URBU). Within a service class, emission rates are grouped by NO_x family emission limit (FEL) and weighted by the production volume for the same NO_x FEL groups.

MOVES Operating Modes (OpMode)



MOVES Scaled Tractive Power: ECU Torque

$$P_{eng} = \omega_{eng} \tau_{eng}$$

$$P_{axle} = \eta_{driveline} (P_{eng} - P_{loss,acc})$$

$$STP = \frac{P_{axle}}{f_{scale}}$$

P_{eng} – engine out power

W_{eng} – engine angular speed

T_{eng} – ECU reported engine out torque

$N_{driveline}$ – driveline efficiency (90%)

$P_{loss,acc}$ – power loss due to accessory loads

P_{axle} – power at the wheel

F_{scale} – scaling factor (used to align STP values for OpMode bins with the VSP values from light-duty analysis)

Accessory load losses

Table 2-4. Estimates of accessory load in kW by power range

Engine power	HDT	MHD	Urban Bus
Low	8.1	6.6	21.9
Mid	8.8	7.0	22.4
High	10.5	7.8	24.0

Accessory loads for LHDD are assumed negligible.

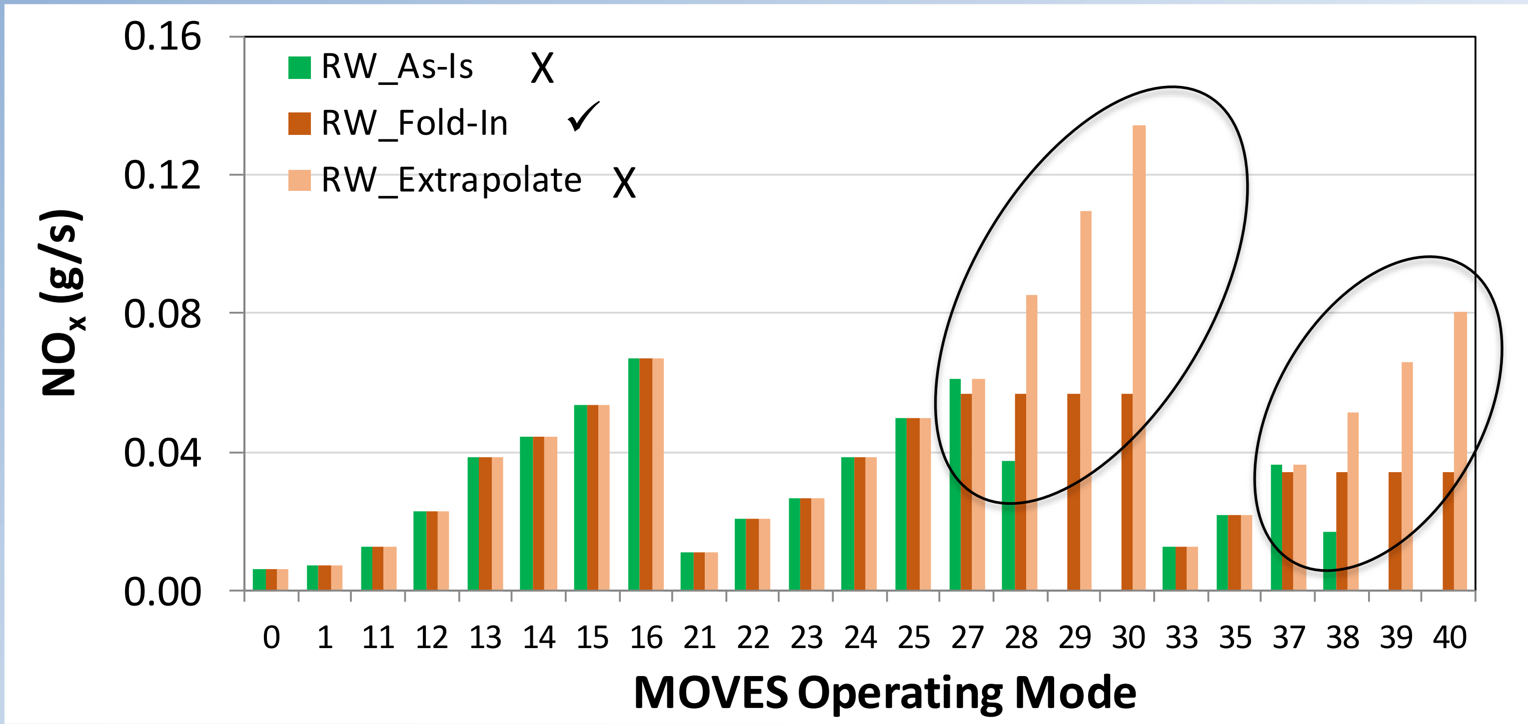
		Vehicle Speed		
		Low (0-25 mph)	Mid (25-50 mph)	High (above 50 mph)
Engine Power (of max hp)	Lowest Third	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
	Middle Third	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Air cond. Engine Access. Alternator
	Highest Third	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator Air Compress	Cooling Fan Air cond. Engine Access. Alternator

Bradley, Ron. “Technology Roadmap for the 21st Century Truck Program.” U.S. Department of Energy: Energy Efficiency and Renewable Energy, Washington, D.C., December 2000

