MOVES
Motor Vehicle Emission Simulator

Updated emission rates for extended idle & auxiliary power units (APUs)

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Extended Idle Activity in MOVES

- Hotelling
  - Time spent in layovers between trips where the truck is used as a residence, with a stopped duration of more than one hour
- Extended idle
  - Idling that occurs during hotelling
  - Can include higher engine speed settings and use of accessories by the vehicle operator
- Auxiliary power units (APUs)
  - Optional power source (A/C, heat, and auxiliary power) during hotelling without idling the main engine
- Diesel long-haul combination trucks are only vehicle types with extended idle and APU use in MOVES

Updates to Extended Idle Emission Rates and Activity

- Extended idling activity and MY 2007+ extended idle emission rates were updated in the regulatory version of MOVES used for the final HD GHG Phase 2 rulemaking
- We propose making the same updates in the next version of MOVES
  - Additional details in USEPA (2016) in references

Hotelling Activity Operating Modes

- The assumption for the penetration of diesel and battery APUs was updated in HD GHG Phase 2 final rulemaking
- Based on:
  - Industry data
  - Projected use of APUs to meet the GHG Phase 2 standards for MY 2021 and later trucks

<table>
<tr><th></th><th colspan="2">MOVES2014</th><th colspan="2">HD GHG Phase 2</th></tr>
<tr><td>Model Years</td><td>Diesel APU Penetration</td><td>Battery APU Penetration</td><td>Diesel APU Penetration</td><td>Battery APU Penetration</td></tr>
<tr><td>2009 and earlier</td><td>0%</td><td rowspan="5">0%</td><td>0%</td><td rowspan="2">0%</td></tr>
<tr><td>2010-2020</td><td rowspan="4">30%</td><td>9%</td></tr>
<tr><td>2021-2023</td><td>30%</td><td rowspan="2">10%</td></tr>
<tr><td>2024-2026</td><td rowspan="2">40%</td></tr>
<tr><td>2027+</td><td>15%</td></tr>
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Extended Idle Emission Rate Datasets (1/2)

1. Texas Transportation Institute (TTI, 2014)
   - 15 heavy-duty diesel tractors (2005-2012 model years)
   - Tested in environmental chamber under hot and cold conditions
   - Used 'stabilized' extended idle emission rates
     - Trucks soaked overnight for 12-hours under ambient conditions, no pre-conditioning driving
     - Trucks idled for at least one hour, until emissions reached a 'stabilized' condition
     - No other auxiliary loads besides A/C or heater
     - Trucks were not commanded to be in the 'high-idle' state
     - Two of the cold tests, the trucks had high RPM (>1000 rpm) during the cold test from a 'cold ambient protection' engine control strategy

Test ID	Temperature	Relative Humidity	Auxiliary Load
Hot	100°F (37.8°C)	70%	Air conditioning
Cold	30°F (-1.1°C)	N/A	Heating System

Extended Idle Emission Rate Datasets (2/2)

2. California Air Resources Board (ARB, 2015)
   - 5 heavy-duty diesel tractors (2007 and 2010 model years)
   - Extended Idle emission rates from the 10-minute ‘Idle’ mode from the ARB HHDDT 4-mode cycle
   - Before testing the ‘Idle’ mode, the vehicle was first warmed on a pre conditioning cycle, and then soaked from 10-20 minutes
   - Testing occurred in the laboratory at moderate temperatures with no auxiliary loading

- Note: After we completed this analysis, ARB shared with us additional emissions tests they have conducted on four 2011-2014 trucks (with idling times ~ 1 hr)
  - New ARB program had similar average NOx idling emissions as the ARB, 2015 study we used
    - 20.5 g/hr (ARB, 2015)
    - 23.4 g/hr (new ARB data)

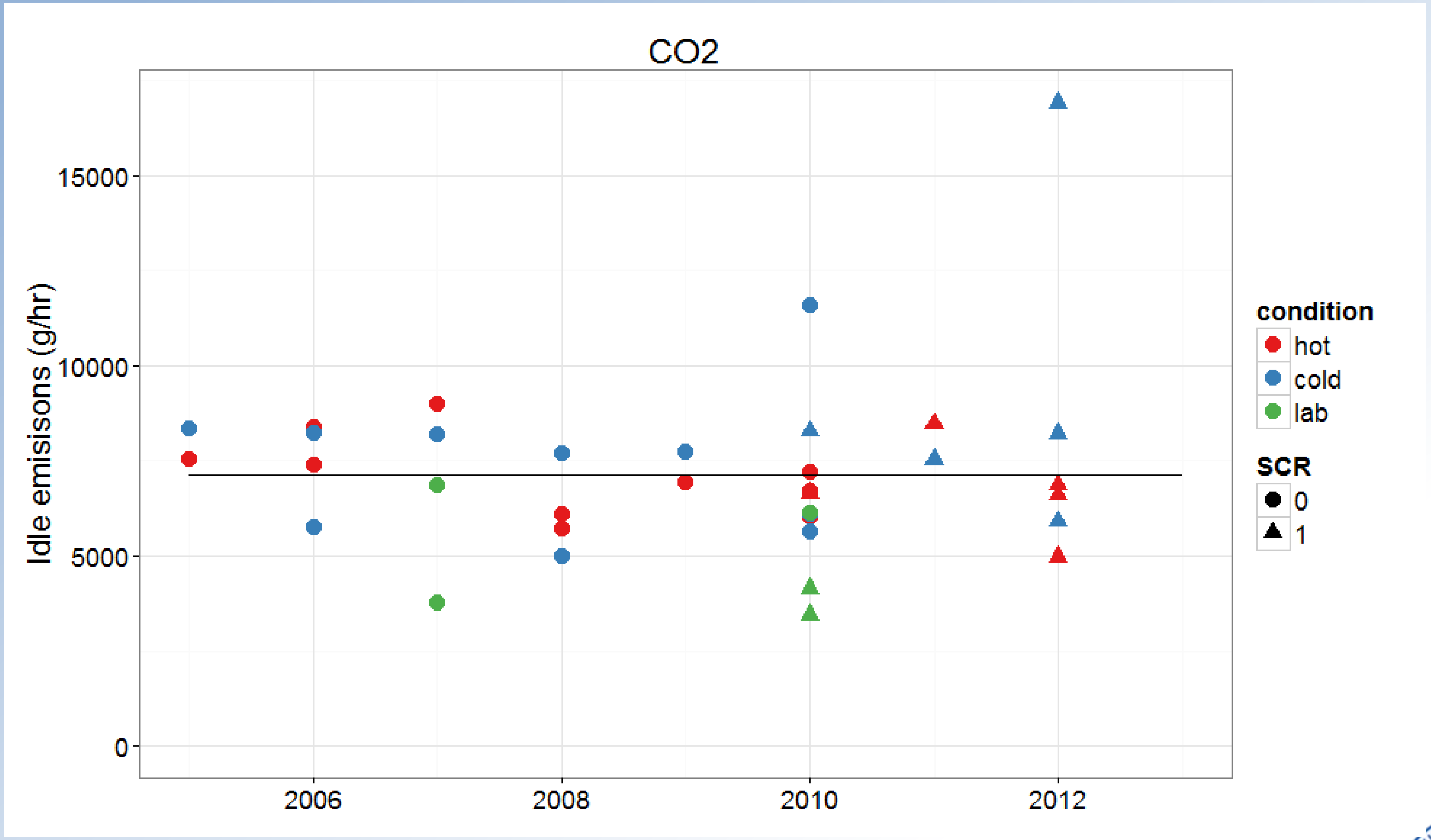
Heavy-duty trucks from the TTI and ARB studies

