Assessing the impact of real-world driving cycles, fuel economy and tailpipe exhaust emissions on eco-rating of passenger cars

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Outline

- Objective
- ACEEE Green Score
- Field Measurements
- Scenarios:
  - Baseline (ACEEE-reported Green Scores)
  - Real-world cycles
  - Real-world emissions
  - Real-world fuel economy
- Sensitivity Analysis

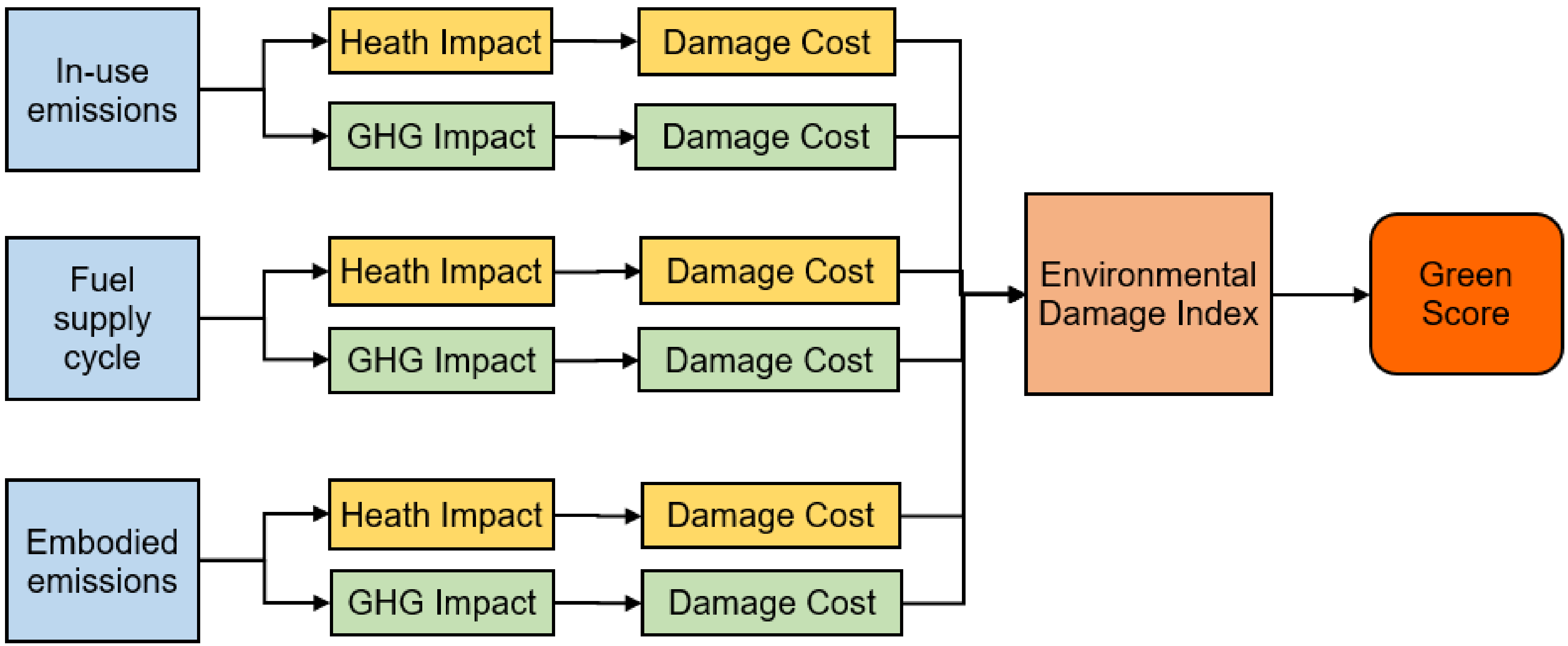
Introduction

- "Eco-rating": rating passenger cars based on environmental impact
- Examples: Green Score and US EPA Green Vehicle Guide (US), Ecoscore (Belgium), Green Car Rating (UK)
- **Green Score** developed by **American Council for an Energy-Efficient Economy (ACEEE)**[2]
- Green Score based on **life cycle assessment** (LCA):
  - vehicle in-use
  - fuel supply cycle
  - vehicle manufacture, assembly and disposal
- Health and Greenhouse Gas (GHG) impacts are assessed

Motivation and Objective

- Green Score is based on:
  - **rated fuel economy**
  - **tailpipe exhaust emission standards**
- These data depend on dynamometer tests or dynamometer-based standards
- Real-world driving often differs from fuel and emissions dynamometer driving cycles
- **Objective**: Quantify sensitivity of the Green Score to driving cycles, real world fuel economy, and real-world exhaust emission rates

ACEEE Green Score



Standard Test Cycles

- **Federal Test Procedure (FTP)**
  - Represents urban driving, in which a vehicle is started with the engine cold and driven in stop-and-go rush hour traffic
- **Highway- Highway Fuel Economy Test (HWFET)**
  - Represents a mixture of rural and Interstate highway driving with a warmed-up engine, typical of longer trips in free-flowing traffic
- High Speed/Supplemental FTP (US06)
  - Represents city and highway driving at higher speeds with more aggressive acceleration and braking
- Air Conditioning (SC03)
  - Account for air conditioning use under hot outside conditions (95°F sun load)
- Cold Temperature (Cold FTP)
  - Tests the effects of colder outside temperatures on cold-start driving in stop-and-go traffic

Key Inputs to Green Score: Fuel Economy

- 2007 and earlier model year: Fuel economy based on **FTP** and **HWFET** for city and highway, respectively

- 2008 and later, approach is based on
  - FTP, HWFET, US06, SC03 and Cold FTP
  - "Derived" approach based on **FTP** and **HWFET** only

- Green Score based on 43% city and 57% highway

Key Inputs to Green Score: Emissions

- FTP-based emission standards
  - carbon monoxide (CO)
  - non-methane organic gases (NMOG)
  - nitrogen oxides (NO_x)
  - particulate matter smaller than 10 microns (PM_{10})

Estimation of Green Score

Vehicle In-use

- Emissions as a result of vehicle operation
- CO, HC, NO_x and PM_{10} emitted at the level of standard (g/mile)
- Non-regulated pollutants such as CO_2, CH_4, N_2O and SO_2 are dependent on fuel consumption rate (g/gallon)
- Fuel-economy is used to convert g/gal emission rates to g/mile emission factors

Estimation of Green Score

Fuel-Supply cycle

- Emissions resulting from production, transport and storage of fuel
- Emission rates (g/gal)
- Fuel-economy is used to convert g/gal emission rates to g/mi emission factors

Estimation of Green Score

- **Vehicle manufacture, assembly and disposal**
  - Assumes pollutants emitted in proportion to curb weight
  - Stratified by vehicle class – e.g., car, pickup, SUV
  - Total mass of pollutants (grams) divided by mean vehicle useful life (miles) to obtain emission factors (g/mi)

Emission Impacts

- **Health Impacts**:
  - Product of emission factor and damage cost for each pollutant at each stage

- **GHG Impacts**:
  - Product of emission factor, global warming potential and damage cost of each GHG at each stage

Environmental Damage Index

Total environmental impact of a vehicle (g/mile):

$$EDX = \sum d_{pj} e_{pj}$$

Where,

p	=	index over pollutant species;
j	=	index over stage;
d_{pj}	=	environmental damage cost in cents per gram of a pollutant *p* at stage *j*;
e_{pj}	=	quantity of emissions of pollutant *p* at stage *j*, averaged over the vehicle operational life, in grams/mile

Green Score

- EDX is mapped inversely from a [0,∞] range to a [0,100] range using a Gamma function
- EDX 0 corresponds to a Green Score 100

$$\text{Green Score} = x\,\frac{e^{-\mathrm{EDX}/z}}{(1+\mathrm{EDX}/z)^{y}}$$

Where,

x	=	100
y	=	3
z	=	8.19 ¢/mi (units conversion)

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

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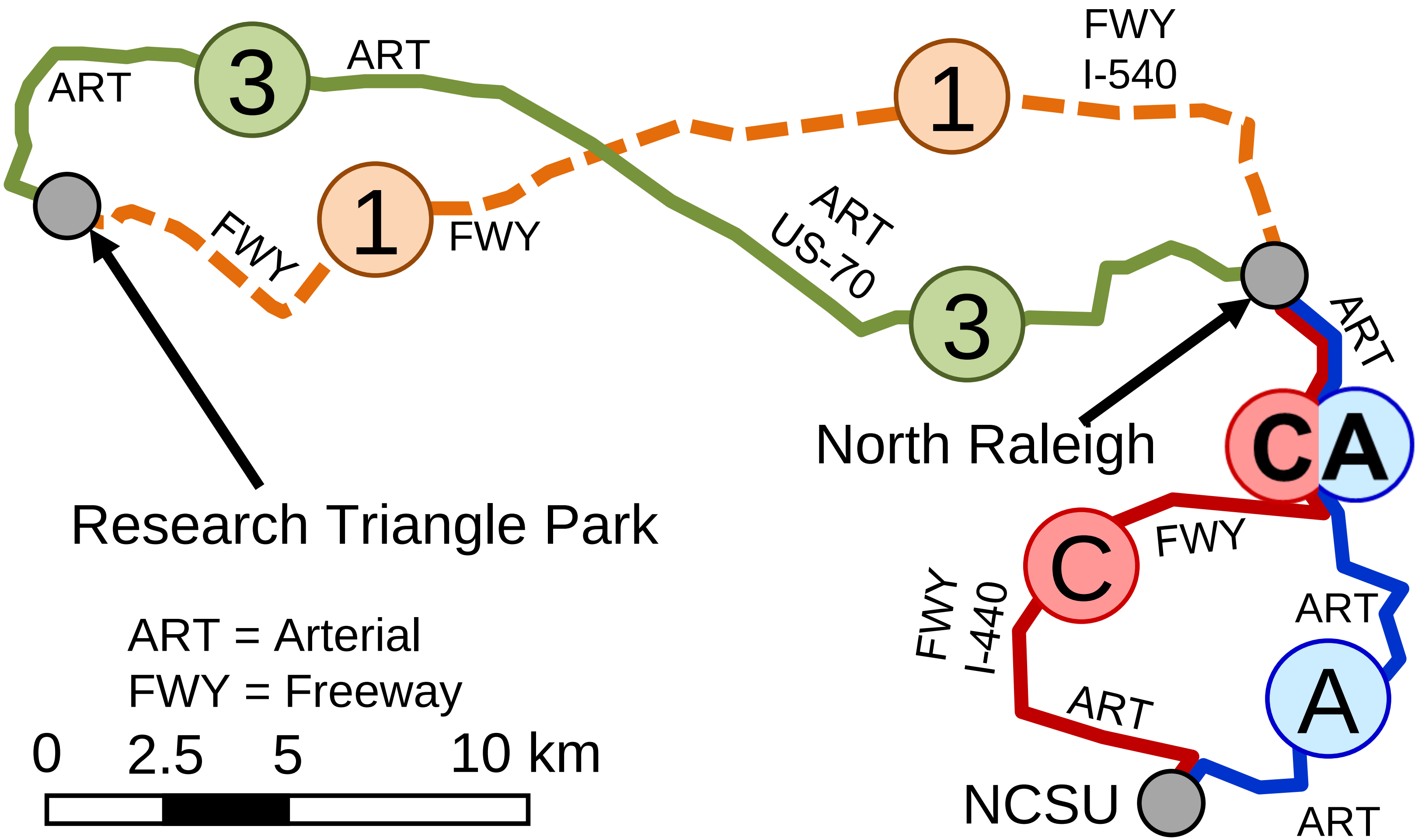
Methods: Test Routes



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Estimating Vehicle Fuel Use Based on 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)
ε	= factor accounting for rotational masses (~ 0.1)
ρ	= ambient air density (1.207 kg/m^3 at 20 ºC)

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	39 ≤ VSP

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Methods: Cycle Average Fuel-use and Emission Rates

Mass (in grams) of fuel consumed or pollutant emitted over a driving cycle

$$E_{p,V,DC} = \sum_{i=1}^{14} (t_m \times ER_{p,V,DC,m})$$

Where,

$E_{p,V,DC}$ = cycle-based mass of specie p (grams) for vehicle V for a driving cycle DC;

t_m = average number of seconds of the driving cycle in each VSP mode *m*;

$ER_{p,V,DC,m}$ = average mass rate (grams/second) for of specie *p*, vehicle *V*, driving cycle *DC*, and VSP mode *m*.

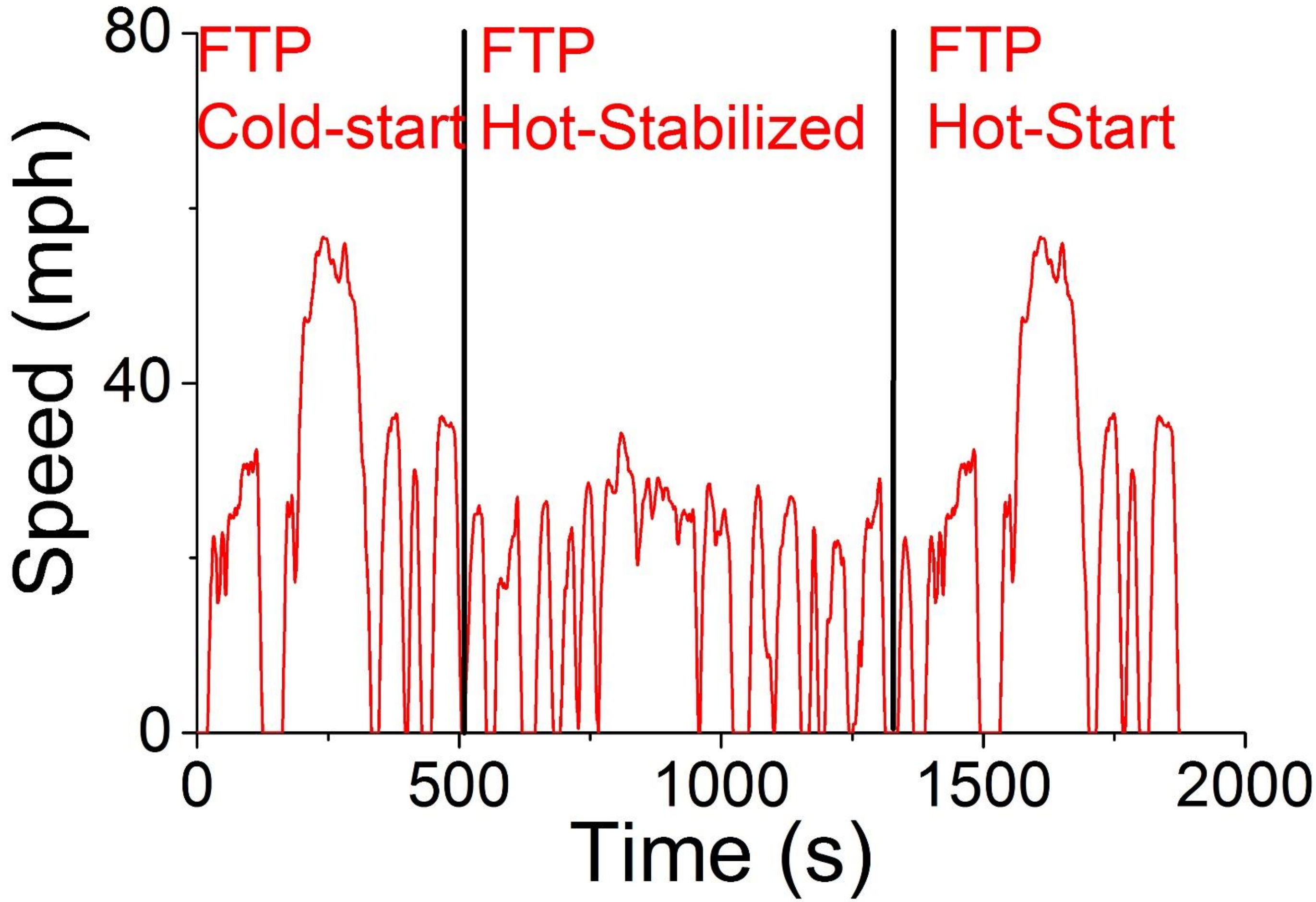
Methods: Cycle Average Fuel-use and Emission Rates

$$\mathrm{E}_{\mathrm{CAR},p,V,DC} = \frac{E_{p,V,DC}}{D_{DC}}$$

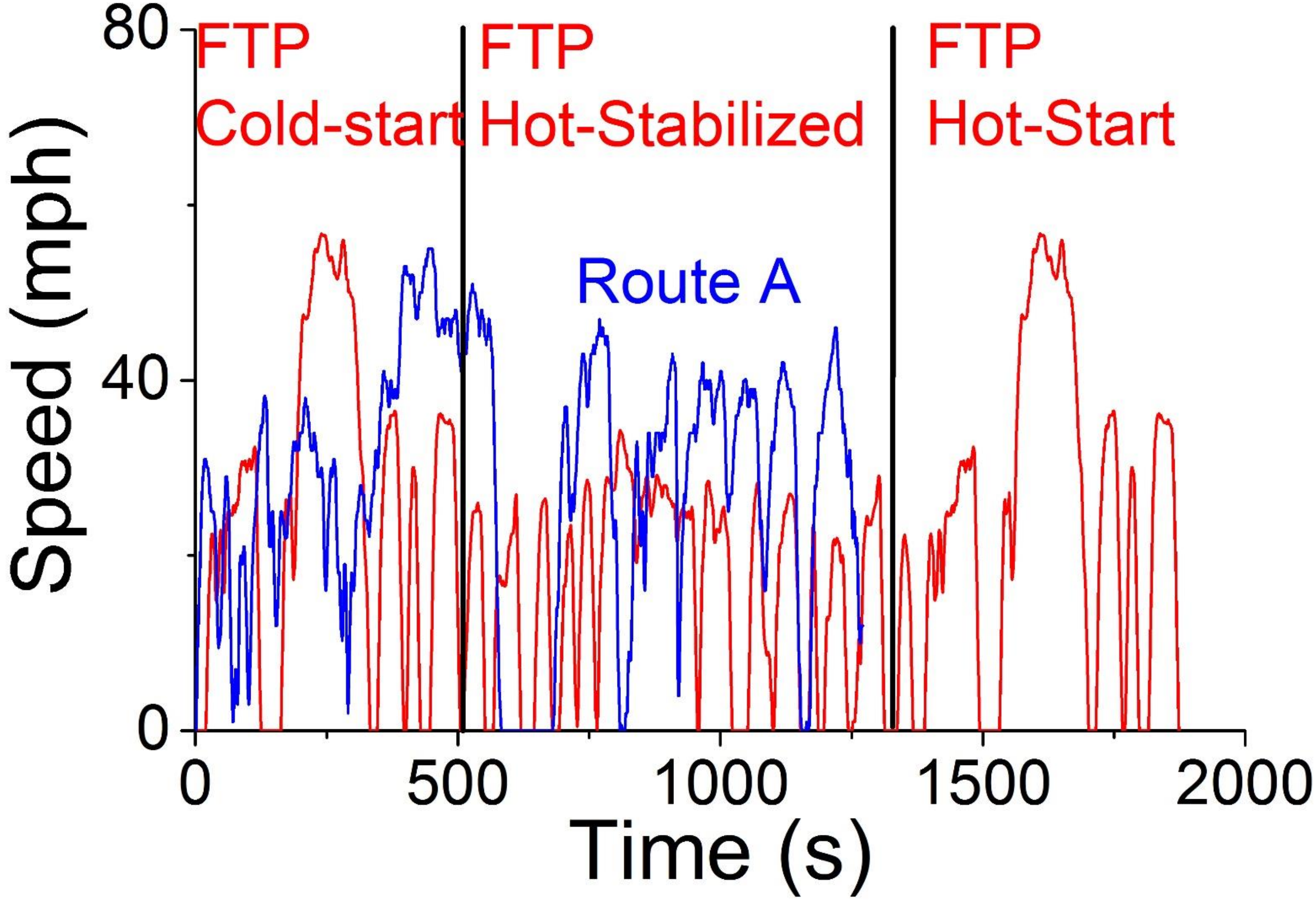
Where,

$E_{CAR,p,V,DC}$	=	cycle average rate of species p from a vehicle *V* for a driving cycle *DC* (grams/mile);
$E_{p,V,DC}$	=	cycle-based mass of species *p* (grams) for vehicle *V* for a driving cycle *DC*;
D_{DC}	=	distance (miles) of applicable driving cycle *DC*.

