In-Use Emission Rates for MY 2010+ Heavy-Duty Diesel Vehicles

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Scope

1. Compare Heavy-Duty In-Use Testing and MOVES2014
2. Inter-engine and intra-engine variability
3. SCR efficacy analysis: exhaust temperature
4. Real-world NOx in g/bhp-hr and g/mile

MOVES2014 – **MO**tor **V**ehicle **E**mission **S**imulator, 2014 version
SCR – **S**elective **C**atalytic **R**eduction

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.

HDIUT Data Overview

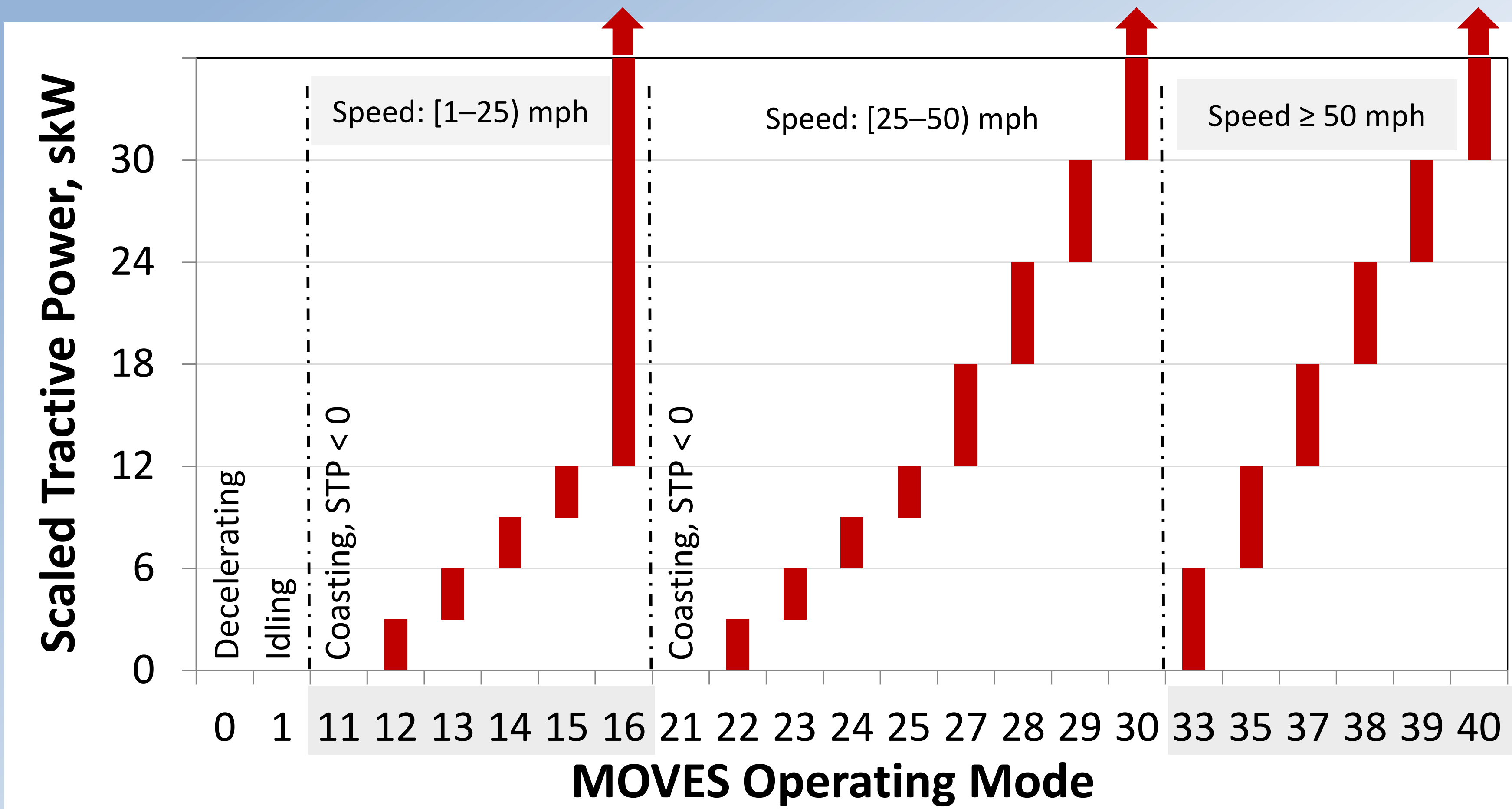
- Service Class: Light-/Medium-/Heavy-Heavy-Duty Diesel (LHDD, MHDD, HHDD) and Urban Bus (URBU)
- MY 2010-2013 engine families
- Over 30 unique engine families
- Over 230 vehicles
- Over 6 million seconds of data
- Current work based on HDIUT data from engines selected for testing in CY 2010-2014. Data for engines selected in CY 2015 will soon be added.

