Update to running exhaust criteria pollutant emission rates for model year 2010+ heavy-duty diesel vehicles

Gurdas S. Sandhu and Darrell Sonntag
Outline

1. Motivation and Proposed Updates
2. Manufacturer-run heavy-duty in-use testing (HDIUT) - Overview and Data Description
3. Analysis Methodology – Emission Rates and Production Volume
4. Preliminary Results – OpMode Avg. and Cycle Total Emissions
5. Emerging Questions
## Motivation

**MOVES2014a NO\textsubscript{x} Data Sources**

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Regulatory Class</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ROVER and Consent Decree Testing</strong></td>
<td></td>
</tr>
<tr>
<td>1991-1997</td>
<td>19</td>
</tr>
<tr>
<td>1998</td>
<td>12</td>
</tr>
<tr>
<td>1999-2002</td>
<td>78</td>
</tr>
<tr>
<td>2003-2006</td>
<td>91</td>
</tr>
<tr>
<td><strong>HDIU</strong></td>
<td></td>
</tr>
<tr>
<td>2003-2006</td>
<td>40</td>
</tr>
<tr>
<td>2007-2009</td>
<td>68</td>
</tr>
<tr>
<td><strong>Houston Drayage</strong></td>
<td></td>
</tr>
<tr>
<td>1991-1997</td>
<td>8</td>
</tr>
<tr>
<td>1998</td>
<td>1</td>
</tr>
<tr>
<td>1999-2002</td>
<td>10</td>
</tr>
<tr>
<td>2003-2006</td>
<td>8</td>
</tr>
</tbody>
</table>

**HDIU**: Heavy-duty in-use

Table 2-2 (pg 16), *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES2014*, EPA-420-R-15-015a, November 2015

Proposed updates

• Update running emission rates for MY 2010+ heavy-duty vehicles.
  – Update NO\textsubscript{x}, CO, and HC
  – Update energy use (which affects CO\textsubscript{2} emissions)
  – Currently do not plan to update PM due to limited data
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.
Data Overview

- Service Class: Light-/Medium-/Heavy-Duty Diesel (LHDD, MHDD, HHDD) and Urban Bus (URBU)
- MY 2010-2013 engine families
- Over 30 unique engine families
- Over 230 vehicles
- Over 6 million seconds of data
- Current work involves updating emission rates using HDIUT data from engines selected for testing in CY 2010-2014. Data for engines selected in 2015 is expected by January 2017 and the plan is to include it in the update.
Subset of Heavy-heavy-duty Vehicles (GVWR>33K+ lbs) in HDIUT

<table>
<thead>
<tr>
<th>ID</th>
<th>Engine MY</th>
<th>Disp (L)</th>
<th>hp</th>
<th>Odo (10^3 mi)</th>
<th>Test Miles</th>
<th>Test Secs</th>
<th>Controls</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1_T1</td>
<td>2010</td>
<td>15.0</td>
<td>475</td>
<td>246</td>
<td>266</td>
<td>23684</td>
<td>TC, CAC, EGR, DPF, SCR-U</td>
<td>Line Haul</td>
</tr>
<tr>
<td>E1_T3</td>
<td>2010</td>
<td>15.0</td>
<td>475</td>
<td>268</td>
<td>330</td>
<td>30279</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1_T4</td>
<td>2010</td>
<td>15.0</td>
<td>475</td>
<td>261</td>
<td>153</td>
<td>27034</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1_T5</td>
<td>2010</td>
<td>15.0</td>
<td>475</td>
<td>324</td>
<td>258</td>
<td>39344</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2_T1</td>
<td>2012</td>
<td>16.0</td>
<td>525</td>
<td>78</td>
<td>394</td>
<td>38039</td>
<td>TC, CAC, EGR, DPF, SCR-U, AMOX</td>
<td>Line Haul</td>
</tr>
<tr>
<td>E2_T2</td>
<td>2012</td>
<td>16.0</td>
<td>575</td>
<td>127</td>
<td>253</td>
<td>31685</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2_T3</td>
<td>2012</td>
<td>16.0</td>
<td>525</td>
<td>153</td>
<td>322</td>
<td>39021</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2_T4</td>
<td>2012</td>
<td>16.0</td>
<td>525</td>
<td>107</td>
<td>317</td>
<td>33742</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2_T5</td>
<td>2012</td>
<td>16.0</td>
<td>525</td>
<td>166</td>
<td>393</td>
<td>36670</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3_T1</td>
<td>2011</td>
<td>10.5</td>
<td>380</td>
<td>321</td>
<td>489</td>
<td>34241</td>
<td>TC, CAC, EGR, DPF</td>
<td>Delivery</td>
</tr>
<tr>
<td>E3_T2</td>
<td>2011</td>
<td>10.5</td>
<td>400</td>
<td>205</td>
<td>190</td>
<td>23744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3_T3</td>
<td>2011</td>
<td>10.5</td>
<td>380</td>
<td>206</td>
<td>325</td>
<td>34290</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3_T4</td>
<td>2011</td>
<td>10.5</td>
<td>400</td>
<td>131</td>
<td>191</td>
<td>35622</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4_T1</td>
<td>2011</td>
<td>15.0</td>
<td>450</td>
<td>184</td>
<td>432</td>
<td>33474</td>
<td>TC, CAC, EGR, DPF</td>
<td>Delivery</td>
</tr>
</tbody>
</table>

