MOVES
Motor Vehicle Emission Simulator

Recommended Updates to MY 2010+ Heavy-Duty Vehicles – Fixed Mass Factor and Diesel Particulate Matter Rates

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Context

- December 2016 MOVES Review Work Group[1]: recommended update to Heavy-Duty (HD) MY2010+ criteria pollutants:
  - Used the Heavy-Duty In-Use Testing (HDIUT) data set
    - Manufacturer-run, five vehicles per engine family, no malfunction lights, within useful life, doing regular work, measured using PEMS certified to 40 CFR 1065
    - LHD/MHD/HHD, MY 2010-2013 engines, 230 vehicles, 6+ million seconds of data (and more data coming in)
  - Rates were developed using MOVES2014 f_{scale} values
  - Particulate matter (PM) was not included in the recommended update (NO_x, HC, CO, and Energy/CO_2 were included)
- This presentation: plans to update HD MY2010+ f_{scale} values and PM rates; based on the HDIUT data set

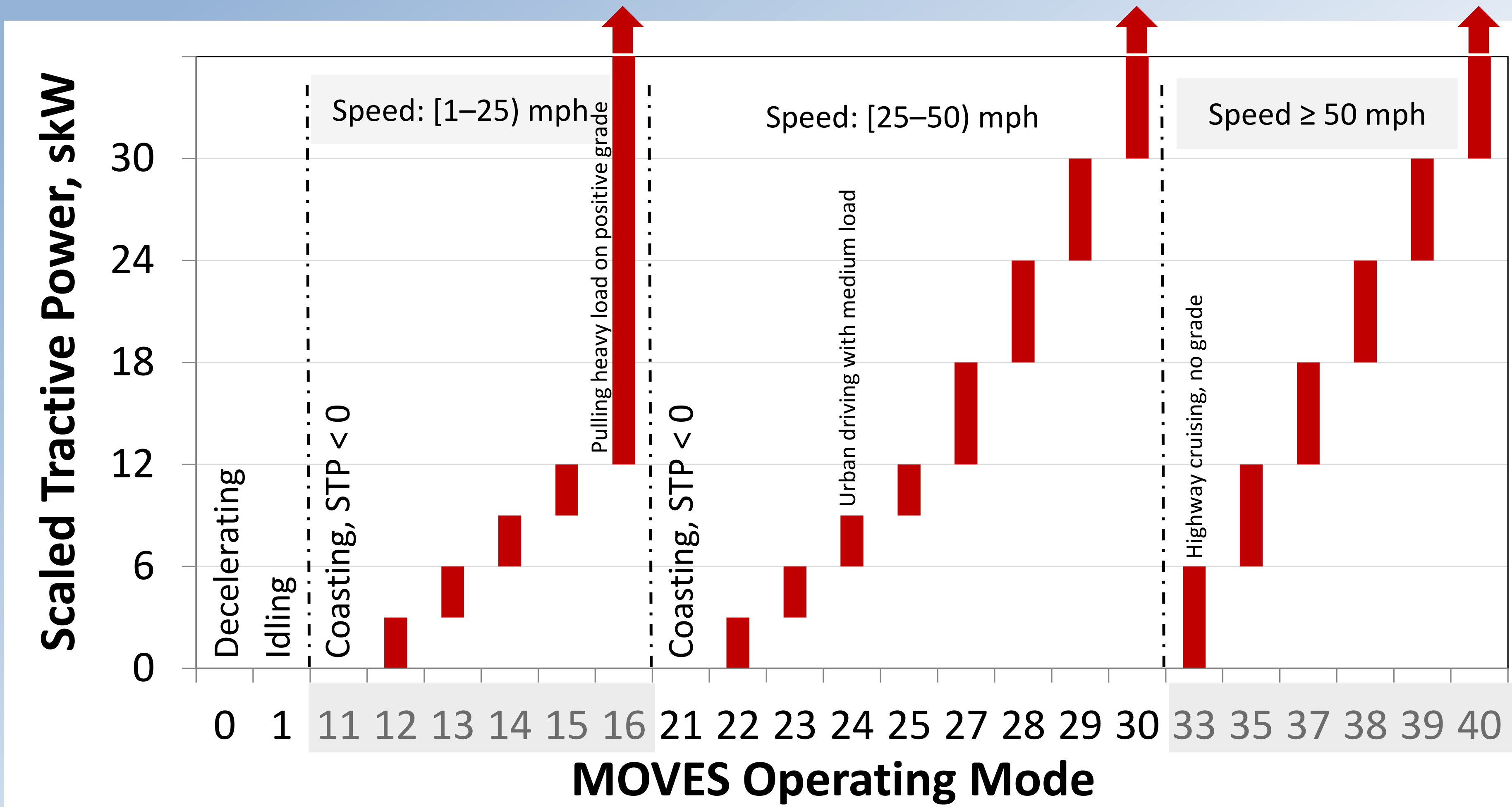
1. https://www.epa.gov/moves/december-2016-moves-model-review-work-group-meeting-materials

Contents

- Fixed Mass Factor (f_{scale}) topic:
  - How f_{scale} is used in MOVES
  - Motivation to update f_{scale}
  - Effect of f_{scale} on OpMode-based activity and emission rates
  - Plan and next steps
- PM rates topic:
  - Data sources and recommended updates
  - HDIUT-based PM rates
  - Comparison to MOVES2014
  - Comparison to literature
  - Plan and next steps

The HDIUT-based NO_x and PM rates in this presentation are from vehicles with MY 2010+ diesel engines equipped with DPF and SCR and certified to 0.20 g-NO_x/bhp-hr

MOVES Operating Modes (OpMode)



MY 2010+ Heavy-Duty Vehicles – Fixed Mass Factor (f_{scale})

Background: How f_{scale} is used

Scaled Tractive Power (STP) estimates the tractive power exerted by a vehicle and is scaled (or normalized) by f_{scale}

$$STP = \frac{\eta_{driveline}\left(\omega_{eng}\tau_{eng} - P_{loss,acc}\right)}{f_{scale}}$$

Used when analyzing HDIUT data

$$STP = \frac{Av + Bv^2 + Cv^3 + M \cdot (a + g \cdot sin\theta) \cdot v}{f_{scale}}$$

