Evaluation of Light Duty Gasoline Vehicle Rated Fuel Economy based on in-use Measurements

Tanzila Khan

Dr. H. Christopher Frey

NC STATE UNIVERSITY

Department of Civil, Construction and Environmental Engineering

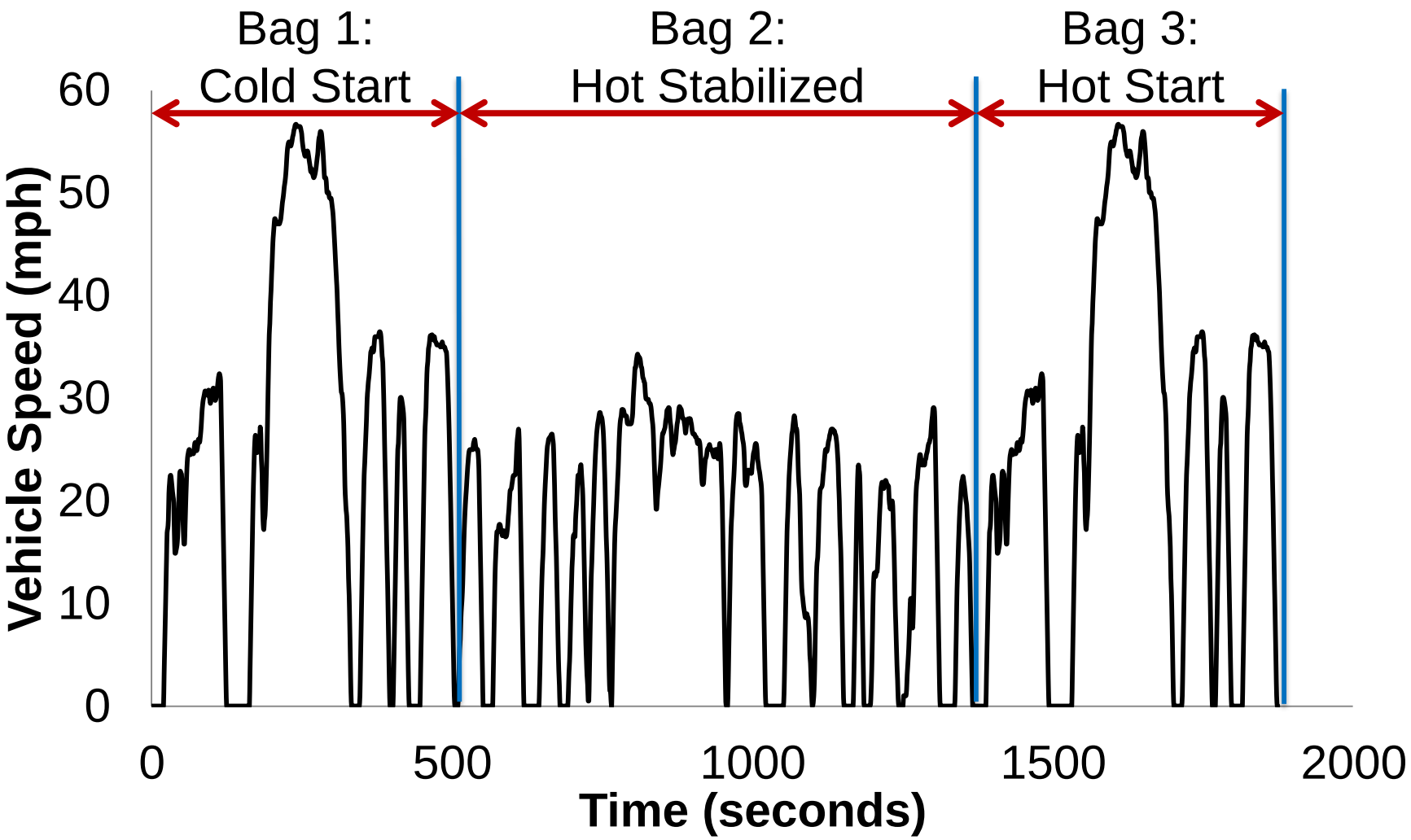
North Carolina State University

Transportation Research Board Annual Meeting
Washington DC
January 13, 2016

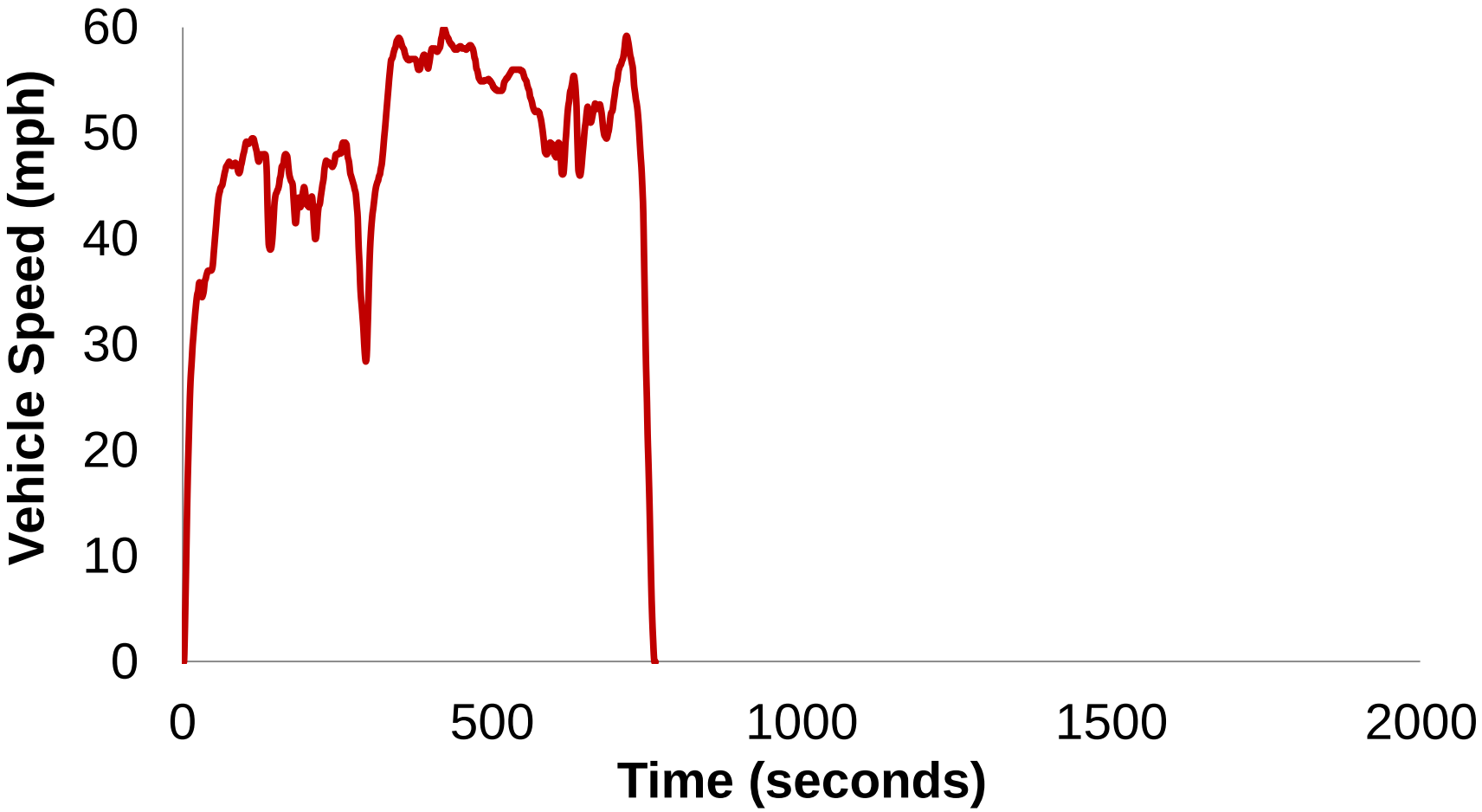
Background

- **Fuel economy ratings of light duty vehicles:** Jointly conducted by the U.S. Environmental Protection Agency & Department of Energy
- Chassis dynamometer standard driving cycles
- Major revision in 2006

3-Bag Federal Test Procedure (FTP) Driving Cycle



Highway Fuel Economy Test (HWFET) Driving Cycle



Background (Contd.)

