Comparison of Real-World Vehicle Emissions for Gasoline-Ethanol Fuel Blends

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PORTABLE EMISSIONS MEASUREMENT SYSTEMS INTERNATIONAL CONFERENCE & WORKSHOP
University of California at Riverside
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Background and Motivation

- Splash Blend versus Match Blend
- Role of Octane
  - Spark timing advance
  - May affect chemical residence time for combustion reactions
  - May affect combustion efficiency, emissions
- How well do vehicles adapt to fuel blends
  - Flex Fuel Vehicles – ethanol sensor
  - Non-FFVs: Long-term fuel trim
Objective

Evaluate the effect of gasoline ethanol blends on real-world fuel use and emission rates
Study Design

- Fuels
- Vehicles
- Routes
- Instruments
Fuels

- E0 (neat gasoline)
- E10R (10% ethanol by volume) Regular
- E10P Premium
- E25 (splash blended with E10R)
Fuel Sampling and Blending
# Selected Fuel Properties

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heating Value (BTU/gal)</th>
<th>Composition</th>
<th>Distillation</th>
<th>PMI</th>
<th>AKI</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>O (wt%)</td>
<td>Aromatics (wt%)</td>
<td>$T_{50}$ (°F)</td>
<td>$T_{90}$ (°F)</td>
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<tr>
<td>E0</td>
<td>115,700</td>
<td>0.0</td>
<td>41</td>
<td>226</td>
<td>322</td>
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<tr>
<td>E10R</td>
<td>110,000</td>
<td>4.1</td>
<td>28</td>
<td>155</td>
<td>321</td>
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<tr>
<td>E10P</td>
<td>110,800</td>
<td>3.8</td>
<td>39</td>
<td>198</td>
<td>316</td>
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<tr>
<td>E25</td>
<td>103,700</td>
<td>10.5</td>
<td>22</td>
<td>163</td>
<td>307</td>
</tr>
</tbody>
</table>
Measured Vehicles

2016 Ford Focus GDI

2017 Chevrolet Cruze GDI TC

2018 Toyota Camry GDI

2017 Chevrolet Equinox GDI, FFV

2016 Nissan Quest PFI
Portable Emission Measurement System (PEMS)
Results

• Driving Cycles
• Engine Performance
  – Ignition Timing Advance
  – Long-Term Fuel Trim
• Fuel Use and Emission Rates
  – VSP (Vehicle Specific Power) Modal Analysis
  – Cycle-Average Analysis
  – Statistical Significance
Driving Cycles: Route 1 (Inbound)

Example: 2018 Toyota Camry, Route 1-inbound

![Graph showing speed vs distance for different fuel types (E0, E10R, E10P, E25).]
Ignition Timing Advance vs. Calculated Load: Cruze

Note: Error bars are 95% confidence intervals based on mean ignition timing advance for each engine calculated load bin for the Cruze.
Long-Term Fuel Trim (LTFT)

Note: Error bars are 95% confidence intervals based on average LTFT for each vehicle/fuel measurement.
Estimating Vehicle Fuel Use Based on Vehicle Specific Power (VSP)

\[ VSP = \nu \left\{ a \left( 1 + \varepsilon \right) + gr + gC_R \right\} + \frac{1}{2} \rho \nu^3 \left( \frac{C_D A}{m} \right) \]

Where

- \( a \) = vehicle acceleration (m/s\(^2\))
- \( A \) = vehicle frontal area (m\(^2\))
- \( C_D \) = aerodynamic drag coefficient (dimensionless)
- \( C_R \) = rolling resistance coefficient (dimensionless, ~ 0.0135)
- \( g \) = acceleration of gravity (9.8 m/s\(^2\))
- \( m \) = vehicle mass (in metric tons)
- \( r \) = road grade
- \( \nu \) = vehicle speed (m/s)
- \( VSP \) = Vehicle Specific Power (kw/ton)
- \( \varepsilon \) = factor accounting for rotational masses (~ 0.1)
- \( \rho \) = ambient air density (1.207 kg/m\(^3\) at 20 °C)
Definition of VSP Modes

<table>
<thead>
<tr>
<th>VSP mode</th>
<th>Definition (kW/ton)</th>
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<tbody>
<tr>
<td>1</td>
<td>VSP &lt; -2</td>
</tr>
<tr>
<td>2</td>
<td>-2 ≤ VSP &lt; 0</td>
</tr>
<tr>
<td>3</td>
<td>0 ≤ VSP &lt; 1</td>
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<td>1 ≤ VSP &lt; 4</td>
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<td>5</td>
<td>4 ≤ VSP &lt; 7</td>
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<td>6</td>
<td>7 ≤ VSP &lt; 10</td>
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<td>7</td>
<td>10 ≤ VSP &lt; 13</td>
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<td>8</td>
<td>13 ≤ VSP &lt; 16</td>
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<td>9</td>
<td>16 ≤ VSP &lt; 19</td>
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<td>10</td>
<td>19 ≤ VSP &lt; 23</td>
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<td>11</td>
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<tr>
<td>12</td>
<td>28 ≤ VSP &lt; 33</td>
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<tr>
<td>13</td>
<td>33 ≤ VSP &lt; 39</td>
</tr>
<tr>
<td>14</td>
<td>VSP Over 39</td>
</tr>
</tbody>
</table>