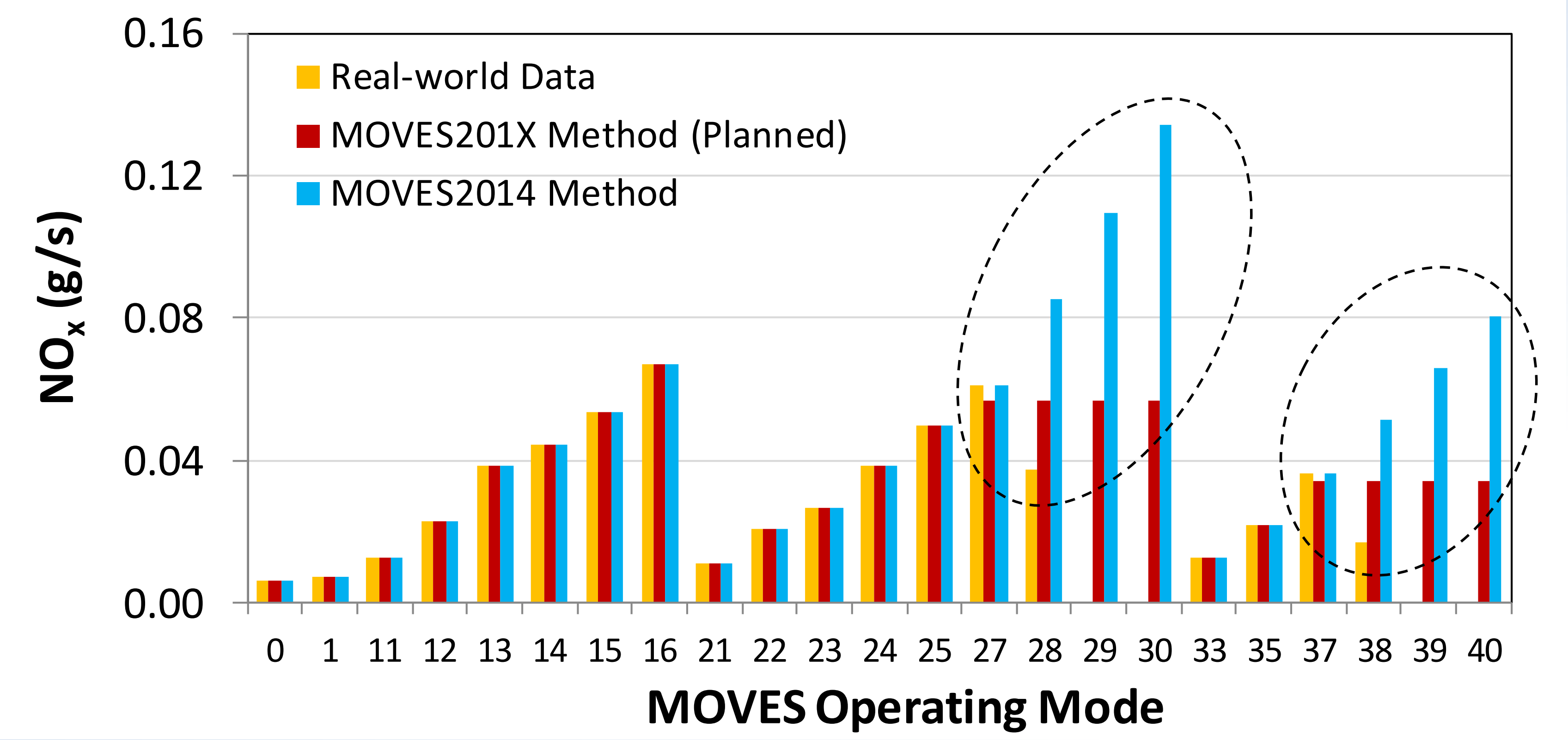
Used during MOVES run

Currently in MOVES,

- RegClass 40 use $f_{scale} = 2.06$, which is equal to the mass of source type 32 (light commercial truck) in metric tons
- RegClass 41-48 use $f_{scale} = 17.1$, which is roughly equivalent to the average running weight in metric tons of all heavy-duty vehicles

RegClass 40: Class 2b trucks with 2 axles and 4 tires (8,500 lbs <GVWR< 14,000 lbs)
RegClass 41: Class 2b trucks with at least 6 tires and Class 3 trucks (8,500 lbs <GVWR< 14,000 lbs)
RegClass 42, 46, 47, 48: Heavier heavy-duty weight class vehicles (GVWR > 14,000 lbs)

Background: High f_{scale} limits data in higher OpModes; requires gap-filling



Need: Choose new f_{scale} values such that vehicle activity covers more high power OpModes, thus minimizing or eliminating the need for gap-filling.

Effect of f_{scale}: Vehicle Count

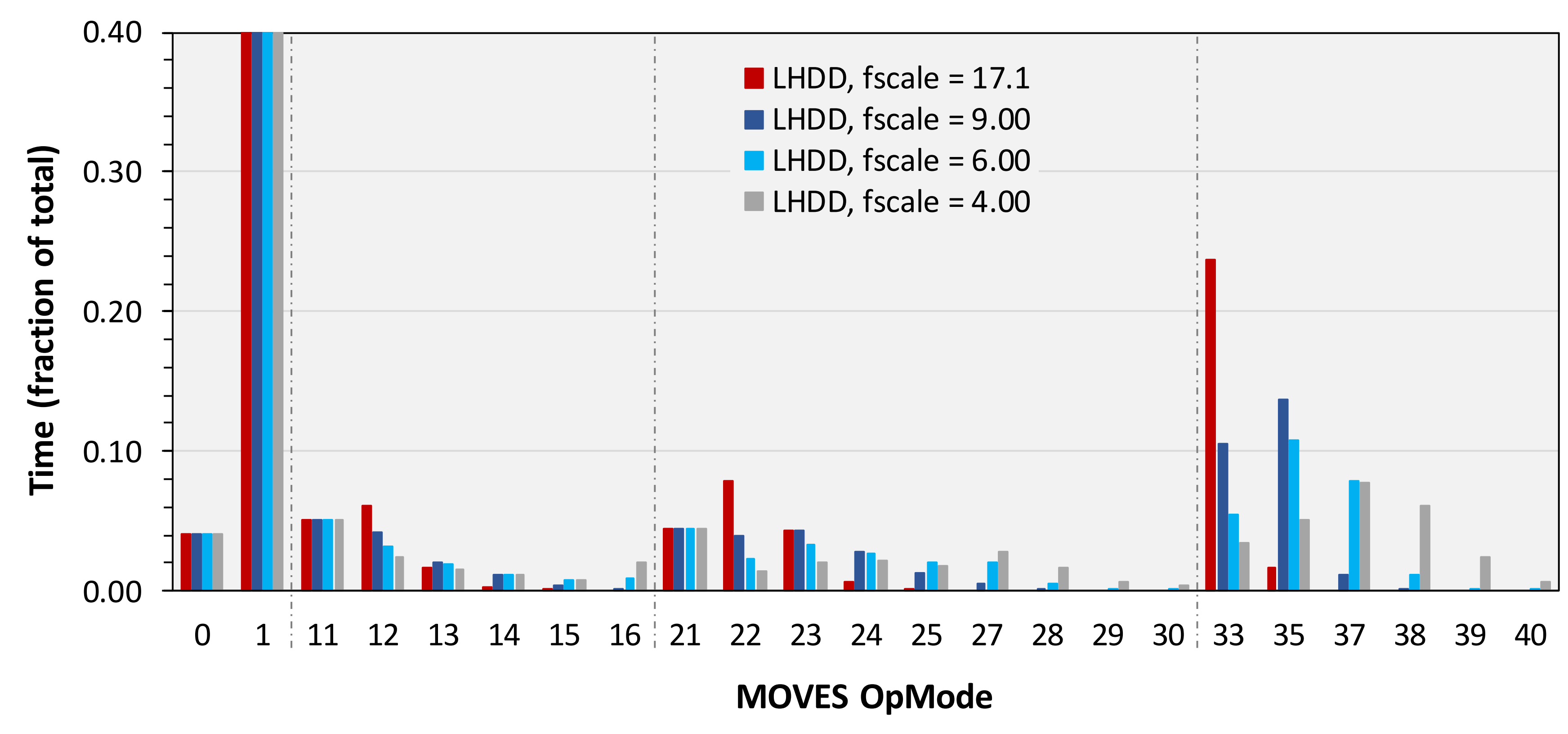
OpMode	Number of Vehicles (n)									
	LHDD (n = 42)				MHDD (n = 16)			HHDD (n = 65)		
	fscale 17.1	fscale 9.00	fscale 6.00	fscale 4.00	fscale 17.1	fscale 9.00	fscale 6.00	fscale 17.1	fscale 14.0	fscale 12.0
0	42	42	42	42	16	16	16	65	65	65
1	42	42	42	42	16	16	16	65	65	65
11	42	42	42	42	16	16	16	65	65	65
12	42	42	42	42	16	16	16	65	65	65
13	42	42	42	42	16	16	16	65	65	65
14	25	42	42	42	16	16	16	65	65	65
15	9	41	42	42	1	16	16	65	65	65
16		23	42	42		16	16	65	65	65
21	42	42	42	42	16	16	16	65	65	65
22	42	42	42	42	16	16	16	65	65	65
23	42	42	42	42	16	16	16	65	65	65
24	27	42	42	42	16	16	16	65	65	65
25	9	42	42	42	5	16	16	65	65	65
27		24	42	42		16	16	65	65	65
28		9	24	42			16	9	62	65
29			9	42			9		5	29
30			4	24						1
33	42	42	42	42	16	16	16	65	65	65
35	26	42	42	42	16	16	16	65	65	65
37		25	42	42		16	16	65	65	65
38		9	25	42		4	16	9	59	65
39			9	42			6		5	31
40			5	23						

