Real-world Versus Certification Emission Rates for Light Duty Gasoline Vehicles

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Emission Regulations

- New light-duty vehicles must comply with the U.S. Environmental Protection Agency exhaust emission standards
- **Phased in emission regulations:**
  - Tier 1 (1994 – 1997)
  - Tier 2 (2004 – 2009)
- Tier 3: started phasing in with 2017 model year vehicles

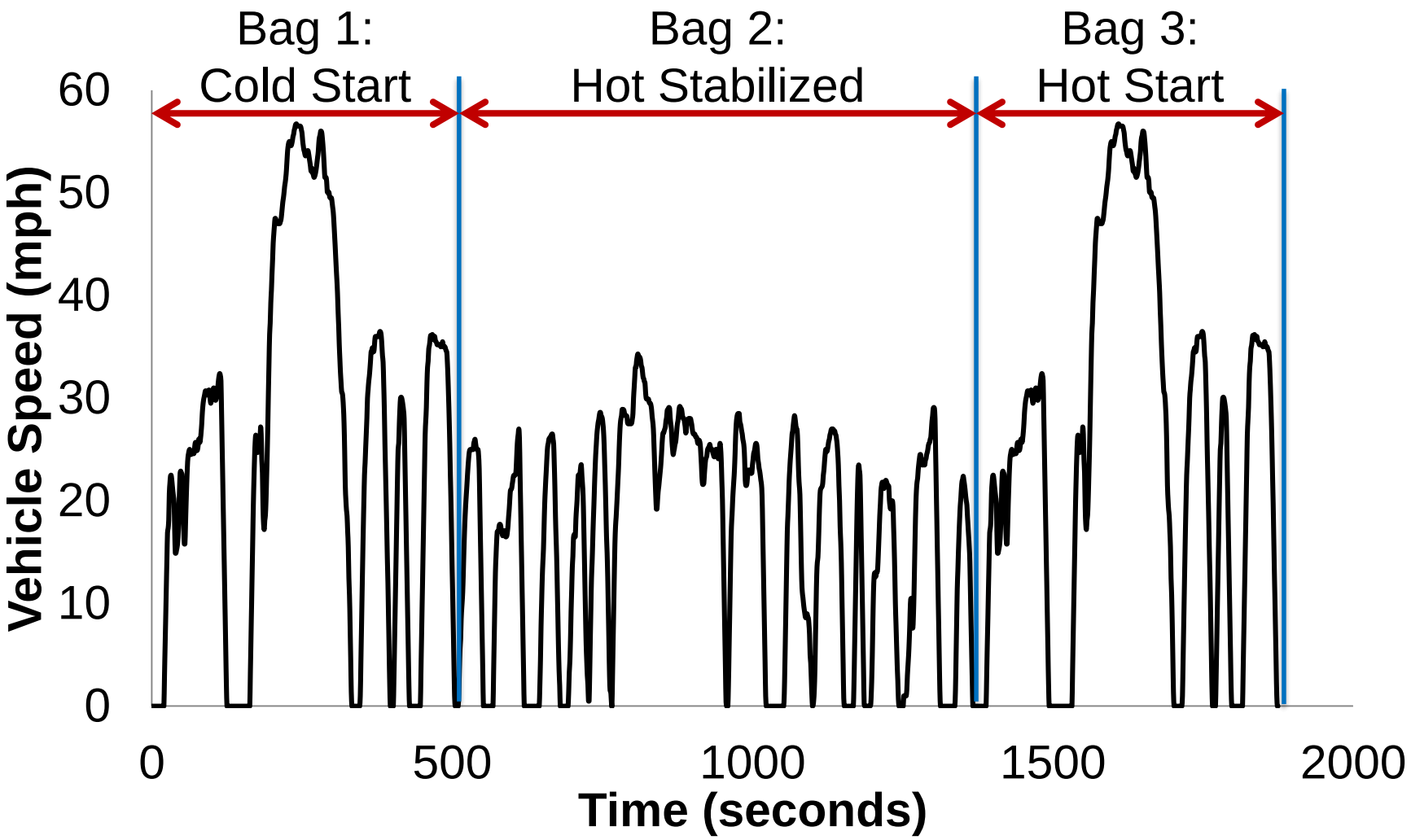
Emission Compliance

- Chassis dynamometer measurements
- Standard driving cycles: defined 1 Hz speed traces
- Representative vehicles
- Specified pollutants
- **Certification Level (CL):** Cycle average rates adjusted with ‘deterioration factors’
- CL must be lower than the emission standard

Standard Driving Cycles

- FTP
- Cold FTP
- US06
- SC03

3-Bag Federal Test Procedure (FTP) Driving Cycle



Knowledge Gap

- Standard driving cycles
  - Based on specific real-world driving observations
  - Not necessarily representative of real-world operation of a given vehicle
- Recent focus on selected diesel vehicles in U.S. market
- Recent focus broadly in Europe
- Need systematic comparison of real-world emission rates versus CL and emission standard for the larger share of gasoline vehicles in U.S. market

Cold Start Emissions

- Higher fuel use and emissions than hot stabilized operation
- Certification levels and emission standards account for cold start in the FTP cycle

Research Objectives

- To compare light duty gasoline vehicles real-world emission rates versus certification levels and standards
- To test sensitivity of the comparisons to cold start