Study	Engine MY	Engine	Odometer	NOx cert (g/bhp-hr)	Clean Idle Certified?	Aftertreatment
TTI	2005	Caterpillar	484,550	2.4	No	OC
TTI	2006	Cummins	505,964	2.4	No	
TTI	2006	Volvo	640,341	2.4	No	
TTI	2007	Cummins	406,740	1.2	No	OC, DPF
ARB	2007	Cummins	390,000	2.2	No	OC, DPF
ARB	2007	DDC	10,700	1.2	No	OC, DPF
TTI	2008	Cummins	353,945	2.4	Yes	OC, DPF
TTI	2008	Mack	82,976	1.2	Yes	DPF
TTI	2009	Mack	96,409	1.2	Yes	OC, DPF
TTI	2010	Mack	89,469	0.2	Yes	OC, DPF, SCR
TTI	2010	Navistar	73,030	0.5	Yes	OC, DPF
TTI	2010	Navistar	57,814	0.5	Yes	OC, DPF
TTI	2010	Navistar	10,724	0.5	Yes	OC, DPF
ARB	2010	Cummins	13,500	0.35	Yes	OC, DPF, SCR
ARB	2010	Navistar	70,000	0.5	Yes	OC, DPF
ARB	2010	Volvo	68,000	0.2	Yes	OC, DPF, SCR
TTI	2011	Mack	95,169	0.2	Yes	OC, DPF, SCR
TTI	2012	Mack	6,056	0.2	Yes	OC, DPF, SCR
TTI	2012	Mack	11,989	0.2	Yes	OC, DPF, SCR
TTI	2012	Mack	25,148	0.2	Yes	OC, DPF, SCR

Data Analysis

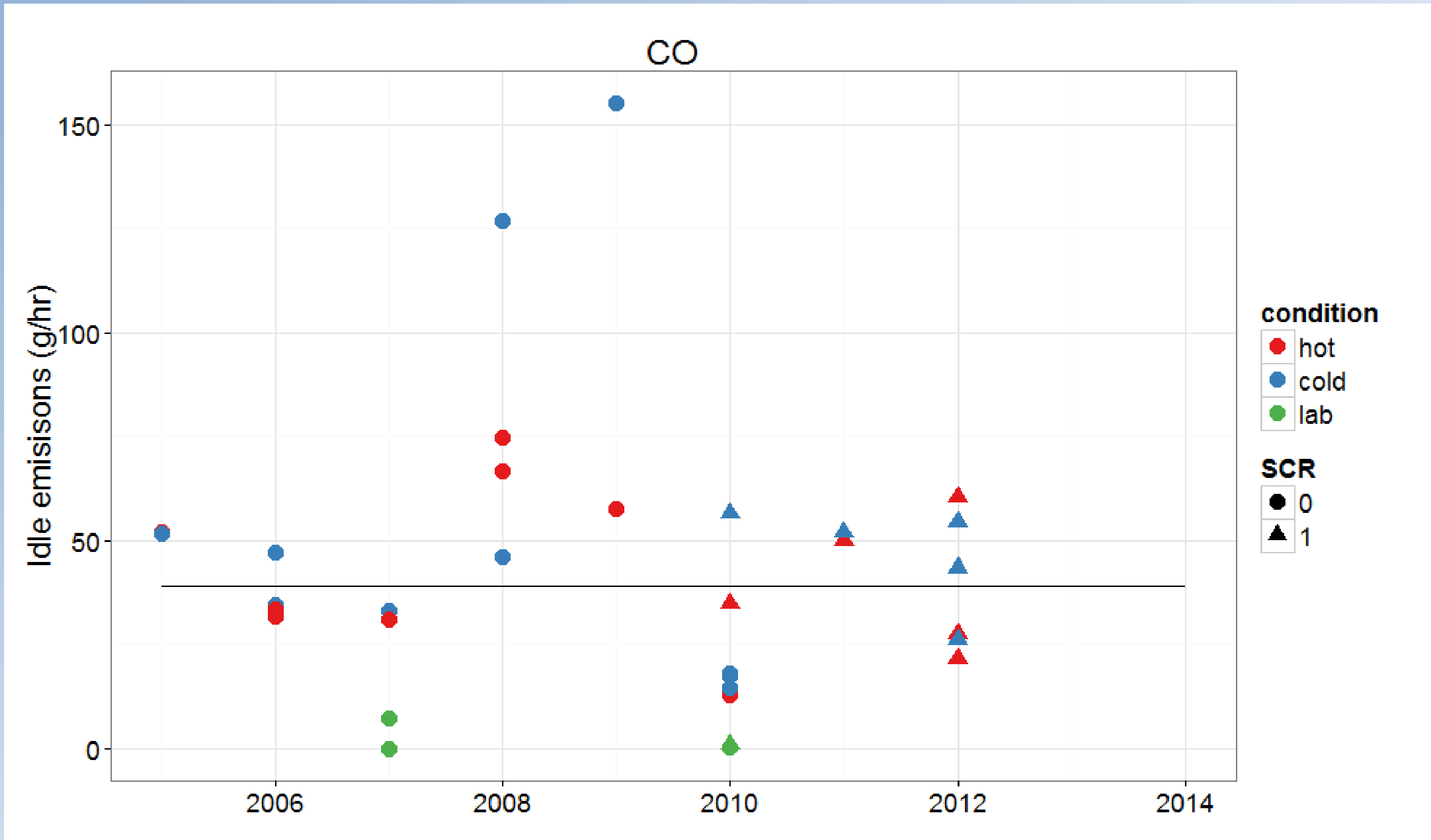
- Emission rates from all the tests are plotted by:
  - Model year
  - Test Conditions: Cold (TTI), Hot (TTI), Lab (ARB)
  - Selective Catalytic Reduction (SCR)
    - More explanatory than diesel particulate filter (DPF) or oxidation catalyst (OC)
- Compute the average, treating each test equally
    - TTI: 15 trucks X 2 conditions = 30 tests
    - ARB: 5 trucks X 1 condition = 5 tests
- Average weighted significantly towards the TTI tests
  - We believe the TTI tests to be more representative of real-world extended idle conditions in the nation, compared to ARB tests
- Compute separate averages by model year ranges where trend is evident in data