Number of vehicles with activity in each OpMode for alternate f_{scale} values. Current established analysis uses f_{scale} = 17.1

f_{scale} < 17.1 are exploratory analysis to show the effect of changing the f_{scale}.

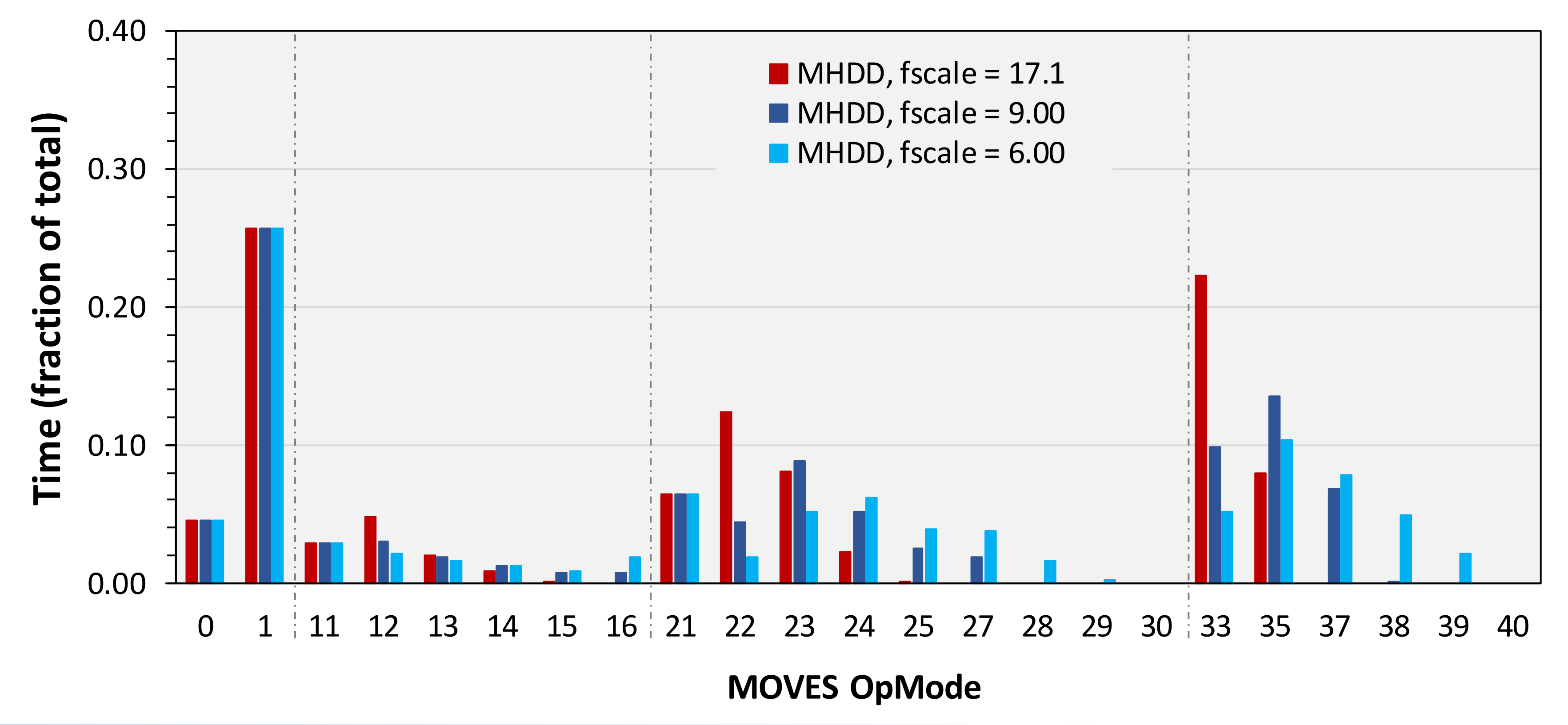
Final f_{scale} values yet to be decided.

Effect of f_{scale}: LHDD - Time



As the f_{scale} is reduced from 17.1 (current method) to 9, 6, and 4, increasingly more activity is assigned to higher power OpModes within a speed bin. The increased time fraction in higher OpModes comes with a reduction in lower OpModes. Changes to f_{scale} do not affect OpModes based only on acceleration (OpMode 0), only on speed (OpMode 1), or single bin STP < 0 (OpModes 11 and 21).