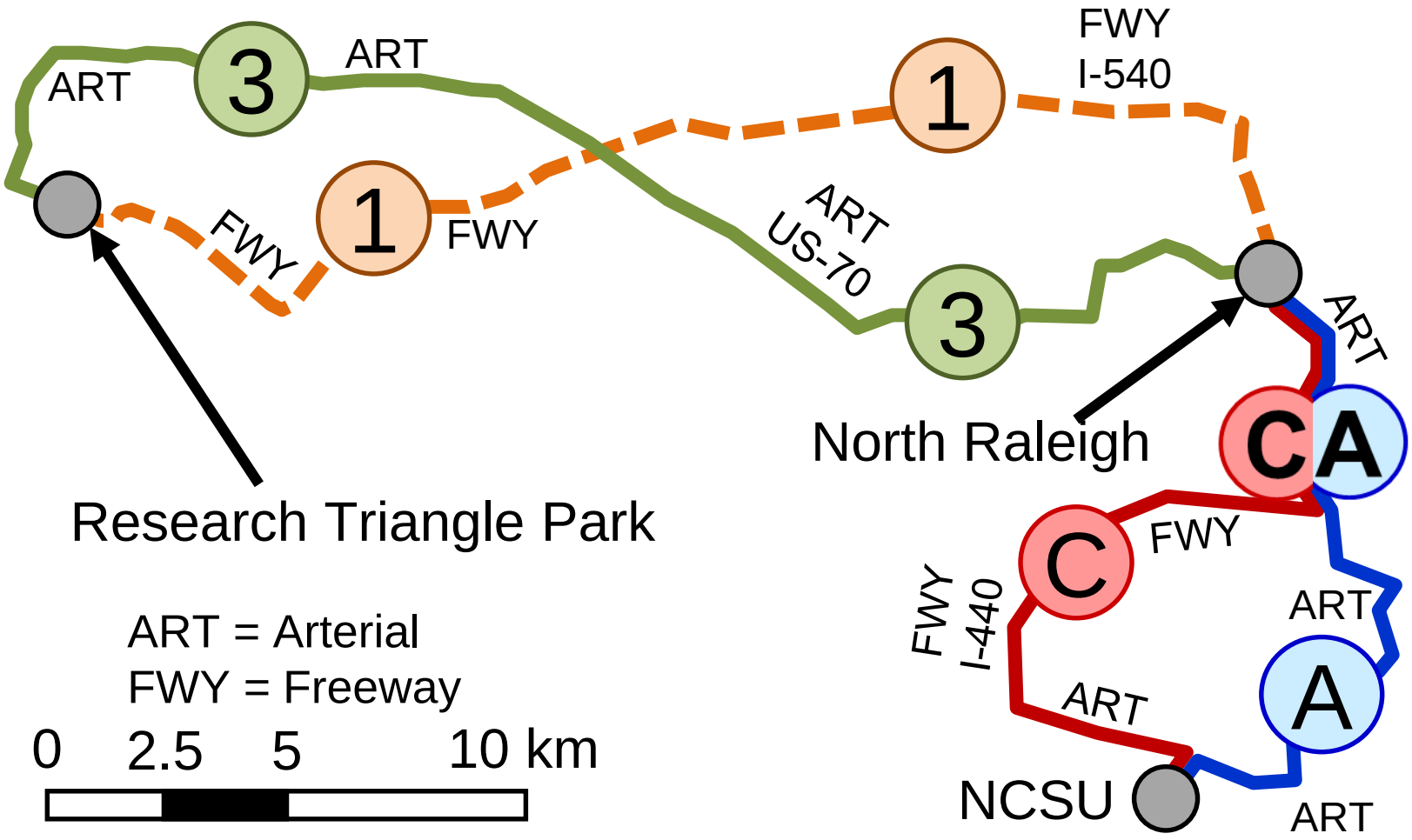
Emission Measurements

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

Test Routes


ART
3
ART
1
FWY
I-540
FWY
1
FWY
ART
US-70
3
ART
North Raleigh
C
A
Research Triangle Park
FWY
C
FWY
I-440
ART
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ART
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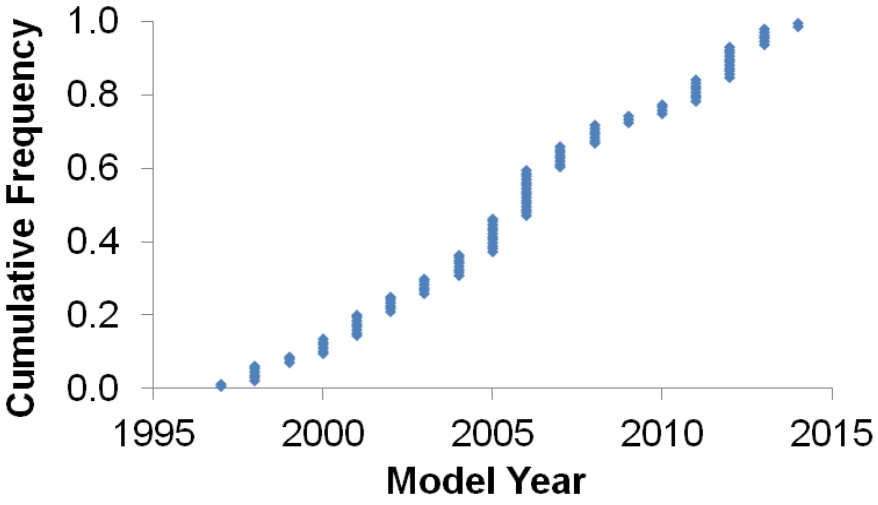
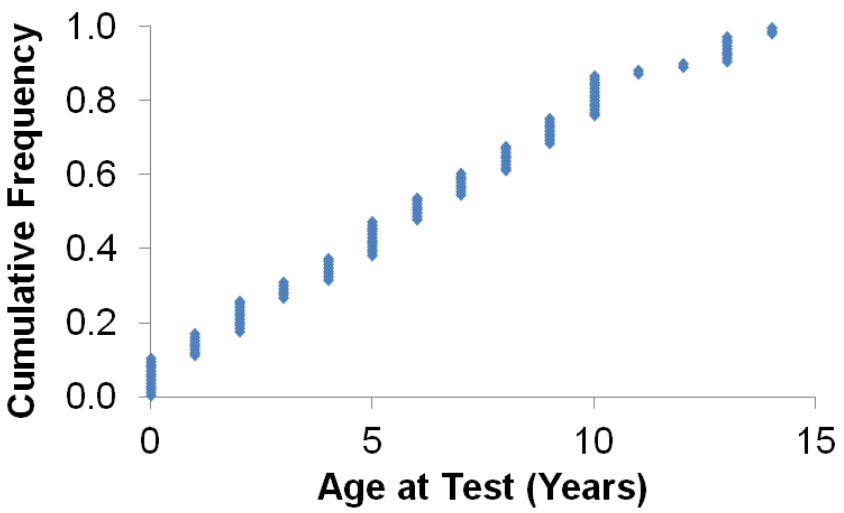
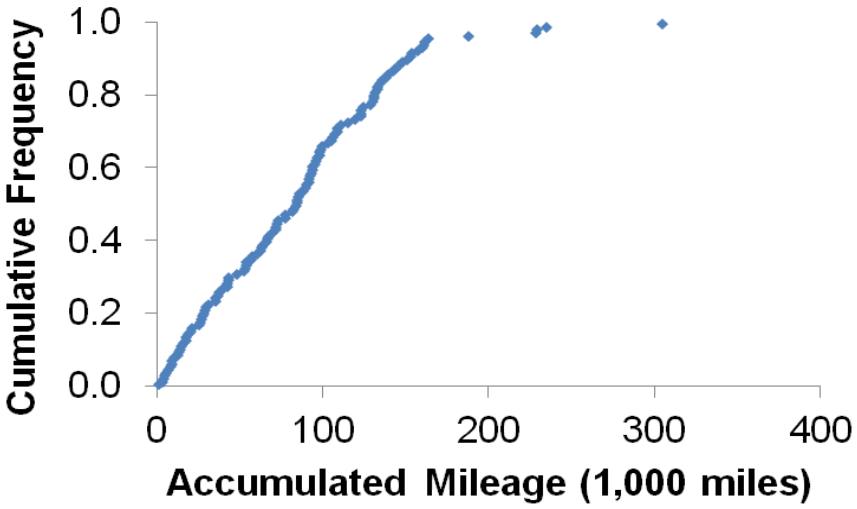
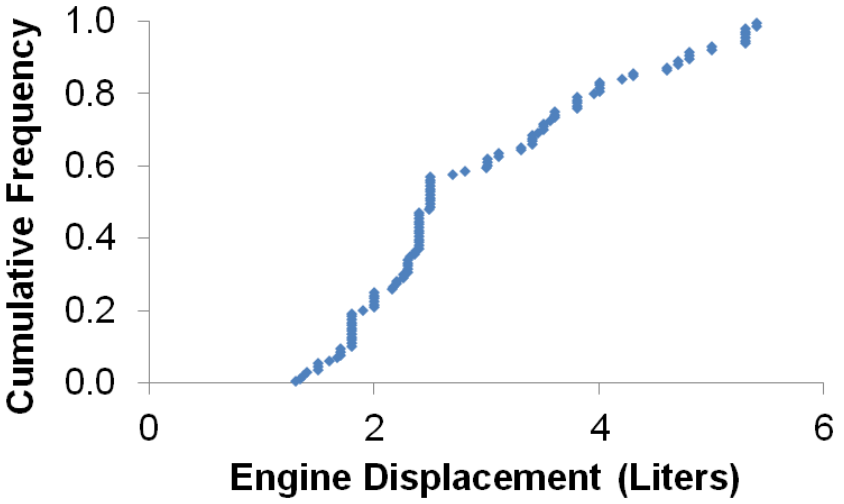
ART = Arterial
FWY = Freeway
0
2.5
5
10 km

Characteristics of Measured 122 Vehicles









Vehicle Manufacturers of Measured Vehicles

- Chrysler (Chrysler, Dodge, Jeep)
- Ford (Ford, Lincoln)
- GMC (Buick, Chevrolet, GMC)
- Honda (Honda, Acura)
- Hyundai (Hyundai, Kia)
- Nissan (Nissan, Infiniti)
- Toyota (Toyota, Scion, Lexus)
- Volkswagen
- Fiat
- Mazda
- Others: Mitsubishi, Saab, Subaru, Volvo