Deceleration or Downhill

Idle

Cruising, Acceleration, or Uphill
Note: Error bars are 95% confidence intervals based on mean fuel use rates for 5 vehicles for each VSP mode.
Note: Error bars are 95% confidence intervals based on mean cycle-average fuel economy for 5 vehicles for each driving cycle.
Cycle Average Analysis – Energy Efficiency

Note: Error bars are 95% confidence intervals based on mean cycle-average energy efficiency for 5 vehicles for each driving cycle.
Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average CO emission rates for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.
Cycle Average Analysis – PM

Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM emission rates for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.
Cycle Average Analysis – PM1 Index

Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM1 index for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.
Cycle Average Analysis – PM2 Index

Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM2 index for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.
Cycle Average Analysis – PM3 Index

Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM3 index for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.
## P-values for Paired-t Test – Fuel Economy

<table>
<thead>
<tr>
<th>Pairs</th>
<th>Driving Cycles</th>
<th></th>
<th></th>
<th></th>
<th>FTP</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>C</td>
<td>1</td>
<td>3</td>
<td>FTP</td>
<td>HFET</td>
<td>US06</td>
<td>SC03</td>
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<tr>
<td>E10R &lt; E0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
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<td>E10P &gt; E10R</td>
<td>0.21</td>
<td>0.19</td>
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<td>0.29</td>
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<tr>
<td>E25 &lt; E10R</td>
<td>0.11</td>
<td>0.14</td>
<td>0.63</td>
<td>0.43</td>
<td>0.01</td>
<td>0.13</td>
<td>0.78</td>
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<td>E25 &lt; E0</td>
<td>0.00</td>
<td>0.01</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>E25 &lt; E10P</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
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<td>0.05</td>
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<tr>
<td>E10P &lt; E0</td>
<td>0.62</td>
<td>0.63</td>
<td>0.63</td>
<td>0.62</td>
<td>0.68</td>
<td>0.60</td>
<td>0.62</td>
<td>0.68</td>
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### P-values for Paired-t Test – CO₂

<table>
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<td>A</td>
</tr>
<tr>
<td>E10R &lt; E0</td>
<td>0.49</td>
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<tr>
<td>E10P &lt; E10R</td>
<td>0.89</td>
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<tr>
<td>E25 &lt; E10R</td>
<td>0.17</td>
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<tr>
<td>E25 &lt; E0</td>
<td>0.05</td>
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<tr>
<td>E25 &lt; E10P</td>
<td>0.44</td>
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<tr>
<td>E10P &lt; E0</td>
<td>0.59</td>
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### P-values for Paired-t Test – CO

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<th>FTP</th>
<th>HFET</th>
<th>US06</th>
<th>SC03</th>
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<tbody>
<tr>
<td>E0 &lt; E10R</td>
<td>0.50</td>
<td>0.41</td>
<td>0.20</td>
<td>0.23</td>
<td>0.85</td>
<td>0.71</td>
<td>0.18</td>
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<tr>
<td>E10R &lt; E10P</td>
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<td>0.67</td>
<td>0.69</td>
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<td>0.59</td>
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<td>0.10</td>
<td>0.04</td>
<td>0.09</td>
<td>0.05</td>
<td>0.54</td>
<td>0.28</td>
<td>0.12</td>
<td>0.31</td>
</tr>
<tr>
<td>E25 &lt; E0</td>
<td>0.50</td>
<td>0.39</td>
<td>0.22</td>
<td>0.31</td>
<td>0.51</td>
<td>0.33</td>
<td>0.20</td>
<td>0.49</td>
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<tr>
<td>E25 &lt; E10P</td>
<td>0.29</td>
<td>0.28</td>
<td>0.21</td>
<td>0.25</td>
<td>0.37</td>
<td>0.21</td>
<td>0.23</td>
<td>0.36</td>
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<tr>
<td>E0 &lt; E10P</td>
<td>0.52</td>
<td>0.54</td>
<td>0.72</td>
<td>0.60</td>
<td>0.55</td>
<td>0.41</td>
<td>0.95</td>
<td>0.56</td>
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</table>
Findings

• E25, splash-blended from E10R, had
  – low aromatic content
  – low PM index
  – Low $T_{90}$
  – Lower $T_{50}$ except for E10R
  – Higher AKI octane except for E10P

• E0 and E10P had similar aromatic content

• PM indices were relatively high for E0, E10R, and E10P
Findings

• Able to obtain similar (although not identical) driving cycles when running real-world routes
• Ignition timing advance for the Cruze appeared to be sensitive to octane.
• Ignition timing advance for other vehicles did not change much among the fuels
• FFV was able to detect ethanol content
• Non-FFVs adjusted long-term fuel-trim during the conditioning trip
Findings

