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


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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

| Fuel | Heating Value (BTU/gal) | Composition | | Distillation | | PMI | AKI |
|---|---|---|---|---|---|---|---|
| | | O (wt%) | Aromatics (wt%) | $T_{50}$ (°F) | $T_{90}$ (°F) | | |
| E0 | 115,700 | 0.0 | 41 | 226 | 322 | 1.9 | 90 |
| E10R | 110,000 | 4.1 | 28 | 155 | 321 | 1.7 | 88 |
| E10P | 110,800 | 3.8 | 39 | 198 | 316 | 1.7 | 93 |
| E25 | 103,700 | 10.5 | 22 | 163 | 307 | 1.4 | 92 |

# Measured Vehicles

2016 Ford Focus GDI

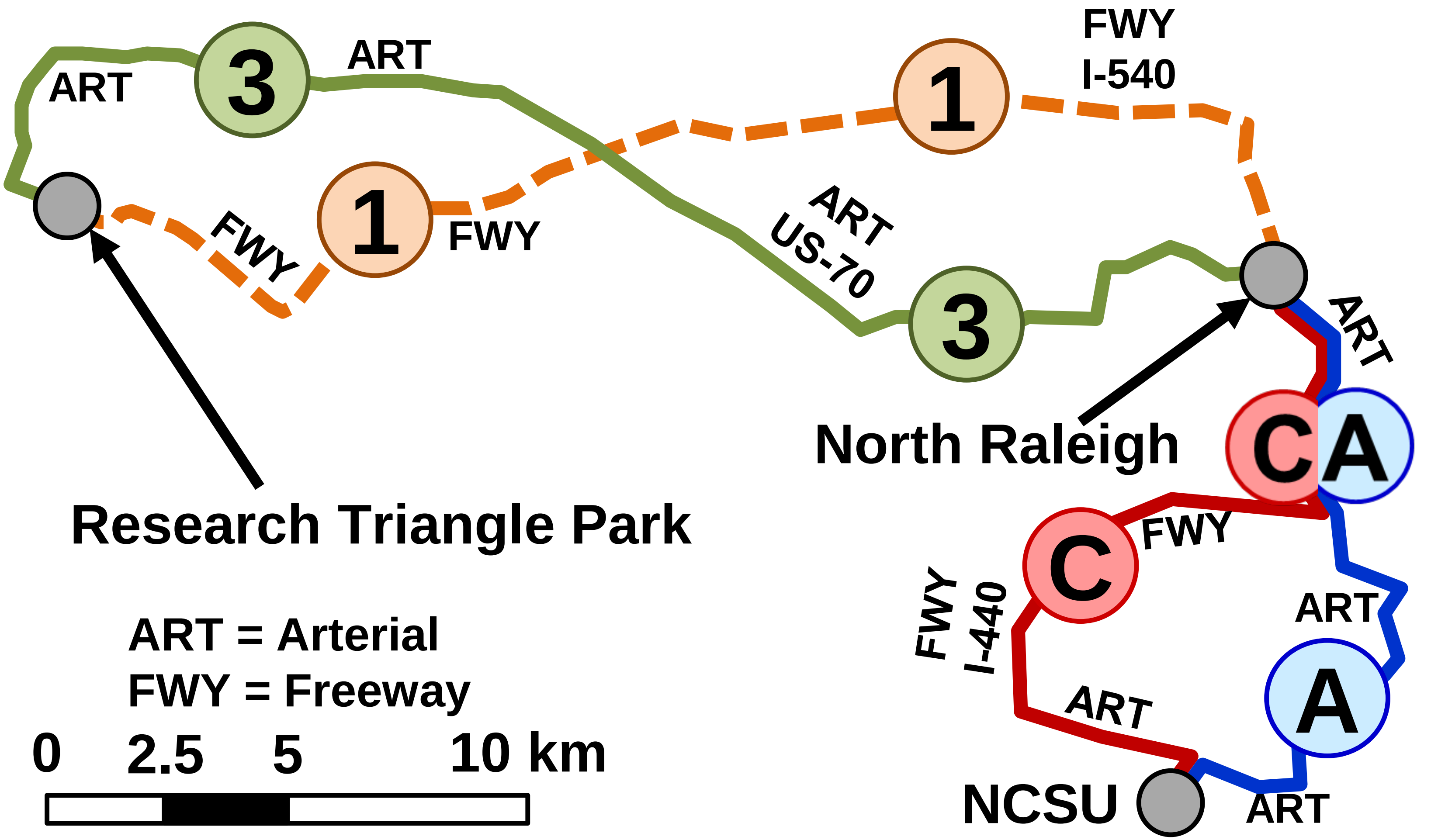
2017 Chevrolet Cruze GDI TC

2018 Toyota Camry GDI

2017 Chevrolet Equinox GDI, FFV

2016 Nissan Quest PFI

# Test Routes in Raleigh



# Portable Emission Measurement Systems (PEMS)

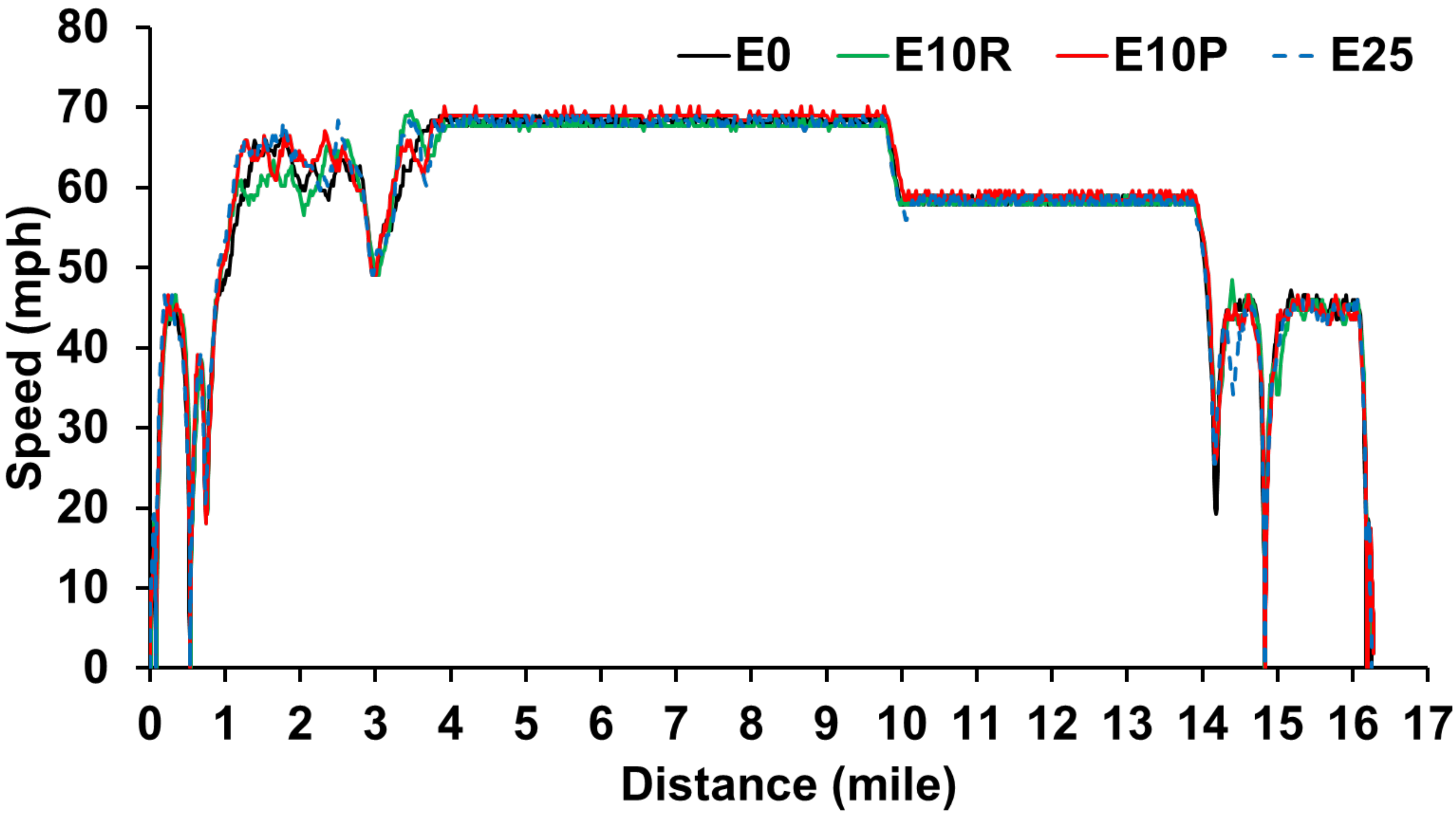



# Results

- 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



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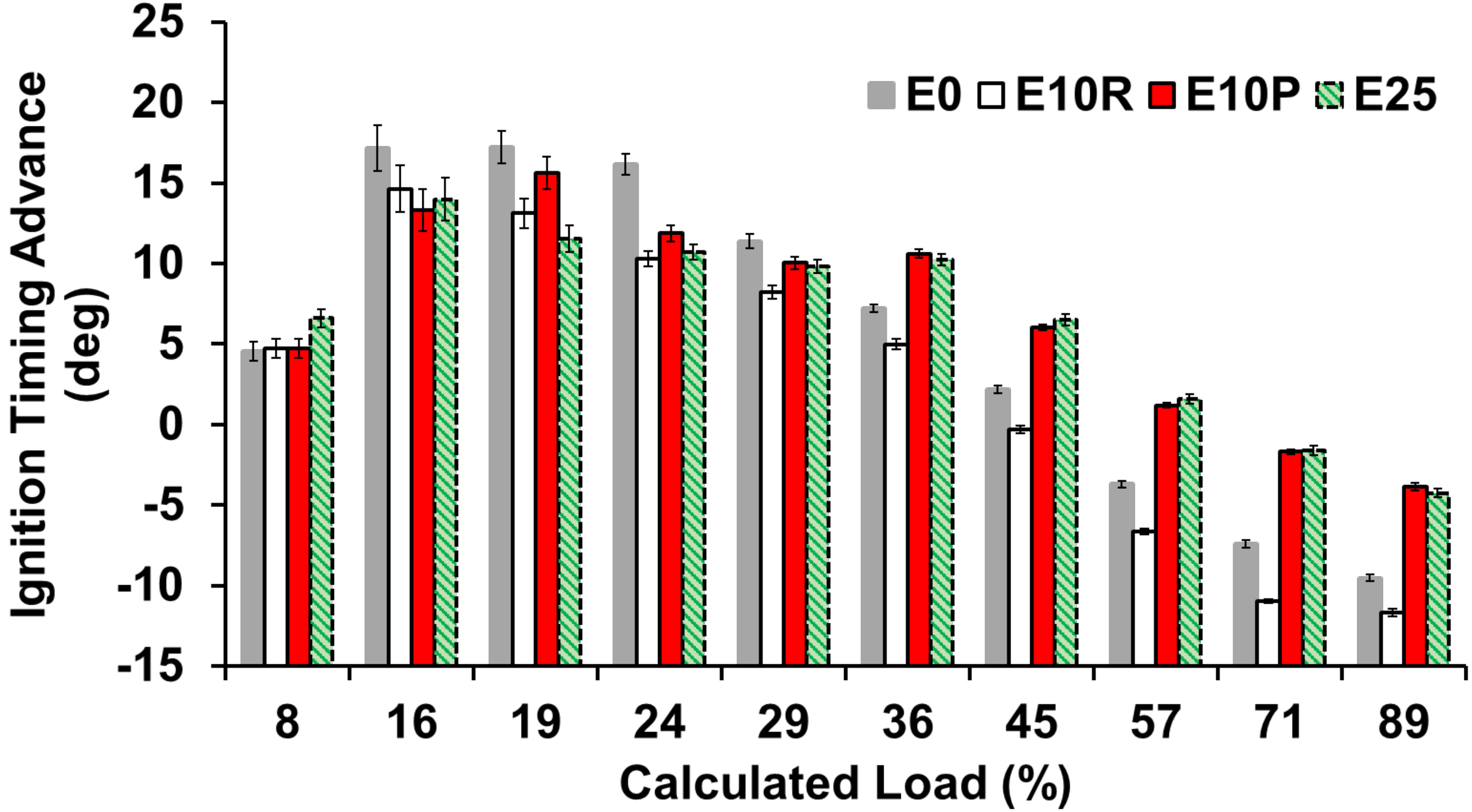
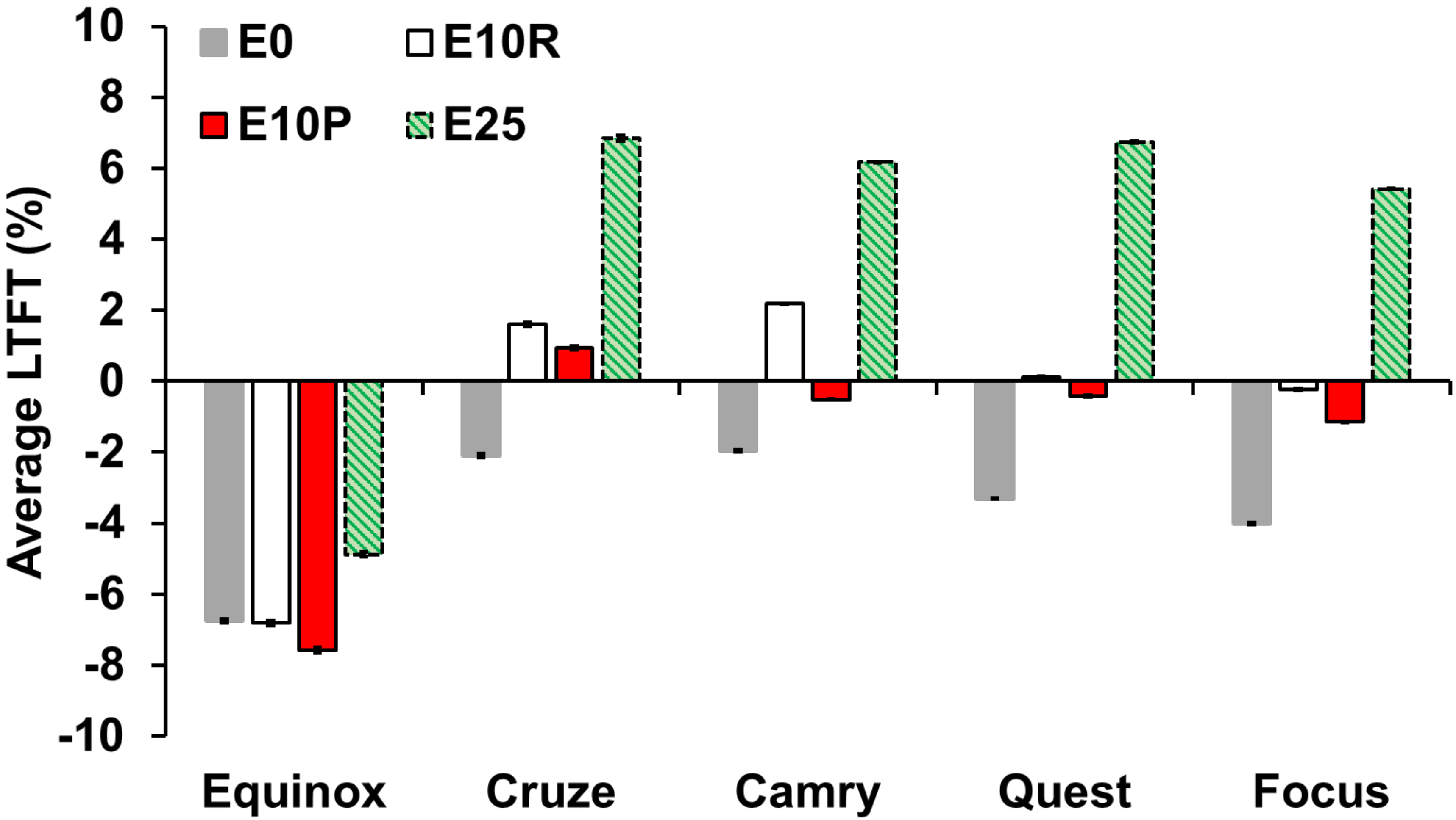
# Ignition Timing Advance vs. Calculated Load: 2017 Chevrolet Cruze




