Identifying Areas of High NO_x Operation in Heavy-Duty Vehicles

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Scope

1. Total NO_x from Activity and Emission Rates
   - SCR efficacy analysis: effect of exhaust temperature
2. Comparison of $bsNO_x$ and NO_x/CO_2 Metrics
3. Comparison of NO_x Rates of MY 2010-2012 *vs* MY 2013-2014
4. Potential Effect of Mileage Accumulation of NO_x Emissions

$bsNO_x$ – **b**rake-**s**pecific **N**itrogen **Ox**ide; MY – **M**odel **Y**ear; 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.

MY 2010+ HDIUT Data Overview

Number of Diesel Test Vehicles

Service Class	NOx FEL Group 0.20	0.35	0.50	Total
LHDD	49	0	15	64
MHDD	26	23	9	58
HHDD	93	31	35	159
URBU	0	10	0	10
Total	168	64	59	**291**

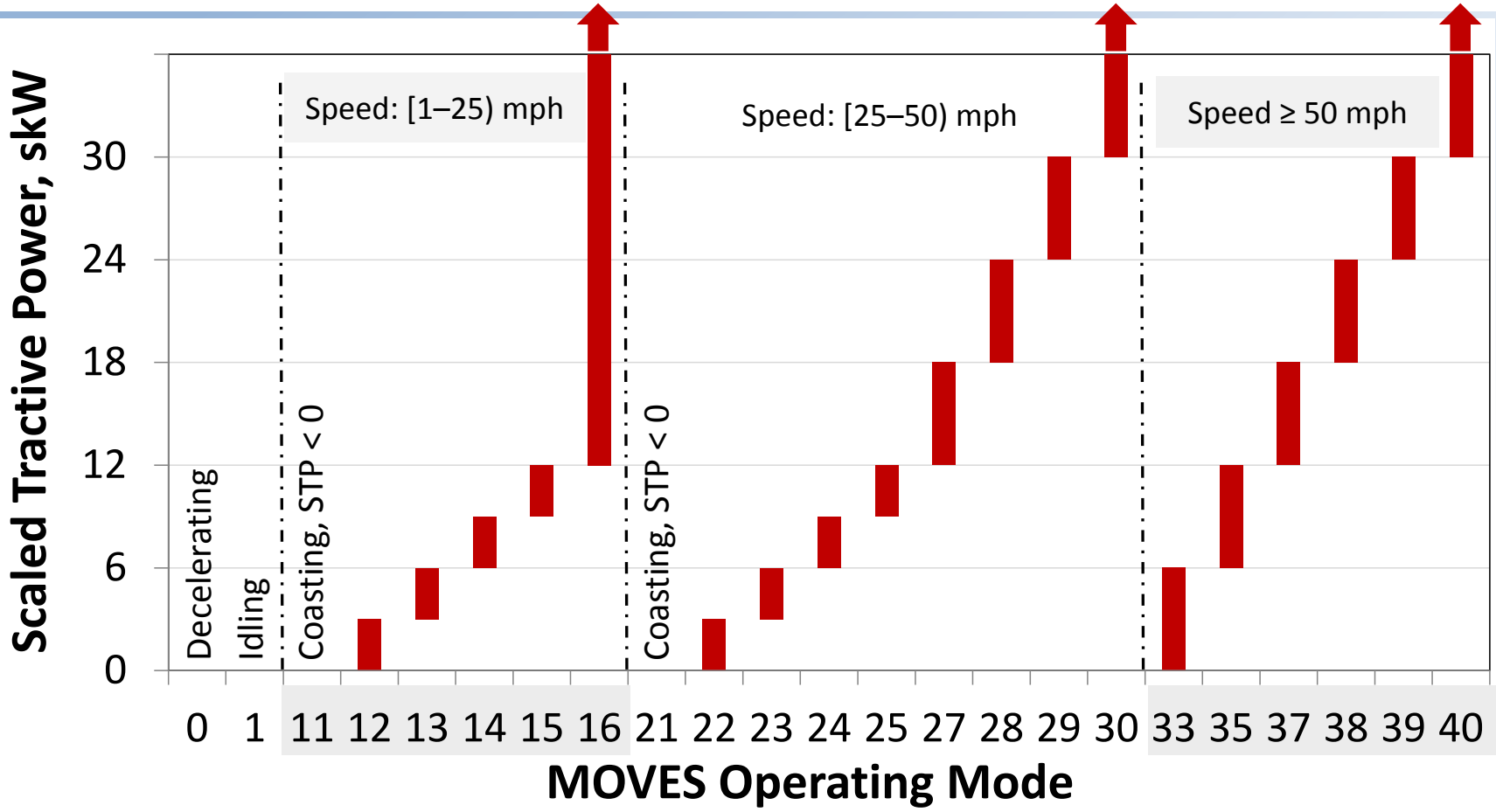
QA'ed Seconds of Data (Million)

Service Class	NOx FEL Group 0.20	0.35	0.50	Total
LHDD	1.17		0.30	1.47
MHDD	0.67	0.46	0.17	1.30
HHDD	2.96	0.89	1.02	4.88
URBU		0.25		0.25
Total	4.81	1.60	1.50	7.91

- Service Classes: Light-/Medium-/Heavy-Heavy-Duty Diesel (LHDD, MHDD, HHDD) and Urban Bus (URBU)
- Fuels: Diesel and Natural Gas
- Manufacturers: Cummins, Detroit Diesel, Ford, FPT, GM, Hino, Isuzu, Iveco, Navistar, Paccar, Volvo
- Engine Families: MY 2010-2015, 46 total and 38 “base” engine families (see slide 19)
- Vehicles: Over 300 vehicles
- Size: Over 10 million seconds of raw data

FEL – **F**amily **E**mission **L**imit (the emission limit, in g/bhp-hr, of all engines in an engine family)

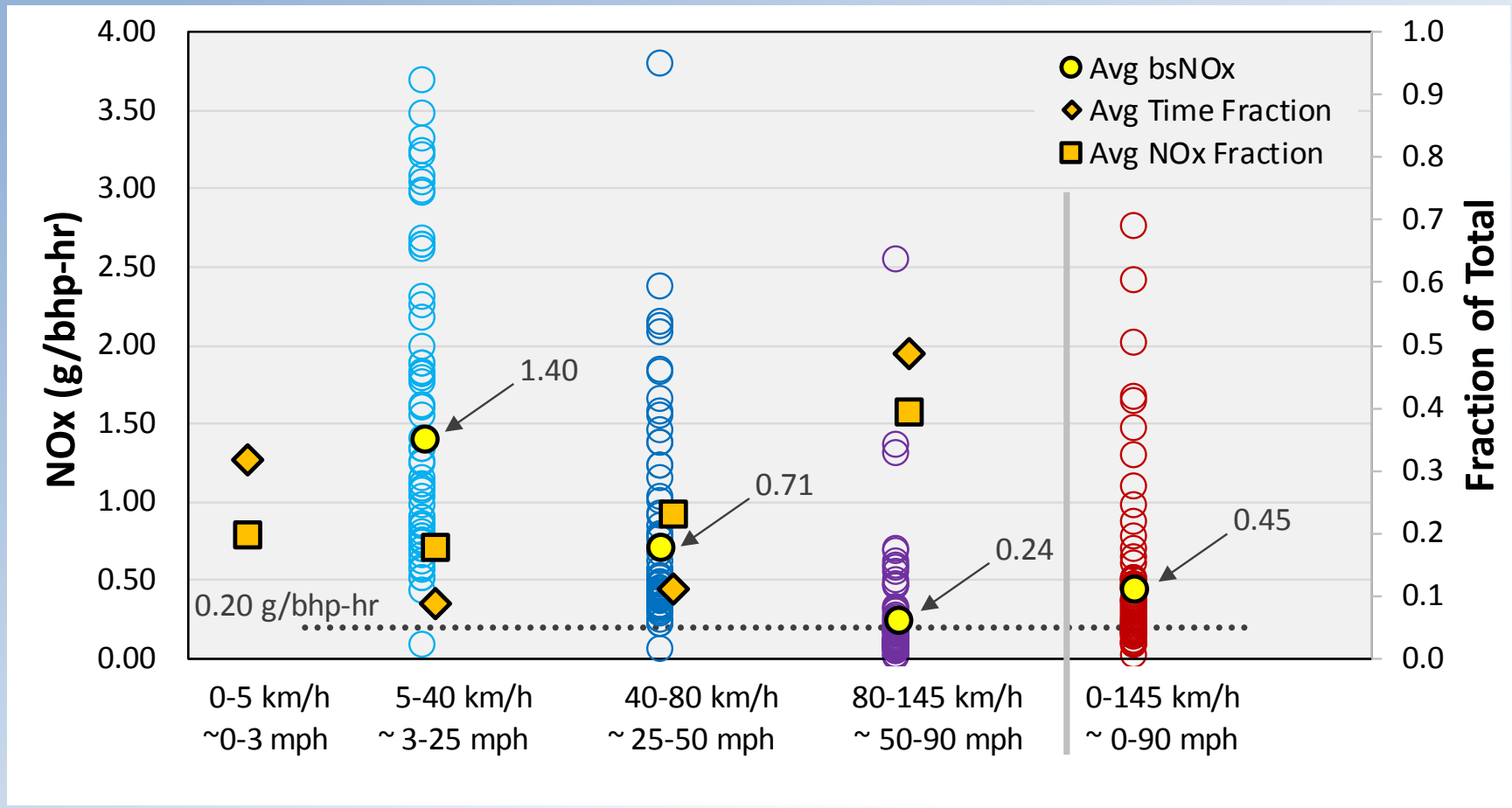
MOVES Operating Modes (OpMode)