Gap-filling Emission Rates for High Power OpModes

- MOVES estimates little activity in the high power OpMode bins (28-30 and 38-40); and real-world (RW) data often lacks these modes as well.
- In MOVES 2014, the emission rates for these OpMode bins were calculated from emission rates of the highest OpMode with sufficient data (27 or 37) and then “extrapolated” based on STP mid-point values.
- For the next version of MOVES, rates from sparse data OpMode bins are folded-in with highest power OpMode with sufficient data. The “fold-in” is achieved, for the participating OpModes, by taking a sum-product of time and emission rates per OpMode and dividing by total time across OpModes.
- This “fold-in” emission rate is assigned to all participating OpMode bins, including and upward of the highest OpMode with sufficient data.
- The cycle total emissions from the “fold-in” method are identical to real-world “as-is”

Gap-filling Emission Rates for Higher OpModes



Engine Family Name

BCEXH0912XAQ

"base engine family"

Model year (1-9 = 2001-2009, A-Y = 2010-2030 with I,O,Q,U,Z absent)

EPA assigned manufacturer code

Industry sector (H = HD highway diesel >8,500 lbs GVWR)

Engine Displacement (liters XX.X or cubic inches XXXX)

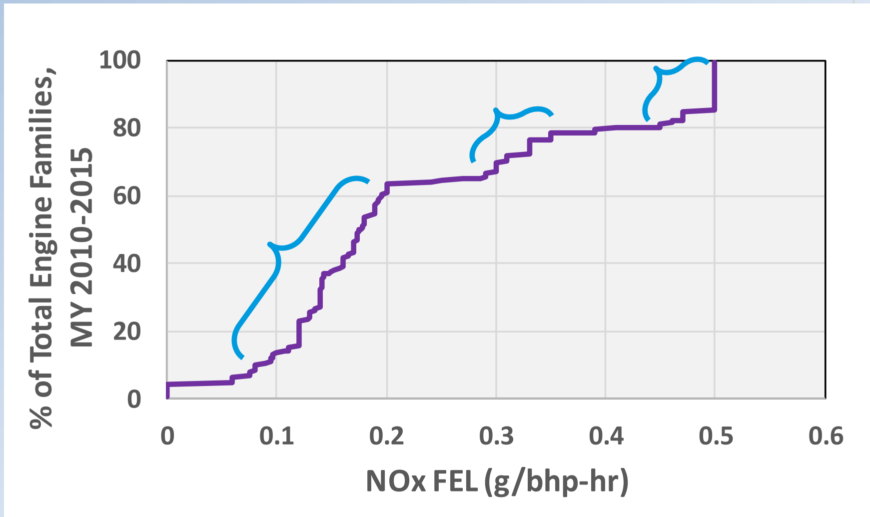
Manufacturer assigned characters

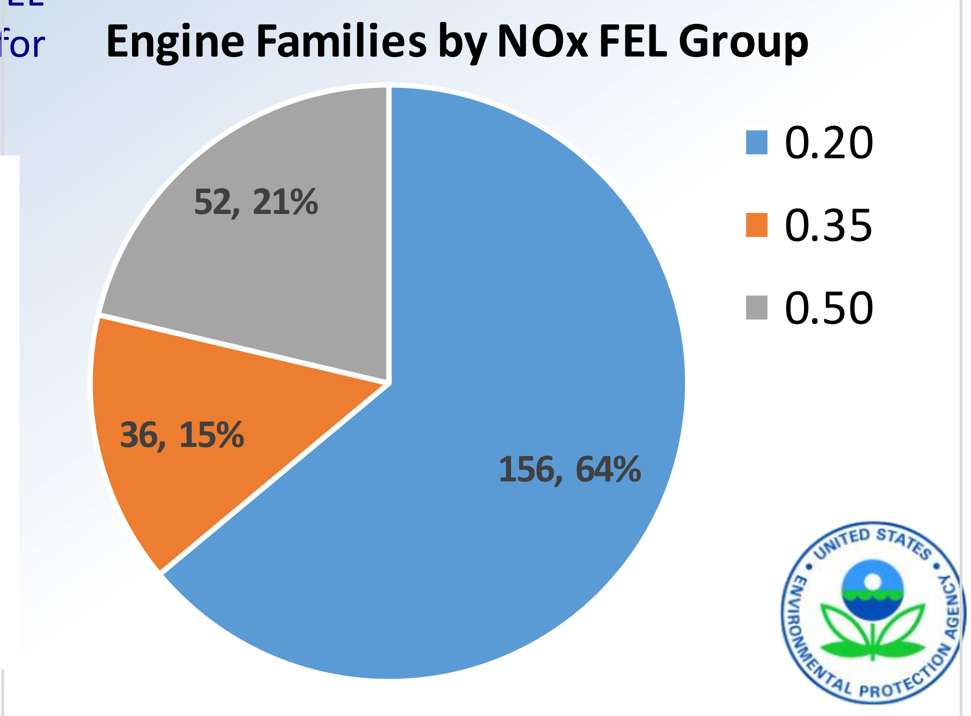
40CFR86.096-24(a)(1): Engine families are "expected to have similar emission characteristics throughout their useful life."

Engine Families Grouped by NO_x FEL

- Group engines within a service class by NO_x FEL.
- NO_x FEL grouping is applied across all pollutants because NO_x FEL data is more widely available and best captures the differences in emission levels.
- Find average emission rates for the given NO_x FEL group and weight it by the production volume for the same group for a given MY.