*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.*

# Vehicle Specific Power (VSP)

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

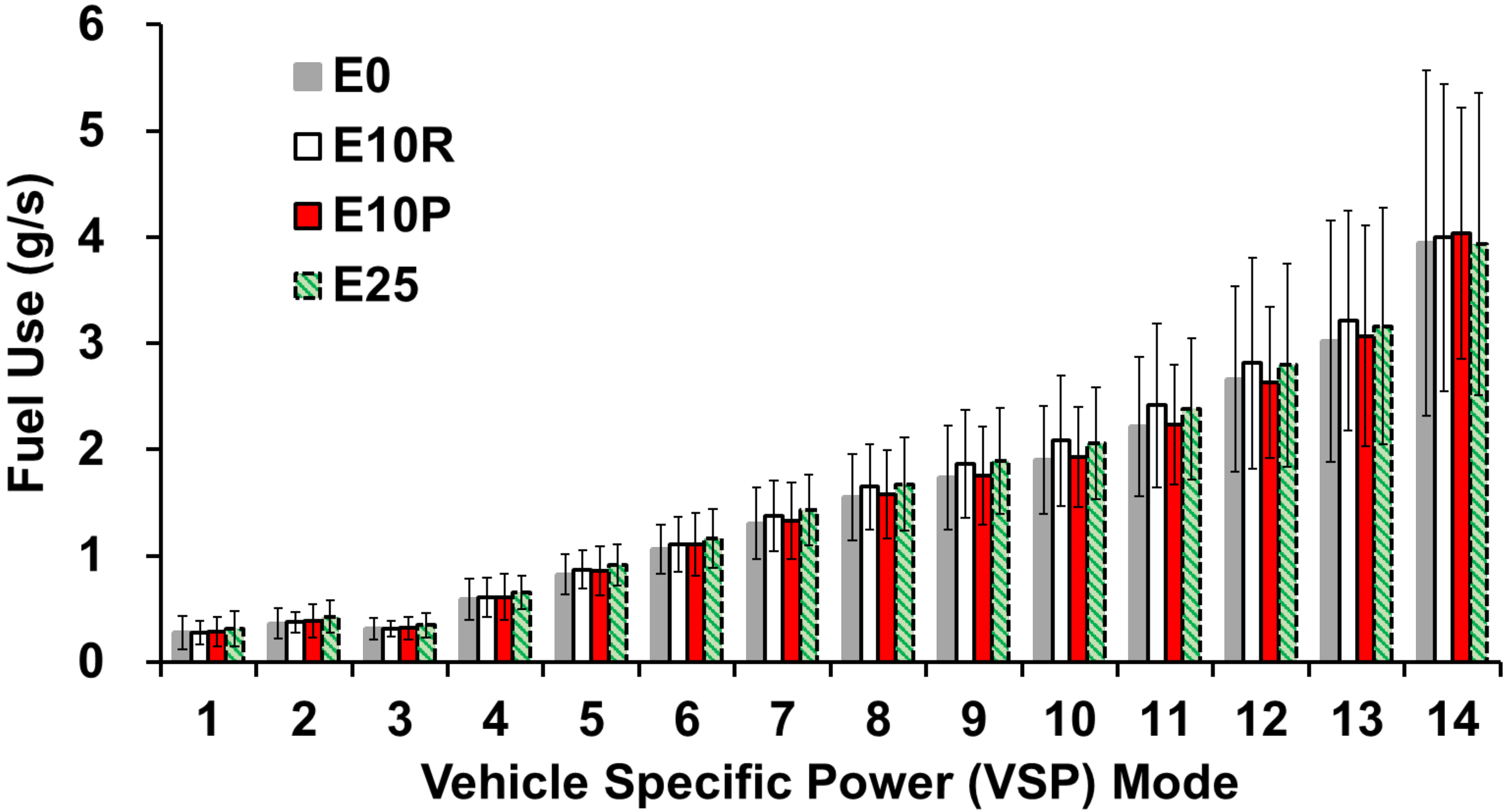
Where

| | |
|---|---|
| $a$ | = 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 |
| $v$ | = 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 $^o$C) |

# Vehicle Specific Power Modes

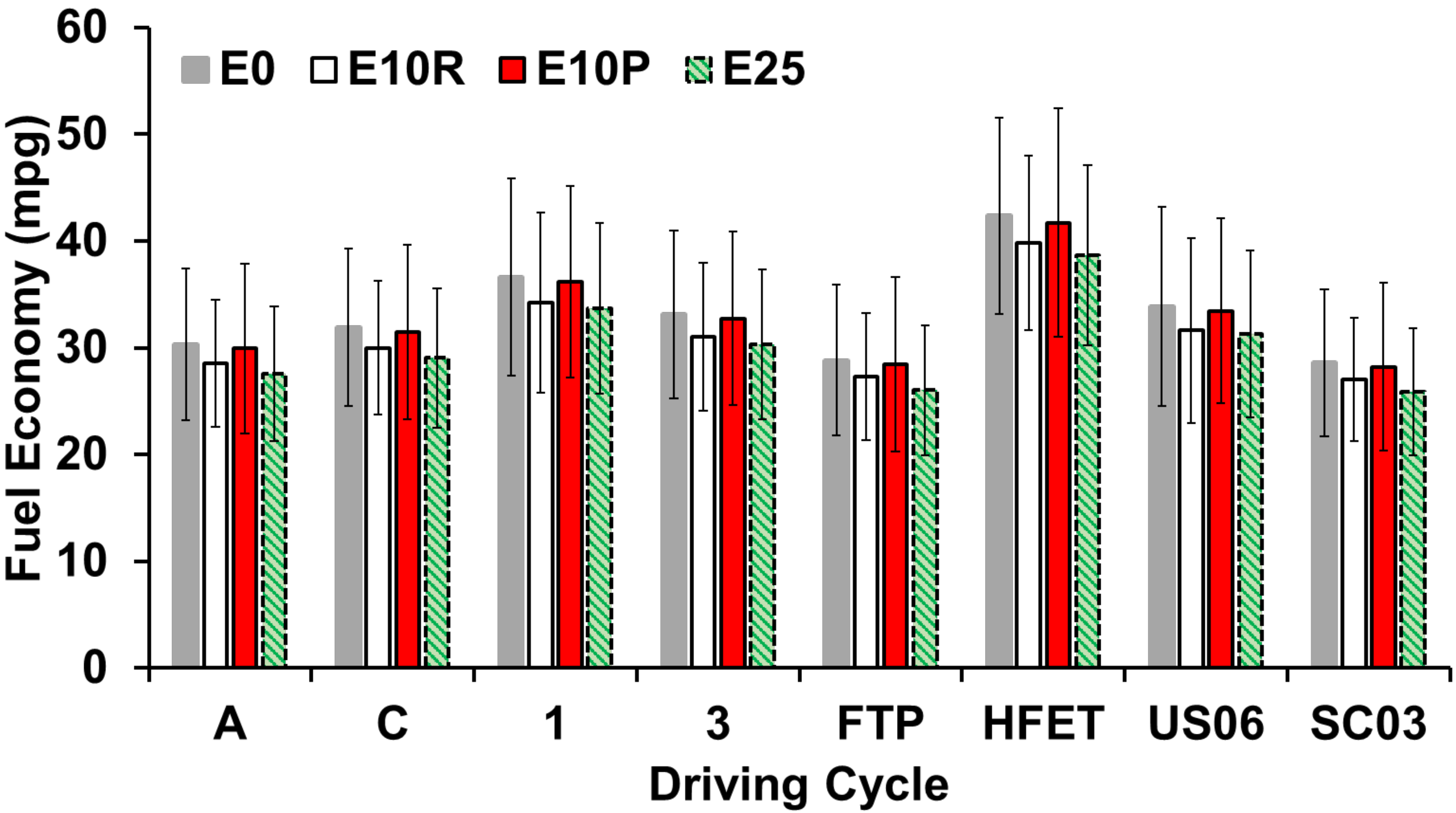
| | VSP mode | Definition (kW/ton) |
|---|---|---|
| Deceleration or Downhill | 1 | VSP < -2 |
| | 2 | -2 ≤ VSP < 0 |
| Idle | 3 | 0 ≤ VSP < 1 |
| Cruising, Acceleration, or Uphill | 4 | 1 ≤ VSP < 4 |
| | 5 | 4 ≤ VSP < 7 |
| | 6 | 7 ≤ VSP < 10 |
| | 7 | 10 ≤ VSP < 13 |
| | 8 | 13 ≤ VSP < 16 |
| | 9 | 16 ≤ VSP < 19 |
| | 10 | 19 ≤ VSP < 23 |
| | 11 | 23 ≤ VSP < 28 |
| | 12 | 28 ≤ VSP < 33 |
| | 13 | 33 ≤ VSP < 39 |
| | 14 | VSP Over 39 |