The OpMode definition in this presentation is same as shown above. **However**, the STP (eqn. on slide 22) is calculated using f_{scale} values 4, 4, and 9 for LHD, MHD, and HHD, respectively. These f_{scale} values are different from the f_{scale} in the MOVES model and thus, OpMode based rates and results in this presentation cannot be compared to MOVES default. Similarly, the OpMode based HHD results here cannot be compared to MHD and LHD results (due to different f_{scale} values).

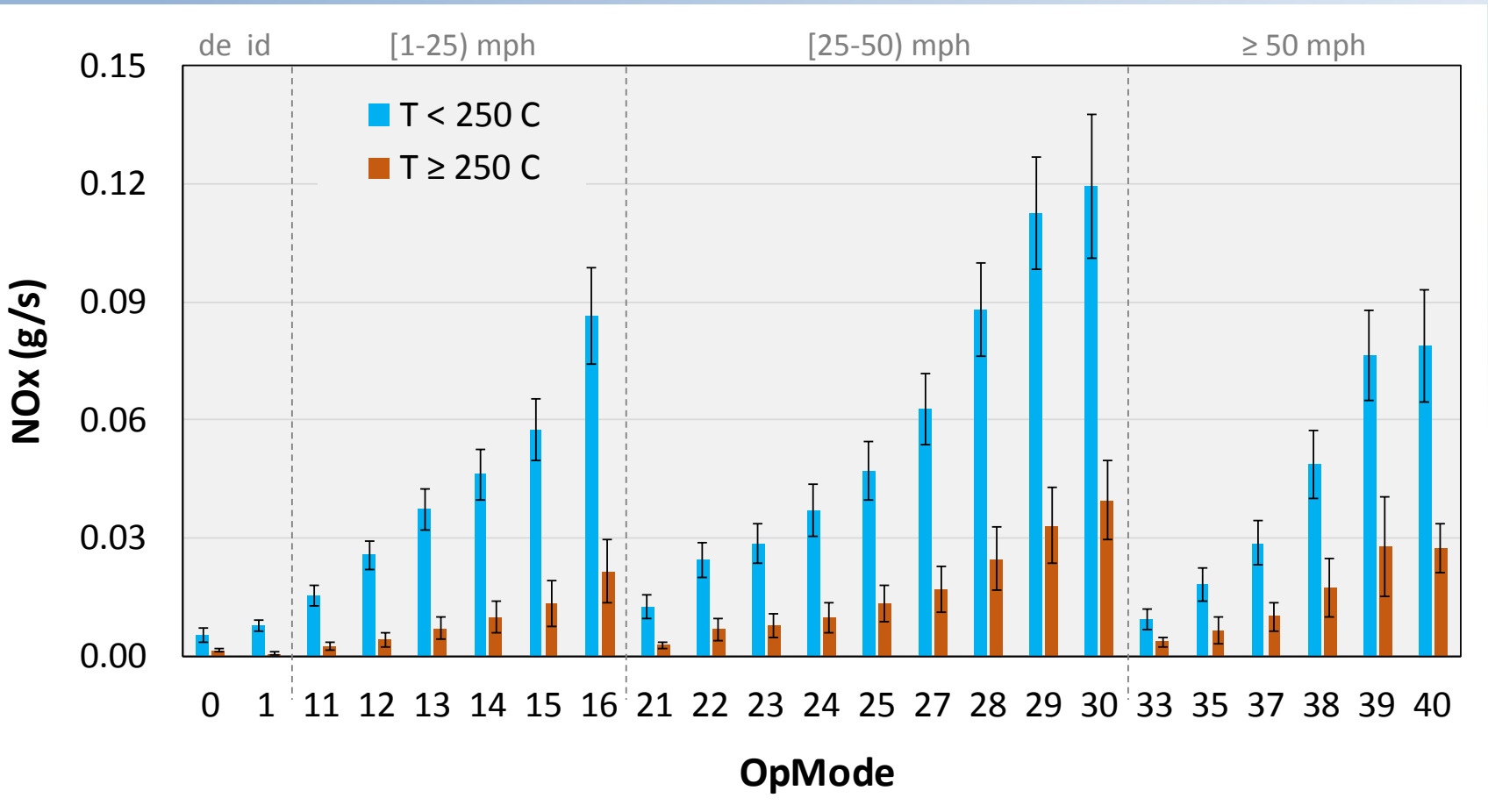
Total NO_x from Activity and Emission Rates

HHD: NO_x by Speed Modes



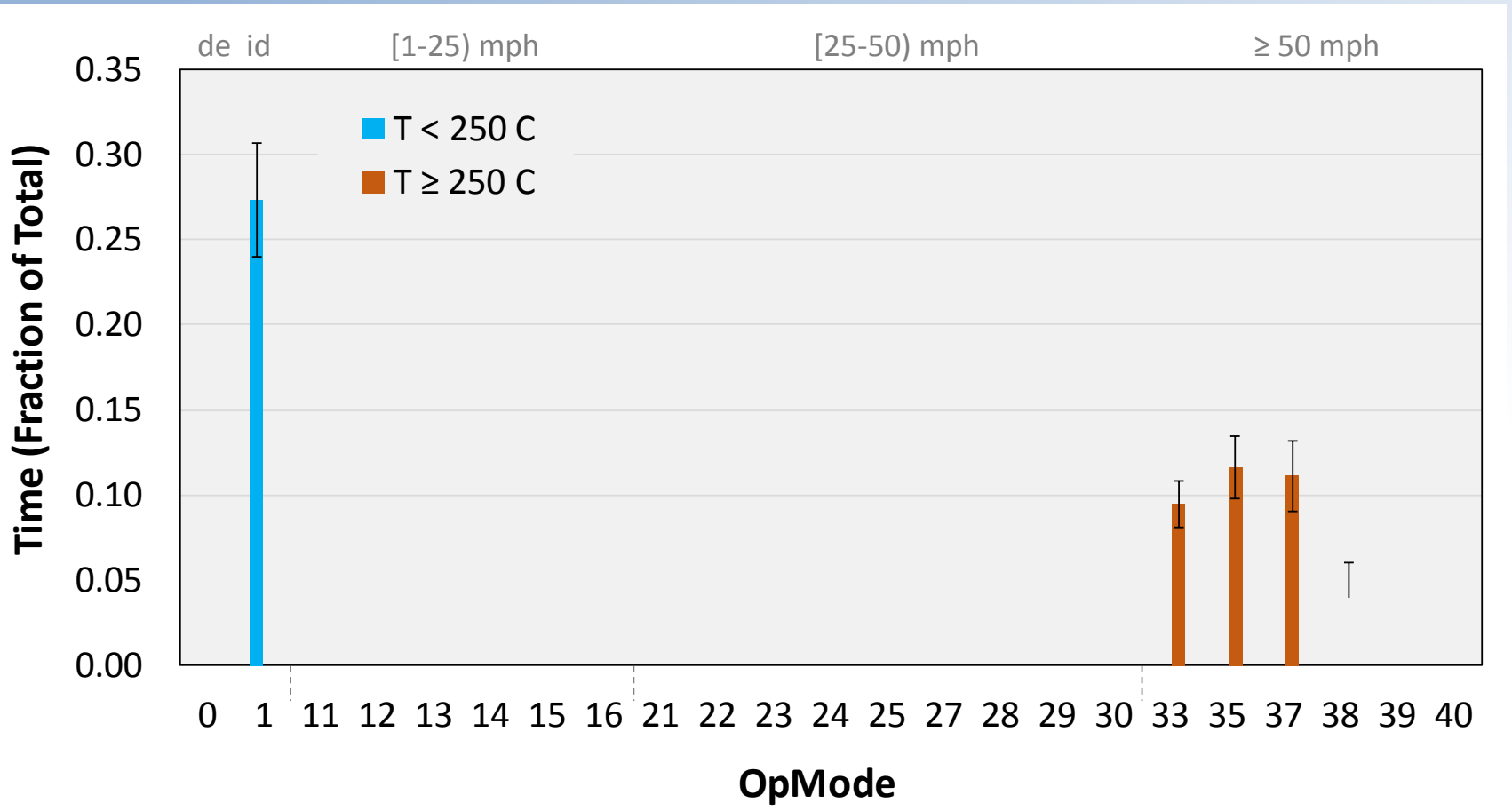
HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 93 vehicles, 2.96 million seconds of data
Each circle is a HHDD vehicle.
Average for the 0-5 km/h group is 6.38 g/bhp-hr.
Fractions add up to 1.00

