Cold Start, Hot Start, and Idle Emissions as Measured on Northern Utah Vehicles

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Study Problem Statement

• Automobile emissions are known to be a large portion of Utah’s air pollutant emissions
  – approx. 50% of NO$_x$, VOC, SO$_x$, and direct PM wintertime emissions

Source: Utah Division of Air Quality (data shown for Utah, Salt Lake, Davis, and Weber counties)
Study Problem Statement

• Utah has focused on reducing automobile emissions as a core component of the plan to improve the state’s air quality (SIPs)
  – Emissions inspection & maintenance programs
  – Anti-idling programs
  – Driving modification & outreach programs
    • 25 driving-related suggestions at UDAQ’s “Choose Clean Air”,
      http://www.cleanair.utah.gov/winter/50wintersuggs.htm

• However, sparse literature and data exist identifying the benefits or atmospheric penalties involved with these issues, particularly under Utah-specific conditions in relation to vehicle fleet, temperature regimes, etc.
Study Objectives

Study Tasks:

1) Measure the differences in emissions between (1) cold starts, (2) hot starts, and (3) continuous idling
   • difference in magnitude of cold starts vs. hot starts
   • is okay to idle (emission-wise) or shut off the engine during short stops,

2) Verify whether emissions are different under different weather (temperature) conditions – e.g. as per MOVES2014

- To accomplish these tasks, researchers at Utah State University (USU) and the National Center for Automotive Science and Technology (NCAST) at Weber State University (WSU) tested a group of vehicles (planned n = 50) representative of the vehicle fleets typical of the Cache Valley and Wasatch Front Counties
Target Vehicle Breakdown

• Light-Duty (LD), with Gross Vehicle Weight Ratings (GVWR) ≤ 8,500 lbs.

• Representative of the Wasatch Front counties
  – Box Elder, Cache, Davis, Salt Lake, Tooele, Utah, and Weber Counties
  – separated by EPA “Tier Level”
    • surrogate for vehicle age (average of target counties = 8.9 yrs)
    • specifies emission requirements per Tier

<table>
<thead>
<tr>
<th>Tier Level</th>
<th>Pre-Tier 0</th>
<th>Tier 0</th>
<th>Tier I</th>
<th>NLEV</th>
<th>Tier II</th>
<th>Tier III</th>
</tr>
</thead>
<tbody>
<tr>
<td># of vehicles</td>
<td>22,447 (1.4%)</td>
<td>92,827 (5.9%)</td>
<td>372,927 (23.7%)</td>
<td>271,522 (17.3%)</td>
<td>811,802 (51.7%)</td>
<td>-----</td>
</tr>
<tr>
<td># tested</td>
<td>1</td>
<td>3</td>
<td>14</td>
<td>10</td>
<td>36</td>
<td>64 total</td>
</tr>
</tbody>
</table>

NLEV = National Low Emission Vehicle
Methodologies

• Targeted measurement of tailpipe concentrations of hydrocarbons (VOCs or HCs), oxides of nitrogen (NO$_x$), and carbon monoxide (CO)
  – Autologic Applus 5-Gas Analyzer
    • reports concentrations or mixing ratios (volume % or ppm)
    • also measures carbon dioxide (CO$_2$) and oxygen (O$_2$)
  – Measure “Cold Start” emissions
    • vehicle off, stored outside, for ≥ 12 hours prior to testing
  – Measure “Hot Start” emissions (5, 10, 20 min)
    • after on-road drive cycle, shut off motor and start after specified period of time
  – Measure “Idle” emissions
    • Continued measurement for ≥ 5 min after start equilibrium reached
Methodologies (cont.)

Autologic Applus 5-Gas Emissions Analyzer
Average Mileage of Tested Vehicles

Tested Pre-Tier 0 vehicle reported >300,000 miles
- roughly in range of assumption of 12,000 miles per year
Sample Emission Measurements

- Start & idle emissions for 2007 Dodge Ram 1500

![Graphs showing emission measurements for different start conditions.](image)
Average Equilibrium Times

Across all tested age classifications and pollutants (VOCs, NO\textsubscript{x}, CO), the average cold start equilibrium times ranged from 0.7-3.5 minutes and the average hot start equilibrium times ranged from 0.3-1.2 minutes

- meaning most vehicles do not require lengthy “warm up time”
Cold Start vs. Hot Start Emissions