# VSP Modal Average Fuel Use Rate By Fuel




*Note: Error bars are 95% confidence intervals based on mean fuel use rates for 5 vehicles for each VSP mode.*

# Cycle Average Fuel Economy




*Note: Error bars are 95% confidence intervals based on mean cycle-average fuel economy for 5 vehicles for each driving cycle.*

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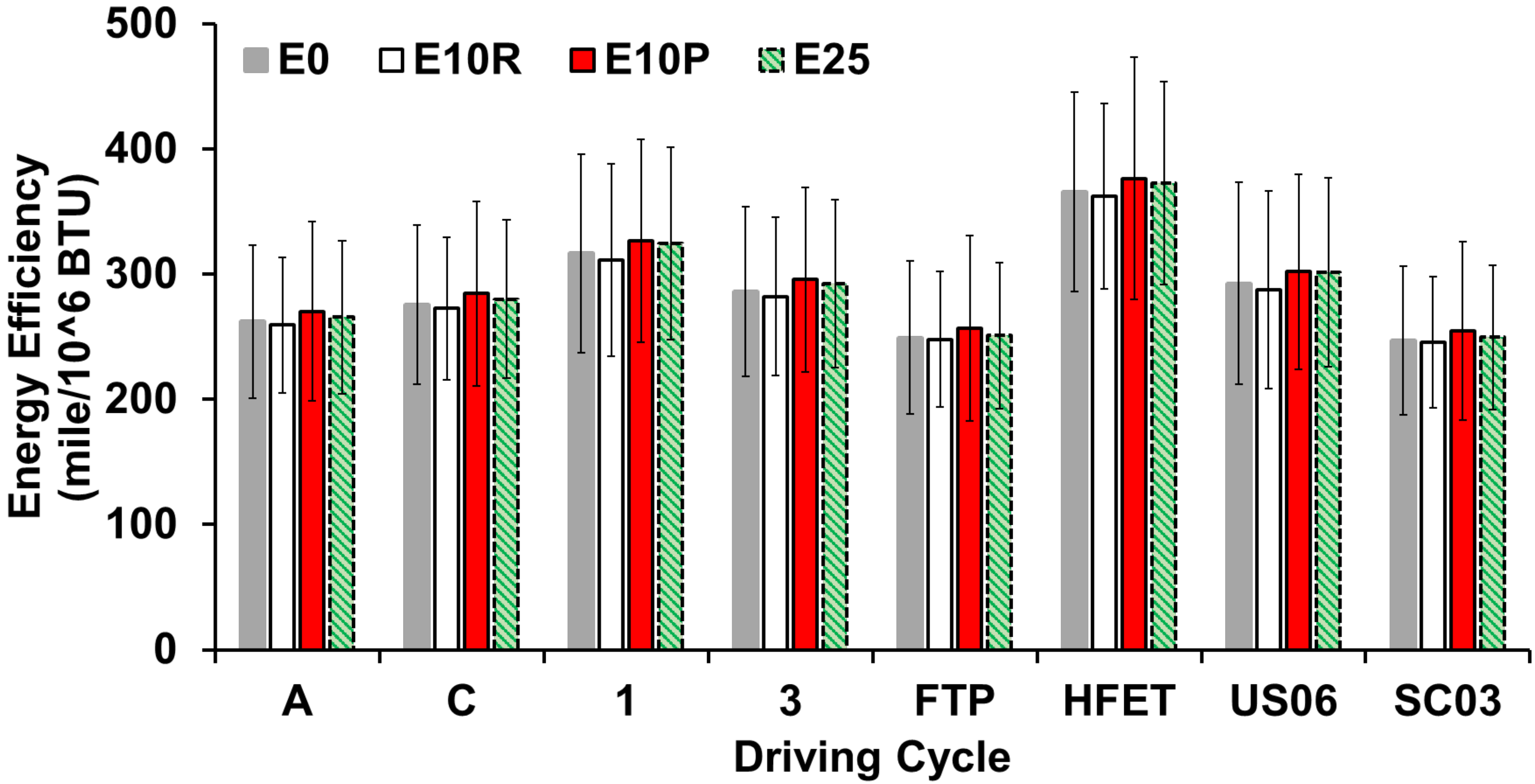
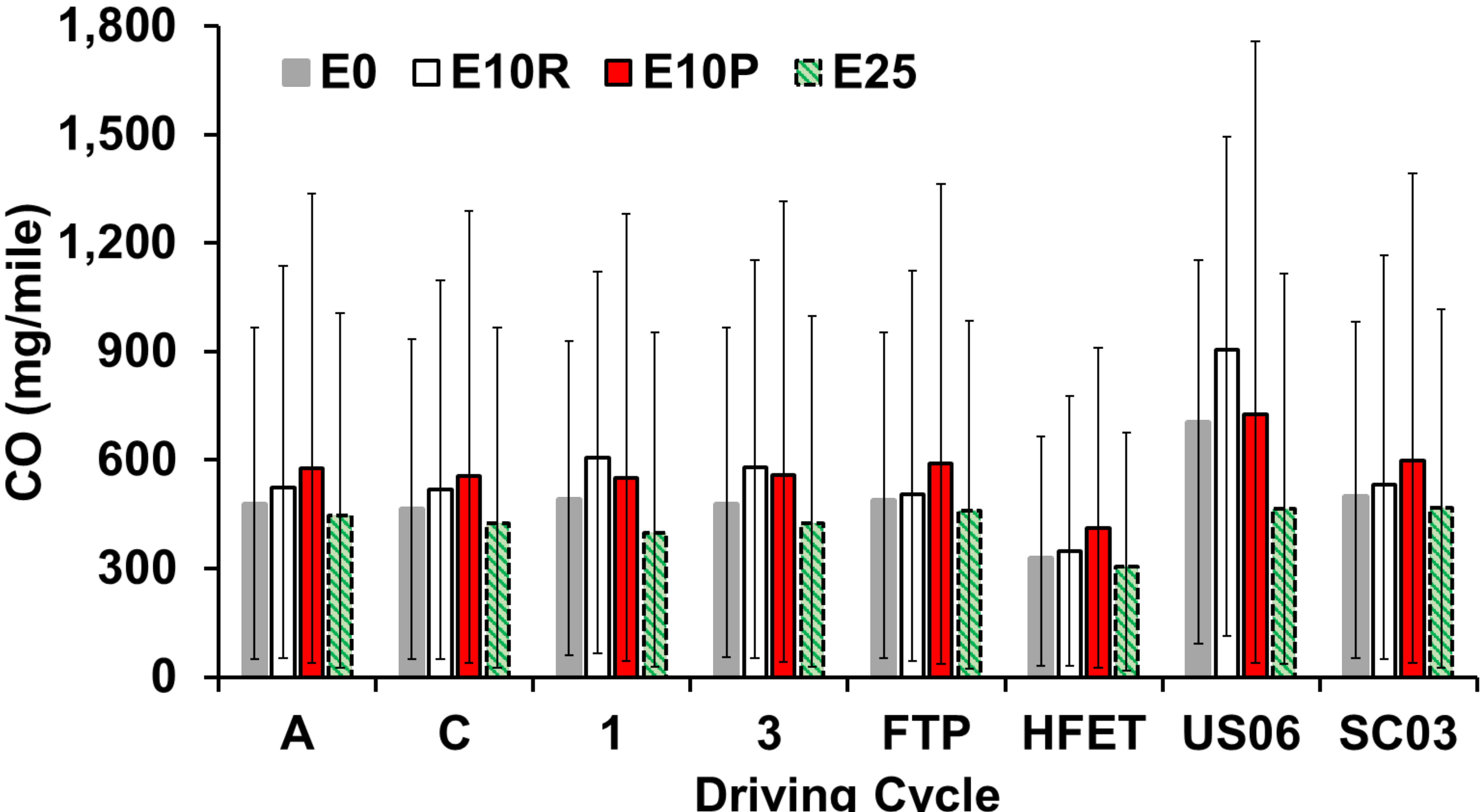
# Cycle Average Energy Efficiency