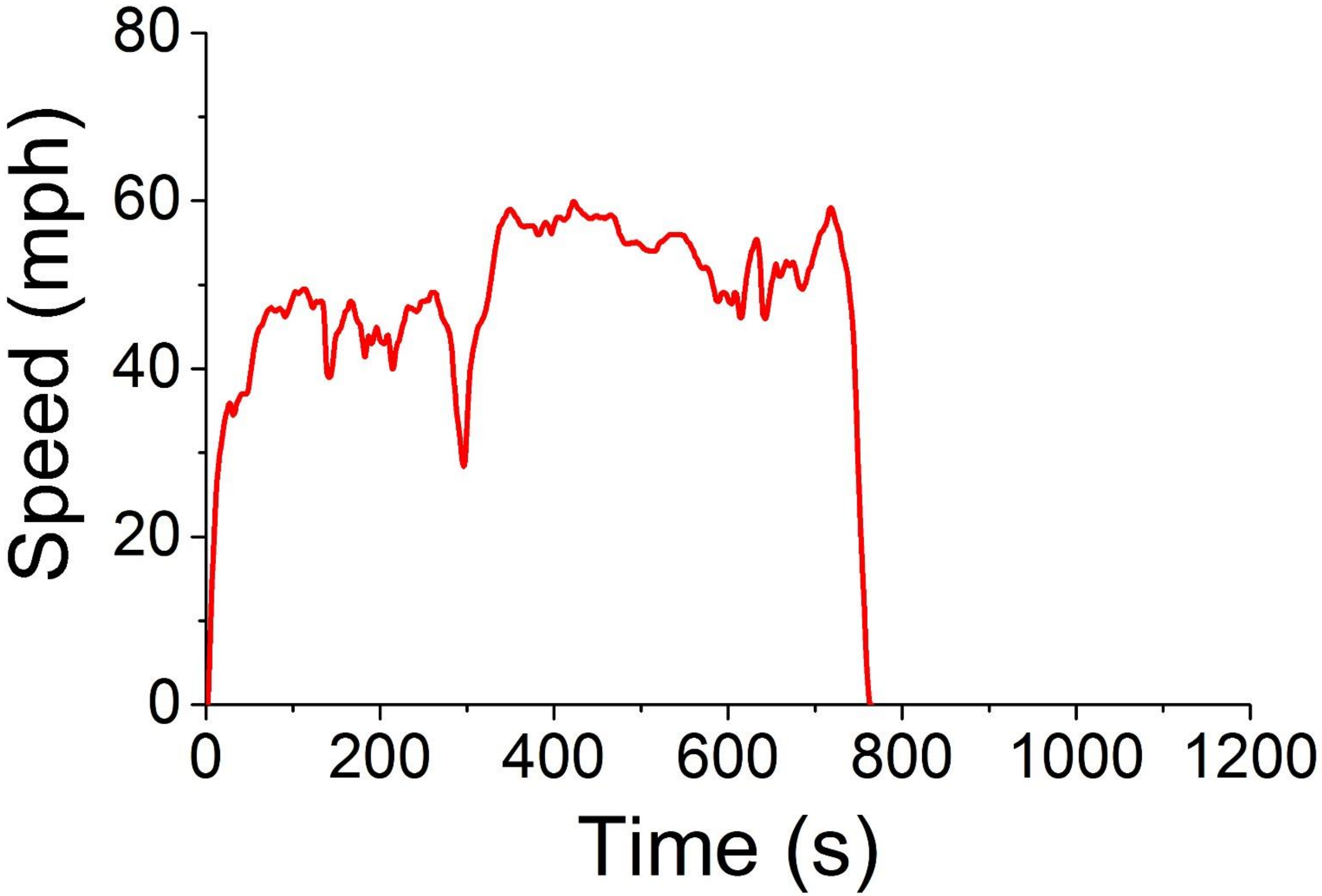
FTP Driving Cycle



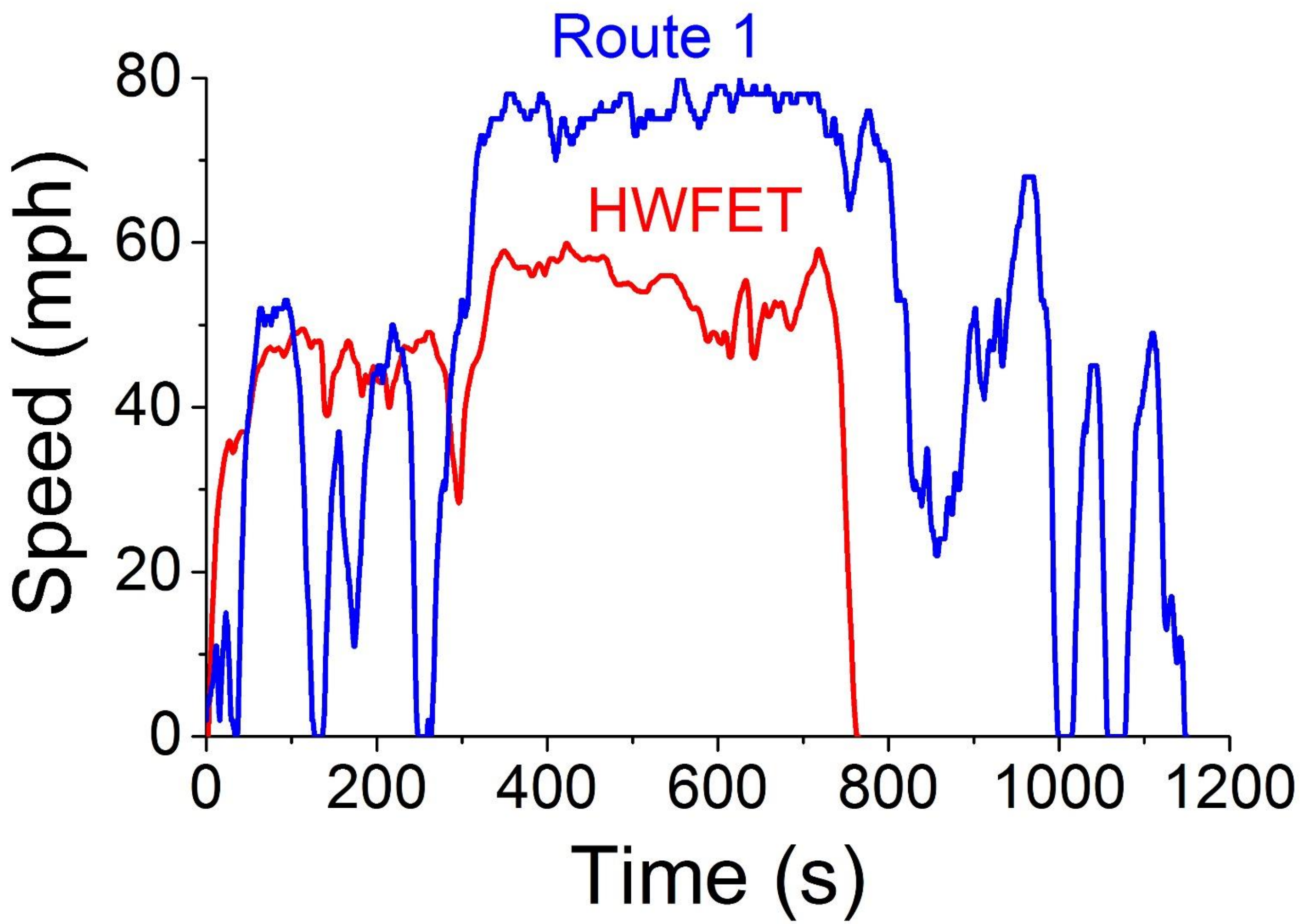
Comparison of a Real-World Cycle vs. FTP



Highway Fuel Economy Test (HWFET) Cycle



Comparison of a Real-World Cycle vs. HWFET



Methods: Vehicle Sample

- Vehicles (84): 13 light duty pickup trucks
  66 passenger cars
  5 hybrid electric vehicles (HEVs)
- Model years: 2004 to 2014
- Engine size: 1.3 L to 5.4 L
- Curb weight: 2200 lbs. to 5900 lbs.
- Age: 0 years to 10 years
- Mileage: 600 miles to 230,000 miles

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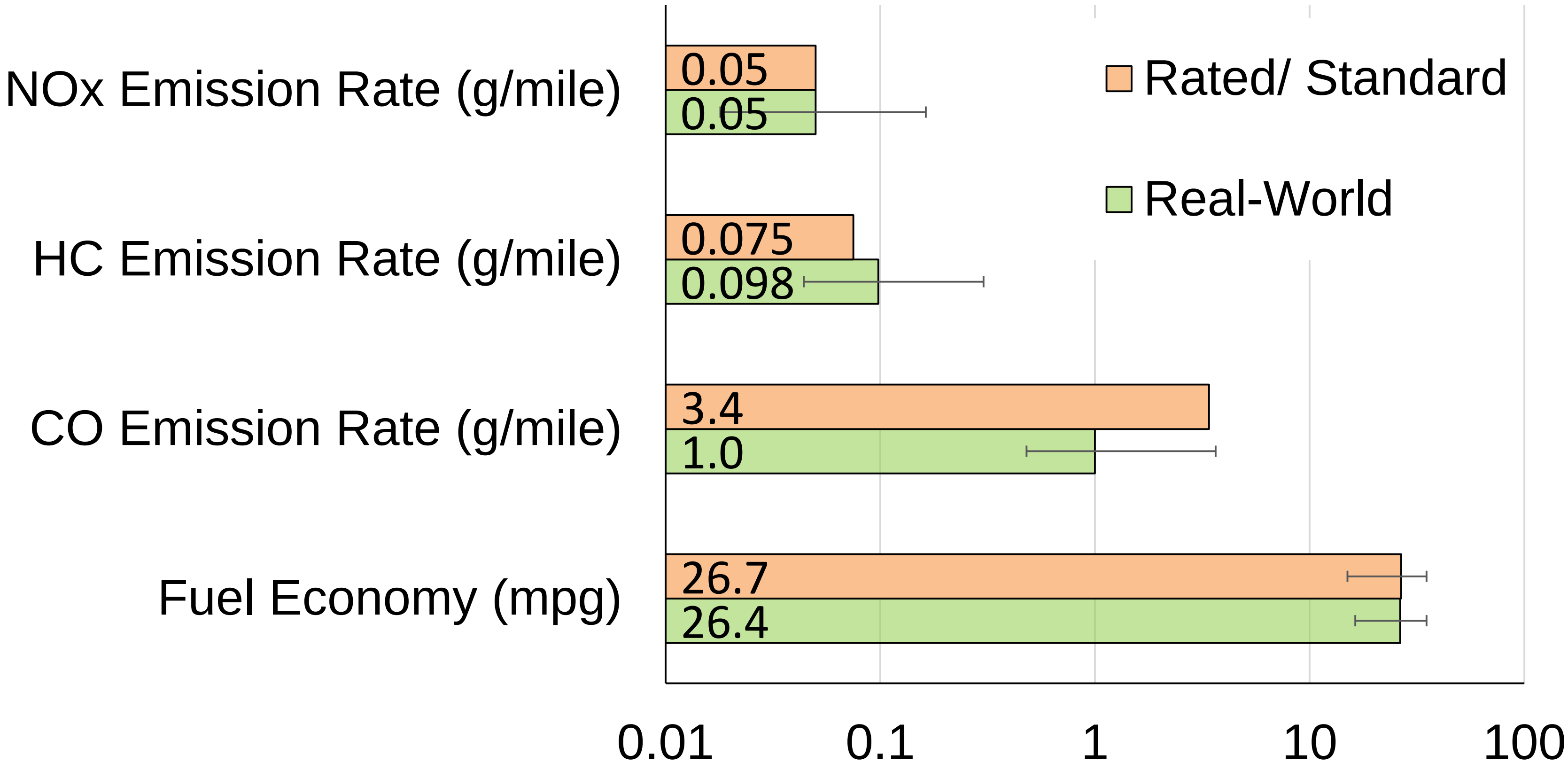
Comparison of EPA and Real-World Cycle Average Data



- The real-world database includes 56 vehicles compliant to Federal Tier 2 Bin 5 standards, measured by North Carolina State University (NCSU)
- Real world rates have been weighted to standard test cycles

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Scenarios

Scenario Identification	Input Assumptions			
	Fuel Economy		Tailpipe Emissions	
	Driving Cycle	Fuel Use	Driving Cycle	Emissions
1: Baseline	FTP/HFET	EPA Rated	FTP	Emissions Standard
2: FTP-HFET/FTP	FTP/HFET	VSP Modal Rates	FTP	VSP Modal Rates
3: R1-R1	Route 1	VSP Modal Rates	Route 1	VSP Modal Rates
4: RA-RA	Route A	VSP Modal Rates	Route A	VSP Modal Rates
5: Rated-FTP	FTP/HFET	EPA Rated	FTP	VSP Modal Rates
6: Rated-R1	FTP/HFET	EPA Rated	Route 1	VSP Modal Rates
7: Rated-RA	FTP/HFET	EPA Rated	Route A	VSP Modal Rates
8: FTP/HFET-Std.	FTP/HFET	VSP Modal Rates	FTP	Emissions Standard
9: R1-Std.	Route 1	VSP Modal Rates	FTP	Emissions Standard
10: RA-Std.	Route A	VSP Modal Rates	FTP	Emissions Standard

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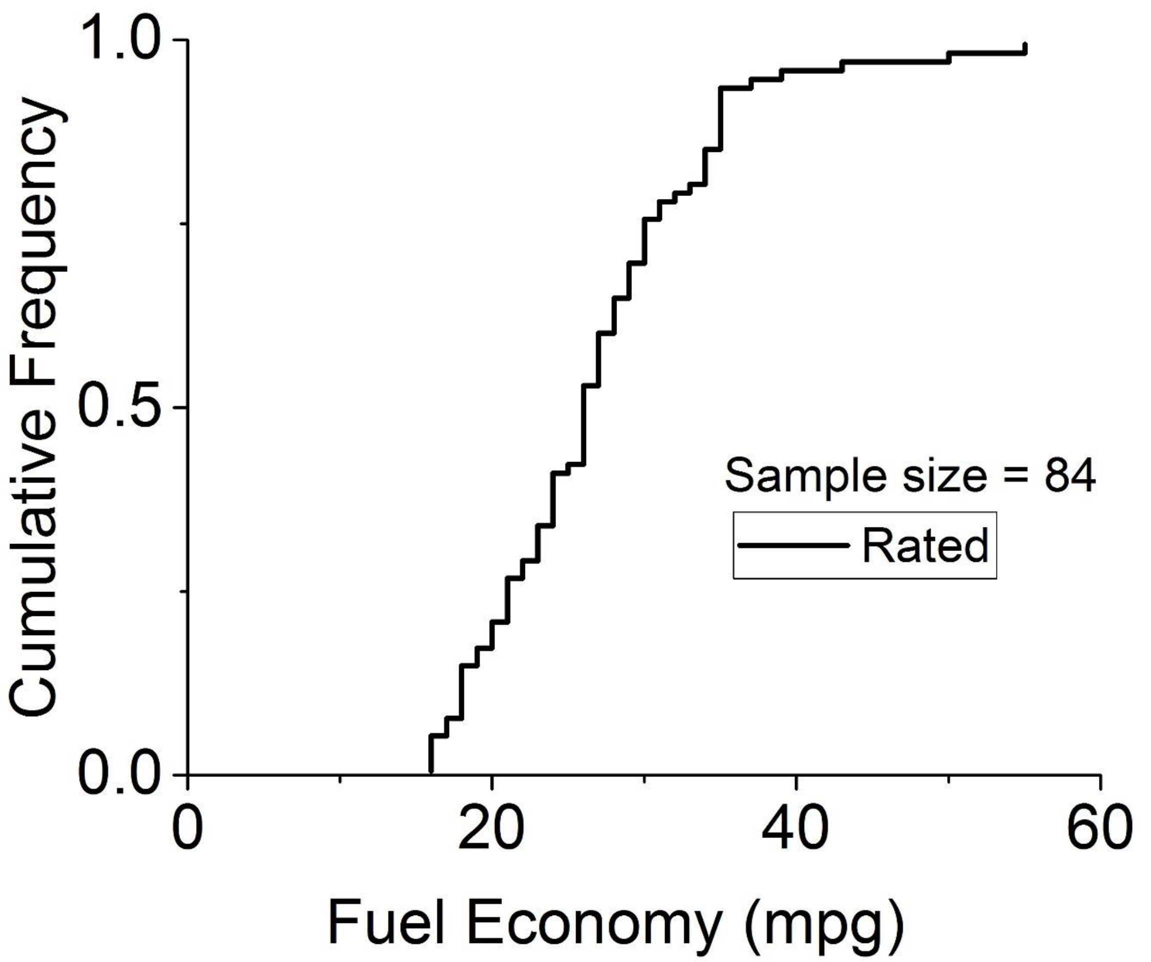
Results: Cycle Average Fuel Economy