Group Name	NO_x FEL Limits (g/bhp-hr)
0.20	(0.00, 0.20]
0.35	(0.20, 0.35]
0.50	(0.35, 0.50]





Method to Estimate Production Volume Weighted Emission Rate, MY 2010-2015

$$ER_{C,MY,pol} = \frac{\sum_{FEL}\left(ER_{C,pol,FEL} \times PV_{C,MY,FEL}\right)}{PV_{C,MY}}$$

Service Class (C) = LHDD, MHDD, HHDD

Model Year (MY) = 2010 to 2015

Pollutant (pol) = NOx, HC, CO

FEL = NO_x FEL of engine family, grouped in to 0.2g/bhp-hr, 0.35g/bhp-hr, and 0.5g/bhp-hr.

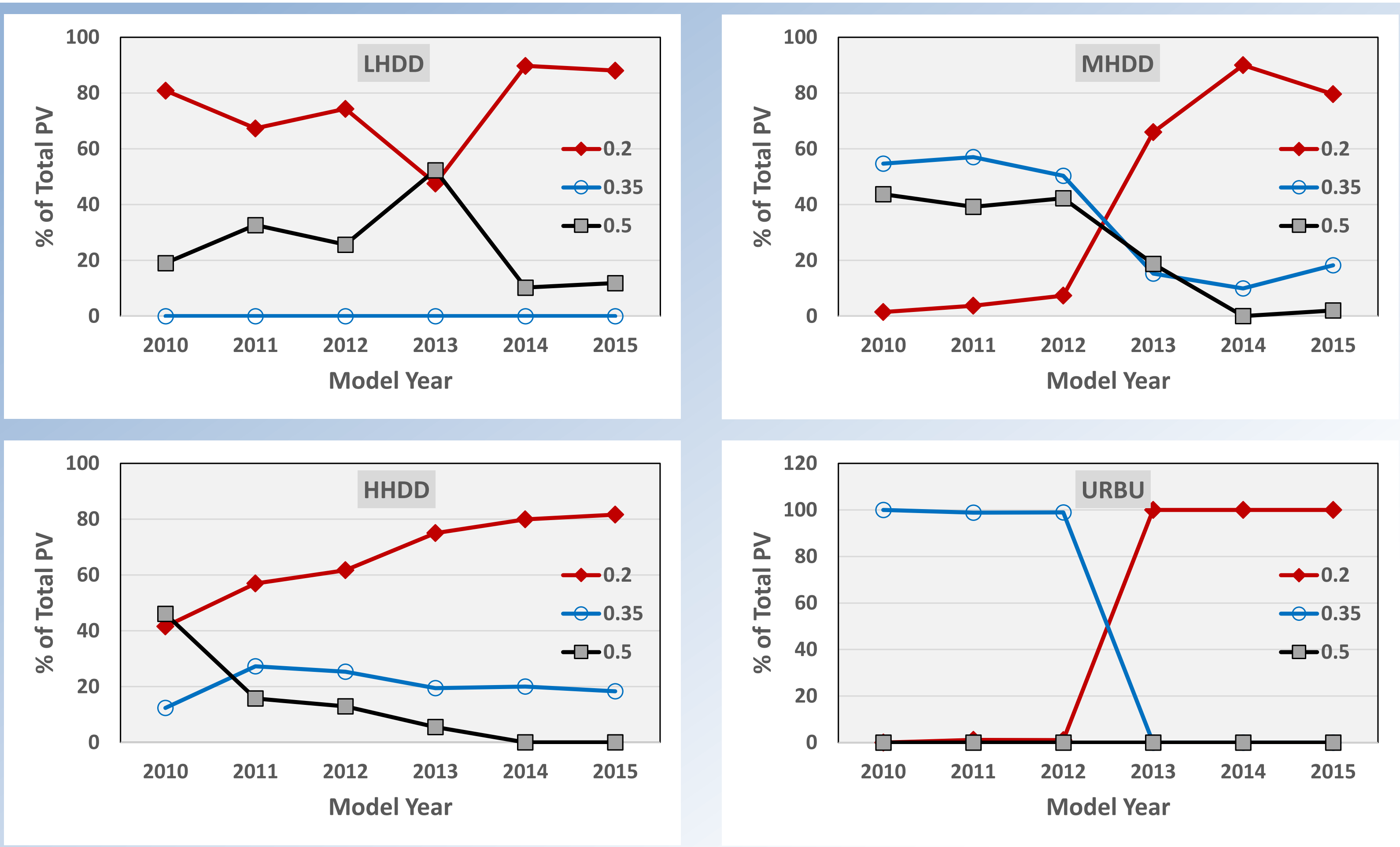
$ER_{C,MY,pol}$ = Emission Rate (ER) for a given Class (C), Model Year (MY), and Pollutant (pol).

$ER_{C,pol,FEL}$ = Emission rate by class, pollutant, and NOx family emission limit (FEL). This is average of all HDIUT data for all engines meeting the *C,pol,FEL* criteria.

$PV_{C,MY,FEL}$ = Production volume by class, model year, and NOx FEL group

$PV_{C,MY}$ = Total production volume for a class and model year

Production Volume by NOx FEL Group



Q: How to assign production volume distribution, by FEL NOx groups, for future years?

