MOVES

Motor Vehicle Emission Simulator

Light-Duty PM Emission Rates Update

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MOVES Review Work Group

Background

The base emission rates for particulate matter (PM) in MOVES2014 are derived from the Kansas City study from 2004/2005

- No Tier 2 vehicles were yet available for the KC study
- All vehicles tested were port fuel injected (PFI)
- MOVES2014 Tier 2 and Tier 3 rates were projected from the certification standards
- Temperature and fuel effects on PM have been updated using more recent studies

Since the Kansas City study:

- SFTP and CAP2000 certification requirements were fully implemented
- Tier 2 standards have phased in, and we now have PM data for Tier 2 vehicles
- Tier 3 standards begin to phase in this year
- Roughly 50% of gasoline light-duty vehicles purchased in 2015 use gasoline direct injection (GDI)

Proposed updates

This proposed emission rate update for the next public version of MOVES addresses:

- Start and running exhaust emissions for Tier 2 and later vehicles (MY 2004+)
- The effect of GDI engines on elemental and non-elemental carbon PM
- Temperature effects on running PM emissions (all model years)

Datasets analyzed

- Aggregated 6 studies into a common format.
- Dataset includes:
  - 1307 measurements,
  - 102 unique vehicles (14 GDI)
  - 32 models (13 GDI)
  - 31 fuels

Study Name	Vehicles
EPA Tier 2 sulfur[1]	72 in-use Tier 2 PFI
EPAct Phase 1 FTP[2]	6 Tier 2 PFI
EPAct Phase 3[3]	14 Tier 2 PFI
EPAct Phase 4[4]	5 Tier 2 PFI
CARB GDI[5]	6 GDI
EPA CFI Program[6]	8 GDI

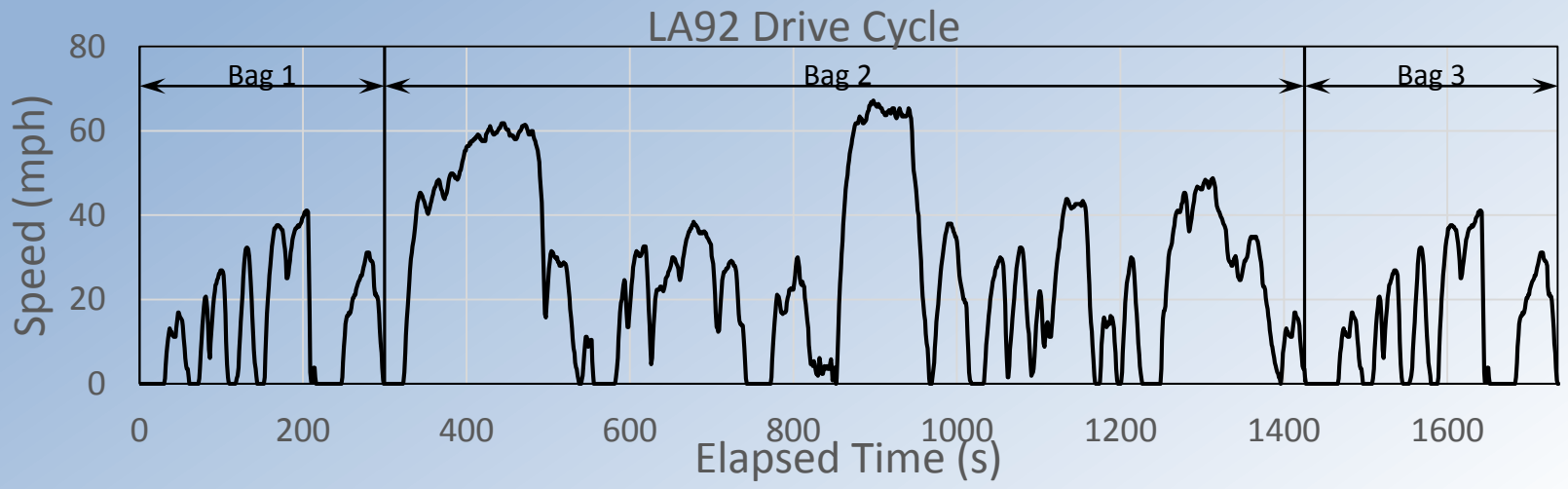
1. EPA, The Effects of Ultra-Low Sulfur Gasoline on Emissions from Tier 2 Vehicles in the In-Use Fleet Final Report, EPA-420-R-14-002, March 2014
2. EPA, EPAct Fuel Effects Study Pilot Phases 1 and 2. Memorandum to the Tier 3 Docket. U.S. EPA, 2013 Available at: http://www.regulations.gov. Docket ID: EPA-HQ-OAR-2011-0135
3. EPA, Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier-2 Standards, Analysis of Data from EPAct Phase 3, EPA-420-R-13-002, April 2013
4. NREL, Effect of Gasoline Properties on Exhaust Emissions from Tier 2 Light-Duty Vehicles – Final report: Phases 4,5, & 6, Subcontract Report NREL/SR-5400-61099, June 2014
5. California Air Resources Board, Technical Support Document: An Update on the Measurement of PM Emissions at LEV III Levels, October 2015
6. EPA, Tier 3 Certification Fuel Impacts Test Program, 2016

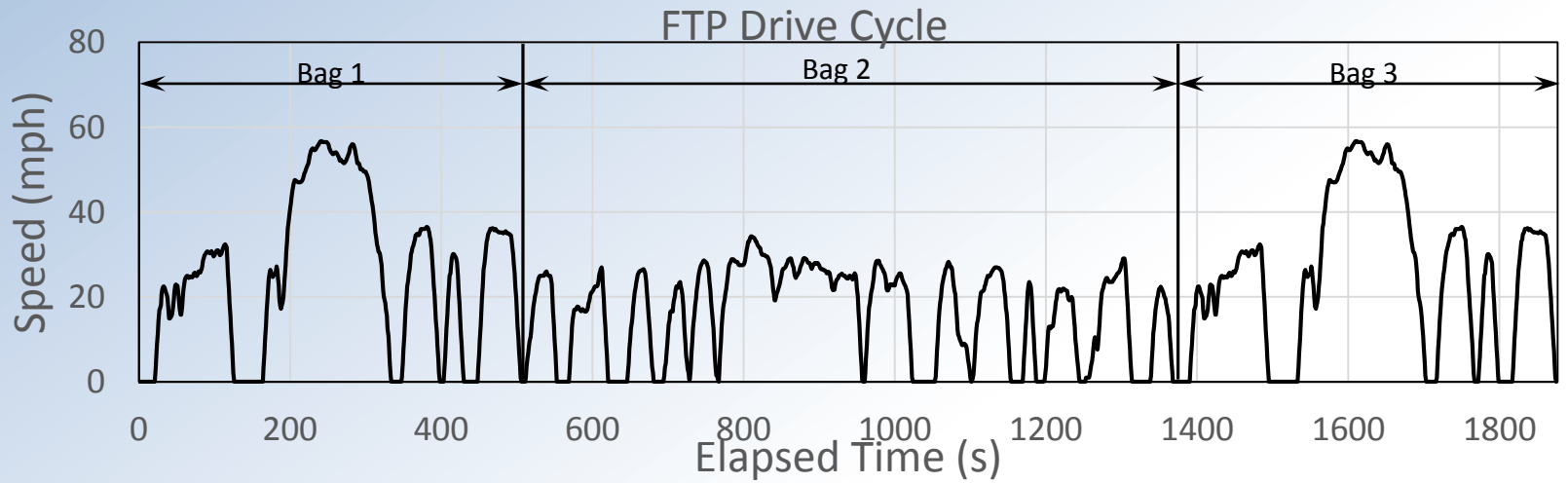
Considered variables

The following fields were used for analyzing the merged datasets:

- Test program information
  - Test program, Test number, Test date, Drive cycle
- Vehicle information
  - Vehicle ID, Make, Model, Model year, RegClass, Injection type
- Fuel information
  - Fuel ID, Ethanol (vol%), T50, T90, RVP, Aromatics (vol%), Sulfur content (ppm)
- Test data (for each bag)
  - Test cell temperature, distance driven, PM weight

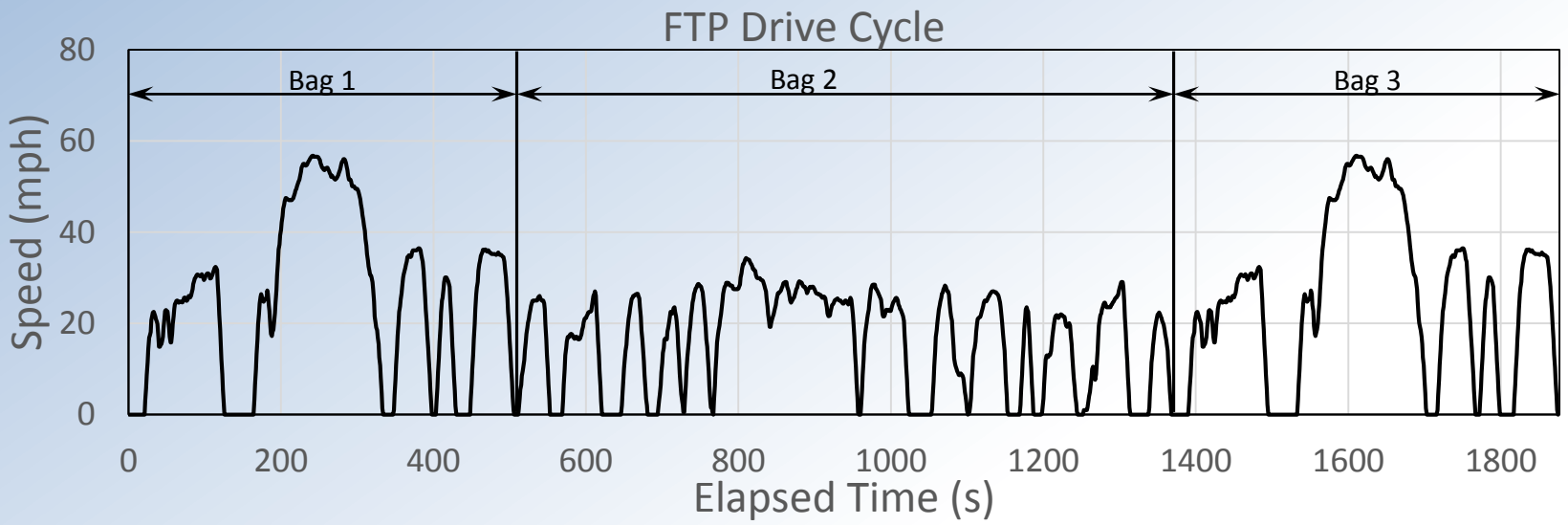
Drive cycles





Measured emission rates

- PM filters are collected and weighed for each Bag of the test cycle
- Bag 1 captures the engine warm-up period (cold starts)
- Bag 2 captures running emissions
- Bag 3 replicates the drive trace of Bag 1 with a warmed-up engine (hot starts)
- Start emissions are the difference in mass between Bag 1 and Bag 3



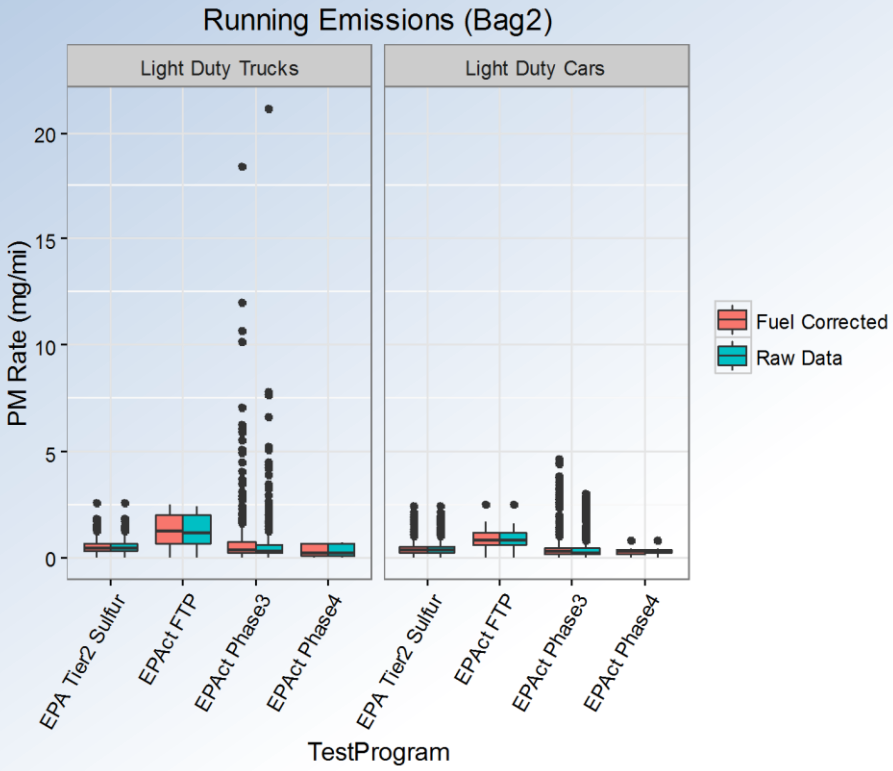
Data filters applied

- Removed all data points that were excluded from their original studies for having experimental errors
- Only used tests with complete 3-bag FTP or LA92 test cycles (no missing bags)
- Test cell temperatures between 20°C and 25°C
- Bag1, Bag2, and Bag3 mass < 80 mg/mi
  - removes 2 outliers, more than double the next highest bag1 rate