- **Cold start influence:** higher fuel use and emission rates than hot stabilized
- EPA ratings account for cold start in the FTP cycle
- Need to incorporate cold start in estimation of real-world fuel economy

Research Objectives

- To assess the degree of concordance between the real-world and rated fuel economy
- To test sensitivity of the comparisons to cold start

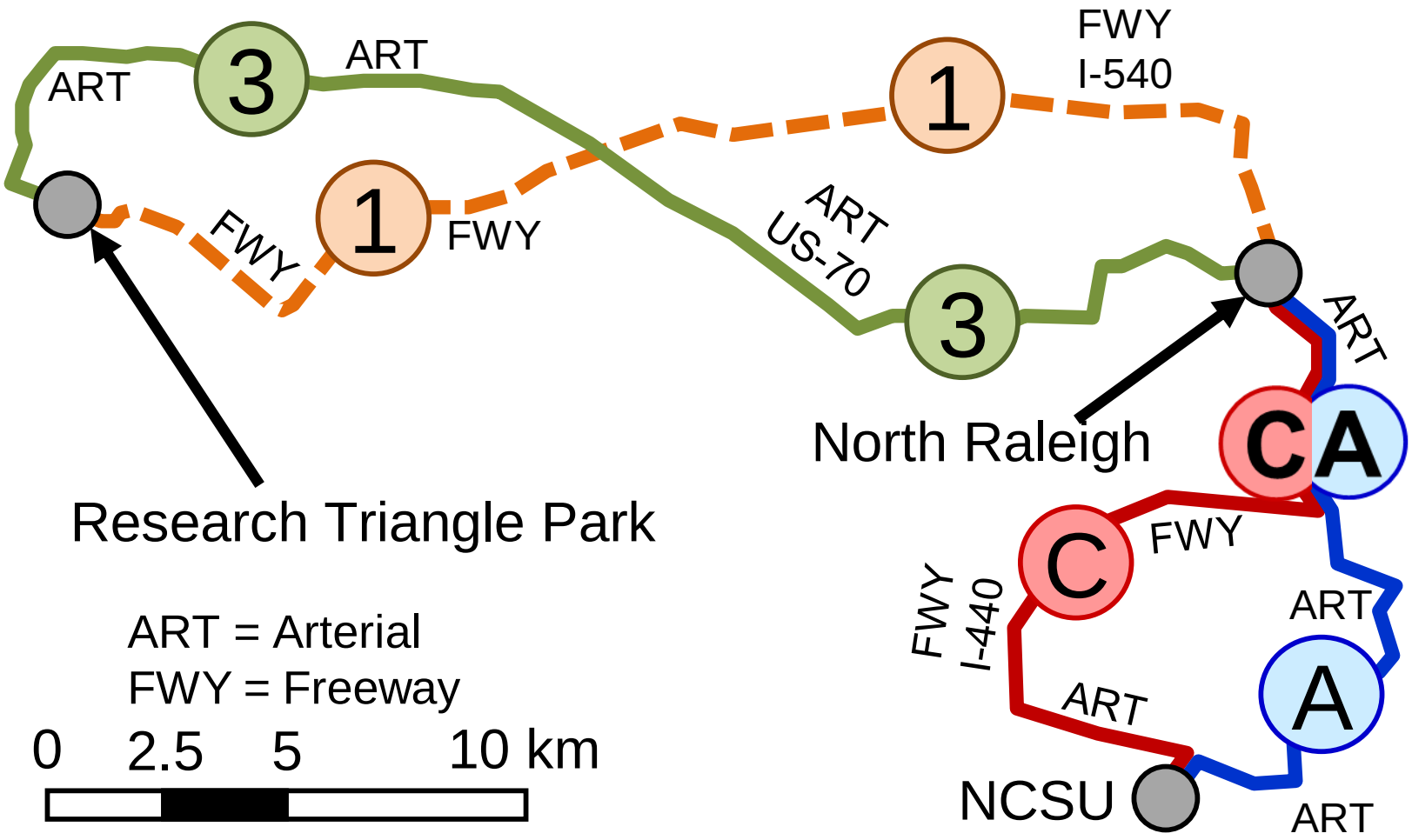
Methods: Emission Measurements

Portable Emissions Measurement System (PEMS)
CO_2, CO, HC, NO_x

On-Board Diagnostic Data
- RPM
- Manifold Absolute Pressure
- Intake Air Temperature
- Mass Air Flow Rate
- Fuel Flow Rate
- Vehicle Speed

Global Positioning System (GPS) receiver with Barometric Altimeter

Methods: Test Routes



Methods: Study Design

- **Choice of Vehicles**
  - most recruited from students
  - some rented
  - Chrysler, Ford, GM, Honda, Nissan, Toyota, and Volkswagen, and others

- **Drivers**
  - 73% of the vehicles have a unique driver
  - 4 people drove the other 27% vehicles

Fuel Flow Rate

- For most of the vehicles, fuel flow rate was logged from the electronic control unit via the OBD interface
- For a few vehicles, mass fuel flow was not reported via OBD:
  - reported mass air flow was used, in combination with air/fuel ratio inferred from exhaust composition; or
  - speed density method was used. Volumetric efficiency was calibrated to "actual" fuel use
- Estimated fuel use (gallons) was compared to "actual" fuel (gallons) needed to top off the fuel tank
- On average, estimated fuel use is 98%±2% of the "actual" fuel use

Characteristics of Measured 122 Vehicles

Vehicle Group	No. of Vehicles	Model Year	Engine Size (L)	Rated horse-power	Curb Weight (lbs)
PC-T1	26	1997-2003	1.6-3.8	106-236	2300-3800
PC-T2	55	2004-2014	1.3-4.6	76-301	2300-4400
PT-T1	11	1998-2003	2.3-5.4	135-285	3000-5200
PT-T2	30	2004-2014	2.2-5.4	155-385	3200-5800

PC = Passenger Car
PT = Passenger Truck
T1 = Tier 1
T2 = Tier 2

Vehicle Specific Power (VSP)

- Highly correlated with fuel use and emissions
- Basis for modal average fuel use and emission rates

Potential Energy Aerodynamic drag

$$VSP = v[1.1a + 9.81r + 0.132] + 0.000302v^3$$

Kinetic energy Rolling and rotational resistance

Where,

v = vehicle speed (km/h)

a = acceleration (km/h per sec)

r = road grade (%)

VSP = vehicle specific power (kW/ton)

Vehicle Specific Power Modes

Frey *et al*. (2002)