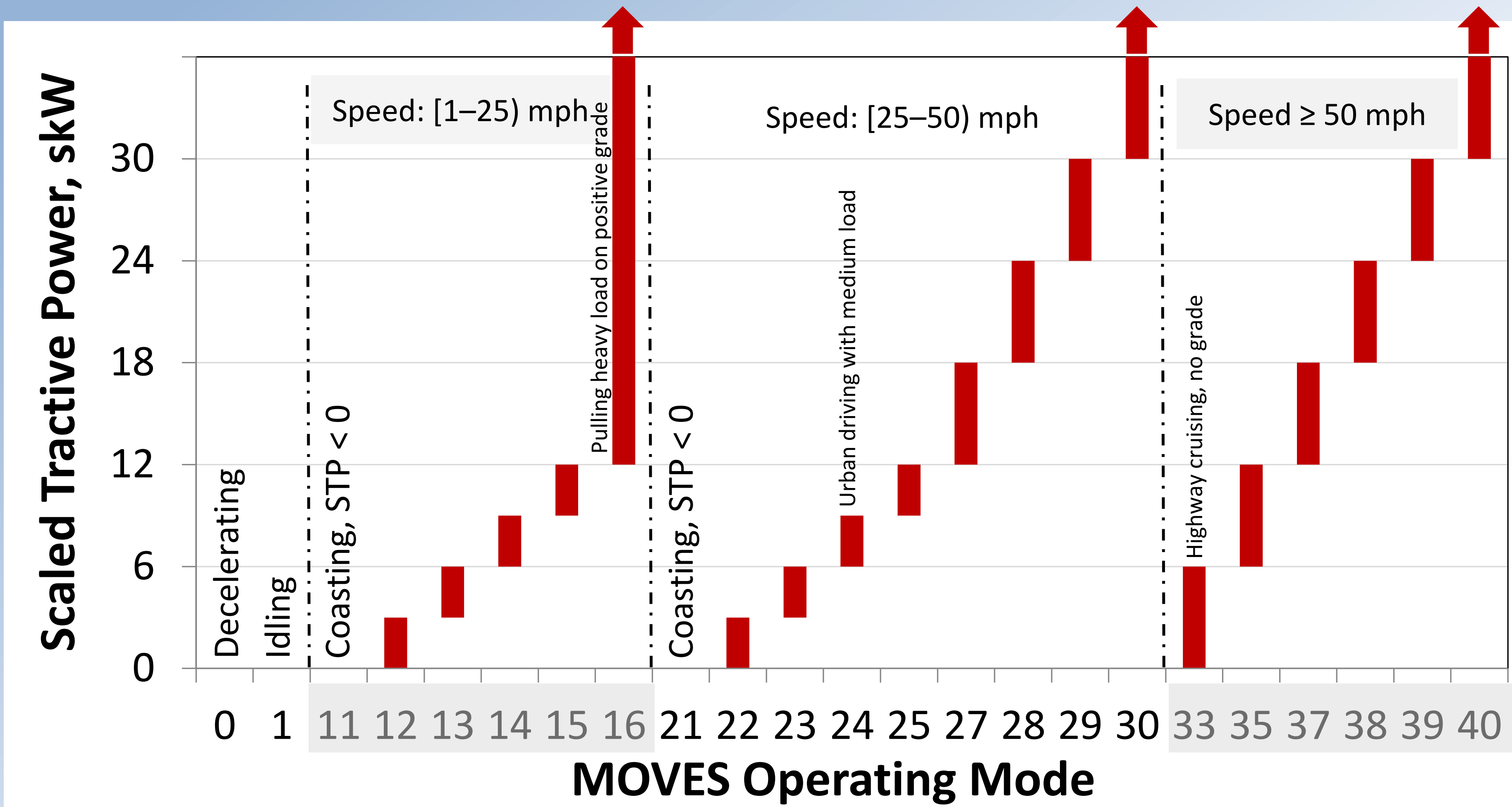
Method to Estimate Production Volume Weighted Emission Rate

- HDIUT emissions data is not split by model year. The assumption is that engines within a service class and NOx FEL group have the same emissions profile across model years.
- However, the final emissions rates are by model year because they include the production volume weighting by model year.
- URBU rates will be based on HHDD emissions data due to sparse URBU emissions data