Vehicle Specific Power (VSP)

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

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

Where,

v = vehicle speed (km/h)

a = acceleration (km/h per sec)

r = road grade (%)

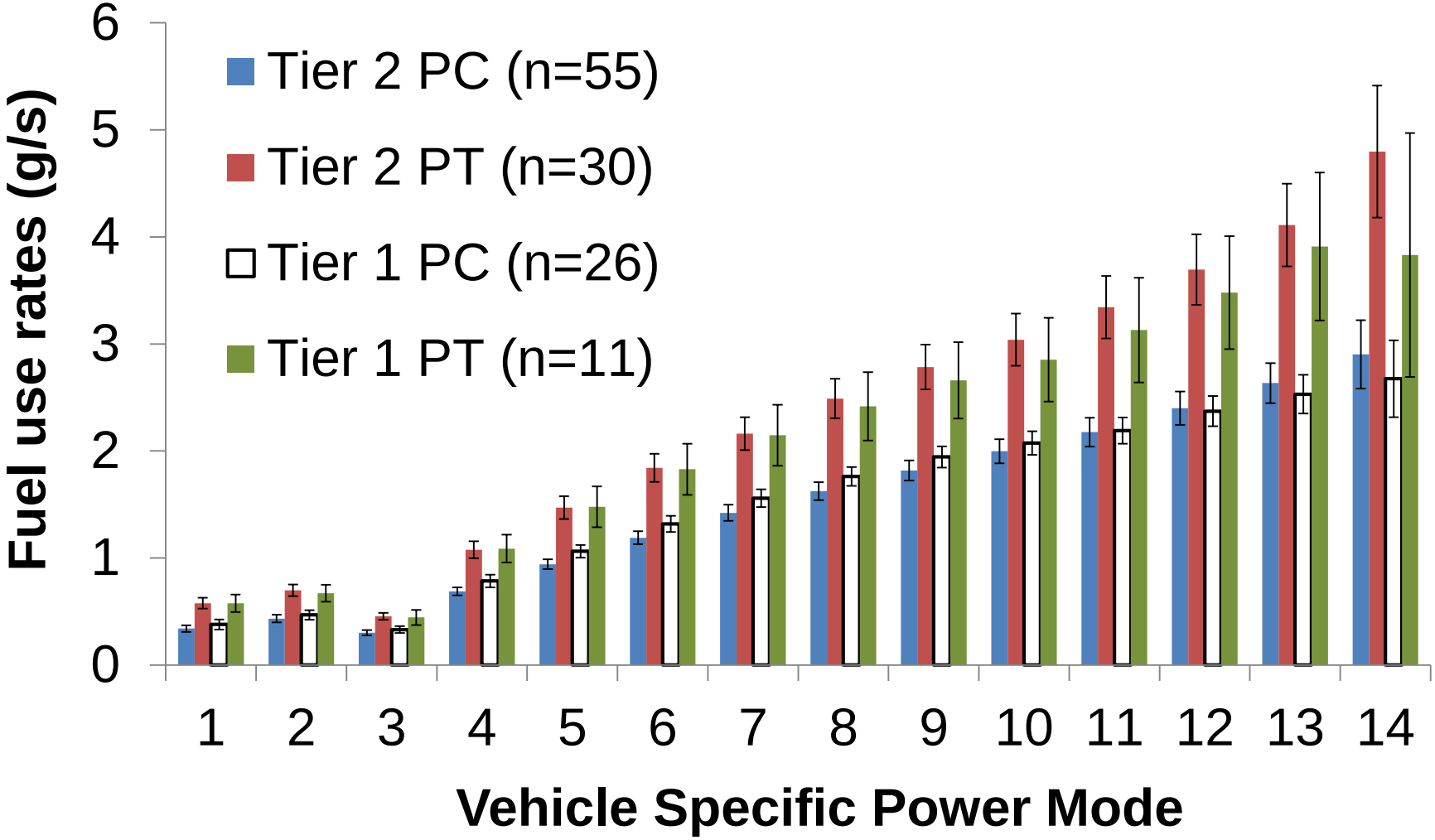
VSP = vehicle specific power (kW/ton)

Definition of VSP 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

Frey et. al., EPA Report, 2002

Average Vehicle Specific Power (VSP) Modal Fuel Use Rates (g/s) of 122 Measured Vehicles



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

Real-World Cycle Average Emission Rates without Cold Start (CAER)

- VSP modal emission rates (grams/second) weighted by time spent in each VSP mode for any driving cycle
- Cycles: **FTP**, **US06**, **SC03**, and **Real-World**

For pollutant p, VSP mode i, and driving cycle DC:

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

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

Mass Emissions (grams)

Modal time (seconds)

Modal emission rates (gm/sec)

CAER (gm/mile)

Distance (mile)

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

$$\mathbf{E_{p,c} = E_p + E_{cs,p}} \rightarrow \mathbf{E_{CAER,p,c}} = \frac{\mathbf{E_{p,c}}}{\mathbf{D_{DC}}}$$

Emissions with cold start (grams)

Cold start increment (grams)

CAER with cold start (gm/mile)

Matching Vehicles with EPA Certification Database

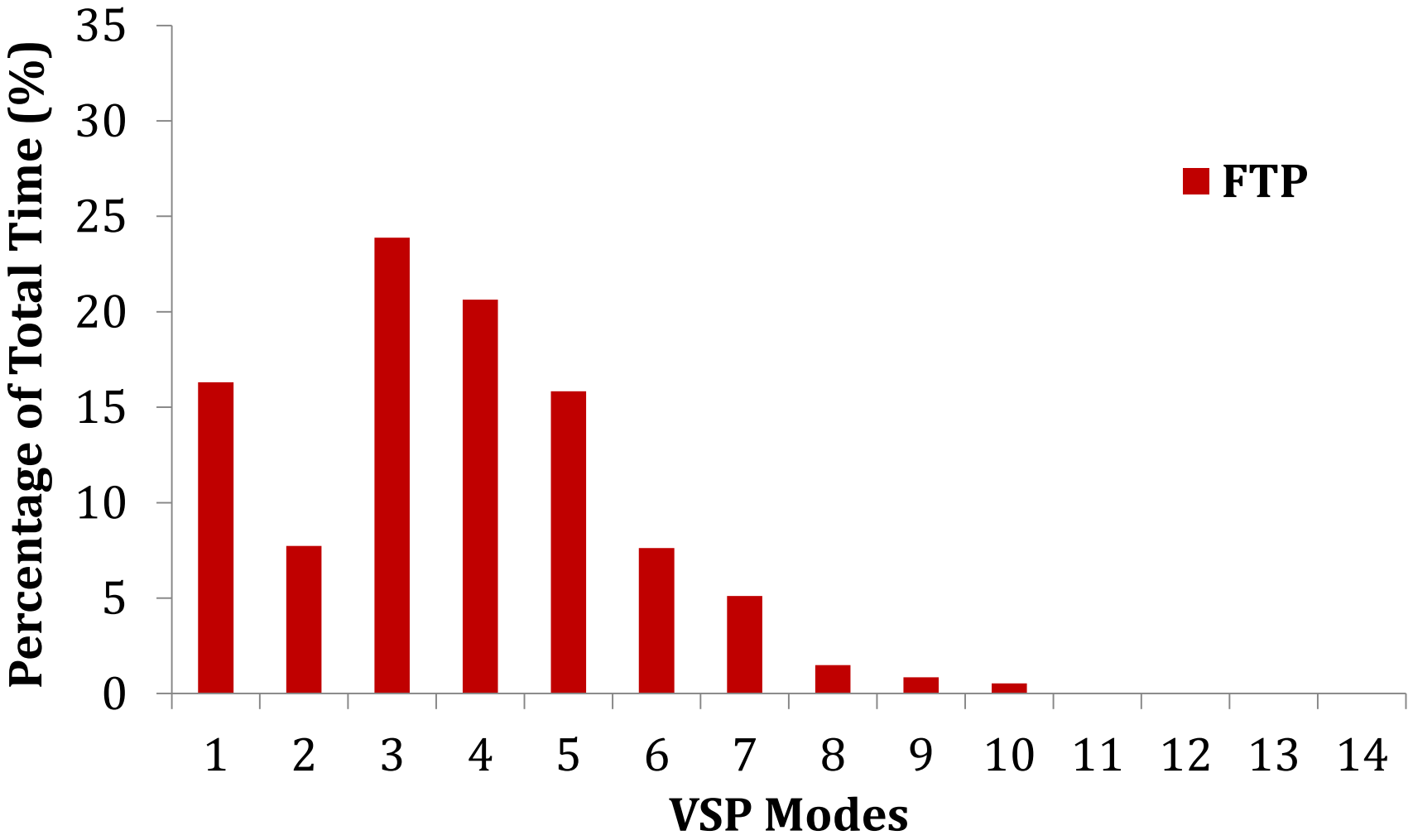
Matching Criteria:

- Model year
- Make
- Model
- Engine displacement
- Rated horsepower
- Fuel type
- Curb weight
- Gross weight
- Generations
- Corporate twins

Comparison between Standard and Real-World Driving Cycles

Criteria	FTP	US06	SC03	Route A	Route C	Route 1	Route 3
Average Speed (mph)	21.2	47.9	21.4	26.9	29.6	49.1	31.4
Maximum Speed (mph)	56.7	80.3	54.8	55.7	70.6	76.6	64.1
Average Positive VSP (KW/ton)	5.4	14.9	5.9	7.5	8.5	13.4	10.1
Maximum VSP (KW/ton)	22.9	58.7	31.2	34.4	39.5	51.2	37.1

VSP Modal Time Distribution of Selected Driving Cycles



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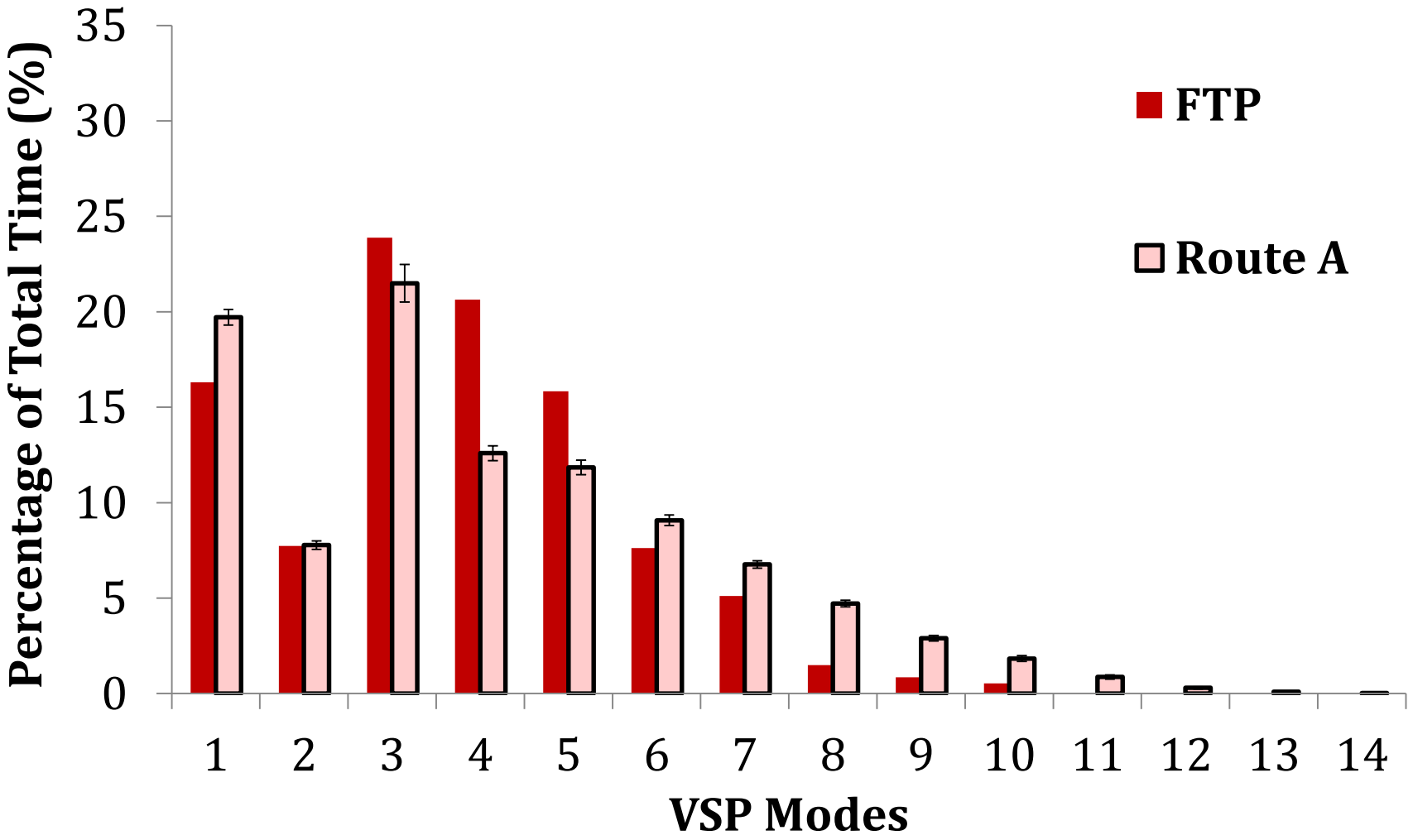
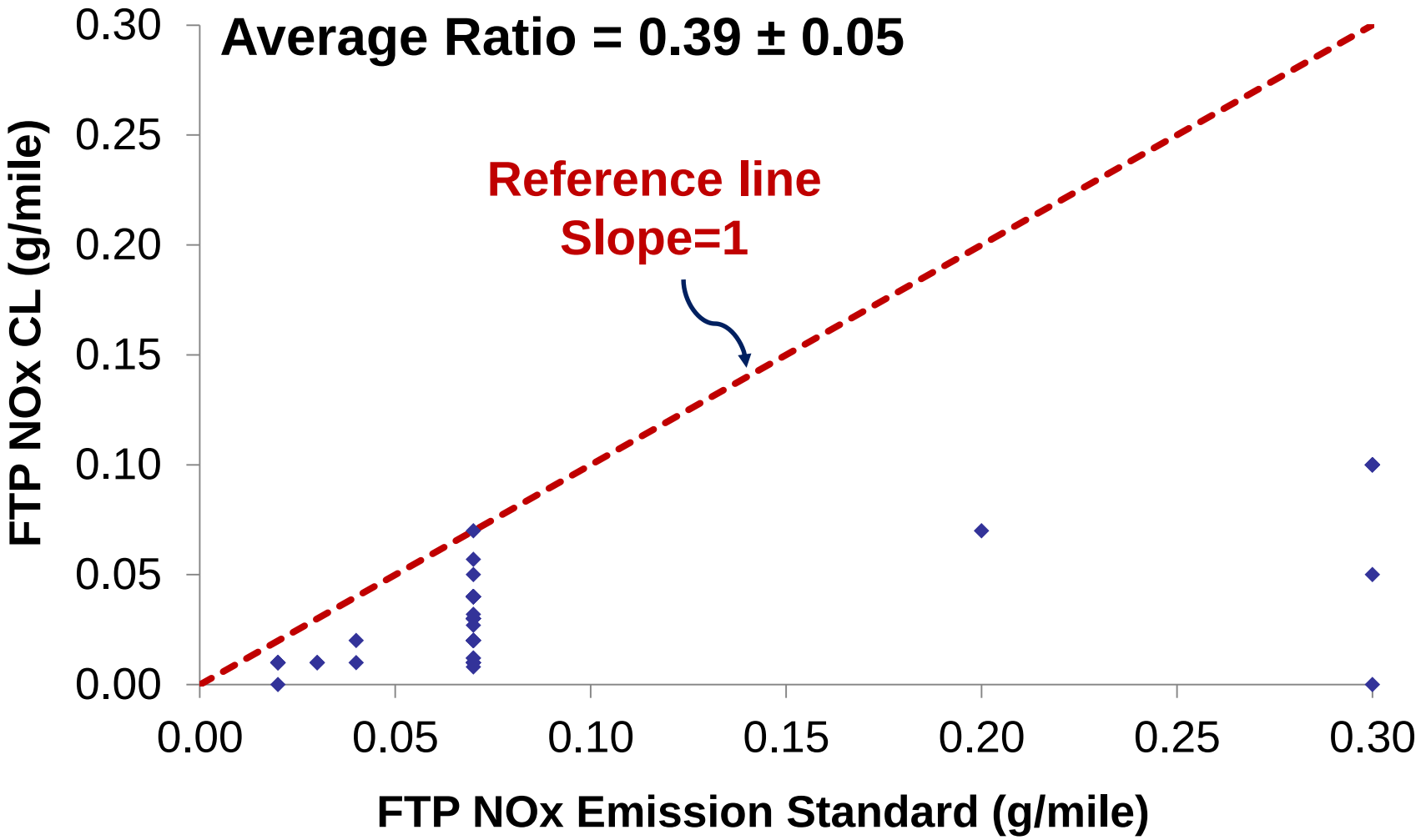