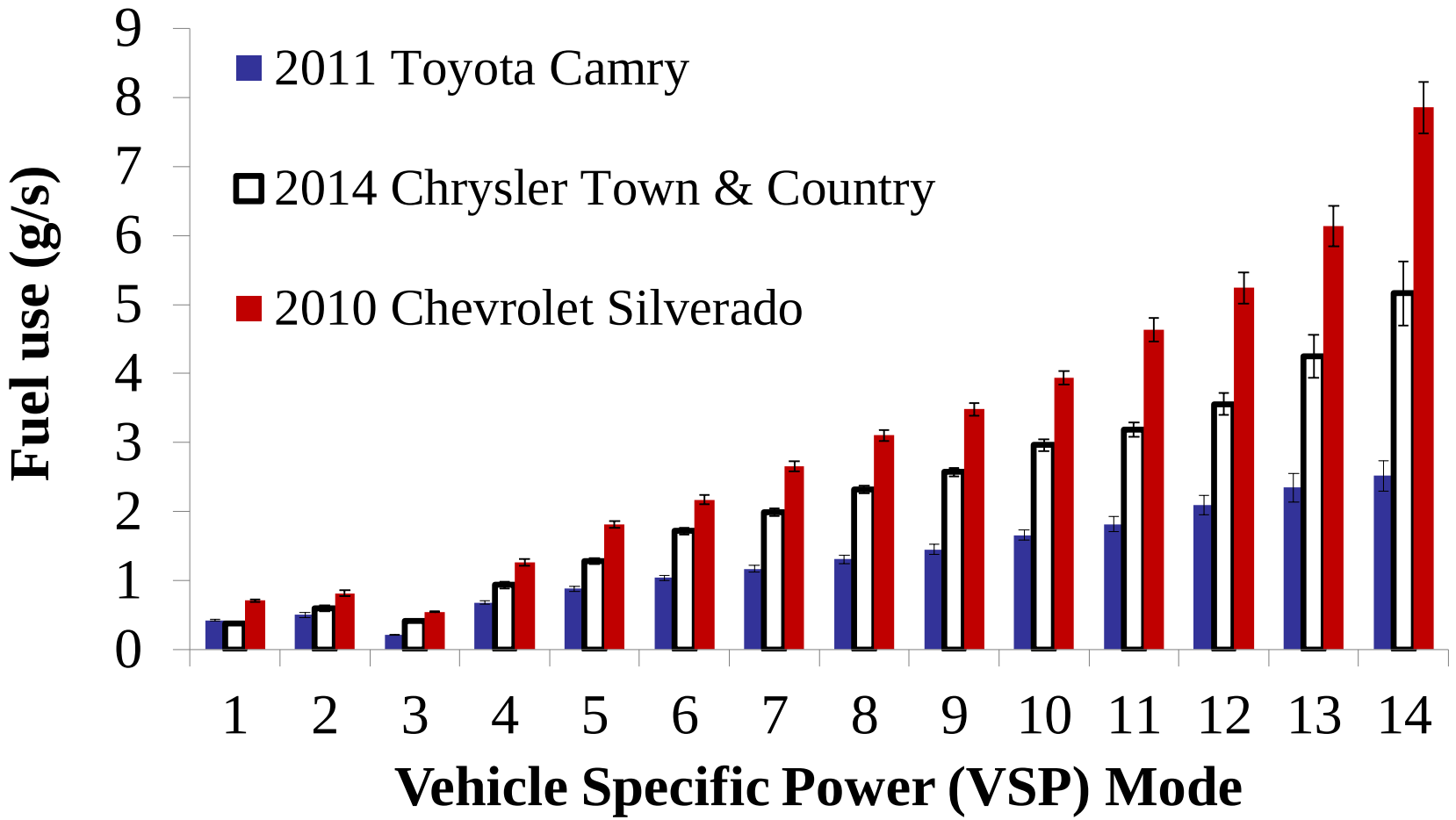
VSP mode	Definition (kW/ton)
1	VSP < -2
2	-2 ≤ VSP < 0
3	0 ≤ VSP < 1
4	1 ≤ VSP < 4
5	4 ≤ VSP < 7
6	7 ≤ VSP < 10
7	10 ≤ VSP < 13
8	13 ≤ VSP < 16
9	16 ≤ VSP < 19
10	19 ≤ VSP < 23
11	23 ≤ VSP < 28
12	28 ≤ VSP < 33
13	33 ≤ VSP < 39
14	39 ≤ VSP

Deceleration or Downhill

Idle

Cruising, Acceleration, or Uphill

VSP Modal Fuel Use Rates (g/s) for 2011 Toyota Camry, 2014 Chrysler Town & Country, 2010 Chevrolet Silverado



Rated Fuel Economy

- **General Methods**

  - Carbon balance
  - Cycle average emission rates of CO_2, CO, THC
  - Standard driving cycles
  - Fuel properties
  - Downward adjustments
  - City, Highway and Combined ratings

- **Prior Rating Scheme (Before 2006)**

  - FTP: City fuel economy
  - HWFET: Highway fuel economy

Rated Fuel Economy

- **Revised Rating Scheme (Since 2006)**

  - **Vehicle Specific 5 Cycle Label (VS5CL) method**
    - Standard driving cycles
    - FTP, cold FTP, US06, SC03, HWFET

  - **Derived 5 Cycle Label (D5CL) method**
    - **FTP-based 'City'** and **HWFET-based 'Highway'** fuel economy
    - Calibrated to 5 cycle based estimates

- **Combined Fuel Economy (in both schemes)**

$$FE_{combined} = 0.55 \times FE_{City} + 0.45 \times FE_{Highway}$$

Methods: Measurement of Cold Start Emissions

- Soak time: 12 hours or more
- 16 Passenger Cars and 16 Passenger Trucks
- Emissions of CO_2, CO, THC, and NO_x measured with PEMS during idling for 15 minutes
- Hot stabilized measurements conducted for the same vehicles
- Cold Start Emissions Increment =

  Mass of emissions during cold start –

  Mass of emissions during hot stabilized condition

Methods: Real-World Fuel Economy

Real-World Fuel Economy Estimates

- Based on Real-World Cycle Average Emission Rates
    - Real-world VSP modal emission rates
    - Cycles: **FTP**, **HWFET**, and **Real-World**

Methods: Real-World Cycle Average Emission Rates (CAER)

- VSP modal emission rates (grams/second) weighted by time spent in each VSP mode for any driving cycle

- Real-world cycle average emission rates are estimated for
  - **FTP and HWFET Cycles**
  - **Real-World Driving Cycles**

$$E_p = \sum_{i=1}^{14} (t_i \times ER_{p,i})$$

$$E_{CAER,p} = \frac{E_p}{D_{DC}}$$

Mass Emissions (grams)

Modal time (seconds)

Modal emission rates (gm/sec)

CAER (gm/mile)

Distance (mile)

Methods: Real-World Cycle Average Emission Rates (CAER) with Cold Start

- Average of cold start increment (grams) for each group of vehicles: PC-T1, PT-T1, PC-T2, PT-T2
- Average mass cold start increment, $\mathbf{E_{cs,p}}$ is added to hot start mass emissions, $\mathbf{E_p}$
- Estimate the CAER (grams/mile) with cold start

$$\mathbf{E_{p,c} = E_p + E_{cs,p}}$$

$$\mathbf{E_{CAER,p,c}} = \frac{\mathbf{E_{p,c}}}{\mathbf{D_{DC}}}$$

Emissions with cold start (grams)

Cold start increment (grams)

CAER with cold start (gm/mile)

Methods: Matching Vehicles with EPA Fuel Economy Database

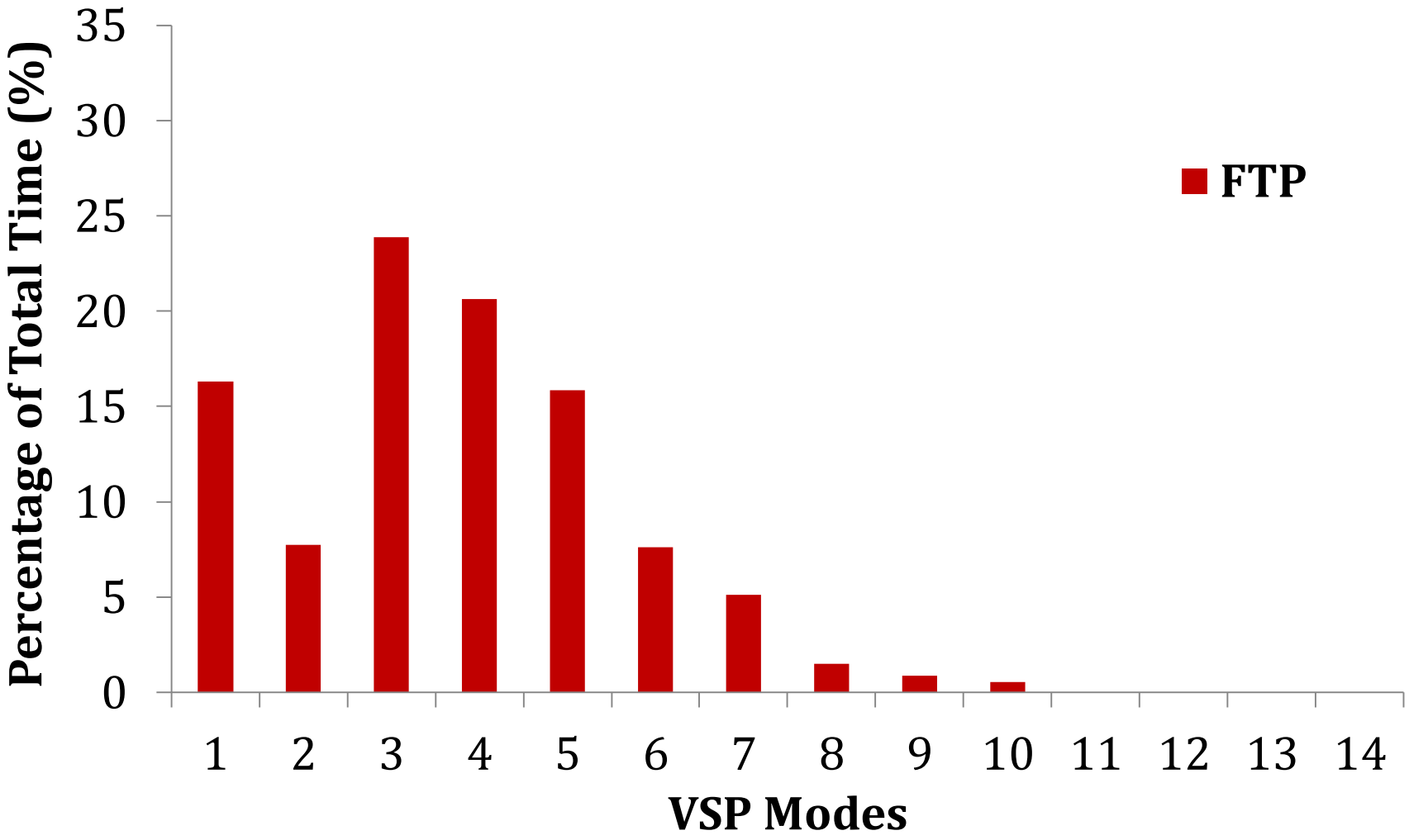
Matching Criteria:

- Model year
- Make
- Model
- Engine displacement
- Rated horsepower
- Number of cylinders

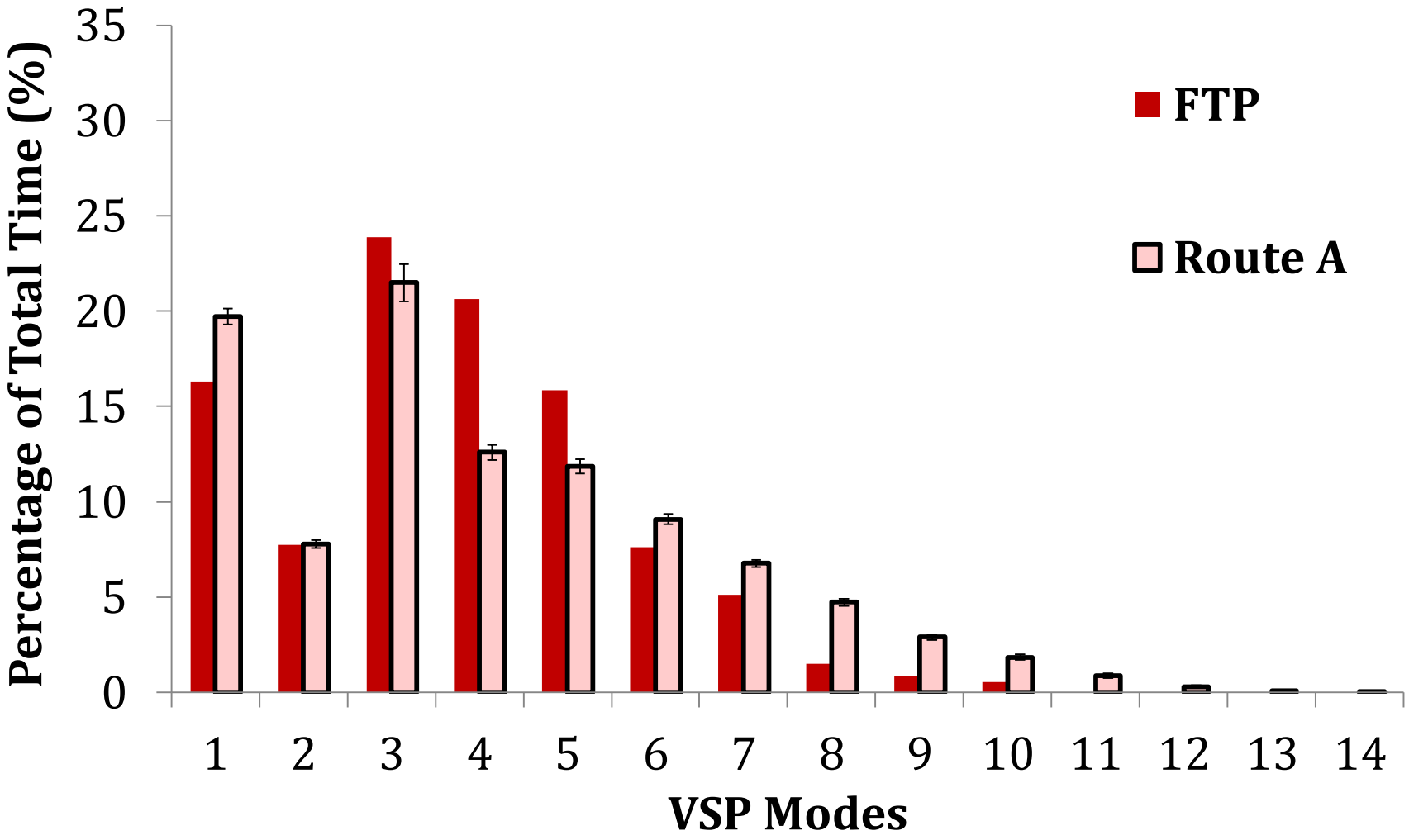
Comparison between Standard and Real-World Driving Cycles

Criteria	FTP	Route A	Route C	HWFET	Route 1	Route 3
Average Speed (mph)	21.2	25.9	28.6	48.3	48.0	31.8
Maximum Speed (mph)	56.7	57.0	73.5	59.9	77.0	65.5
Average Positive VSP (kW/ton)	5.4	17.6	17.9	7.5	18.0	17.8
Maximum VSP (kW/ton)	22.9	34.8	42.4	19.1	44.9	39.5

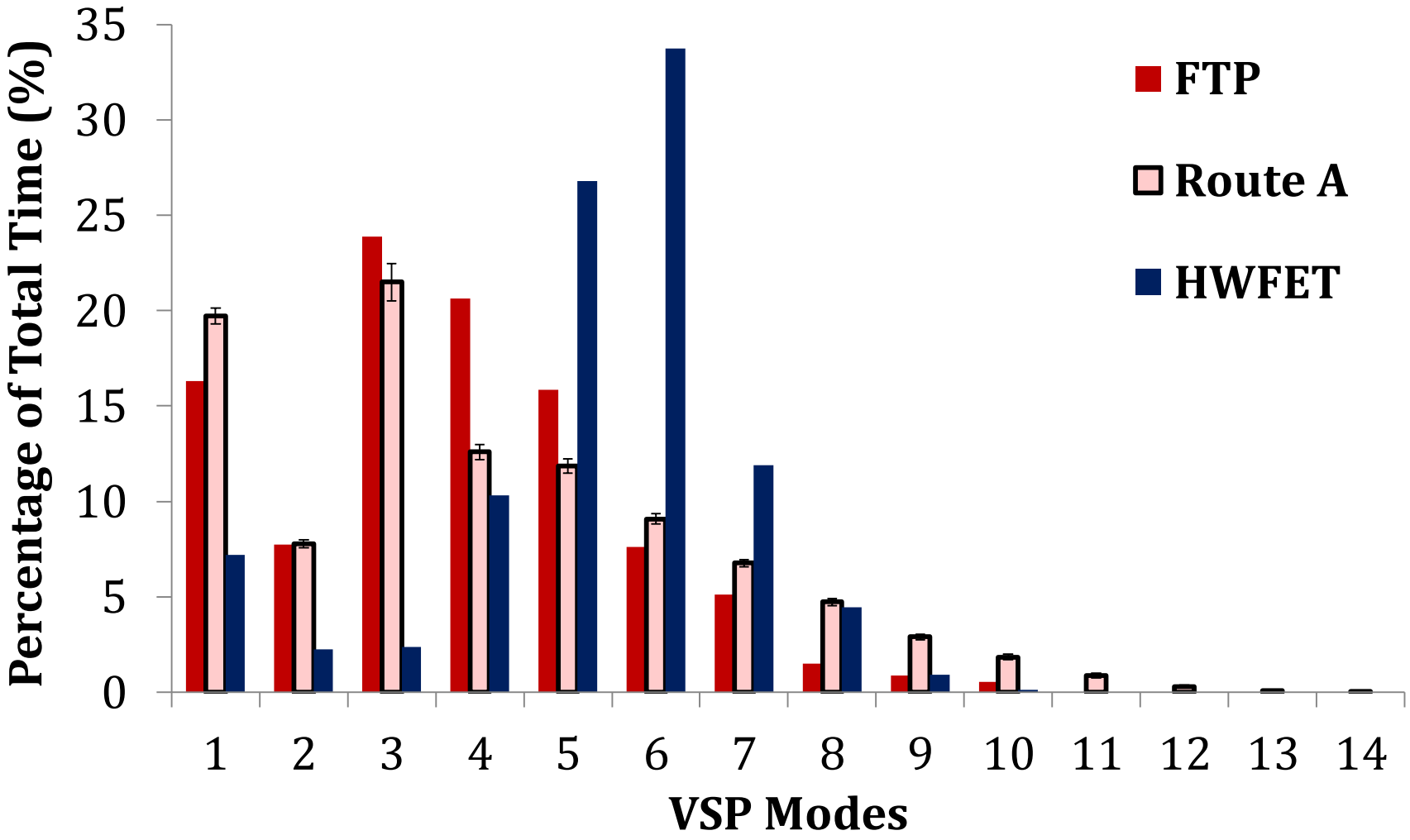
VSP Modal Time Distribution of Selected Driving Cycles



