Appendix A: Proposal to Update Fixed Mass Factor (f_{scale})

For background on this proposal, see the following sections in the *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* report:

- Section 1.3 – Provides background and overview regarding scaled tractive power (STP) and the assignment of operating modes.
- Section 2.1.1.1 – Describes the heavy-duty diesel in-use (HDIU) data set, which is used for the preliminary analysis presented here.
- Section 2.1.1.2 – Describes the method for calculating scaled tractive power (STP) and the role of the fixed mass factor (f_{scale}) in the STP equations.
- Section 2.1.1.3.2 – Describes how the average emission rates are estimated from second-by-second data. Note that the preliminary results presented here are based on only the 0.20 NO_X family emission limit (FEL) group vehicles and do not incorporate production volume weighting. This is because the issue with f_{scale} values applies to all NO_X FEL groups and is unaffected by production volume weighting.
- Section 2.1.1.4.1 – Describes the approaches for hole-filling missing operating modes, which is the issue we are trying to address in this proposal by assigning more appropriate f_{scale} values.

We are considering updating the fixed mass factors (f_{scale}), because the changes planned to be made to MOVES201X will now allow varying f_{scale} by regulatory class. In MOVES2014, f_{scale} value is 2.06 for regClassID 40 and 17.1 for regClassIDs 41 through 48. The underlying need for the update to the f_{scale} framework comes from calculation of base emissions rates for light and medium heavy-duty regulatory classes. Recall that f_{scale} is the only term in the denominator of the equation to calculate STP, while the numerator estimates power at the wheel based on road-load coefficients or engine torque. Compared to heavy heavy-duty vehicles, the numerator term for light and medium heavy-duty vehicles is generally a smaller quantity. Thus, for light and medium heavy-duty vehicles, using an f_{scale} of 17.1 constrains the data to lower OpModes since the calculated STP never gets high enough. Which in turn means, we have to apply hole-filling for high power OpModes within each speed-bin. Although this is less of an issue for heavy heavy-duty vehicles, binning data in to OpModes can be improved by assigning a more appropriate f_{scale} value. We believe constraining real-world data to a few OpModes by using f_{scale} of 17.1 reduces the ability of the model to differentiate the effect of vehicle type and activity on the emissions.

Based on the above discussion, we are considering assigning a different f_{scale} value to each regulatory class such that it allows the emissions data to be spread over as many OpModes as reasonably possible. We propose to apply this update in MOVES201X only to model year (MY) 2010 and beyond because we are updating the emission rates for only MY 2010+ heavy-duty vehicles for MOVES201X. The emission rates for MY 2009 and older are unchanged from MOVES2014 and thus, f_{scale} values for those model years remain the same as well.

Figure 1 and Figure 2 are based on preliminary analyses of the data from HDIU program and show how different f_{scale} values affect OpMode-based emissions rates for light heavy-duty diesel (LHDD) and medium heavy-duty diesel (MHDD) vehicles, respectively. All the LHDD analyses presented here are based on the same data sub-set of 42 vehicles, each with a MY 2010+ engine certified as LHDD and NO_X FEL up to 0.20 g/bhp-hr. The only difference between these analysis variations is the f_{scale} value used to calculate the STP and in turn assign an OpMode to each second of data. Similarly, all the MHDD analyses presented here have different f_{scale} values but are based on the same data sub-set of 16 vehicles, each with a MY 2010+ engine certified as MHDD and NO_X FEL up to 0.20 g/bhp-hr. As mentioned previously, this preliminary analysis does not include LHDD and MHDD data for other NO_X FEL groups. In Figure 1, if the data is analyzed with f_{scale} of 17.1, there are no data points for OpModes 27 through 30. When f_{scale} is reduced from 17.1 to 9.00, we get emission rates for OpModes 27 and 28, and a further reduction of f_{scale} to 6.00 allows the data to populate OpModes 29 and 30. A similar (but not identical) effect is seen for the low-speed OpModes (11 through 16) and high-speed OpModes (33 through 40) emission rates for LHDD vehicles, and low/medium/ high-speed OpMode emission rates for MHDD vehicles (Figure 2). Thus, there is a strong case to reduce the f_{scale} for most regulatory classes from its current value of 17.1. The final value of f_{scale} for each regulatory class will be based on further analyses.