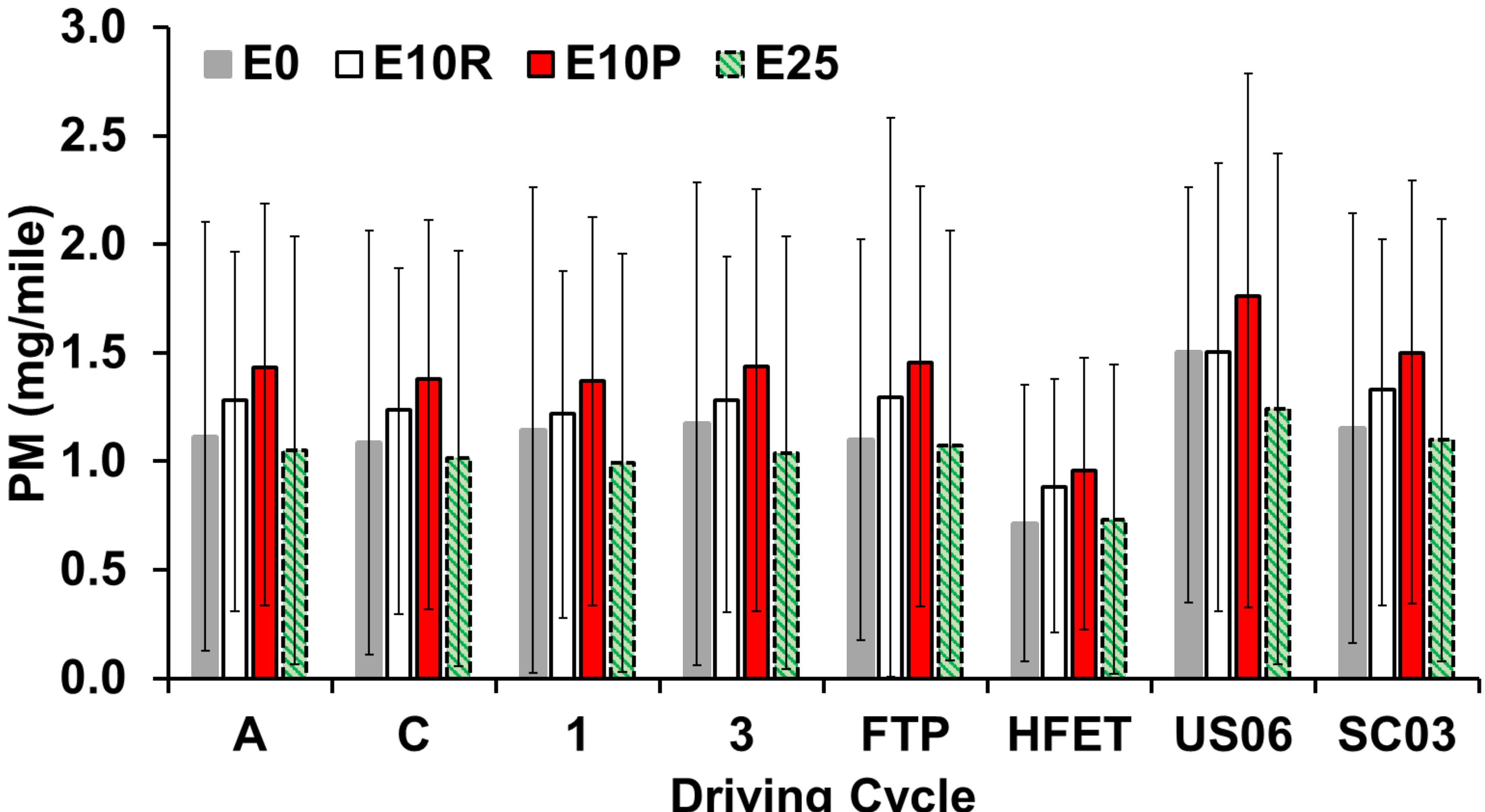

*Note: Error bars are 95% confidence intervals based on mean cycle-average energy efficiency for 5 vehicles for each driving cycle.*

# Cycle Average CO Emission Rates



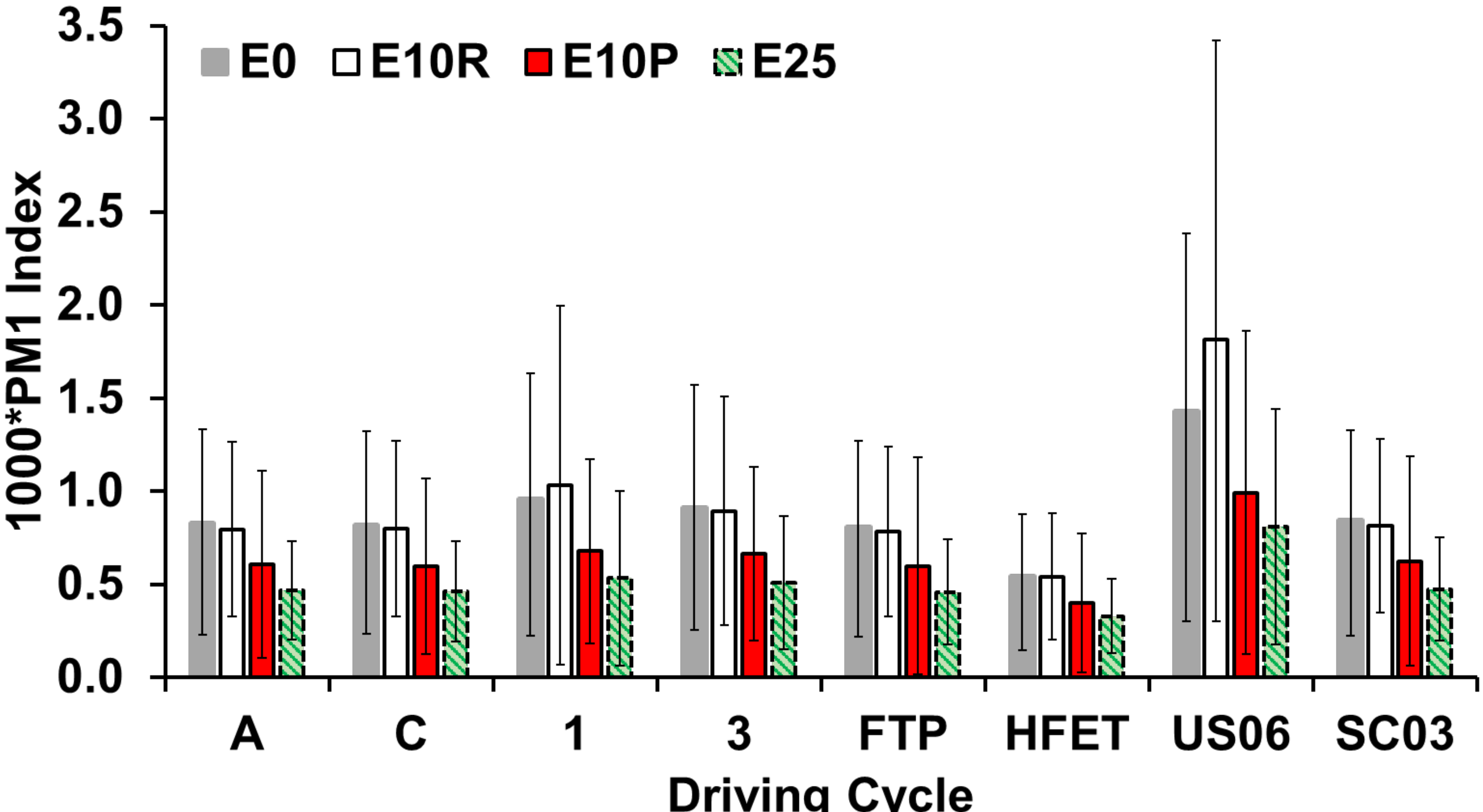

*Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average CO emission rates for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.*