- Observed cold start emissions usually within a factor of 2 of EPA estimates
  - some higher, some lower
- Cold starts resulted in higher average emissions across vehicle types and pollutants
  - warm starts average about 4% of cold start emissions
Hot Start Emissions vs. Idle (HC)

- Hot Starts resulted in lower average HC emissions as compared to an equivalent idle
  - note logarithmic scales
  - idle emissions roughly an order of magnitude or great
- Pre-Tier 0 not presented owing to n =1
Similar to HCs, in that greatest NO\textsubscript{x} emissions typically observed during idle periods (but much lower than HCs)

- a few exceptions noted with NLEV and Tier II vehicles: short term Hot Starts (5-min) trended higher than corresponding idles
Hot Start Emissions vs. Idle (CO)

- Highest CO emissions more frequently observed from “Starts” as opposed to “Idles”
  - again, seemingly more evident with newer vehicles (NLEV & TIER II) for short term idles
Question 1: How long does my engine need to warm up after a “cold start” (engine off for more than 12 hours)?

Warming up the engine by idling for more than 2-3 minutes IS NOT needed. After start, warm up the engine by driving it normally.

START UP AND GO!
Question 2: During short stops, is it better to let my engine idle or shut off and restart it?

As a good rule of thumb, always turn off your engine when the vehicle’s transmission is in the “Park Position”. When the engine is warm, idling for 5 minutes produces:

- 4 times more VOC
- 3 times more NO\textsubscript{x} and
- 10 times more CO

than restarting the engine and the differences become even greater for longer time periods.
Continuing Research

- Catalyst temperature behavior (cooling rate, etc.) & efficiency
  - sampling probes (dual systems) before and after catalyst
- Verify previous measurements
  - additional older cars (more robust statistics for Tier 0 and Tier 1)
  - Colder ambient temperatures
- Sample at least a couple more Pre-Tier 0 vehicles – if we can find them
- Effect of ambient temperature on cold starts
  - we have recently gotten some colder temperature measurements,
- Additional Drive cycle tests – road/dyno emissions tests

Future Research (?)

- CO₂ emission analysis
- Analysis of collected catalyst temperature data
- Test effectiveness of catalyst replacement on previously tested vehicles
  - CA-certified catalyst vs. “normal” catalysts
To Ponder... (Nov. 2015 Observations)

Questions?

Acknowledgements:
Utah State Legislature & Utah Division of Air Quality
USU’S Utah Water Research Laboratory (UWRL)
WSU’S National Center for Automotive Science & Technology (NCAST)
Numerous friends & colleagues for use of their automobiles

Clay Woods (USU)
Stetson Bassett (USU)
Chris Woodhave (NCAST)
Alan Walker (NCAST)
Additional Slides
Other’s Past Research

- Transportation Air Quality Facts and Figures January 2006

- Typical 7 trips/day, 29 VMT
- Cold Start
  - 7.7 g VOCs (25% daily)
  - 88 g CO (26% daily)
  - 5.0 g NOx (19% daily)
- Running cycle
  - 7.8 g VOCs (25% daily)
  - 251 g CO (74% daily)
  - 20.2 g NOx (81% daily)

Methodologies

- Additional supporting measurements
  - Tailpipe velocity (flow rate)
    - to convert concentrations to emissions (e.g. g/s)
    - developed algorithms to relate engine RPM and exhaust gas temperature to tailpipe velocity
      - velocities measured with a high temp. propeller anemometer
Methodologies

• Additional supporting measurements (cont.)
  – Engine operating conditions
    • through the OBD II sensor, if available
      – RPM, catalyst temp., engine coolant temp., oxygen sensor data
      – If OBD sensor unavailable, RPMs manually recorded
  – System external (surface) temperatures
    • engine block, cat skin temperature, exhaust gas, ambient
• **Average Hot Start Emissions (g) as a percentage of Cold Start Emissions (g)**
  
  - For Pre-Tier 0: Average hot start HC emissions were equal to cold start emissions
  
  Average hot start NO\textsubscript{x} and CO emissions were \(\approx 4\%\) of the cold start emissions
Methodologies (cont.)

OBDII measurements, ideally, RPM, temperatures, oxygen (pre & post cat), etc.
• not all parameters available from all models
Methodologies (cont.)