Fuel corrections

- **31 fuels were used between the 6 studies being analyzed**
- To compare test data across fuel types, the emission rates were normalized to a standard fuel using the EPAct Model Calculator:

  https://www.epa.gov/sites/production/files/2016-05/epact-models-calculator-may-2013.xlsx
- This is the same calculation that MOVES currently uses for fuel corrections to emission rates
- The standard fuel parameters were selected to match the Tier 2 cert fuel used in the Tier 2 sulfur study

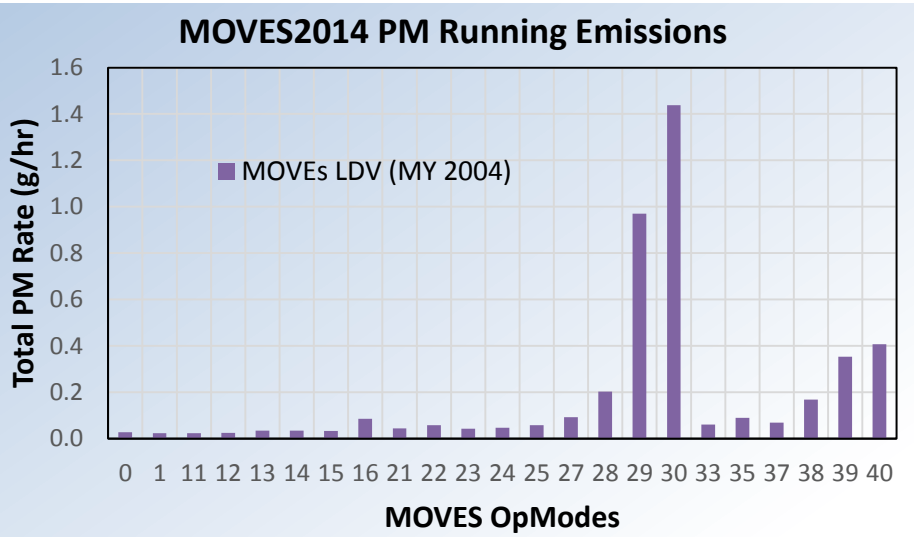


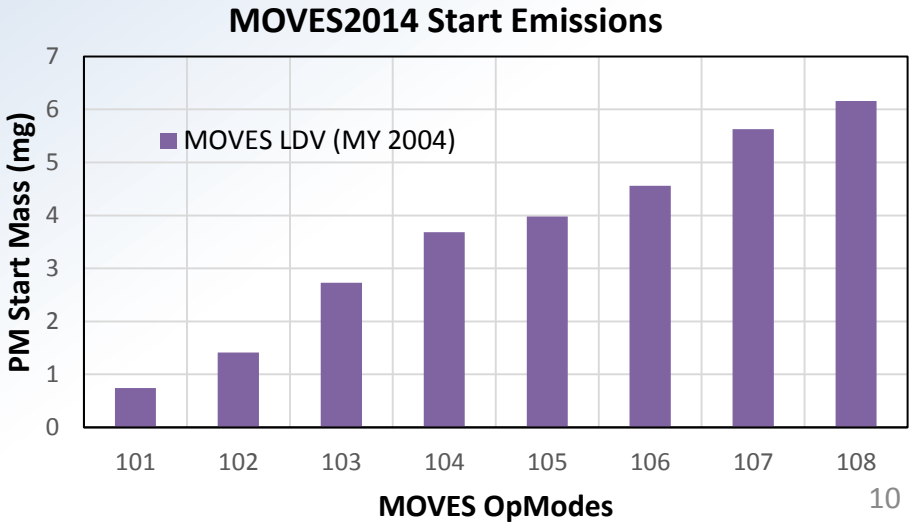
Tier 2 cert fuel parameters

Ethanol (vol%)	Aromatics (vol%)	RVP (PSI)	T50 (deg. F)	T90 (deg. F)
0.1	30.6	8.93	223.1	315.2

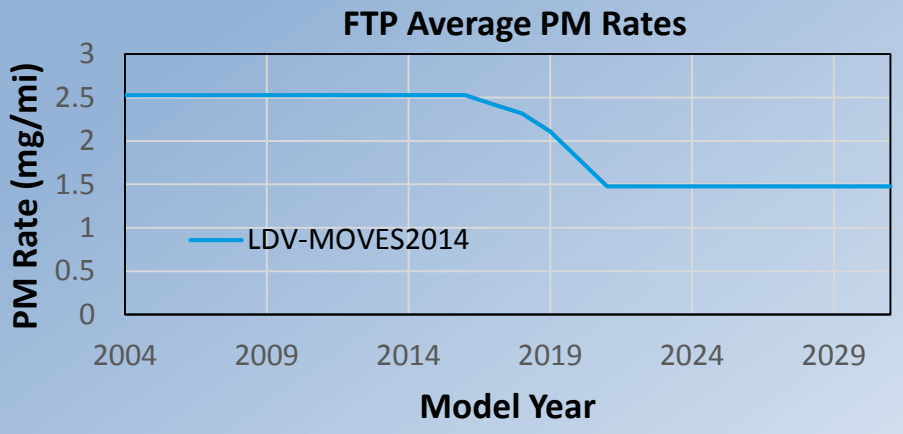
MOVES2014 PM rates

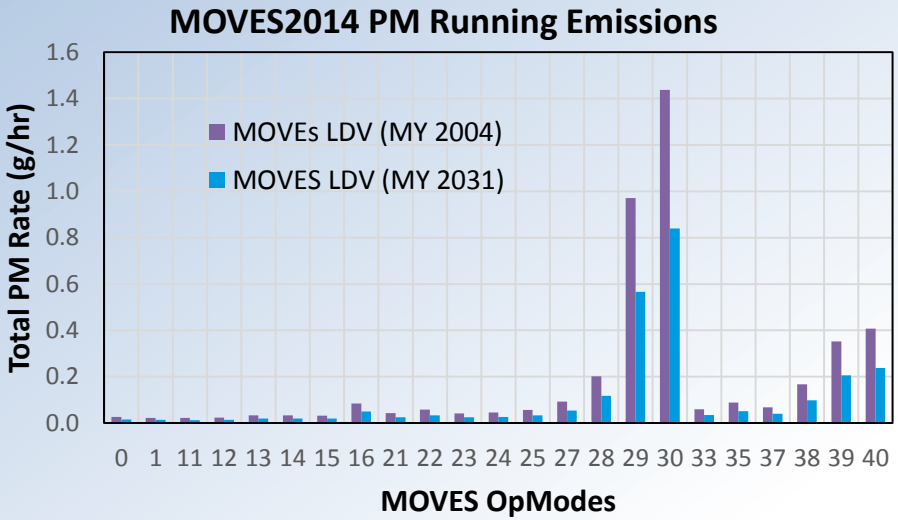
- MOVES running and start emission rates are divided into operating modes (OpModes)
- The start OpModes (101 – 108) are determined by the amount of time since the engine has last been run (soak time)
  - 101 → soak time < 6 min
  - 108 → soak time > 720 min
- Running OpModes are determined by vehicle speed and acceleration
  - 0, 1 → Braking and Idling
  - 11 - 16 → 1 mph <= speed < 25 mph
  - 22 - 30 → 25 mph <= speed < 50 mph
  - 33 - 40 → 50 mph <= speed
- Adjusting rates for individual OpModes cannot be done using data from typical certification test procedures
  - Test procedures have strictly defined soak times
  - Filter weights do not capture second by second speed and acceleration needed for running OpModes