• There were few statistically significant differences between fuels:
  – Fuel Economy: E0 highest, E25 lowest
  – Energy economy: was slightly better for E25 and E10P versus E0 and E10R
  – \( \text{CO}_2 \) emissions were lower for E25 vs. E0
  – CO, PM, PM1 (scattering), PM2 (ionization) tends to be lower for E25 than other fuels, but not significantly
  – No significant differences for NO, HC
Conclusions

• Results imply sensitivity to:
  – Ethanol content (e.g., potentially lower CO)
  – Aromatic content (e.g., the fuel with lowest aromatic content tends to have lower PM emission rates)
  – Octane rating (e.g., effect on spark timing advance for one of the vehicles)

• Although only suggestive, the apparent small increase in energy efficiency for E25 is consistent with literature

• Non-FFVs easily adapted to E25 based on change in long term fuel trim
Conclusions

- The scattering, ionization, and opacity indices of the ParSYNC appear to provide complementary information.
- Merits further investigation (e.g., also see talks by Trevits, Ropkins).
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• Per my talk at CRC, need a larger vehicle sample size 😊
Conclusions

• The scattering, ionization, and opacity indices of the ParSYNC appear to provide complementary information

• Merits further investigation (e.g., also see talks by Trevits, Ropkins)

• Per my talk at CRC, need a larger vehicle sample size 😊

• As my academic colleagues say: “more research is needed”
Acknowledgements

• This work was funded by the Urban Air Initiative
THANK YOU
# Vehicle Characteristics

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<tbody>
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<td>Equinox</td>
<td>SUV</td>
<td>4</td>
<td>2.4</td>
<td>NA</td>
<td>GDI</td>
<td>11.2</td>
<td>Y</td>
<td>6</td>
<td>17K</td>
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<tr>
<td>Cruze</td>
<td>Sedan</td>
<td>4</td>
<td>1.4</td>
<td>TC</td>
<td>GDI</td>
<td>9.5</td>
<td>N</td>
<td>6</td>
<td>22K</td>
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<td>Camry</td>
<td>Sedan</td>
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<td>NA</td>
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<td>PFI</td>
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<td>N</td>
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<td>Focus</td>
<td>Sedan</td>
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<td>GDI</td>
<td>12.0</td>
<td>N</td>
<td>6</td>
<td>37K</td>
</tr>
</tbody>
</table>
Switching Fuels

- Standard procedure of fuel switching:
  1. defuel original fuel
  2. add 1 gal new fuel
  3. defuel the 1 gal new fuel
  4. add new fuel
  5. disconnect battery terminals for 1 min then reconnect (except Equinox FFV)
  6. conditioning for new fuel by driving 29 (±1) miles for ~ 40 min (except Equinox FFV)
  7. emissions test
  8. verify fuel conditioning based on long-term fuel trim
Drivers

• Drivers:
  - One driver per vehicle for all fuels
    o Two drivers in total
    o Driver #1: Equinox
    o Driver #2: Cruze, Camry, Quest, and Focus
  - Both drivers were trained on use of cruise control and waypoints.
Fuel Conditioning Route in Raleigh

Legend
- Conditioning Route
- Fuel Shed
- Lab

Length: 29 mi

Cruze, Camry, Quest, Focus
## Test Conditions

<table>
<thead>
<tr>
<th>Test Order</th>
<th>Vehicle</th>
<th>Order of Fuels</th>
<th>Weather Condition $[\mu(\pm\sigma)]^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Equinox</td>
<td>E25</td>
<td>E10P</td>
</tr>
<tr>
<td>2</td>
<td>Cruze</td>
<td>E10R</td>
<td>E25</td>
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<td>3</td>
<td>Camry</td>
<td>E10R</td>
<td>E0</td>
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<td>4</td>
<td>Quest</td>
<td>E10R</td>
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</tr>
<tr>
<td>5</td>
<td>Focus</td>
<td>E10R</td>
<td>E0</td>
</tr>
</tbody>
</table>

* standard deviation is based on the daily variability for four-day measurement periods for four fuels.
Axion PEMS

Portable Emissions Measurement System (PEMS):
Carbon Dioxide (CO₂), CO, and Hydrocarbons (HC) - NDIR
Nitric Oxide (NO) – electrochemical
PM – laser light scattering

Global Positioning System (GPS) Receivers with Barometric Altimeter
On-board Diagnostic Data Logger (OBD)
ParSYNC PEMS

- ParSYNC PEMS manufactured by 3DATX
- PM:
  - Light-scattering (PM1 index)
  - Ionization (PM2 index)
  - Opacity (PM3 index)
  - Used for relative comparisons
Driving Cycles: Route C (Outbound)

Example: 2018 Toyota Camry, Route C-outbound

![Graph showing speed vs. distance for different driving cycles.]

- E0
- E10R
- E10P
- E25
Ignition Timing Advance vs. Calculated Load: Camry

Camry:

Note: Error bars are 95% confidence intervals based on mean ignition timing advance for each engine calculated load bin for the Camry.
Example of Fuel Conditioning:

**Adjustment in Long Term Fuel Trim**

**Fuel Conditioning:**

**Example:** Cruze, from E10R (old fuel) to E25 (new fuel)