Effect of f_{scale}: MHDD - Time



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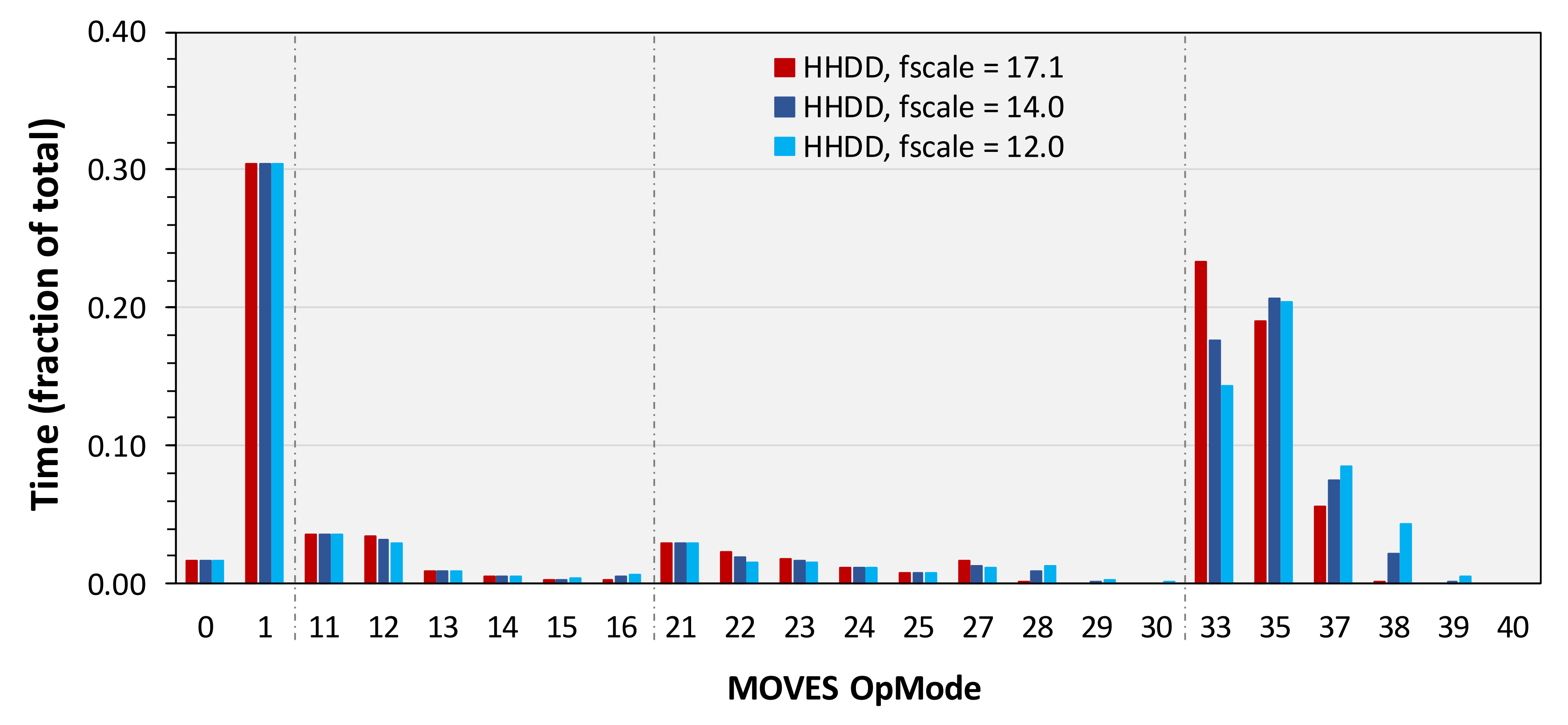
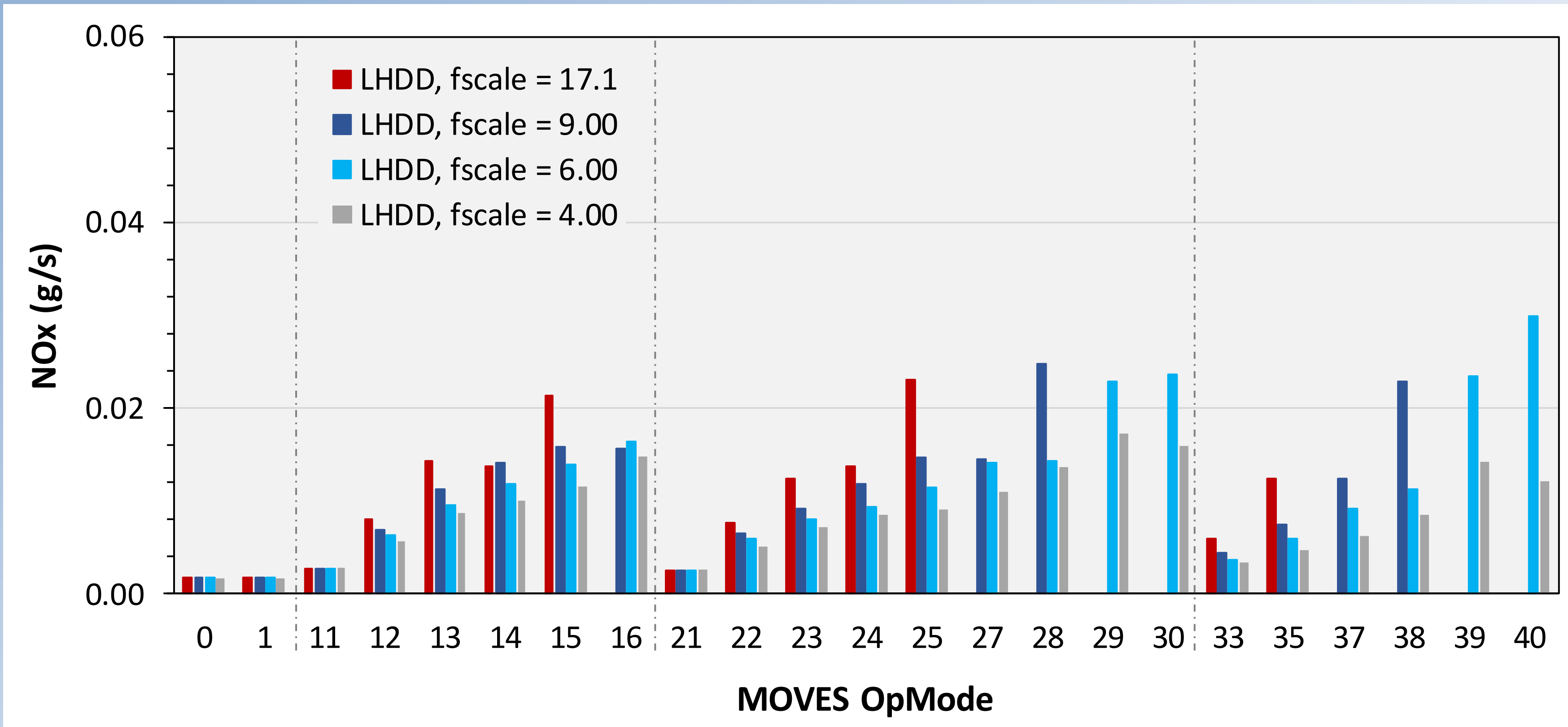
Effect of f_{scale}: HHDD - Time



