Implications of Emerging Trends and Needs for MOVES

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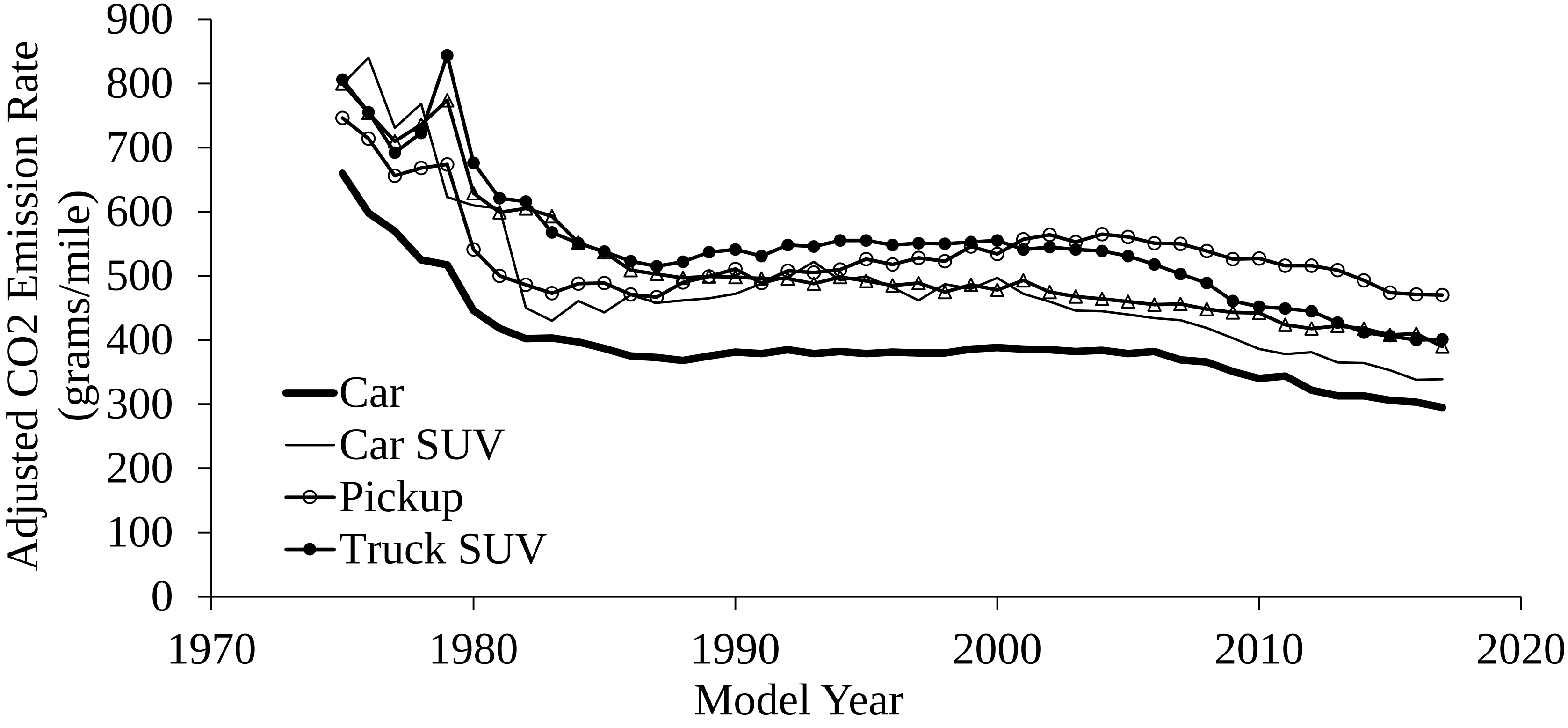
Outline

- Trends in Light Duty Vehicle Technology
- Gas Direct Injection
- Beyond E10
- Flex Fuel Vehicles
- Hybrid Electric Vehicles
- Plug-In Hybrid Electric Vehicles
- Vocational Vehicles and Duty Cycles
- Vehicle Load
- Other Needs

Trends in Light Duty Gasoline Vehicle CO_2 Emission Rates



Source: (EPA, 2018)