TC: Turbocharger | CAC: Charge Air Cooler | EGR: Exhaust Gas Recirculation | DOC: Diesel Oxidation Catalyst  
DPF: Diesel Particulate Filter | SCR-U: Selective Catalytic Reduction using Urea | AMOX: Ammonia Oxidation Catalyst
Overview of Emission Rates Update Method

• Vehicle activity and emission rates are mapped onto an operating mode (OpMode) modal model.

• For each vehicle tested:
  – OpModes are assigned to each second of real-world emissions data based on estimated power demand at the wheel
  – Average the emissions from all seconds assigned the same OpMode

• Emission rates are estimated by service class (LHDD, MHDD, HHDD, URBU). Within a service class, emission rates are grouped by NO$_x$ family emission limit (FEL) and weighted by the production volume for the same NO$_x$ FEL groups.
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 losses

Accessory loads for LHDD are assumed negligible.

<table>
<thead>
<tr>
<th>Engine Power (of max hp)</th>
<th>Vehicle Speed</th>
<th>Low (0-25 mph)</th>
<th>Mid (25-50 mph)</th>
<th>High (above 50 mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest Third</td>
<td>Cooling Fan</td>
<td>Air cond.</td>
<td>Engine Access.</td>
<td>Alternator</td>
</tr>
<tr>
<td></td>
<td>Engine Access.</td>
<td></td>
<td>Alternator</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alternator</td>
<td></td>
<td>Air Compress</td>
<td></td>
</tr>
<tr>
<td>Middle Third</td>
<td>Cooling Fan</td>
<td>Air cond.</td>
<td>Engine Access.</td>
<td>Alternator</td>
</tr>
<tr>
<td></td>
<td>Engine Access.</td>
<td></td>
<td>Alternator</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alternator</td>
<td></td>
<td>Air Compress</td>
<td></td>
</tr>
<tr>
<td>Highest Third</td>
<td>Cooling Fan</td>
<td>Air cond.</td>
<td>Engine Access.</td>
<td>Alternator</td>
</tr>
<tr>
<td></td>
<td>Engine Access.</td>
<td></td>
<td>Alternator</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alternator</td>
<td></td>
<td>Air Compress</td>
<td></td>
</tr>
</tbody>
</table>

Gap-filling Emission Rates for High Power OpModes

- MOVES estimates little activity in the high power OpMode bins (28-30 and 38-40); and real-world (RW) data often lacks these modes as well.
- In MOVES 2014, the emission rates for these OpMode bins were calculated from emission rates of the highest OpMode with sufficient data (27 or 37) and then “extrapolated” based on STP mid-point values.
- For the next version of MOVES, rates from sparse data OpMode bins are folded-in with highest power OpMode with sufficient data. The “fold-in” is achieved, for the participating OpModes, by taking a sum-product of time and emission rates per OpMode and dividing by total time across OpModes.
- This “fold-in” emission rate is assigned to all participating OpMode bins, including and upward of the highest OpMode with sufficient data.
- The cycle total emissions from the “fold-in” method are identical to real-world “as-is”
Gap-filling Emission Rates for Higher OpModes