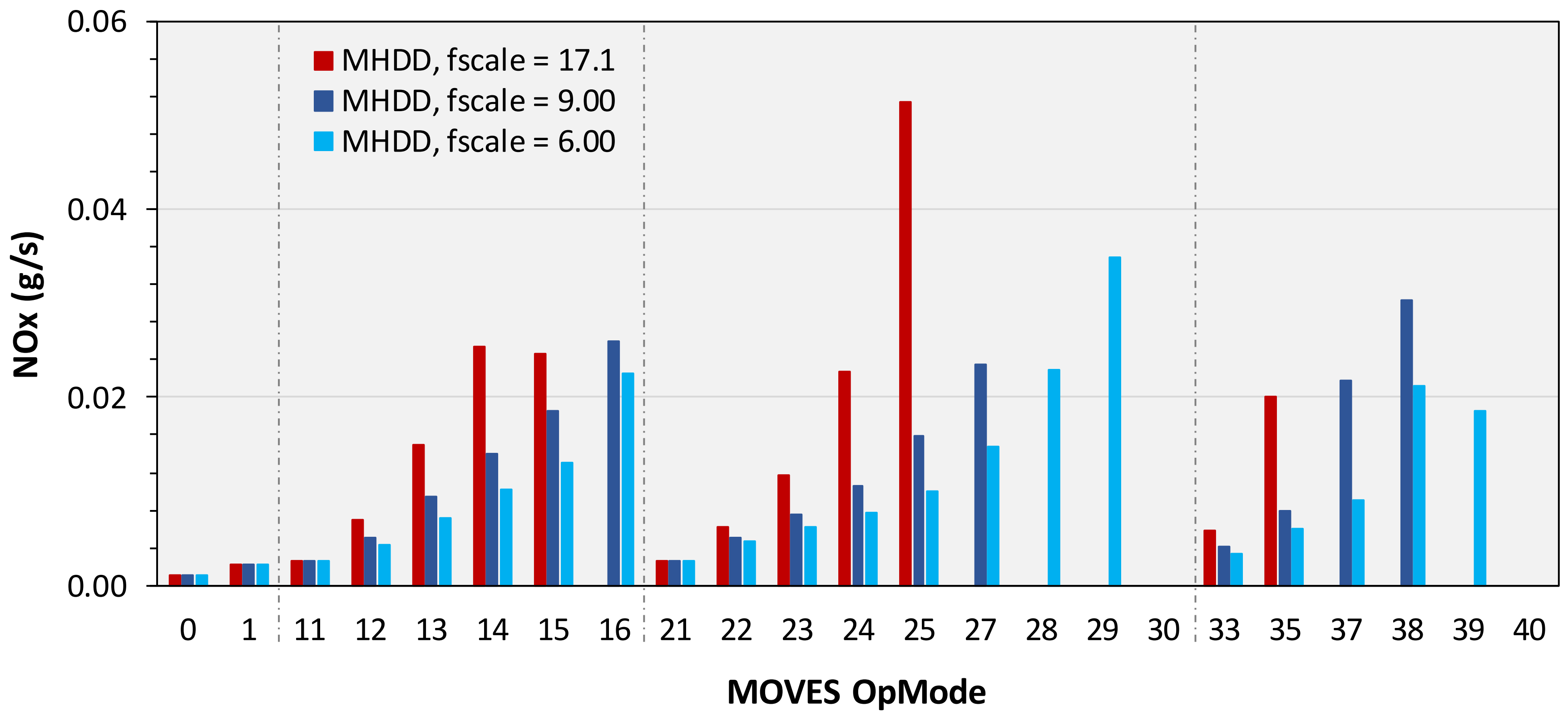
As the f_{scale} is reduced from 17.1 (current method) to 9, 6, and 4, increasingly more activity is assigned to higher power OpModes within a speed bin. The increased time fraction in higher OpModes comes with a reduction in lower OpModes. Changes to f_{scale} do not affect OpModes based only on acceleration (OpMode 0), only on speed (OpMode 1), or single bin STP < 0 (OpModes 11 and 21).

Effect of f_{scale}: LHDD – NO_X



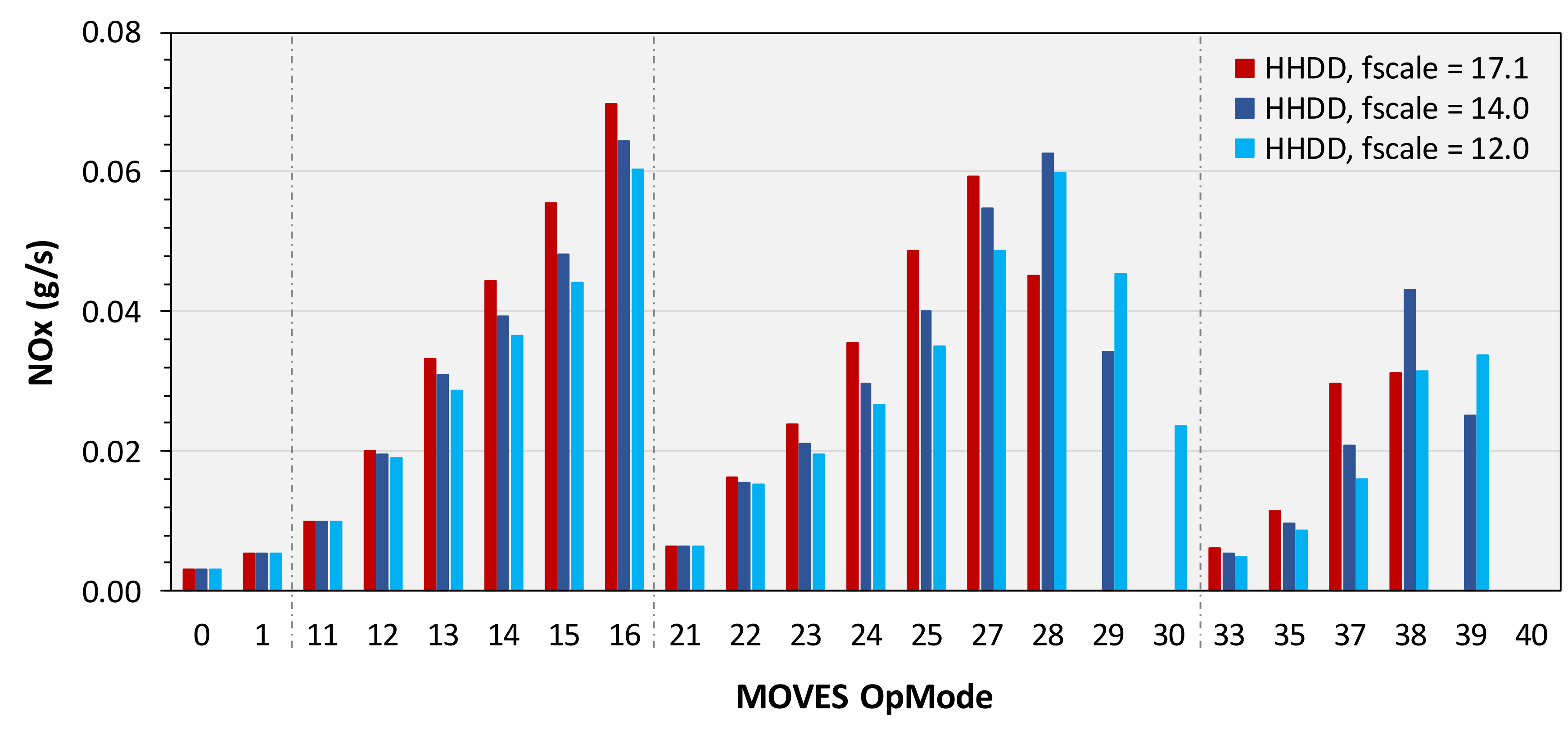
Reduction in f_{scale} value lowers emission rates for already populated OpModes while simultaneously populating the higher power OpModes within a speed bin. This is because a lower f_{scale} means higher STP, which shifts the highest STP data points to higher OpMode bins. Spreading the data over more OpModes allows us to better see the underlying patterns in the data, with the highest emissions typically in the highest bins. Changes to f_{scale} do not affect OpModes based only on acceleration (OpMode 0), only on speed (OpMode 1), or single bin STP < 0 (OpModes 11 and 21).