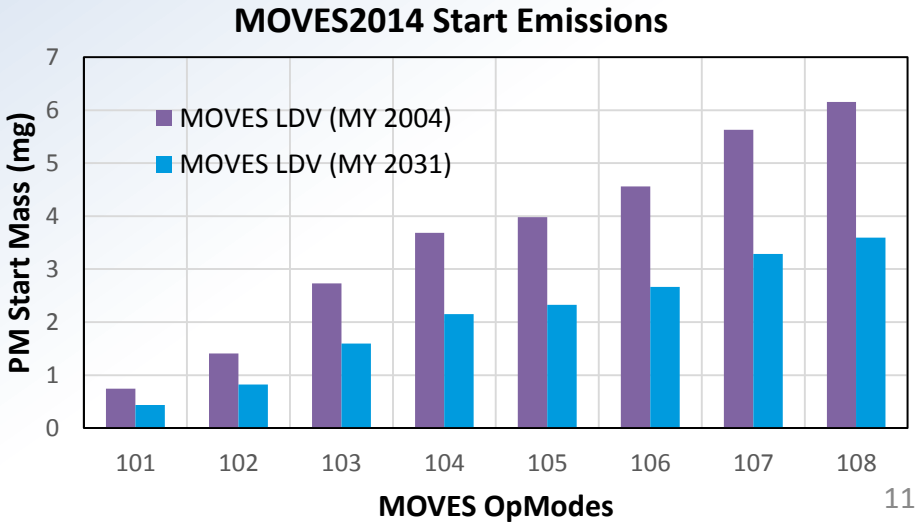


MOVES2014 PM rates

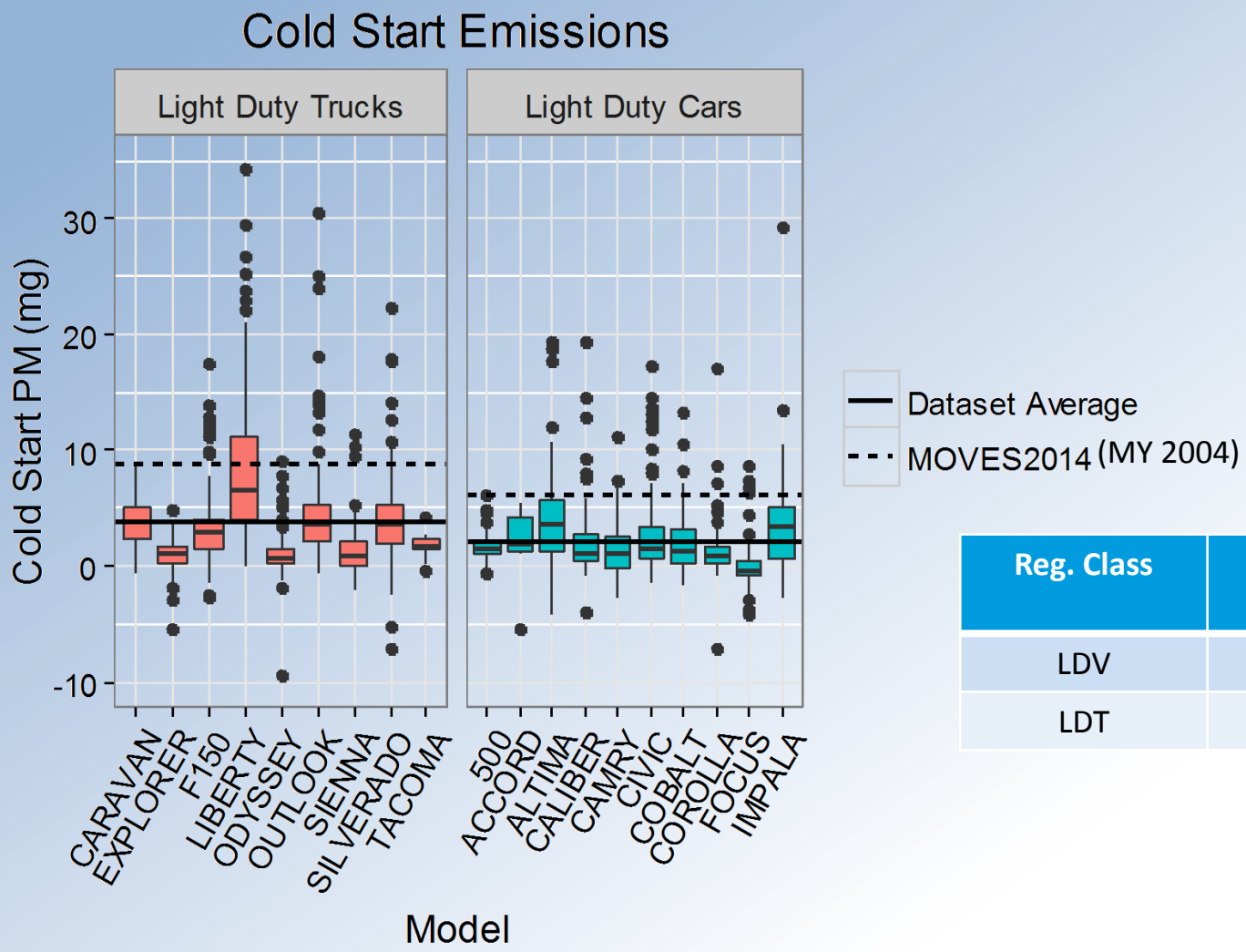




- MOVES does not distinguish PFI and GDI vehicles. The model includes an average rate for light-duty vehicles and light-duty trucks.
- Changes in average rates are accomplished by uniformly rescaling across all OpModes
- The proposed new rates are built by rescaling The MOVES2014 MY 2004 rates using population weighted PFI and GDI rescale factors determined from the new data