CO2 Extended Idle Emission Rates



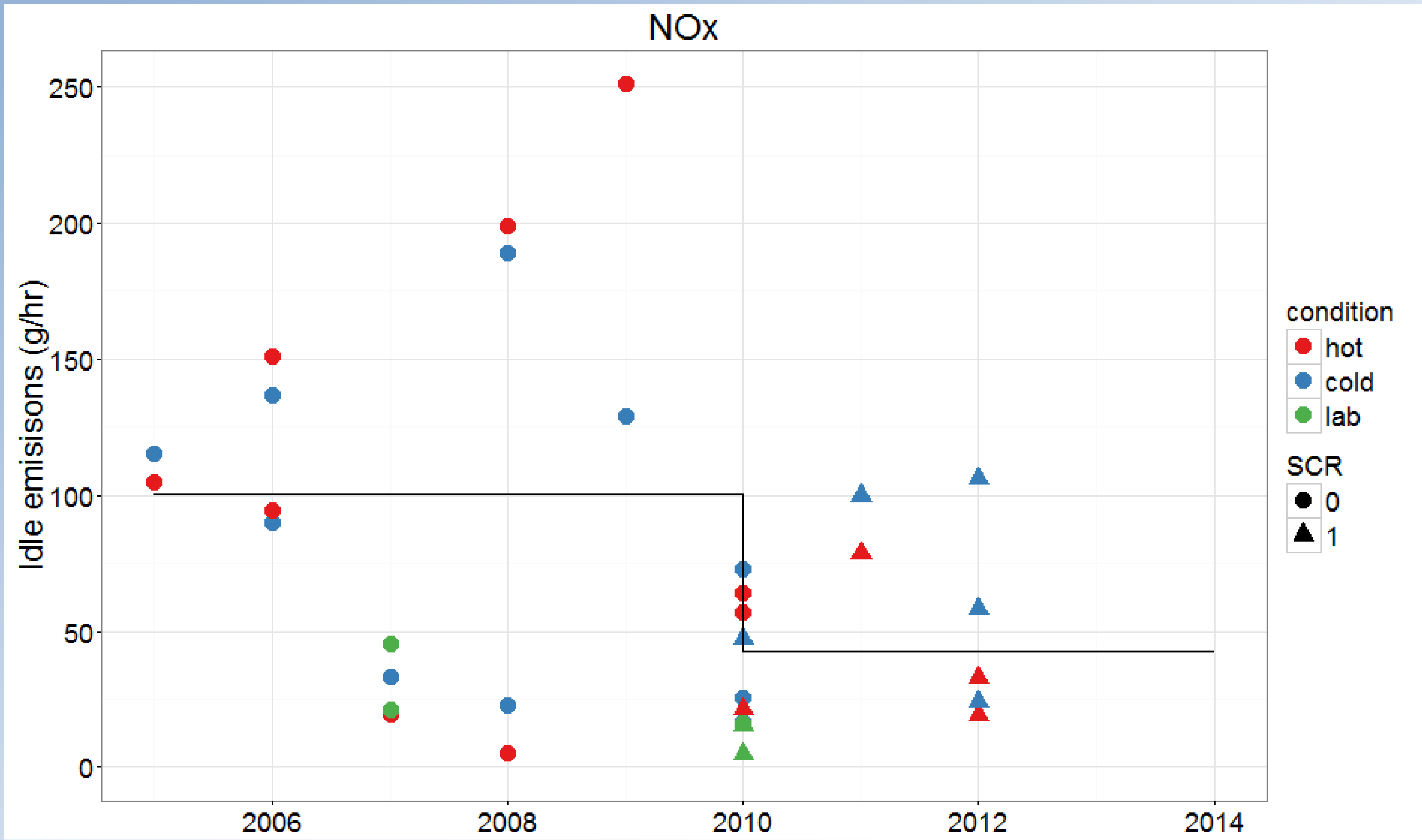
Proposal: Use single average (7,151 g/hr) for all 2007+ trucks