External temperature measurements and datalogger
Selected Results

- Not all vehicles “equilibrate” quickly or behaved consistently - one of several examples – 1998 Toyota Avelon

1998 Toyota Avelon Cold Start

1998 Toyota Avelon 5 min Start

- CO (g/s)
- HC and NO (g/s)
Sample Emission Measurements

• However, not all vehicles “equilibrate” quickly after a cold start...
  – 2001 Dodge Durango (NLEV, pre Tier II vehicle)
Sample Emission Measurements

• Not all vehicles “equilibrate” quickly - another example
  – 1991 Ford F150 (Tier 0)
    • additionally......catalytic convertor was removed 😑
### Selected Results
(compiled format → lots-o-data)

<table>
<thead>
<tr>
<th></th>
<th>Pre-Tier 0 (≤1980)</th>
<th></th>
<th>Tier 0 (1981 - 1993)</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Mileage</td>
<td>300,000 miles</td>
<td>274,327 miles</td>
<td>180,023 miles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T(Amb)</td>
<td>3.8 °C</td>
<td>5.8 °C</td>
<td>3.1 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td>NO</td>
<td>CO</td>
<td>HC</td>
<td>NO</td>
</tr>
<tr>
<td>Peak Emiss (g/s)</td>
<td>8.77</td>
<td>0.455</td>
<td>82.7</td>
<td>0.0470</td>
<td>9.06E-04</td>
</tr>
<tr>
<td>Time to Equil (sec)</td>
<td>170</td>
<td>165</td>
<td>170</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Avg Start Emiss (g/s)</td>
<td>1.06</td>
<td>0.0730</td>
<td>13.3</td>
<td>0.0180</td>
<td>6.24E-04</td>
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<tr>
<td>Total CS Emiss (g)</td>
<td>180</td>
<td>12.0</td>
<td>2,262</td>
<td>1.08</td>
<td>0.0374</td>
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<td>Avg CS Idle Emiss (g/s)</td>
<td>1.61</td>
<td>0.0780</td>
<td>13.9</td>
<td>9.84E-03</td>
<td>6.18E-04</td>
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<tr>
<td>Total CS 5-min Idle Emiss (g)</td>
<td>483</td>
<td>23.4</td>
<td>4,175</td>
<td>2.95</td>
<td>0.186</td>
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<tr>
<td></td>
<td>5-min Hot Start</td>
<td></td>
<td>10-min Hot Start</td>
<td></td>
<td></td>
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<tr>
<td>Peak Emiss (g/s)</td>
<td>3.18</td>
<td>0.109</td>
<td>41.5</td>
<td>0.0341</td>
<td>8.18E-04</td>
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<td>Time to Equil (sec)</td>
<td>68</td>
<td>80</td>
<td>15</td>
<td>45</td>
<td>50</td>
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<tr>
<td>Avg Start Emiss (g/s)</td>
<td>2.21</td>
<td>0.0753</td>
<td>16.1</td>
<td>1.28E-02</td>
<td>7.26E-04</td>
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<td>Total 5-min Hot Start Emiss (g)</td>
<td>151</td>
<td>6.02</td>
<td>241</td>
<td>0.578</td>
<td>0.0363</td>
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<td>Avg 5-min Idle Emiss (g/s)</td>
<td>1.75</td>
<td>0.0780</td>
<td>1.21</td>
<td>7.34E-03</td>
<td>5.38E-04</td>
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<td>Total 5-min Idle Emiss (g)</td>
<td>525</td>
<td>23.4</td>
<td>364</td>
<td>2.202</td>
<td>0.161</td>
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<tr>
<td></td>
<td>10-min Hot Start</td>
<td></td>
<td>10-min Hot Start</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Emiss (g/s)</td>
<td>3.55</td>
<td>0.123</td>
<td>8.38</td>
<td>1.61E-02</td>
<td>8.03E-04</td>
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<tr>
<td>Time to Equil (sec)</td>
<td>78</td>
<td>80</td>
<td>10</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>Avg Start Emiss (g/s)</td>
<td>2.71</td>
<td>0.0785</td>
<td>3.14</td>
<td>8.46E-03</td>
<td>7.32E-04</td>
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<tr>
<td>Total 10-min Hot Start Emiss (g)</td>
<td>212</td>
<td>6.28</td>
<td>31.4</td>
<td>0.381</td>
<td>0.0439</td>
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<tr>
<td>Avg 10-min Idle Emiss (g/s)</td>
<td>2.35</td>
<td>0.0874</td>
<td>1.07</td>
<td>5.88E-03</td>
<td>5.48E-04</td>
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<tr>
<td>Total 10-min Idle Emiss (g)</td>
<td>1,413</td>
<td>52.4</td>
<td>641</td>
<td>3.53</td>
<td>0.329</td>
</tr>
<tr>
<td></td>
<td>20-min Start</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Emiss (g/s)</td>
<td>3.42</td>
<td>0.106</td>
<td>8.49</td>
<td>3.18E-02</td>
<td>7.71E-04</td>
</tr>
<tr>
<td>Time to Equil (sec)</td>
<td>98</td>
<td>98</td>
<td>8</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>Avg Start Emiss (g/s)</td>
<td>1.88</td>
<td>0.0515</td>
<td>3.58</td>
<td>1.02E-02</td>
<td>6.09E-04</td>
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<tr>
<td>Total 20-min Hot Start Emiss (g)</td>
<td>184</td>
<td>5.04</td>
<td>28.6</td>
<td>0.815</td>
<td>0.0457</td>
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<tr>
<td>Avg 20-min Idle Emiss (g/s)</td>
<td>2.25</td>
<td>0.0769</td>
<td>0.988</td>
<td>6.85E-03</td>
<td>5.57E-04</td>
</tr>
</tbody>
</table>
Average Equilibrium Times