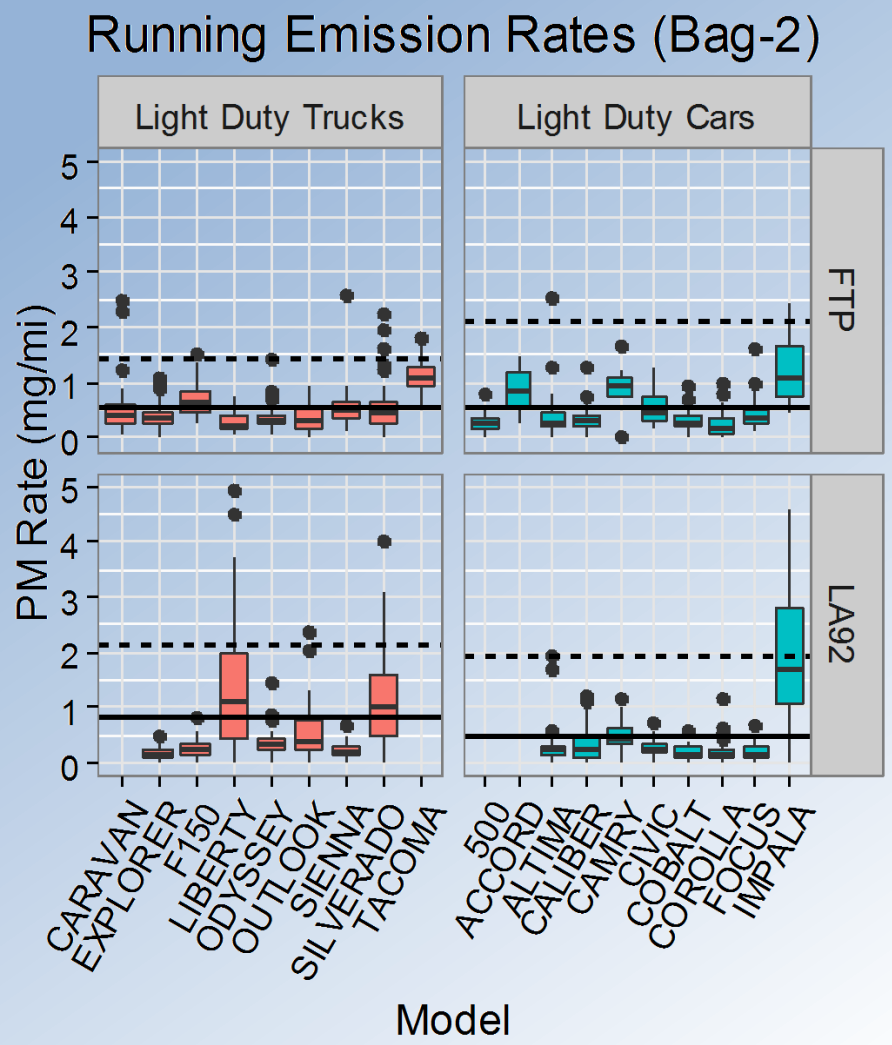


PFI PM data (starts)



Reg. Class	Rescale Factor (Dataset Average/MOVES)
LDV	0.335
LDT	0.427

PFI PM data (running)

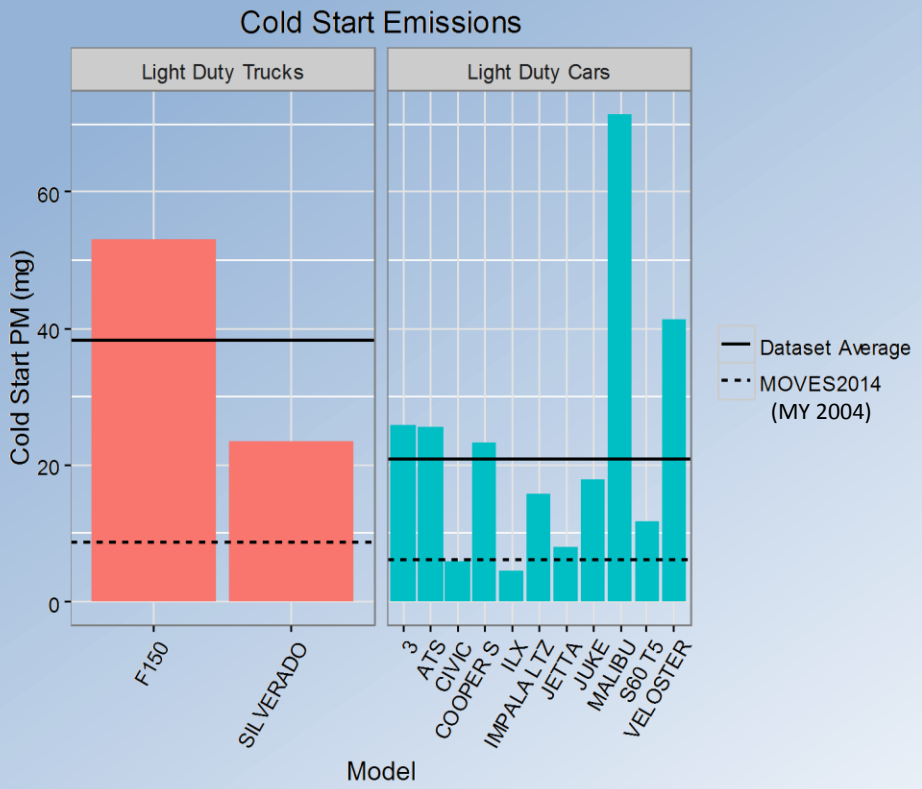


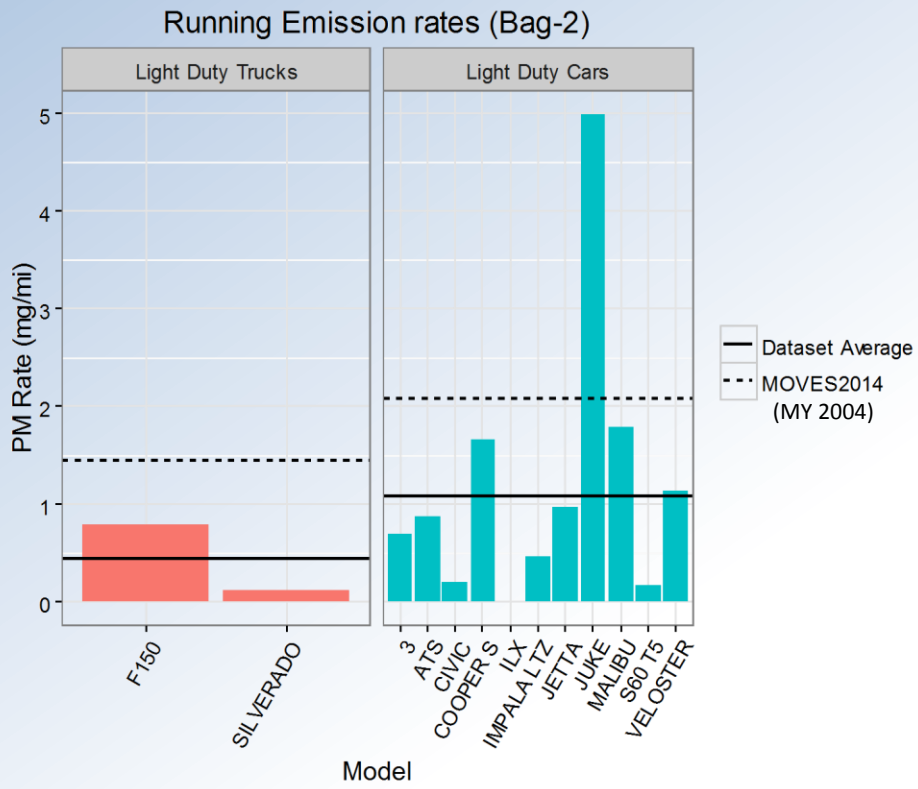
Dataset Average

MOVES2014 (MY 2004)