CO Extended Idle Emission Rates



Proposal: Use single average (39.3 g/hr) for all 2007+ trucks

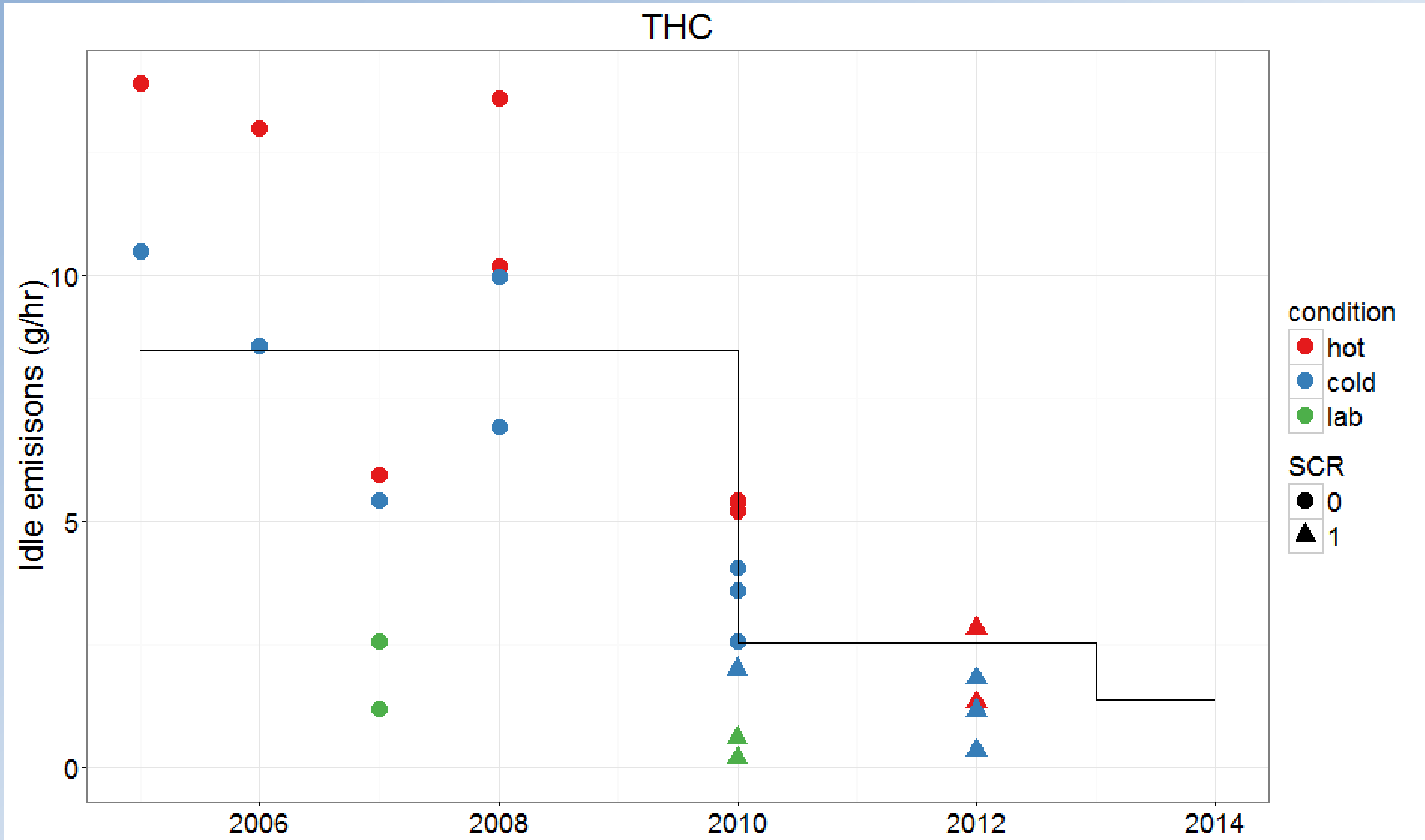
NOx Extended Idle Emission Rates



Proposal: Two groups: 2007-2009 (100.4 g/hr) and 2010+ (42.6 g/hr)

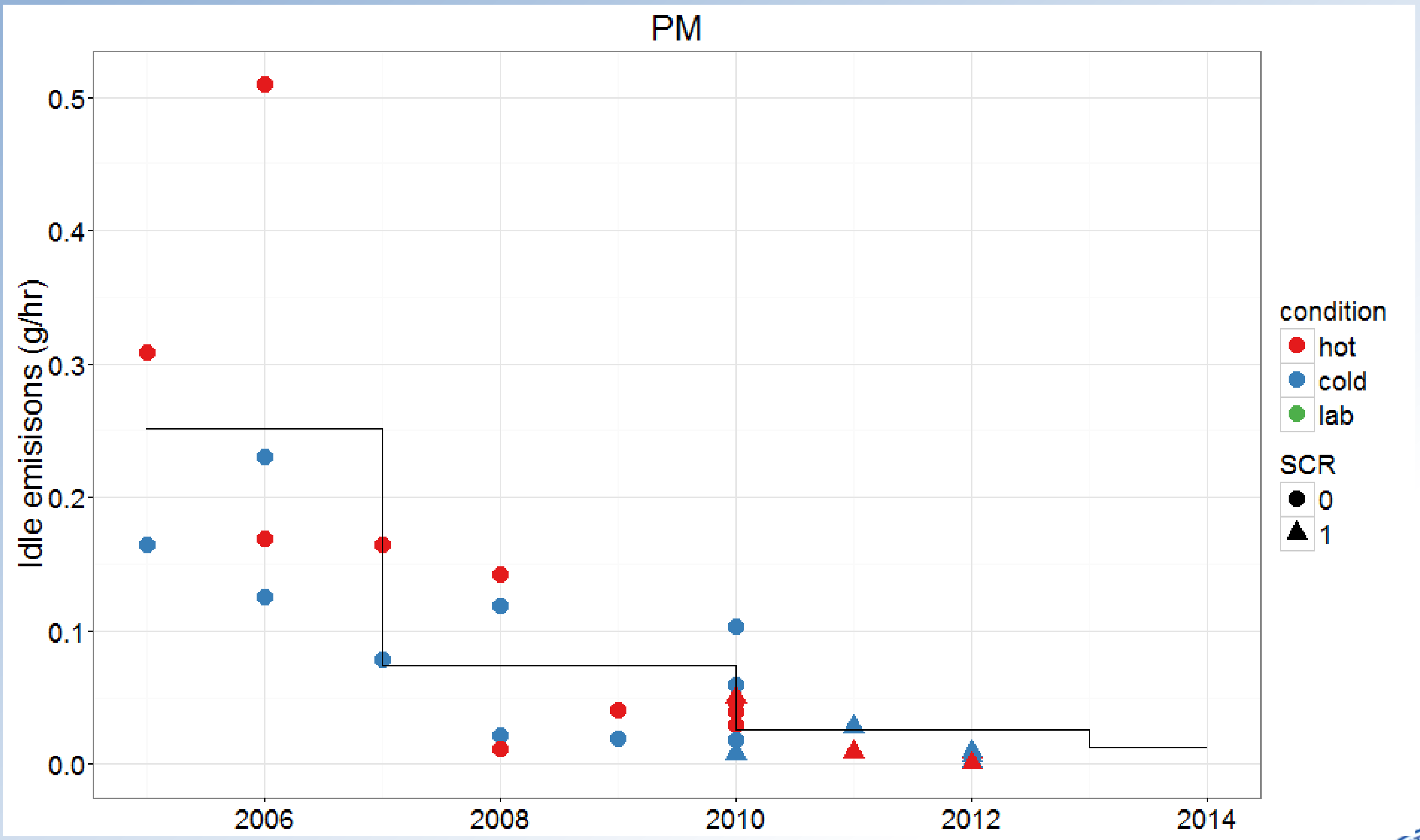
- 2010 and later trucks are certified to lower standards
- Average of 2010+ trucks are lower than the pre-2010 emission rates