Effect of f_{scale}: MHDD – NO_X



Reduction in f_{scale} value lowers emission rates for already populated OpModes while simultaneously populating the higher power OpModes within a speed bin. This is because a lower f_{scale} means higher STP, which shifts the highest STP data points to higher OpMode bins. Spreading the data over more OpModes allows us to better see the underlying patterns in the data, with the highest emissions typically in the highest bins. Changes to f_{scale} do not affect OpModes based only on acceleration (OpMode 0), only on speed (OpMode 1), or single bin STP < 0 (OpModes 11 and 21).

Effect of f_{scale}: HHDD – NO_X



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f_{scale} Plan and Next steps

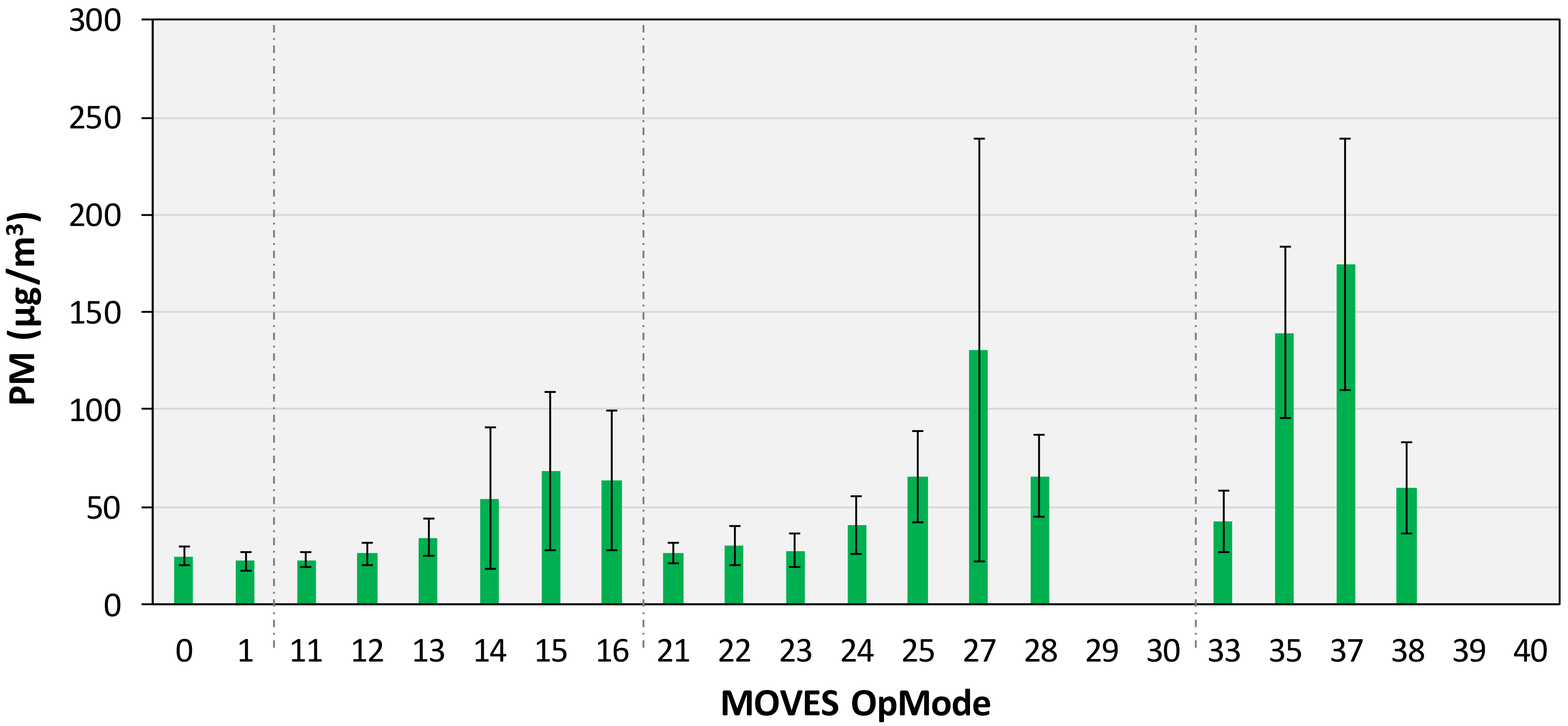
- MY 2010+ : determine the appropriate f_{scale} value for each Regulatory Class, such that we obtain broader OpMode coverage
  - Considerations:
    - Should we determine f_{scale} from HDIUT data set, such that we have a robust emission rate estimate at the highest operating modes? (e.g. 40?)
    - Should we determine the f_{scale} such that we can extrapolate emission rates in high-power operation that may not be captured in the HDIUT data set (e.g. triple trailer combination truck weighing ~ 80,000 lbs)
  - Expect significant reduction in f_{scale} for LHD and MHD and significant but smaller reduction for HHD
- MY pre-2010: *not* recommending to update the f_{scale} values at this time