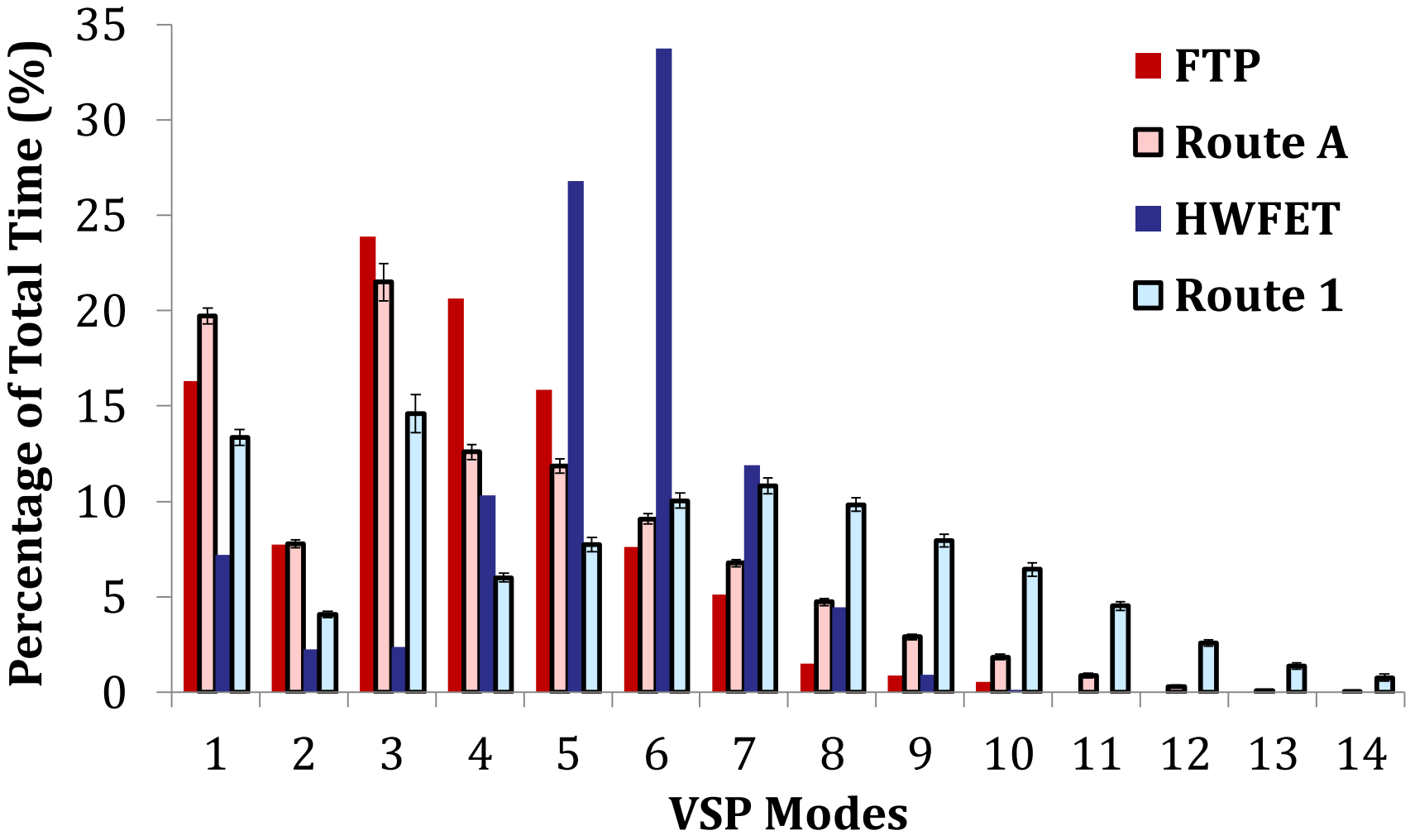
VSP Modal Time Distribution of Selected Driving Cycles



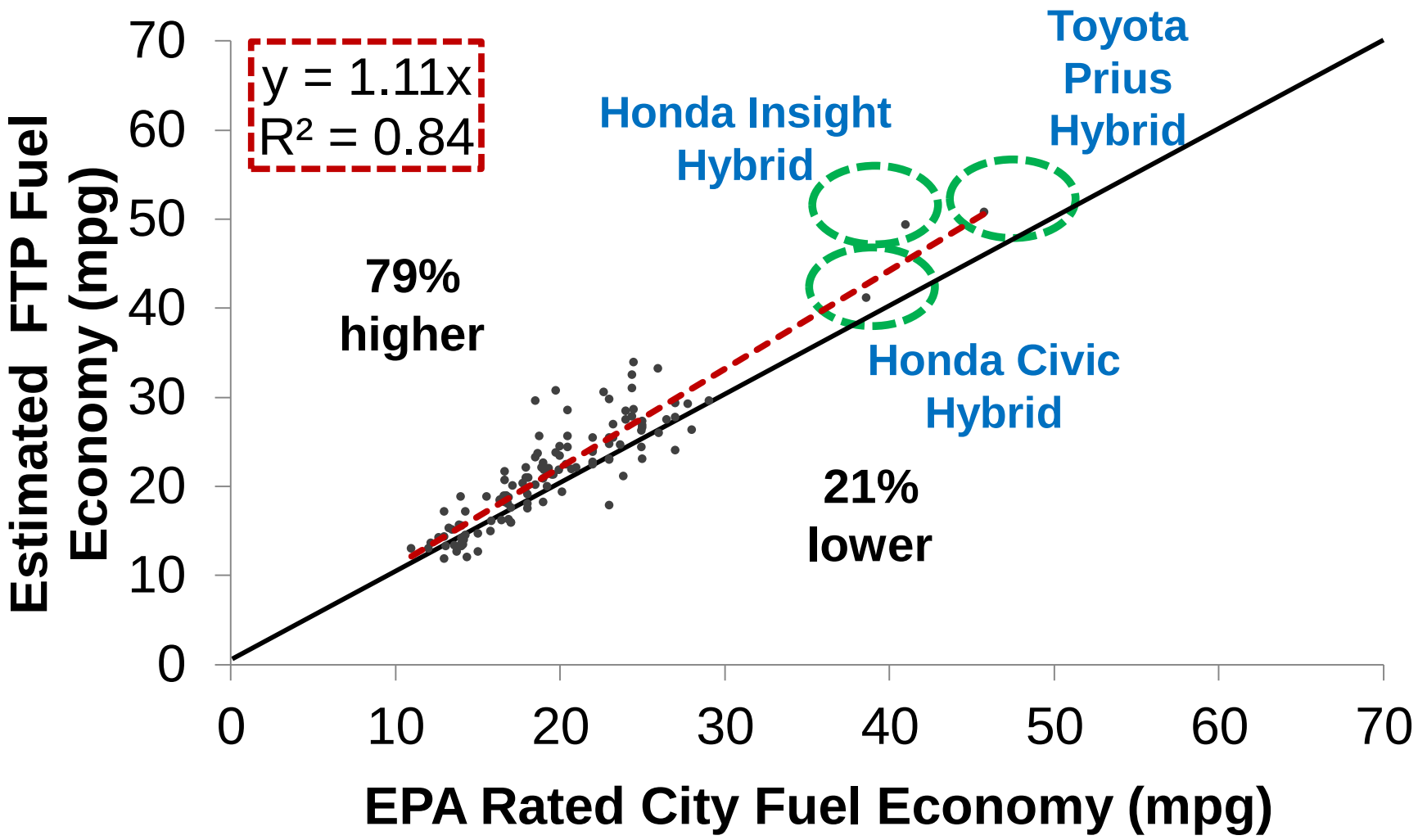
VSP Modal Time Distribution of Selected Driving Cycles