Reg. Class	Rescale Factor (Dataset Average/MOVES)
LDV	0.260
LDT	0.382

GDI PM data





Reg. Class	Rescale Factor (Dataset Average/MOVES)
LDV	3.398
LDT	4.367*

Reg. Class	Rescale Factor (Dataset Average/MOVES)
LDV	0.515
LDT	0.312*

* See next slide

GDI truck rescale factors

- Data from 2 vehicles is not enough information to adjust the emission factors for light-duty GDI trucks.
- Instead we developed GDI truck adjustment factors based on the effect on car emissions of GDI relative to PFI as a reasonable approximation :

- Start Emissions: $Start(Truck_{GDI}) = Start(Truck_{PFI}) \frac{Start(CAR_{GDI})}{Start(Car_{PFI})}$
- Running Emissions: GDI trucks we assume will rescale by the same ratio as GDI cars

Emission Process	Rescale factor (from dataset)	Rescale factor (from assumptions)
Start	4.367	4.32
Running	0.312	0.515

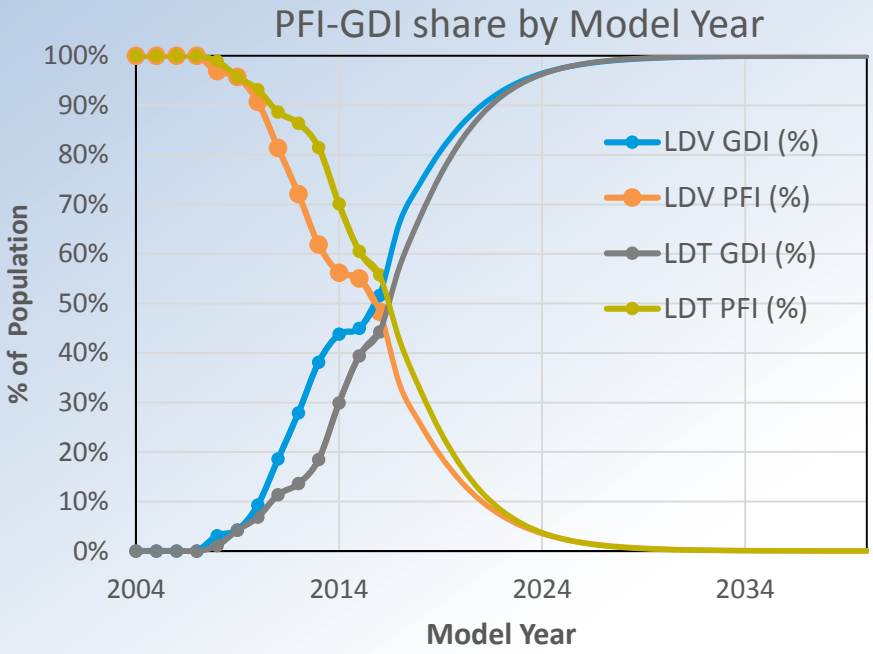
GDI elemental carbon fractions

- The CARB GDI dataset included black carbon measurements (EC) as well as filter masses
  - Other studies did not measure EC.
- The MOVES2014 ratios of EC to total PM are significantly lower than those seen in the CARB GDI data.
  - Used the EC fraction from the CARB data to represent GDI rates
  - Used the existing MOVES2014 rates for PFI engines
- Incorporating GDI rates into MOVES requires adjusting the relative rates for both the EC and Non-EC PM pollutants

	Start EC/Total PM	Running EC/Total PM
MOVES2014	0.487	0.140
CARB GDI Data	0.698	0.669

Combining GDI and PFI rates

- Emission rates were weighted by the relative populations of GDI and PFI vehicles
- MY 2004 – 2016: Use sales data from 2016 Fuel Economy Trends Report[1]
- MY 2017+ : Fit sigmoid function to trends data:
- $PFI(MY) = 1 - \frac{1}{1+e^{-K(MY-MY_0)}}$
- $GDI(MY) = 1 - PFI(MY)$

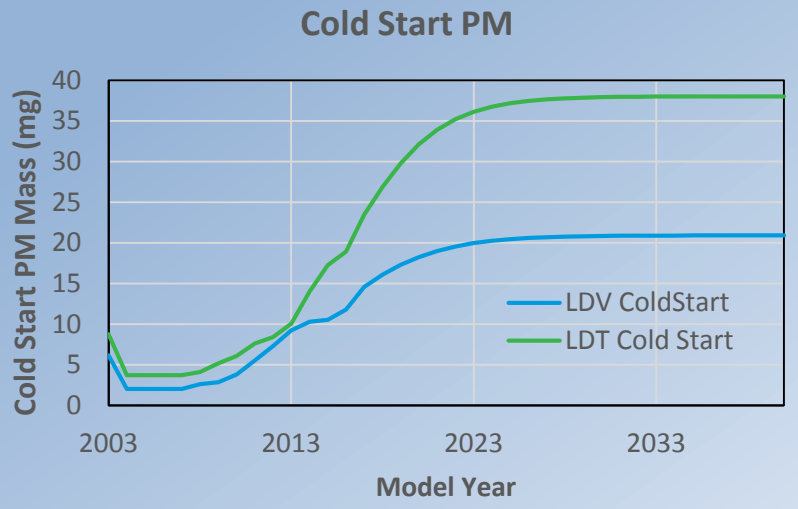


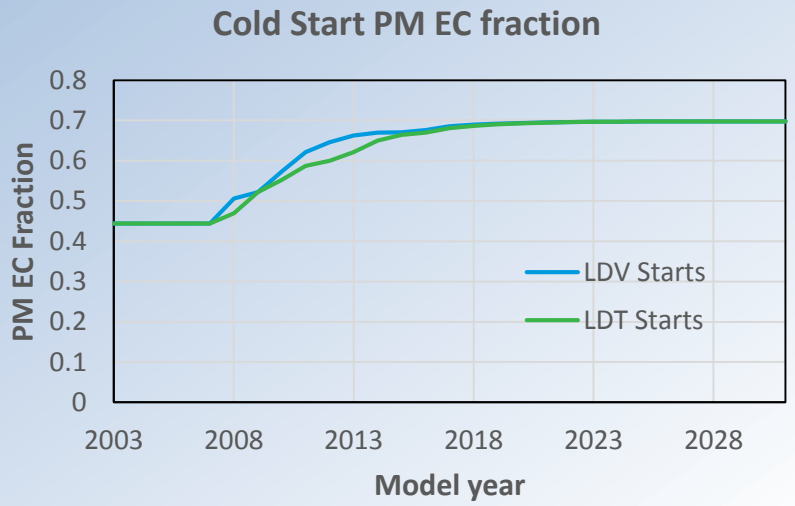
	K	MY_0
LDT	0.421	2016.27
LDV	0.375	2015.17