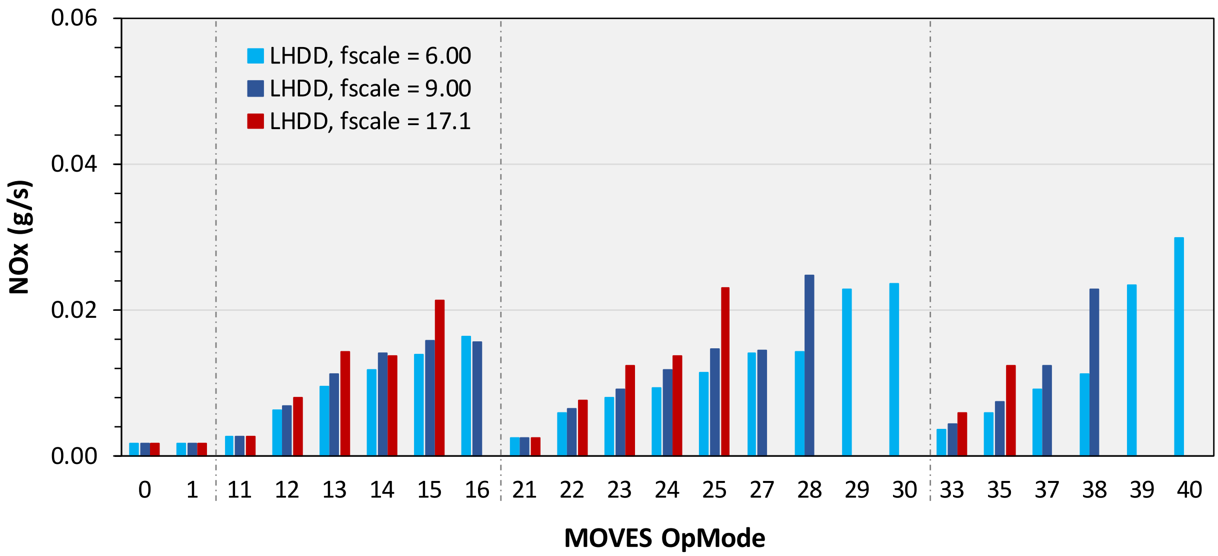

Figure 1. NO_X Emission Rates for MY 2010-2013 Light Heavy-Duty Diesel (LHDD) Vehicles Calculated Using Various F_{scale} Values (n = 42 Vehicles in the NO_X FEL 0.20 Group)

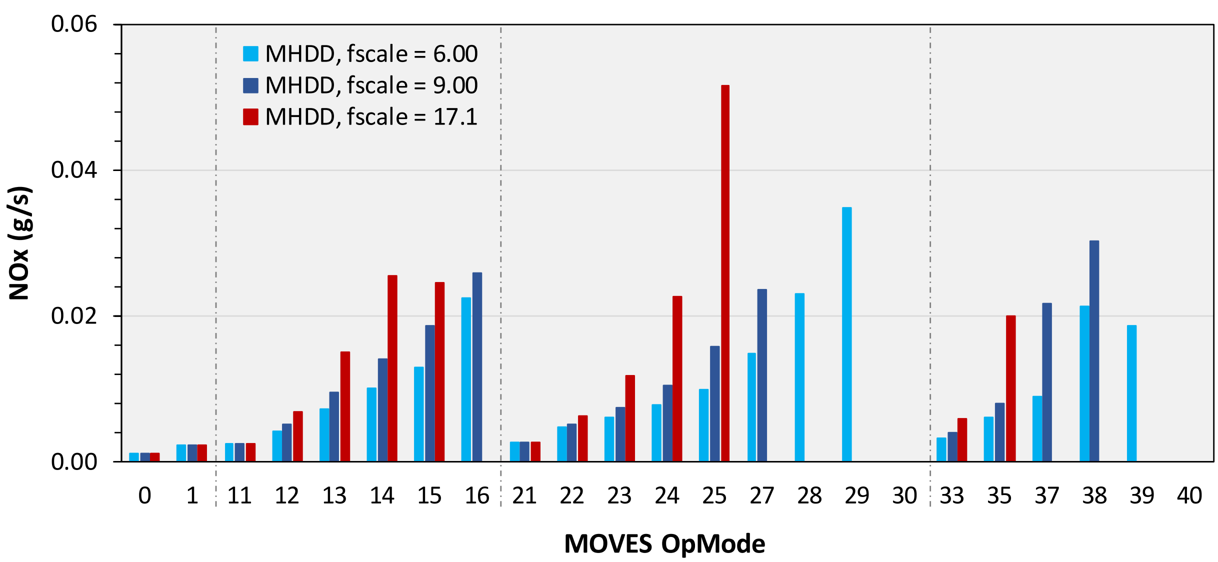

Figure 2. NO_X Emission Rates for MY 2010-2013 Medium Heavy-Duty Diesel (MHDD) Vehicles Calculated Using Various F_{scale} Values (n = 16 Vehicles in the NO_X FEL 0.20 Group)