HHD: NO_x Rate by Exhaust Temperature



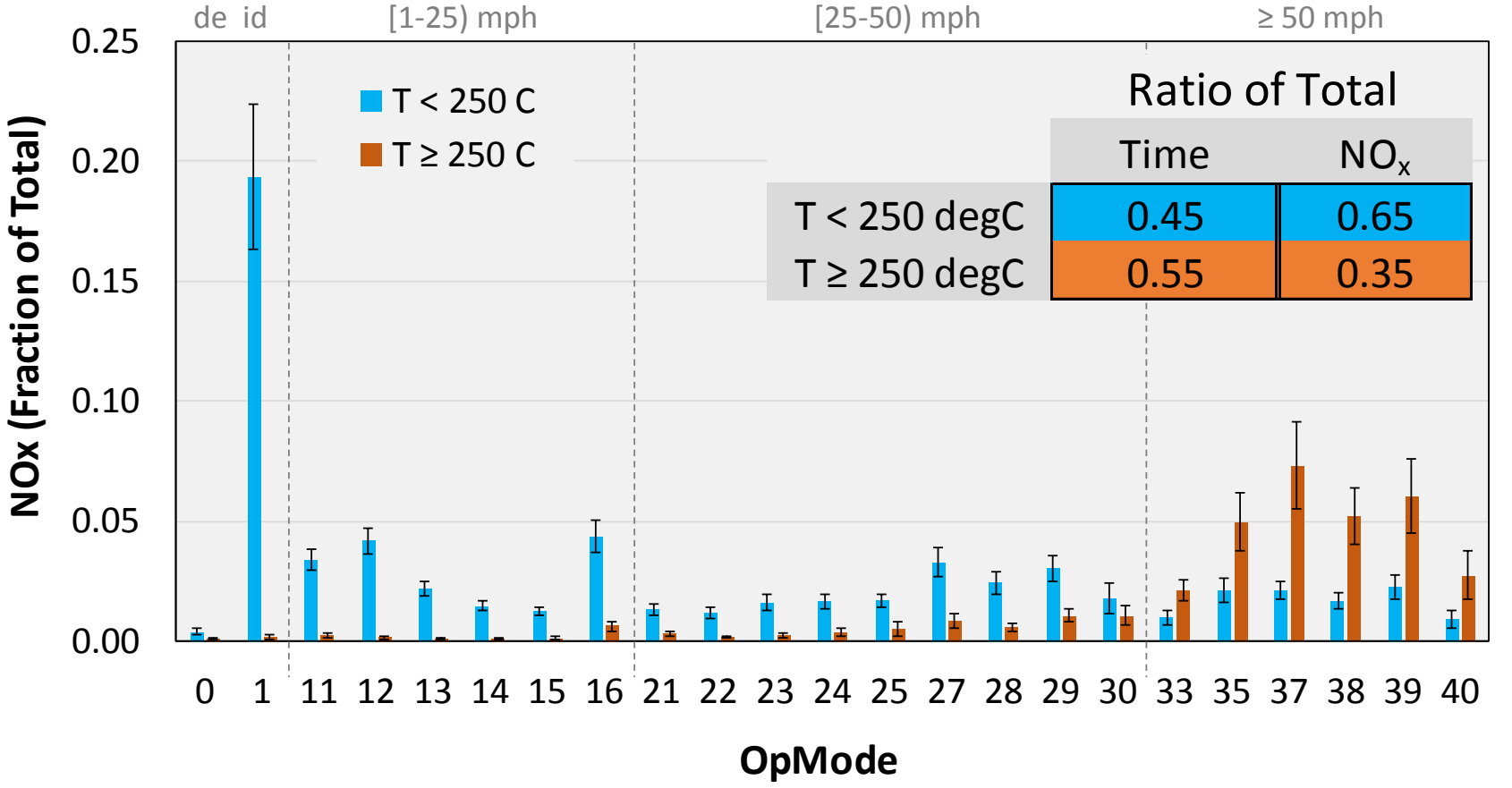
HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 81 vehicles, 2.61 million seconds of data
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars add up to 1.00

HHD: Time by Exhaust Temperature



HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 81 vehicles, 2.61 million seconds of data
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars add up to 1.00

HHD: Total NO_x by Exhaust Temperature

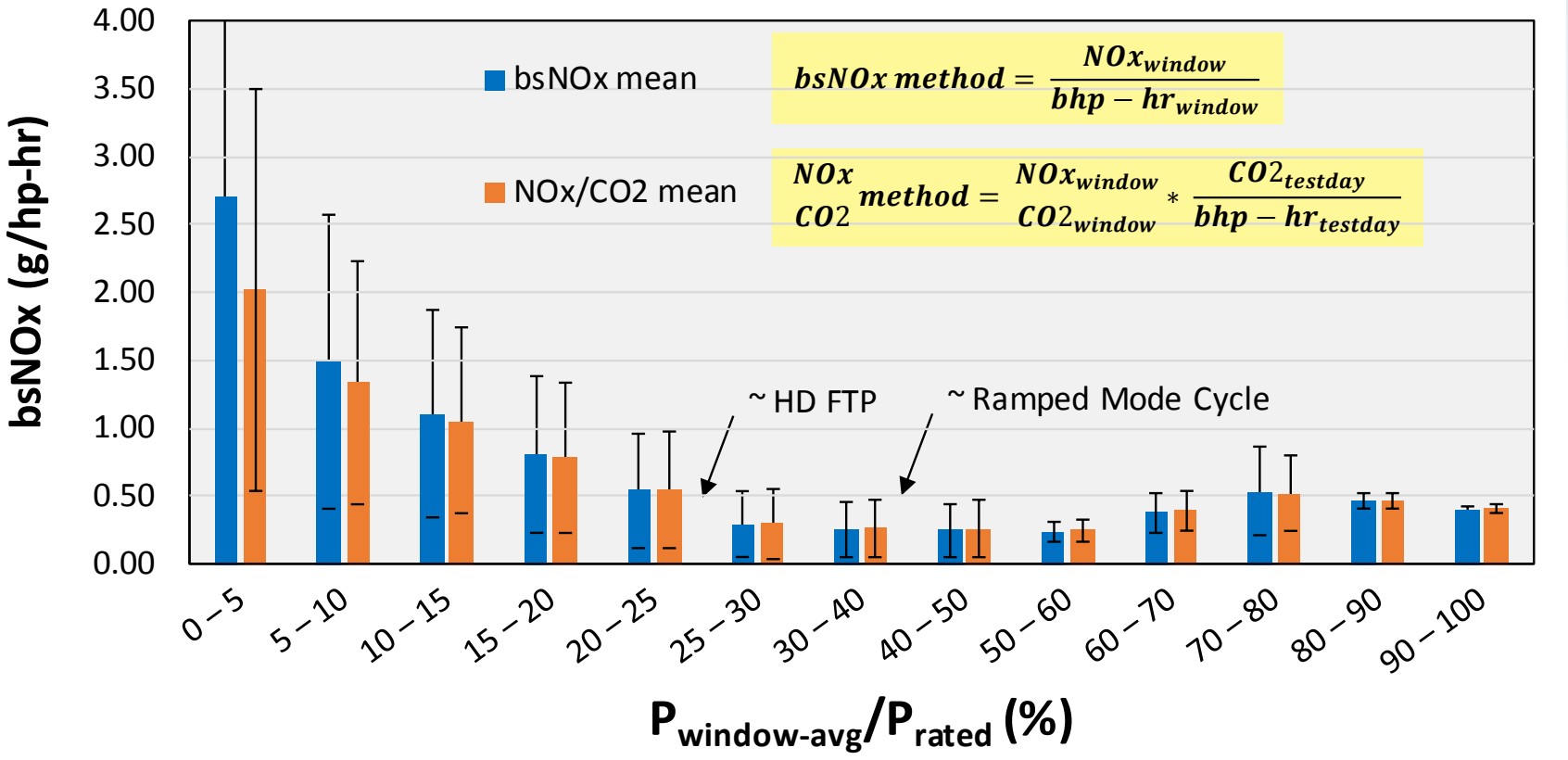


HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 81 vehicles, 2.61 million seconds of data
12 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars add up to 1.00