FTP NO_x Certification Level versus Emission Standard for Tier 2 PC (n = 55)



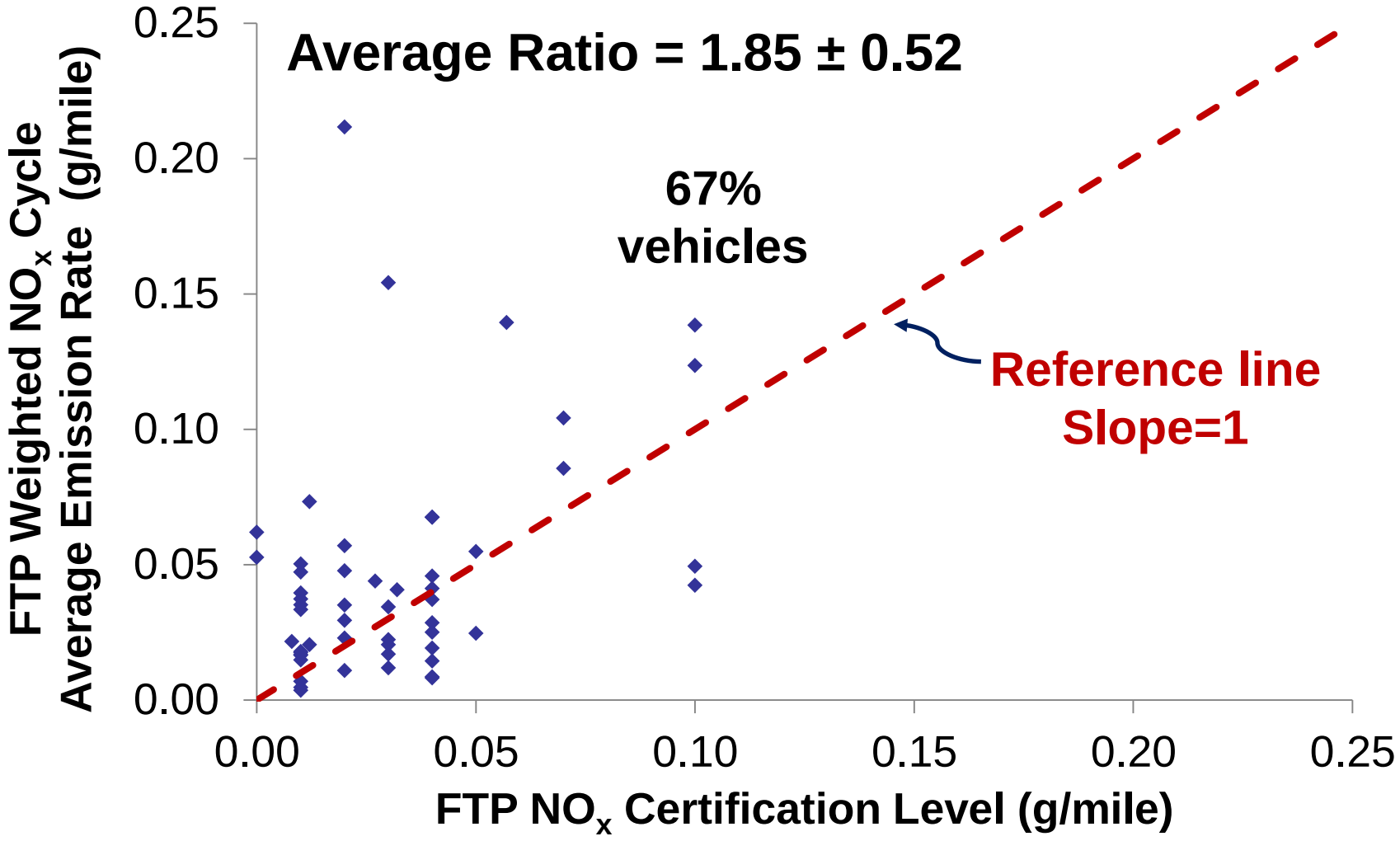
Average Ratio of Certification Level to Emission Standard

Driving Cycle	Pollutants	Average Ratio of Certification Level to Emission Standard (Mean ± 95% Conf. Interval)			
		PC-T1	PT-T1	PC-T2	PT-T2
FTP	CO	0.32±0.06	0.32±0.17	0.16±0.04	0.27±0.06
FTP	NMHC	0.52±0.07	0.38±0.09		
FTP	NMOG			0.42±0.05	0.42±0.07
FTP	HC	0.23±0.07	0.18±0.08		
FTP	NO_x	0.37±0.07	0.33±0.10	0.39±0.05	0.33±0.07

GREEN → Certification Level < Standard
BLUE → Certification Level ≈ Standard (within confidence interval)
RED → Certification Level > Standard

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

FTP-based Real-World NO_x Cycle Average Rate w/o Cold Start vs. Certification Level for Tier 2 PC (n = 55)