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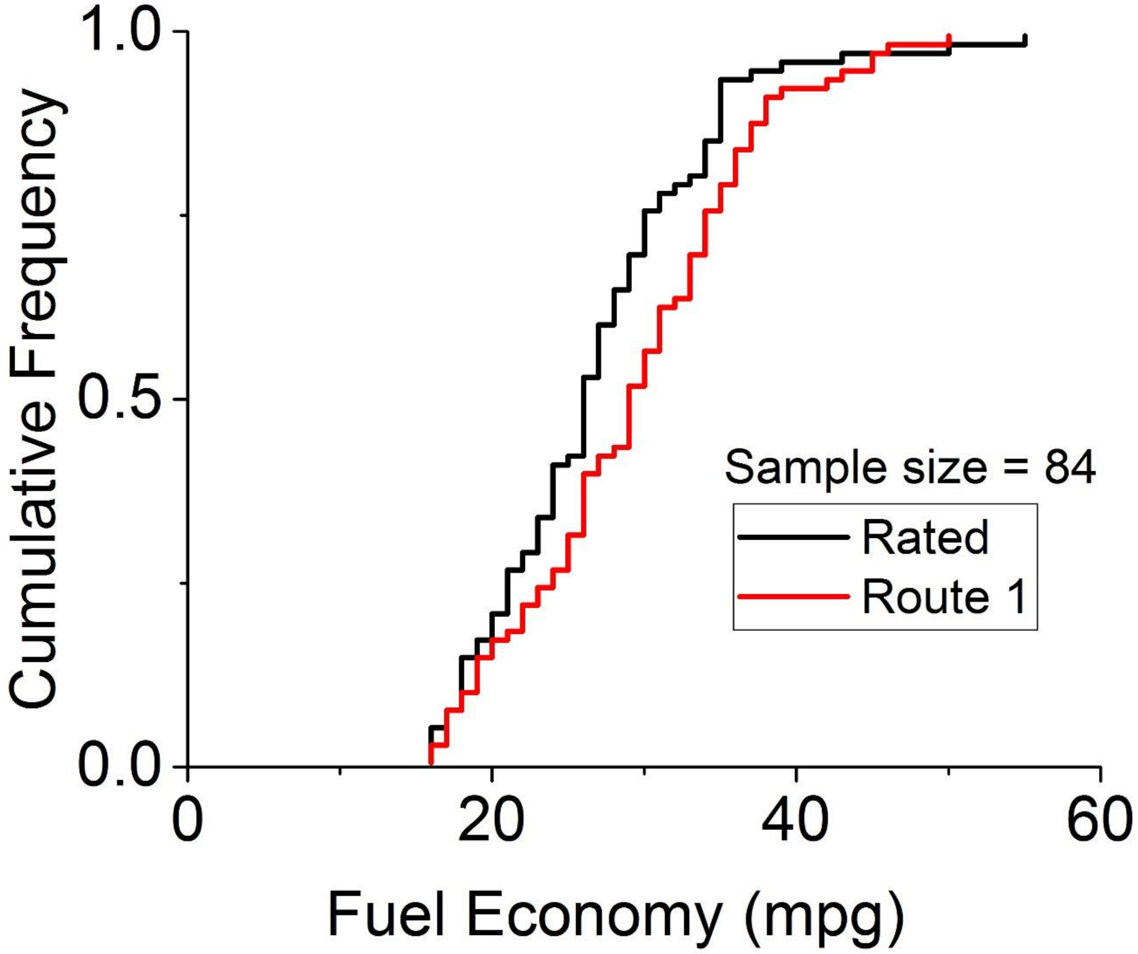
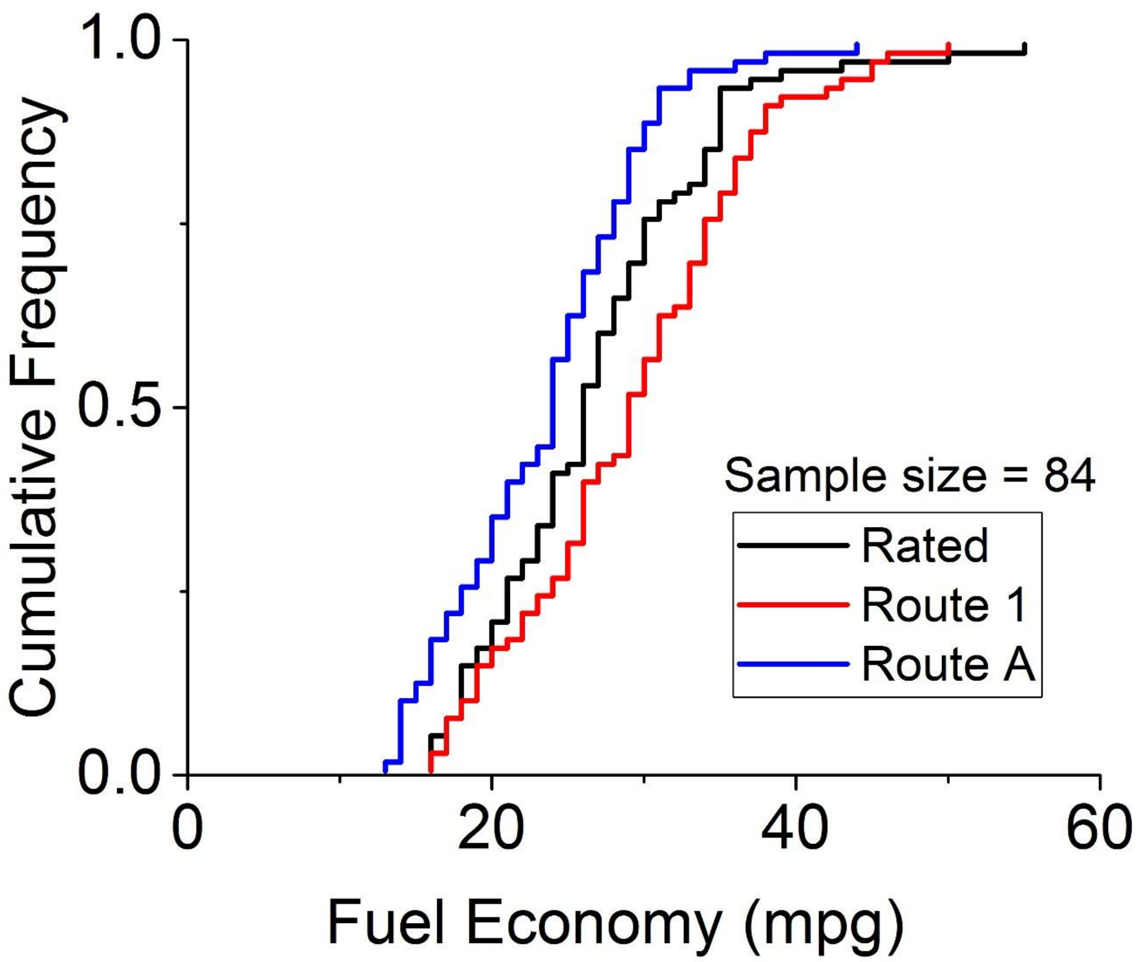
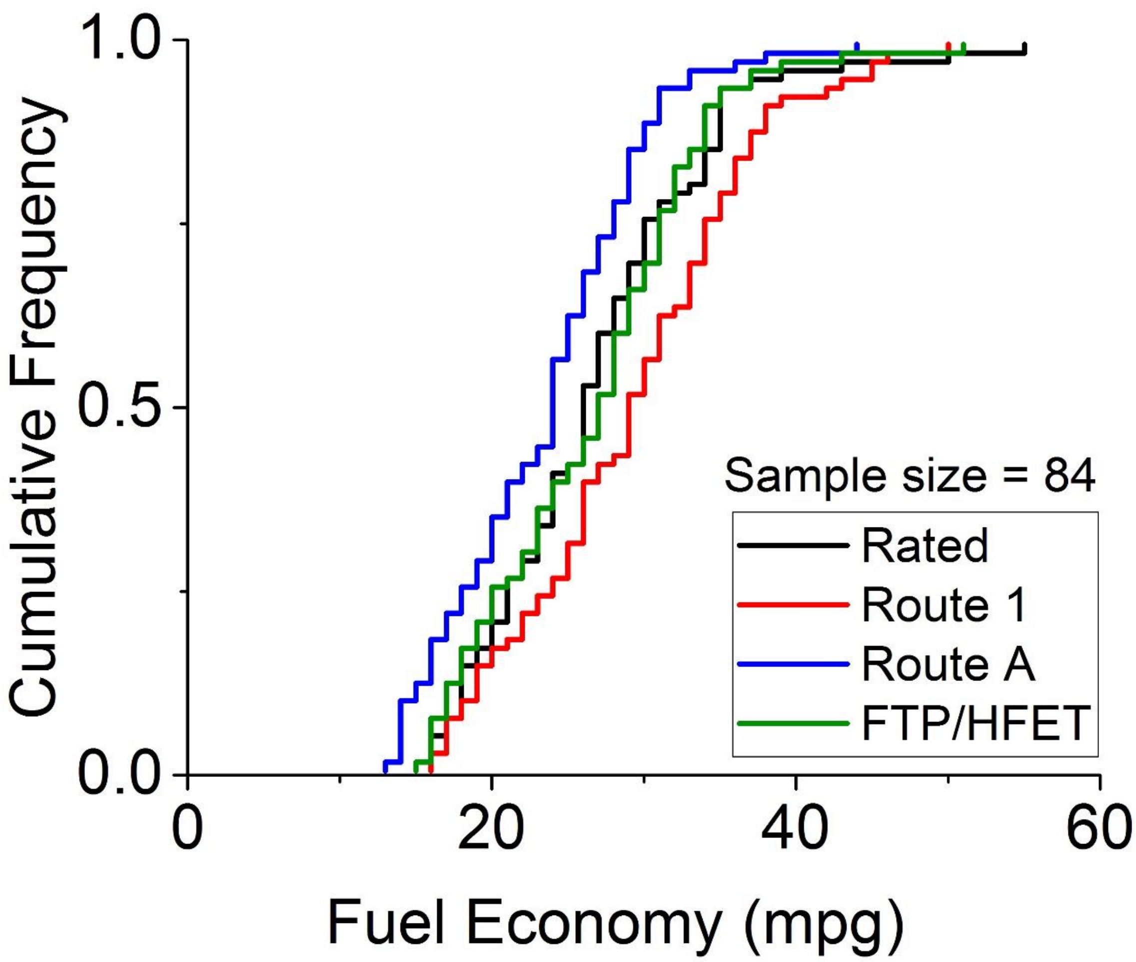


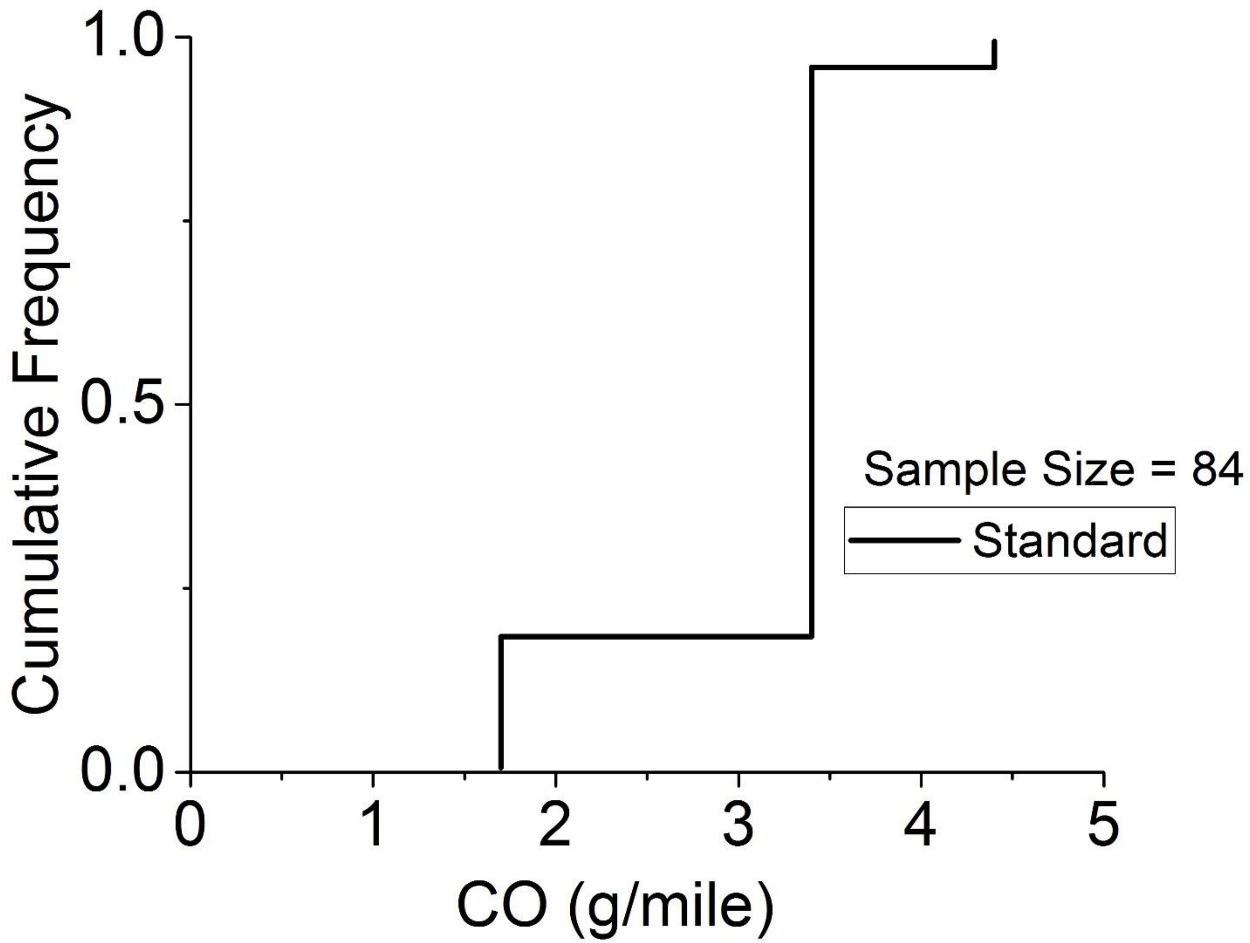
Results: Cycle Average Fuel Economy



Results: Cycle Average Fuel Economy



Results: Cycle Average CO Emission Rate



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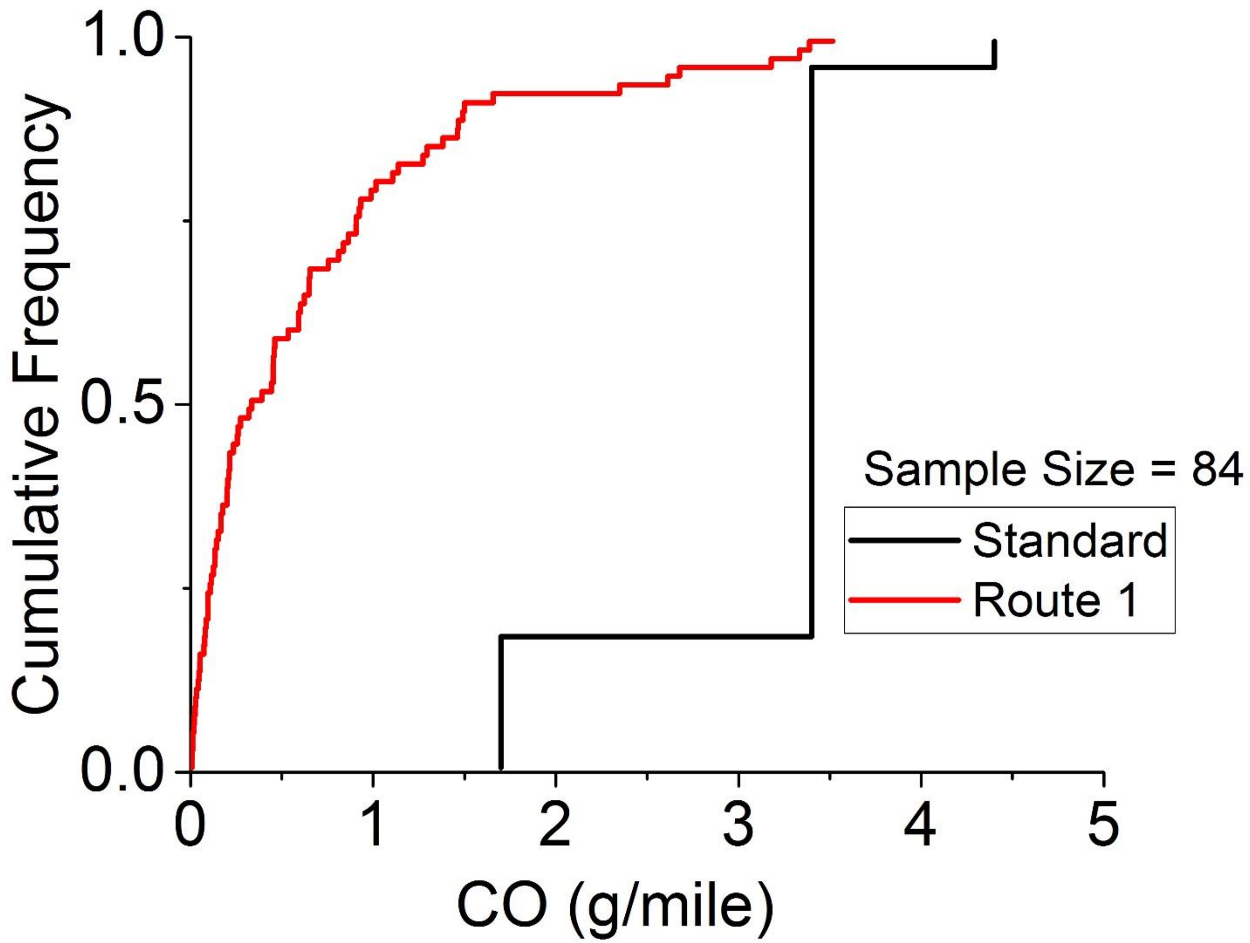