Exploratory Analysis:

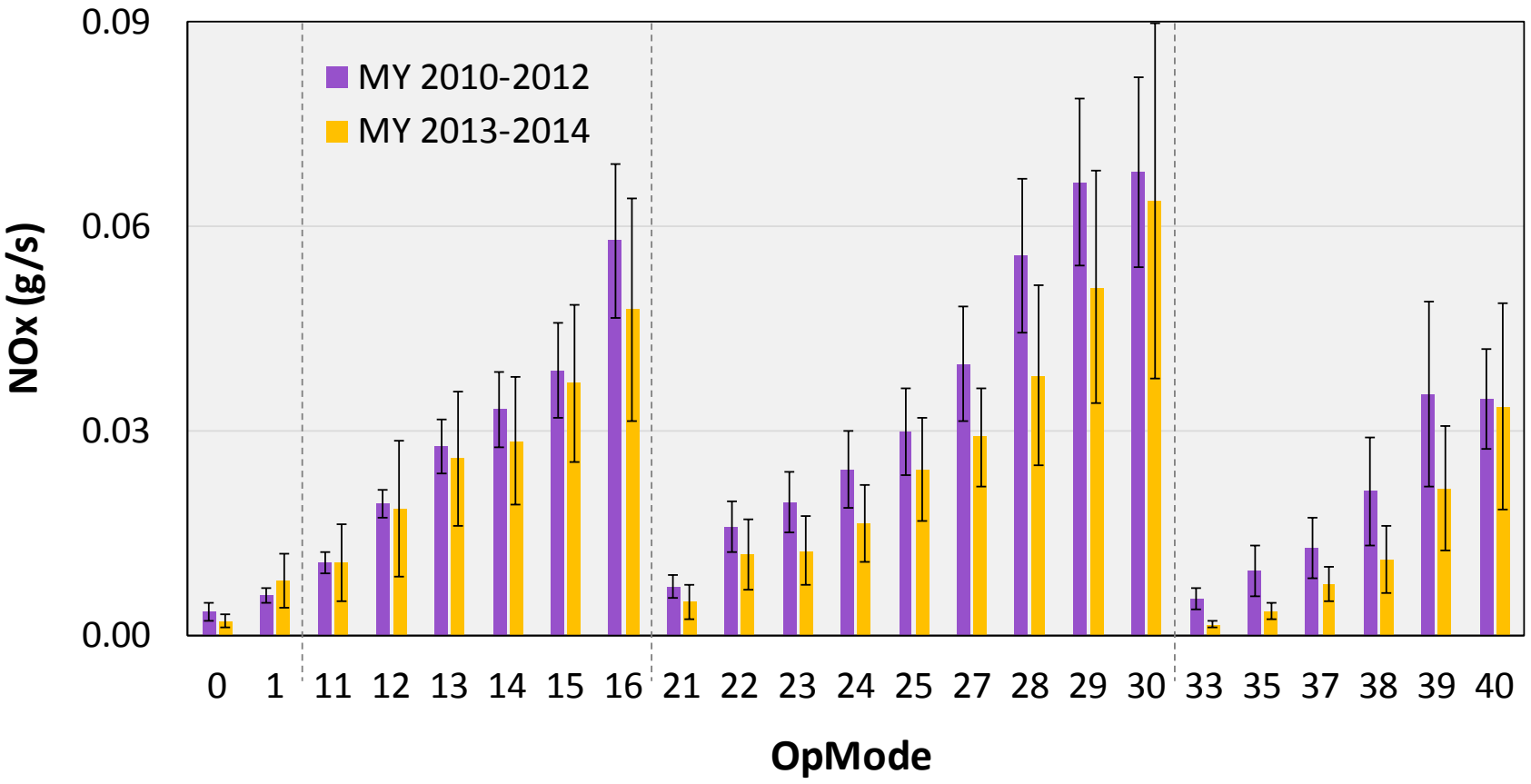
Work-based Window
Model Year Improvements
Mileage Accumulation

HHD: Brake-specific vs CO_2-specific Metrics



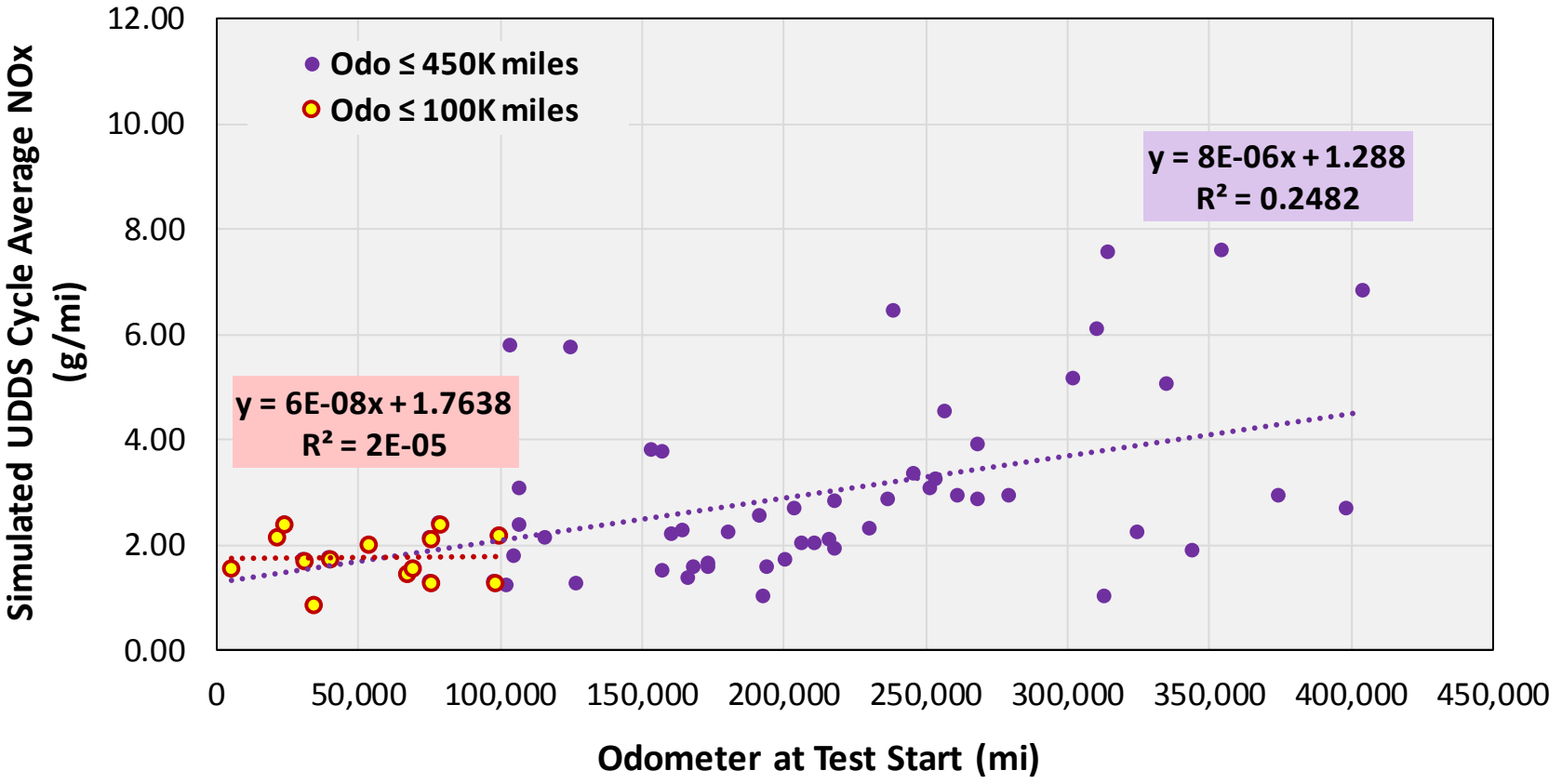
HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 85 vehicles, 2.90 million windows
Work-windows are calculated over continuous seconds. Consecutive windows have overlapping seconds.
Error bars are SD of the mean. The 95% CI is not shown since windows are not independent.