# Cycle Average PM Emission Rate (Axion)



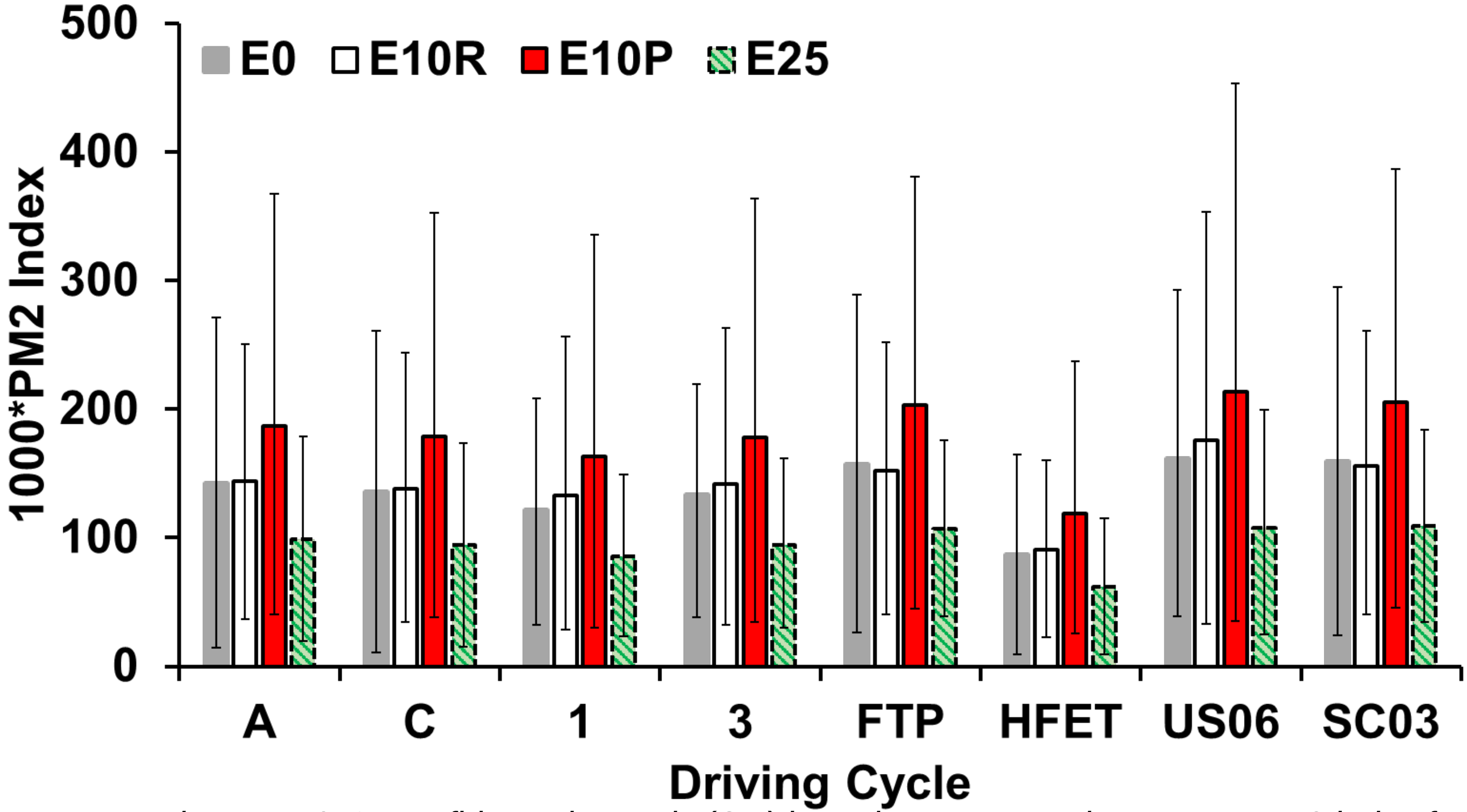

*Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM emission rates for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.*

# Cycle Average Scattering PM Index (ParSYNC)



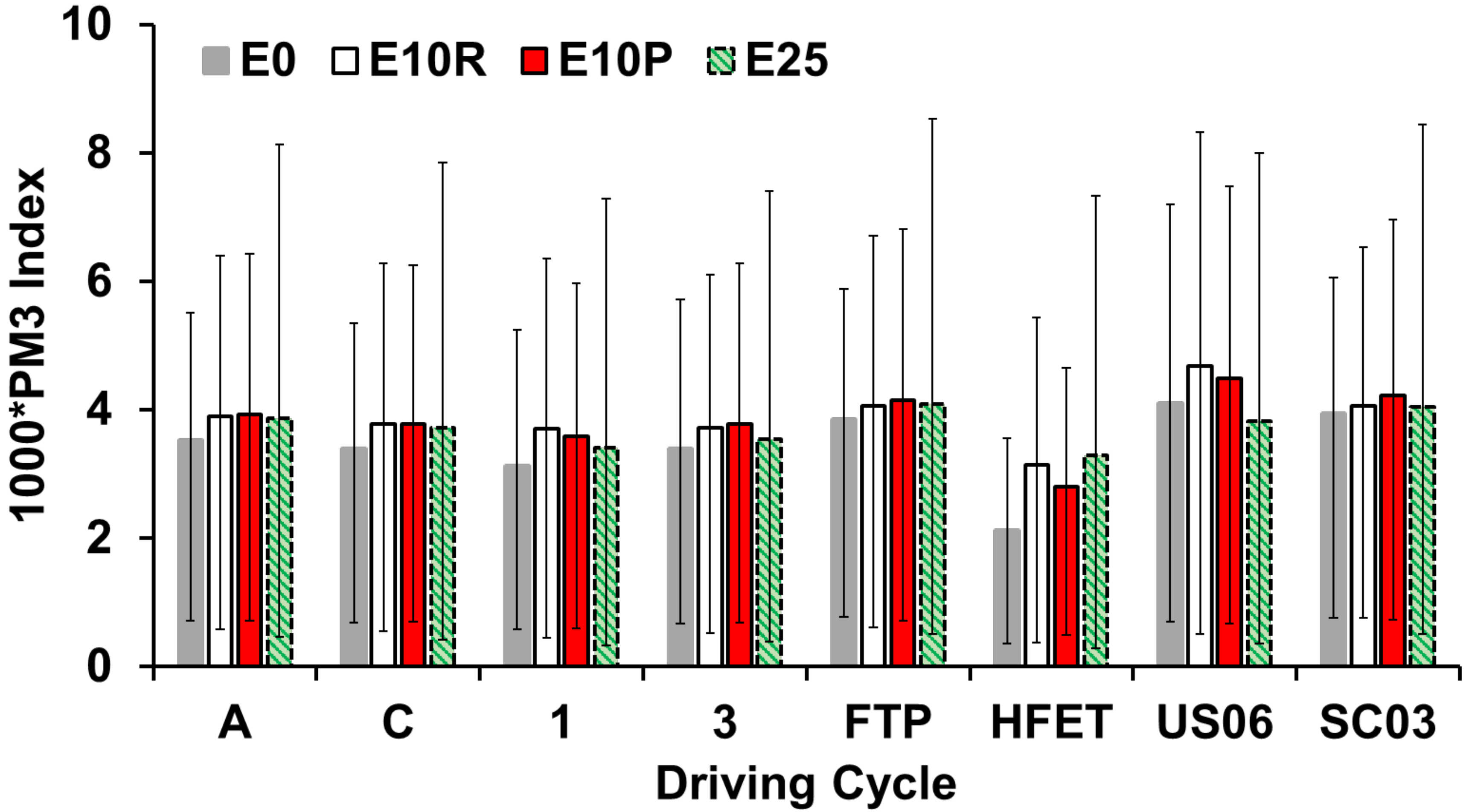

*Note: Error bars are 95% confidence intervals (CIs) based on mean cycle-average PM1 index for 5 vehicles for each driving cycle, and are estimated using bootstrap resampling for negative CIs.*

# Cycle Average Ionization PM Index (ParSYNC)




*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 Opacity PM Index (ParSYNC)