MY 2010+ Heavy-Duty Vehicles – Particulate Matter Rates

Data Sources and Recommended Updates

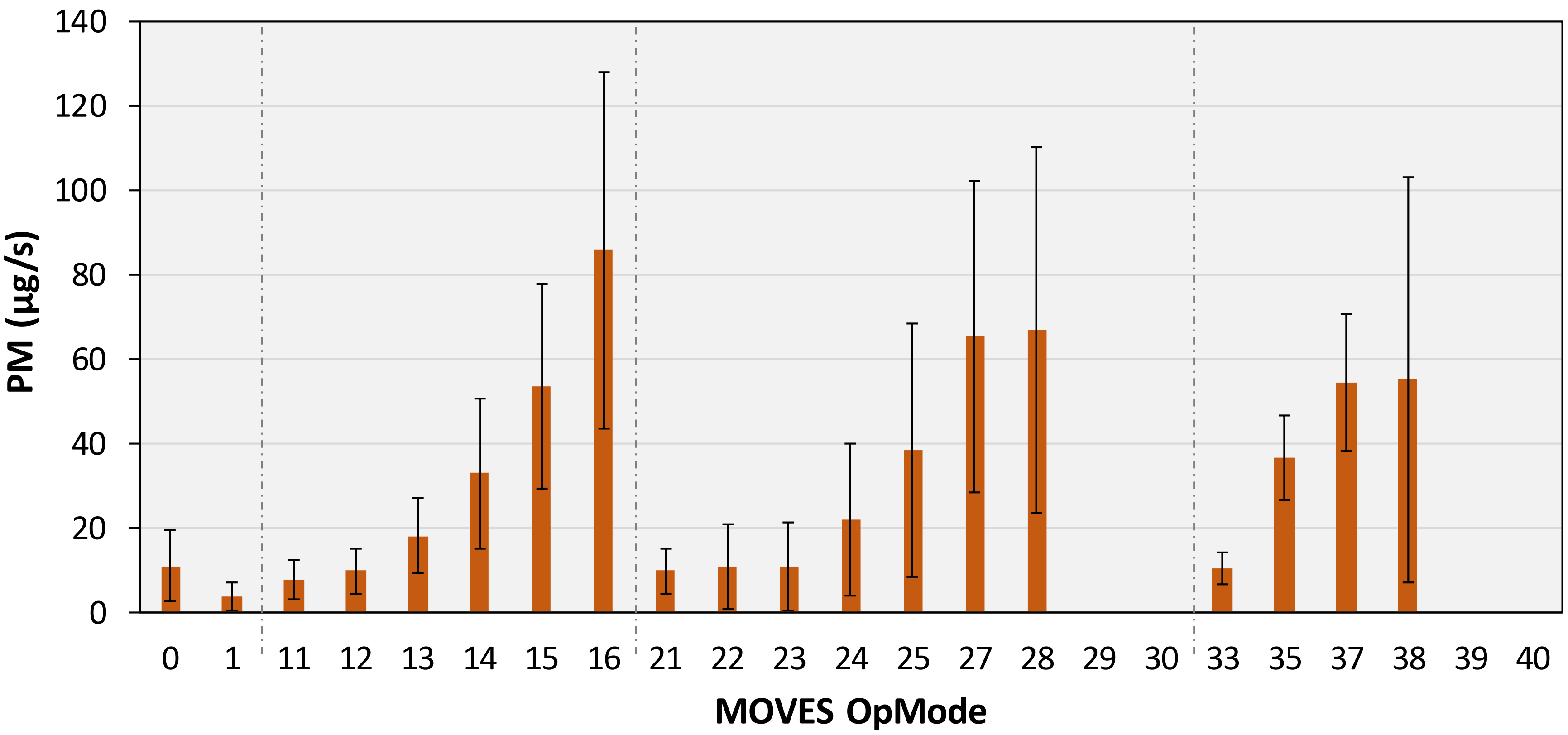
- MY 2010+
  - Generally equipped with both SCR and DPF controls
  - Emission rates based on HDIUT data set with MY 2010-2013 vehicles
  - Use the new f_{scale} values as described earlier
- MY 2007-2009
  - Have DPFs like MY2010+, but generally lack SCR
  - No real-world data readily available
  - For consistency with other pollutants, must use f_{scale} = 17.1 for HHD, MHD, LHD
  - Currently reviewing literature and certification data to determine if using MY2010+ data is appropriate or if additional adjustments are needed

HDIUT – HHD – Concentration



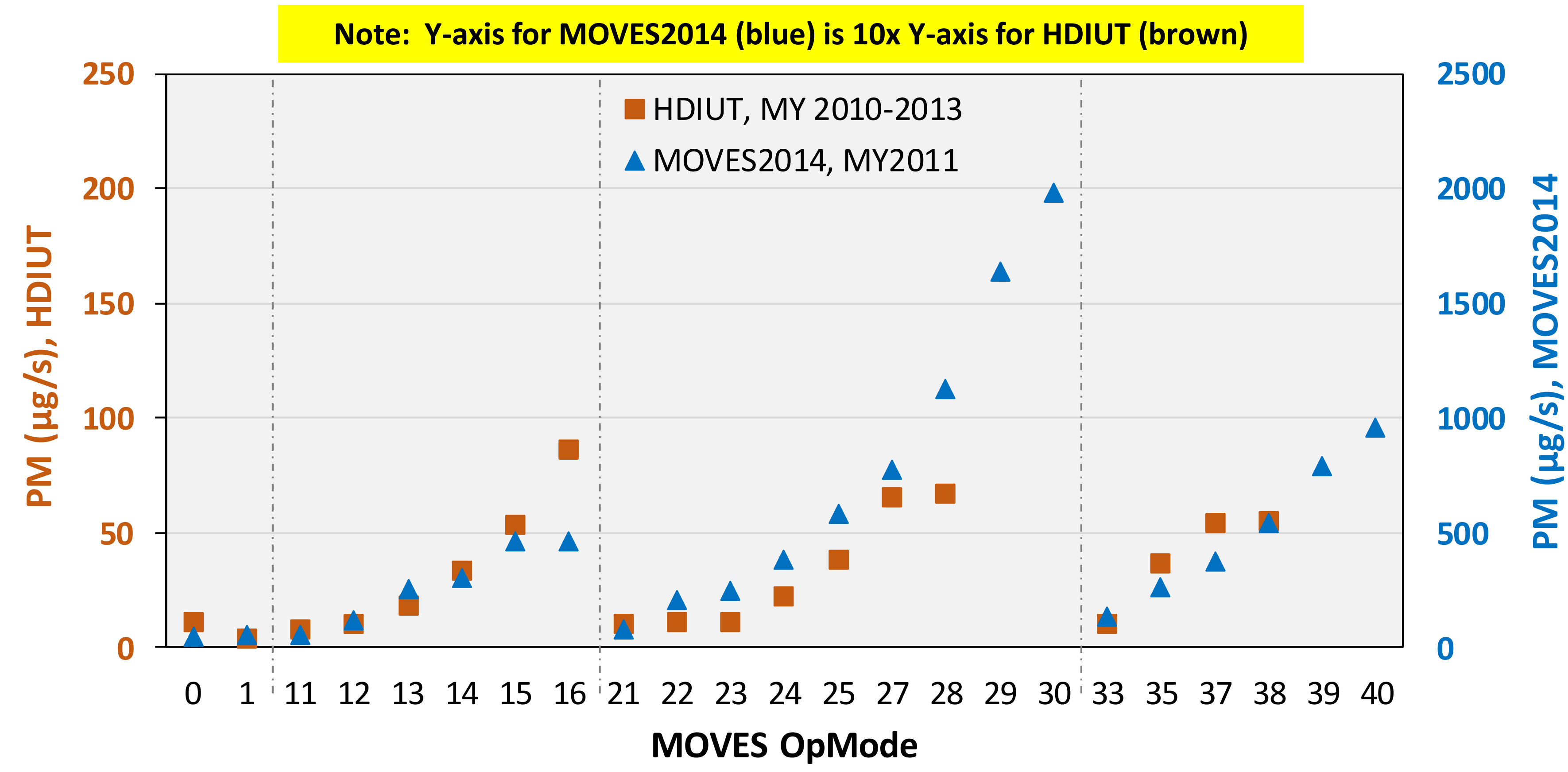
Concentration trends look fine – increasing with power within speed bins. Thus, any mass/time rate trends are not simply due to exhaust flow rate trends.