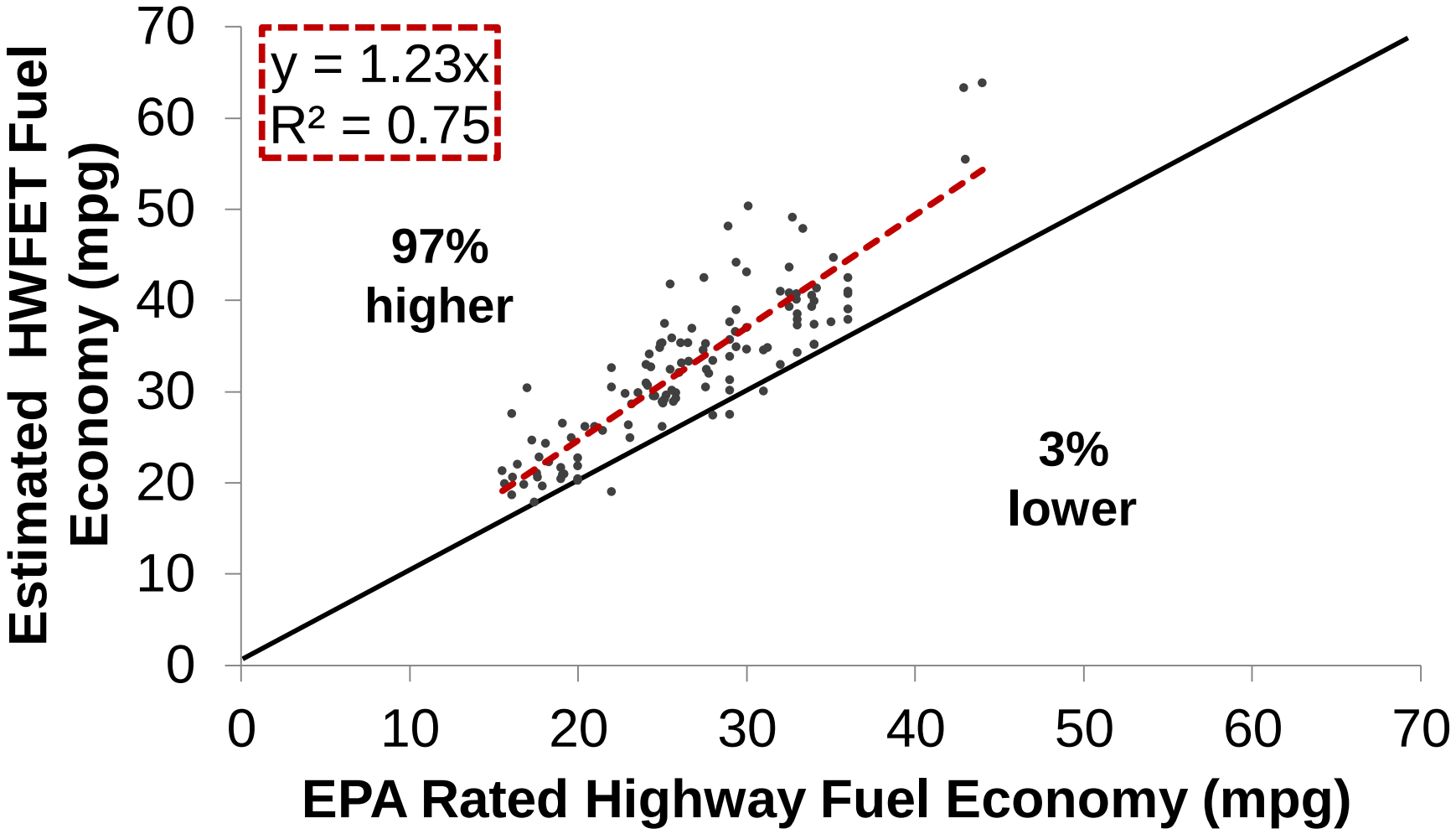
VSP Modal Time Distribution of Selected Driving Cycles



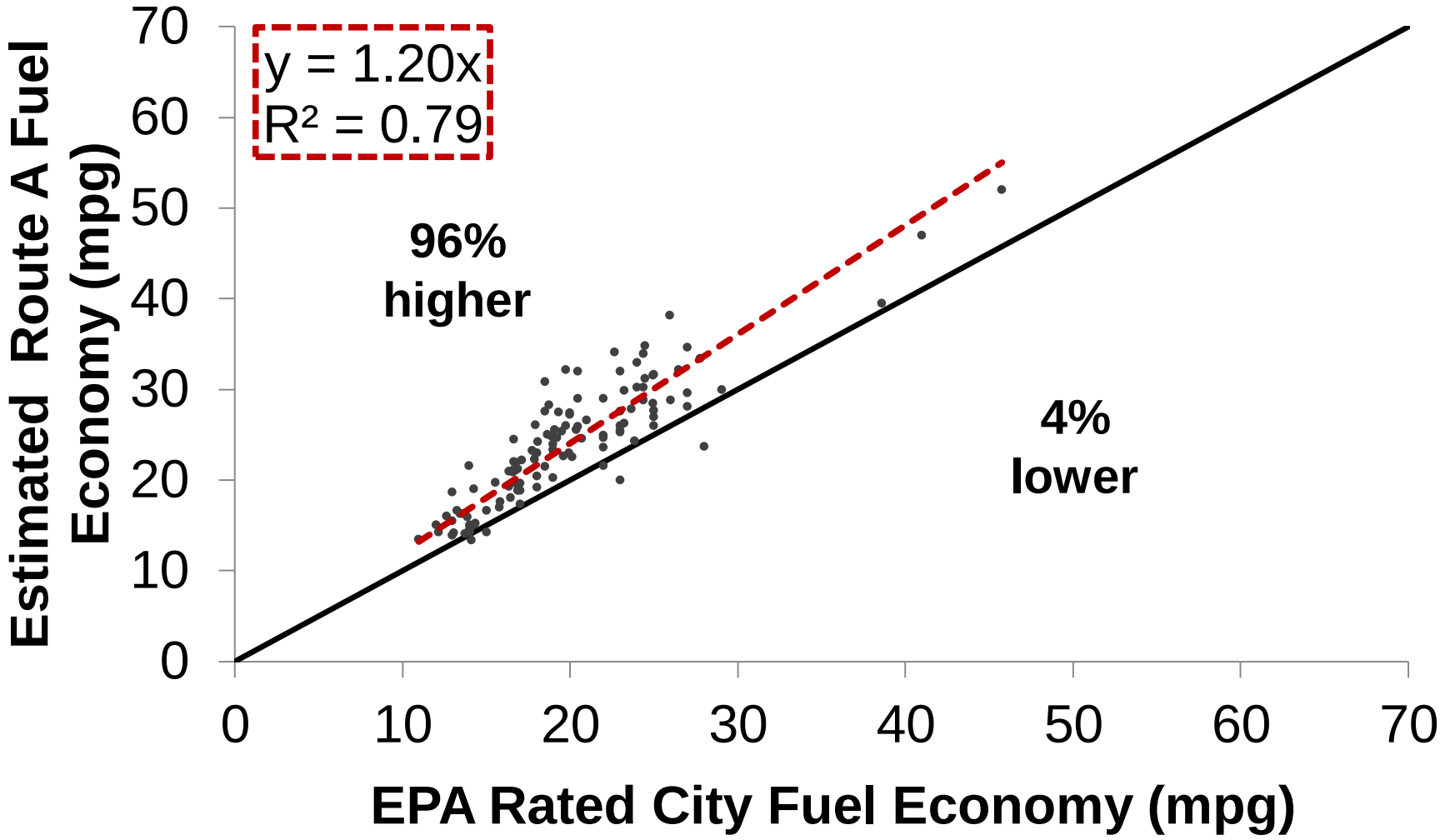
FTP-based Estimated Real-World vs. Rated City Fuel Economy