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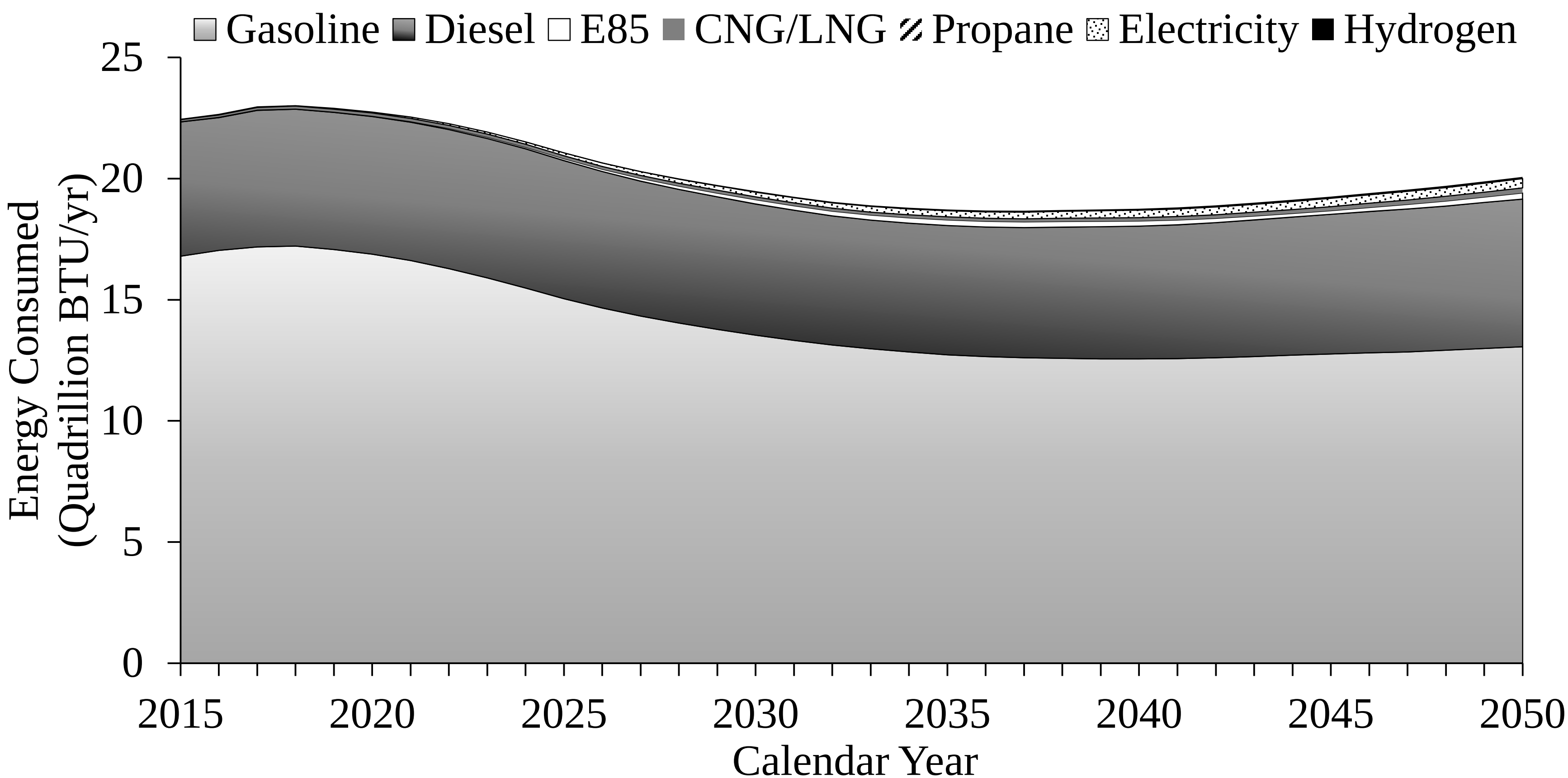
Projected Trend in U.S. Highway Vehicle Energy Consumption: 2015 to 2050