![Bar chart showing emission rates for different operating modes. The chart compares RW_As-Is, RW_Fold-In, and RW_Extrapolate modes, with RW_Fold-In marked with a checkmark. The y-axis represents NOx emissions (g/s), and the x-axis represents MOVES Operating Mode numbers (0 to 40).]
Engine Family Name

BCEXH0912XAQ

“base engine family”

EPA assigned manufacturer code
Industry sector (H = HD highway diesel >8,500 lbs GVWR)
Engine Displacement (liters XX.X or cubic inches XXXX)
Manufacturer assigned characters

40CFR86.096-24(a)(1): Engine families are “expected to have similar emission characteristics throughout their useful life.”
Engine Families Grouped by NO\textsubscript{x} FEL

- Group engines within a service class by NO\textsubscript{x} FEL.
- NO\textsubscript{x} FEL grouping is applied across all pollutants because NO\textsubscript{x} FEL data is more widely available and best captures the differences in emission levels.
- Find average emission rates for the given NO\textsubscript{x} FEL group and weight it by the production volume for the same group for a given MY.

<table>
<thead>
<tr>
<th>Group Name</th>
<th>NO\textsubscript{x} FEL Limits (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>(0.00, 0.20]</td>
</tr>
<tr>
<td>0.35</td>
<td>(0.20, 0.35]</td>
</tr>
<tr>
<td>0.50</td>
<td>(0.35, 0.50]</td>
</tr>
</tbody>
</table>

Engine Families by NO\textsubscript{x} FEL Group

- 0.20: 156, 64%
- 0.35: 36, 15%
- 0.50: 52, 21%
Method to Estimate Production Volume Weighted Emission Rate, MY 2010-2015

\[ ER_{C,MY,pol} = \frac{\sum_{FEL}(ER_{C,pol,FEL} \times PV_{C,MY,FEL})}{PV_{C,MY}} \]

Service Class (C) = LHDD, MHDD, HHDD

Model Year (MY) = 2010 to 2015

Pollutant (pol) = NOx, HC, CO

FEL = NOx FEL of engine family, grouped in to 0.2g/bhp-hr, 0.35g/bhp-hr, and 0.5g/bhp-hr.

\( ER_{C,MY,pol} \) = Emission Rate (ER) for a given Class (C), Model Year (MY), and Pollutant (pol).

\( ER_{C,pol,FEL} \) = Emission rate by class, pollutant, and NOx family emission limit (FEL). This is average of all HDIUT data for all engines meeting the \( C,pol,FEL \) criteria.

\( PV_{C,MY,FEL} \) = Production volume by class, model year, and NOx FEL group

\( PV_{C,MY} \) = Total production volume for a class and model year
Q: How to assign production volume distribution, by FEL NOx groups, for future years?
Method to Estimate Production Volume
Weighted Emission Rate

- HDIUT emissions data is not split by model year. The assumption is that engines within a service class and NOx FEL group have the same emissions profile across model years.

- However, the final emissions rates are by model year because they include the production volume weighting by model year.

- URBU rates will be based on HHDD emissions data due to sparse URBU emissions data

### HDIUT Data: Number of Test Vehicles

<table>
<thead>
<tr>
<th>Service Class</th>
<th>NOx FEL based Groups</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.20</td>
<td>0.35</td>
</tr>
<tr>
<td>LHDD</td>
<td>42</td>
<td>10</td>
</tr>
<tr>
<td>MHDD</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>HHDD</td>
<td>65</td>
<td>21</td>
</tr>
<tr>
<td>URBU</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>123</td>
<td>54</td>
</tr>
</tbody>
</table>
MOVES Operating Modes (OpMode)

- **Idling**: Speed: [1–25) mph
- **Decelerating**: Speed: [25–50) mph
- **Coasting, STP < 0**: Speed ≥ 50 mph
- **Pulling heavy load on positive grade**: Moving heavy load on positive grade
- **Urban driving with medium load**: Urban driving with medium load
- **Highway cruising, no grade**: Highway cruising, no grade
OpMode Distribution for Heavy-heavy-duty - MOVES National Mode Run, CY2016

Scale: Onroad, National, Inventory
Time Spans: Year, CY 2016, All Months, Weekend and Weekday, All Hours
Geographic Bounds: Nation
Vehicles: Diesel Fuel
Road Type: Rural and urban, Restricted and Unrestricted
Preliminary result: NO$_x$ for Heavy-heavy-duty

For the OpMode distribution in slide 20, HDIUT data rates lead to a **42% increase** in cycle total NO$_x$ emissions over MOVES2014 rates.