HHD: MY 2010-2012 *vs* MY 2013-2014



HHDD with NOx FEL ≤ 0.20 g/bhp-hr
MY 2010-2012: 72 vehicles, 2.41 million secs of data
MY 2013-2014: 21 vehicles, 0.55 million secs of data

HHD: Potential Effect of Mileage Accumulation



HHDD with NOx FEL ≤ 0.20 g/bhp-hr | 64 vehicles, 2.18 million seconds of data
59 vehicles from MY 2010-2012 and 5 vehicles from MY 2013

Conclusions

- Important to consider both activity and emission rate for optimum reduction in NO_x inventory
  - Emissions increase due to lower SCR temperature is not uniform across operating modes
  - Low to mid speeds contribute disproportionately to the test emissions
- Work-based window approach can highlight engine optimization needs
- HDIUT data suggests newer model year HHDD vehicles have lower NO_x rates. Maybe due to better thermal management?
  - Confounded by mileage-based deterioration
  - Limited sample size

Acknowledgements

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Supplemental Information

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."

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

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

STP_t = scaled tractive power at time t, skW

A = rolling resistance coefficient [kW-s/m]

B = rotational resistance coefficient [kW-s^2/m^2]

C = aerodynamic drag coefficient [kW-s^3/m^3]

a_t = vehicle acceleration at time t [m/s^2]

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

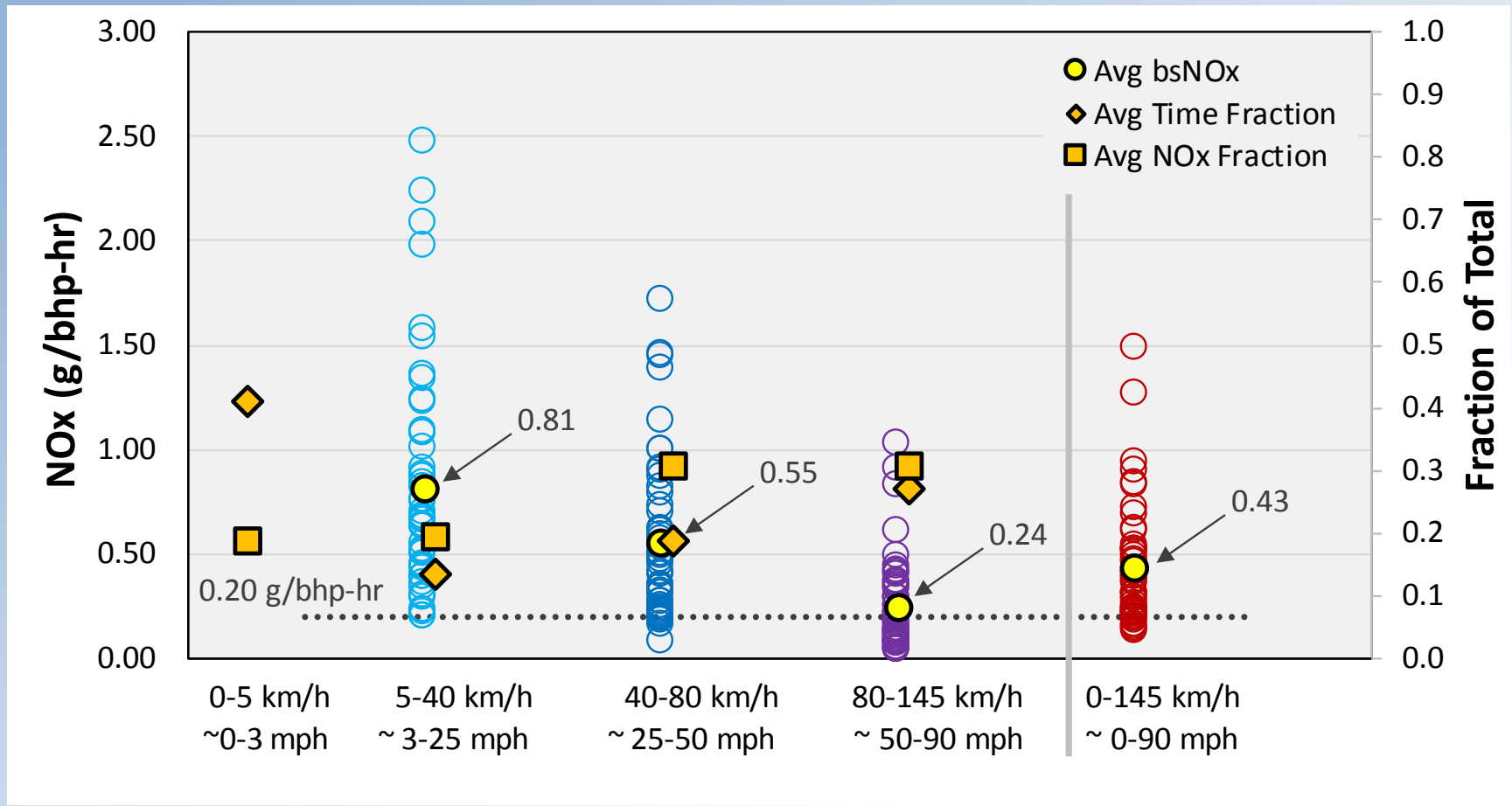
m = vehicle mass [metric ton]

r_t = road grade at time t [%]