Source: EIA, 2018

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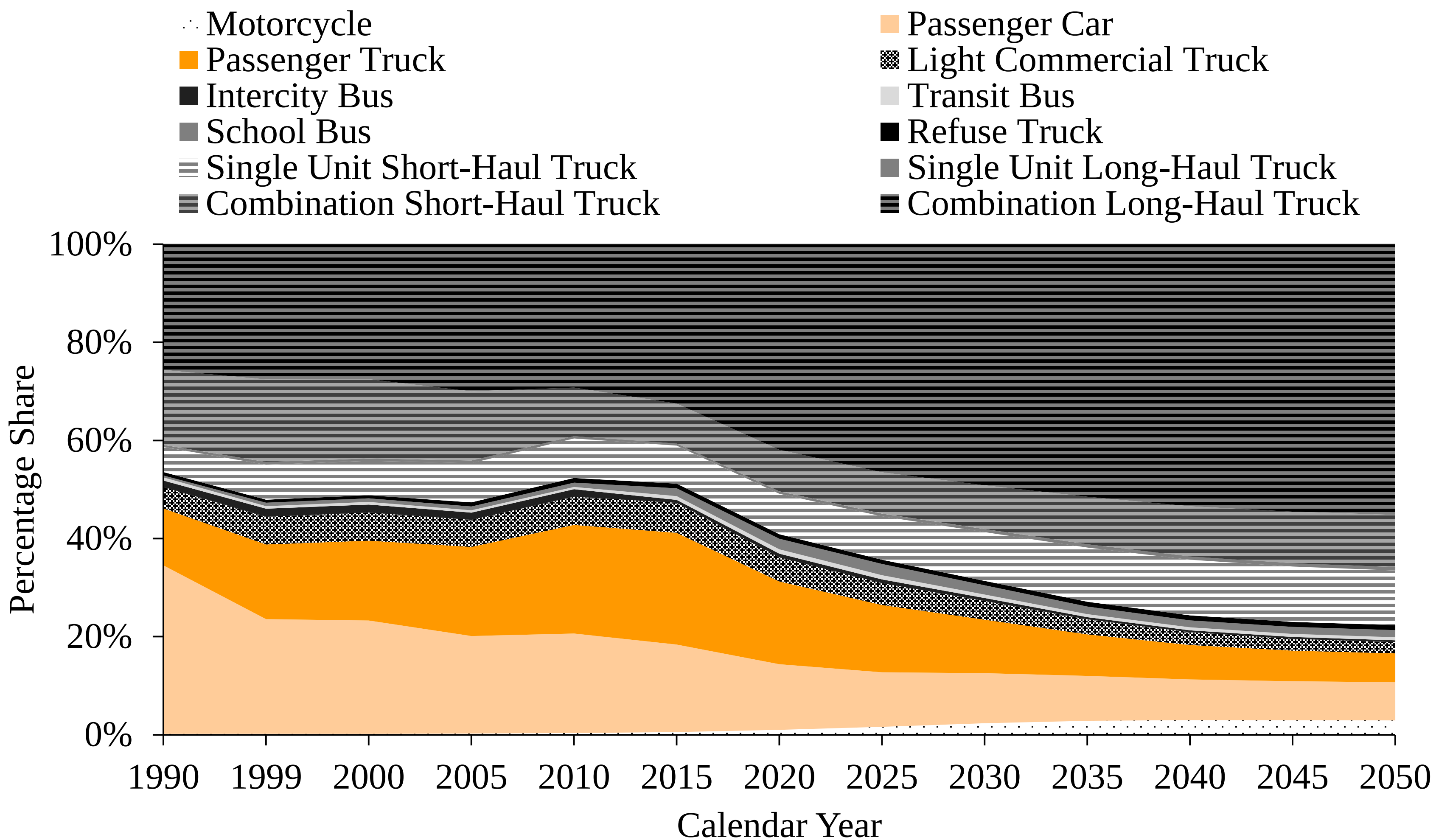
