MOVES

Motor Vehicle Emission Simulator

Updates to MOVES Heavy Duty Running Exhaust Rates: Diesel, Gasoline, and Natural Gas

Gurdas S. Sandhu* and Darrell Sonntag

* ORISE participant supported by an interagency agreement between EPA and DOE

MOVES Review Work Group | April 10, 2019 | Ann Arbor, MI, USA

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Context

- December 2016[1]: presented initial analysis of criteria emission rates for Heavy-Duty (HD) diesel MY2010+ vehicles
  - Based on Heavy-Duty In-Use Testing (HDIUT) data set
  - Rates were developed using MOVES2014 f_{scale} values
  - NO_x, HC, CO, and Energy/CO_2 were included. PM was not included.
  - New NO_x rates higher due to ineffective control at low temperatures

- December 2017[1] : Described work on HD MY2010+ f_{scale} values and PM rates
  - f_{scale} values needed update to better distinguish operating modes
  - MY2010+ PM rates based on HDIUT are much below MOVES2014 rates

- This Presentation: Rates based on final f_{scale} values and impact on inventory

1. https://www.epa.gov/moves/moves-model-review-work-group

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

Selection Order Calendar Years 2010 – 2016

Number of Diesel Test Vehicles

Service Class	NOx FEL Group			Total
	0.20	0.35	0.50	
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			Total
	0.20	0.35	0.50	
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)
- Model Years: 2010 – 2015
- Fuels: Diesel and Natural Gas
- Manufacturers: Cummins, Detroit Diesel, Ford, FPT, GM, Hino, Isuzu, Iveco, Navistar, Paccar, Volvo
- Engine Families: 45 Diesel, 2 Natural Gas

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

Contents

- Updates to fixed mass factor (f_{scale})
- *g/mile* rates
- Impact on inventory

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}

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

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

In MOVES2014,

- 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)

Effect of f_{scale}: Vehicle Count

OpMode	Number of Vehicles (n)										
	LHDD (n = 64)			MHDD (n = 58)				HHDD (n = 159)			
	fscale 4.00	fscale 5.00	fscale 6.00	fscale 4.00	fscale 5.00	fscale 6.00	fscale 7.00	fscale 9.00	fscale 10.0	fscale 11.0	fscale 12.0
0	64	64	64	58	58	58	58	159	159	159	159
1	64	64	64	58	58	58	58	159	159	159	159
11	64	64	64	58	58	58	58	159	159	159	159
12	64	64	64	58	58	58	58	159	159	159	159
13	64	64	64	58	58	58	58	159	159	159	159
14	64	64	64	58	58	58	58	159	159	159	159
15	64	64	64	58	58	58	58	159	159	159	159
16	64	64	64	58	58	58	58	159	159	159	159
21	64	64	64	58	58	58	58	159	159	159	159
22	64	64	64	58	58	58	58	159	159	159	159
23	64	64	64	58	58	58	58	159	159	159	159
24	64	64	64	58	58	58	58	159	159	159	159
25	64	64	64	58	58	58	58	159	159	159	159
27	64	64	64	58	58	58	58	159	159	159	159
28	64	64	44	58	58	58	58	154	154	154	153
29	64	42	23	58	58	46	25	153	142	122	75
30	43	22	13	58	39	25	14	114	59	10	1
33	64	64	64	58	58	58	58	159	159	159	159
35	64	64	64	58	58	58	58	159	159	159	159
37	64	64	63	58	58	58	58	159	159	159	159
38	63	62	44	58	58	57	49	154	154	153	152
39	62	41	23	58	53	43	25	152	138	122	83
40	41	23	14	53	39	26	14	114	65	11	1

Analyzed the entire HDIUT dataset with various f_{scale} values to observe their effect on vehicle count, time, and emission rates for criteria pollutants across the OpModes.

Final f_{scale} selected such that the highest power OpModes can be populated without gap-filling but at the same time they are not over-populated by data at the cost of lower power OpModes.

Effect of f_{scale}: Time Distribution

OpMode	Number of seconds = OpMode time fraction * 1 million seconds										
	LHDD			MHDD				HHDD			
	fscale 4.00	fscale 5.00	fscale 6.00	fscale 4.00	fscale 5.00	fscale 6.00	fscale 7.00	fscale 9.00	fscale 10.0	fscale 11.0	fscale 12.0
0	41131	41131	41131	36170	36170	36170	36170	18010	18010	18010	18010
1	358957	358957	358957	349622	349622	349622	349622	297662	297662	297662	297662
11	46235	46235	46235	32693	32693	32693	32693	37453	37453	37453	37453
12	24896	29023	32878	20755	23825	26630	29346	24580	25976	27238	28427
13	14877	16658	18290	11234	12492	13612	14397	9472	9547	9576	9576
14	11394	12304	12431	8252	9101	9517	9898	5545	5557	5579	5533
15	8784	8680	8092	6688	7014	7142	7000	3938	3840	3762	3704
16	20778	14065	9039	28357	22855	18385	14645	10041	8657	7422	6337
21	45157	45157	45157	44291	44291	44291	44291	32325	32325	32325	32325
22	16366	22038	28166	10132	14200	18827	23955	12785	14388	15951	17580
23	24704	31884	38195	19195	25479	31609	37379	14276	15457	16513	17395
24	25290	28989	30288	21109	27513	32401	34297	11401	11865	12272	12453
25	21400	21274	19931	22136	24498	22647	20428	8967	9058	9085	9044
27	28819	25061	18770	32912	28713	25621	22502	12410	11927	11767	12026
28	15281	8422	5020	18677	15863	13842	10424	8660	9619	10875	12433
29	5808	2900	1161	12105	10075	5243	3550	8905	9822	6562	2329
30	3903	1002	40	17304	7229	3379	1034	5861	1127	239	4
33	42467	55797	73408	37996	45307	54057	64727	114214	126216	139731	154101
35	75707	110862	131366	40077	63649	87949	107234	139109	160667	176144	186131
37	86600	79892	67271	63932	76693	81453	80818	115050	102440	91446	83420
38	52178	31818	12100	56697	58308	51520	44843	55279	52010	50633	47483
39	21416	6167	1940	45255	39067	25466	8307	37885	33033	19207	6576
40	7852	1685	135	64411	25344	7923	2440	16174	3344	550	0

Analyzed the entire HDIUT dataset with various f_{scale} values to observe their effect on vehicle count, time, and emission rates for criteria pollutants across the OpModes.

Final f_{scale} selected such that the highest power OpModes can be populated without gap-filling but at the same time they are not over-populated by data at the cost of lower power OpModes.

Final f_{scale} for Heavy-Duty MY 2010+

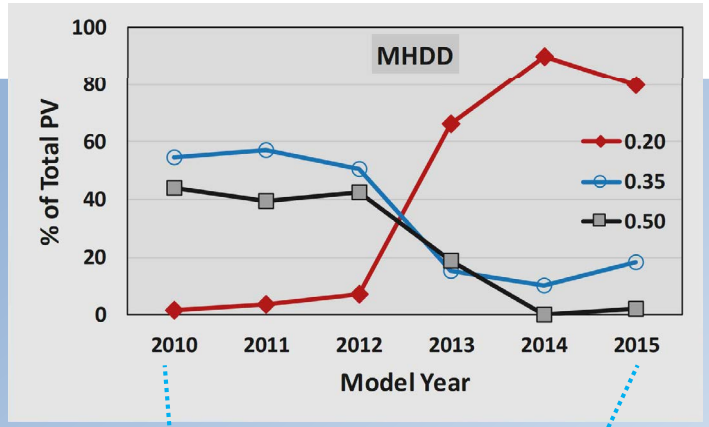
Light Heavy-Duty (LHD) regClass 41, 42	Medium Heavy-Duty (MHD) regClass 46	Heavy Heavy-Duty (HHD) regClass 47, 48
5	7	10

- Base OpMode based emission rates between regClasses with different f_{scale} should not be compared
- regClass 40 and 41 have been merged and are named regClass 41
- Gliders (regClass 49) are modeled with f_{scale} 17.1 because they borrow rates from MY 2000 vehicles, which are not covered by the f_{scale} updates discussed here.

MOVES-generated g/mile Rates

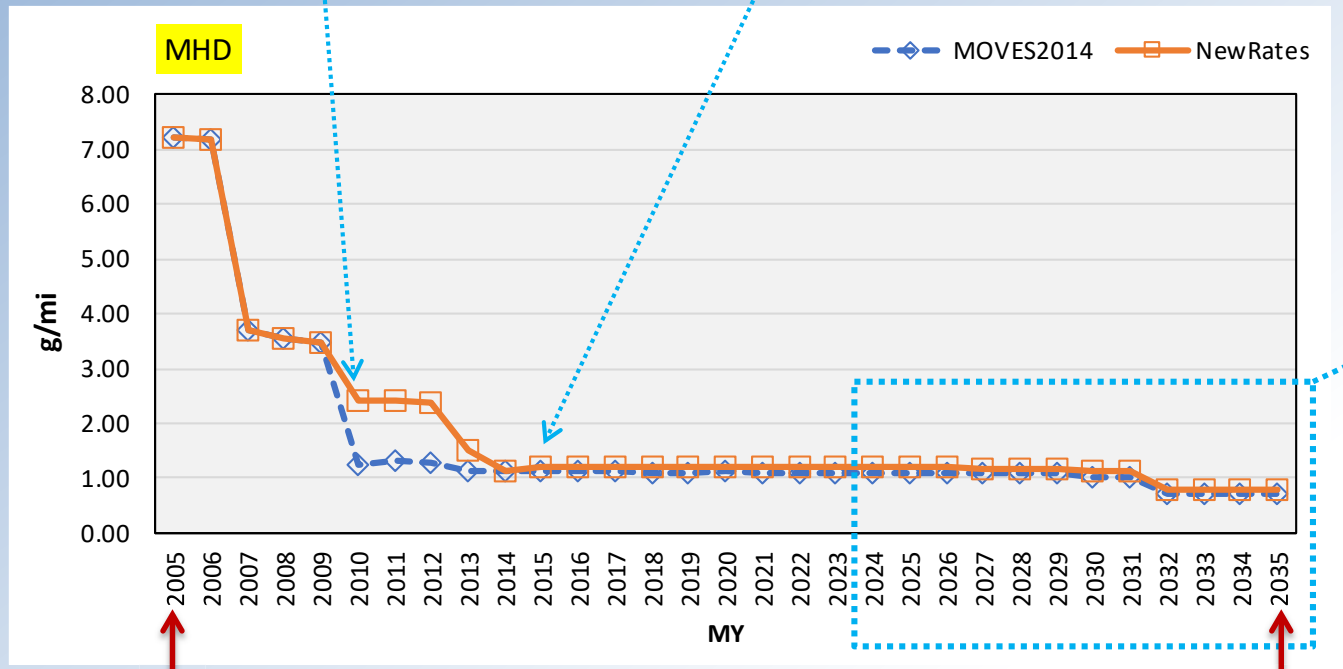
- Based on a “typical” MOVES national scale run
- Emission rates and activity are based on new f_{scale} values for MY 2010+

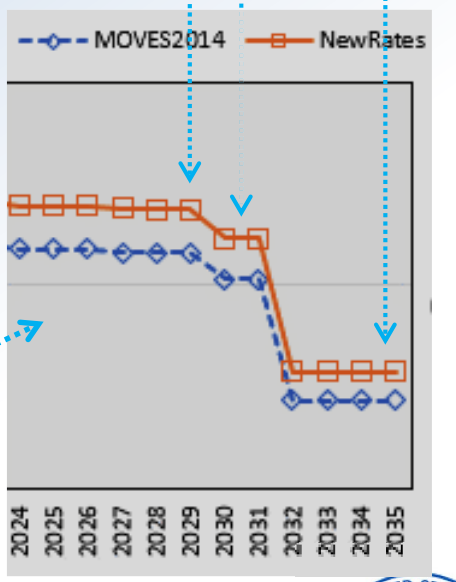
Guide to *g/mile* plots for CY2035



T&M multiplicative adjustment factor by age

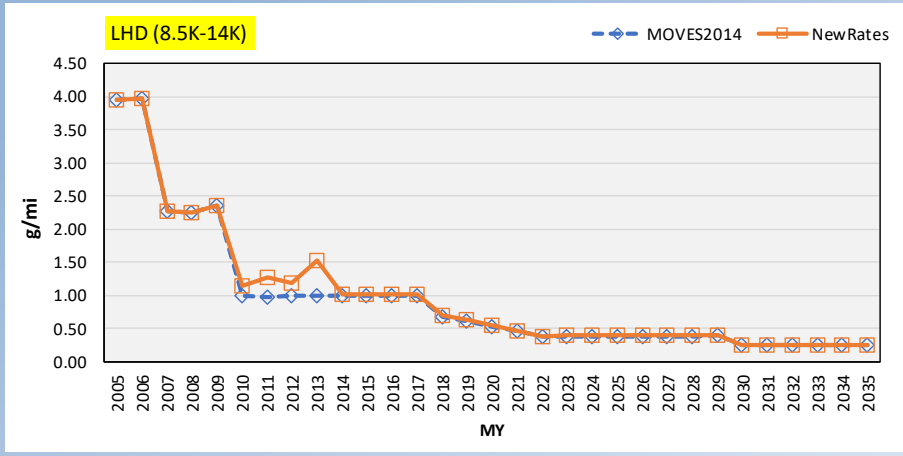
Age Group	MHD (regC 46)
0 – 3	0.083
4 – 5	0.833
6 – 7	1

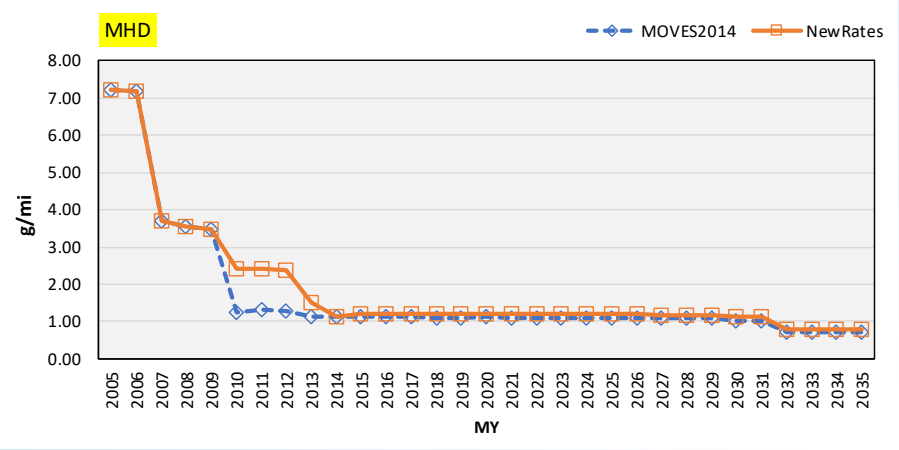


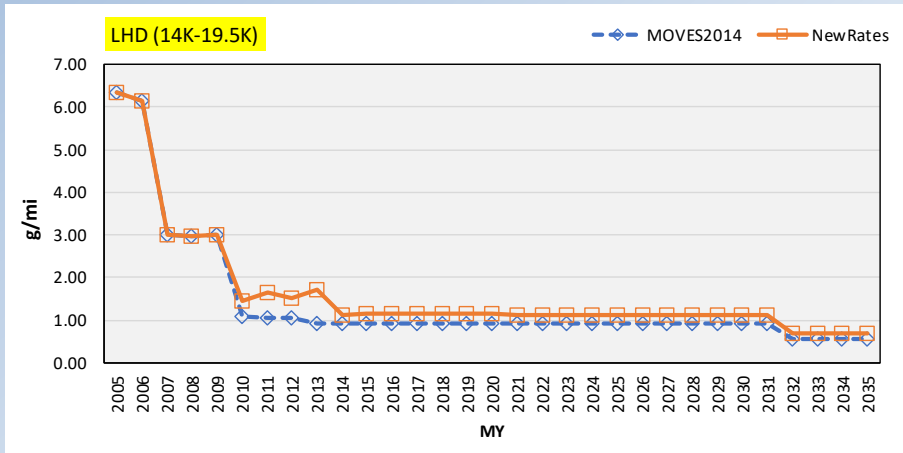


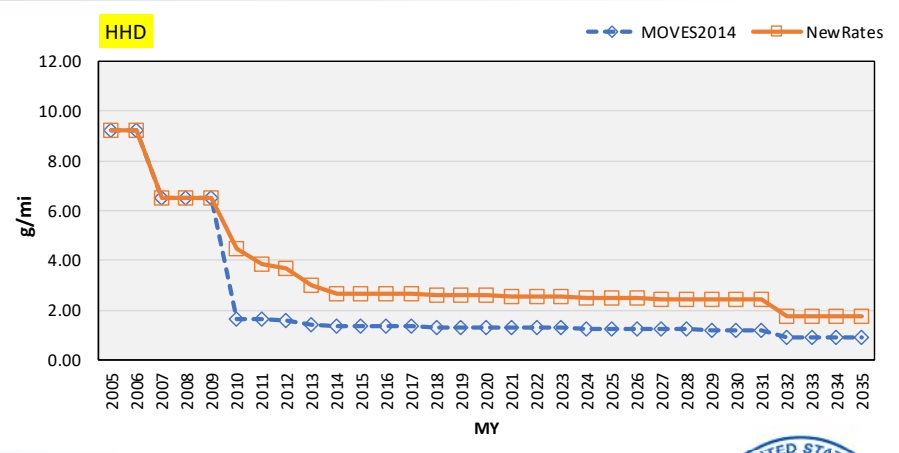
Age 30 <<< Older Vehicles Age 0

NO_x Running Exhaust Rates (CY2035)