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

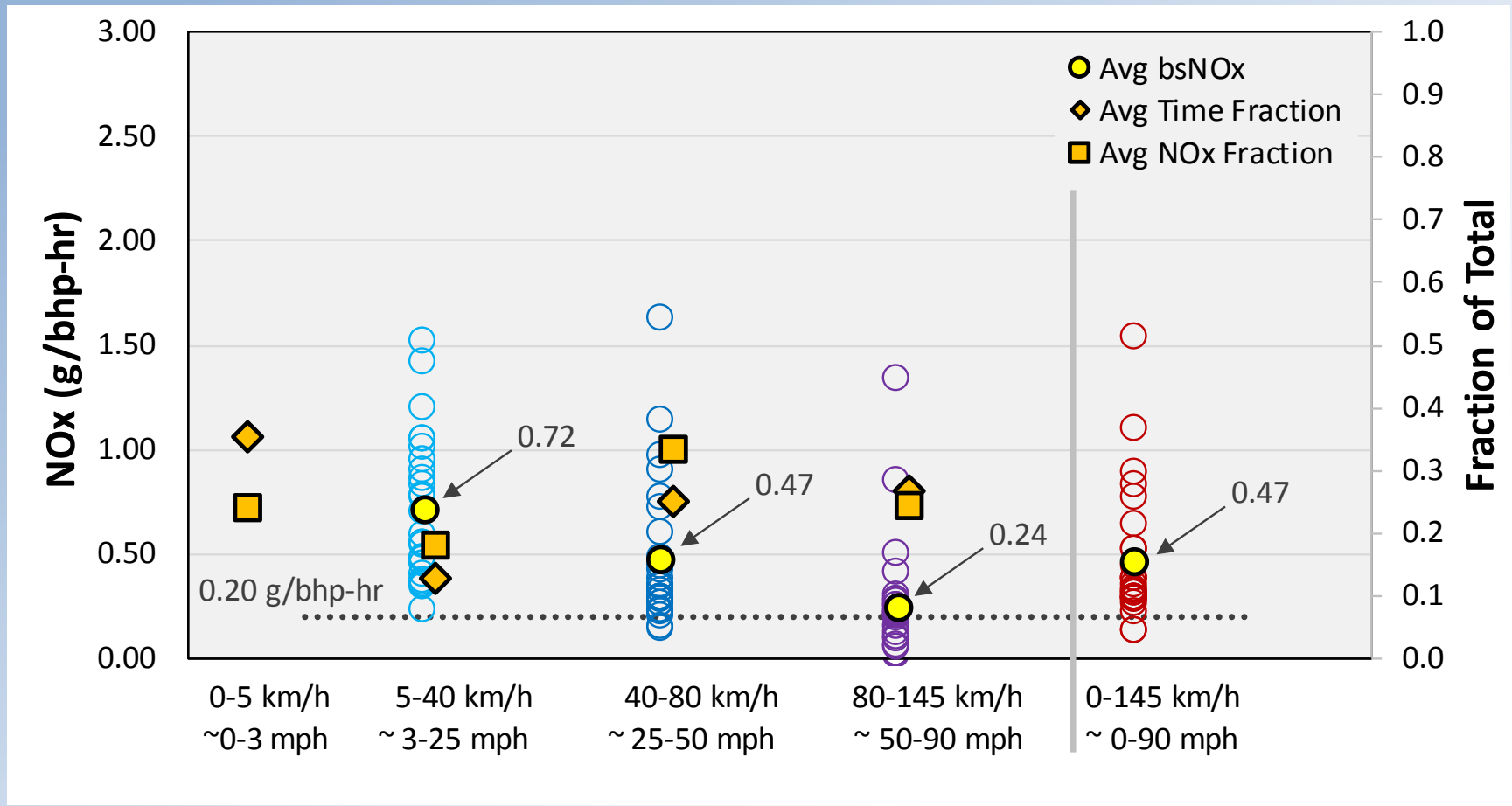
f_{scale} = scaling factor, unitless

LHD: NO_x by Speed Modes



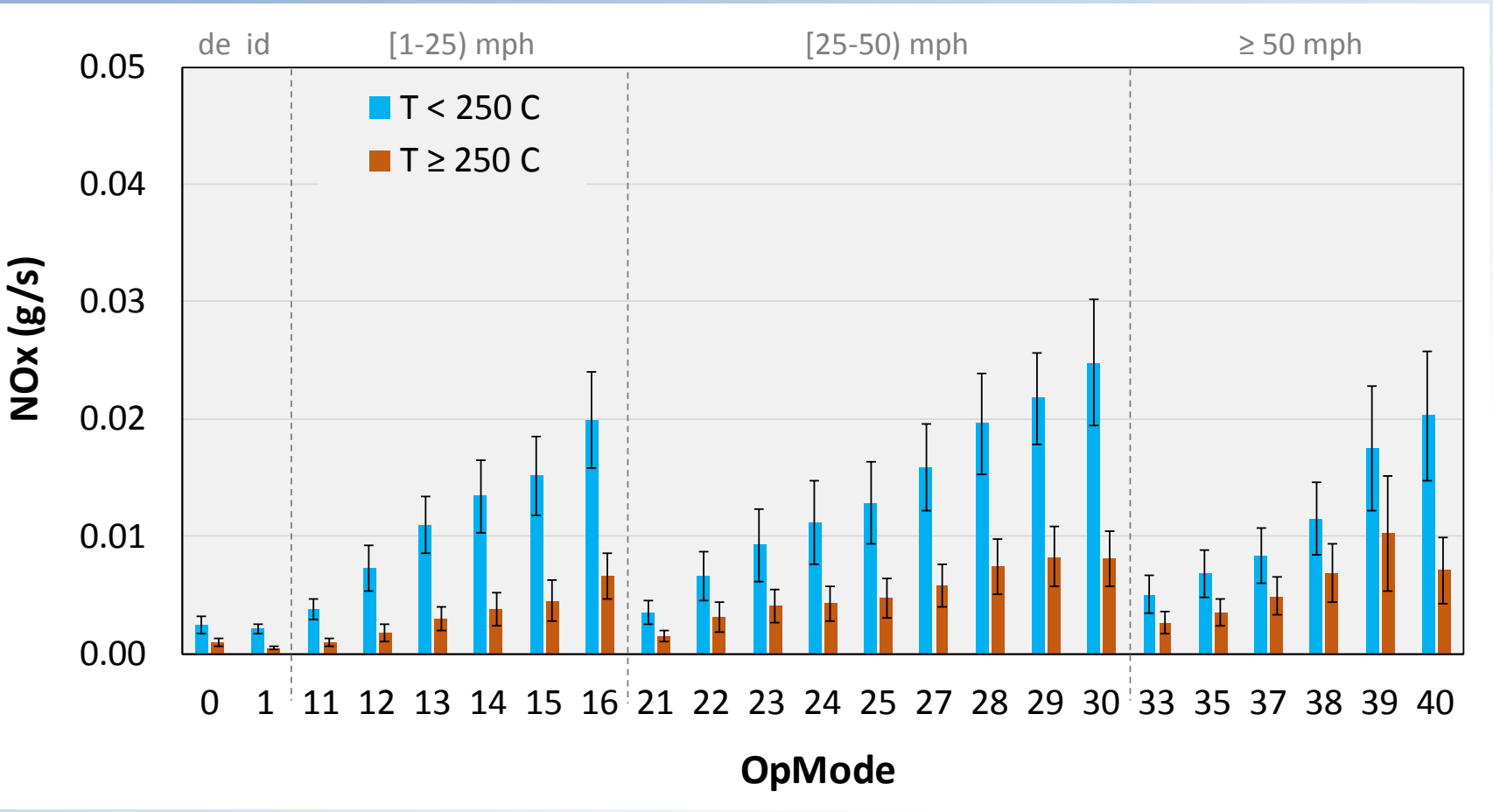
LHDD with NOx FEL ≤ 0.20 g/bhp-hr | 49 vehicles, 1.17 million seconds of data
Each circle is a LHDD vehicle. Average for the 0-5 km/h group is 4.61 g/bhp-hr.
Fractions add up to 1.00

MHD: NO_x by Speed Modes



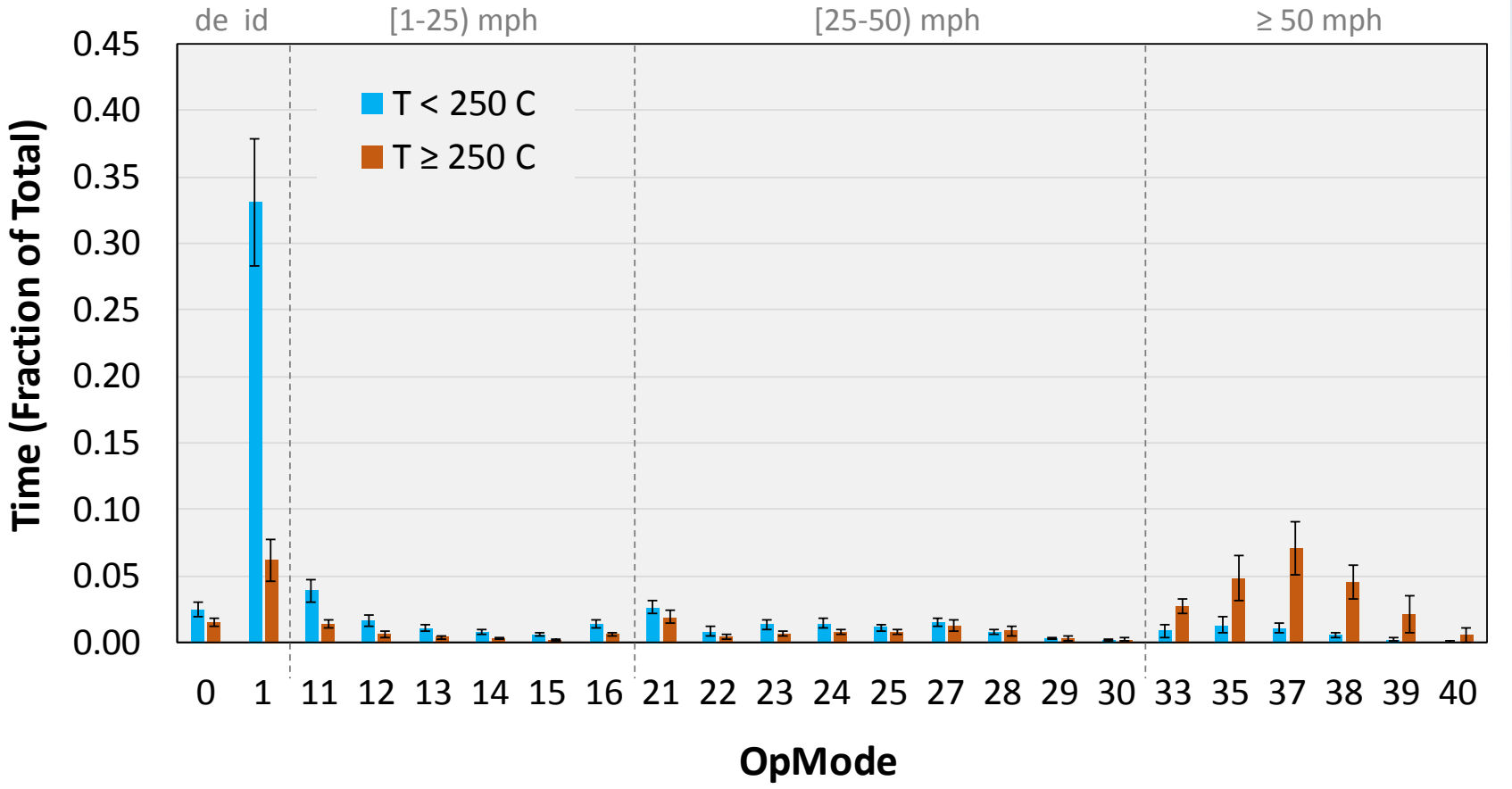
MHDD with NOx FEL ≤ 0.20 g/bhp-hr | 26 vehicles, 0.67 million seconds of data
Each circle is a MHDD vehicle. Average for the 0-5 km/h group is 7.65 g/bhp-hr.
Fractions add up to 1.00