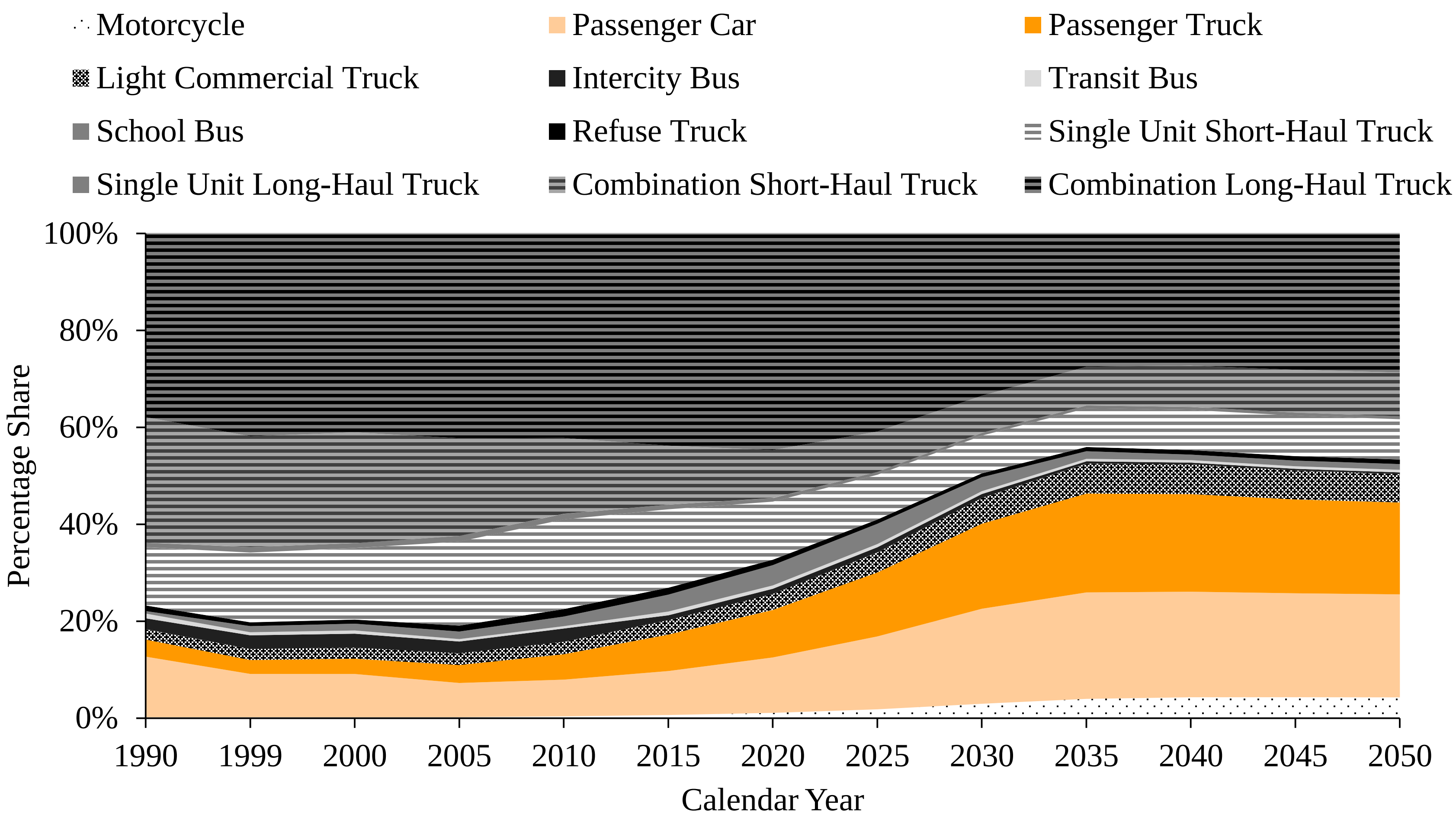
Estimated Trends in U.S. NO_x Onroad Vehicle Emissions