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**

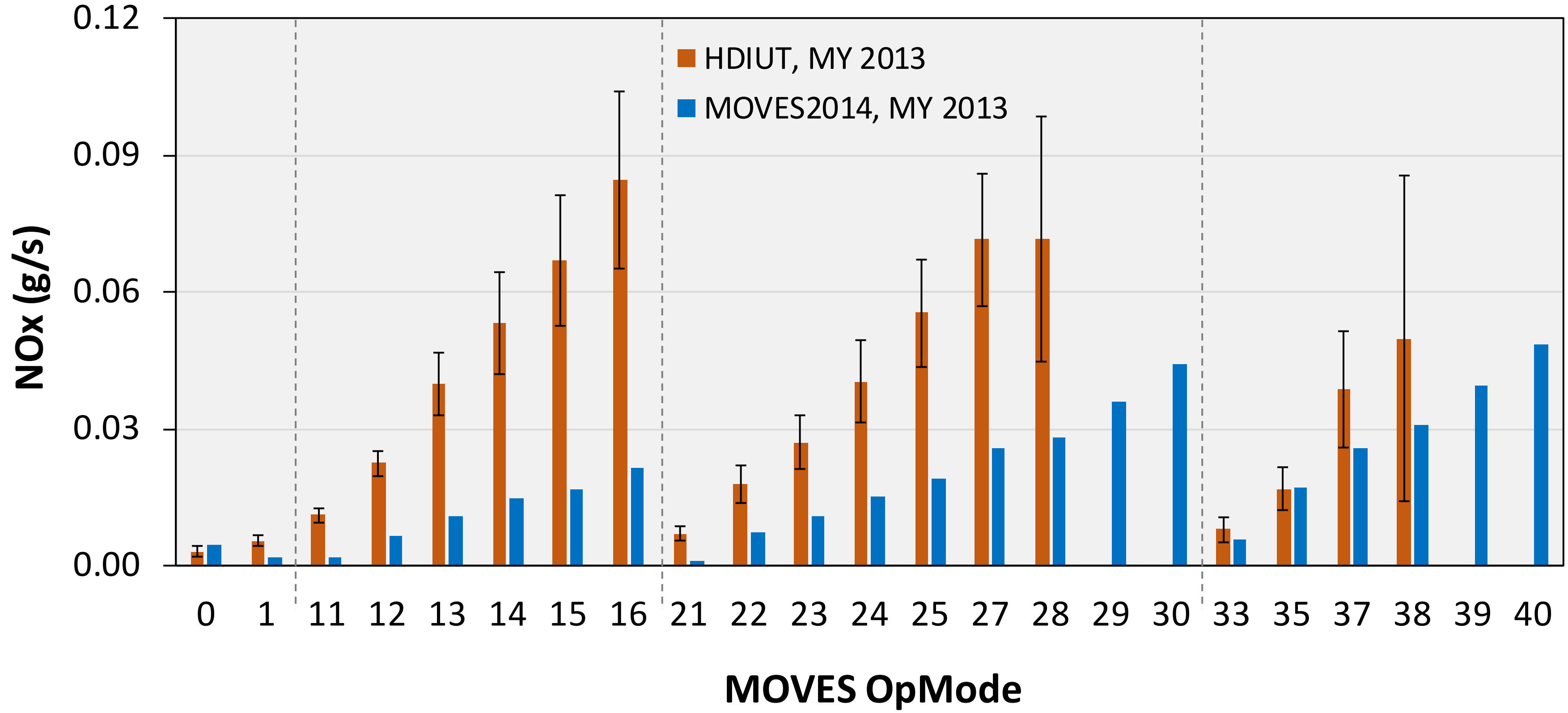
FEL – **F**amily **E**mission **L**imit

MOVES Operating Modes (OpMode)



Compare HDIUT and MOVES2014

HHDD - NO_x, HDIUT vs. MOVES2014

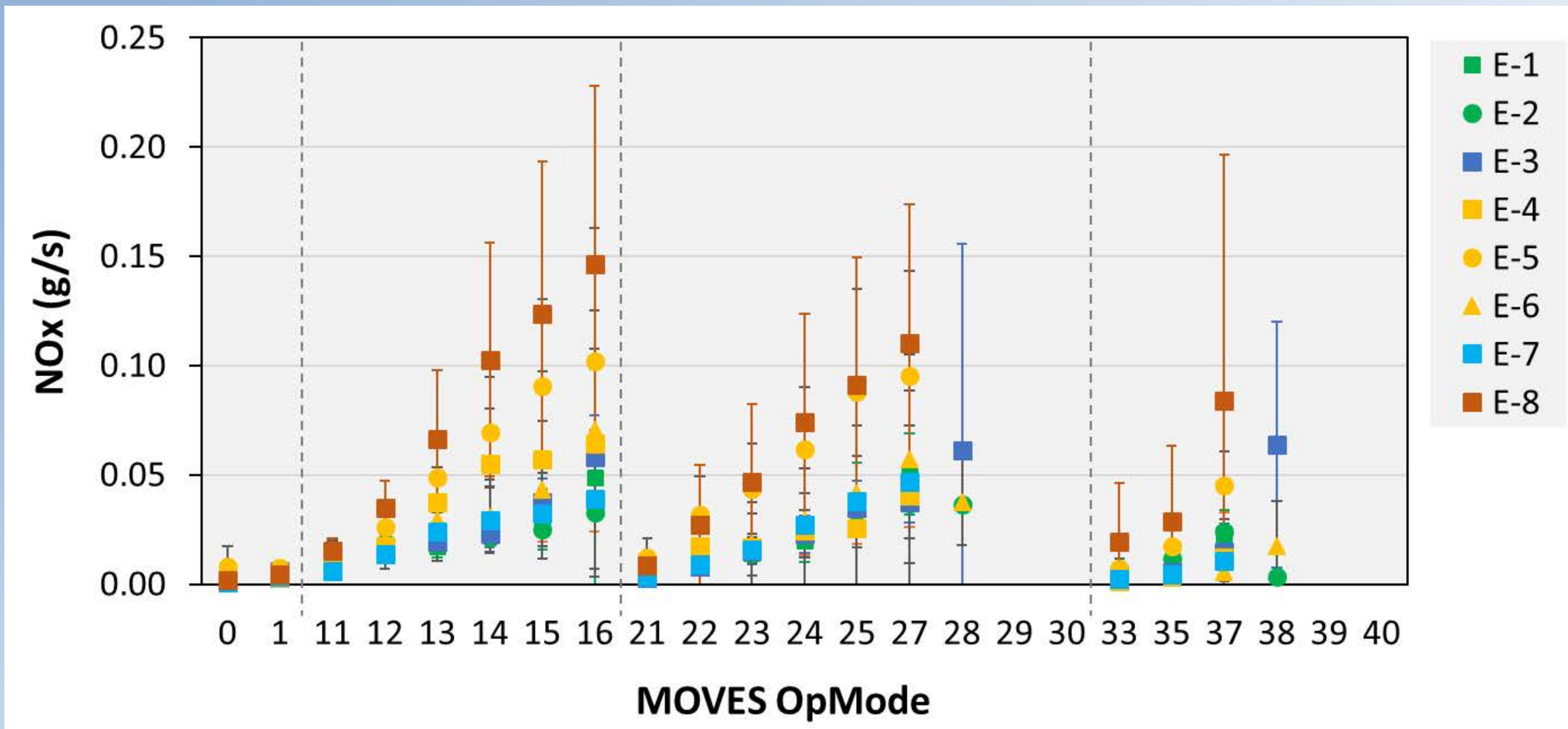


Based on HHDD 0.20, 0.35, and 0.50 groups >> 121 vehicles, 3.77 million seconds of data
HDIUT rates have MY specific production volume weighting
Error bars are 95% confidence intervals of the mean

High-power OpMode gap filling method was presented at the December 2016 MOVES Review Work Group meeting, https://www.epa.gov/moves/moves-model-review-work-group