LHD: NO_x Rate by Exhaust Temperature



LHDD with NOx FEL ≤ 0.20 g/bhp-hr | 42 vehicles, 0.97 million seconds of data
7 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars add up to 1.00

LHD: Time by Exhaust Temperature



LHDD with NOx FEL ≤ 0.20 g/bhp-hr | 42 vehicles, 0.97 million seconds of data
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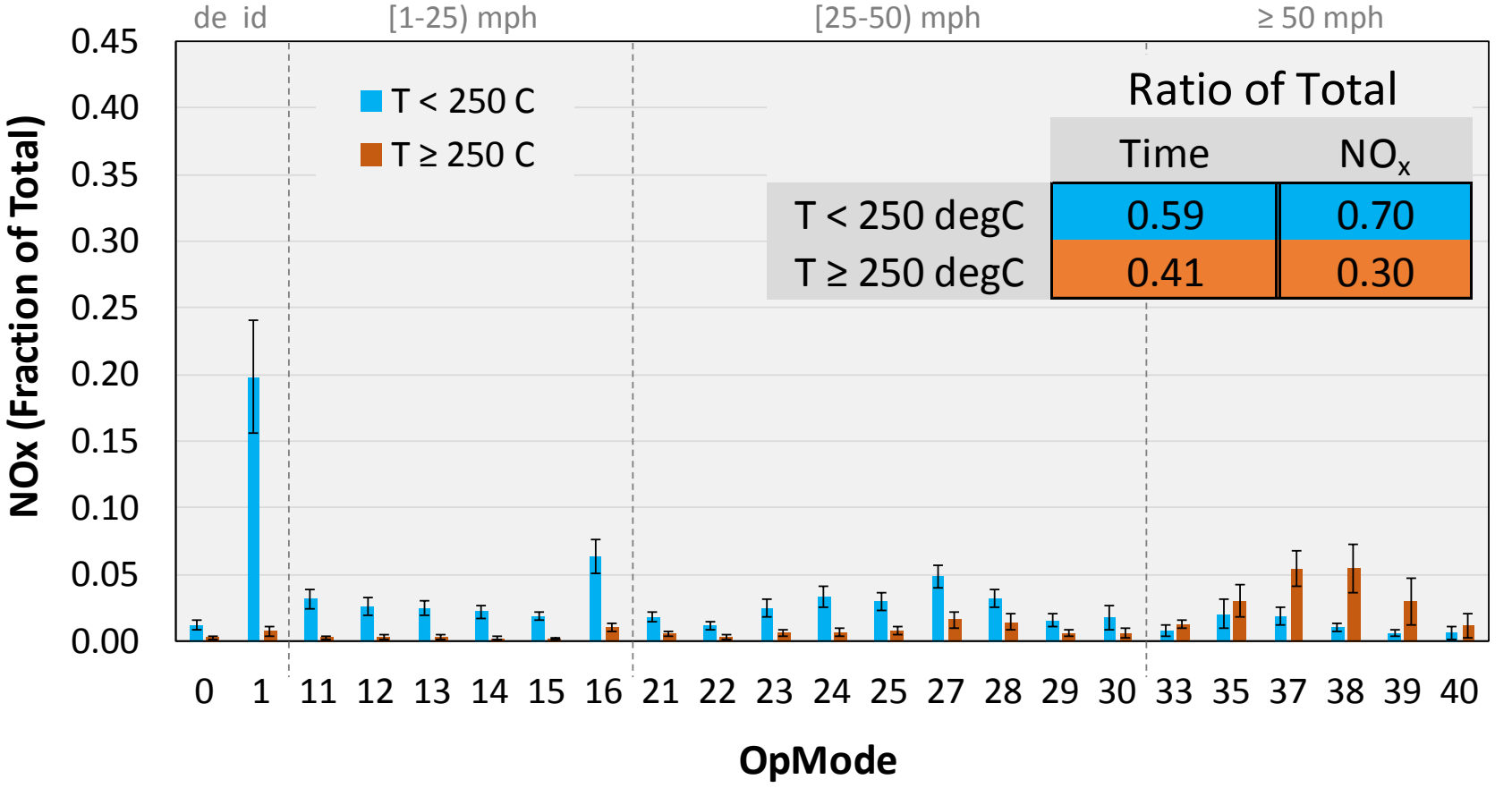
LHD: Total NO_x by Exhaust Temperature