Based on National Emissions from MOVES for a July Weekday

Estimated Trends in U.S. $PM_{2.5}$ Onroad Vehicle Emissions



Based on National Emissions from MOVES for a July Weekday

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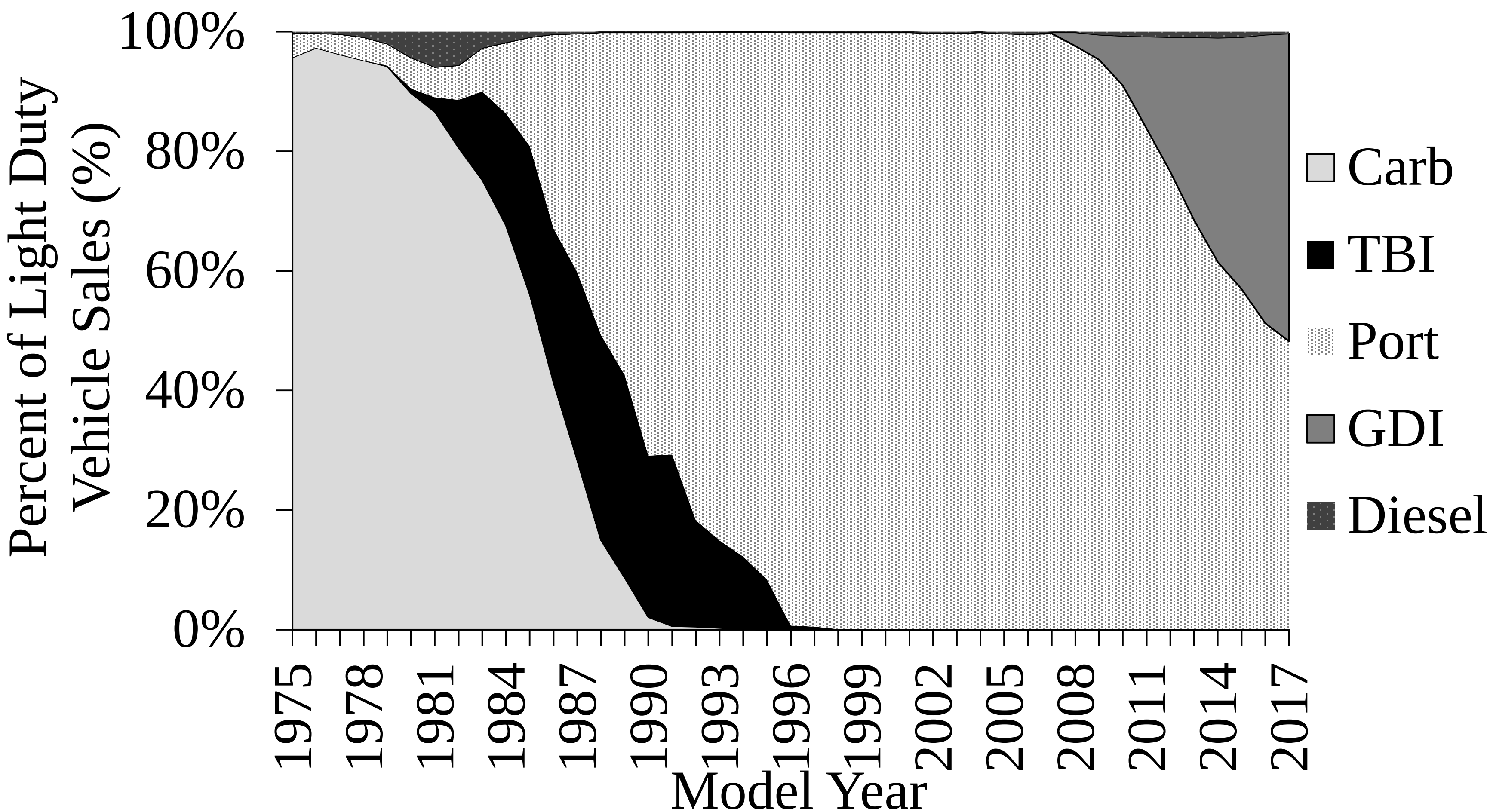
Trends in LDGV Fuel Delivery



Source: (EPA, 2018)

Background: Gas Direct Injection

- Much focus has been on studying Particulate Matter (PM), especially ultrafine particles (UFP) from GDI engines
- Total Soot Particle Number emitted by GDI engines is generally higher than PFI engines by more than an order of magnitude, and than Diesel engines equipped with a Diesel Particulate Filter (DPF)
- Gasoline Particulate Filters (GPFs) are being considered for GDI engines