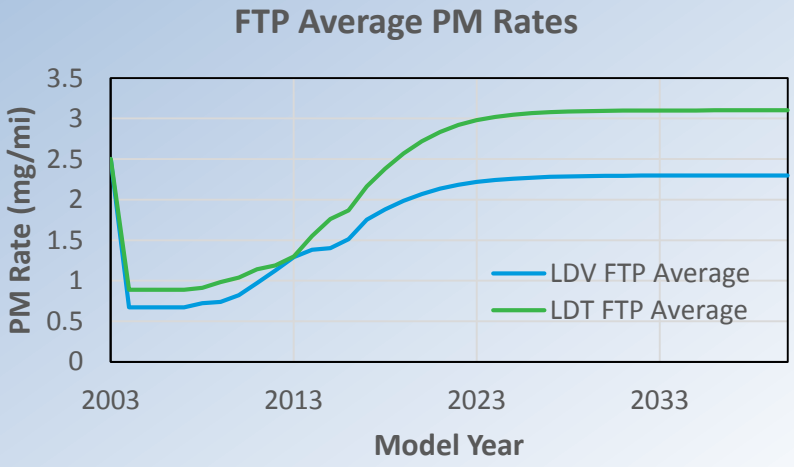
New PM rates were calculated by population weighting the calculated rescale factors for GDI and PFI engines, and applying them to the MOVES2014 rates

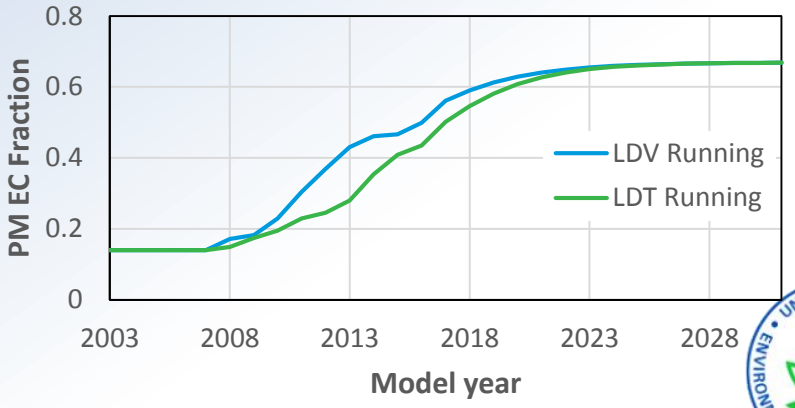
1. EPA, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016, EPA-420-R-16-00, November 2016

Combined GDI and PFI rates









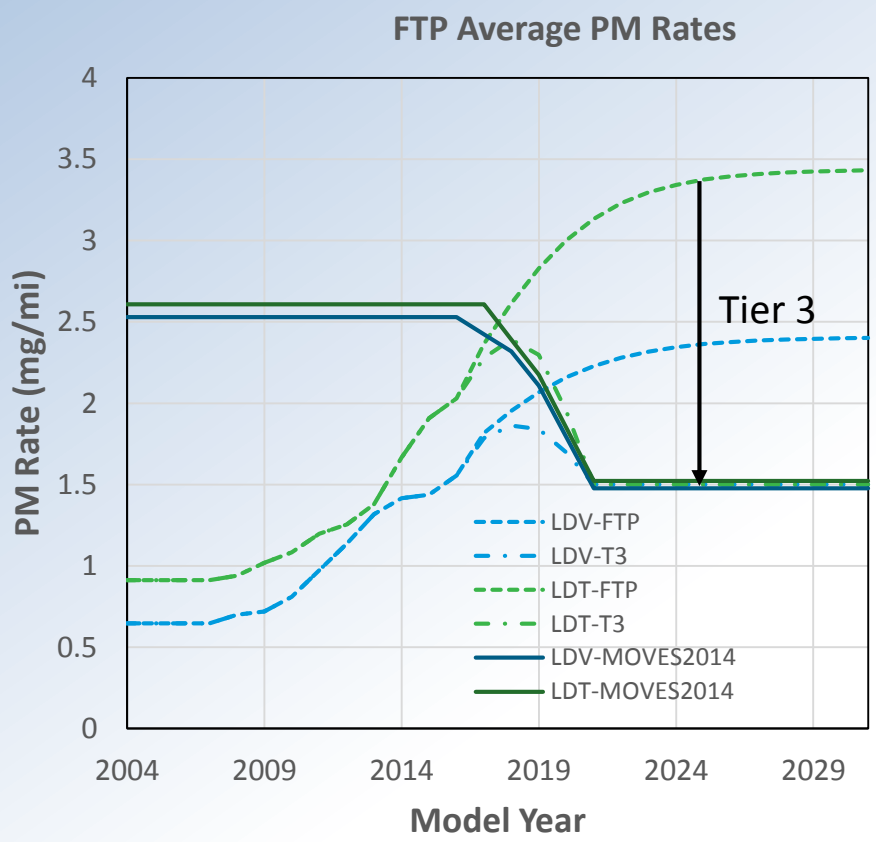
Phase in of Tier 3 standard

Tier 3 - Phase In

	2017	2018	2019	2020	2021	2022
% Sales	20%	20%	40%	70%	100%	100%
Standard (mg/mi)	3	3	3	3	3	3

Compliance margin = 50%

The Tier 3 PM standard is applied to the new PM rates using the same method that was used for MOVES2014