Table 1 shows how, for the LHDD and MHDD data sub-sets, the vehicle count per OpMode is affected by the choice of f_{scale}. As the f_{scale} is reduced from 17.1 to 6.00, more vehicles are able to have data points assigned to high power OpModes within a speed-bin. For example, for LHDD, when f_{scale} is 17.1 all 42 vehicles have some seconds of data in OpMode 23, only 9 vehicles in OpMode 25, and no vehicles in OpModes 27 through 30. However, if the f_{scale} is reduced to 6.00, OpModes 27 through 30 get populated, though the highest power OpModes (29 and 30) have only a few vehicles.

Table 1. Number of Vehicles by OpMode for Light Heavy-Duty Diesel (LHDD) and Medium Heavy-Duty Diesel (MHDD)

	Number of Vehicles					
	LHDD (Total 42 Vehicles)			MHDD (Total 16 Vehicles)		
OpMode	f_{scale} = 6.00	f_{scale} = 9.00	f_{scale} = 17.1	f_{scale} = 6.00	f_{scale} = 9.00	f_{scale} = 17.1
0	42	42	42	16	16	16
1	42	42	42	16	16	16
11	42	42	42	16	16	16
12	42	42	42	16	16	16
13	42	42	42	16	16	16
14	42	42	25	16	16	16
15	42	41	9	16	16	1
16	42	23		16	16	
21	42	42	42	16	16	16
22	42	42	42	16	16	16
23	42	42	42	16	16	16
24	42	42	27	16	16	16
25	42	42	9	16	16	5
27	42	24		16	16	
28	24	9		16		
29	9			9		
30	4					
33	42	42	42	16	16	16
35	42	42	26	16	16	16
37	42	25		16	16	
38	25	9		16	4	
39	9			6		
40	5					

Appendix B: Proposal to Update Particulate Matter (PM) Emission Rates for MY 2010+

For background on this proposal, see the following section in the *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES201X* report:

- Section 2.1.2.2.6 – Describes the estimation of PM rates for MY 2007 and later heavy-duty vehicles equipped with diesel particulate filters (DPFs)

In past versions of MOVES, PM emission rates for DPF equipped vehicles (MY 2007 and later) were estimated by reducing PM emission rates from non-DPF vehicles (MY 2006 and earlier) by a factor of 27.7. Note that this is a much greater reduction than what the standards require, a reduction of 10 times, due to the high efficacy of DPFs observed in the certification data.

While analyzing the HDIU data for MY 2010+ vehicles, we also estimated the PM emission rates. However, our initial decision was to not use the PM measurements from the HDIU data to update the MOVES default rates because either the PM data was zero for about half of the measurements (as discussed in more detail below) or, when non-zero, the measured rate was very low and could be near the detection limit of the portable emissions measurement system (PEMS). In this appendix, we are presenting the PM rates from the HDIU data and ask you to comment if the rates are what you would expect from DPF equipped vehicles.

PM concentrations and mass per time emission rates are shown in Figure 3 and Figure 4, respectively. These rates are based on analysis of 65 heavy heavy-duty diesel (HHDD) vehicles, each with a MY 2010+ engine equipped with DPF and SCR and with NO_X FEL up to 0.20 g/bhp-hr. While the absolute rates are small, both concentration and mass per time analysis show an increasing trend for higher power OpMode (within a speed bin). The trend is more fully developed in the mass per time analysis (Figure 4) because it includes the effect of exhaust flow rate, which is also expected to increase for higher power OpModes within a speed bin.