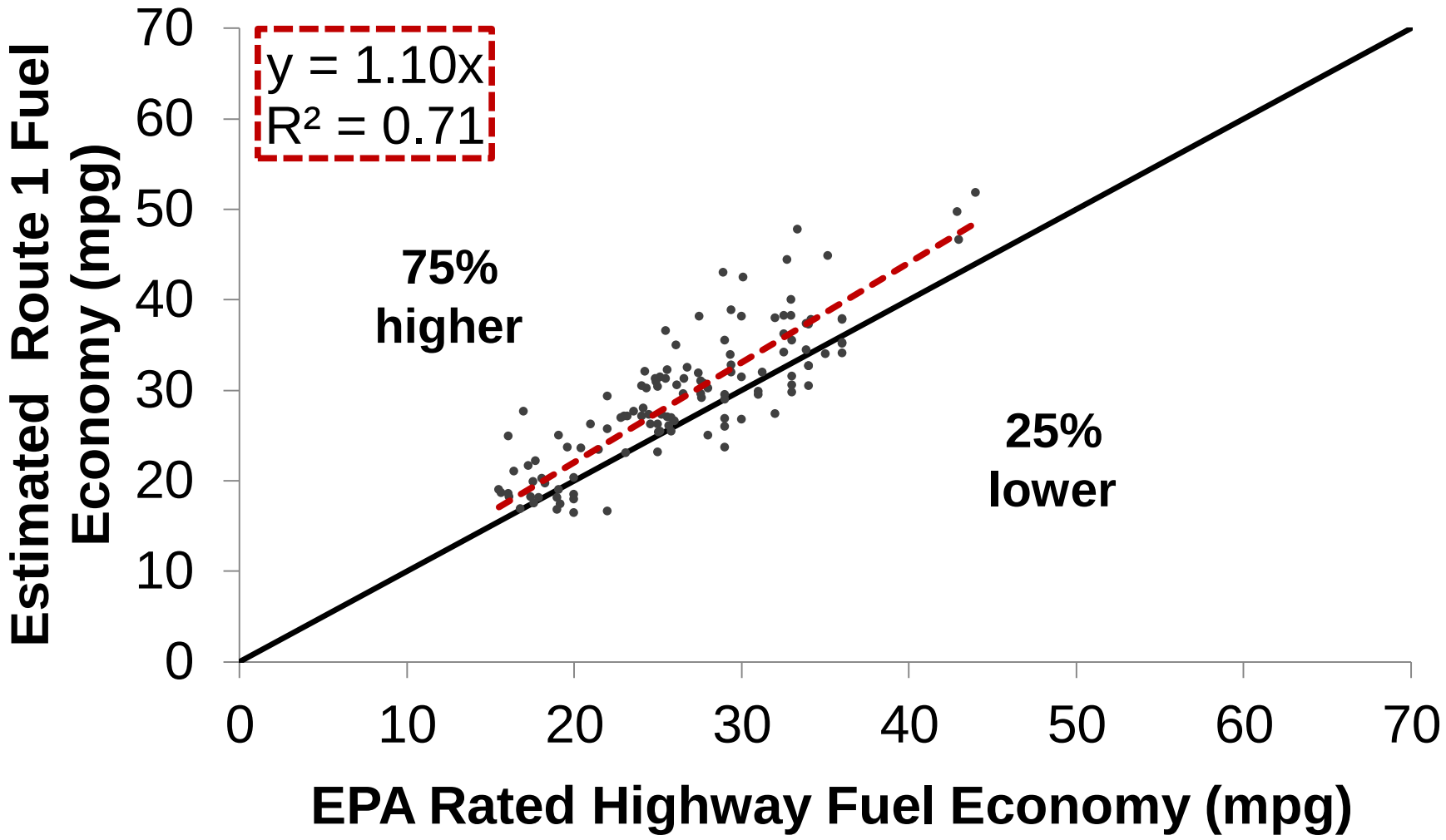
HWFET-based Estimated Real-World vs. Rated Highway Fuel Economy



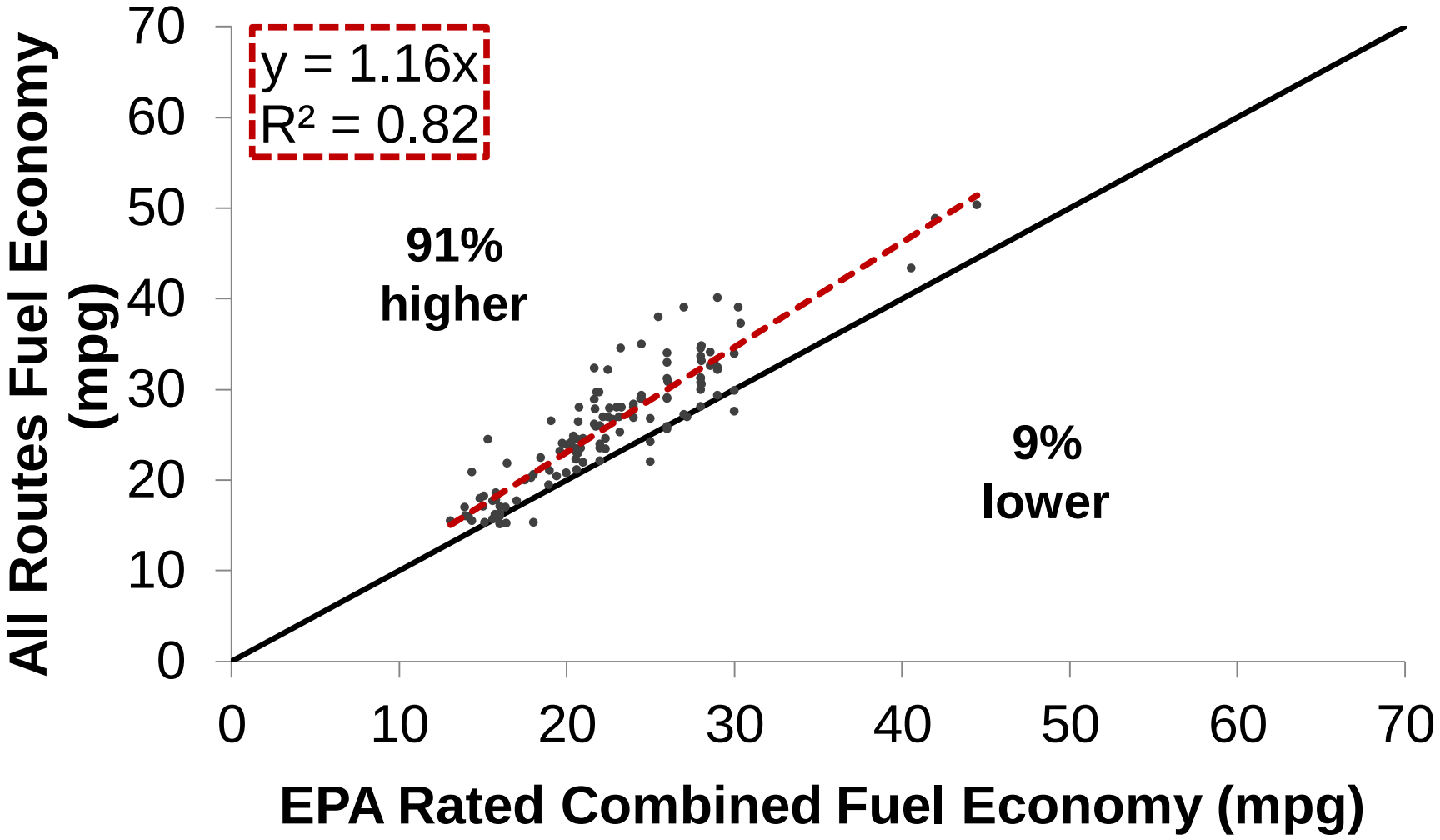
Route A Fuel Economy vs. EPA Rated City Fuel Economy