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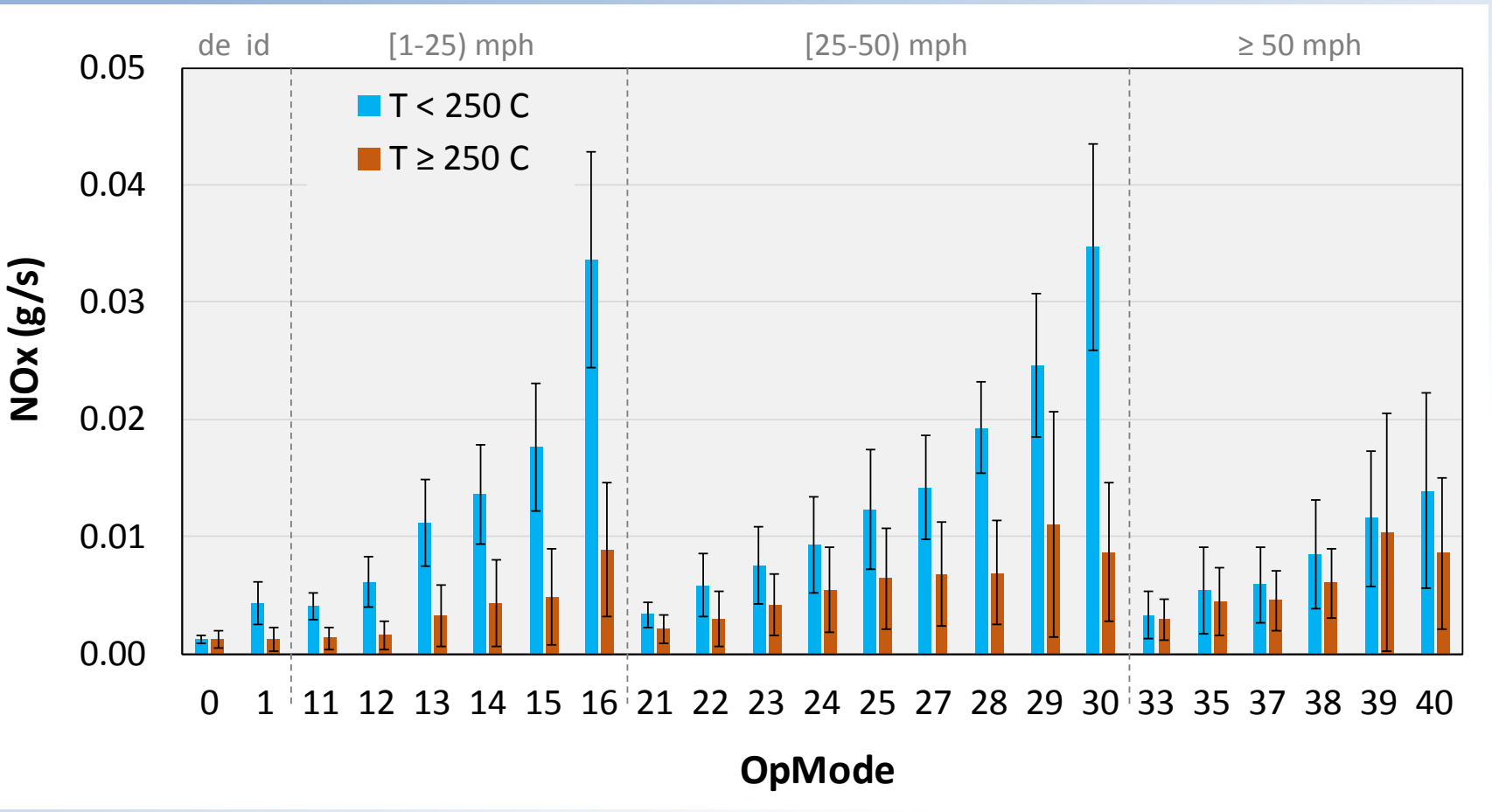
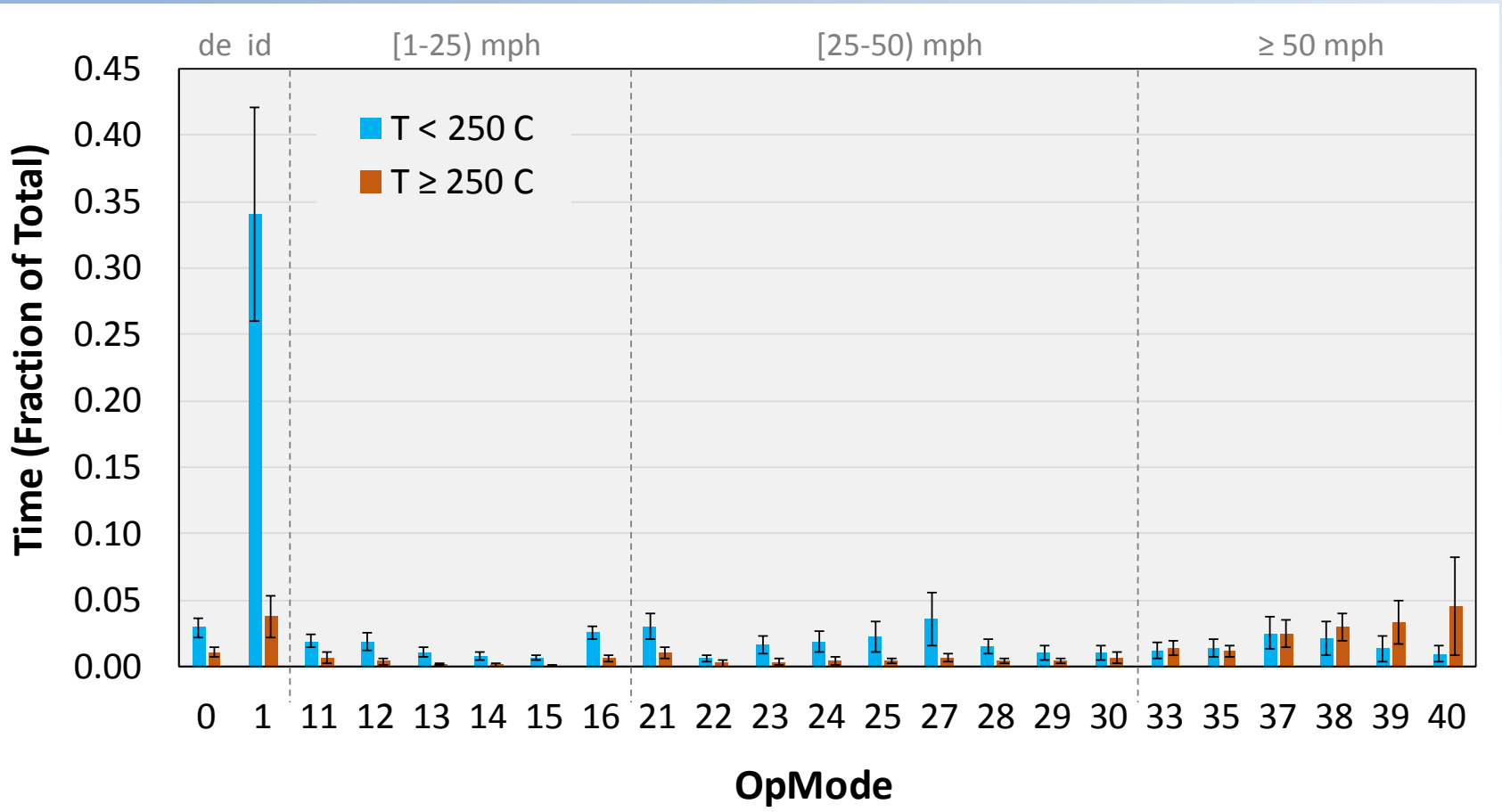
MHD: NO_x Rate by Exhaust Temperature



MHDD with NOx FEL ≤ 0.20 g/bhp-hr | 20 vehicles, 0.57 million seconds of data
6 vehicles did not report after-treatment (AT) temperature and are excluded from this analysis
Bars add up to 1.00

MHD: Time by Exhaust Temperature



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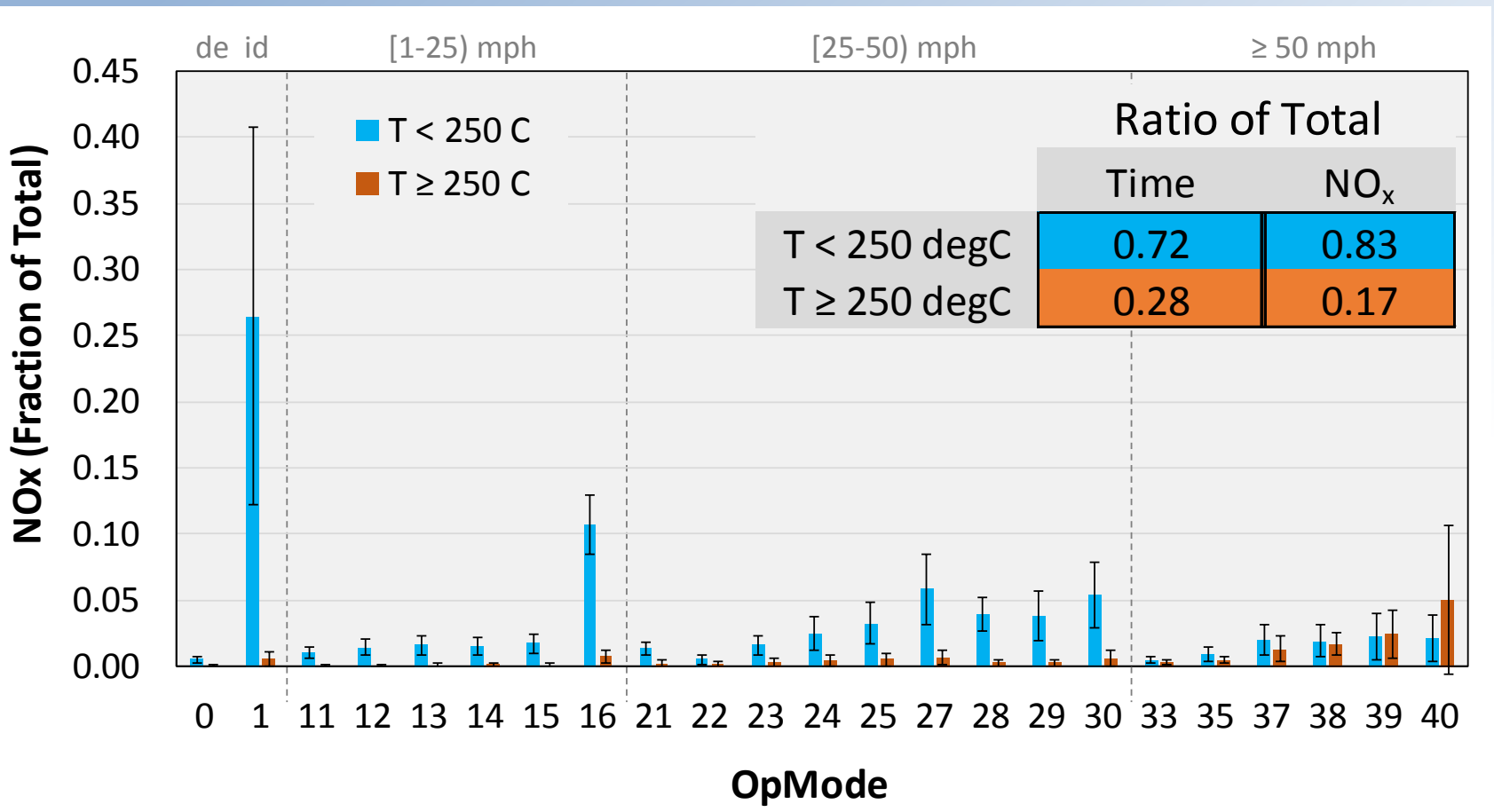
MHD: Total NO_x by Exhaust Temperature



MHDD with NOx FEL ≤ 0.20 g/bhp-hr | 20 vehicles, 0.57 million seconds of data
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Bars add up to 1.00