Tier 0 Emission Equilibration Times

Tier 1 Emission Equilibration Times

NLEV Emission Equilibration Times

Tier 2 Emission Equilibration Times
Cold Start Emissions at Different Ambient Temperatures (2007 Dodge Ram 1500)

- HCs rate of change similar to MOVES2014 – until leveling off at approximately 7.5°C
  - also similar across temp’s of Sentoff et al. (2009)
- NO\textsubscript{x} more insensitive
  - MOVES2014 given as insensitive, but greater rate of change and opposite slope of this study
- CO also similar to MOVES2014
Tailpipe Drive Cycle Example

- 2007 Dodge Ram 1500 drive around emissions
- Three replicate, measured drive tests (Jan. 8, Feb. 13, Apr. 9, 2015)

2-13-15 2007 Dodge RAM 1500 Drive Cycle

- 5.6 total miles
- Approx. 12 minute transect
- Average speed: 25.8 mph
  - Max speed: 53.0 mph
- $T_{Amb} = -1.6^\circ C, 6.0^\circ C$ and $6.3^\circ C$
Tailpipe Drive Cycle Emissions

Following 2006 DOT study
(7 trips/starts & 29 VMT)...

Average Drive Cycle Emissions

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>CO</th>
<th>(as propane)</th>
<th>HC</th>
<th>O₂</th>
<th>(as NO) NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g/s)</td>
<td>4.97</td>
<td>0.029</td>
<td>4.93 x 10⁻⁴</td>
<td>0.063</td>
<td>4.72 x 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>3,839</td>
<td>22.1</td>
<td>0.380</td>
<td>49.1</td>
<td>0.364</td>
<td></td>
</tr>
<tr>
<td>(g/mi)</td>
<td>689</td>
<td>3.97</td>
<td>0.0683</td>
<td>8.80</td>
<td>0.0658</td>
<td></td>
</tr>
</tbody>
</table>

EPA, Tier 2 Bin Standards (120,000+ miles)
(CO₂ is for 2016 base, light trucks)

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>CO</th>
<th>(as propane)</th>
<th>HC</th>
<th>O₂</th>
<th>(as NO) NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g/mi)</td>
<td>298</td>
<td>4.20</td>
<td>0.09</td>
<td>8.20</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

This Study (Tier 2)       DOT, 2006 (NLEV)

<table>
<thead>
<tr>
<th></th>
<th>This Study (Tier 2)</th>
<th>DOT, 2006 (NLEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCs (g)</td>
<td>3.1</td>
<td>15.5</td>
</tr>
<tr>
<td>CO (g)</td>
<td>155</td>
<td>339</td>
</tr>
<tr>
<td>NOₓ (g)</td>
<td>1.8</td>
<td>25.2</td>
</tr>
</tbody>
</table>