Inter- and Intra-Engine Variability within a NOx FEL

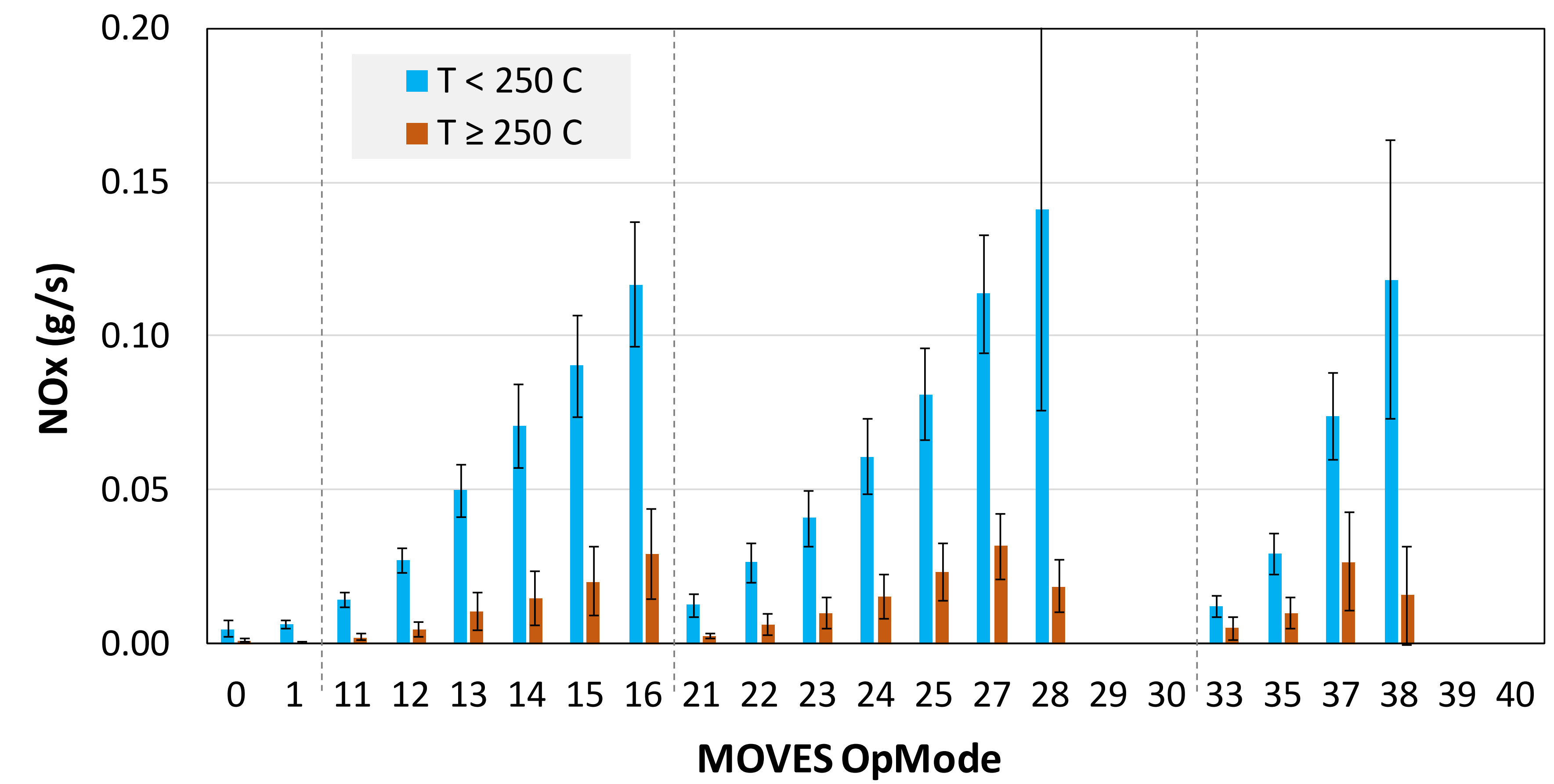
Differences between Engines Certified to the Same Level



Based on HHDD 0.20 group >> 65 vehicles, 2.20 million seconds of data
Error bars are 95% confidence intervals of the mean

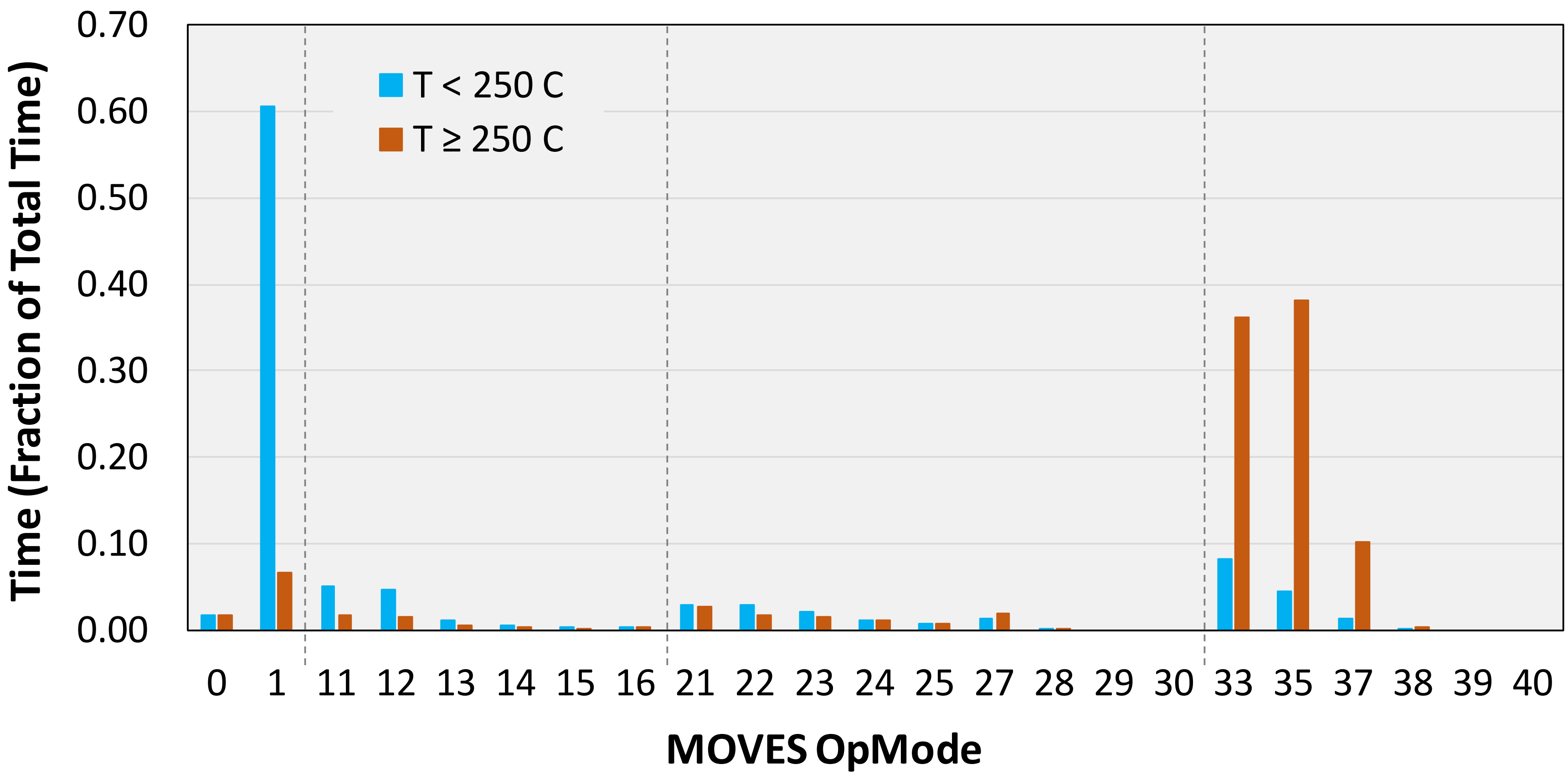
SCR Efficacy Analysis: Exhaust Temperature