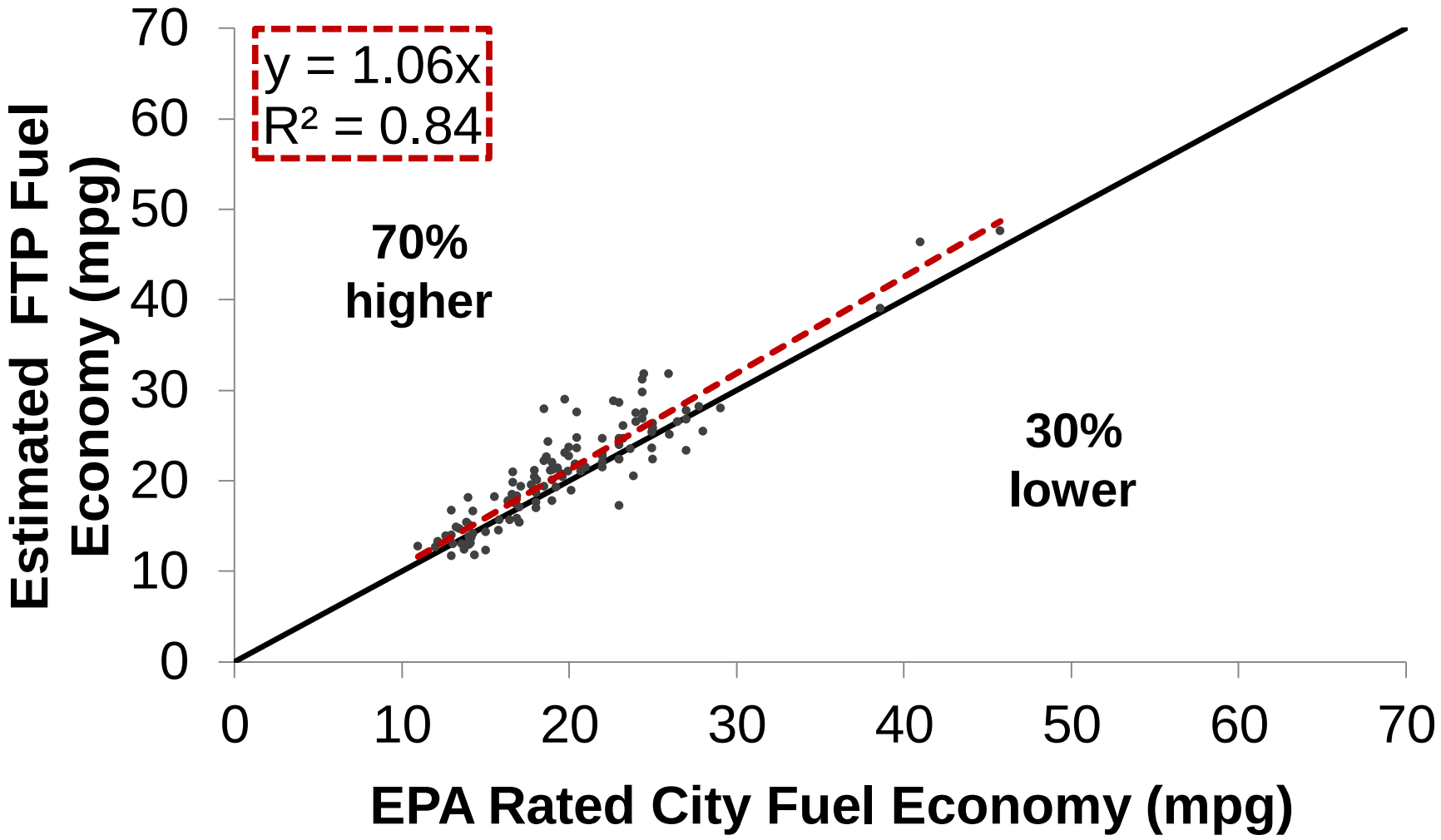
Route 1 Fuel Economy vs. EPA Rated Highway Fuel Economy



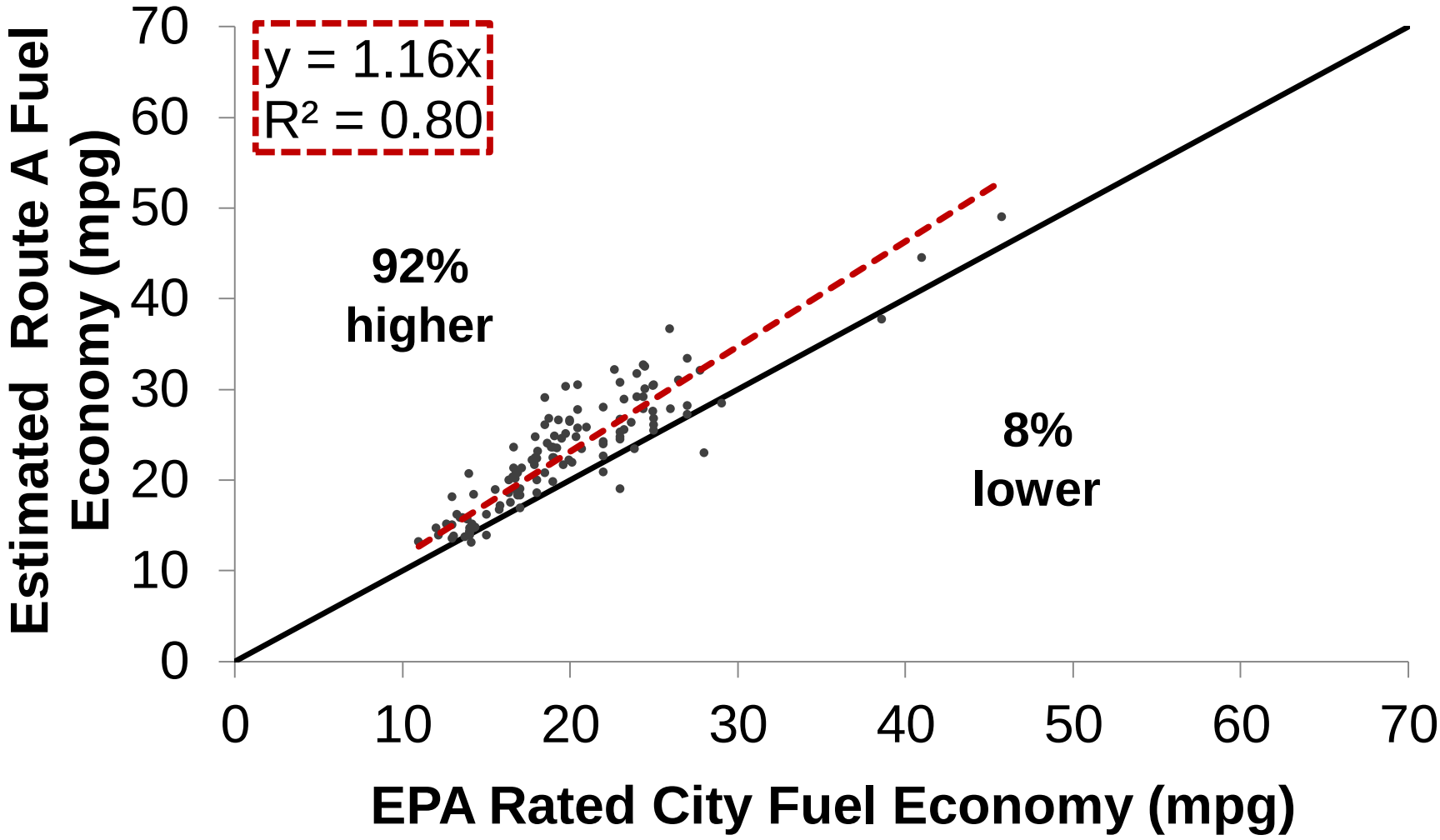
All Routes Fuel Economy vs. EPA Rated Combined Fuel Economy



Estimated FTP-based Fuel Economy with Cold Start vs. Rated City Fuel Economy



Route A Fuel Economy with Cold Start vs. Rated City Fuel Economy



Findings

- On average, real-world fuel economy is higher
  - Route A: 16% (3 mpg) higher than City rating
  - Route 1: 10% (2 mpg) higher than Highway rating
- Nonetheless, approximately 9% vehicles have lower real-world versus rated fuel economy
- Cold start influenced fuel economy is on average 4% (1 mpg) lower versus without cold start

Discussion

- **Inter-driver variability and Inter-run variability:** differences in driving behavior, differences in traffic conditions

- **Possible Options:**
  - In the short run, more accurate calibration and adjustments in D5CL method to increase accuracy
  - In the long run, replace standard driving cycles with more real-world representative driving cycles
  - Policy choice: Keep the current rating scheme to avoid increase in the fraction of vehicles which have lower real-world fuel economy than rated

Acknowledgements

This material is based upon work supported by the **National Science Foundation** under Grant No. 0853766. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

Research Team Members who were associated with field measurements and data analysis, including Mary Delavarrafiee, Brandon Graver, Jiangchuan Hu, Wan Jiao, Bin Liu, Gurdas Sandhu, Yuanfang Sun, Behdad Yazdani, Xiaohui Zheng

THANK YOU

QUESTIONS ???