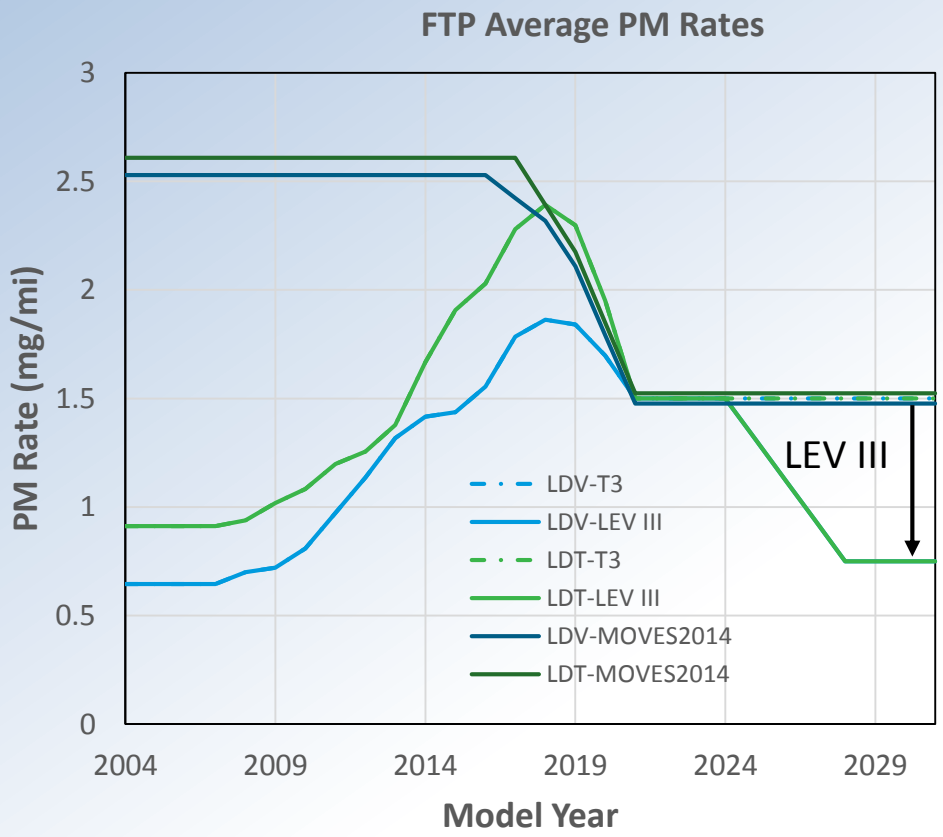


LEVIII standard

LEV III - Phase In

	2025	2026	2027	2028
% Sales	25%	50%	75%	100%
Standard (mg/mi)	1	1	1	1

Compliance margin = 25%

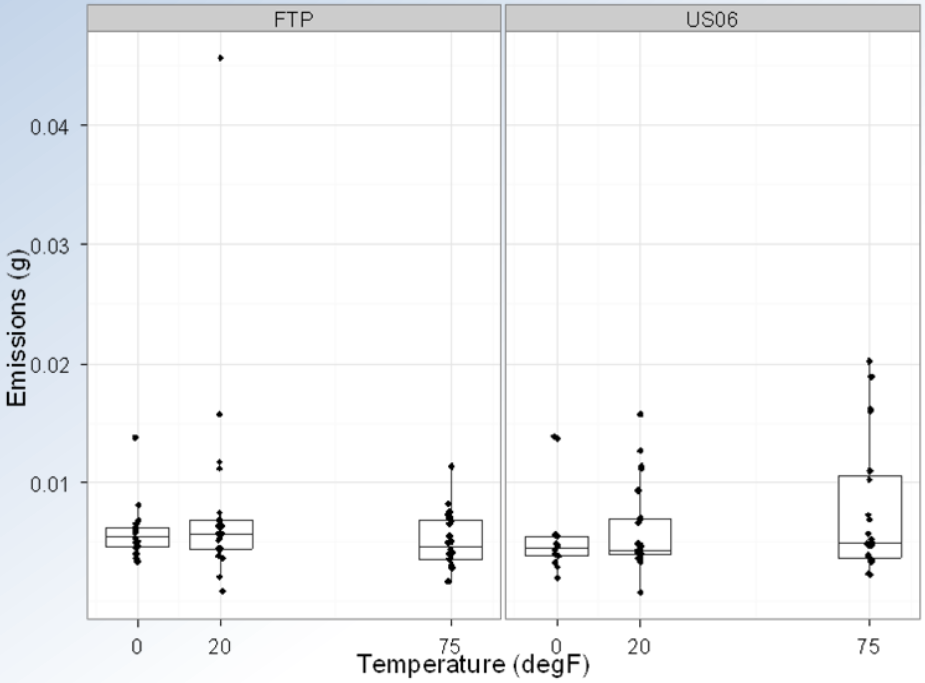


As with MOVES2014, a separate database will be made available to model states that have adopted the California LEV standards

Background: Temperature effects for PM running emissions in MOVES2014

- MOVES2010
  - PM running emissions increase at cold temperatures
  - Temperature effects based on the Kansas City study measurements of pre-2004 model year vehicles from the LA-92 (bag 2) drive cycle
- Cold Temperature Program (2012)
  - EPA cold temperature test program on 2010 vehicles (Figure on the right)
  - No significant temperature effect on running PM emissions of the FTP (bag 2) or the US06 cycle
- MOVES2014
  - Removed temperature effect for running emissions for 2004+ vehicles
  - Retained the Kansas City temperature effect on running PM emissions for pre-2004 vehicles

Hot-running PM Emissions measured on two Cycles (FTP Bag 2, US06) by temperature on MY 2010 gasoline vehicles, reported as grams/cycle.



Proposed update for temperature effects

- Remove temperature effect on PM running emissions for all model years
- Kansas PM temperature effect for running PM is mainly due to the short bag 1 of the LA-92 cycle
  - FTP bag 1: 505 seconds (3.59 miles)
  - LA-92 bag 1: 310 seconds (1.18 miles)
- Review of data from other studies supports removing the temperature effect on hot-stabilized PM emissions for pre-2004 vehicles
  - No significant temperature effect found for FTP bag 2 PM emissions from pre-1997 model year vehicles
    - Northern Front Range Air Quality Study (Cadle et al. 1998)
  - Carbonaceous $PM_{2.5}$ (EC+OC) emission rates (g/km) lower in the winter than the summer in Milwaukee, WI Tunnel in calendar years 2000 and 2001
    - 93%-98% gasoline vehicles
    - HEI Characterization of Metals Emitted from Motor Vehicles (Schauer et al. 2006)

1. Cadle, S. H.; Mulawa, P. A.; Hunsanger, E. C.; Nelson, K.; Ragazzi,R. A.; Barrett, R.; Gallagher, G.; Lawson, D. R.; Knapp, K. T.; Snow, R. Measurement of Exhaust Particulate Matter Emissions from In-Use Light-Duty Motor Vehicles in the Denver, Colorado Area; CRC Project E-24-1 Final Report, 1998.
2. Schauer, J., G. Lough, S. MM, C. WF, M. Arndt, J. DeMinter and J. Park (2006). Characterization of Metals Emitted from Motor Vehicles. Health Effects Institute Research Report Number 133. http://pubs.healtheffects.org/.

Summary

Proposed updates for next MOVES release:

- Start and running exhaust PM rates for light-duty vehicles from MY 2004+
  - Accounting for new data & phase-in of GDI vehicles
- EC, Non-EC ratios from MY 2004 – 2050
  - Accounting for higher EC ratio from GDI vehicles
- Temperature effects for PM running emissions (all model years)
  - Setting to zero based on new data.

Updates not considered for the next MOVES release:

- Temperature effects for start emissions
- Brake and tire wear PM emissions
- Deterioration effects for both start and running emissions
- Changes in the proportion of PM emissions attributed to each MOVES operating mode