NOx Emissions by Temperature Modes



Based on HHDD 0.20 group >> 53 vehicles, 1.84 million seconds of data
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Error bars are 95% confidence intervals of the mean

Time Spent by Temperature Modes



Based on HHDD 0.20 group >> 53 vehicles, 1.84 million seconds of data
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars for a color add up to 1.00

Cycle Total NOx Contribution: Trucks with SCR

	Contribution (Ratio)	
	Time	NO_x
T < 250 degC	0.48	0.61
T ≥ 250 degC	0.52	0.39

Based on 53 HHDD vehicles in the 0.20 FEL group

	Contribution (Ratio)	
	Time	NO_x
T < 250 degC	0.49	0.65
T ≥ 250 degC	0.51	0.35

Presented at CRC 2016 Based on 9 HHDD Vehicles in the 0.20 FEL group

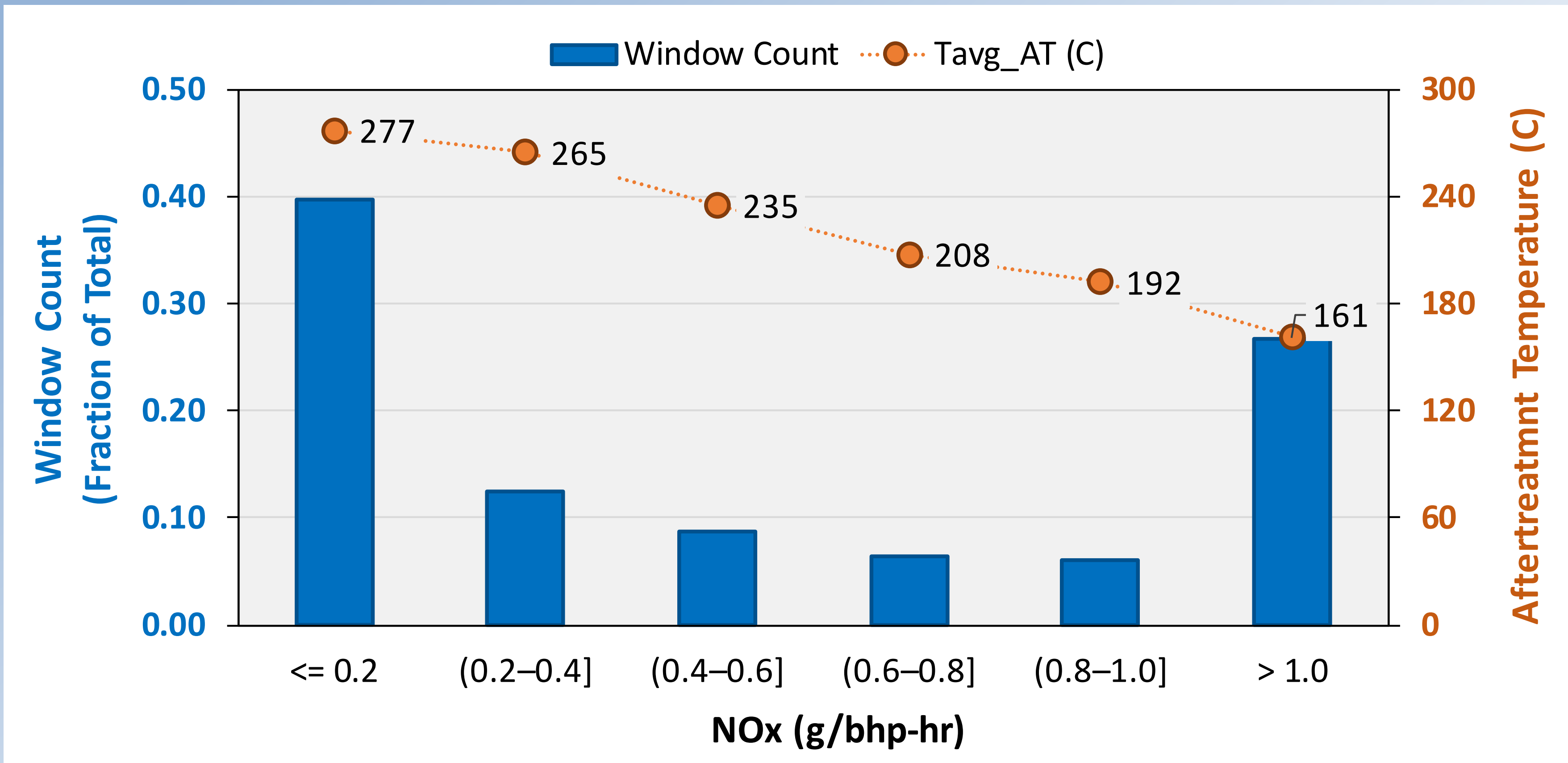
Real-world NOx:

Work-window

Speed-mode

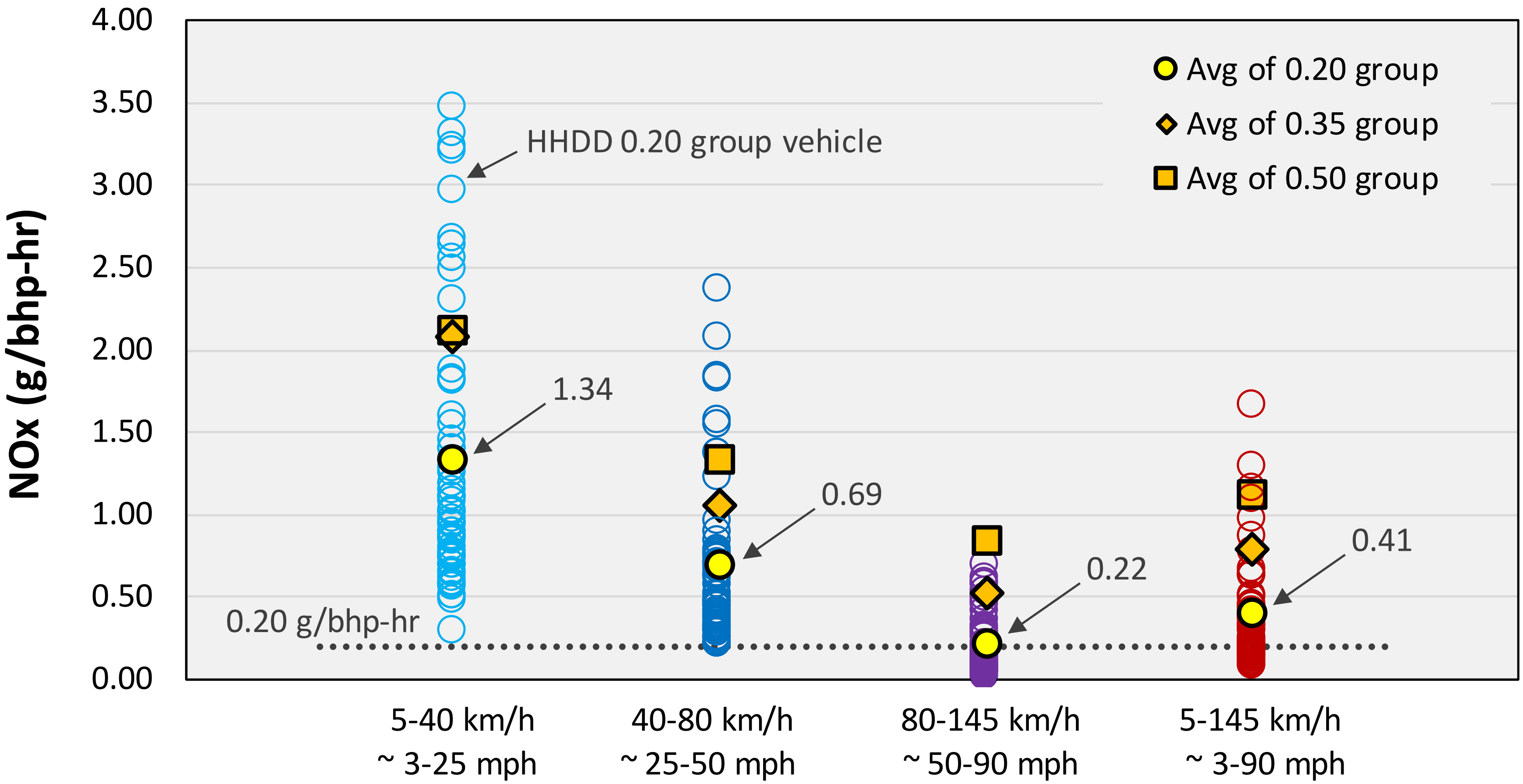
Cycle average

FTP Work-window based NOx Emissions



Based on HHDD 0.20 group >> 53 vehicles, 1.58 million FTP work-windows
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Work-windows are calculated over continuous seconds. Consecutive windows have overlapping seconds.

Vehicle Speed based NOx Emissions

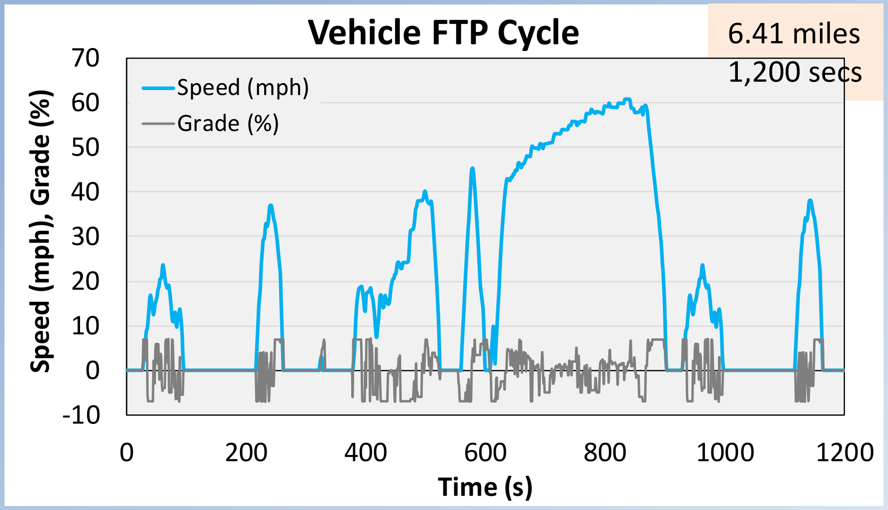


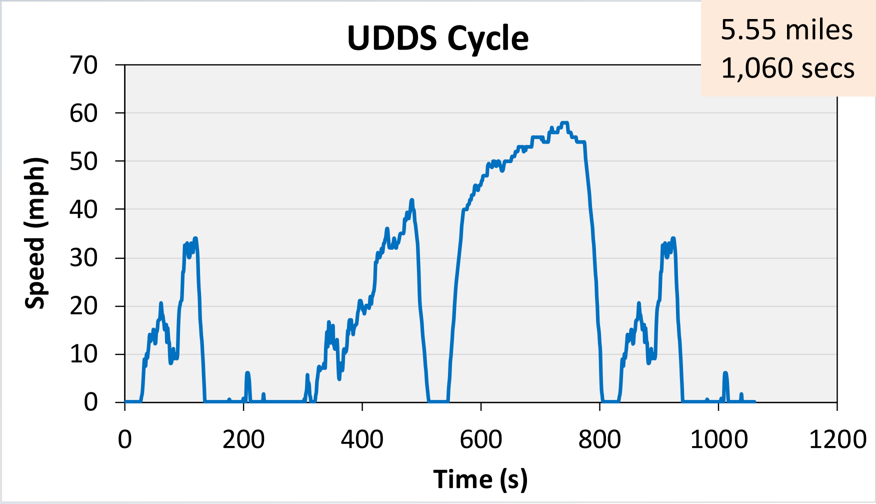
0.20 group >> 65 vehicles, 2.20 million seconds of data