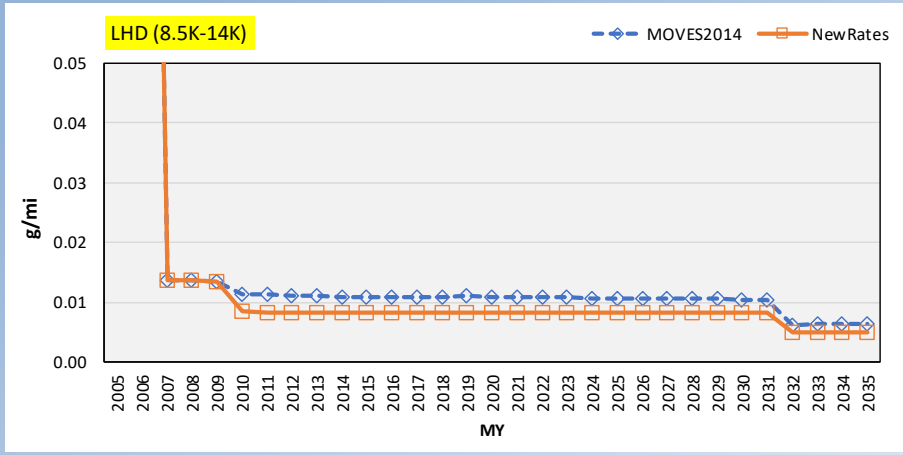


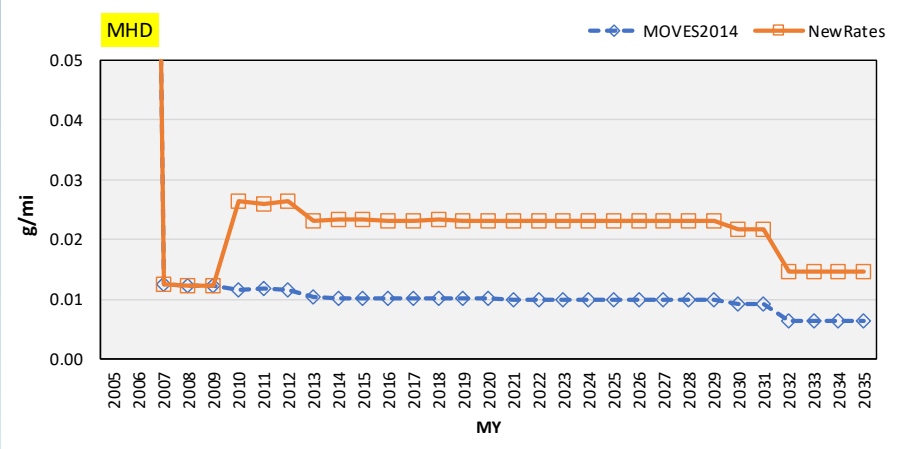


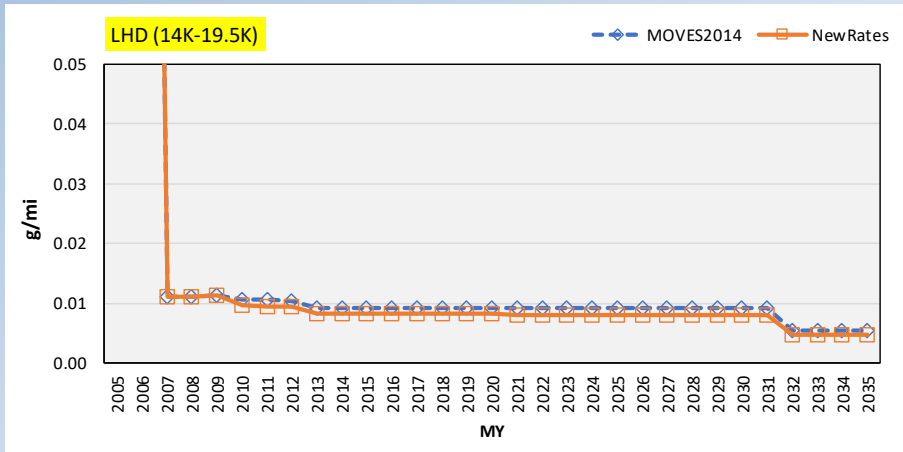


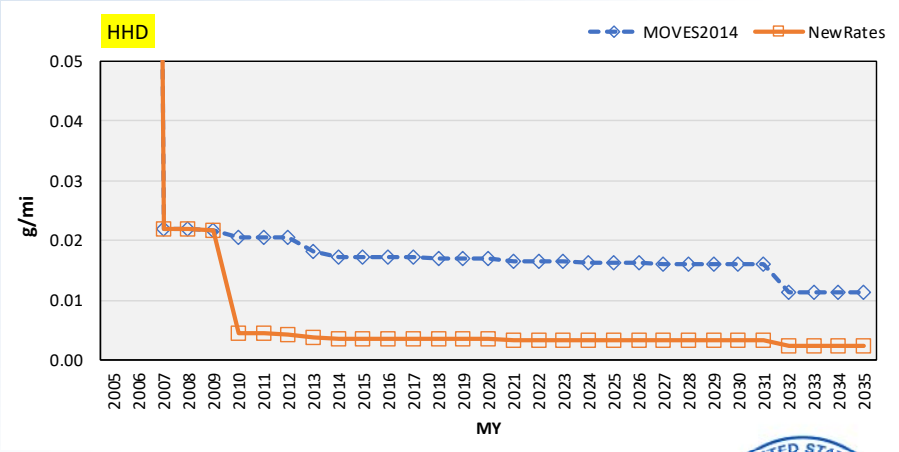


$PM_{2.5}$ Running Exhaust Rates (CY2035)

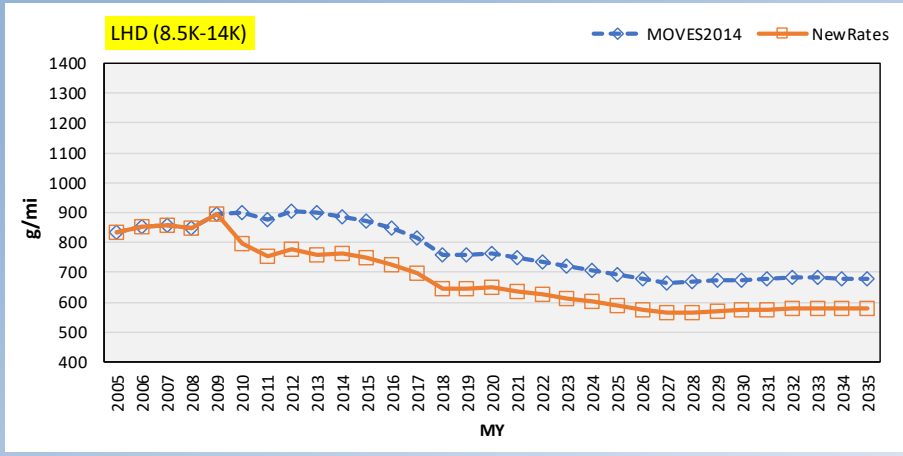


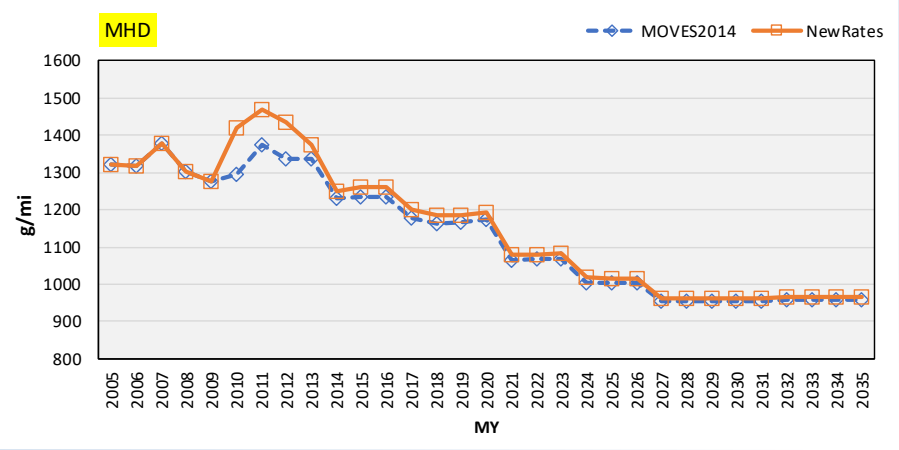


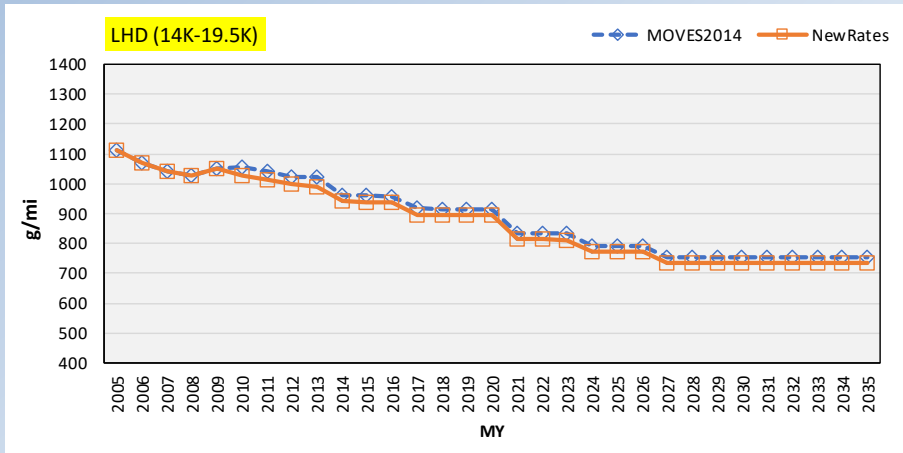


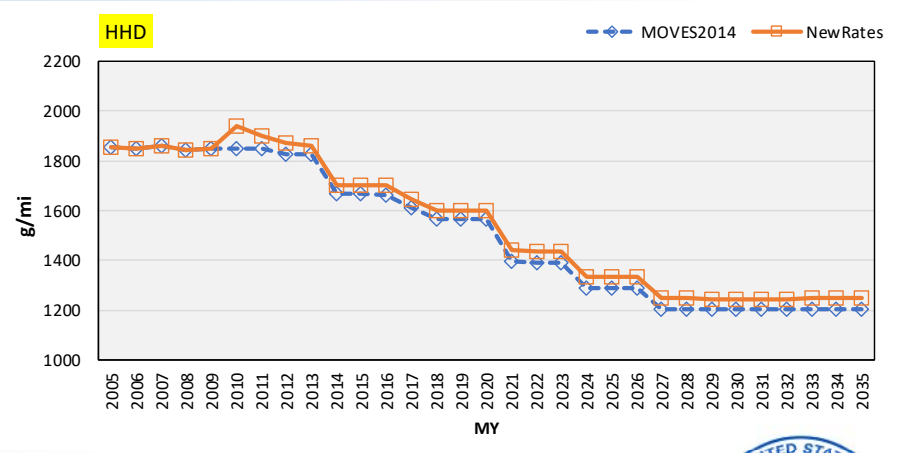


CO_2 Running Exhaust Rates (CY2035)

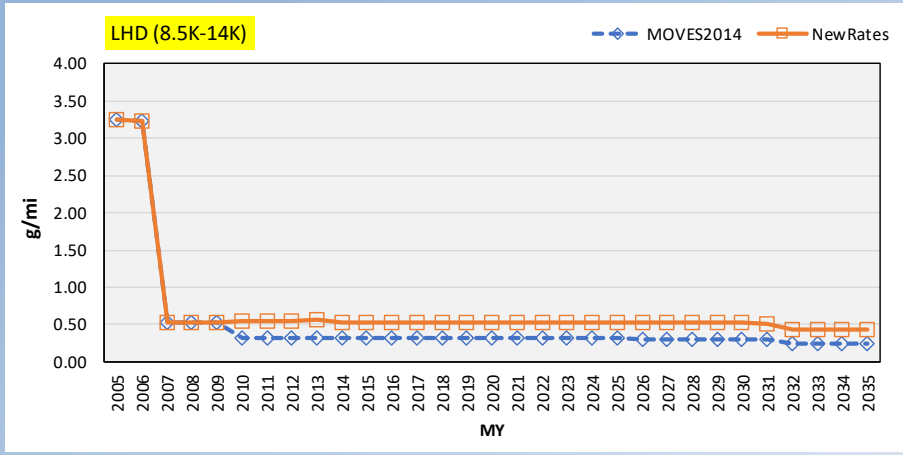


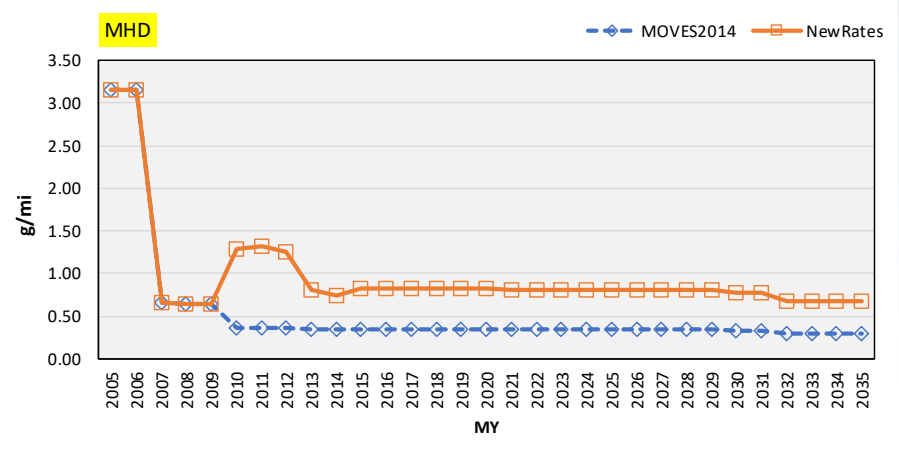


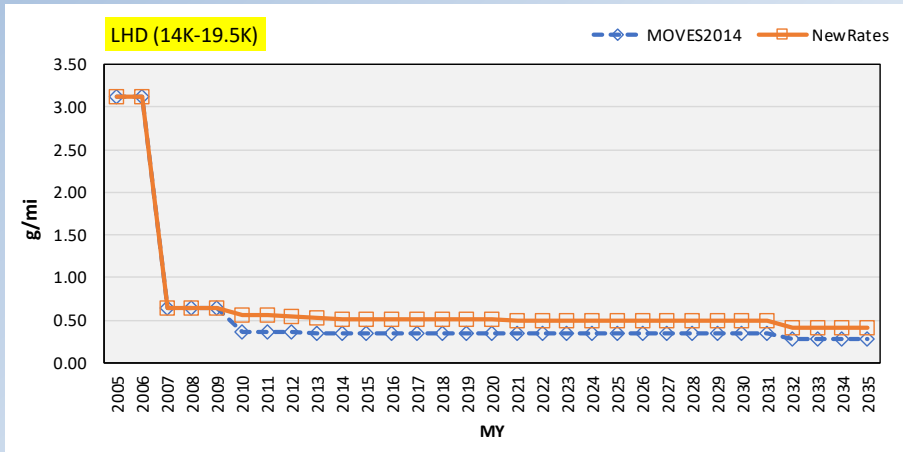


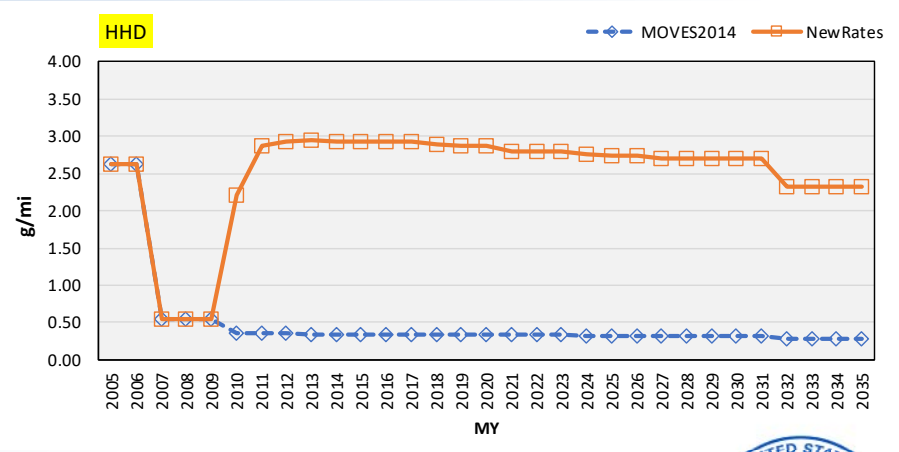


CO Running Exhaust Rates (CY2035)