THC Extended Idle Emission Rates



Proposal: Three groups: 2007-2009, 2010-2012, 2013+ (SCR only)

PM2.5 Extended Idle Emission Rates



Proposal: Four groups: 2005-2006, 2007-2009, 2010-2012, 2013+ (SCR only)

PM2.5 Extended Idle Emission Rates

- Elemental carbon to PM2.5 fraction (EC/PM) assumed for extended idling

Model Year Group	EC/PM	Source
Pre-2007	0.26	MOVES2014
2007-2009	0.10	ACES Phase I[a]
2010+	0.16	ACES Phase II[b]

Advanced Collaborative Emissions Study (ACES)

[a]Khalek, Imad, Thomas L Bougher and Patrick M. Merritt. *Phase 1 of the Advanced Collaborative Emissions Study (ACES)*. SwRI Project No. 03.13062. Southwest Research Institute, San Antonio, TX; Coordinating Research Council (CRC), Alpharetta, GA; Health Effects Institute, Boston, MA. June 2009. http://www.crcao.org/reports/recentstudies2009/ACES%20Phase%201/ACES%20Phase1%20Final%20Report%2015JUN2009.pdf

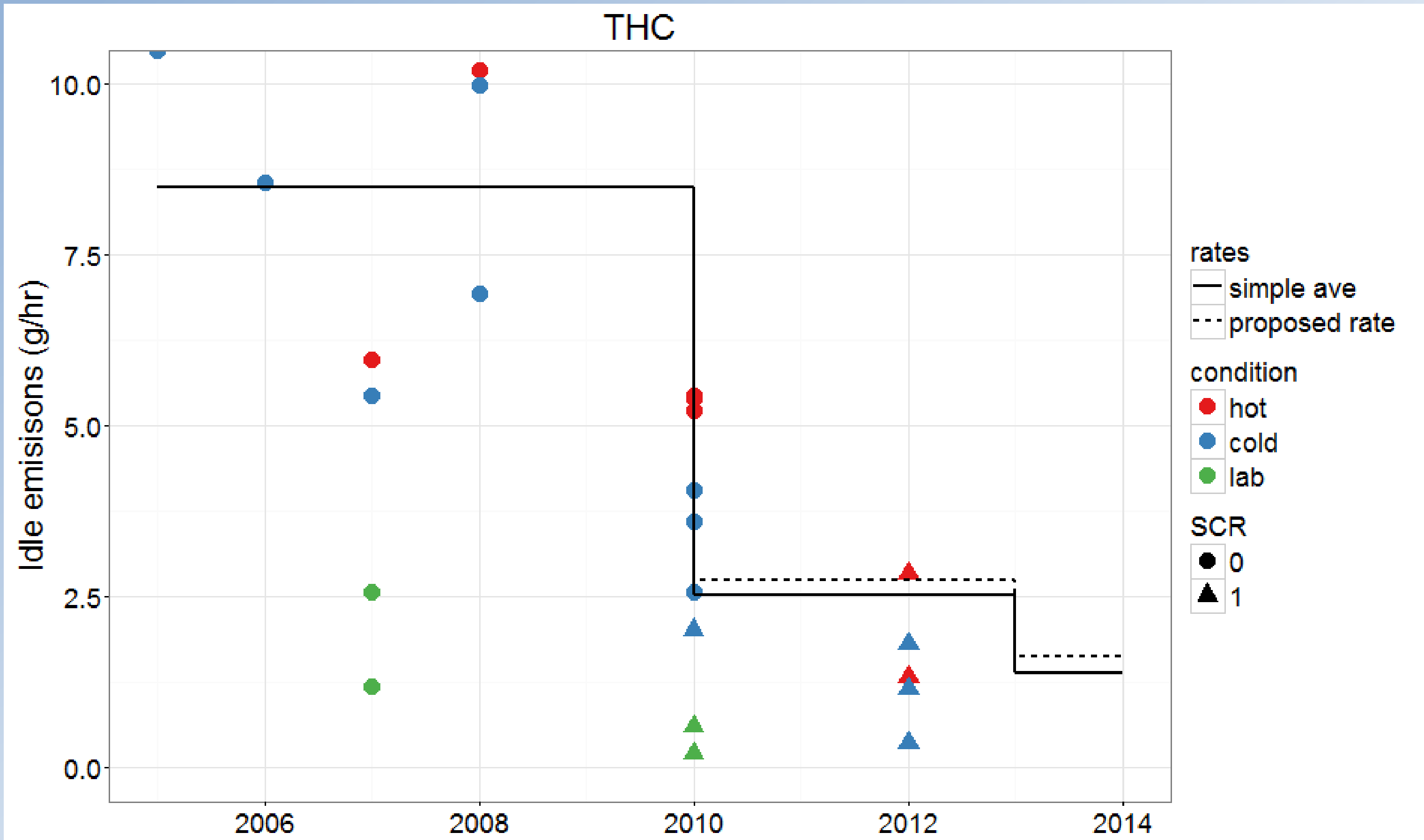
[b]Khalek, I. A., M. G. Blanks, P. M. Merritt and B. Zielinska (2015). Regulated and unregulated emissions from modern 2010 emissions-compliant heavy-duty on-highway diesel engines. Journal of the Air & Waste Management Association, 65 (8), 987-1001. DOI: 10.1080/10962247.2015.1051606.

DPF Deterioration

- We estimated deterioration of emissions in calculating the THC and PM2.5 emission rates for 2007-2009, 2010-2012, and 2013+ model years
  - THC and PM2.5 extended idle emissions demonstrated the largest reductions in 2007 and 2010 and later trucks
  - Believed to be due to continued effectiveness of the diesel particulate filter (DPF) under extended idle conditions
- We estimated the emissions deterioration due to DPF failure
  - We assume that deterioration of properly functioning engine is small compared to the increase in emissions to component failure (tampering and mal-maintenance)
- Assumed DPF failure rate[1] by the end of the engine useful life
  - 10% in 2007-2009 MY
  - 5% for 2010+ MY
- We incorporated the impact of age & deterioration into a single emission rate for extended idle
  - Unlike running and start emission rates, MOVES does not have separate extended idle emission rates by different age
  - 2005-2006 average emission rates used to represent the ‘failed’ DPF emission rates
  - Assume long-haul combination trucks have a lifetime of 1,530,000 miles
  - Assume failures occur after the end of the engine useful life (435,000 miles)