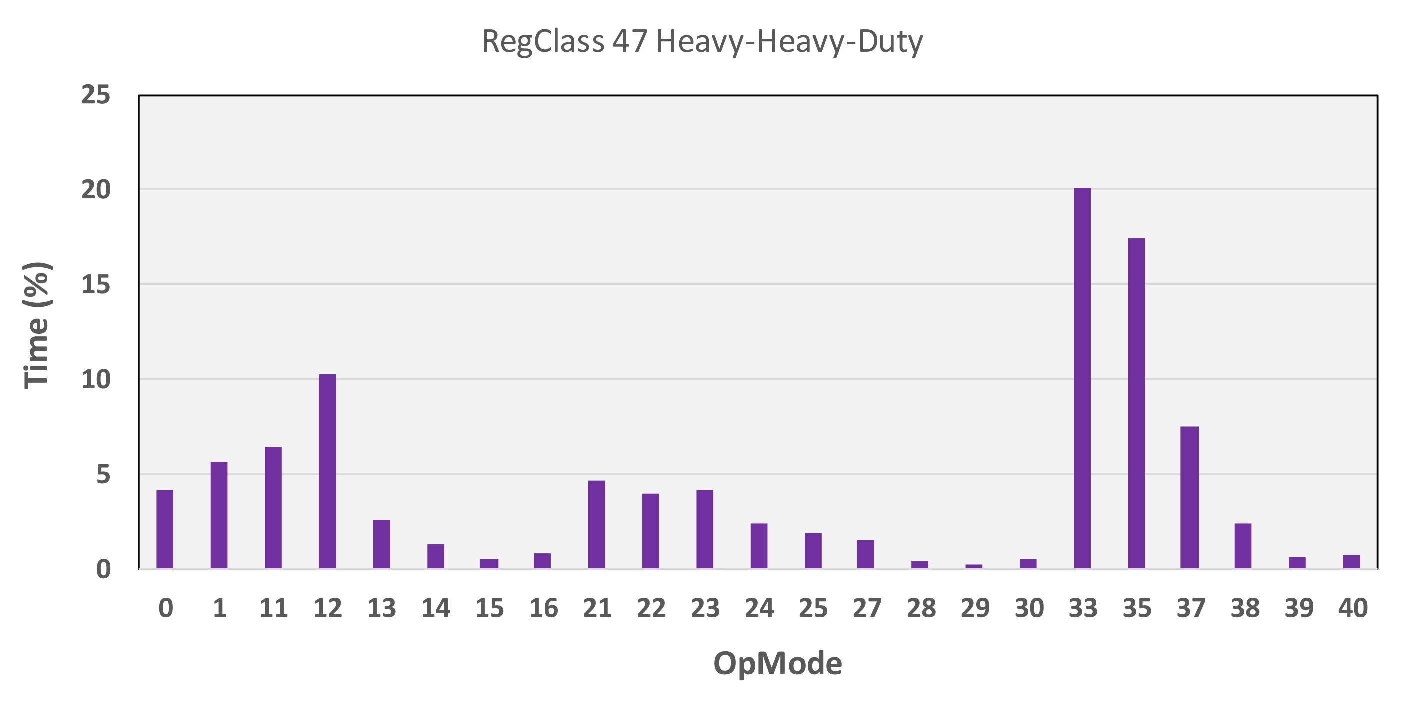
HDIUT Data: Number of Test Vehicles

	NOx FEL based Groups			
Service Class	**0.20**	**0.35**	**0.50**	**Total**
LHDD	42		10	52
MHDD	16	23	10	49
HHDD	65	21	35	121
URBU	0	10		10
Total	123	54	55	**232**

MOVES Operating Modes (OpMode)