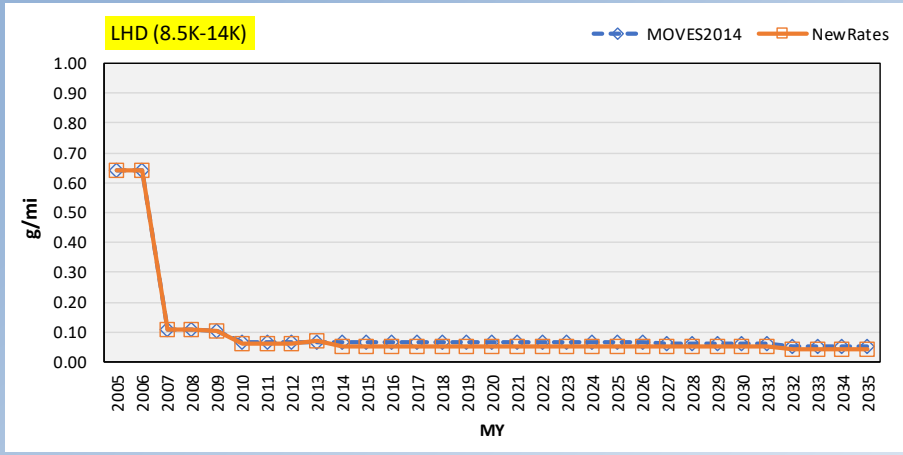


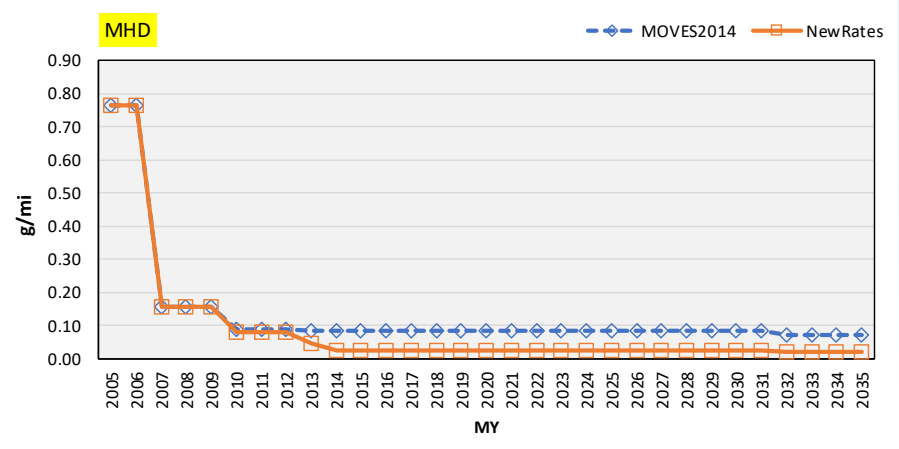


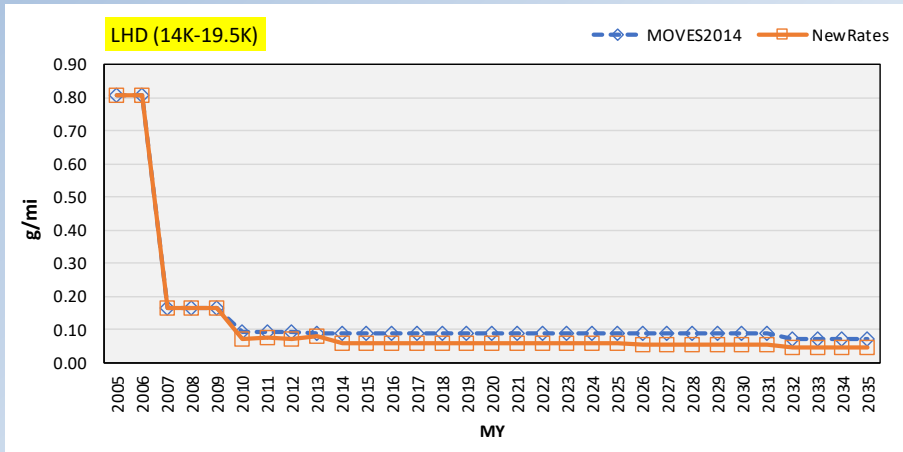


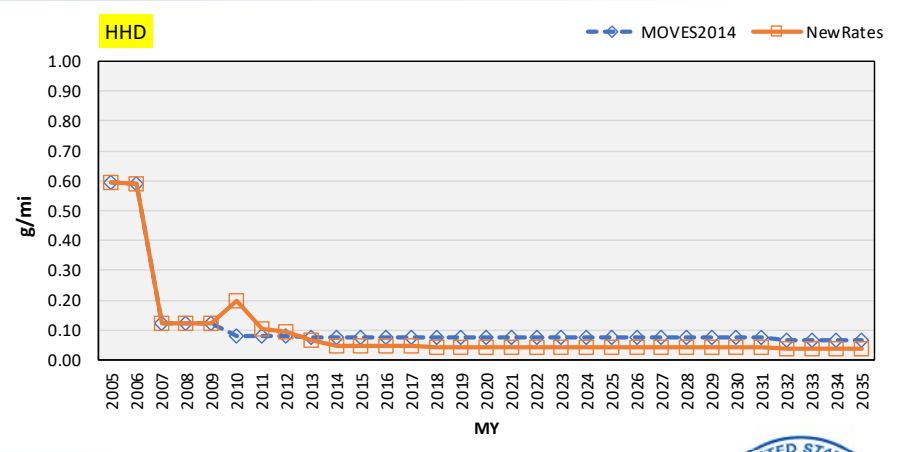


THC Running Exhaust Rates (CY2035)







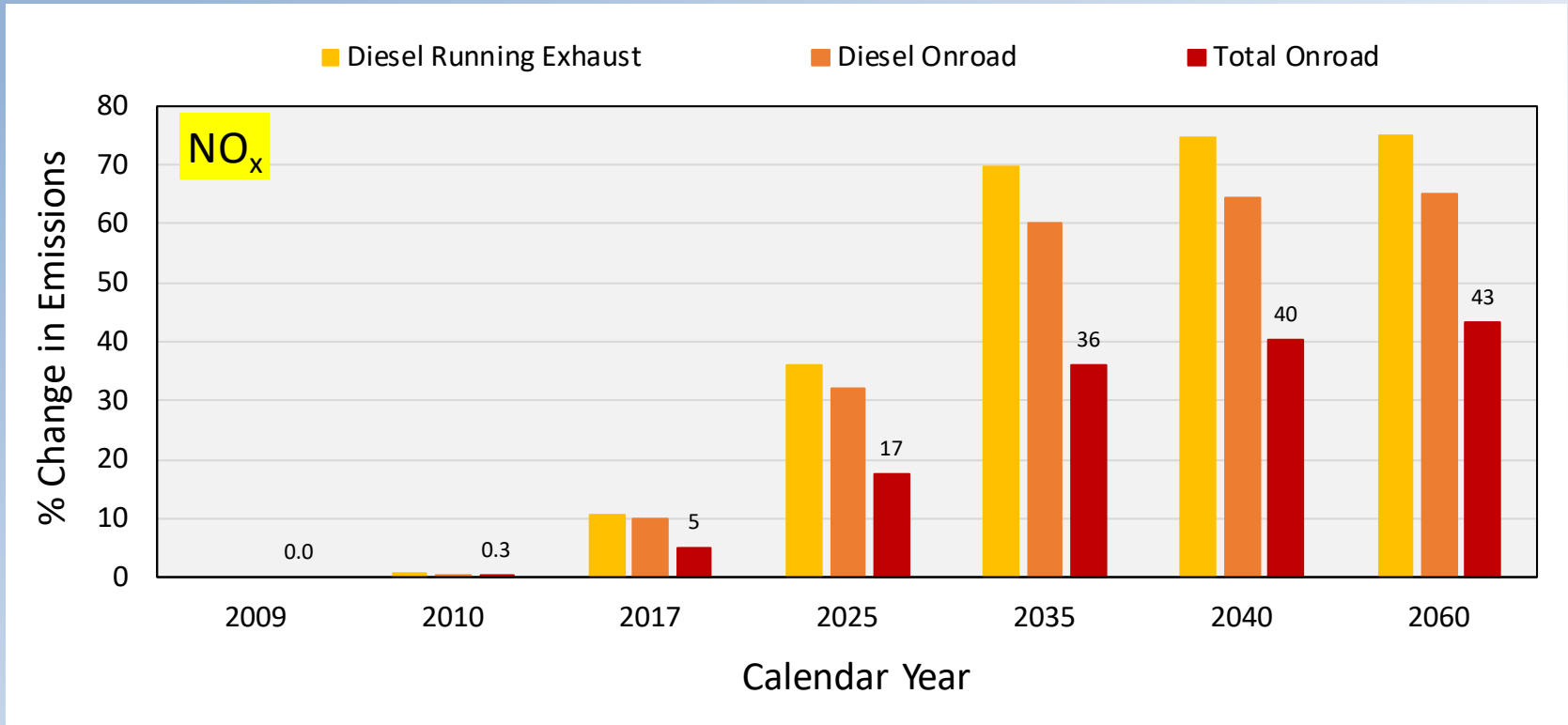


Preliminary Emissions Impact

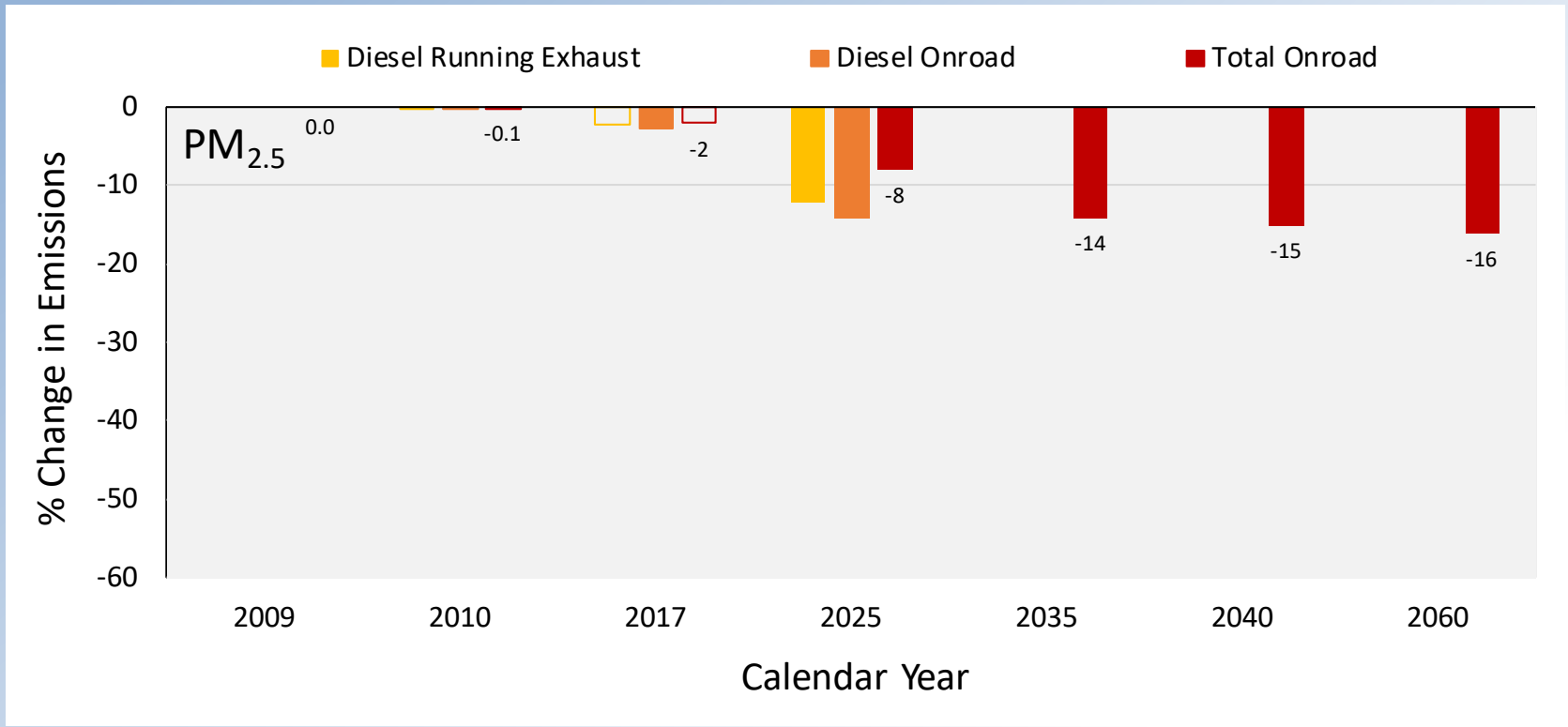
#	Geographic Area	Description
1	National	Diesel Running Exhaust (All Diesel Vehicles)
2	National	Diesel Onroad (All Diesel Vehicles and Processes)
3	National	Total Onroad (All Fuels, Vehicles, and Processes)

- The estimated impacts are for this specific emissions rate update only
- Based on a “typical” MOVES national scale run