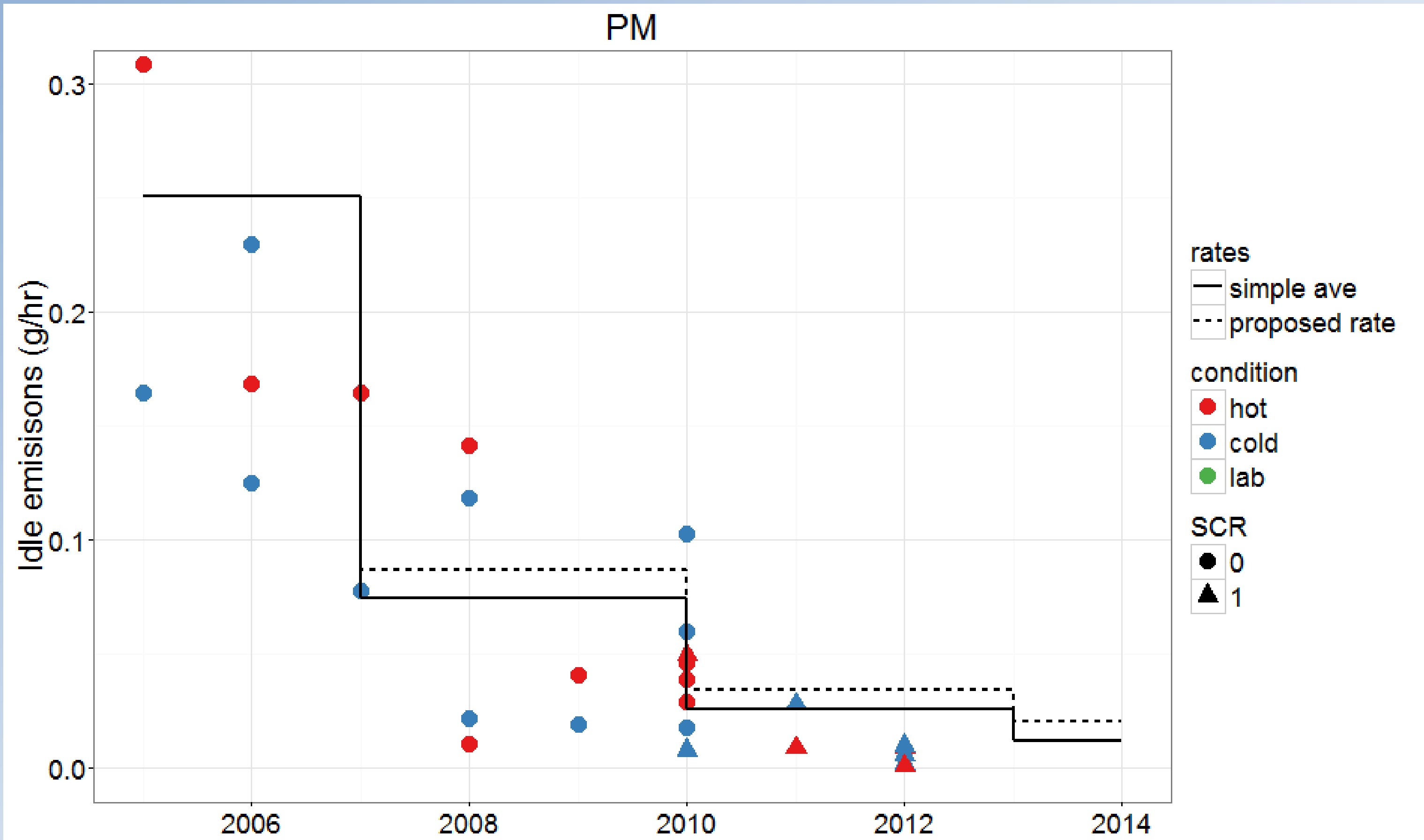
[1]Based on correspondence with ARB and supported with review of data sources listed in the Appendix

Proposed THC Extended Idle Emission Rates



Including deterioration assumption increases THC emissions in the proposed rates by 8% in 2010-2012, and 18% in 2013+

Proposed PM2.5 Extended Idle Emission Rates



Including deterioration assumption increases PM2.5 emissions in the proposed rates by 17% in 2007-2009, 31% in 2010-2012 and 69% in 2013+

Proposed Extended Idle Emission Rates

Model Year Group	CO_2 (g/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	$PM_{2.5}$ (g/hr)	EC (g/hr)	nonEC (g/hr)	EC/PM
2007-2009	7151	39.3	100.5	8.5	0.087	0.012	0.076	0.13
2010-2012	7151	39.3	42.6	2.7	0.034	0.006	0.028	0.18
2013+	7151	39.3	42.6	1.6	0.021	0.004	0.017	0.20

- Applied to both heavy-heavy duty (HHD) and medium heavy-duty (MHD) long-haul diesel trucks

Next Steps: Extended Idle

- We could revise analysis to include additional data sets collected on extended idling trucks
  - Replacing the previous ARB data with new ARB data would have small impact on NOx emission rates
  - Revising methodology (e.g. place additional “weight” on the new ARB data), would have a larger impact on the NOx emission rates

Auxiliary Power Unit Emission Rates

- Emissions data are more limited
- MOVES2014 used an APU emission rate taken from the NONROAD model for small Tier 4 compliant nonroad diesel engine

APU Emission Rate Datasets

1. TTI (2014)
   – One diesel APU system (APU ID 1) with and without diesel particulate filter
     • During testing, the second APU system was found defective and results were removed from analysis
   – Tested in environmental chamber under hot and cold conditions

Test ID	Temperature
Hot	100˚ F
Cold	0˚ F

2. Frey and Kuo (2009)
   – 2 APU systems (APU ID 2 and APU ID 3) tested under a range of electric output loads
   – Measured APU electric loads from a fleet of 20 long-haul trucks for over a year
   – Used relationship between energy demand of the APU to estimate average APU emission rates for mild and high temperature scenario

Scenario	Temperature
Hot	100+˚F
Mild	50-68˚ F

APU System Information

Study	APU ID	Engine Model	Engine Year	Displacement (L)	Power (HP/kW)	Tier
TTI 2014	1	Kubota Z482	2011	0.48	14.2/11	Tier 4
Frey and Kuo 2009	2	Kubota Z482	2006	0.48	10.9/8.1	Tier 2
	3	Kubota Z482	2006	0.48	10.9/8.1	Tier 2