OpMode Distribution for Heavy-heavy-duty - MOVES National Mode Run, CY2016



Scale: Onroad, National, Inventory

Time Spans: Year, CY 2016, All Months, Weekend and Weekday, All Hours

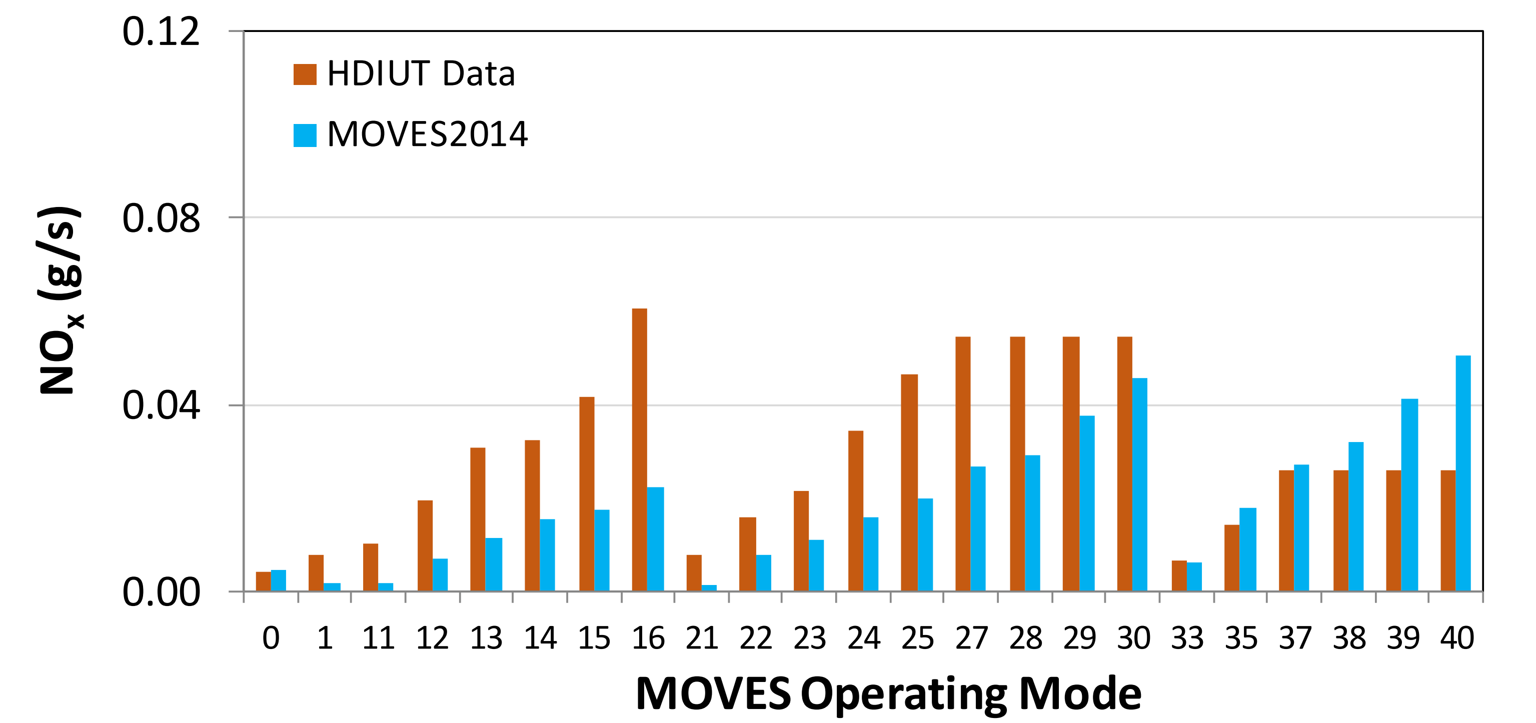
Geographic Bounds: Nation

Vehicles: Diesel Fuel

Road Type: Rural and urban, Restricted and Unrestricted

Preliminary result: NO_x for Heavy-heavy-duty

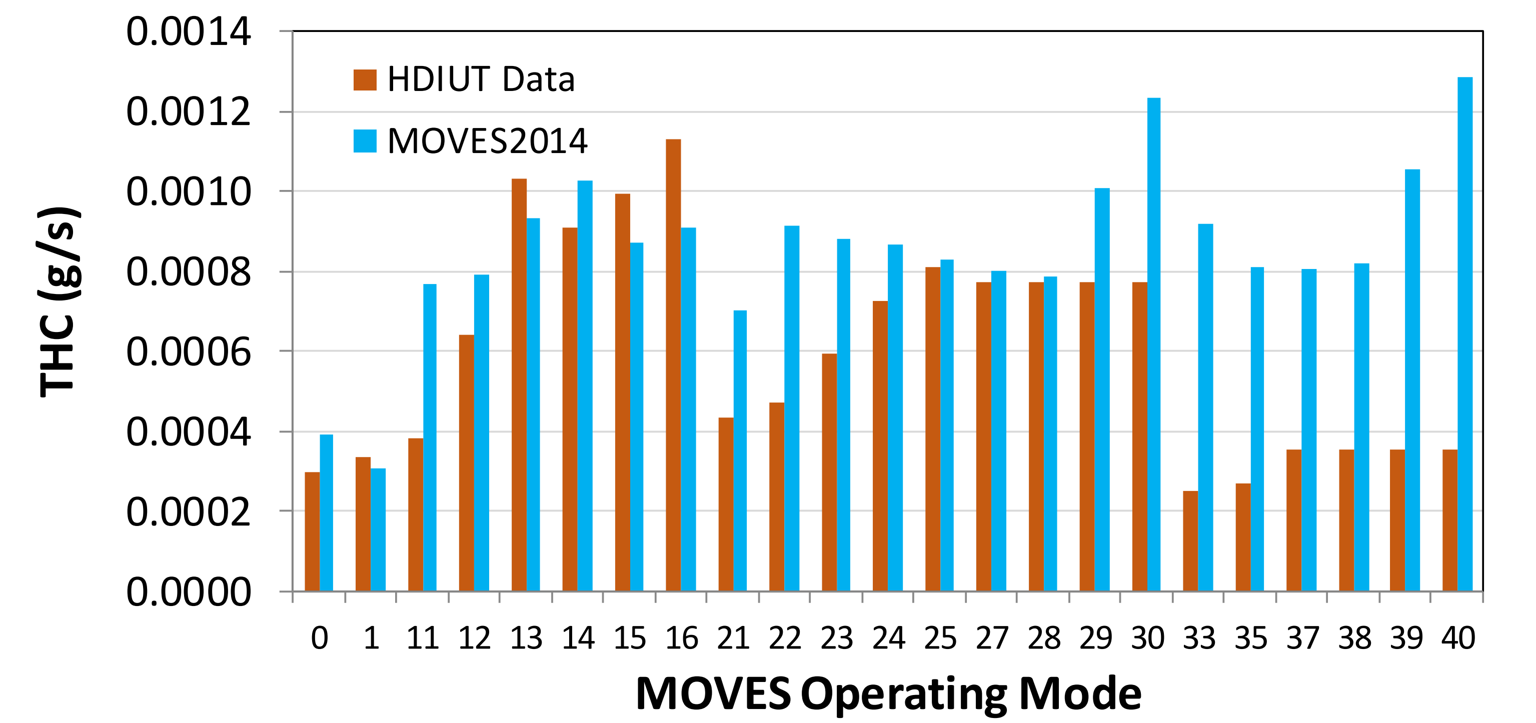
For the OpMode distribution in slide 20, HDIUT data rates lead to a **42% increase** in cycle total NO_x emissions over MOVES2014 rates.



These *preliminary results* are based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.