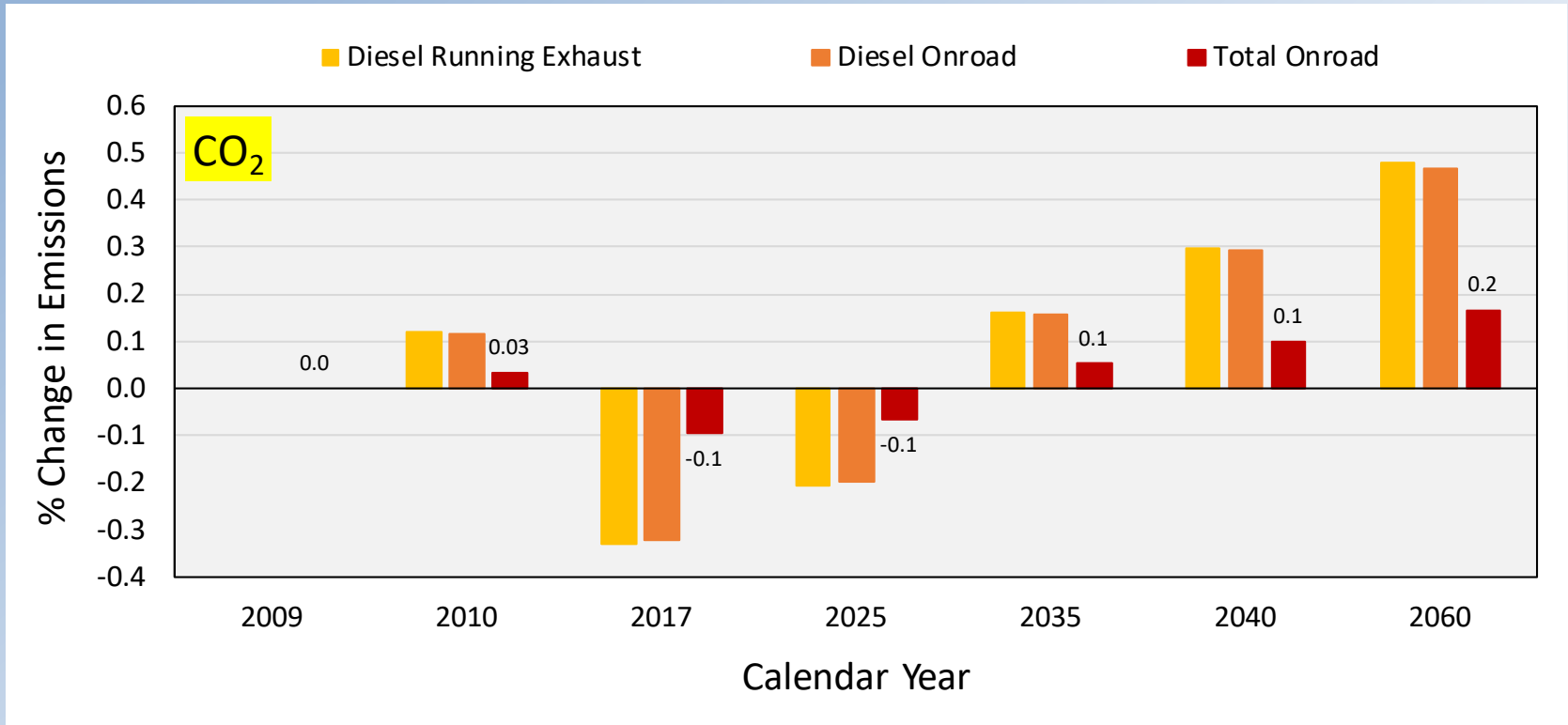
Preliminary Emission Impacts - NO_x



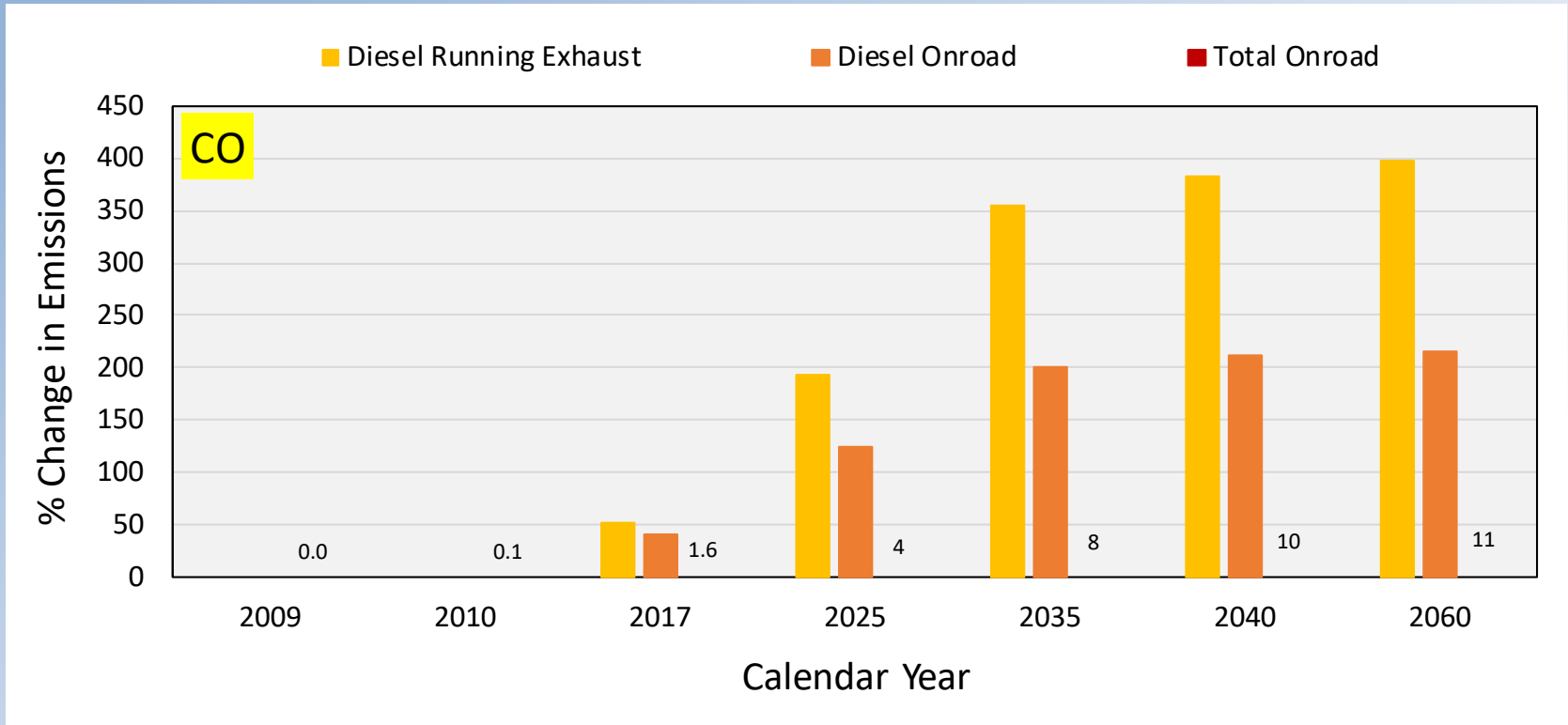
Preliminary Emission Impacts - $PM_{2.5}$



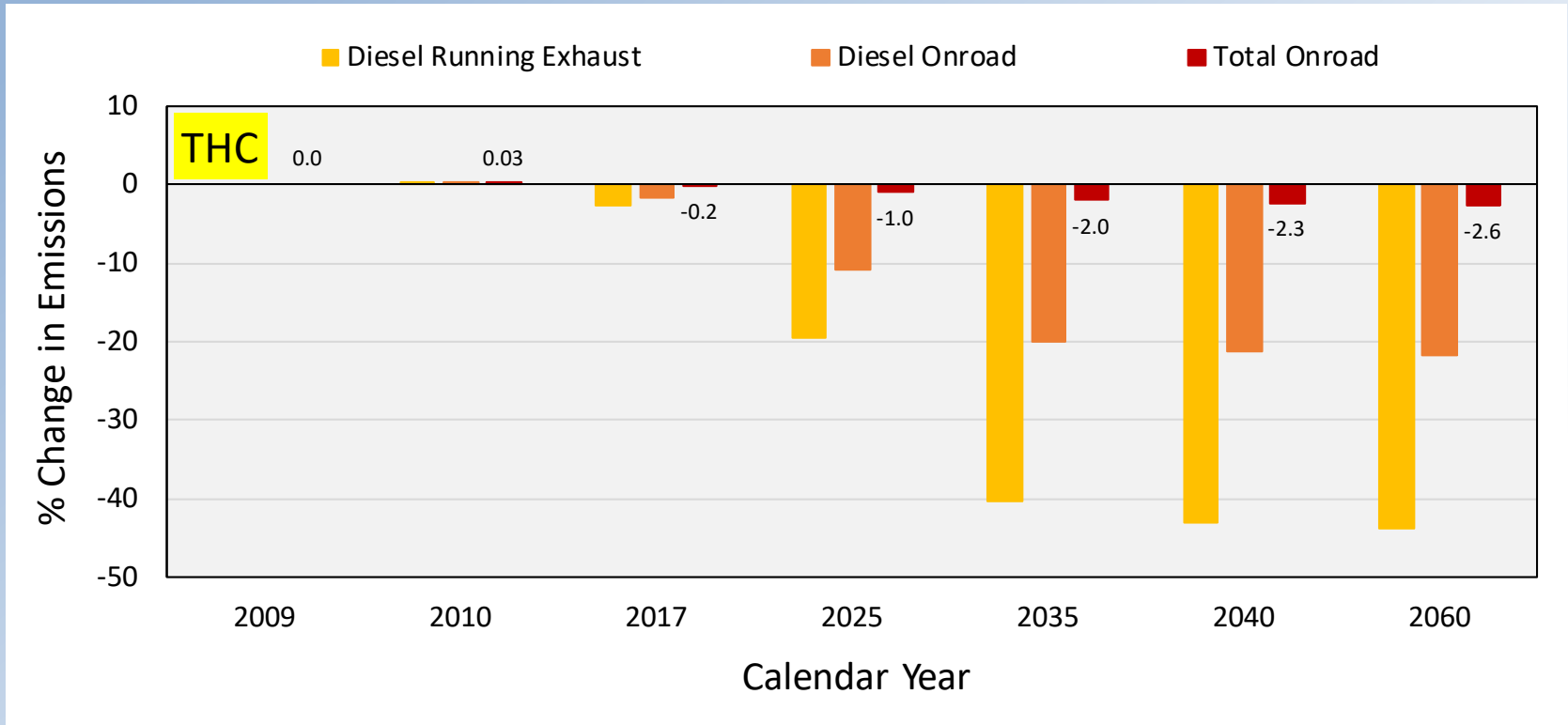
Preliminary Emission Impacts - CO_2



Preliminary Emission Impacts - CO



Preliminary Emission Impacts - THC



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Updates to MY 2010+ Heavy-Duty Gasoline Running Exhaust Rates

Gurdas S. Sandhu* and Darrell Sonntag

* ORISE participant supported by an interagency agreement between EPA and DOE

MOVES Review Work Group | April 10, 2019 | Ann Arbor, MI, USA

Context

- Current MY2010+ rates based on old and limited data:
  - Four MHD gasoline trucks from CRC E-55 program
  - EPA's Mobile Source Observation Database (MSOD), mostly LHD and chassis tests
  - Age effects are based on actual data only for the two age groups shown here. No additional T&M assumptions applied.
  - No distinction of rates by regClass

Model year group	Regulatory class	Age group	
		0-5	6-9
1960-1989	MHD		2
	LHD2b3		10
1990-1997	MHD		1
	LHD2b3	33	19
1998-2002	MHD	1	
	LHD2b3	1	

Background – New Gasoline Test Data

- Three medium heavy-duty gasoline vehicles were tested by EPA. Rates shown here are from on-road PEMS testing over various drive cycles, unladen & laden weights, and AC on/off.
- Engines in this dataset:
  1. MY 2016/2017 Ford E450, GFMXE06.8BWZ (6.8 L)
  2. MY 2015 Isuzu NPR, FGMXE06.0584 (6.0 L), this is a GM engine
  3. MY 2017 Ram 3500, HCRXD06.45W0 (6.4 L), this is a Fiat Chrysler engine
- Raw data size: ~489K seconds. After QA: ~412K (~16% removed). After correction for cold-start: ~389K seconds (~5.5% removed).

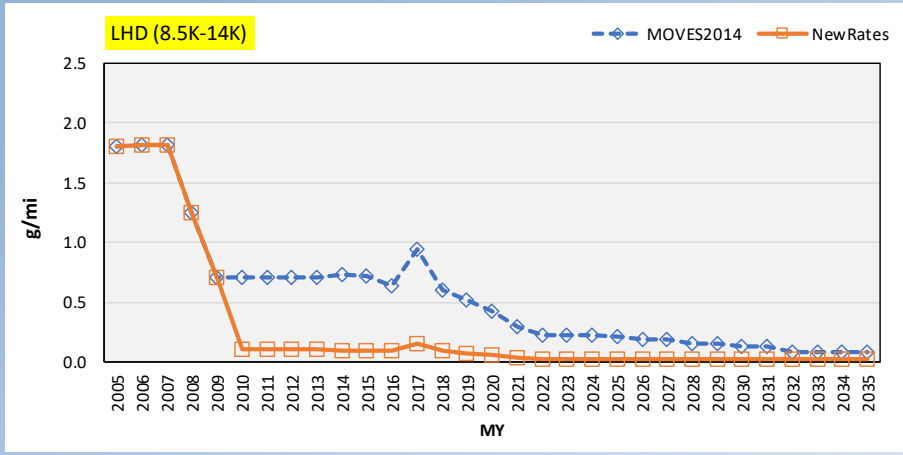
Background – How the Data was Analyzed

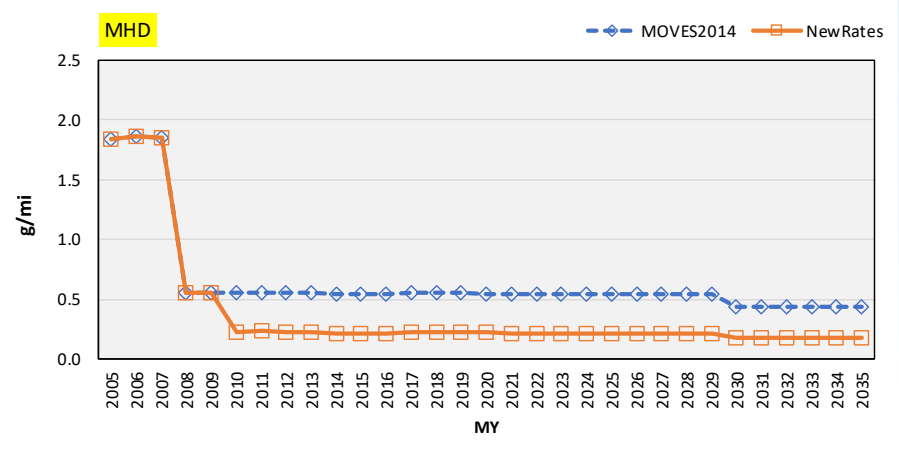
- Test data was analyzed with:
  - road-load (ABC) coefficients for sourceType 52 (single unit short-haul truck),
  - vehicle mass as measured
  - f_{scale} of 5, 7, and 10 to arrive at rates for LHD, MHD, and HHD, respectively.
- NO_x, CO, CO_2, and THC rates are from the on-road testing
- PM was not measured during on-road testing. PM rates are based on HD diesel LHD and HHD rates from the HDIUT data. Note that Gasoline MHD based on Diesel HHD.
- Age effects for gases same as gasoline in MOVES2014, while for PM it is same as diesel in MOVES2014.
- Final rates for gases include projected sales weighting

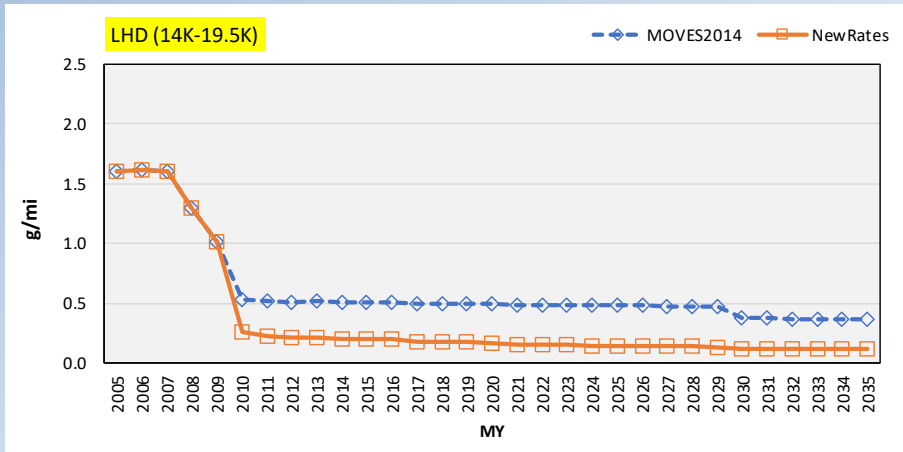
MOVES-generated g/mile Rates

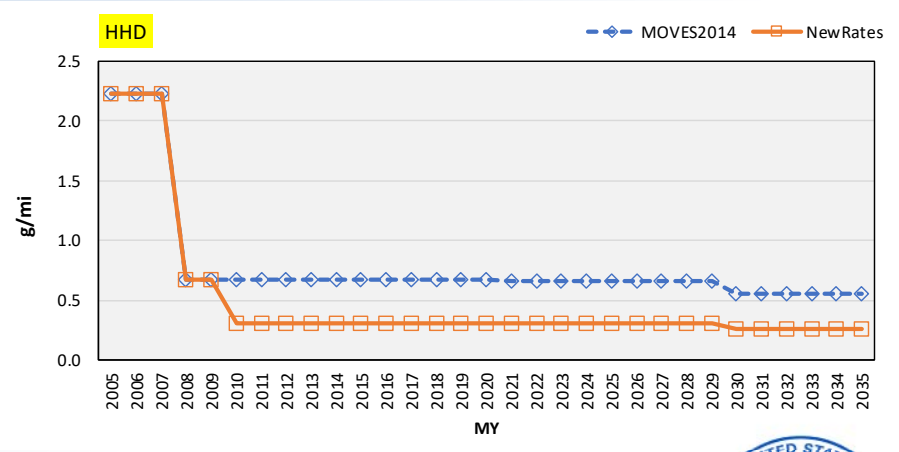
- Based on a “typical” MOVES national scale run
- Emission rates and activity are based on new f_{scale} values for MY 2010+

NO_x Running Exhaust Rates (CY2035)