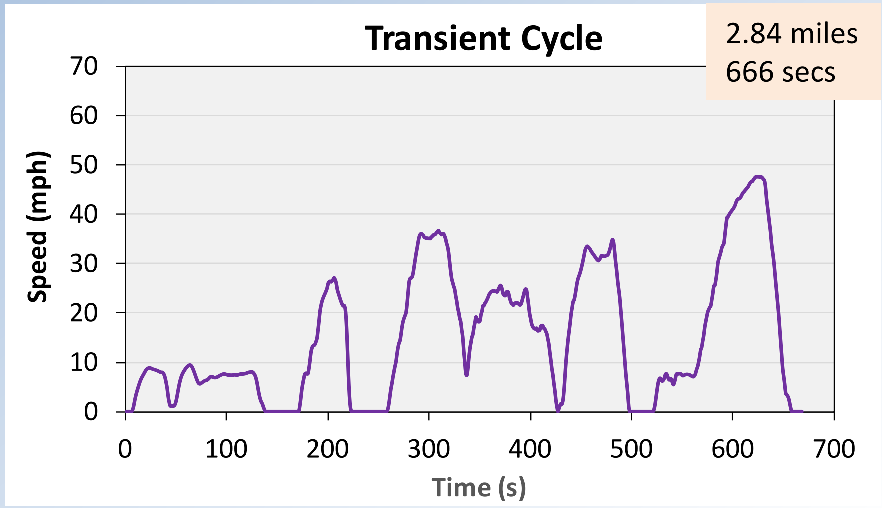
0.35 group >> 21 vehicles, 0.55 million seconds of data