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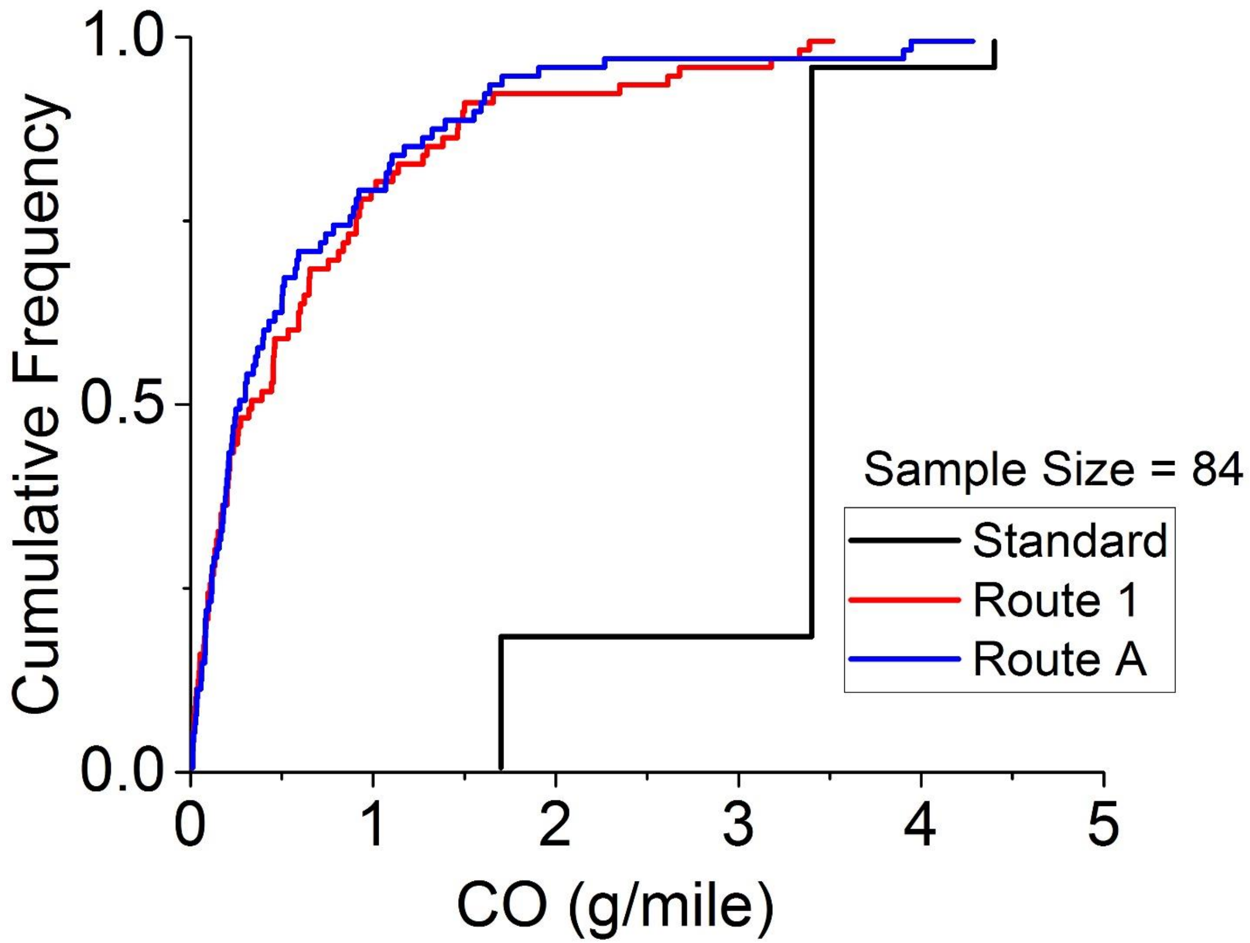
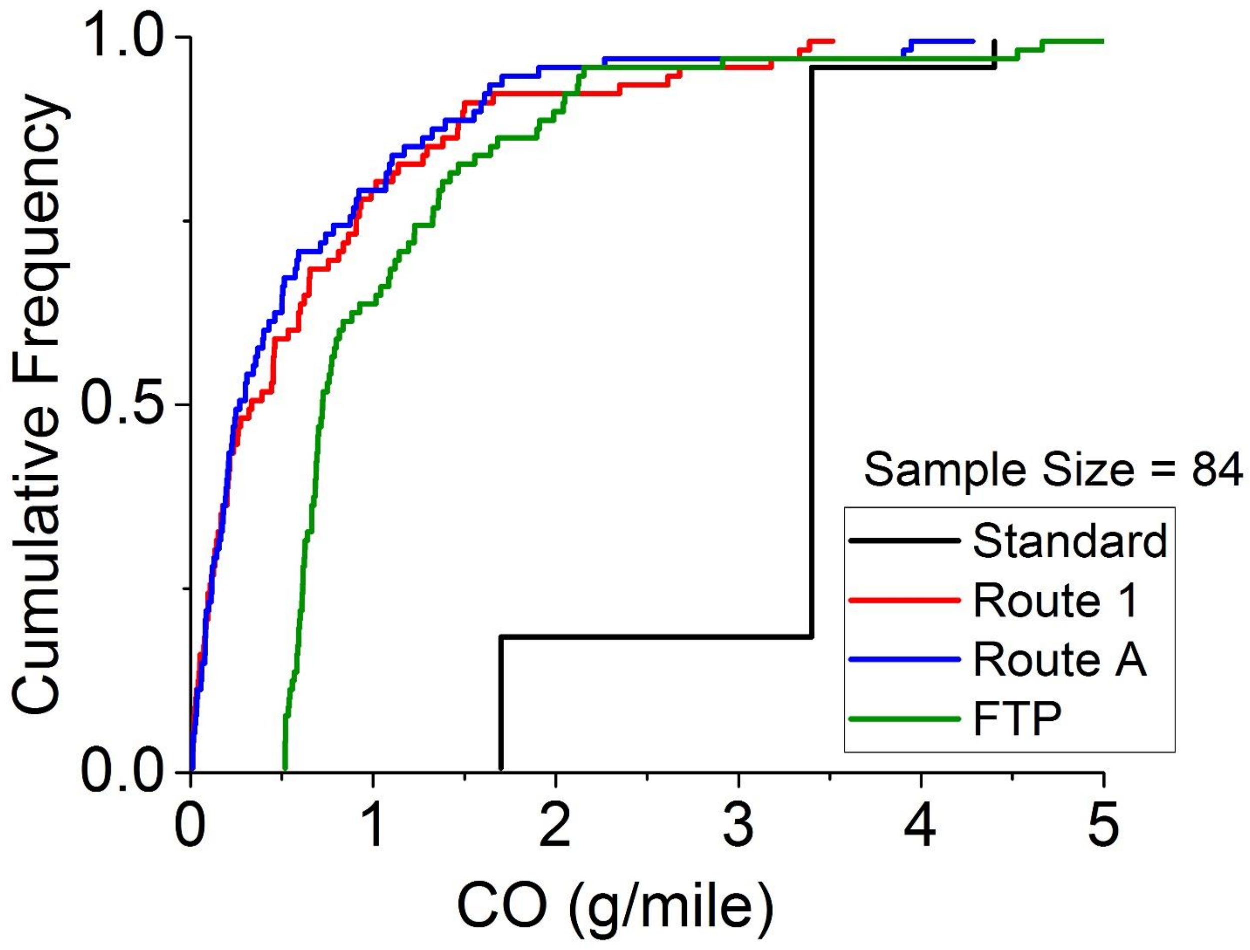
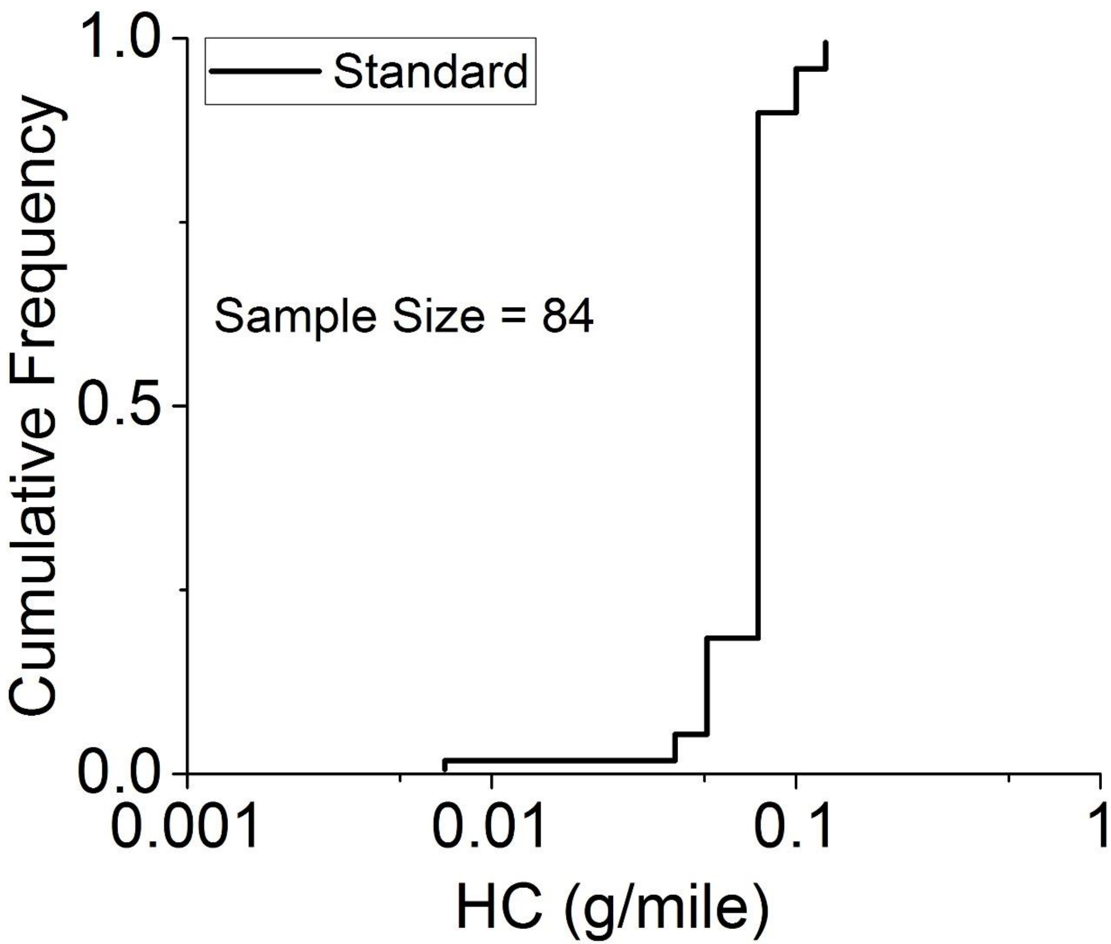


Results: Cycle Average CO Emission Rate



Results: Cycle Average HC Emission Rate



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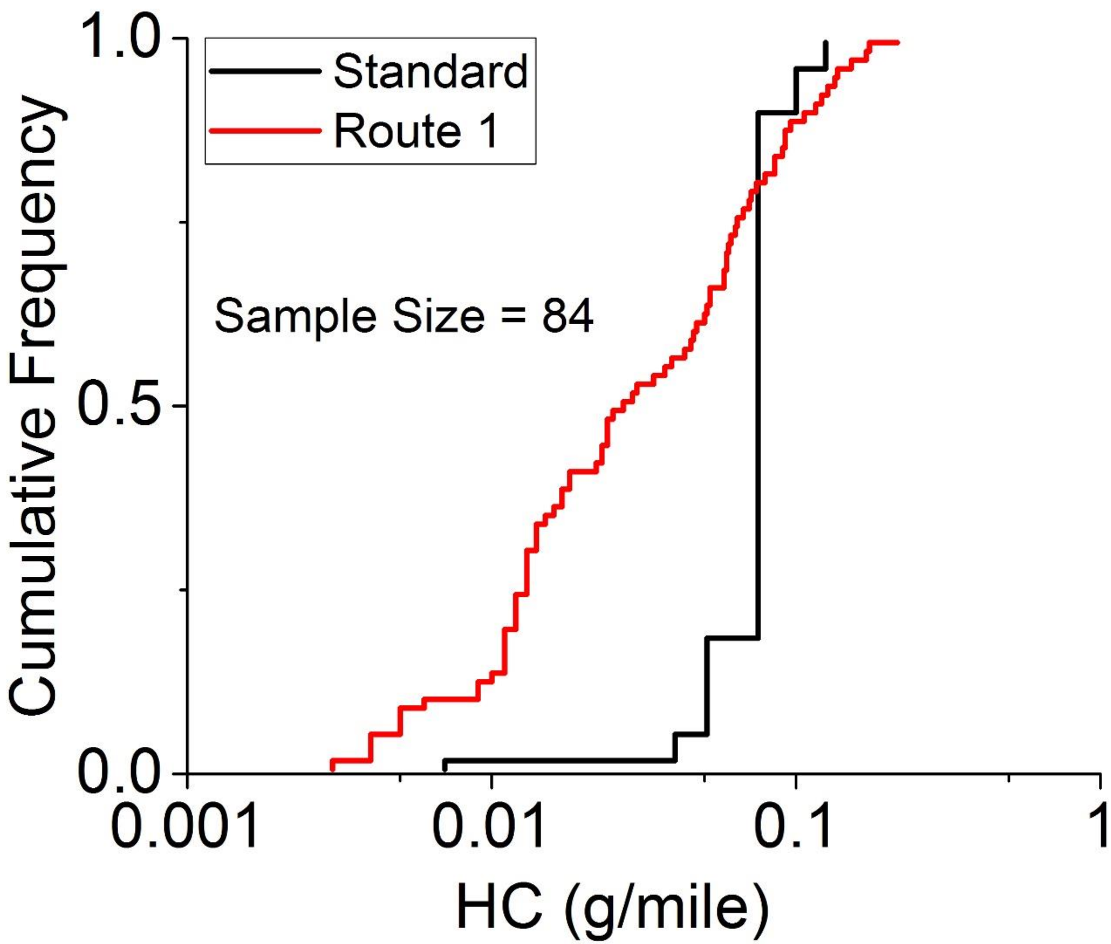