Preliminary result: THC for Heavy-heavy-duty

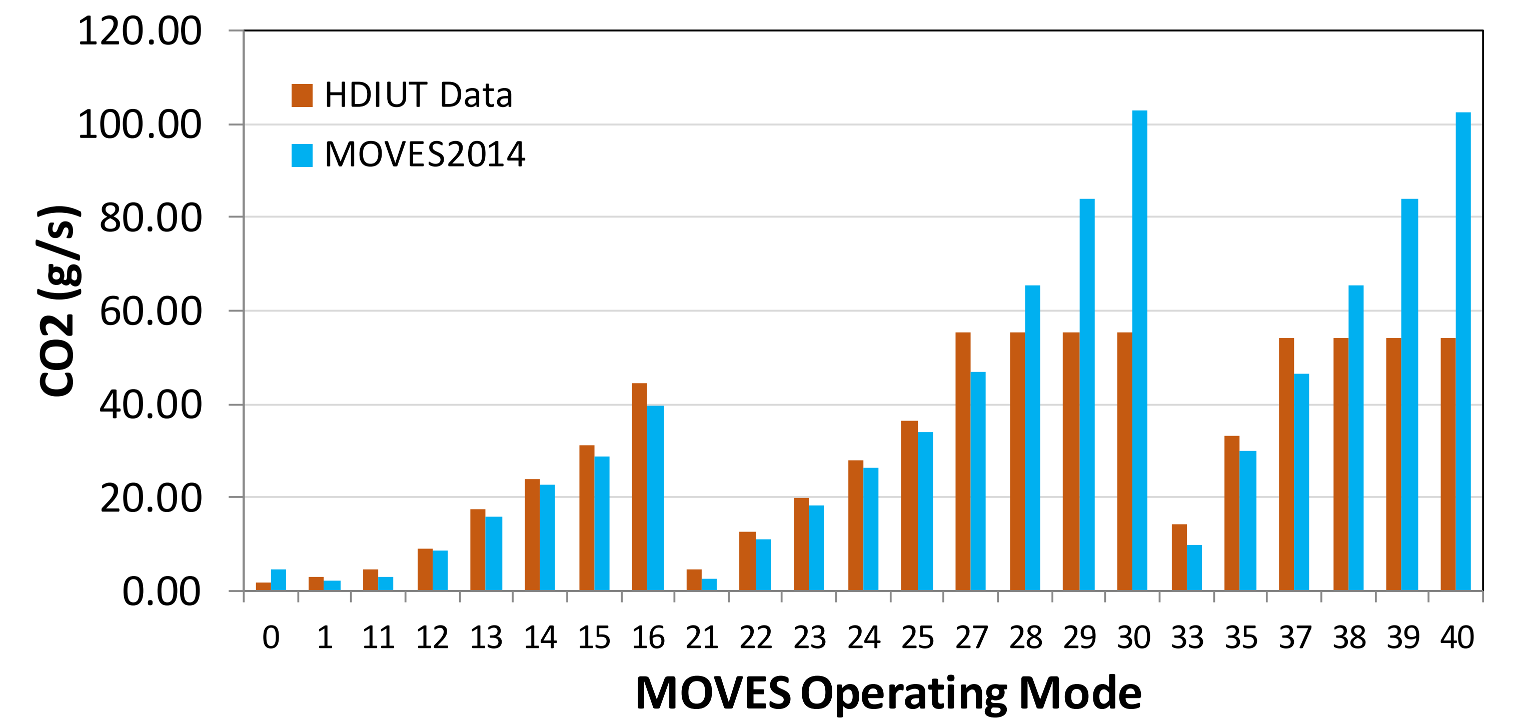
For the OpMode distribution in slide 20, HDIUT data rates lead to a **47% decrease** in cycle total THC emissions over MOVES2014 rates.



These *preliminary results are* based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.

Preliminary result: CO_2 for Heavy-heavy-duty

For the OpMode distribution in slide 20, HDIUT data rates lead to a **8% increase** in cycle total CO_2 emissions over MOVES2014 rates.



These *preliminary results are* based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.

Next Steps

- Complete analysis of all HDIUT data and compile emission rates by RegClass
- Estimating the impact of mal-maintenance and high-emitters
- Conduct MOVES runs to estimate impact from updated emission rates on national inventory
- Possibility to include data from other sources, based on timing, for running emissions, deterioration rates, start emissions.

Emerging Questions

- **Analysis Methods:** Improve accessory loss estimates for newer trucks.
- **DPF Regeneration:** What is the frequency of DPF regeneration? Where to assign this in a driving cycle? What is the impact on cycle total emissions and speciation?
- **Deterioration and Failure:** Is deterioration linear? What are the types of failures – severity and associated impact? What, if any, are the cross-effects - failure in one control device affecting other downstream control devices?
- **Control Strategies:** What are the effects of improvements in thermal management, catalyst treatments, and dosing optimization strategies on emissions profile of newer model year vehicles compared to first generation systems?
- **Driving Cycles:** While formulating representative driving cycles in itself is not an emerging question, the issue is highlighted by concerns of reduction in emission control efficiency during low-load and off-cycle operation. How well do our driving cycles represent low-load and off-cycle operation?
- **History Effects:** Continuing on the theme of driving cycles, how can a modal model such as MOVES represent/capture the real-world influence of past vehicle condition on current emission profile?
- **Assigning OpMode:** Driving cycles are converted to OpMode distribution based on equations that use road-load coefficients or driveline efficiency and auxiliary power losses. What are representative road-load coefficients and auxiliary power losses for the truck fleet as the fleet transitions to more aerodynamic chassis, efficient powertrains, and lower resistant tires?