0.50 group >> 35 vehicles, 1.02 million seconds of data

Driving Cycles for Cycle Average Comparisons



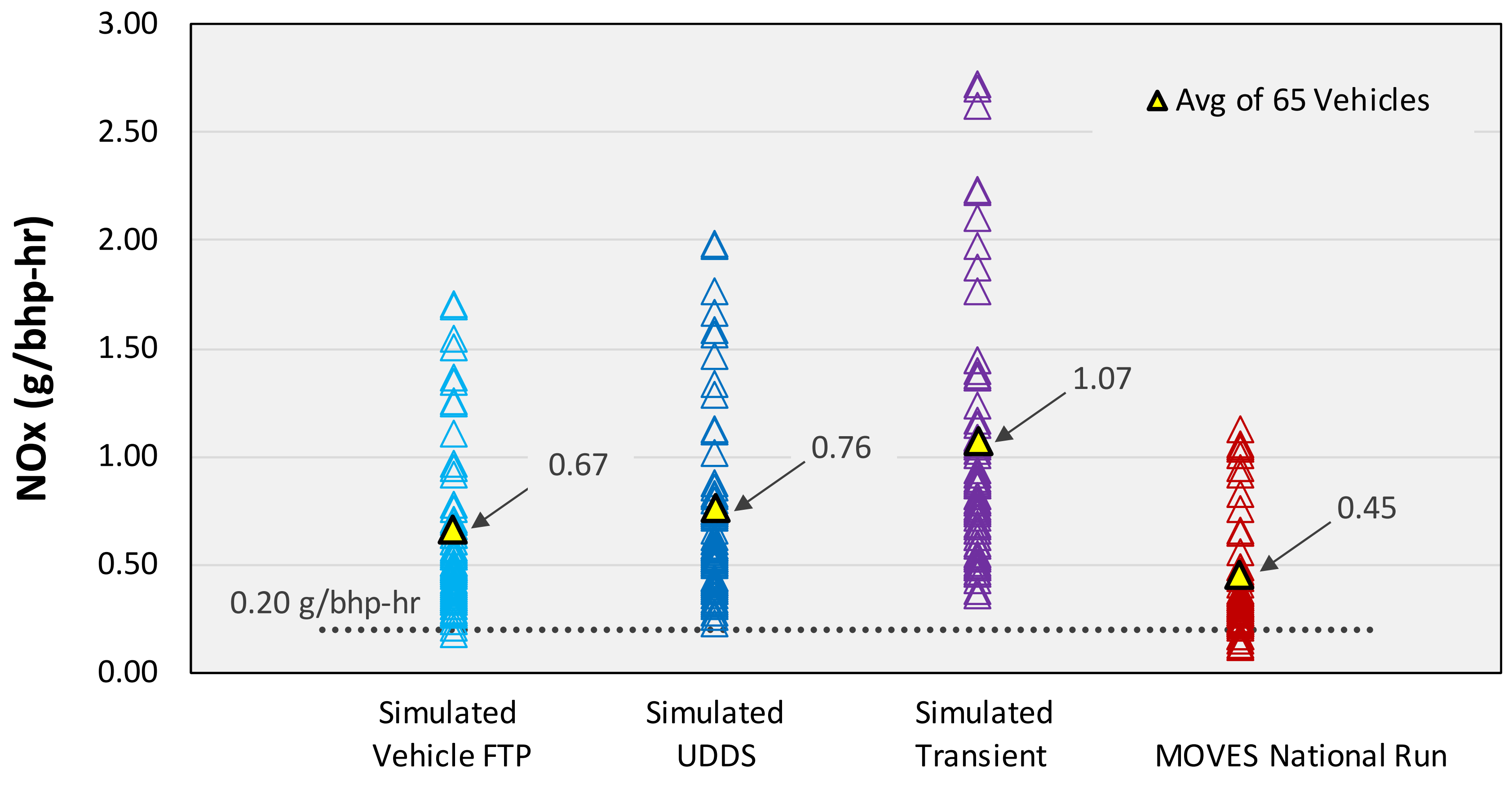




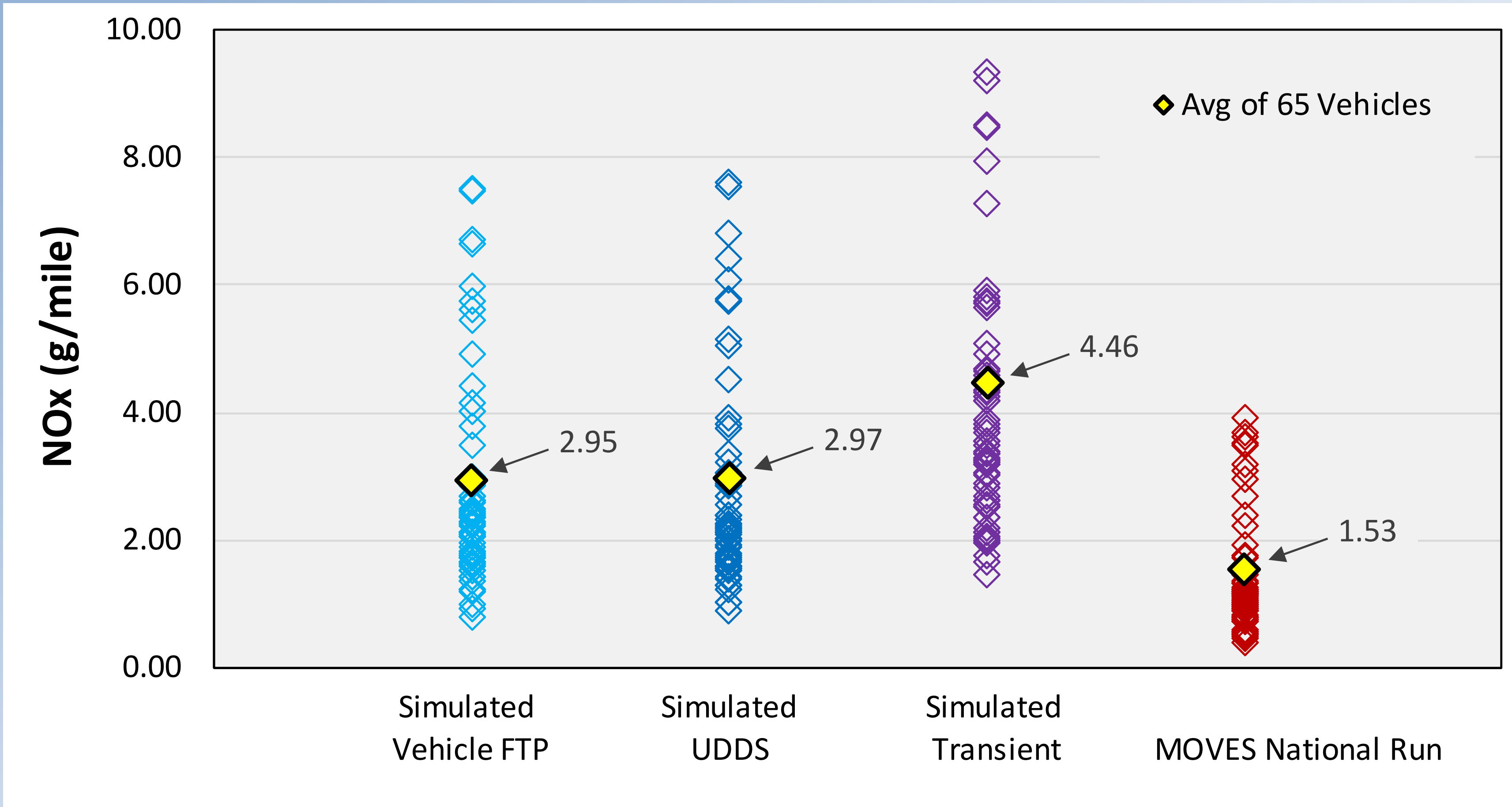
Each driving cycle was converted to an OpMode based time distribution based on the MOVES default road-load coefficients for combination long-haul trucks. Road grade was set to zero for the UDDS and Transient Cycles.

Vehicle FTP Cycle -> Andreae et al., DOI: 10.4271/2012-01-0878, http://papers.sae.org/2012-01-0878/

Cycle Average NOx Emissions



Cycle Average NOx Emissions (g/mile)



Conclusions

- In the real-world, MY 2010+ vehicles have higher NOx rates than indicated by the standards and current MOVES2014 estimates
- There is significant variability across the engines and among trucks with the same engine
- Driving/Duty cycles are a key contributor to real-world variability
- MOVES OpMode framework can be used to capture variability in SCR-equipped HD diesel truck emission rates across drive cycles

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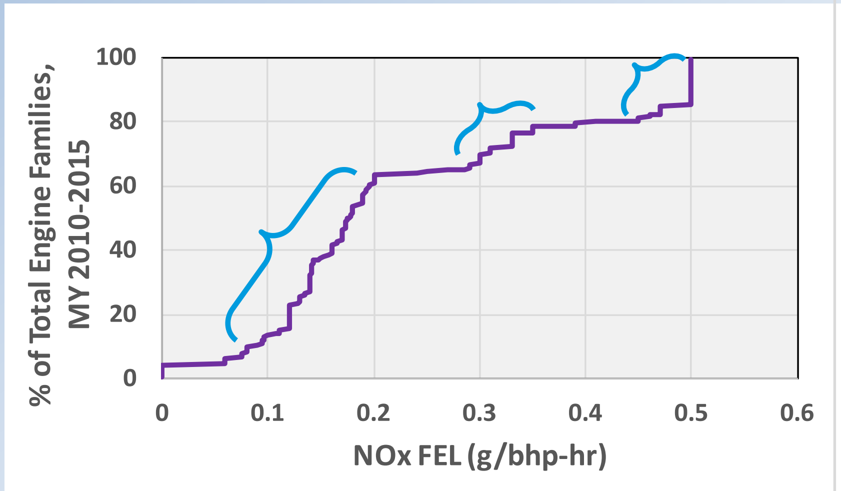
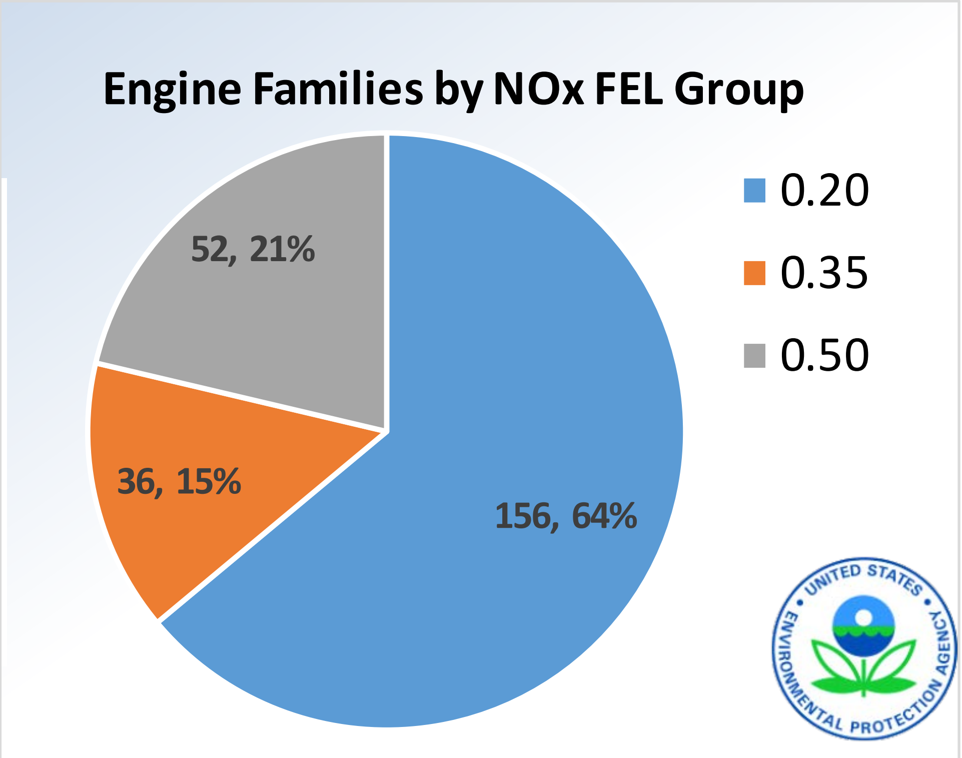
Supplemental Information