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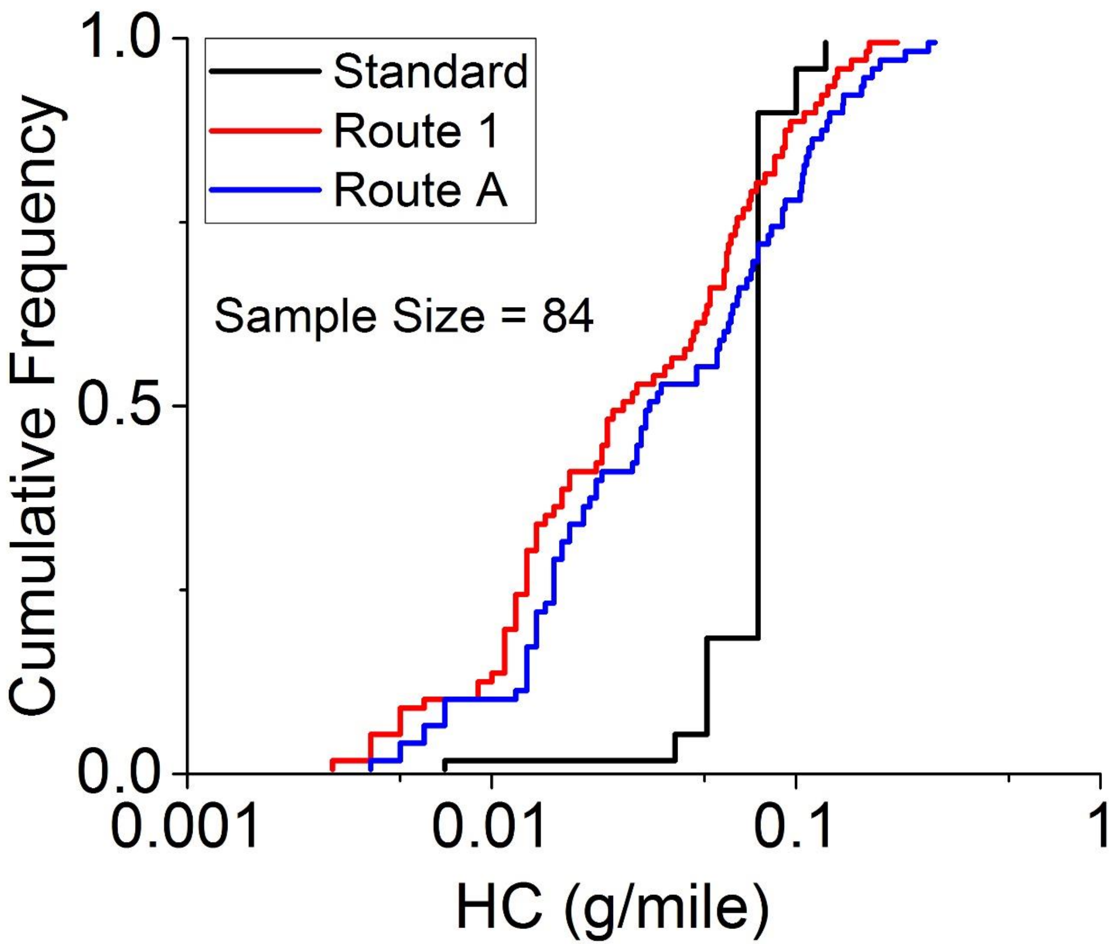
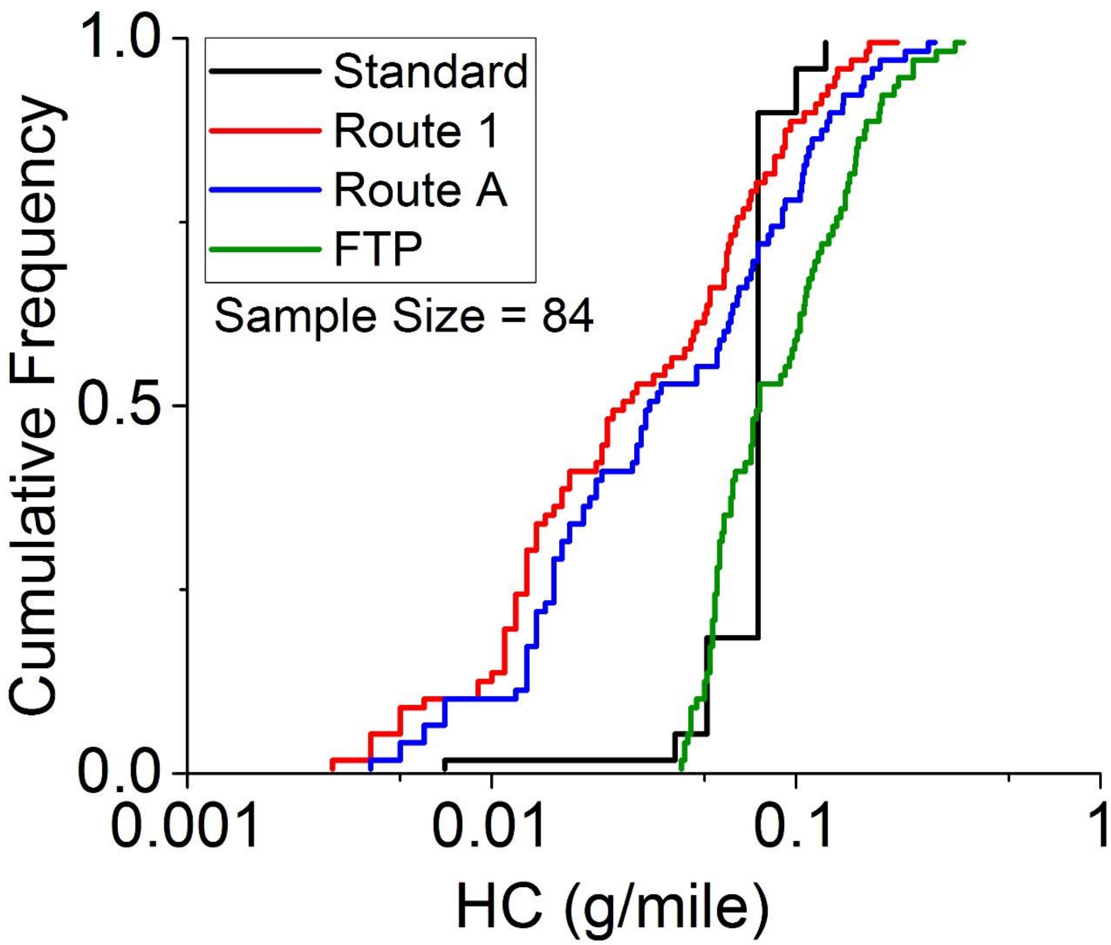


Results: Cycle Average HC Emission Rate



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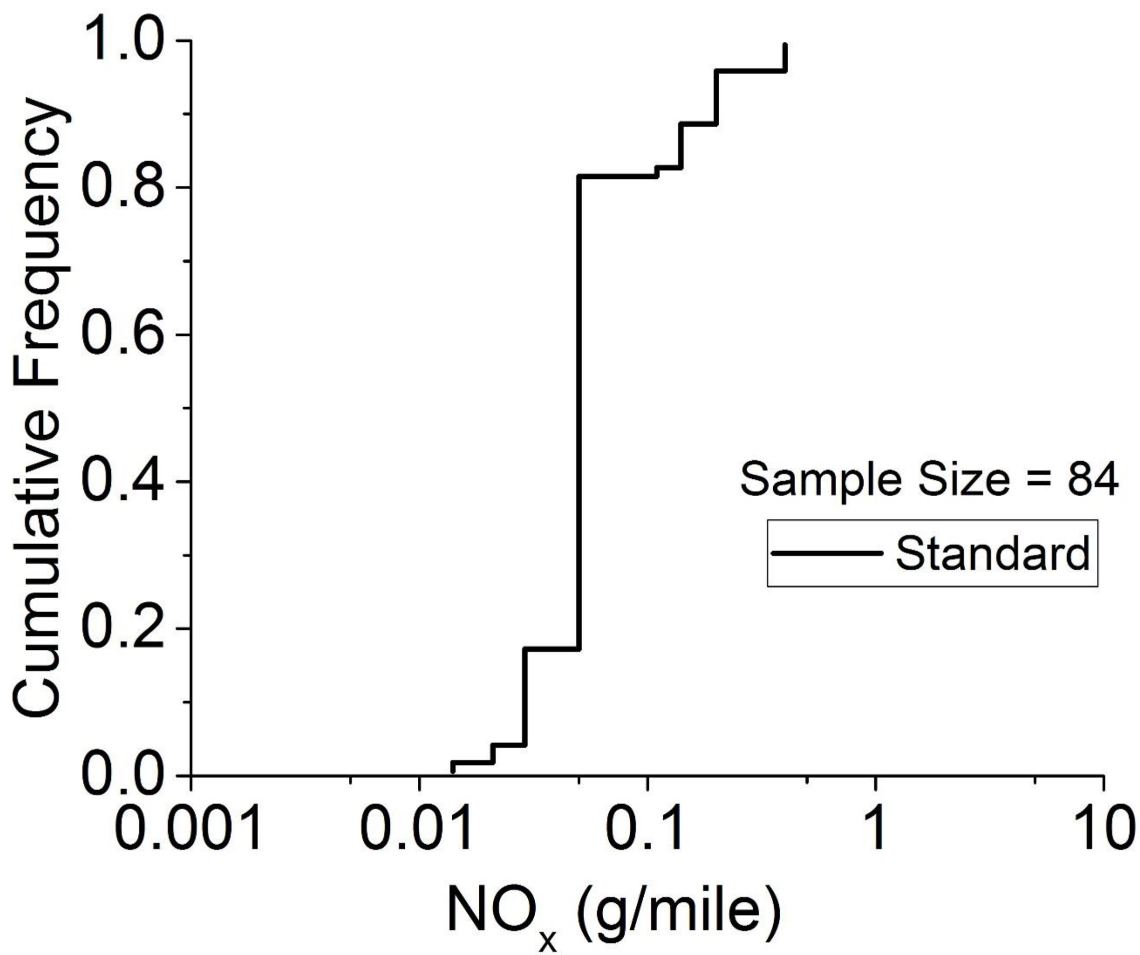
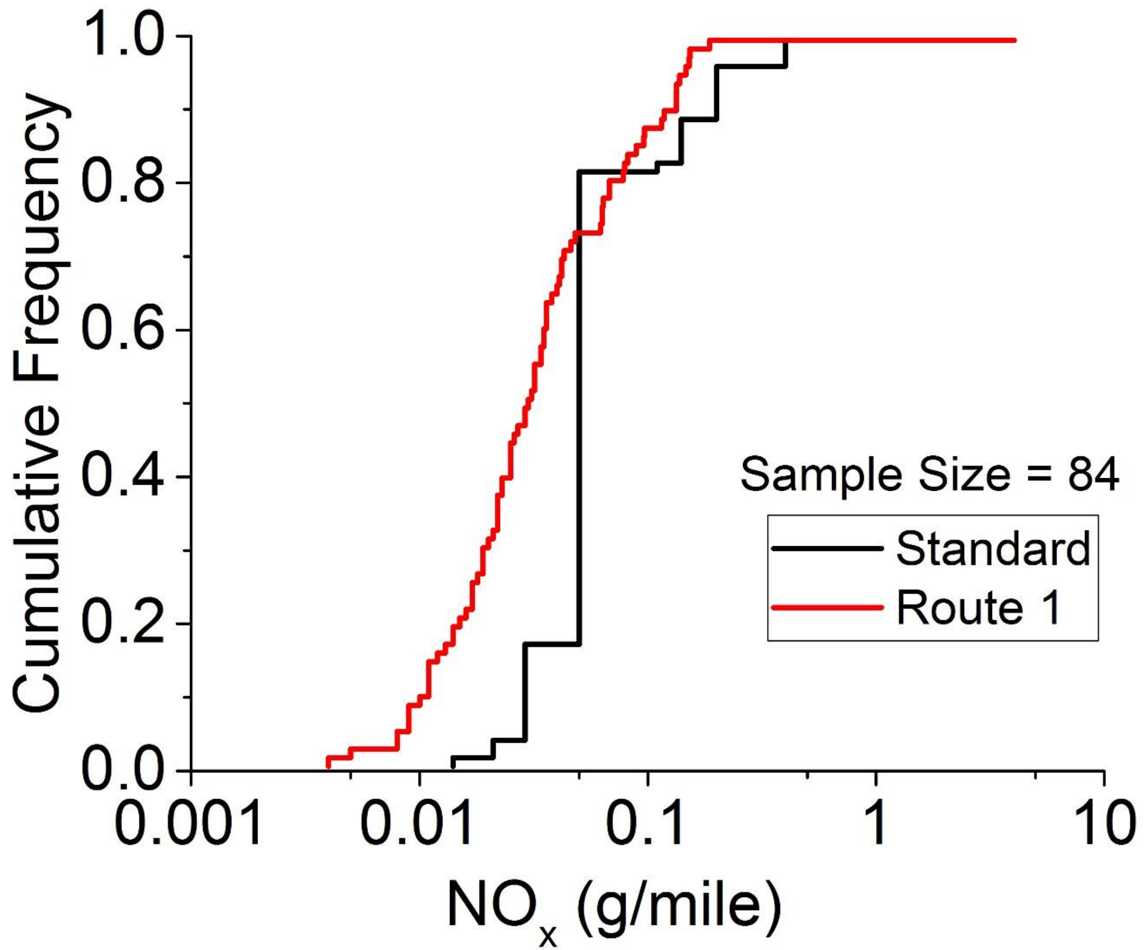
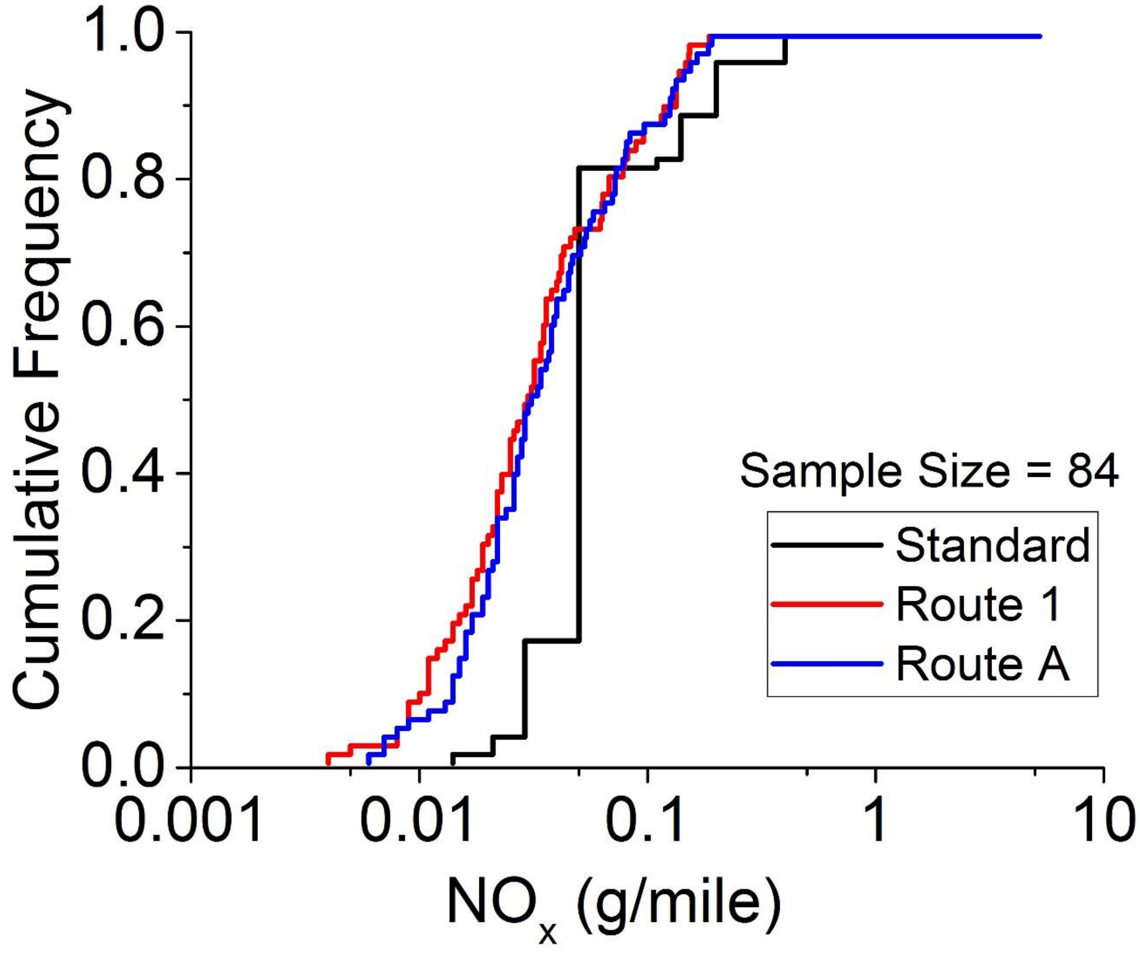
Results: Cycle Average NO_x Emission Rate