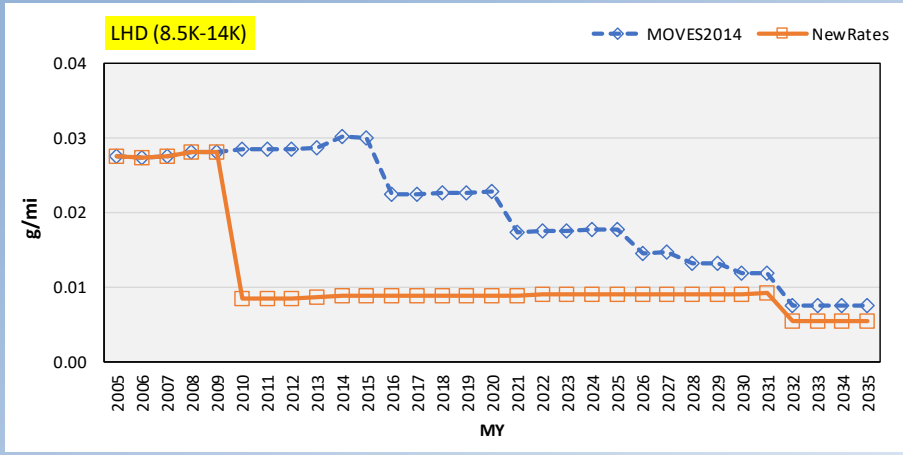


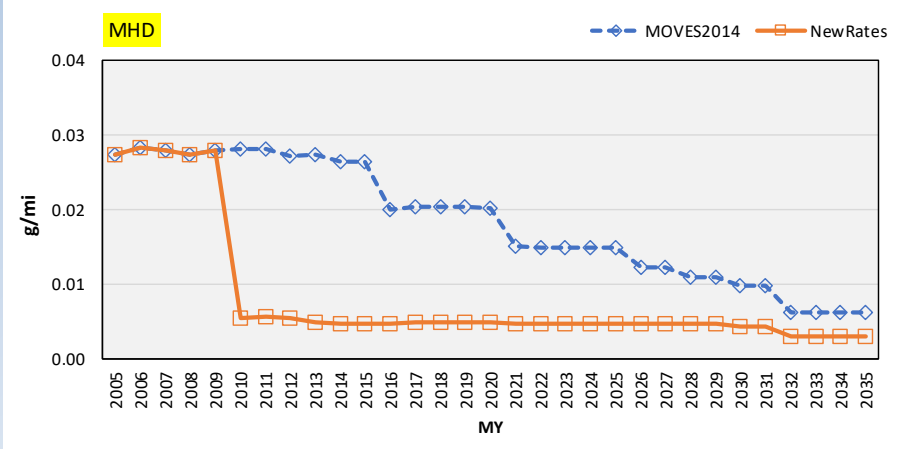


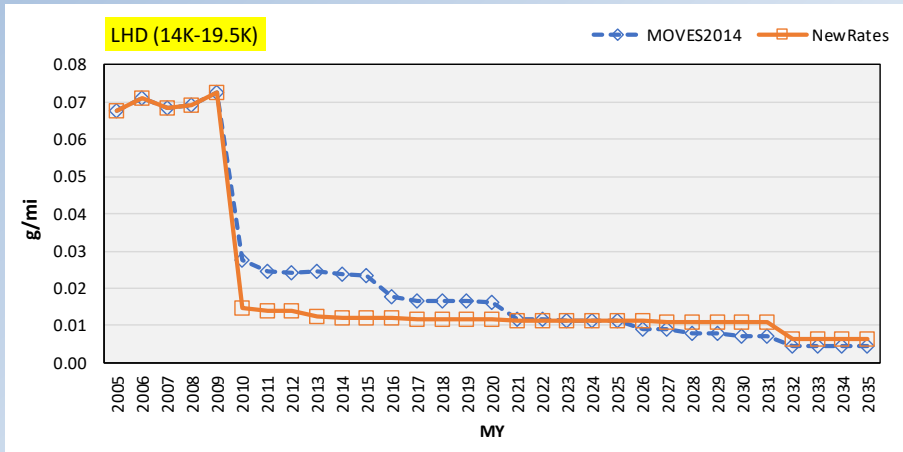


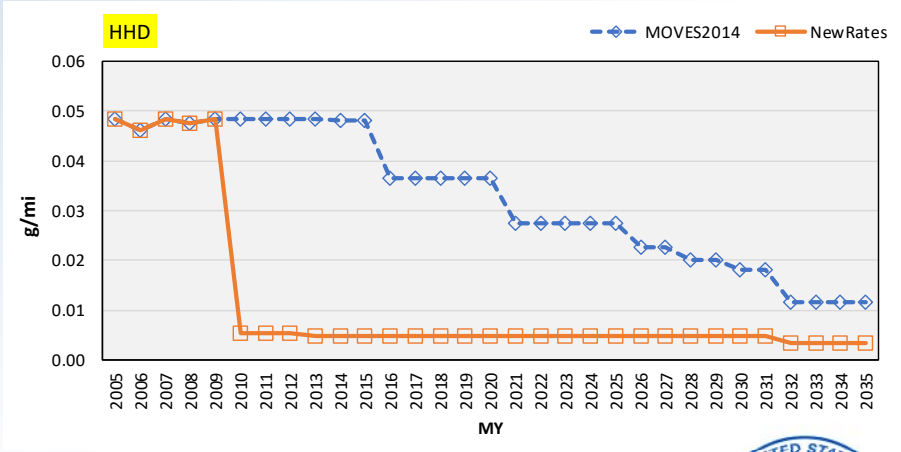


$PM_{2.5}$ Running Exhaust Rates (CY2035)



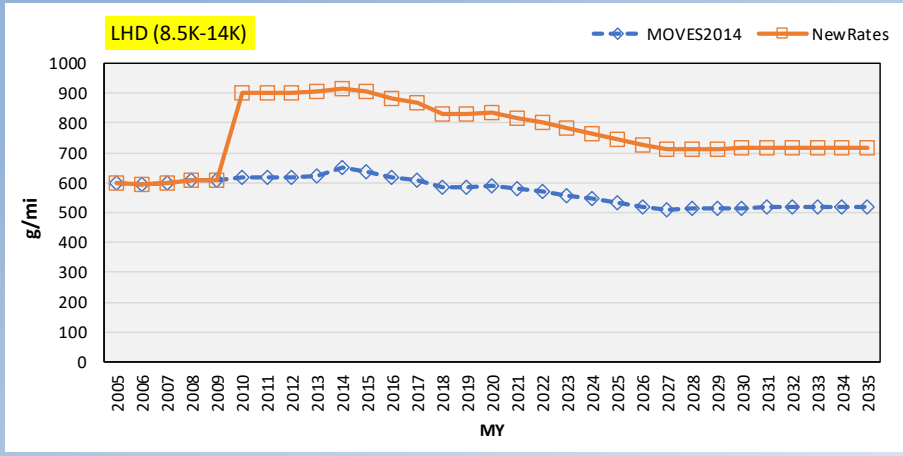


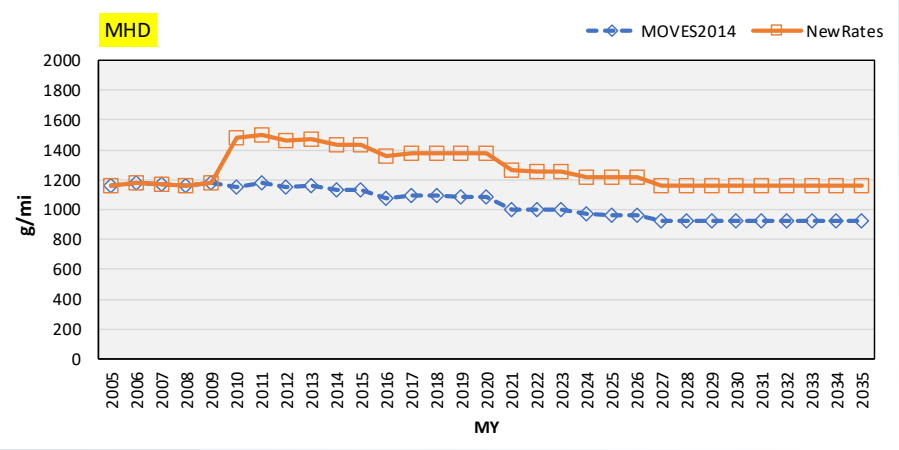


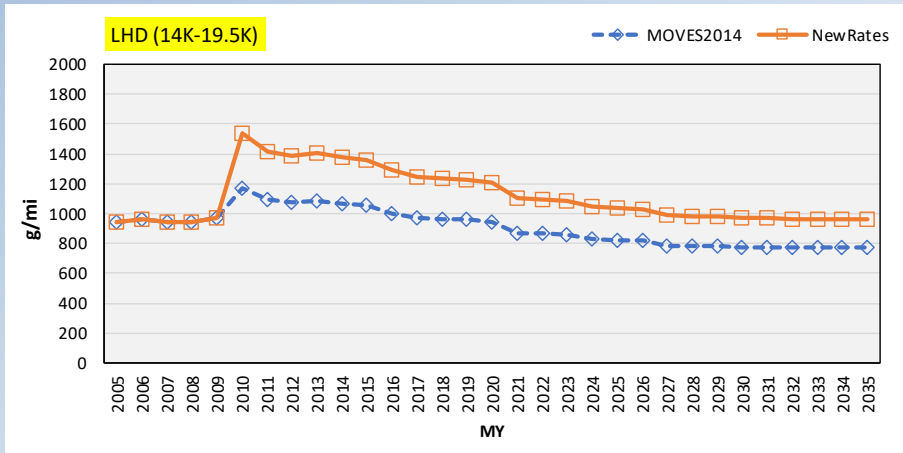


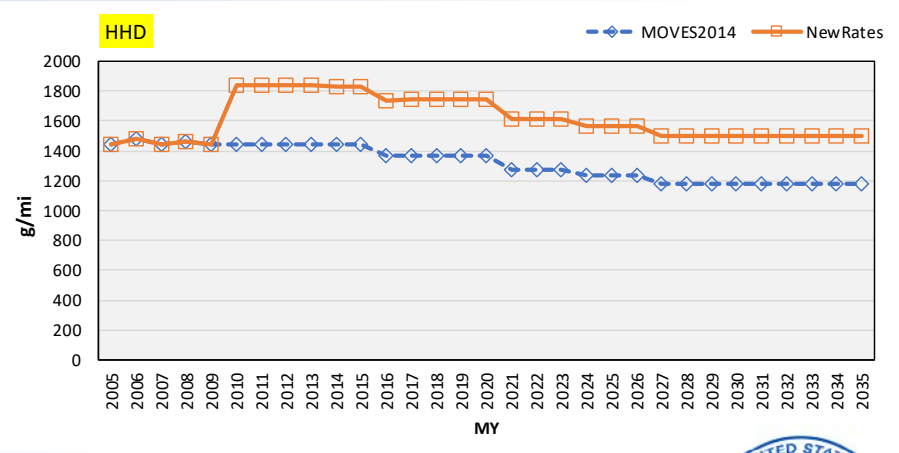
- In MOVES2014, age effects for PM were multi-step based on each of the age groups, while gases had age effect for only ages 0-5 and 6+. The new PM rates use diesel age effects from MOVES2014.

CO_2 Running Exhaust Rates (CY2035)

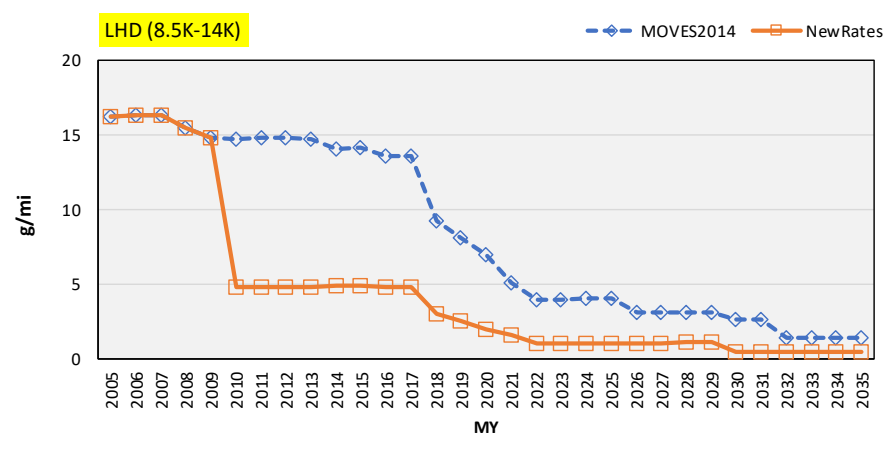


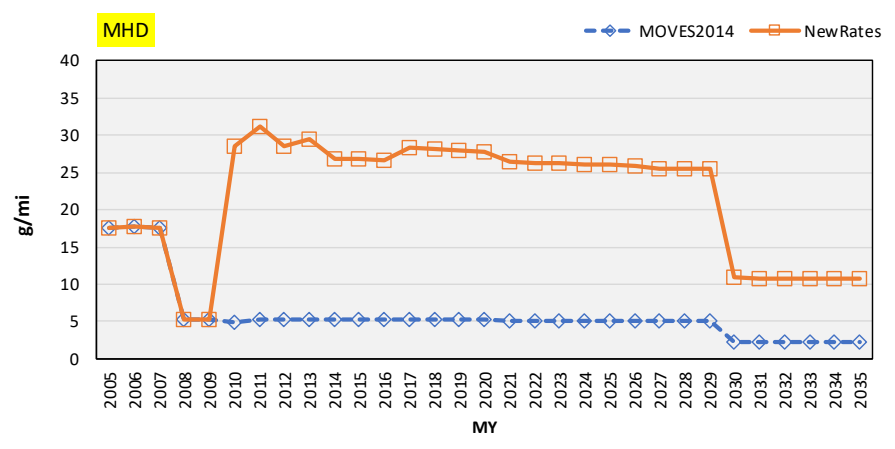


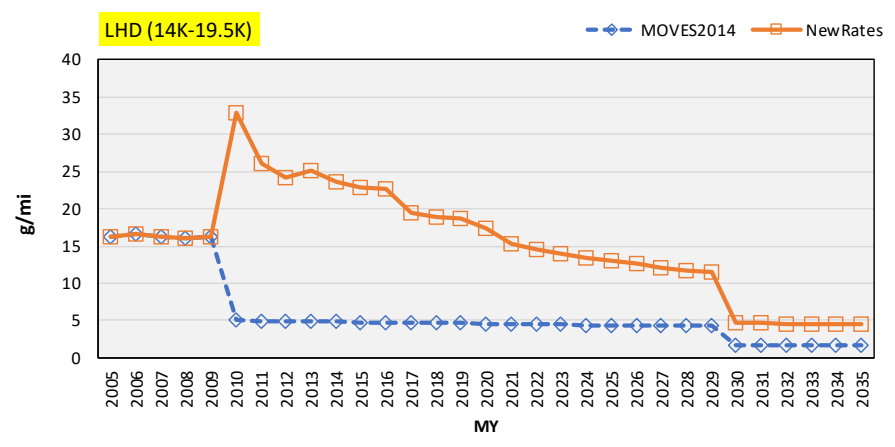


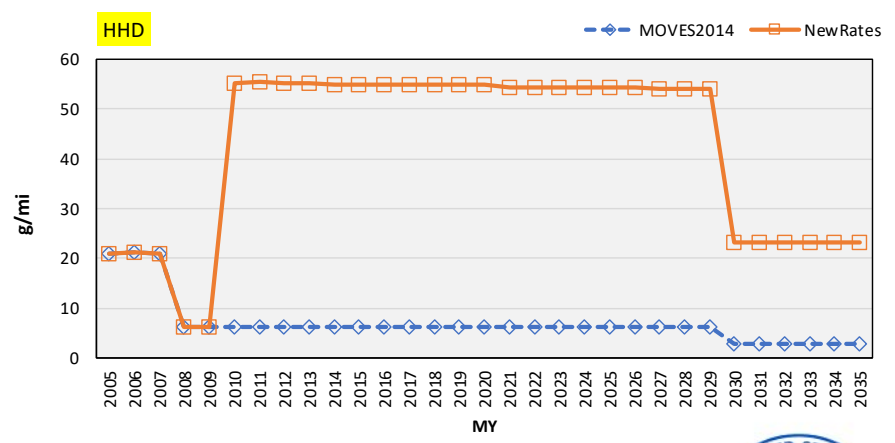


CO Running Exhaust Rates (CY2035)