Engine Families Grouped by NOx 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

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

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 0.20 g/bhp-hr, 0.35 g/bhp-hr, and 0.50 g/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 selection order years 2010-2015 for 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

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
ω_{eng}	= engine angular speed
τ_{eng}	= ECU reported engine out torque
$\eta_{driveline}$	= 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)

MOVES Scaled Tractive Power: Road-Load Coeff

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t(a_t + g\frac{r_t}{100})}{f_{scale}}$$

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]

g = acceleration due to gravity [9.81 m/s^2]

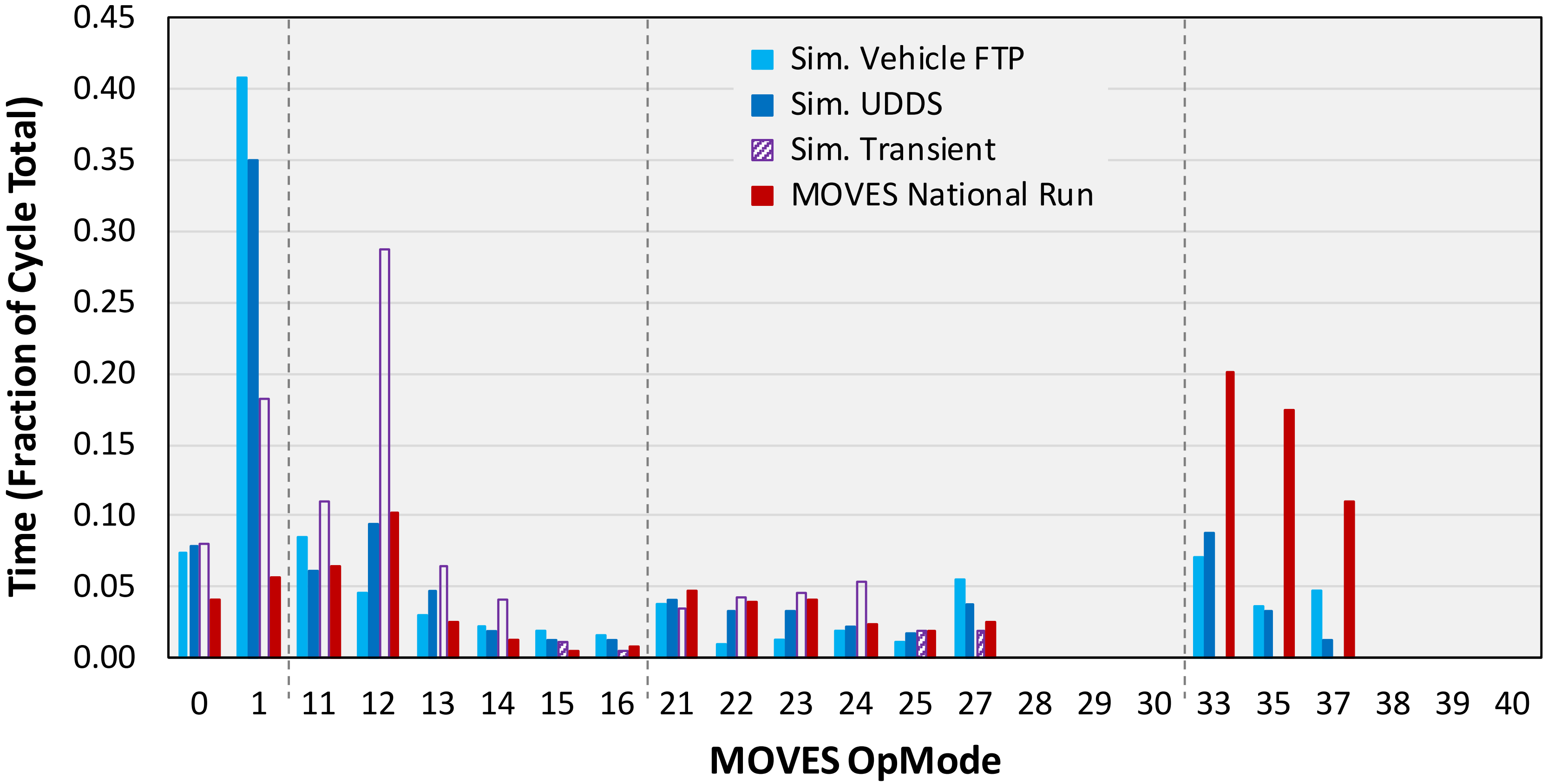
m = vehicle mass [metric ton]

r_t = road grade at time t [%]

v_t = vehicle speed at time t [m/s]

f_{scale} = scaling factor, unitless

OpMode Time Distribution for Cycle Average Comparisons



MOVES National Run OpMode distribution is for RegClass 47. The runspec is:
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