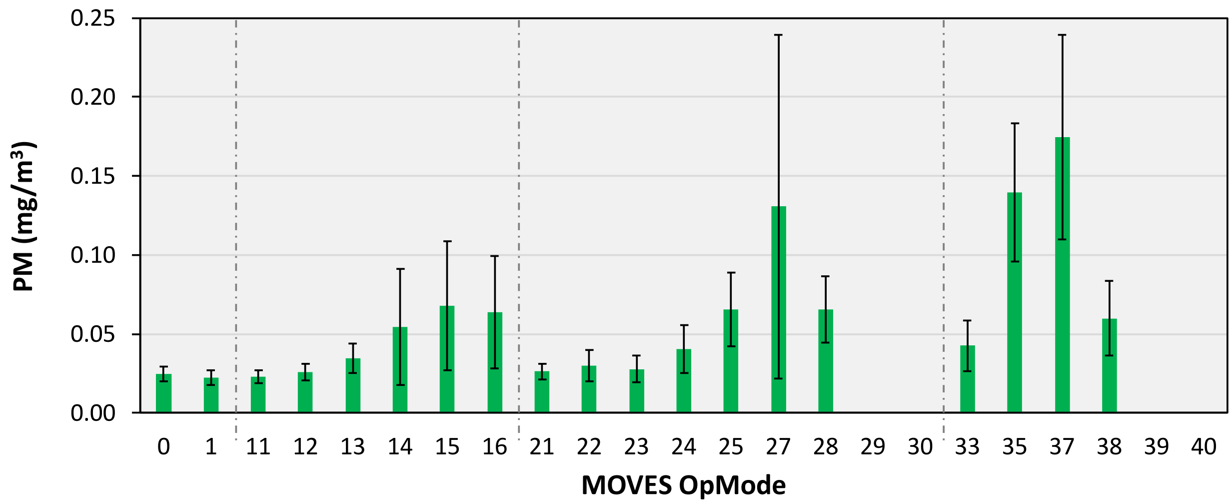

Figure 3. PM Concentration Rates for MY 2010-2013 Heavy Heavy-Duty Diesel (HHDD) Vehicles (n = 65 Vehicles in the NO_X FEL 0.20 Group)

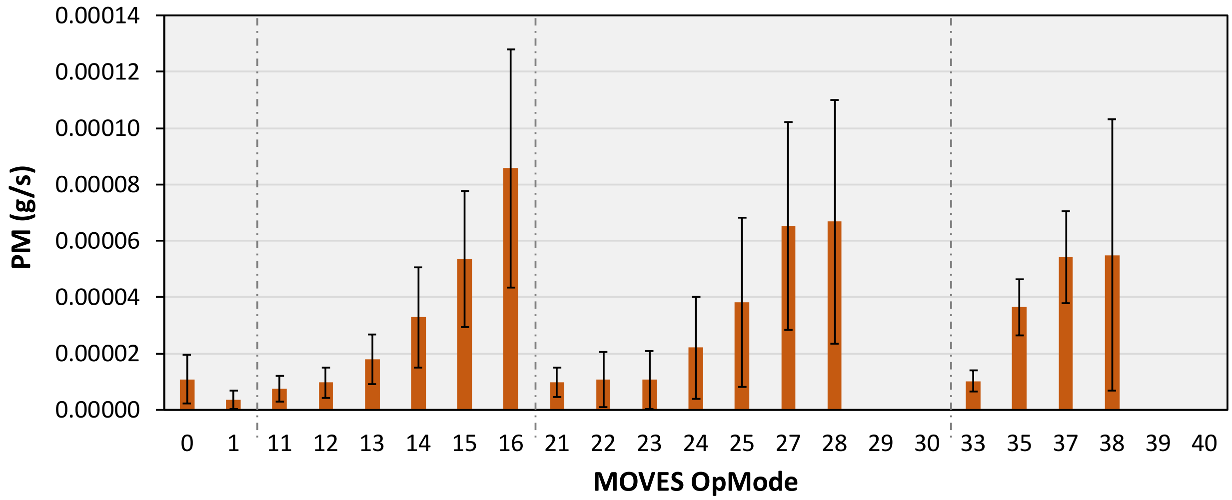

Figure 4. PM Emission Rates for MY 2010-2013 Heavy Heavy-Duty Diesel (HHDD) Vehicles (n = 65 Vehicles in the NO_X FEL 0.20 Group)

While the trends across OpModes are as expected, our concern is mainly with the very low rates that might be close to or below the detection limit of the PEMS used in these tests. Also, these rates are significantly lower than the current default rates in MOVES2014, which were scaled down much more than the expected reduction from just comparing the pre- and post-2006 PM standards.