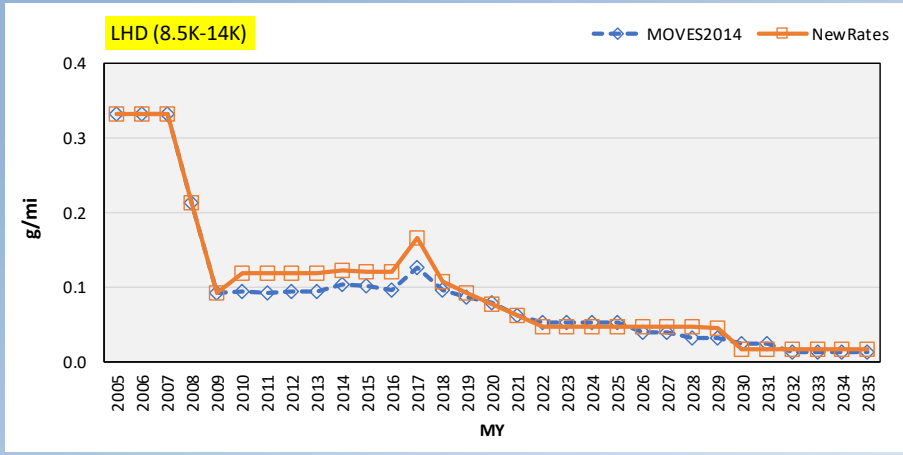


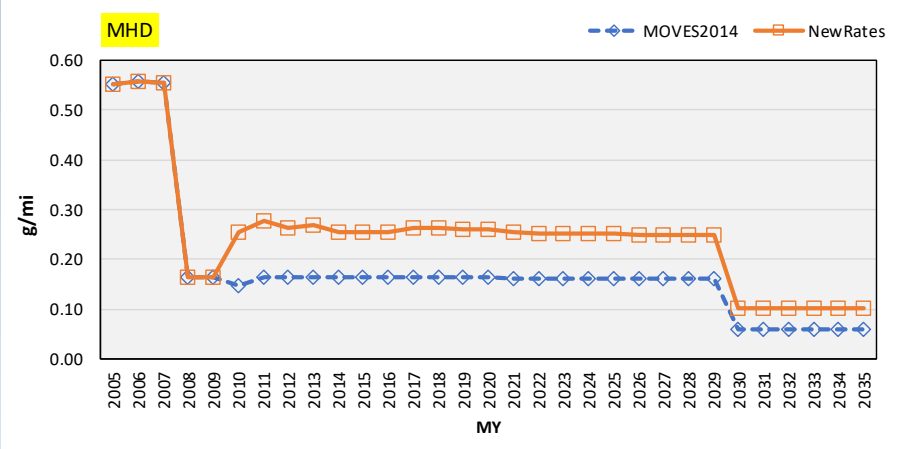


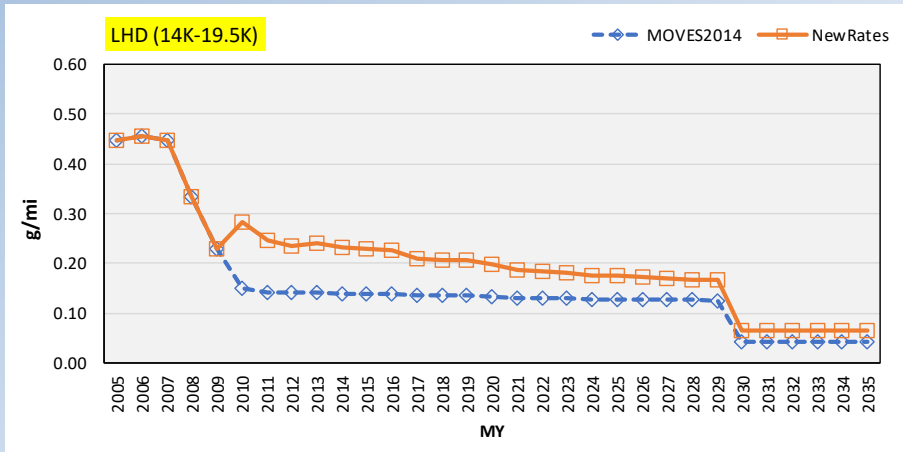


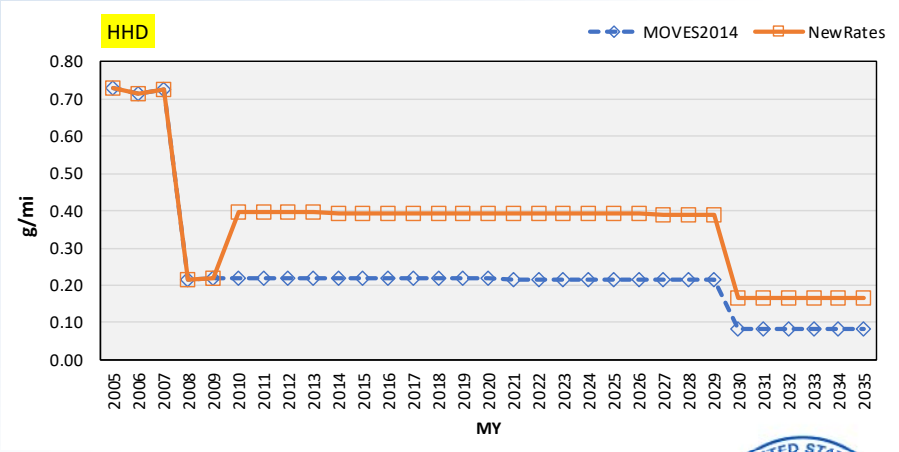


THC Running Exhaust Rates (CY2035)







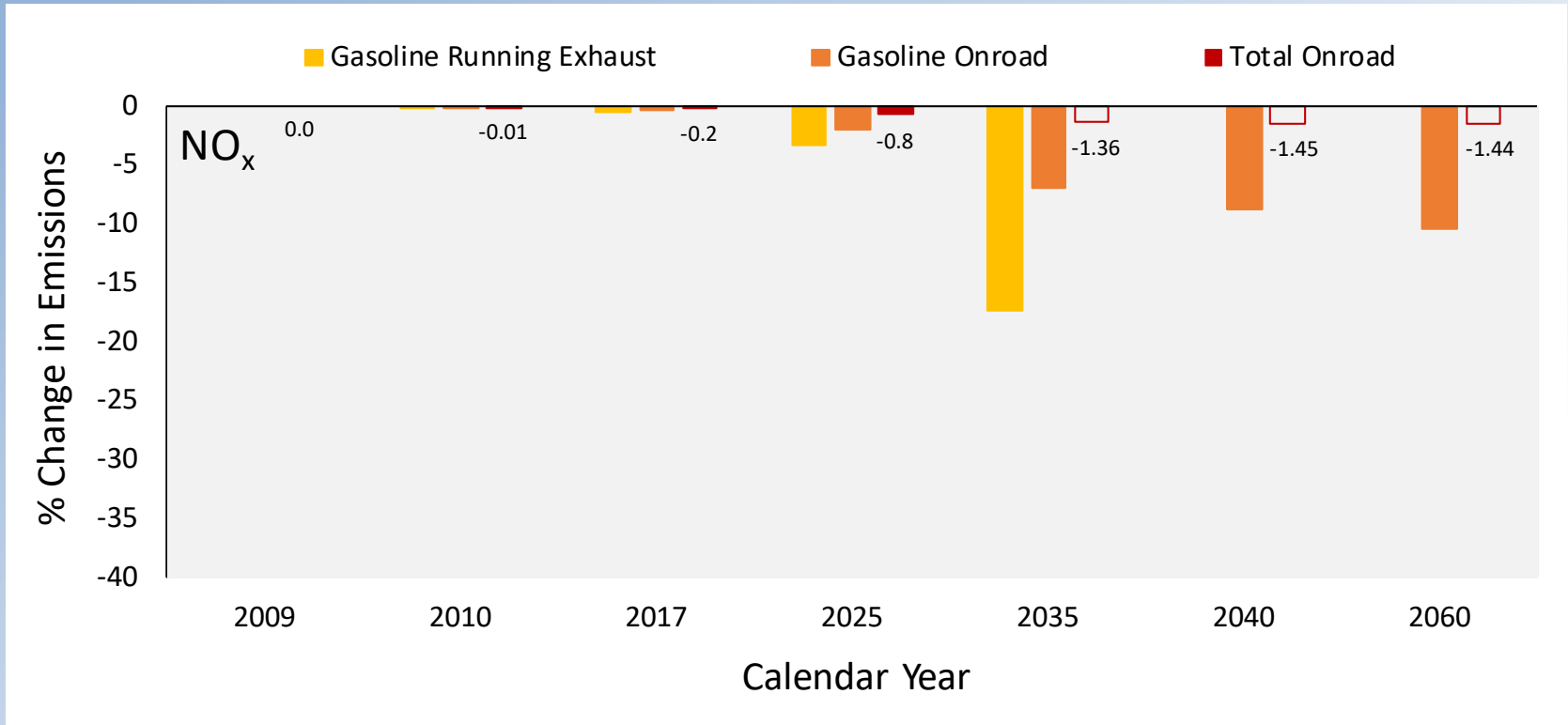


Preliminary Emissions Impact

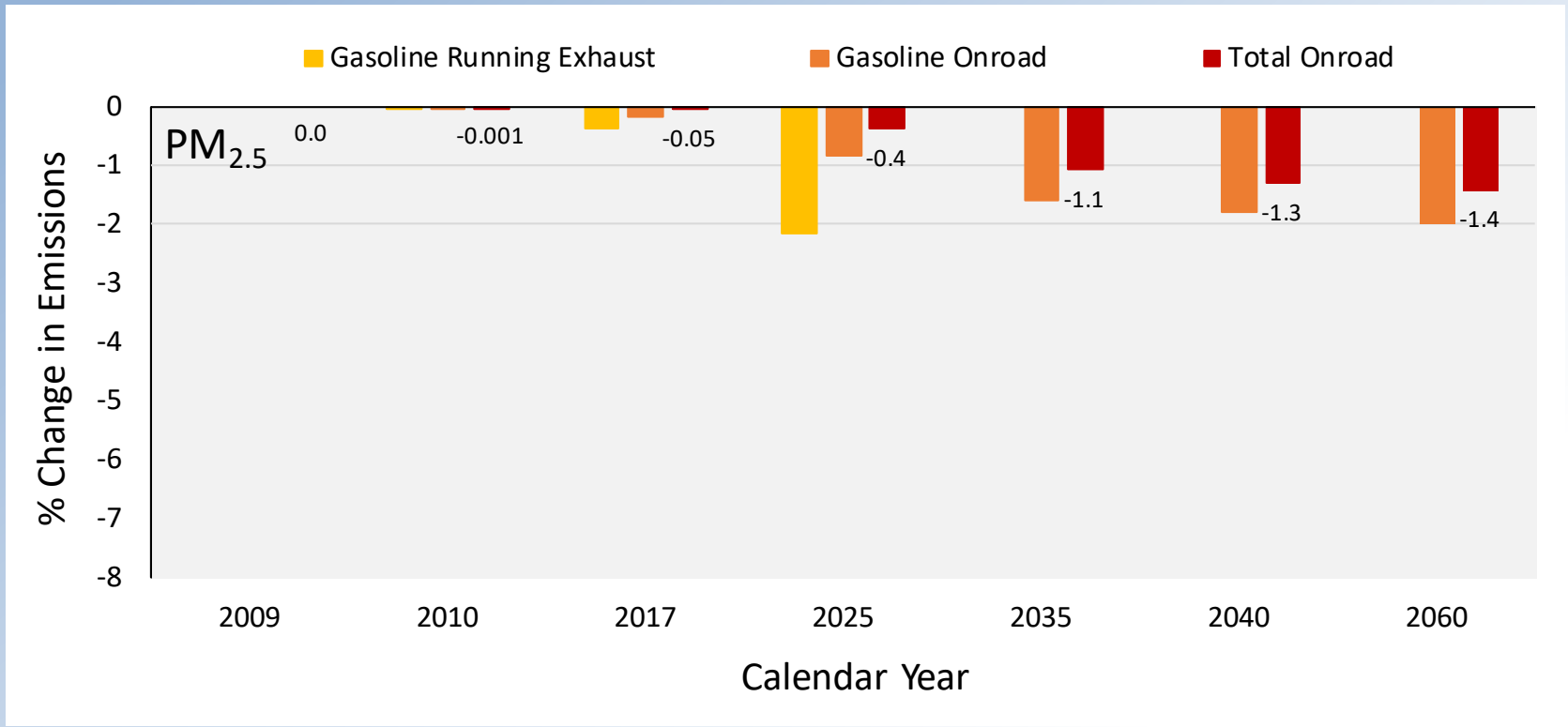
#	Geographic Area	Description
1	National	Gasoline Running Exhaust (All Gasoline Vehicles)
2	National	Gasoline Onroad (All Gasoline Vehicles and Processes)
3	National	Total Onroad (All Fuels, Vehicles, and Processes)

- The estimated impacts are for this specific emissions rate update only
- Based on a “typical” MOVES national scale run

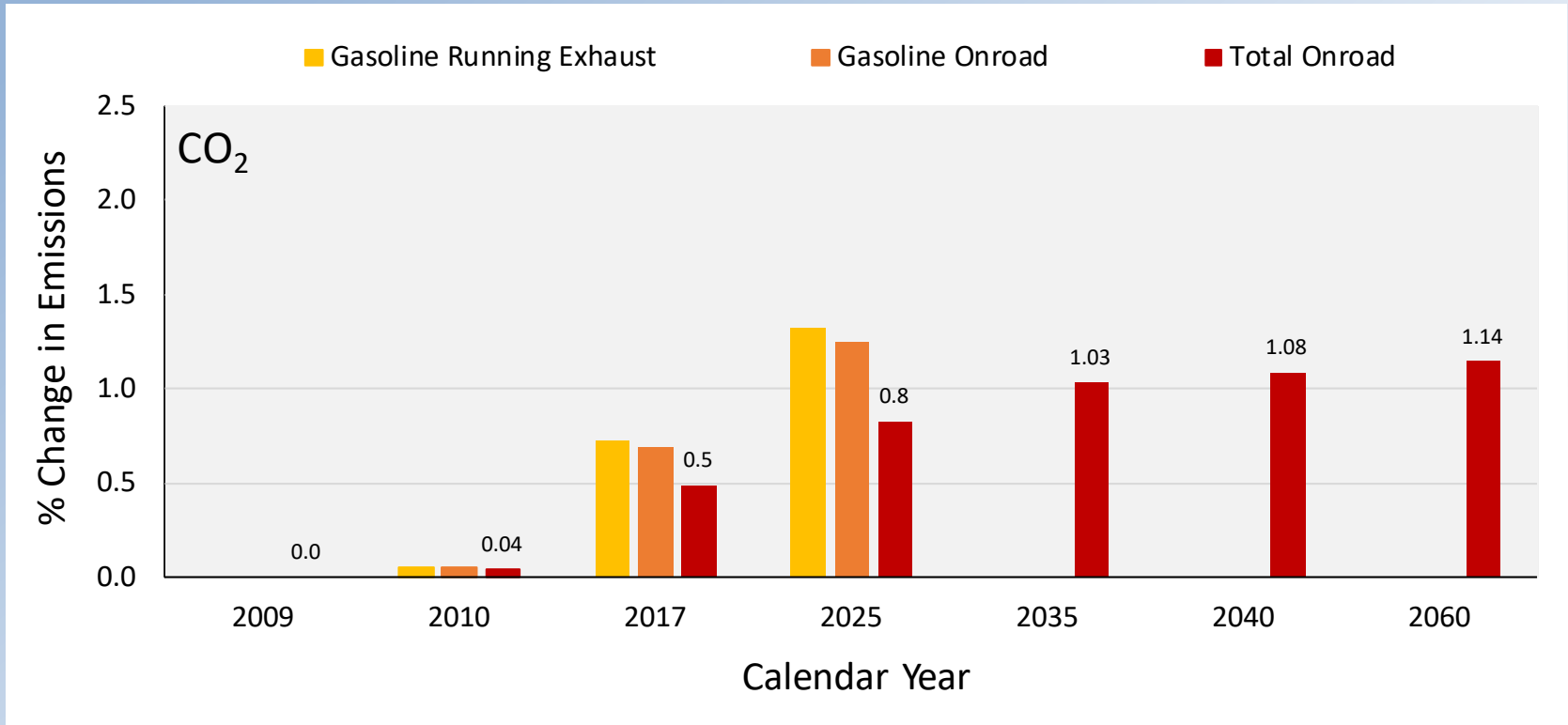
Preliminary Emission Impacts - NO_x



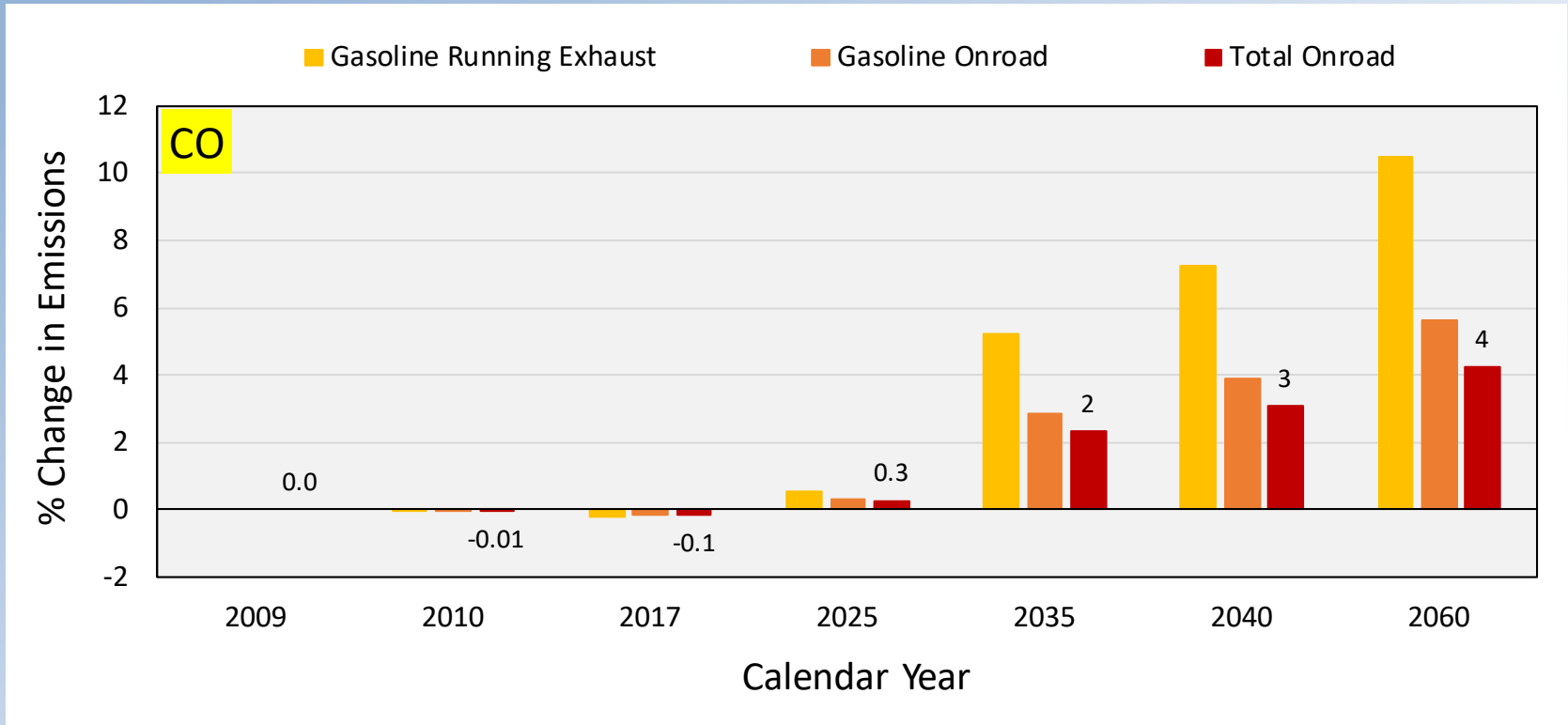
Preliminary Emission Impacts - $PM_{2.5}$