HDIUT – HHD – Mass Rates



Mass rate trends look fine – increasing with power within speed bins. The high power OpModes without data points will be addressed by the new fscale values described earlier.

HHD – HDIUT vs MOVES2014



HDIUT rates are, on average, 90% below MOVES2014 rates. MOVES2014 rates based on MY 1998-2006 rates reduced by 27.7 times (based on certification data for MY 2003-2006 vs MY 2007).
In the HDIUT series, OpModes 29, 30, 39, and 40 do not have a data point because with f_{scale} = 17.1 (to be consistent with MOVES2014), the STP never gets high enough to populate these OpModes.

MOVES2014, HDIUT vs Other Studies

- Using default national activity, MOVES2014 fleet average $PM_{2.5}$ emission rates for a 0-3 year age, MY 2010, long-haul combination diesel truck (including running and starts) is 33.5 mg/mile. The recommended HDIUT-based rates for the same are ~3.4 mg/mile.
- PM emission rates reported in the literature for similar vehicles (MY 2010+ diesel engines equipped with DPF and SCR and certified to 0.20 g-NO_x/bhp-hr):
  - Quiros et al. (2016) report an average of about 6.0 mg/mile
  - Dixit et al. (2017) report an average rate of 0.40 mg/bhp-hr (over local, regional, and UDDS cycles) which comes to 1.6 mg/mile if we use a conversion factor of 4.0 bhp-hr/mile.
  - Thiruvengadam et al. (2015) report an average of 6.2 mg/mi

Recommended PM rates based on HDIUT dataset are within the range of rates reported in the literature.

1. Quiros, D. C., et al. (2016). *Emission Control Science and Technology* 2(3): 156-172. http://dx.doi.org/10.1007/s40825-016-0044-0
2. Dixit, P., et al. (2017). *Atmospheric Environment* 166: 276-285. http://dx.doi.org/10.1016/j.atmosenv.2017.06.037
3. Thiruvengadam, A., et al. (2015). *Environ Science & Technology* 49(8): 5236-5244. http://dx.doi.org/10.1021/acs.est.5b00943

PM Rates Plan and Next steps

- Complete analysis for LHD, MHD, and HHD classes, using the new f_{scale} values
- Conduct further comparisons with literature, for MY 2010+ and MY 2007-2009 rates.
- Continue to evaluate the effect of DPF regeneration on PM emission rates and methods to include such effects in MOVES (if not already captured by the HDIUT data set)
- Possibility: Analyze ACES Phase 2 data to compare with the HDIUT-based recommended PM rates. We have the 1 hz data but need to sort out assignment of torque values and arrive at OpModes.
- Return to MOVES Review Work Group *IF* the rates or methods shared here need to change significantly

Questions for this group: Are PM rates for MY 2007-2009 vehicles (DPF, no SCR) similar to MY 2010+ vehicles (DPF + SCR)? If not, what is your feedback regarding using an adjustment factor based on literature review and/or certification data?

Additional Information

MY 2010+ Heavy-Duty Vehicles – Fixed Mass Factor (f_{scale})

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 Power Losses ($P_{loss,acc}$)

Estimates of Accessory Load in kW by Power Range

Engine power	HDT	MHD	LHD (pre-2010)	LHD (2010+)	Urban Bus
Low	8.1	6.6	0.0	4.1	21.9
Mid	8.8	7.0	0.0	4.8	22.4
High	10.5	7.8	0.0	5.5	24.0

Accessory load losses ($P_{loss,acc}$ on the previous slide) were updated for LHD for MY2010+ because the new data analysis and corresponding updates are limited to MY2010+.

Engine Power (of max hp)	Vehicle Speed: Low (0-25 mph)	Vehicle Speed: Mid (25-50 mph)	Vehicle Speed: High (above 50 mph)
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

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-s^2/m^2]
C	=	aerodynamic drag coefficient [kW-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

MY 2010+ Heavy-Duty Vehicles – Particulate Matter Rates

HHD PM – HDIUT vs MOVES2014

(shown graphically on Slide 21)

OpMode	HDIUT (n = 65 vehicles, NOx FEL 0.20 Group)				MOVES2014, MY2011	HDIUT vs MOVES2014
	PM (µg/m³)		PM (µg/s)		PM (µg/s)	PM (µg/s)
	n	Rate	n	Rate	Rate	% Reduction
0	32	25	12	11	48	77
1	30	22	5	4	52	93
11	31	23	16	8	54	86
12	31	26	20	10	114	92
13	31	34	27	18	254	93
14	30	54	27	33	300	89
15	30	68	30	54	457	88
16	29	64	28	86	457	81
21	32	26	18	10	73	87
22	35	30	27	11	207	95
23	36	28	26	11	240	96
24	38	40	31	22	379	94
25	35	65	34	38	583	93
27	38	131	37	65	772	92
28	6	66	6	67	1125	94
29					1637	
30					1975	
33	52	43	38	10	133	92
35	52	140	42	36	256	86
37	50	175	47	54	373	85
38	6	60	5	55	543	90
39					791	
40					954	