Table 2 shows the number of HDIU vehicles with reported PM rates in each of the OpModes and also compares the PM rates from HDIU with MOVES2014. On average, half of the 65 vehicles reported non-zero PM data. If a vehicle had a mass per time rate less than $1*10^{-6}$ g/s in an OpMode, the vehicle was not included in the count for that OpMode, which is why the number of vehicles in the g/s column is often less than the number of vehicles in the mg/m^3 column. The vehicle count increases for higher power OpModes in the medium-speed bin and are the highest for the high-speed bin. This could be because more PM is emitted in these OpModes allowing more vehicles to exceed the measurement or reporting threshold. The HDIU data based PM g/s rates are, on average, about 90% below the MOVES2014 default rates.

Using the default national activity (age distributions, speed distributions, road type distributions, drive cycles, VMT, meteorology), MOVES2014 estimates that the fleet average $PM_{2.5}$ emission rates for a 0-3 year age, model year 2010, long-haul combination diesel truck (including running and starts) is 33.5 mg/mile. If we assume the HDIU g/s rates are 90% lower than the MOVES2014 across all operating modes, the HDIU rates then would yield long-haul combination truck diesel $PM_{2.5}$ emission rates around ~3.3 mg/mile (assuming similar activity as MOVES2014).

We looked at the PM g/mile emission rates, reported in the literature, for MY 2010+ heavy-duty diesel vehicles equipped with DPF and SCR and having NO_X FEL up to 0.20 g/bhp-hr. Quiros et al. (2016)[1] report an average of 7.5 mg/mile over six cycles (local, regional, interstate, urban, near-dock, and hill climb). Without the near-dock and hill climb cycles, the average PM emission rate is about 6.0 mg/mile. Dixit et al. (2017)[2] 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)[3] report an average of 6.2 mg/mi (over local, regional, and UDDS cycles).

Table 2. Comparison of PM Emission Rates from HDIU Data and MOVES2014

	HDIU (n = 65 vehicles, MY 2010-2013, NO_X FEL 0.20 Group)				MOVES2014 MY 2013	HDIU *vs* MOVES2014
	PM (mg/m3)		PM (g/s) * 10^6		PM (g/s) * 10^6	PM (g/s)
OpMode	n	Rate	n	Rate	Rate	% Reduction
0	32	0.025	12	10.9	45.3	76
1	30	0.022	5	3.6	49.5	93
11	31	0.023	16	7.5	51.5	85
12	31	0.026	20	9.7	108.7	91
13	31	0.034	27	18.0	242.1	93
14	30	0.054	27	32.9	286.2	88
15	30	0.068	30	53.5	435.8	88
16	29	0.064	28	85.8	435.8	80
21	32	0.026	18	9.7	69.4	86
22	35	0.030	27	10.8	197.3	95
23	36	0.028	26	10.7	228.7	95
24	38	0.040	31	22.0	361.4	94
25	35	0.065	34	38.3	555.4	93
27	38	0.131	37	65.3	736.1	91
28	6	0.066	6	66.8	1071.6	94
29	0	-	0	-	1560.1	-
30	0	-	0	-	1882.4	-
33	52	0.043	38	10.3	127.0	92
35	52	0.140	42	36.5	244.3	85
37	50	0.175	47	54.2	355.6	85
38	6	0.060	5	55.0	517.7	89
39	0	-	0	-	753.7	-
40	0	-	0	-	909.4	-

[1] Quiros, D. C., A. Thiruvengadam, S. Pradhan, M. Besch, P. Thiruvengadam, B. Demirgok, D. Carder, A. Oshinuga, T. Huai and S. Hu (2016). Real-World Emissions from Modern Heavy-Duty Diesel, Natural Gas, and Hybrid Diesel Trucks Operating Along Major California Freight Corridors. *Emission Control Science and Technology* 2(3): 156-172. 10.1007/s40825-016-0044-0.
[2] Dixit, P., J. W. Miller, D. R. Cocker, A. Oshinuga, Y. Jiang, T. D. Durbin and K. C. Johnson (2017). Differences between emissions measured in urban driving and certification testing of heavy-duty diesel engines. *Atmospheric Environment* 166: 276-285. http://dx.doi.org/10.1016/j.atmosenv.2017.06.037.
[3] Thiruvengadam, A., M. C. Besch, P. Thiruvengadam, S. Pradhan, D. Carder, H. Kappanna, M. Gautam, A. Oshinuga, H. Hogo and M. Miyasato (2015). Emission Rates of Regulated Pollutants from Current Technology Heavy-Duty Diesel and Natural Gas Goods Movement Vehicles. *Environ Sci Technol* 49(8): 5236-5244. 10.1021/acs.est.5b00943.