Results: Cycle Average NO_x Emission Rate



Results: Cycle Average NO_x Emission Rate



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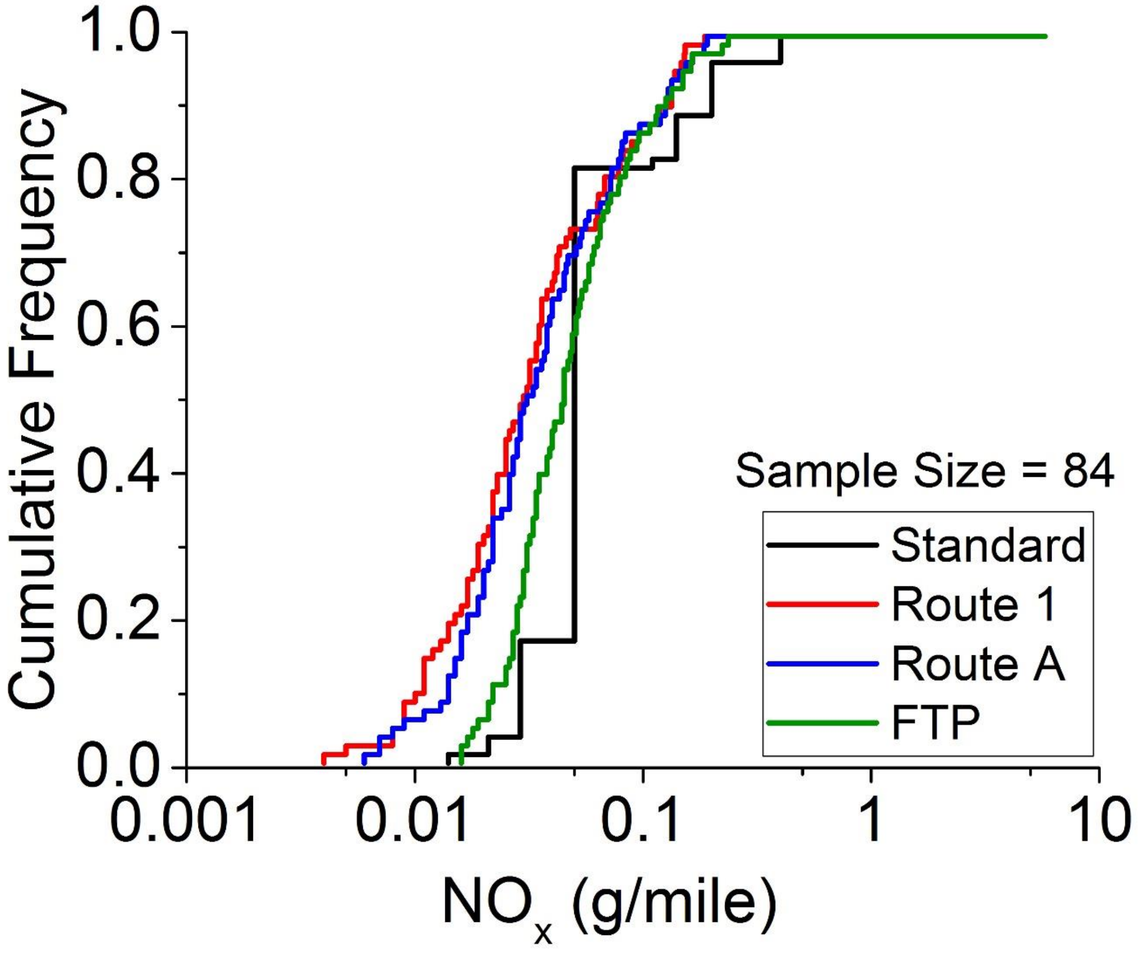
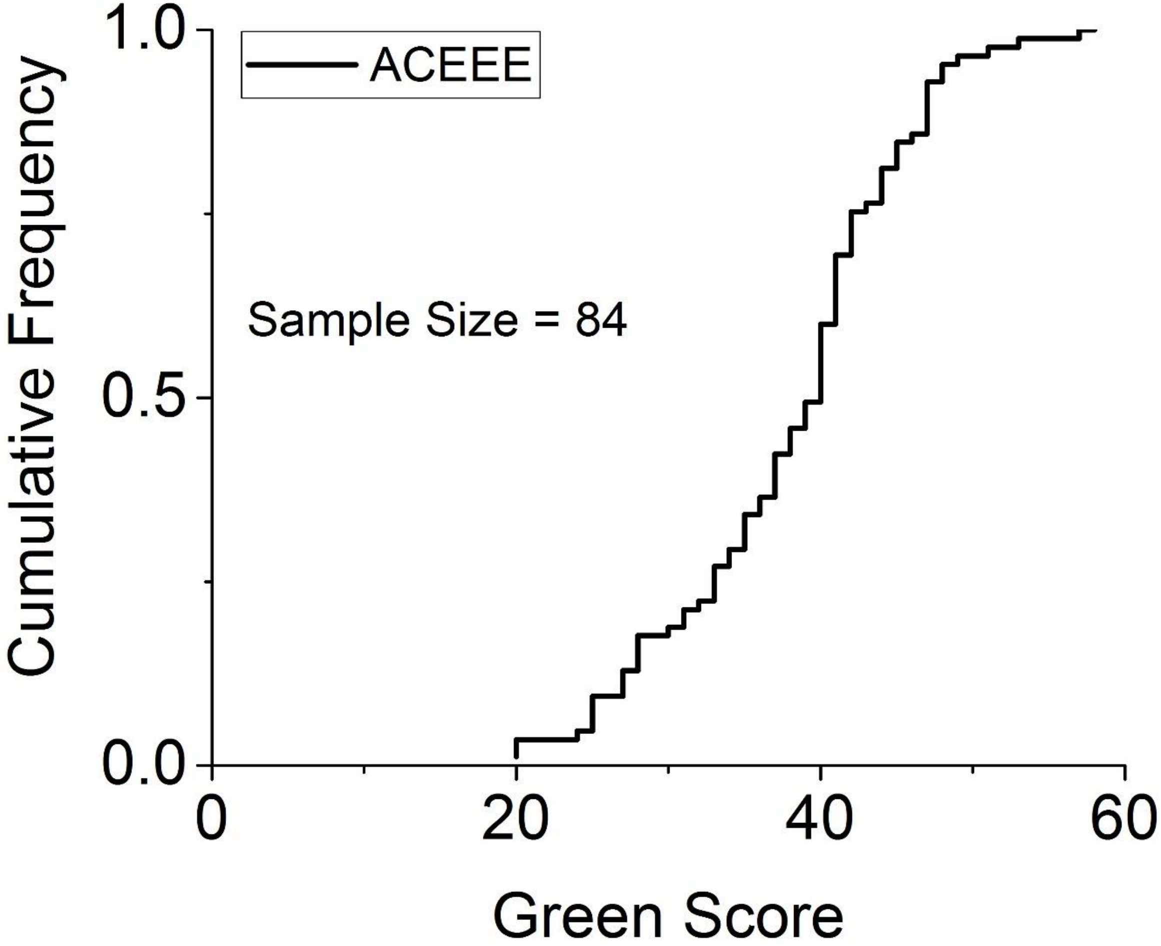
Results: Cycle Average NO_x Emission Rate



Scenarios 8, 9, 10: Fuel Economy

Scenario Identification	Input Assumptions			
	Fuel Economy		Tailpipe Emissions	
	Driving Cycle	Fuel Use	Driving Cycle	Emissions
1: Baseline	FTP/HFET	EPA Rated	FTP	Emissions Standard
2: FTP-HFET/FTP	FTP/HFET	VSP Modal Rates	FTP	VSP Modal Rates
3: R1-R1	Route 1	VSP Modal Rates	Route 1	VSP Modal Rates
4: RA-RA	Route A	VSP Modal Rates	Route A	VSP Modal Rates
5: Rated-FTP	FTP/HFET	EPA Rated	FTP	VSP Modal Rates
6: Rated-R1	FTP/HFET	EPA Rated	Route 1	VSP Modal Rates
7: Rated-RA	FTP/HFET	EPA Rated	Route A	VSP Modal Rates
8: FTP/HFET-Std.	FTP/HFET	VSP Modal Rates	FTP	Emissions Standard
9: R1-Std.	Route 1	VSP Modal Rates	FTP	Emissions Standard
10: RA-Std.	Route A	VSP Modal Rates	FTP	Emissions Standard

Green Score Variation with Fuel Economy



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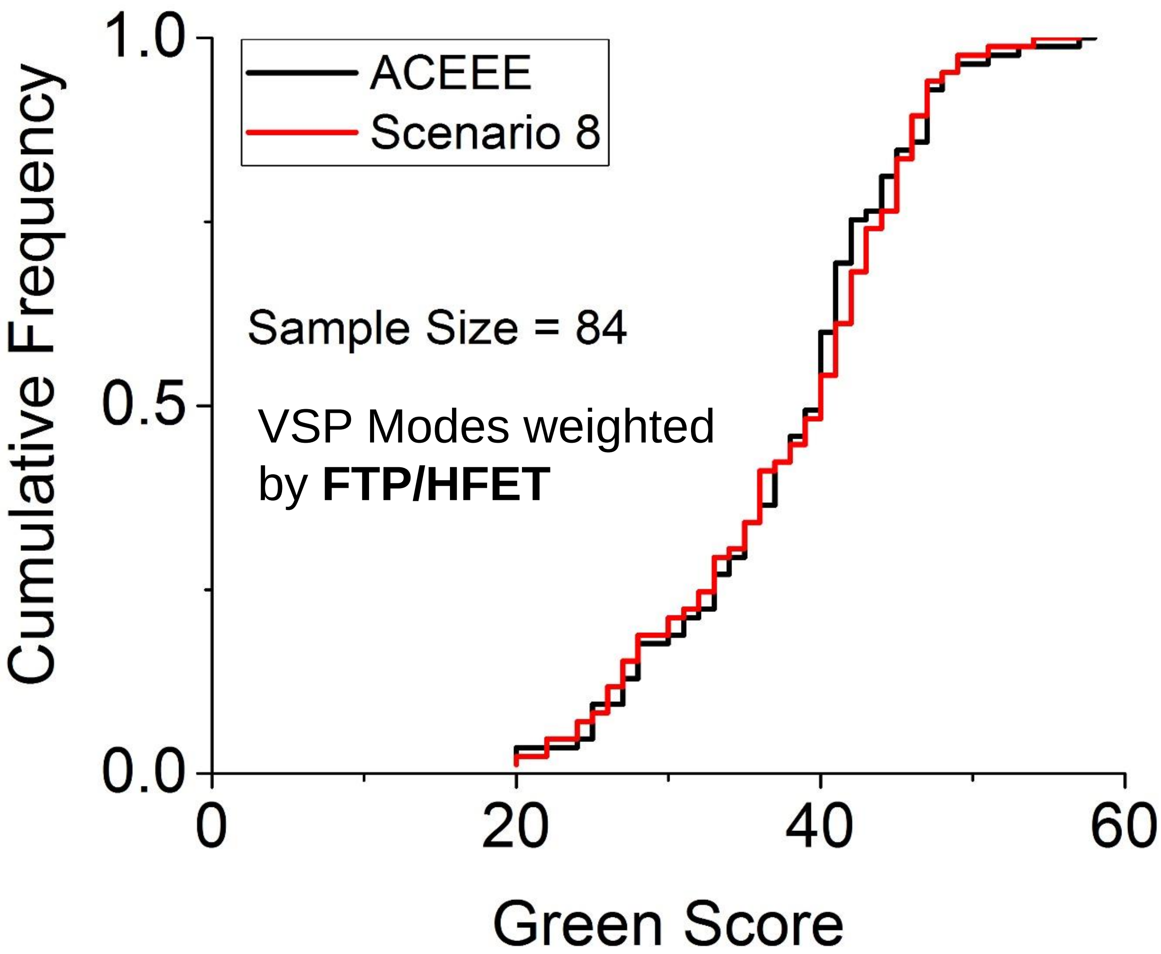
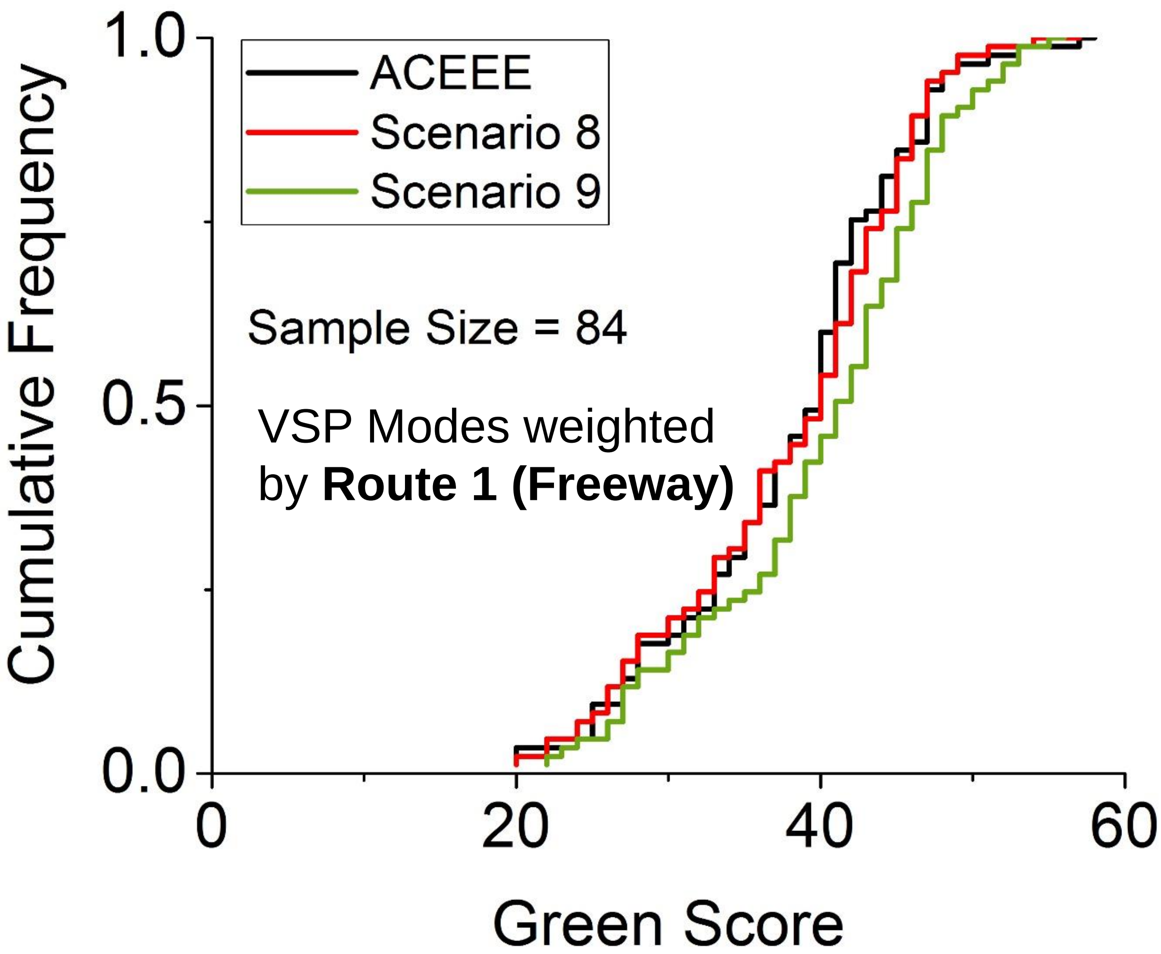


Green Score Variation with Fuel Economy



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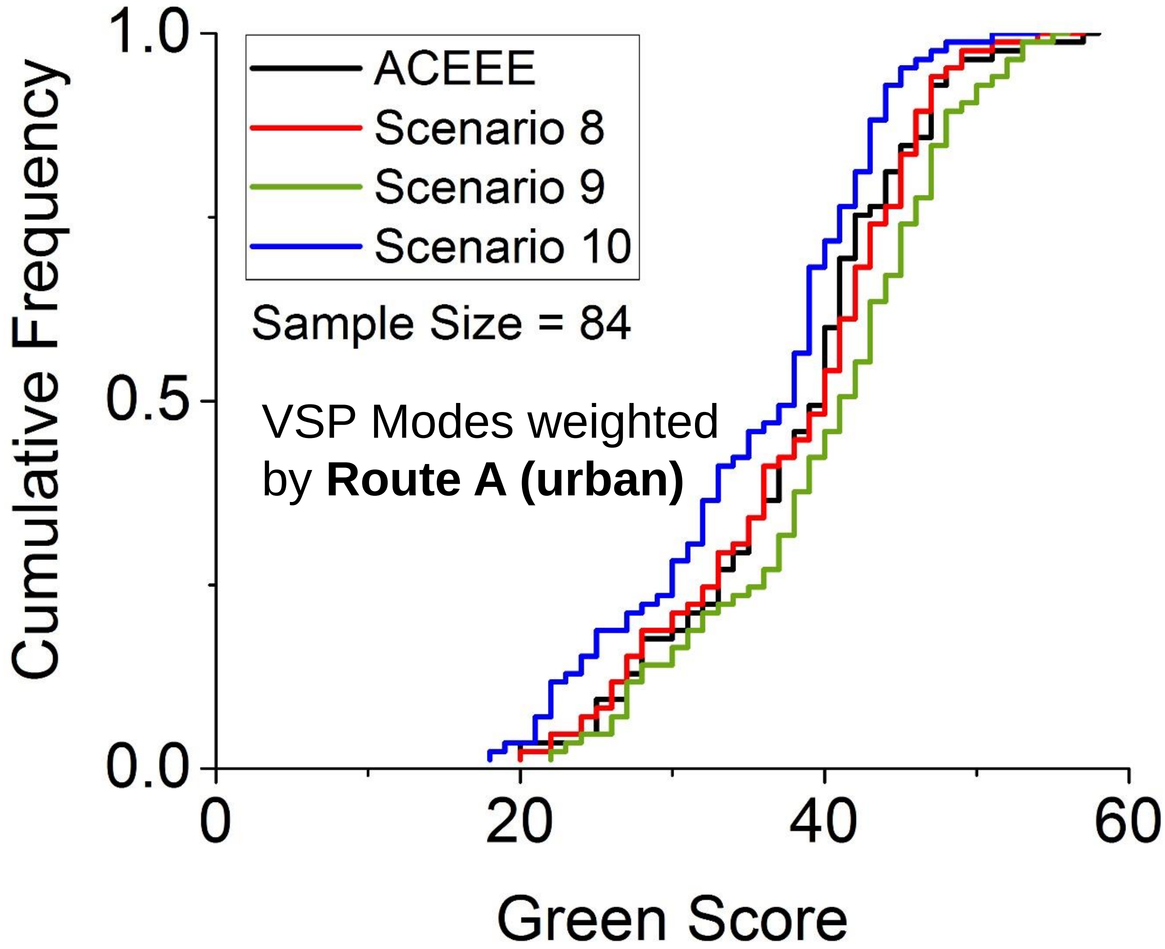
Green Score Variation with Fuel Economy



Scenarios 5, 6, 7: Emissions

Scenario Identification	Input Assumptions			
	Fuel Economy		Tailpipe Emissions	
	Driving Cycle	Fuel Use	Driving Cycle	Emissions
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4: RA-RA	Route A	VSP Modal Rates	Route A	VSP Modal Rates
5: Rated-FTP	FTP/HFET	EPA Rated	FTP	VSP Modal Rates
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8: FTP/HFET-Std.	FTP/HFET	VSP Modal Rates	FTP	Emissions Standard
9: R1-Std.	Route 1	VSP Modal Rates	FTP	Emissions Standard
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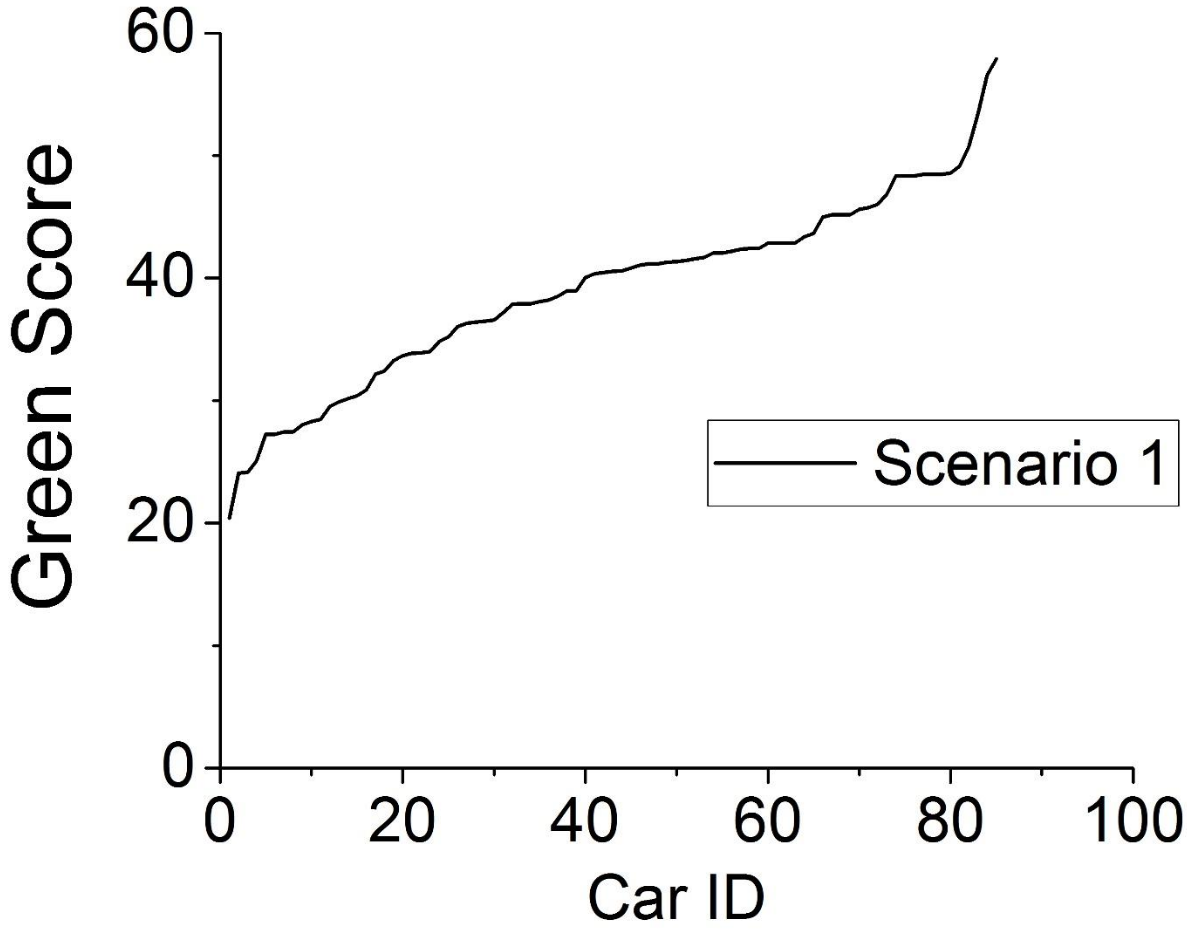
Effect of Exhaust Emissions on Green Score