*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 Tests
# Cycle Average Fuel Economy

| Pairs | Driving Cycles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | C | 1 | 3 | FTP | HFET | US06 | SC03 |
| **E10R < E0** | 0.01 | 0.01 | 0.00 | 0.01 | 0.02 | 0.00 | 0.01 | 0.02 |
| **E10P > E10R** | 0.21 | 0.19 | 0.13 | 0.14 | 0.29 | 0.23 | 0.10 | 0.26 |
| **E25 < E10R** | 0.11 | 0.14 | 0.63 | 0.43 | 0.01 | 0.13 | 0.78 | 0.01 |
| **E25 < E0** | 0.00 | 0.01 | 0.04 | 0.02 | 0.00 | 0.00 | 0.07 | 0.00 |
| **E25 < E10P** | 0.03 | 0.02 | 0.01 | 0.01 | 0.07 | 0.04 | 0.02 | 0.05 |
| **E10P < E0** | 0.62 | 0.63 | 0.63 | 0.62 | 0.68 | 0.60 | 0.62 | 0.68 |

# P-values for Paired-t Tests: Cycle Average $CO_2$ Emission Rates

| Pairs | Driving Cycles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | C | 1 | 3 | FTP | HFET | US06 | SC03 |
| E10R < E0 | 0.49 | 0.49 | 0.85 | 0.74 | 0.40 | 0.42 | 0.77 | 0.41 |
| E10P < E10R | 0.89 | 0.81 | 0.40 | 0.53 | 0.89 | 0.88 | 0.30 | 0.95 |
| E25 < E10R | 0.17 | 0.13 | 0.14 | 0.14 | 0.27 | 0.07 | 0.17 | 0.20 |
| E25 < E0 | 0.05 | 0.05 | 0.09 | 0.07 | 0.06 | 0.03 | 0.11 | 0.05 |
| E25 < E10P | 0.44 | 0.37 | 0.15 | 0.13 | 0.64 | 0.27 | 0.22 | 0.59 |
| E10P < E0 | 0.59 | 0.53 | 0.35 | 0.36 | 0.76 | 0.66 | 0.35 | 0.70 |

# P-values for Paired-t Tests: Cycle Average CO Emission Rates

| Pairs | Driving Cycles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | C | 1 | 3 | FTP | HFET | US06 | SC03 |
| E0 < E10R | 0.50 | 0.41 | 0.20 | 0.23 | 0.85 | 0.71 | 0.18 | 0.69 |
| E10R < E10P | 0.54 | 0.67 | 0.69 | 0.84 | 0.37 | 0.28 | 0.59 | 0.47 |
| E25 < E10R | 0.10 | 0.04 | 0.09 | 0.05 | 0.54 | 0.28 | 0.12 | 0.31 |
| E25 < E0 | 0.50 | 0.39 | 0.22 | 0.31 | 0.51 | 0.33 | 0.20 | 0.49 |
| E25 < E10P | 0.29 | 0.28 | 0.21 | 0.25 | 0.37 | 0.21 | 0.23 | 0.36 |
| E0 < E10P | 0.52 | 0.54 | 0.72 | 0.60 | 0.55 | 0.41 | 0.95 | 0.56 |

# 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
  - $CO_2$ emissions were lower for E25 vs. E0
  - CO, PM, PM Index 1 (scattering), PM2 Index 2 (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)
- 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 byTrevits, Ropkins)
- Larger vehicle sample needed to obtain statistically significant comparisons between fuels for some of the emission rates

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# Acknowledgements


- This work was funded by the Urban Air Initiative

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THANK YOU

# Vehicle Characteristics

| Vehicle | Body Type | Engine | | | | | | # of Spd. | Odo. (mi.) |
|---|---|---|---|---|---|---|---|---|---|
| | | # of Cyl. | Displ. (L) | Aspir. | Inject. | Comp. Ratio | FFV | | |
| Equinox | SUV | 4 | 2.4 | NA | GDI | 11.2 | Y | 6 | 17K |
| Cruze | Sedan | 4 | 1.4 | TC | GDI | 9.5 | N | 6 | 22K |
| Camry | Sedan | 4 | 2.5 | NA | GDI | 13.0 | N | 8 | 7K |
| Quest | Mini-Van | 6 | 3.5 | NA | PFI | 10.3 | N | CVT | 46K |
| Focus | Sedan | 4 | 2.0 | NA | GDI | 12.0 | N | 6 | 37K |

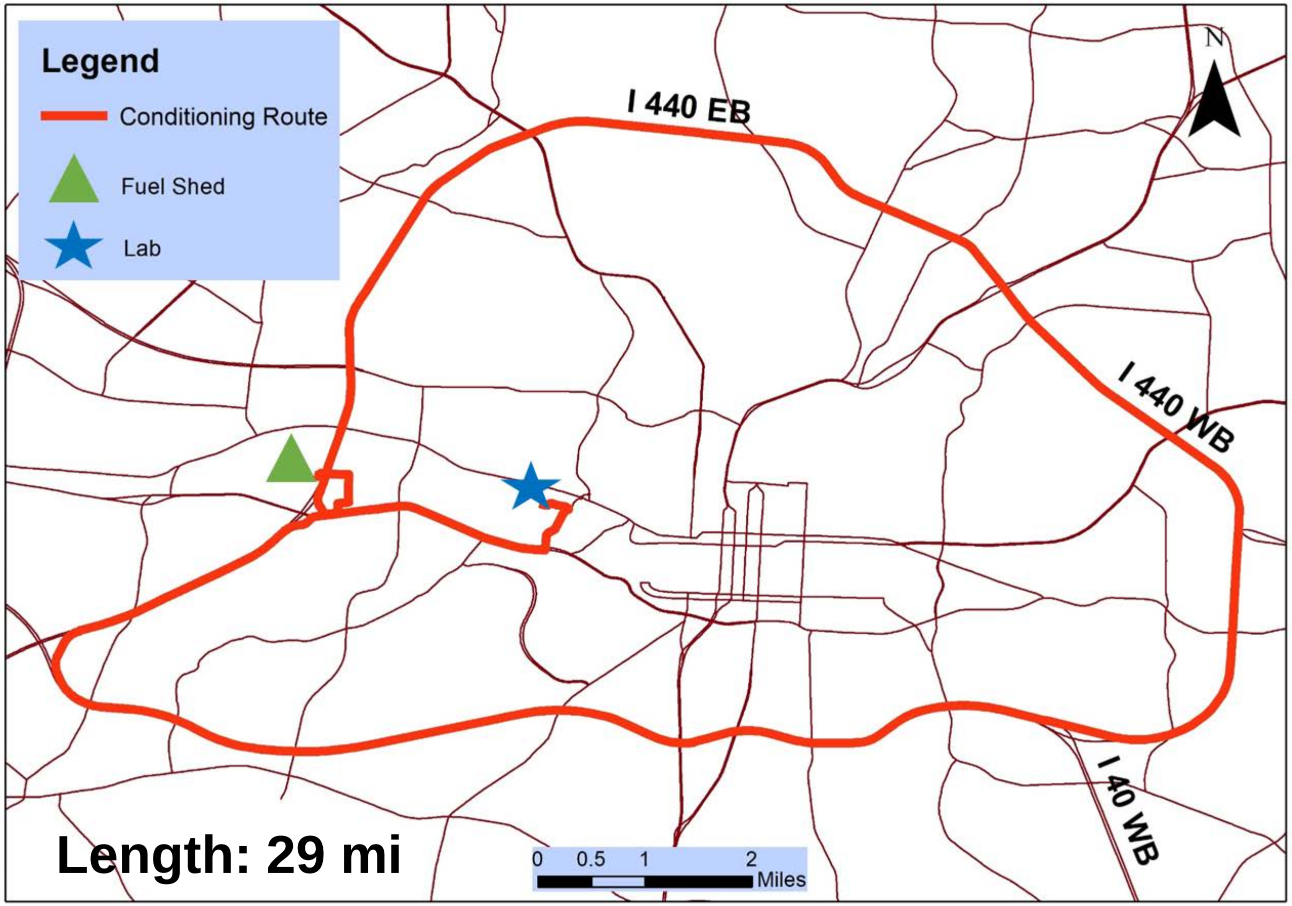
# Switching Fuels

- 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
    - Two drivers in total
    - Driver #1: Equinox
    - Driver #2: Cruze, Camry, Quest, and Focus
  - Both drivers were trained on use of cruise control and waypoints.