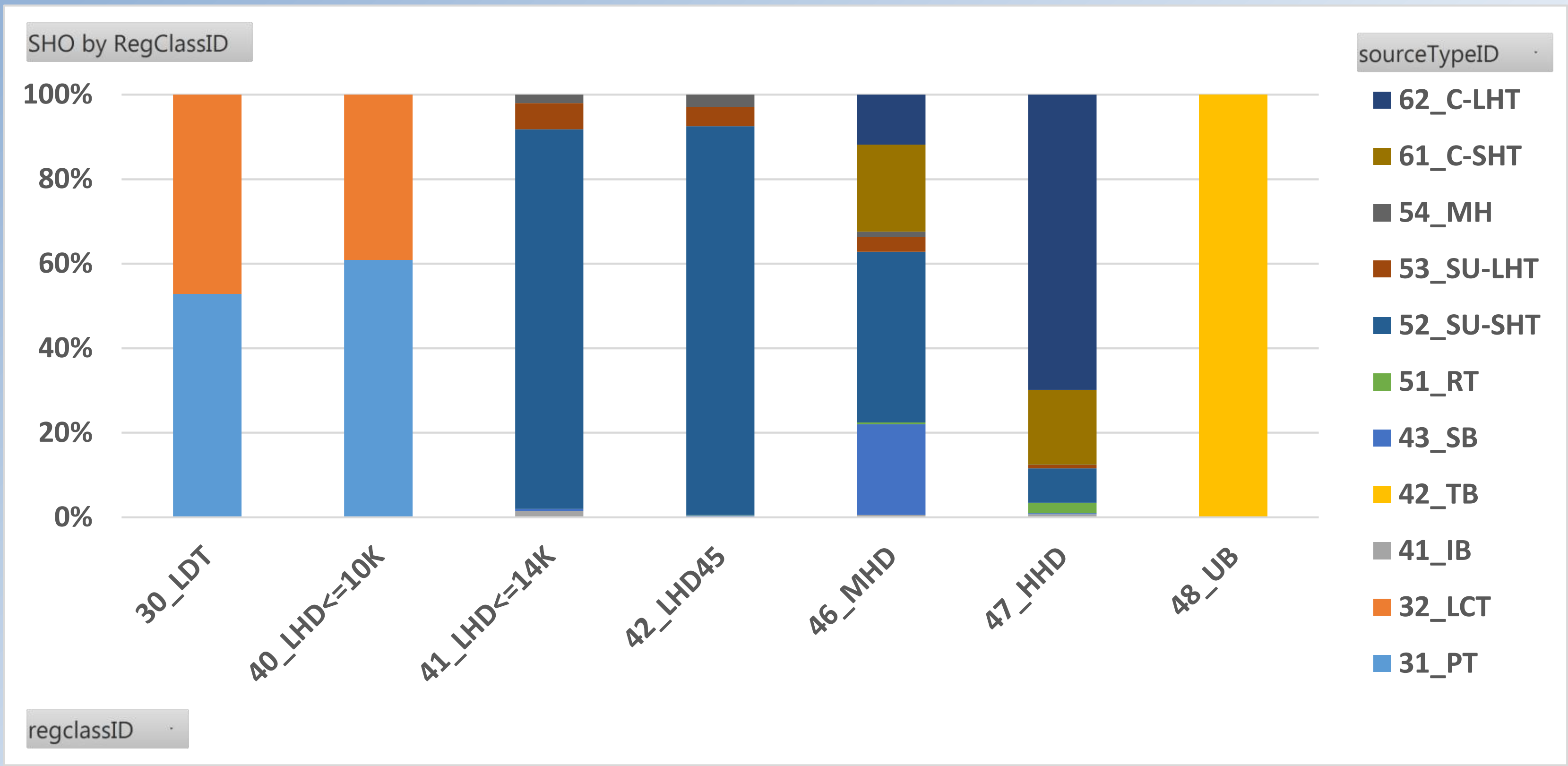
Extra Slides

MOVES Scaled Tractive Power: Road-load Coeff

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{f_{scale}}$$

STP_t	=	scaled tractive power at time t, skW
A	=	rolling resistance coefficient [kW-s/m]
B	=	rotational resistance coefficient [$kW\text{-}s^2/m^2$]
C	=	aerodynamic drag coefficient [$kW\text{-}s^3/m^3$]
a_t	=	vehicle acceleration at time t [m/s^2]
m	=	vehicle mass [metric ton]
v_t	=	vehicle speed at time t [m/s]
f_{scale}	=	scaling factor, unitless

Source Hours Operating for CY 2016 by RegClassID



RegClass 47 is **heavy-heavy-duty**. On a source hours operating (SHO) basis, RegClass 47 is comprised of 88% combination trucks, 8% single-unit trucks, and remaining refuse trucks and buses.

HDIUT Data Coverage of Total Production Volume

- Of the total engines produced in a year, how many are covered by the HDIUT data?
- For any engine family, if HDIUT data includes emissions from the "base" engine family, then full coverage of that particular engine family's production volume is assumed.

% Coverage	0.2						0.35						0.5						AVG
	2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015	
LHDD	100	100	100	100	99	100							100	98	78	100	100	100	98
MHDD	92	100	80	0	6	4	100	100	100	0	0	0	26	51	23	0	0	0	32
HHDD	85	87	86	68	37	36	90	89	88	0	0	0	100	71	24	23			57
Urban Bus		0	0	0	0	0	61	82	82										50
AVG	87	91	90	45	34	35	96	95	94	0	0	0	77	68	34	35	99	72	55

- Example: HDIUT data includes emission rates from base engine families that constitute 86% of the total production volume of MY 2012 HHDD engines with NOx FEL 0.2 g/bhp-hr.
- However, there are categories (shaded grey) where the coverage is below 10% and production volume is more than 100 units.

% Coverage	0.2	0.35	0.5	AVG
LHDD	100		93	98
MHDD	7	72	29	32
HHDD	59	44	68	57
Urban Bus	0	78		50
AVG	53	57	57	**55**