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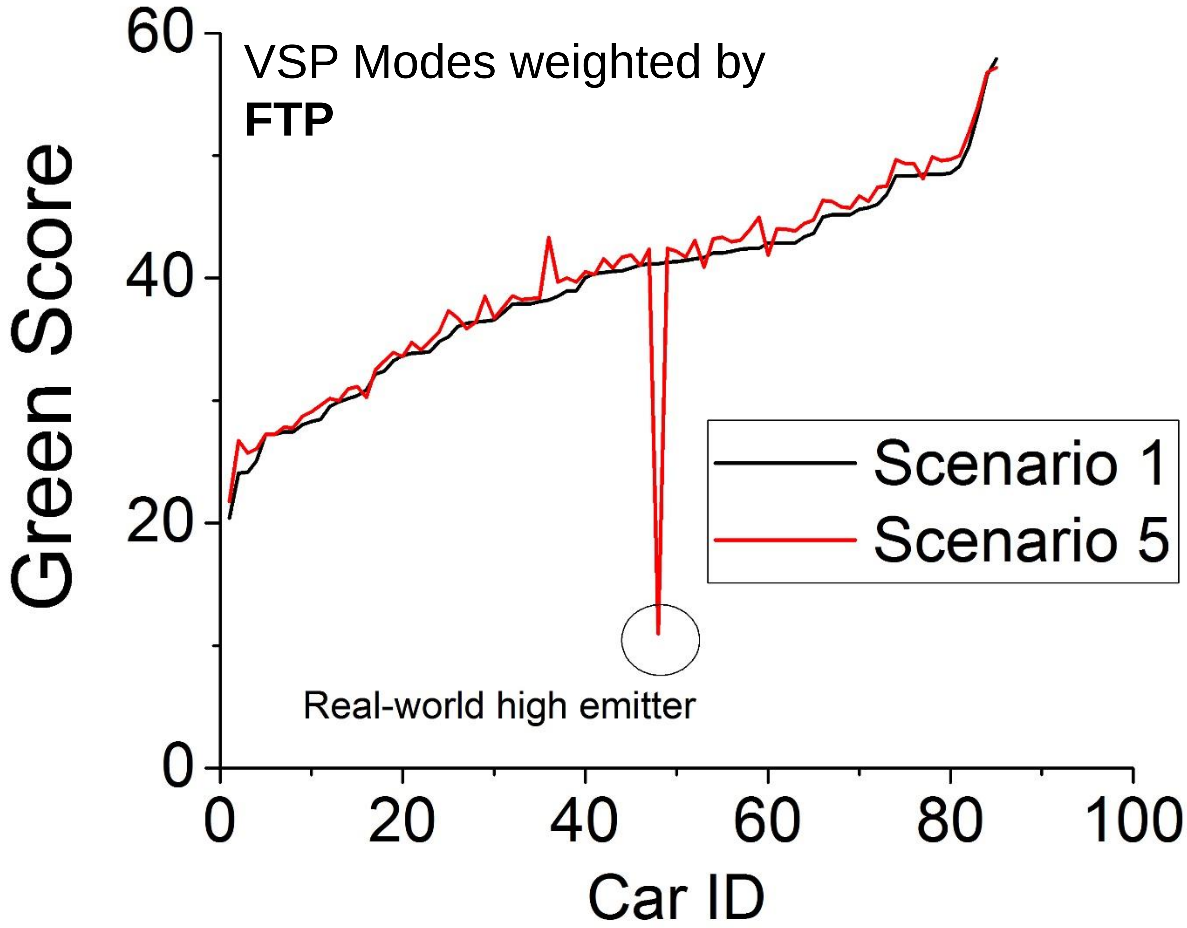
Effect of Exhaust Emissions on Green Score



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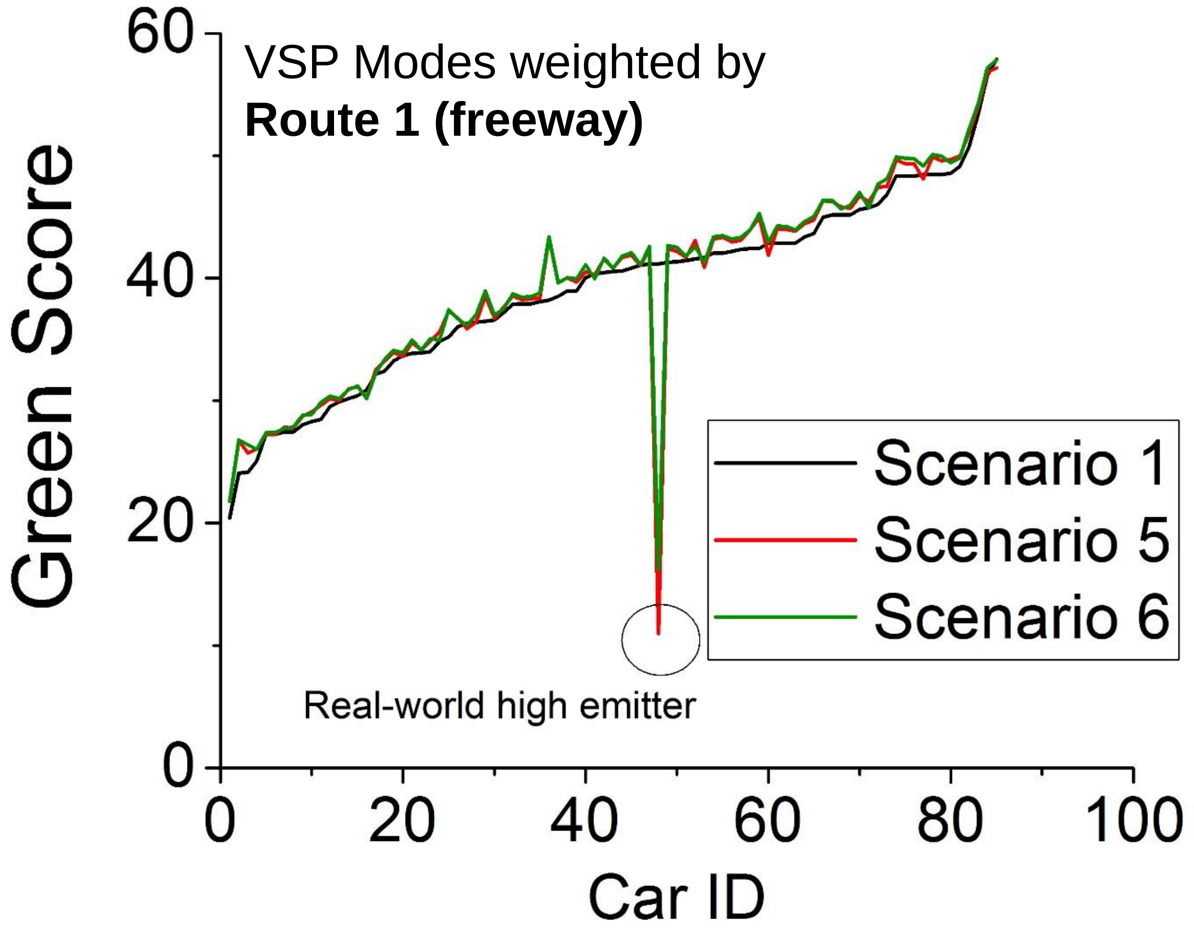

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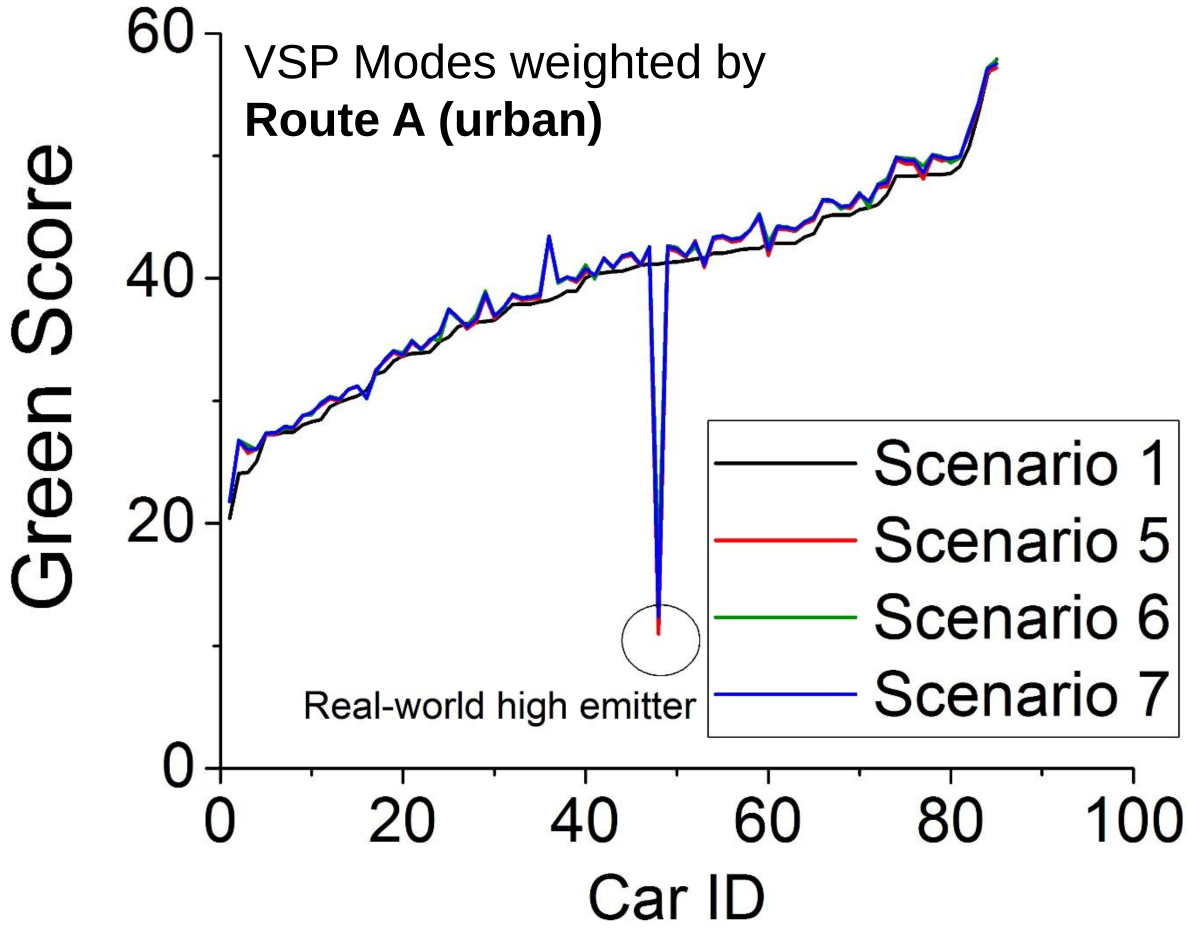

Scenarios 8, 9, 10: Fuel Economy

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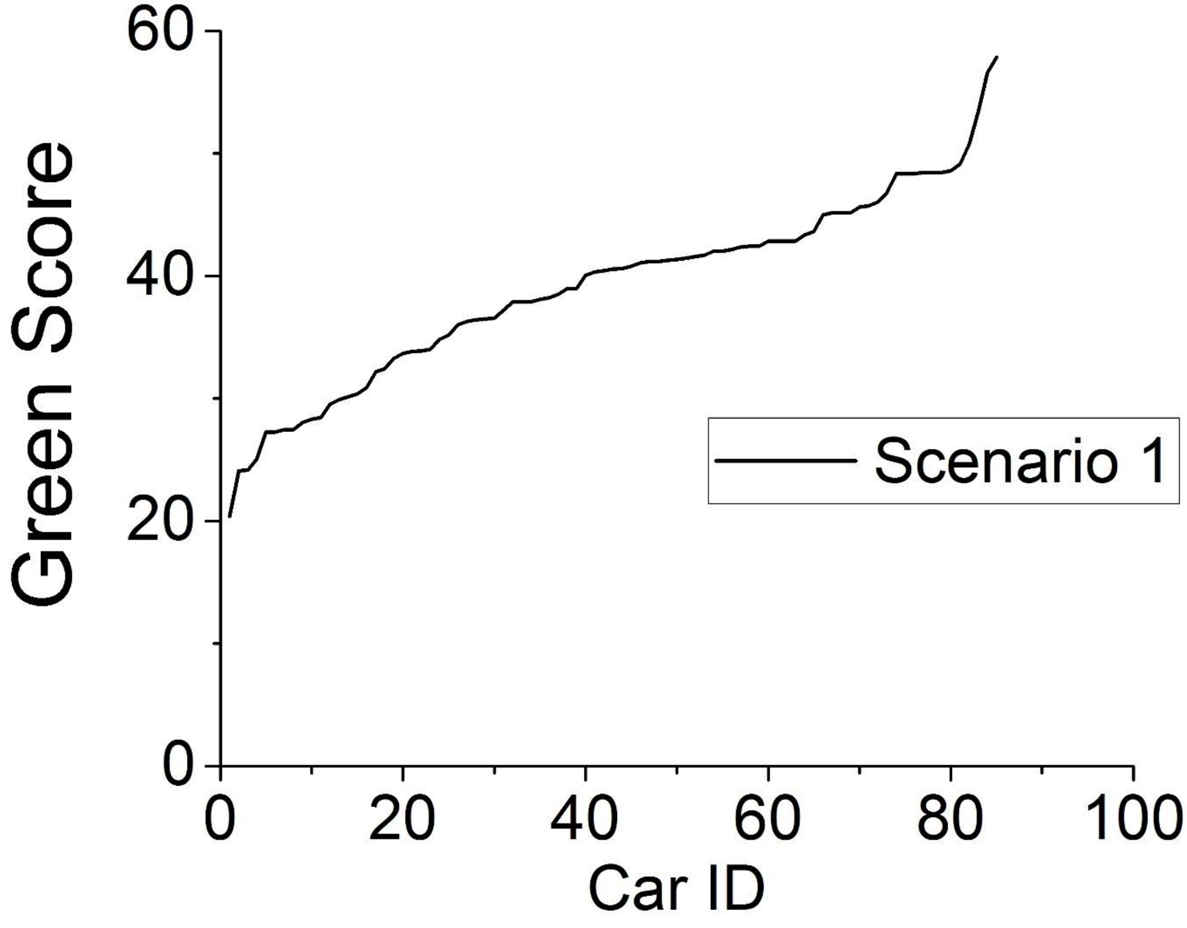
Effect of Fuel Economy on Green Score