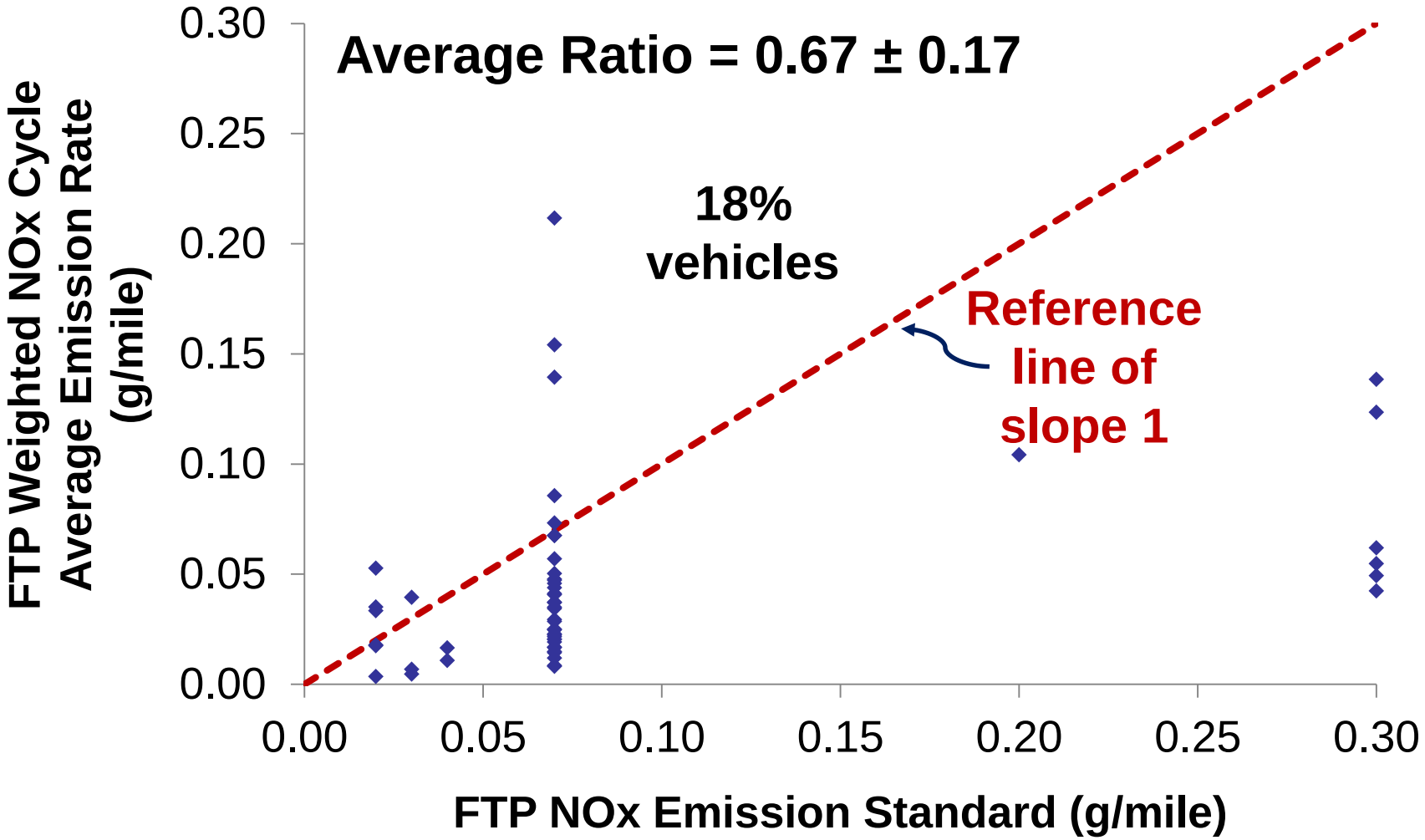


Average Ratio of Cycle Average Emission Rate w/o Cold Start to Certification Level, Standard Cycles

Driving Cycle	Pollutants	Average Ratio of CAER to CL (Mean ± 95% Confidence Interval)			
		Tier 1 PC	Tier 1 PT	Tier 2 PC	Tier 2 PT
FTP	CO	1.27±0.41	1.70±1.22	0.84±0.33	0.91±0.27
FTP	NMHC	1.10±0.38	1.51±0.55		
FTP	NMOG			2.93±1.20	2.27±1.21
FTP	HC	0.93±0.50	0.91±0.39		
FTP	NO_x	2.30±0.83	2.01±1.59	**1.85±0.52**	1.31±0.37
US06	CO			0.55±0.32	0.61±0.44
US06	NMHC+NO_x			2.80±0.66	2.62±1.02
SC03	CO			1.12±0.66	1.45±0.53
SC03	NMHC+NO_x			3.97±0.77	4.69±2.16

GREEN → CAER < CL
BLUE → CAER ≈ CL (within confidence interval)
RED → CAER > CL

FTP-based Real-World NO_x Cycle Average Rate w/o Cold Start vs. FTP Standard for Tier 2 PC (n= 55)

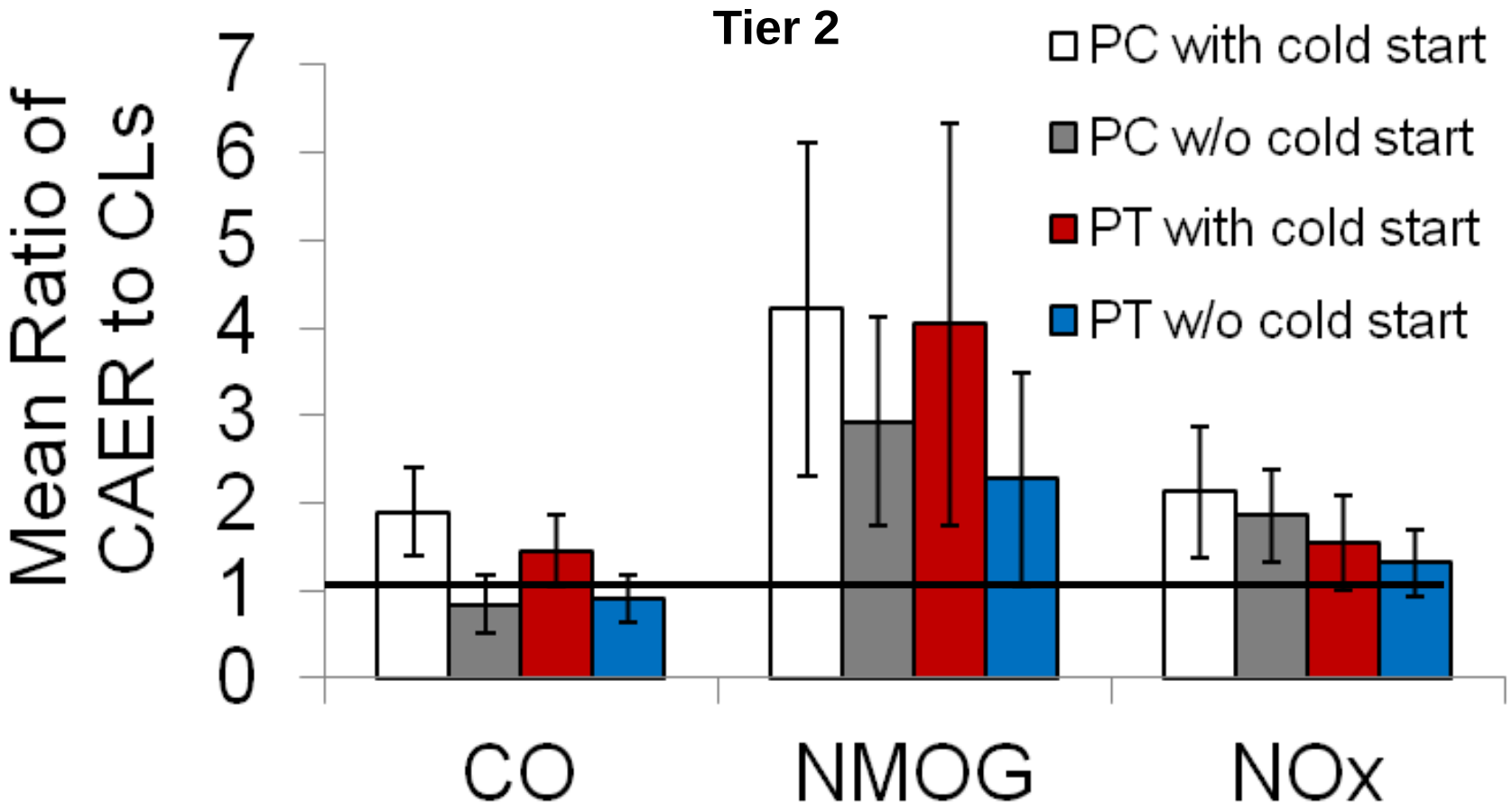


Average Ratio of Cycle Average Emission Rate w/o Cold Start to Level of Standard, Standard Cycles