# Fuel Conditioning Route in Raleigh




Cruze, Camry, Quest, Focus

# Test Conditions

| Test Order | Vehicle | Order of Fuels | | | | Weather Condition [μ(±σ)]* | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | Temp. ($^oF$) | Humidity (%) |
| 1 | Equinox | E25 | E10P | E0 | E10R | 64(±3) | 80(±14) |
| 2 | Cruze | E10R | E25 | E10P | E0 | 59(±4) | 42(±11) |
| 3 | Camry | E10R | E0 | E10P | E25 | 57(±6) | 53(±12) |
| 4 | Quest | E10R | E0 | E10P | E25 | 49(±6) | 49(±9) |
| 5 | Focus | E10R | E0 | E10P | E25 | 28(±2) | 27(±2) |

* *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 ($CO_2$), 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)

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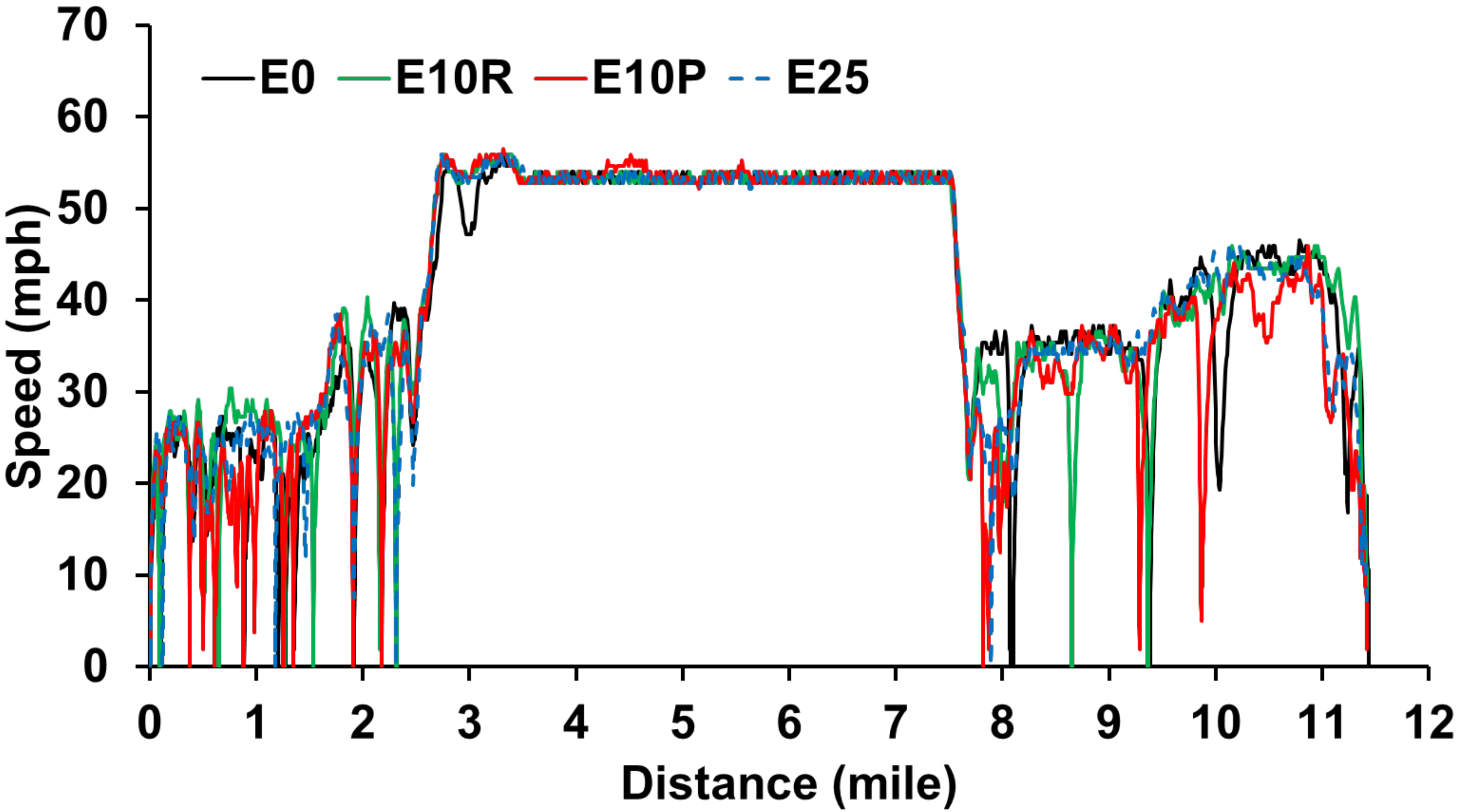
# ParSYNC PEMS

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

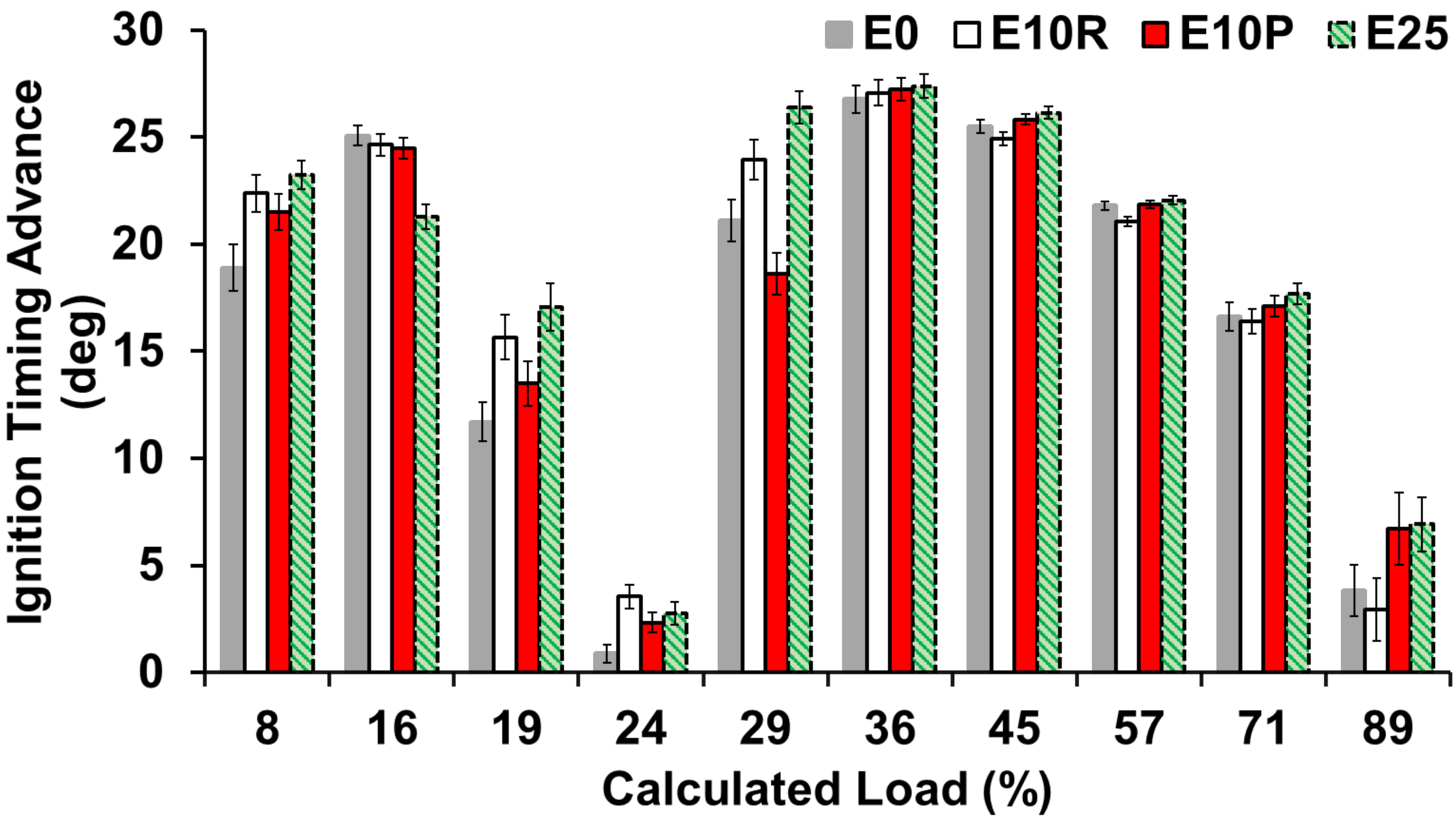
# Driving Cycles: Route C (Outbound)

Example: 2018 Toyota Camry, Route C-outbound



# 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)