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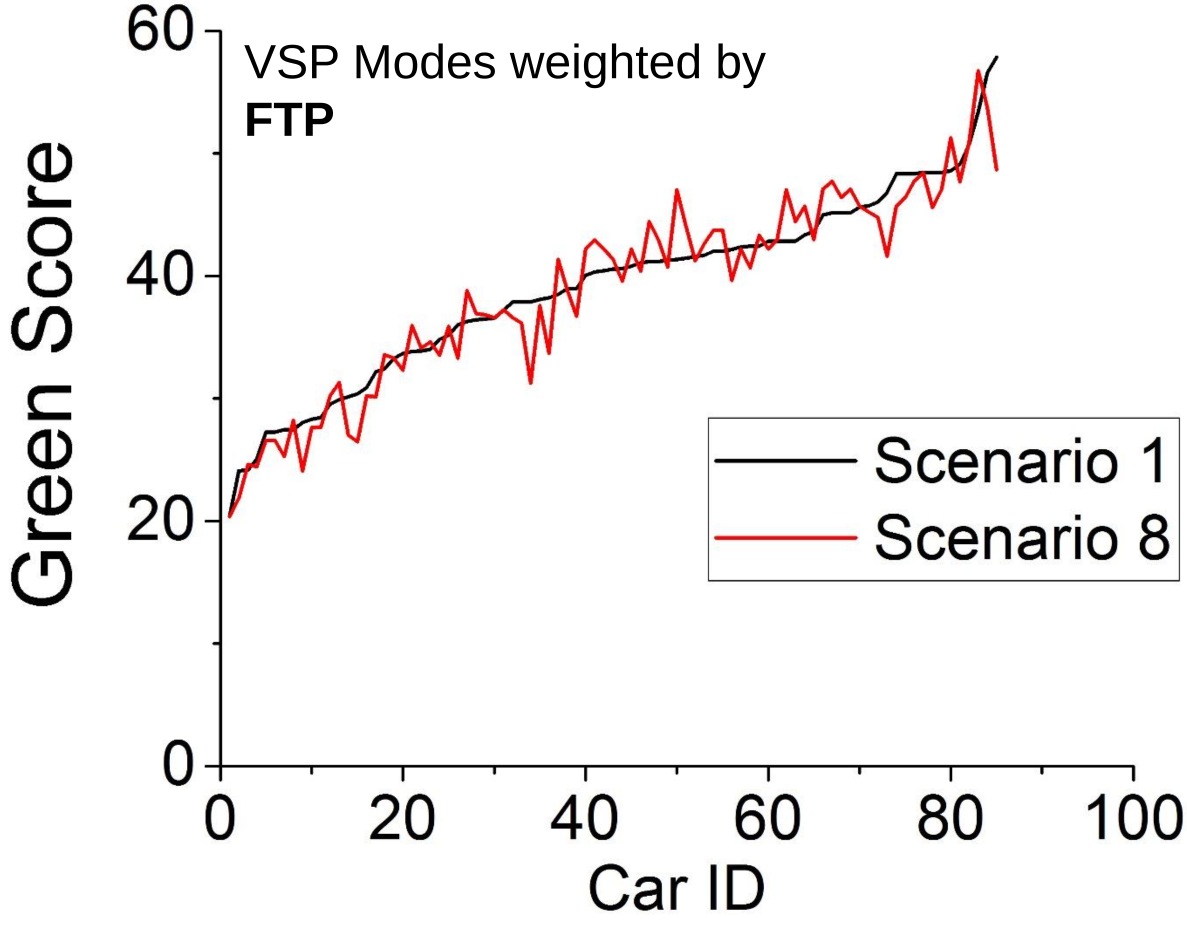

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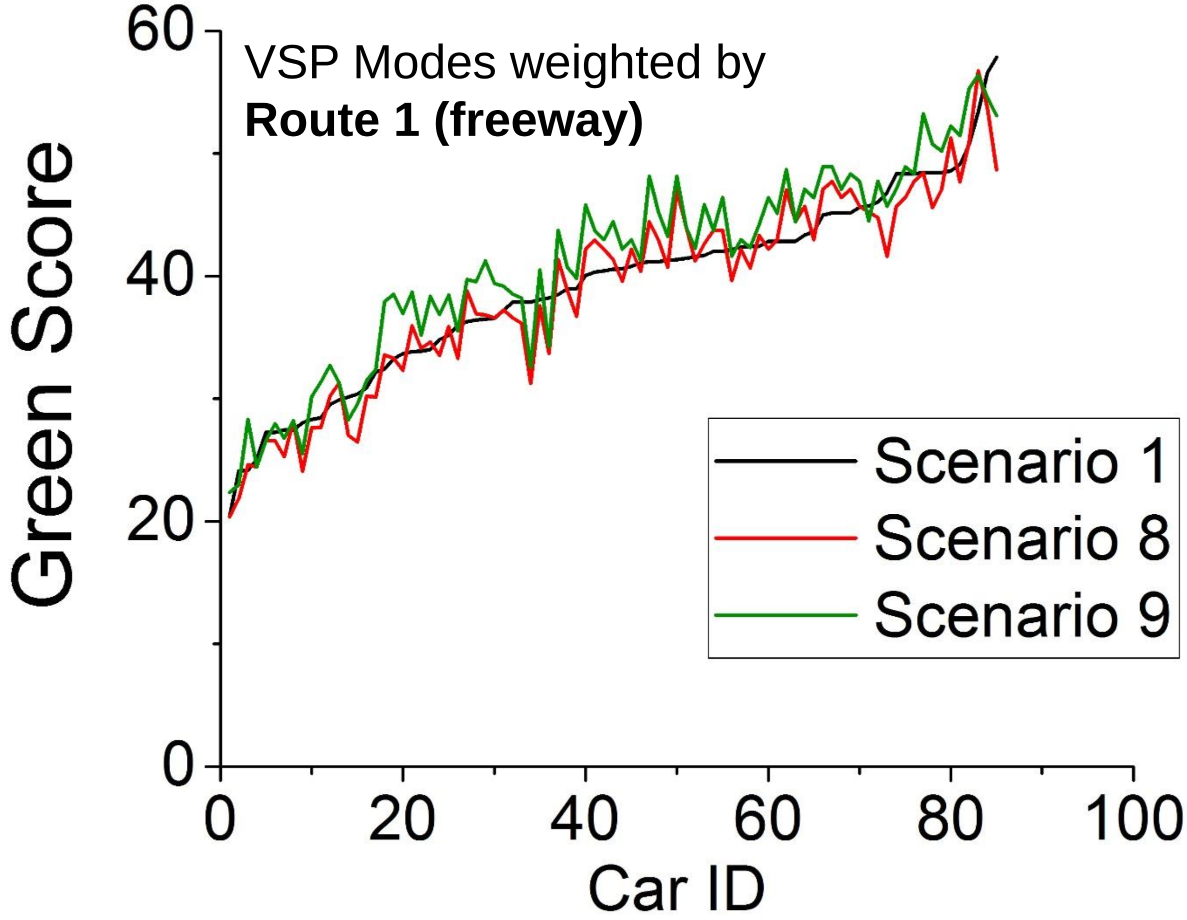
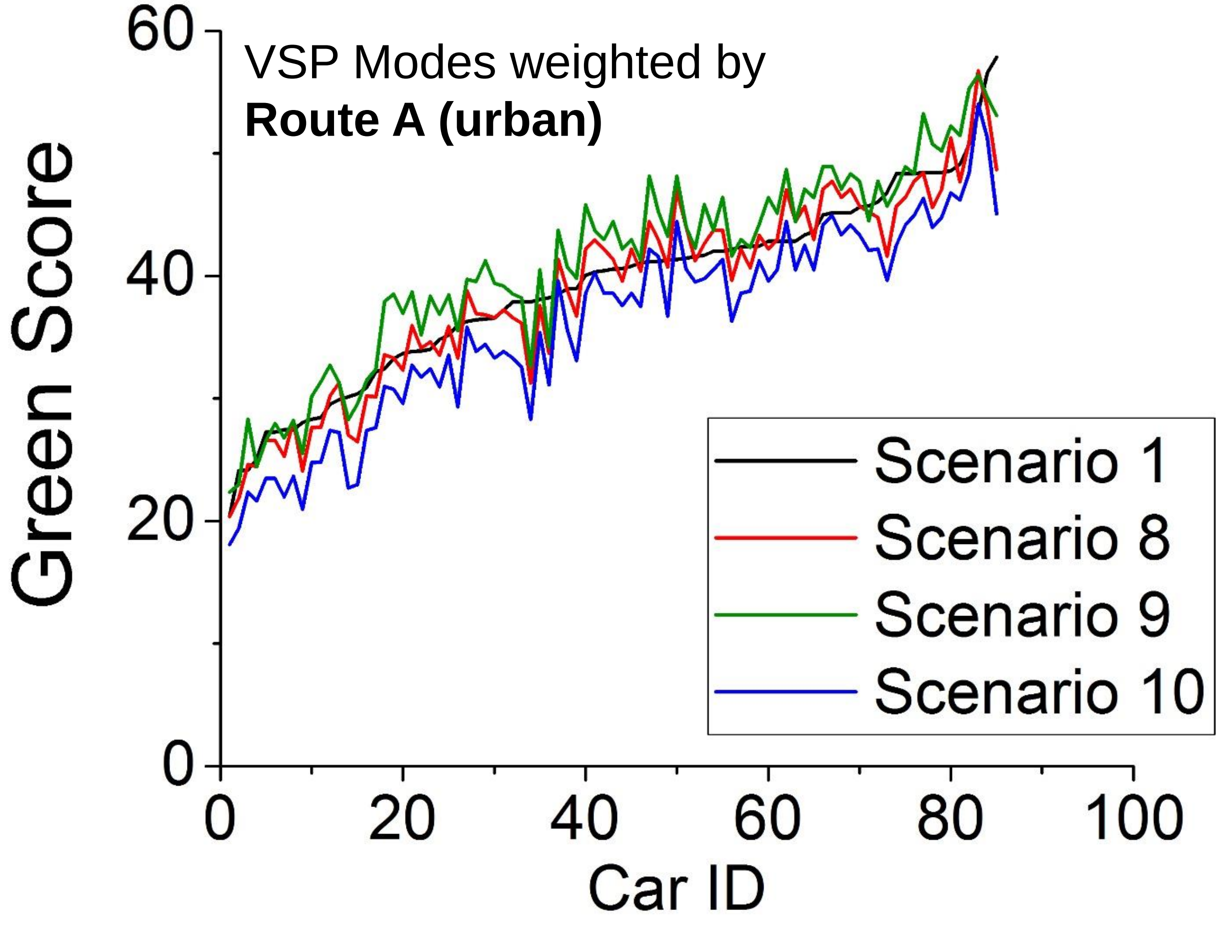
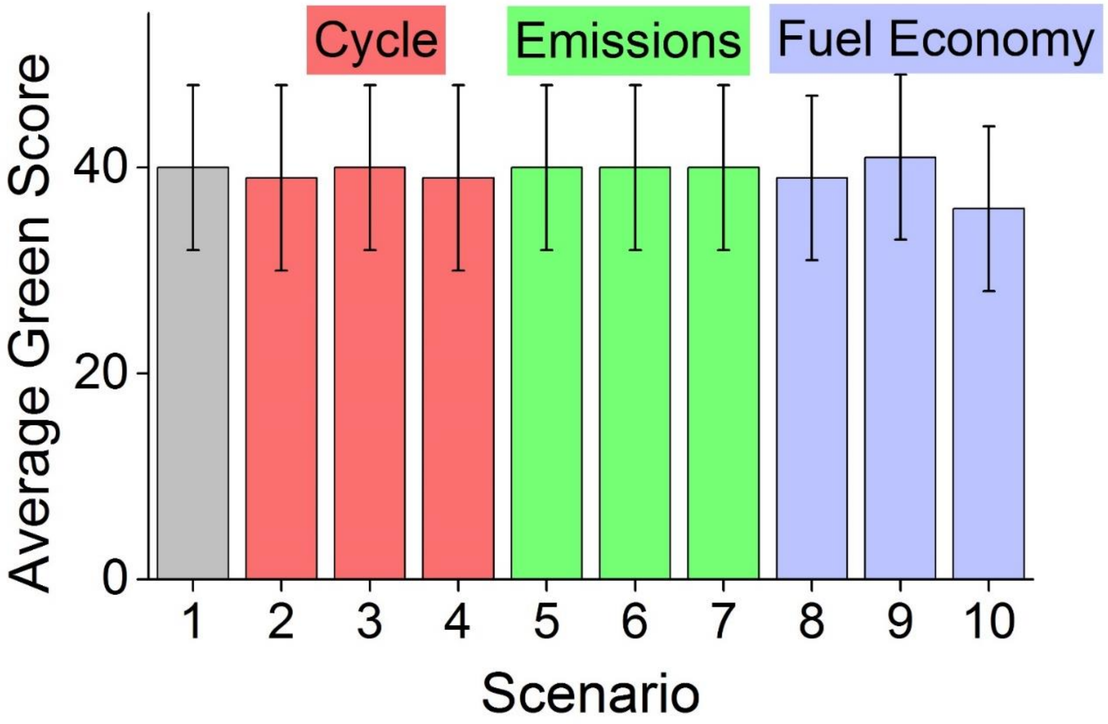


Effect of Fuel Economy on Green Score



The average Green Score within each scenario and their correlation with scenario 1



Error bars indicate ± one standard deviation

Scenario	2	3	4	5	6	7	8	9	10
Correlation with Scenario 1	0.89	0.89	0.86	0.88	0.93	0.92	0.96	0.95	0.95

Rankings of Top 10 Vehicles

Vehicle	Scenario									
	Base	Real-world Cycles			Emissions			Fuel-Economy		
	1	2	3	4	5	6	7	8	9	10
2006 Toyota Prius	1	8	5	9	**1**	**1**	**1**	5	4	7
2006 Honda Civic Hy.	2	2	2	2	**2**	**2**	**2**	2	2	2
2012 Honda Insight	3	1	1	1	**3**	**3**	**3**	1	1	1
2007 Toyota Yaris	4	3	3	4	**4**	**4**	**4**	3	3	3
2012 Fiat 500	5	5		10	**5**	**5**	**5**	6	7	5
2011 Subaru Outback	6	4	4	3	**6**		**6**	4	6	4
2005 Toyota Corolla	7			5	**7**	6	**7**	10	8	
2006 Toyota Corolla	8	9	6		**8**	7	**8**	7	9	8
2005 Toyota Corolla	9	10	7						5	6
2007 Honda Civic	10				9	8	9			

Note: Some of the vehicles moved out of the top 10 in some scenarios. Conversely, some vehicles not listed in the top 10 of Scenario 1 entered the top 10 in other scenarios. The rankings of both of these categories of vehicles are not shown.

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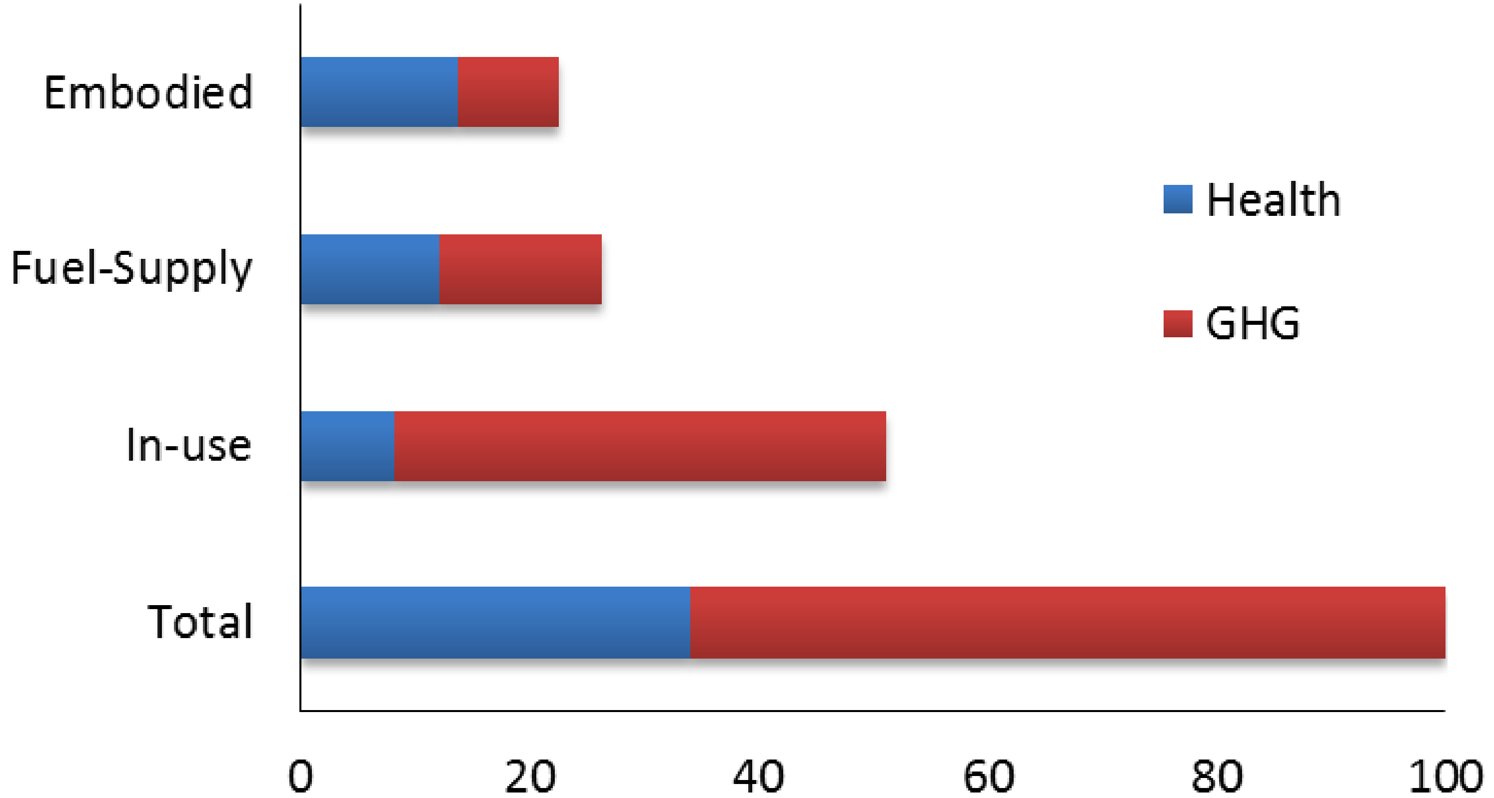
Contribution of each stage of Life Cycle Assessment in the Green Score rating system to the total Green Score



Data based on Scenario 2

Findings Regarding Green Score

- Sensitive to driving cycles
- Sensitive to fuel economy
- Not sensitive to variations in real-world exhaust emission rates

Conclusions

- Robust to differences between real-world emissions and standards (for low emitting vehicles)
- Rated fuel economy is not an accurate representation of real-world fuel economy
- Real-world versus rated fuel economy can change the Green Score by ± 5

Discussion

- Is the ACEEE Green Score the “right” way to rate environmental impact of vehicle?
- Are in-use emissions more important than implied by their contribution to the Green Score?
- What’s not in the Green Score? (a long list of other pollutants and impacts)

References

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3. Frey, H. C.; Unal, A.; Chen, J.; Li, S.; C, X. *Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission Estimation System*; EPA420-R-02-027; U.S. Environmental Protection Agency: Ann Arbor, MI, 2002.