Driving Cycle	Pollutants	Average Ratio of CAER to Emission Standard (Mean ± 95% Confidence Intervals)			
		Tier 1 PC	Tier 1 PT	Tier 2 PC	Tier 2 PT
FTP	CO	0.41±0.15	0.39±0.26	0.12±0.05	0.25±0.08
FTP	NMHC	0.56±0.26	0.58±0.27		
FTP	NMOG			1.28±0.64	0.89±0.49
FTP	HC	0.19±0.09	0.15±0.05		
FTP	NOx	0.74±0.23	0.54±0.30	**0.67±0.17**	0.44±0.18
US06	CO			0.07±0.03	0.10±0.03
US06	NMHC+NOx			0.56±0.09	0.42±0.16
SC03	CO			0.13±0.05	0.28±0.10
SC03	NMHC+NOx			0.45±0.08	0.45±0.16

GREEN → CAER < CL
BLUE → CAER ≈ CL (within confidence interval)
RED → CAER > CL

Sensitivity to Cold Start: Mean Ratio of FTP Weighted Rate to Certification Level: Tier 2



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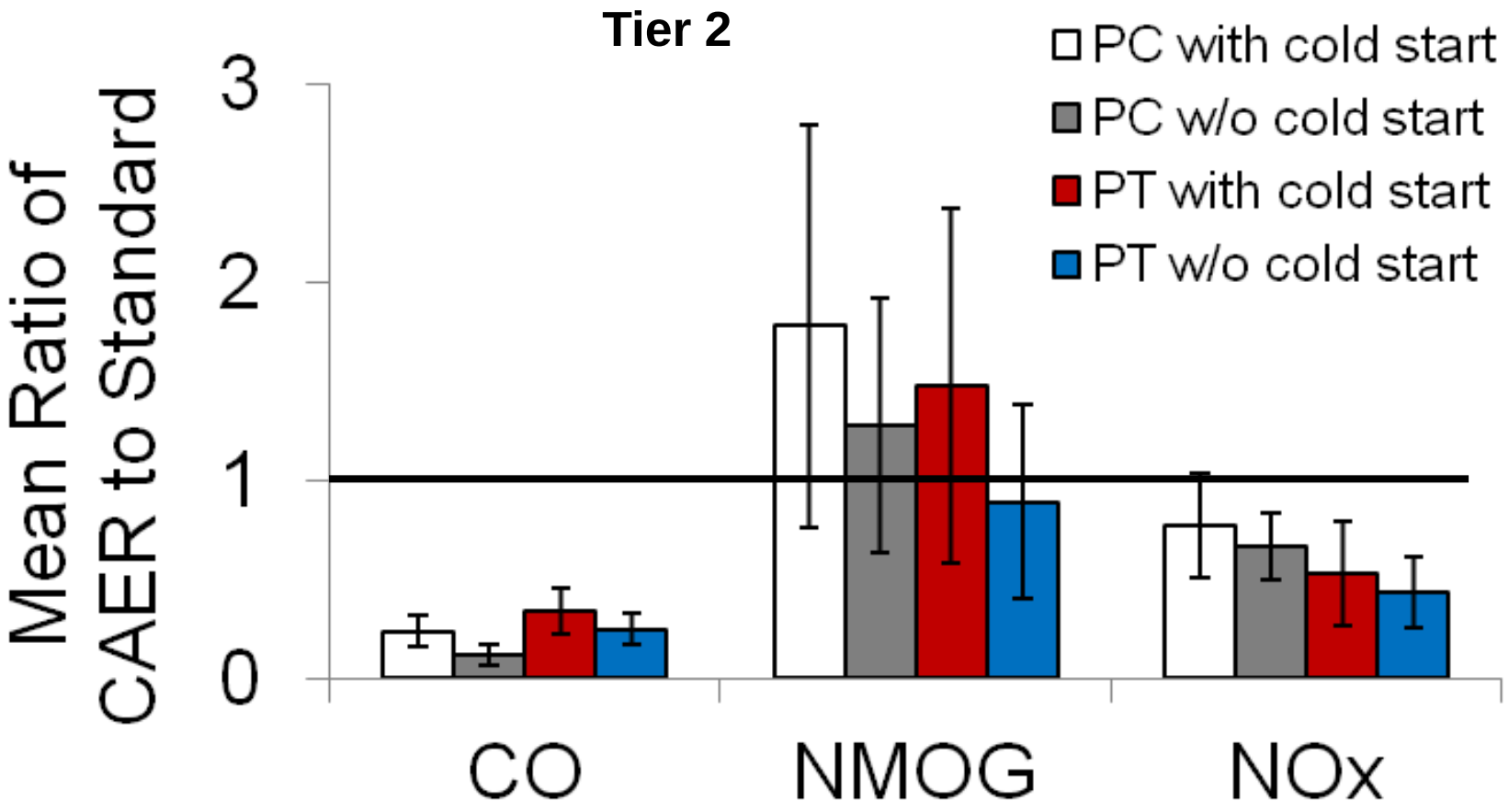
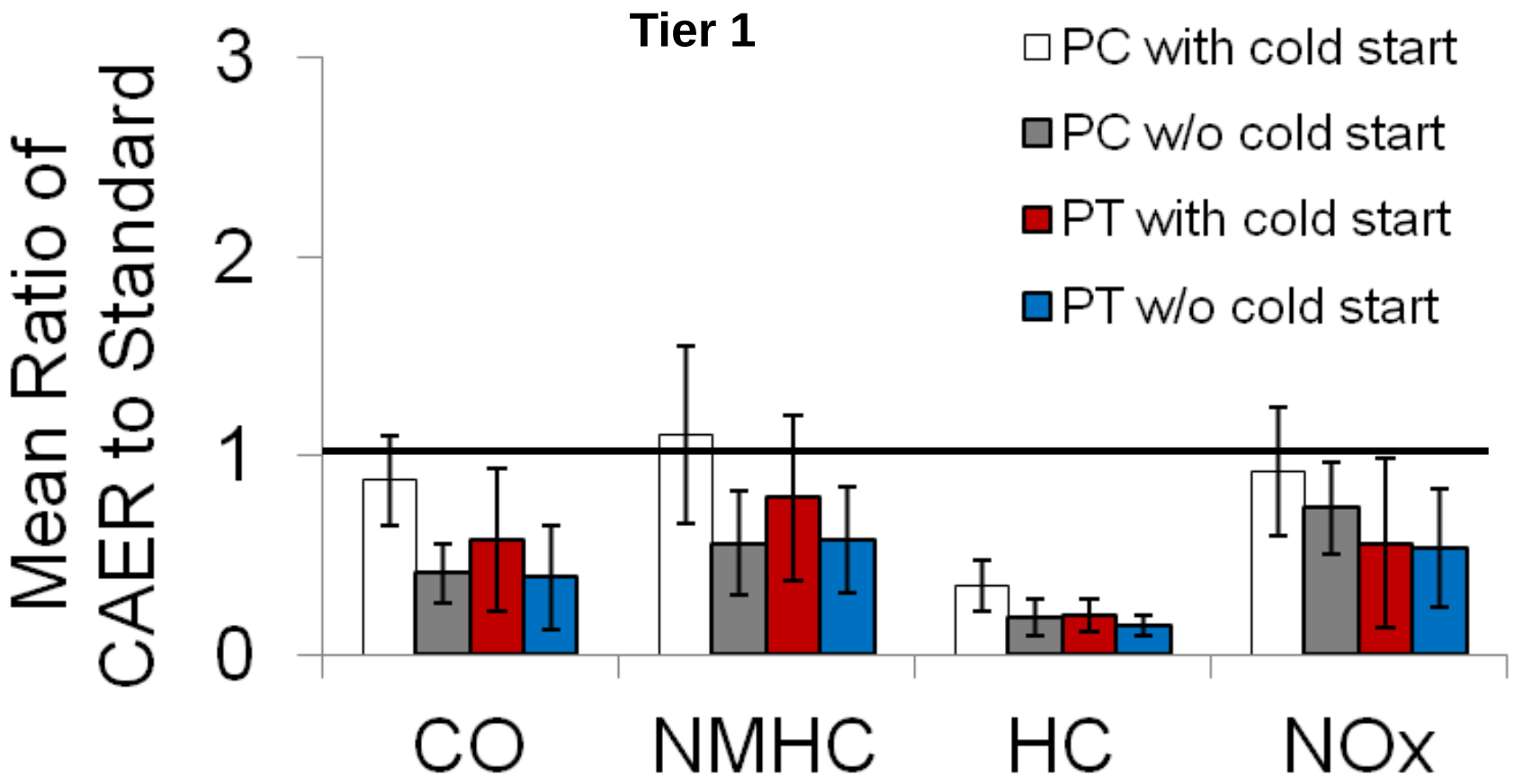
Sensitivity to Cold Start: Mean Ratio of FTP Weighted Rate to Level of the Standard: Tier 2