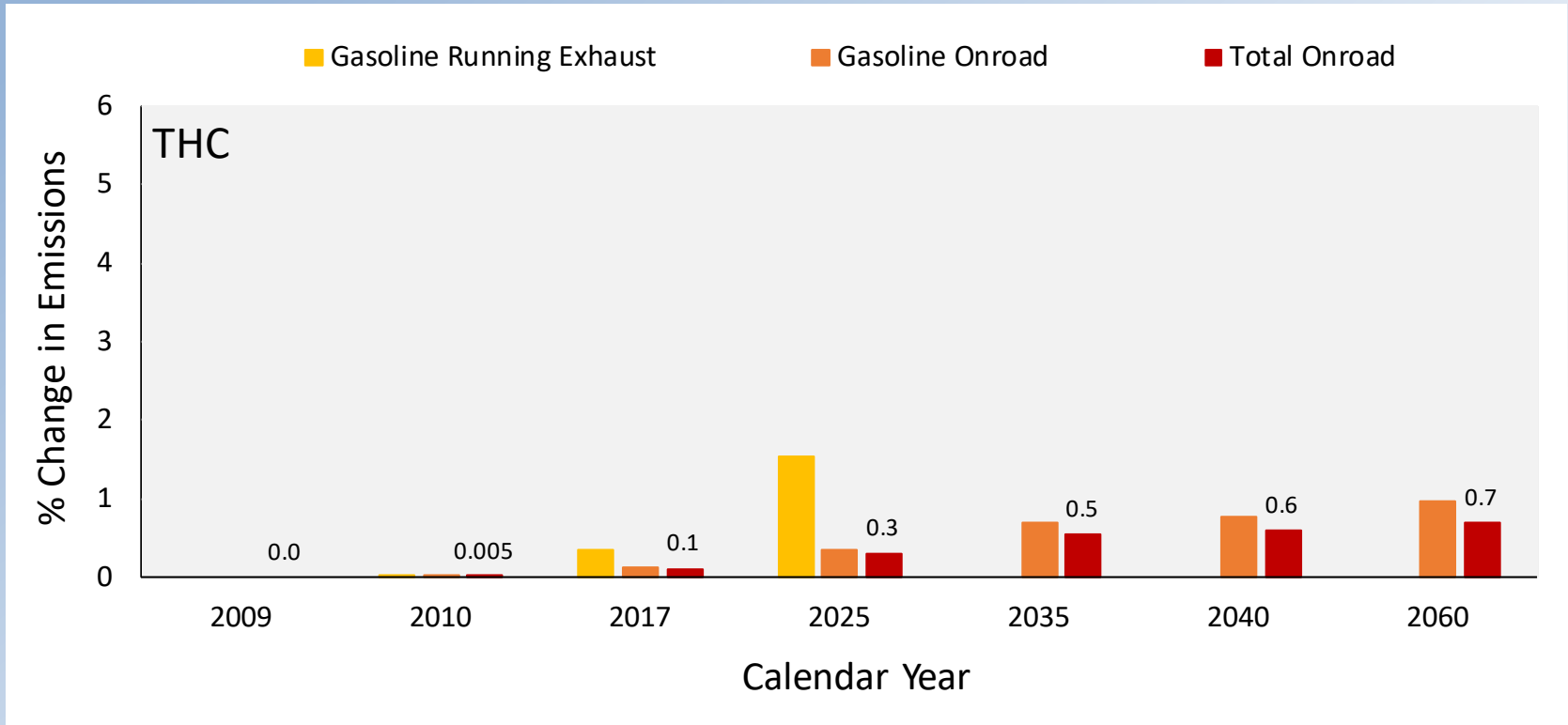
Preliminary Emission Impacts - CO_2



Preliminary Emission Impacts - CO



Preliminary Emission Impacts - THC



MOVES

Motor Vehicle Emission Simulator

Updates to MY 2010+ Heavy-Duty Natural Gas Running Exhaust Rates

Gurdas S. Sandhu* and Darrell Sonntag

* ORISE participant supported by an interagency agreement between EPA and DOE

MOVES Review Work Group | April 10, 2019 | Ann Arbor, MI, USA

Context

- In MOVES2014, the emission rates for MY2010+ CNG bus (regClass 48, sourceType 42) based on
  - MY 1997-2004 MHD gasoline vehicles adjusted by ratios based on chassis dynamometer measurements of CNG buses and certification data.
- June 2017[1]: Presented updates to modeling of CNG vehicles
  - Allowed modeling of CNG for all heavy-duty source types (41 through 62). Consistent with MOVES2014, transit bus (sourceTypeID 42) is mapped to urban bus (regClassID 48). However, all other heavy-duty source types are mapped to the heavy heavy-duty regulatory class (regClassID 47).
  - New model year groups, where certification data based adjustment ratio is applied, are 2007-2009 and 2010-2017. MOVES2014 only had the MY 2007-2012 group.
- This Presentation: MY 2010+ rates based on HDIUT data

1. https://www.epa.gov/moves/moves-model-review-work-group

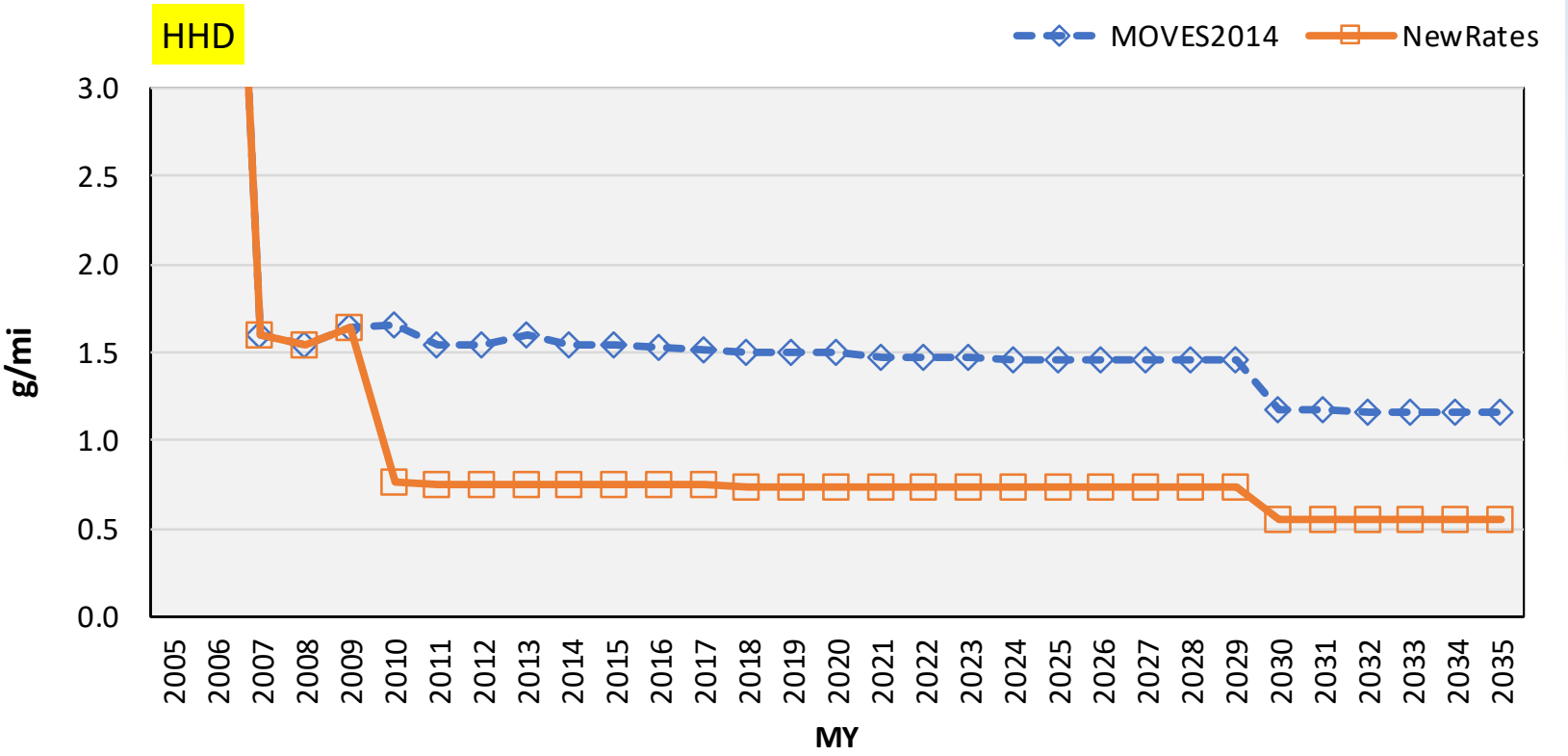
Background

- Data
  - Compressed natural gas (CNG) data from HDIUT
  - Total 11 vehicles from 2 engine families - MYs 2011 and 2014, NOx FEL 0.2 g/bhp-hr
  - Seconds of data before and after QA: approx. 336K vs 310K (~7% removed in QA)
- Analysis
  - Results are shown for only HHD (regClass 47). Base emission rates for Urban Bus (regClass 48) are same as HHD, though the g/mile rates can be different due to activity. The comparison of "NewRates" vs MOVES2014 for HHD are similar to Urban Bus.
  - Age effects same as MOVES2014

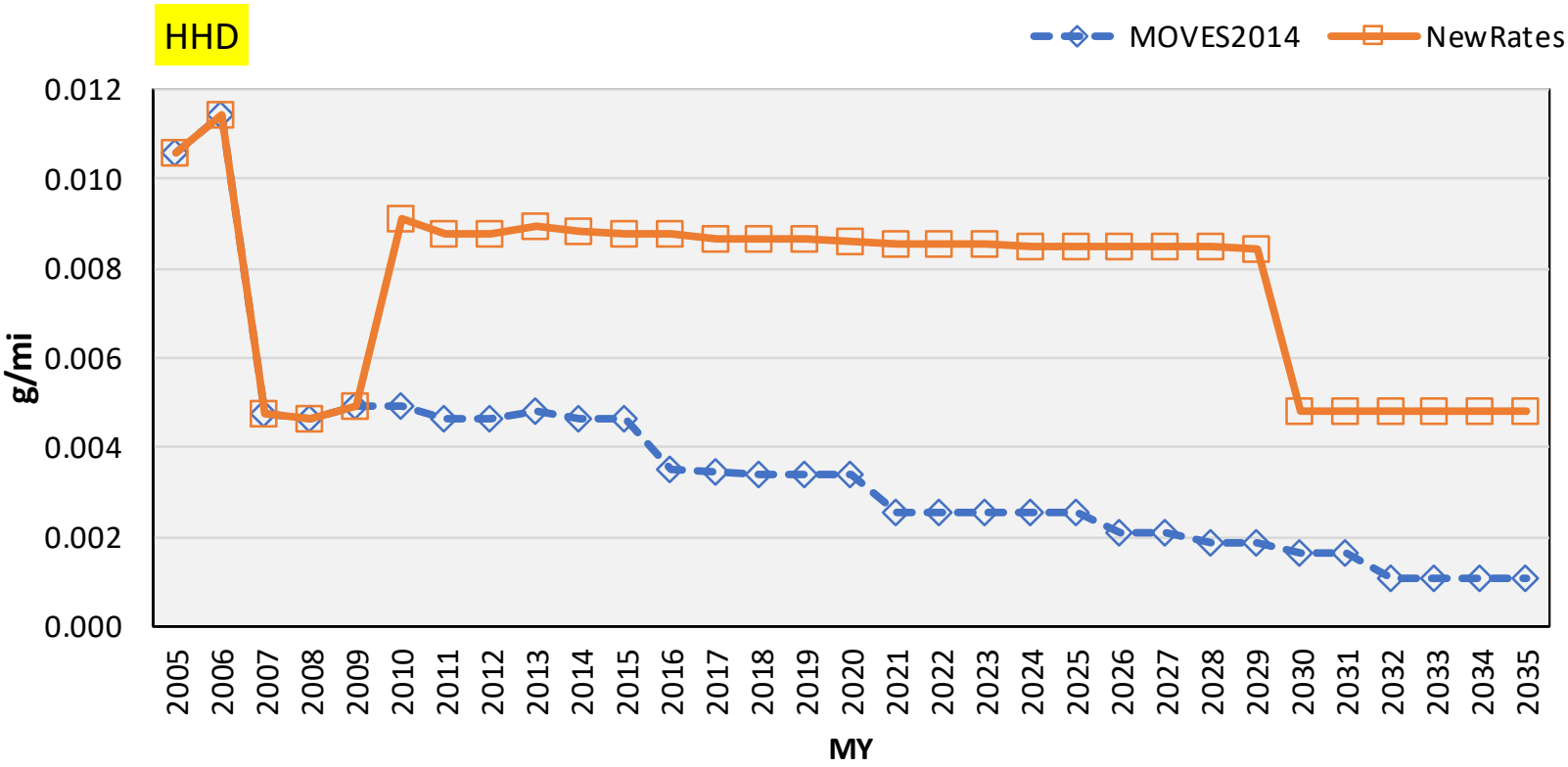
MOVES-generated g/mile Rates

- Based on a “typical” MOVES national scale run
- Emission rates and activity are based on new f_{scale} values for MY 2010+

NO_x Running Exhaust Rates (CY2035)

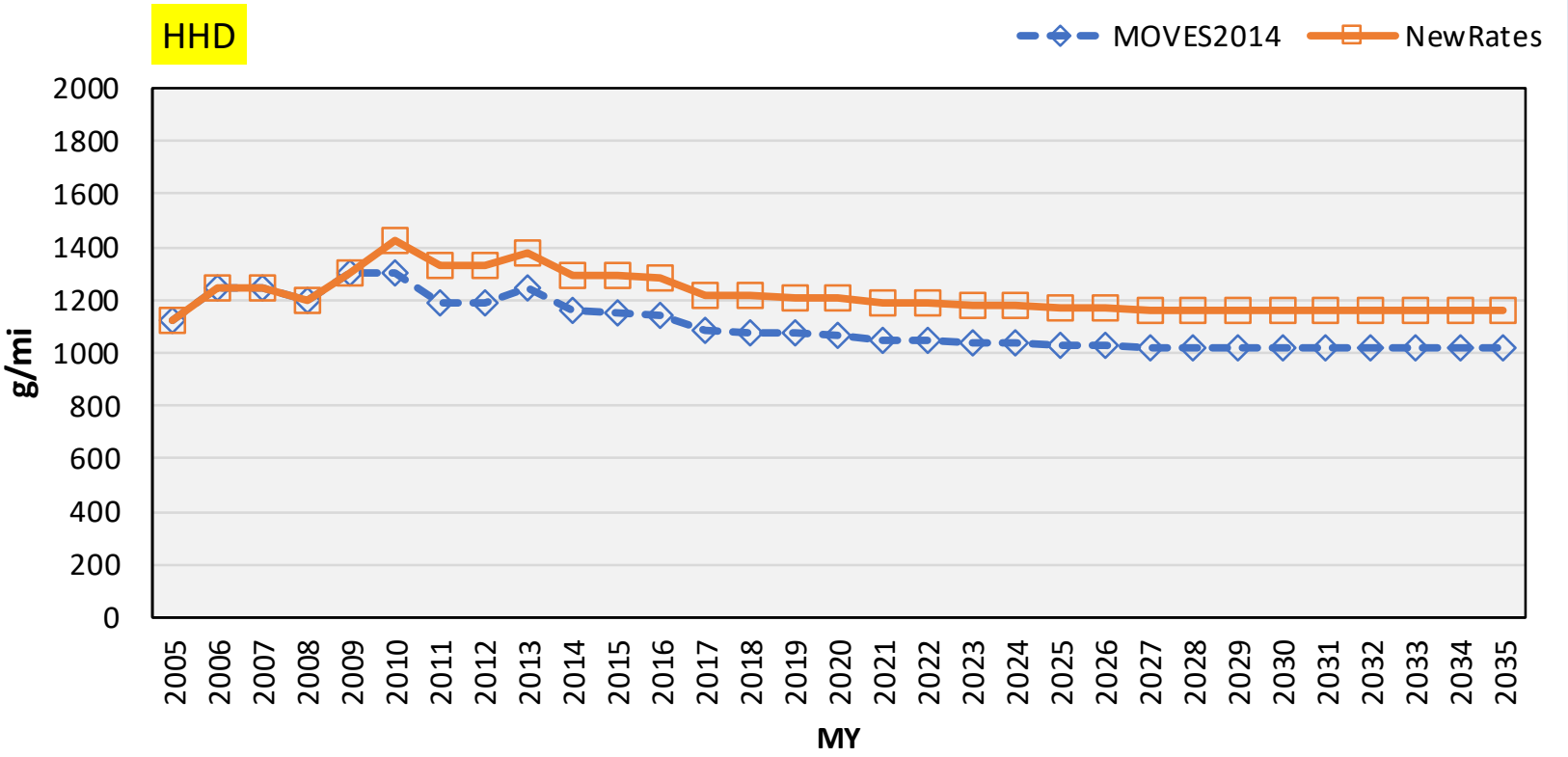


$PM_{2.5}$ Running Exhaust Rates (CY2035)