- Secondary datasets: TTI (2012) and Storey et al. (2013)
  - Tested at hot and cold conditions
  - These studies had incomplete information regarding the APU systems
  - Used as comparative datasets

Observations on the APU emission rates

- Large impact on PM emissions with use of DPF for APU 1
- No notable emission effects between:
  - Emission standard tier (Tier 2 vs Tier 4)
  - Engine model year
  - Gaseous emission rates with DPF
- Ambient temperature
  - Larger fuel use, NOx, and PM at cold and hot conditions compared to ambient conditions (APU 2 and 3)
  - No consistent trends with respect criteria pollutants (CO, NOx, THC, and PM) between cold and hot conditions
- Results from the primary dataset are in the range of the secondary (comparative) dataset
  - Data shown in appendix

Average APU Emission Rates

- First, we calculated the non-DPF equipped APU emission rates from Study 1 and 2 by the ambient conditions (cold, hot, and mild)

Ambient condition	Temperature (˚F)	CO_2 (g/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	PM (g/hr)	Fuel (gal/hr)
Cold	0	4340	7.27	18.59	1.35	0.96	0.43
Hot	100	3440	8.80	18.41	1.28	1.02	0.34
Mild	60	2750	13.80	9.85	1.35	0.90	0.28

- Next, we calculated the average emission rate by "weighting" each ambient condition scenario equally:

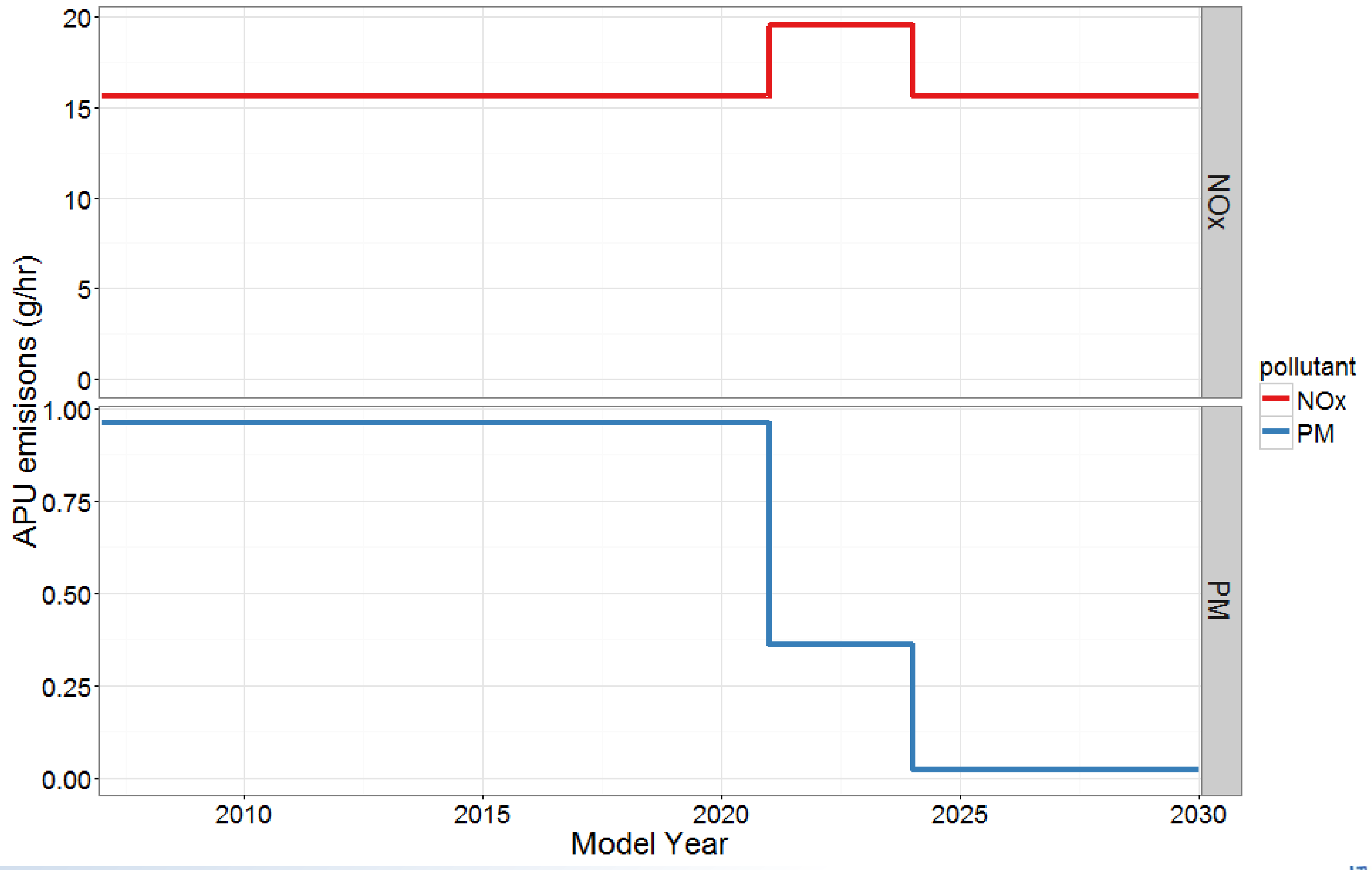
CO_2 (g/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	PM (g/hr)	EC (g/hr)	NonEC (g/hr)	EC/PM [1]	Fuel (gal/hr)
3510	10.0	15.6	1.3	0.96	0.13	0.83	0.14	0.35

[1]The EC/PM fraction was measured in the TTI (2014) study

Proposed APU Emission Rates

- HD GHG2 rule includes new PM standards for APUs in 2021 and 2024
  - These standards replace the current Tier 4 nonroad standards
  - MOVES will incorporate the emission rates used in the rulemaking
- 2021-2023 APUs
  - PM emission rates will decrease by 63%
    - The ratio between the Tier 4 and 2021 APU PM standards
  - NOx emission rates will increase by 25%
    - Feasible for manufacturers to meet the 2021 standard by engine calibration, without the use of a DPF, which will cause a NOx increase
    - 25% NOx increase was based on evaluating emissions certification data of APU diesel engines that meet and do not meet the proposed 2021 PM standard
  - No impact on other pollutants (HC, CO, CO2)
- 2024+ APUs
  - Use average emission rates from the data for HC, CO, NOx, and CO2
  - Use the same PM emission rates as 2013+ extended idling (0.025 g/ hr)
    - Anticipate that the PM standards will be achieved using DPFs (no NOx increase)
    - 2013+ extended idle emission rate is very similar to the average emission rate from the DPF-equipped APU 1 (0.021 g/hr)
    - We are using the same PM emission rate for DPF equipped APU and extended idling trucks because we didn't think we have sufficient data to determine a difference