These *preliminary results* are based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.
**Preliminary result: THC for Heavy-heavy-duty**

For the OpMode distribution in slide 20, HDIUT data rates lead to a **47% decrease** in cycle total THC emissions over MOVES2014 rates.

These *preliminary results are* based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.
Preliminary result: CO$_2$ for Heavy-heavy-duty

For the OpMode distribution in slide 20, HDIUT data rates lead to a 8% increase in cycle total CO$_2$ emissions over MOVES2014 rates.

These preliminary results are based on 10 trucks, of which nine are certified for 0.2 g/hp-hr while one is certified for 0.5 g/bhp-hr.
Next Steps

- Complete analysis of all HDIUT data and compile emission rates by RegClass
- Estimating the impact of mal-maintenance and high-emitters
- Conduct MOVES runs to estimate impact from updated emission rates on national inventory
- Possibility to include data from other sources, based on timing, for running emissions, deterioration rates, start emissions.
Emerging Questions

• **Analysis Methods:** Improve accessory loss estimates for newer trucks.

• **DPF Regeneration:** What is the frequency of DPF regeneration? Where to assign this in a driving cycle? What is the impact on cycle total emissions and speciation?

• **Deterioration and Failure:** Is deterioration linear? What are the types of failures – severity and associated impact? What, if any, are the cross-effects - failure in one control device affecting other downstream control devices?

• **Control Strategies:** What are the effects of improvements in thermal management, catalyst treatments, and dosing optimization strategies on emissions profile of newer model year vehicles compared to first generation systems?

• **Driving Cycles:** While formulating representative driving cycles in itself is not an emerging question, the issue is highlighted by concerns of reduction in emission control efficiency during low-load and off-cycle operation. How well do our driving cycles represent low-load and off-cycle operation?

• **History Effects:** Continuing on the theme of driving cycles, how can a modal model such as MOVES represent/capture the real-world influence of past vehicle condition on current emission profile?

• **Assigning OpMode:** Driving cycles are converted to OpMode distribution based on equations that use road-load coefficients or driveline efficiency and auxiliary power losses. What are representative road-load coefficients and auxiliary power losses for the truck fleet as the fleet transitions to more aerodynamic chassis, efficient powertrains, and lower resistant tires?
MOVES Scaled Tractive Power: Road-load Coeff

\[ STP_t = \frac{A v_t + B v_t^2 + C v_t^3 + m v_t a_t}{f_{scale}} \]

- \( STP_t \) = 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
RegClass 47 is **heavy-heavy-duty**. On a source hours operating (SHO) basis, RegClass 47 is comprised of 88% combination trucks, 8% single-unit trucks, and remaining refuse trucks and buses.
HDIUT Data Coverage of Total Production Volume

- Of the total engines produced in a year, how many are covered by the HDIUT data?
- For any engine family, if HDIUT data includes emissions from the “base” engine family, then full coverage of that particular engine family’s production volume is assumed.

<table>
<thead>
<tr>
<th>% Coverage</th>
<th>0.2</th>
<th>0.35</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHDD</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>MHDD</td>
<td>92</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>HHDD</td>
<td>85</td>
<td>87</td>
<td>86</td>
</tr>
<tr>
<td>Urban Bus</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AVG</td>
<td>87</td>
<td>91</td>
<td>90</td>
</tr>
</tbody>
</table>

- Example: HDIUT data includes emission rates from base engine families that constitute 86% of the total production volume of MY 2012 HHDD engines with NOx FEL 0.2 g/bhp-hr.
- However, there are categories (shaded grey) where the coverage is below 10% and production volume is more than 100 units.