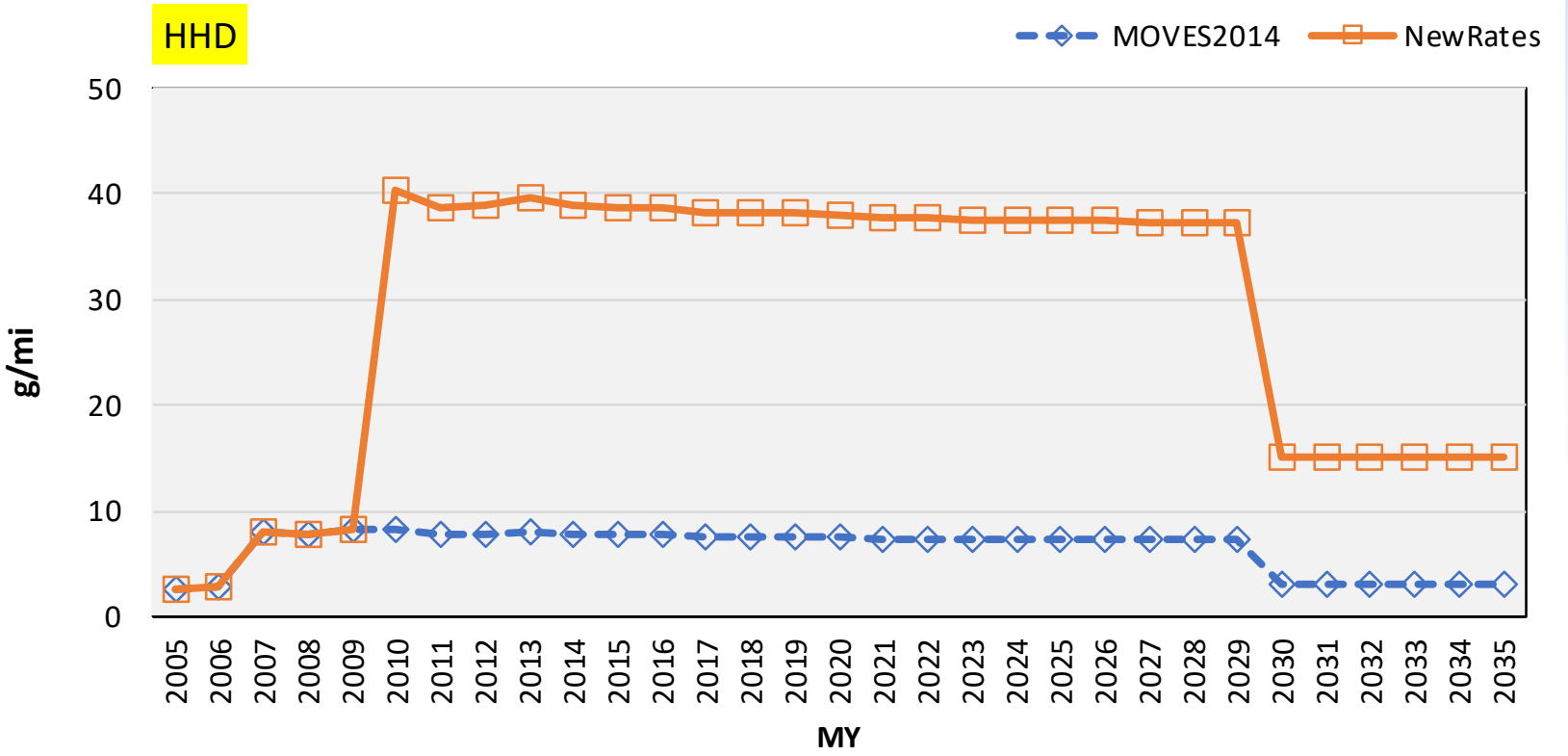


- In MOVES2014, age effects for PM were multi-step based on each of the age groups. The new PM rates use a simplified scheme with steps for ages 0-5 and 6+

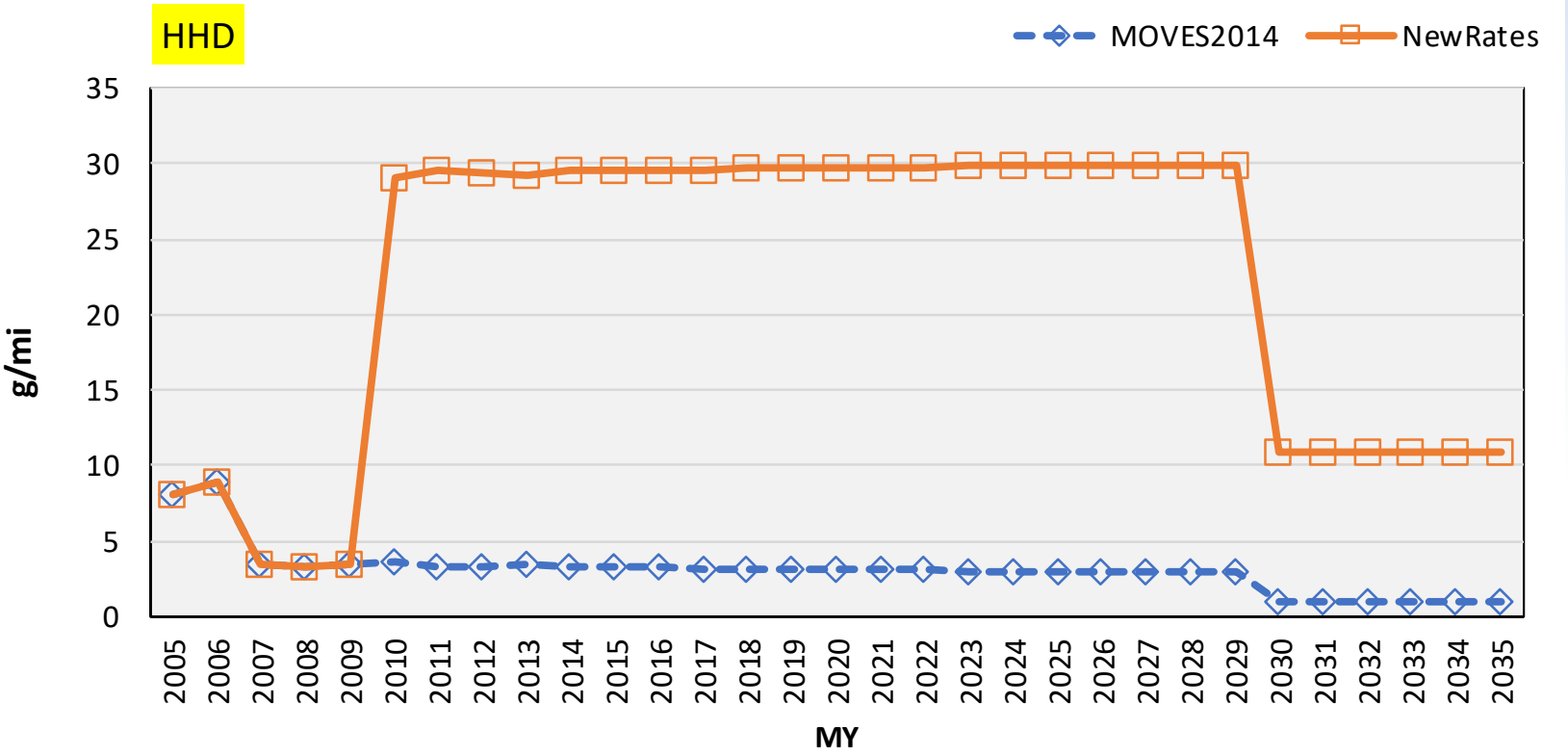
CO_2 Running Exhaust Rates (CY2035)



CO Running Exhaust Rates (CY2035)

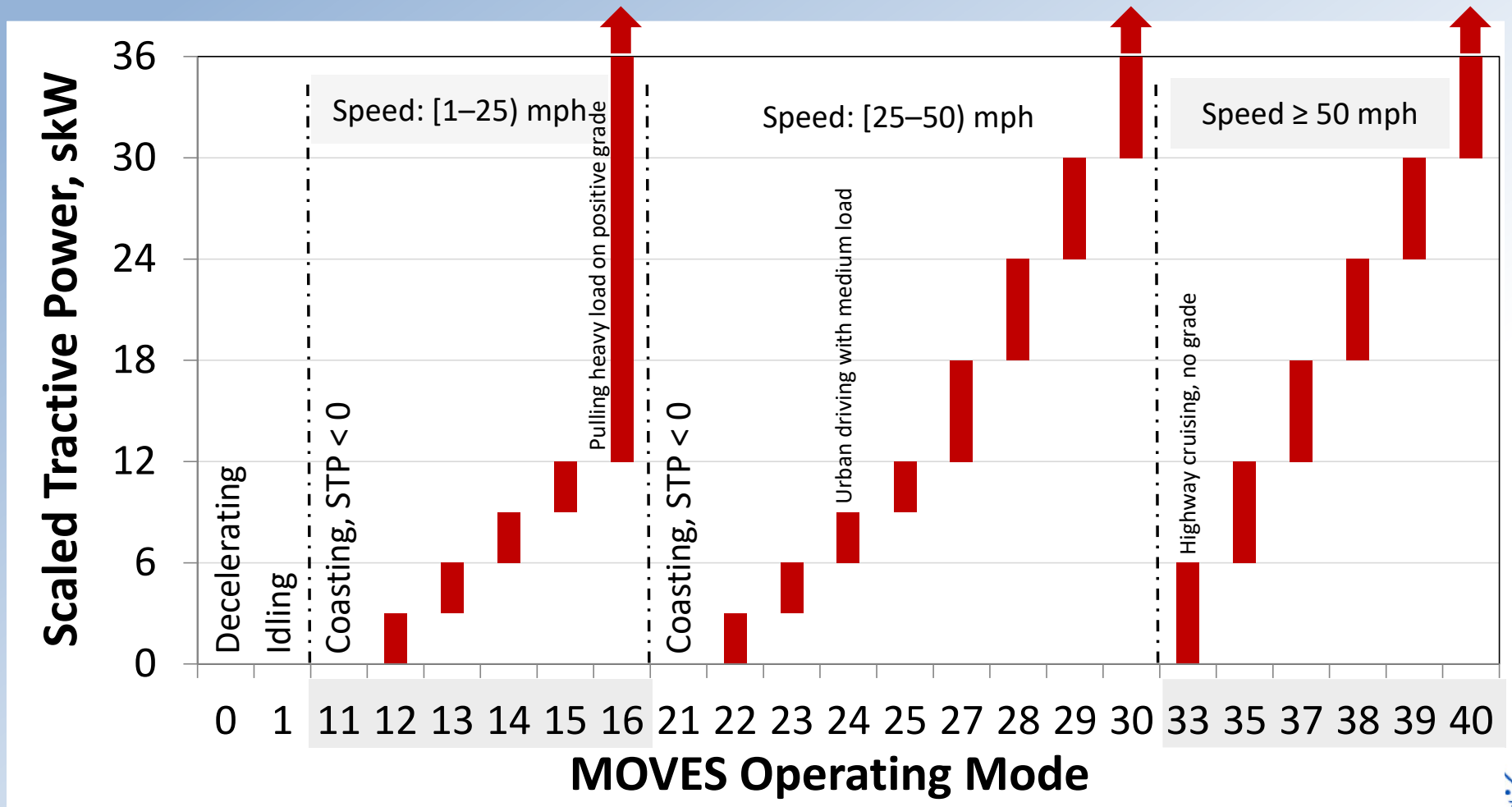


THC Running Exhaust Rates (CY2035)



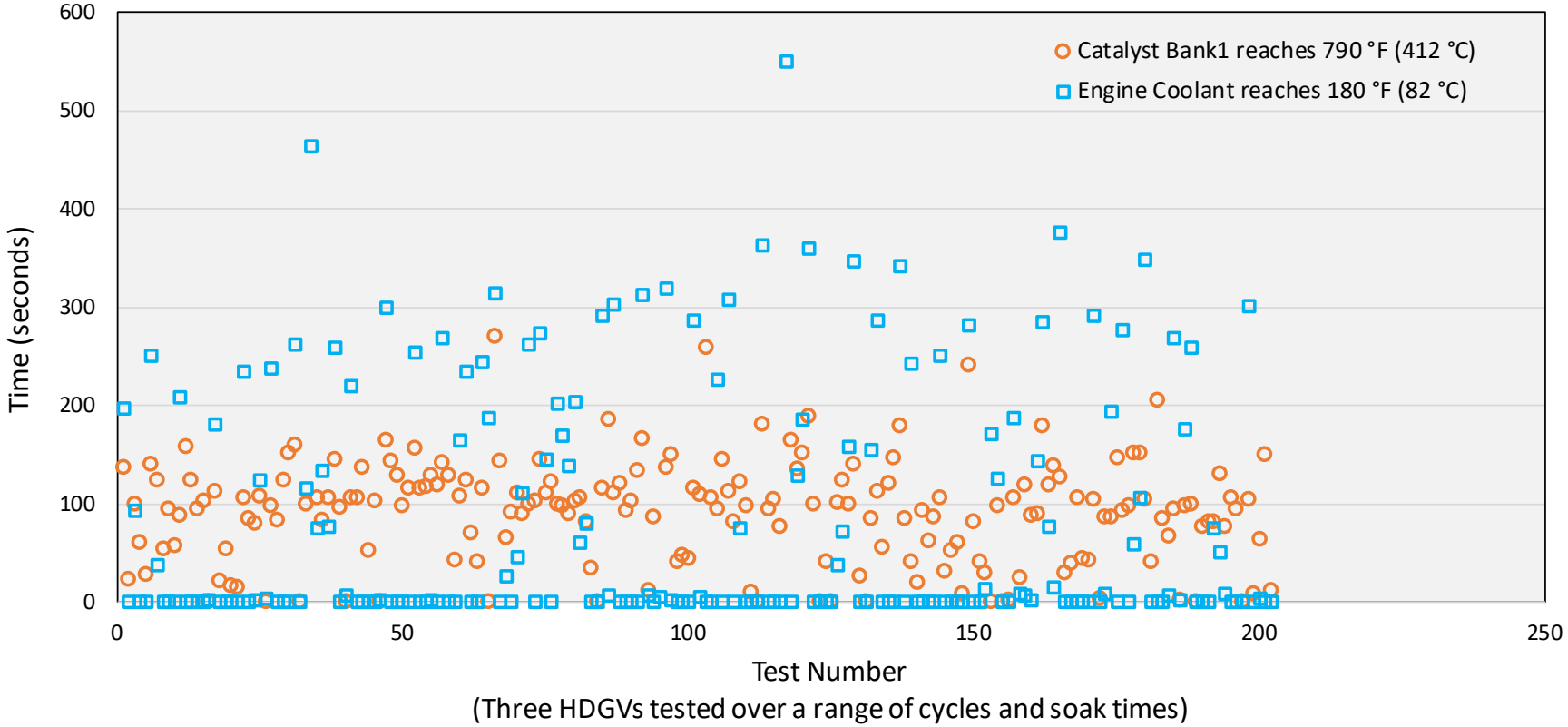
APPENDIX

MOVES Operating Modes (OpMode)



HD Gasoline: Removing the Effect of Cold Start

Criteria Selection



The on-road MHD gasoline test program included various soak periods, from no soak to overnight soak. Since the gasoline rates update is for hot-running exhaust emissions, an effort was made to remove the seconds of data associated with elevated emissions due to the soak. Two candidate criteria were tested - catalyst temperature and engine coolant temperature - to estimate time to reach “hot-running” status . After comparison, catalyst temperature was selected as a better estimator and used to removed the data before catalyst reaches 790 °F (412 °C).
Based on the catalyst temperature criteria, ~5.5% or 22,500 seconds (out of 411,600 total) were removed.

HD Gasoline: Removing the Effect of Cold Start

Results

Soak Time (min)	# of Tests	Avg. Time (sec)[1]	Avg. Grams of Pollutant Removed			
			NO_x	CO_2	CO	HC
0	109	78	0.2	356	3	0.4
3	6	42	0.02	213	1	0.03
18	6	63	0.1	265	3	0.3
30	6	91	0.8	427	9	0.8
45	8	114	1.9	493	14	1.6
75	5	122	1.8	470	16	1.8
105	7	102	2.3	463	19	1.9
180	4	107	3.0	531	22	2.7
240	2	94	1.1	424	18	1.9
360	1	1	0.00	0	0	0.00
720	48	125	2.0	662	25	3.3

[1] Average time for catalyst to reach 412 °C