Proposed APU Emission Rates



Proposed APU Emission Rates

Model Year	CO_2 (g/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	PM (g/hr)	EC (g/hr)	NonEC (g/hr)	EC/PM	Fuel (gal/hr)
2010-2020	3510	10.0	15.6	1.3	0.96	0.13	0.83	0.14	0.35
2021-2023	3510	10.0	19.5	1.3	0.36	0.05	0.31	0.14	0.35
2024-2050	3510	10.0	15.6	1.3	0.02	0.002	0.019	0.073[1]	0.35

- [1]We used the EC/PM fraction from the TTI 2014 from the DPF-equipped APU 1

Summary and Feedback

- Due to competing priorities, we are not planning on conducting new analysis on the extended idle and APU emission rates for the next version of MOVES
- We are also not currently planning on revisiting the pre-2007 extended idling rates in the next version of MOVES
- Our recommendation is to devote our resources to address other improvements in modeling heavy-duty trucks in MOVES
  - E.g incorporating start emissions from SCR-equipped trucks
- Comments?

References

1. USEPA (2016). *Updates to MOVES for Emissions Analysis of Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2 FRM*. Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 - Docket EPA-HQ-OAR-2014-0827. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 8, 2016. www.regulations.gov.

2. Farzaneh, M., J. Zietsman, D.-W. Lee, J. Johnson, N. Wood, T. Ramani and C. Gu (2014). *TEXAS-SPECIFIC DRIVE CYCLES AND IDLE EMISSIONS RATES FOR USING WITH EPA'S MOVES MODEL*. FHWA/TX-14/0-6629-1. Texas A&M Transportation Institute. May, 2014. http://tti.tamu.edu/documents/0-6629-1.pdf.

3. ARB (2015). *EMFAC2014 Volume III - Technical Documentation*. California Environmental Protection Agency, Air Resources Board, Mobile Source Analysis Branch, Air Quality Planning & Science Division. May 12, 2015.

4. Zietsman, J. and J. Johnson (2014). *Auxiliary Power Unit Testing for SmartWay Idle Reduction Verification. DRAFT FOR REVIEW*. EP-11-H-000527, Auxiliary Power Unit Testing for SmartWay Idle Reduction Verification. Texas A&M Transportation Institute. August, 2014.

5. Frey, H. C. and P.-Y. Kuo (2009). Real-World Energy Use and Emission Rates for Idling Long-Haul Trucks and Selected Idle Reduction Technologies. *Journal of the Air & Waste Management Association,* 59 (7), 857-864. DOI: 10.3155/1047-3289.59.7.857.

6. TTI (2012). *Development of a NOx Verification Protocol and Actual Testing of Onboard Idle Reduction Technologies*. New Technology Research and Development Program. Texas Transportation Institute. Revised: January 2012.

7. Storey, J. M., J. F. Thomas, S. A. Lewis, T. Q. Dam, K. D. Edwards, G. LDeVault and D. J. Retrossa (2003). *Particulate matter and aldehyde emissions from idling heavy-duty diesel trucks*. SAE Technical Paper.

EXTRA SLIDES

References used to support DPF failure rate assumptions

Study	Relevant Information
US EPA (2014)	7% of 2007+ trucks in MOVES are assumed to either have a PM filter leak or have the PM filter disabled.
Preble et al. (2015)	20% of trucks produce 80% of black carbon (BC) emissions from Port of Oakland 2013 truck fleet, where 99% of the trucks are equipped with DPFs
Bishop et al. (2014)	3% of 2007+ trucks at Port of LA PM emissions 3× the standard. 9% of 2008+ trucks at Cottonwood site have PM emissions 3× the standard
CARB (2015)	35% to 4% of trucks submitted warranty claims related to the PM filter between 2007 and 2011
CARB (2015)	8% of trucks were classified as high emitters (emitting over 5% opacity) from a sample of >1,800 trucks test in the snap-idle acceleration test by CARB, about ~1/2 equipped with DPFs
CARB correspondence (2016)	~10% of 2007-2009 DPFs and ~5% of 2010+ DPFs to fail in real-world, based on their observations from warranty claims, snap-idle acceleration opacity tests, and their review of the Bishop et al. (2014)[26] and Preble et al. (2015)[25] studies.

In-Use APU Emission Rates

APU ID	CO_2 (g/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	PM (g/hr)	Fuel (gal/hr)	Ambient condition	Temperature (˚F)	DPF
1	4340	7.3	18.6	1.35	0.96	0.43	Cold	0	0
1	4270	5.1	20.0	0.73	0.02	0.43	Cold	0	1
1	2820	6.2	23.5	1.35	0.56	0.29	Hot	100	0
1	2800	5.2	23.7	1.52	0.03	0.28	Hot	100	1
2	3000	20.4	6.3	1.4	1	0.3	Mild	60[a]	0
3	2500	7.2	13.4	1.3	0.8	0.25	Mild	60	0
2	3900	13.9	11.5	1.5	1.3	0.38	Hot	100	0
3	3600	6.3	20.2	1	1.2	0.36	Hot	100	0
4	3100	5.8	19	1.3	1.23	0.3	Hot	100	0
5	3600	7.3	24	0.8	0.58	0.35	Hot	100	0
4	4000	3.9	22	1.2	0.75	0.39	Cold	0	0
5	2800	24	14	2.4	0.98	0.28	Cold	0	0
6	2146	25	8.7	7.8	0.48	0.22	Cold	0	0
6	2351	10.8	11.4	4.2	1.00	0.24	Hot	90	0

[a] Frey and Kuo 2009 report the mild condition for auxiliary loads on the trucks is for ambient temperatures ranging from 10-20˚C (50-68˚F),

Emission Standards that pertain to APU systems

Emission Standard	CO	NMHC + NOx	PM
	g/kW-hr (g/hp-hr)	g/kW-hr (g/hp-hr)	g/kW-hr (g/hp-hr)
Tier 2 2005-2007	6.6 (4.9)	7.5 (5.6)	0.8 (0.6)
Tier 4 2008-2020	6.6 (4.9)	7.5 (5.6)	0.40 (0.30)
APU 2021-2023			0.15 (0.11)
APU 2024+			0.02 (0.015)