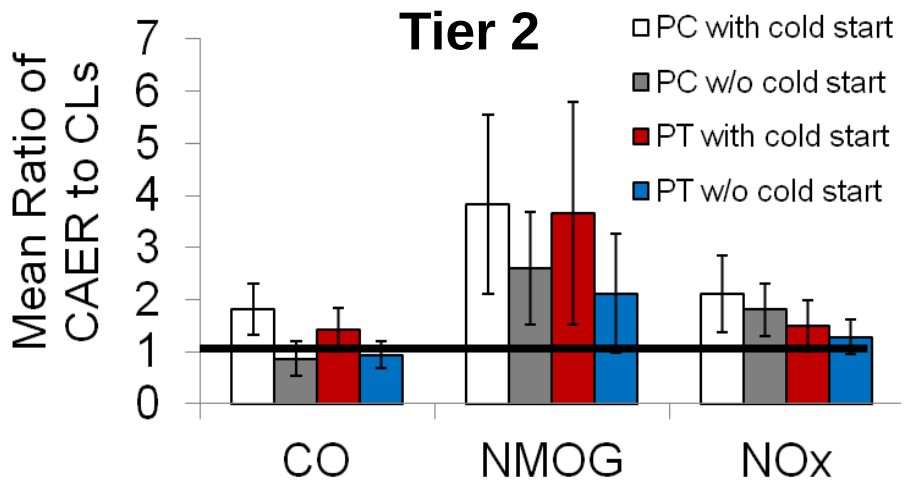
Considering confidence intervals, the FTP-weighted real-world rates are comparable to or lower than the level of the standard

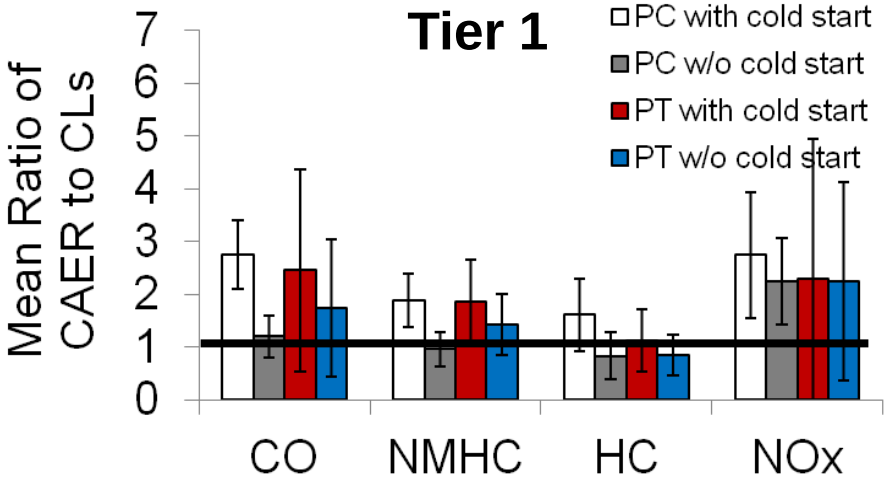
Sensitivity to Cold Start: Mean Ratio of FTP Weighted Rate to Level of the Standard: Tier 1

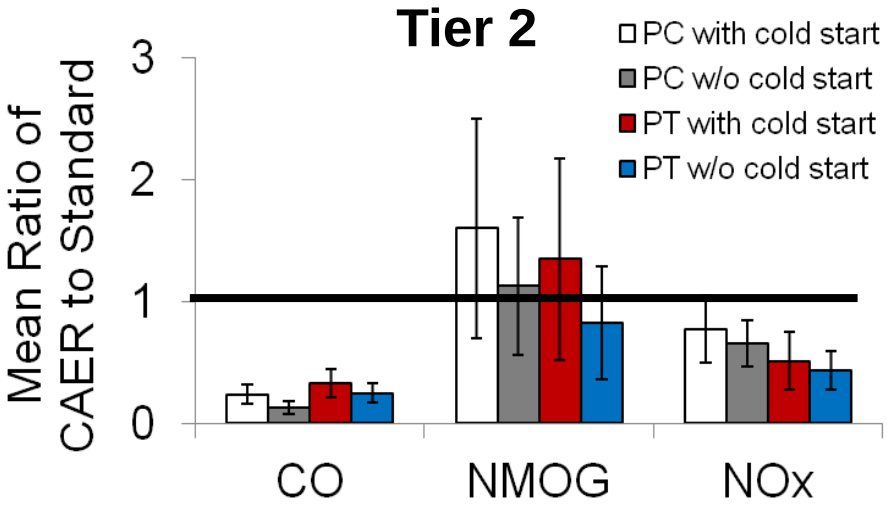


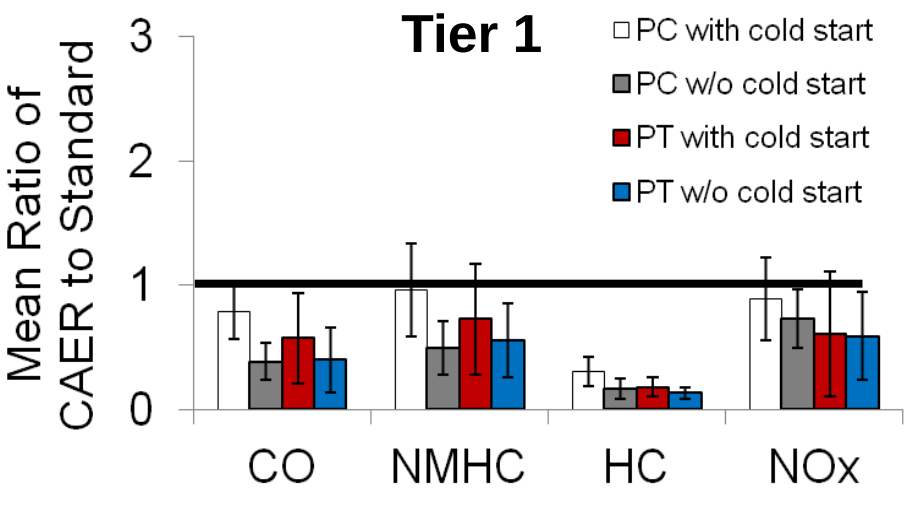
Considering confidence intervals, the FTP-weighted real-world rates are comparable to or lower than the level of the standard

Sensitivity to Cold Start: Mean Ratio of Route A Weighted CAER to CL and CAER to Standards









Conclusions

- Certification levels tend to be much lower than standards
- Real world hot stabilized mission rates tend to be higher than the certification levels and lower than the level of the standards
- For example, for Tier 2 PC, real-world emission rates (w/o cold start) are higher than the FTP certification level but lower than the FTP standards
- With cold starts, real world-based rates are comparable to or lower than the levels of the standards

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