Instruments

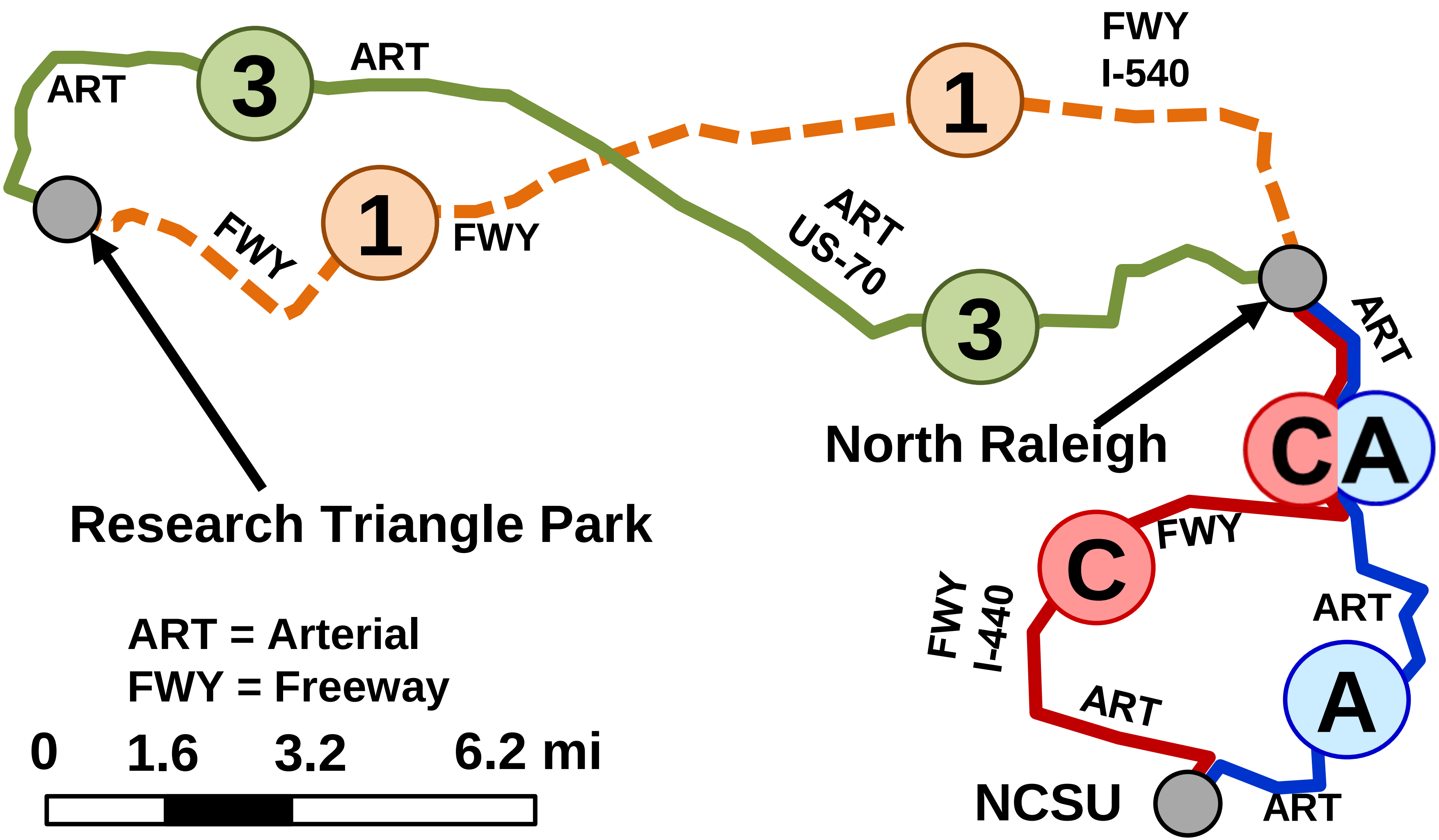
Portable Emissions Measurement System (PEMS):

Carbon Dioxide (CO_2), Nitric Oxide (NO), CO, Hydrocarbons (HC), and O_2

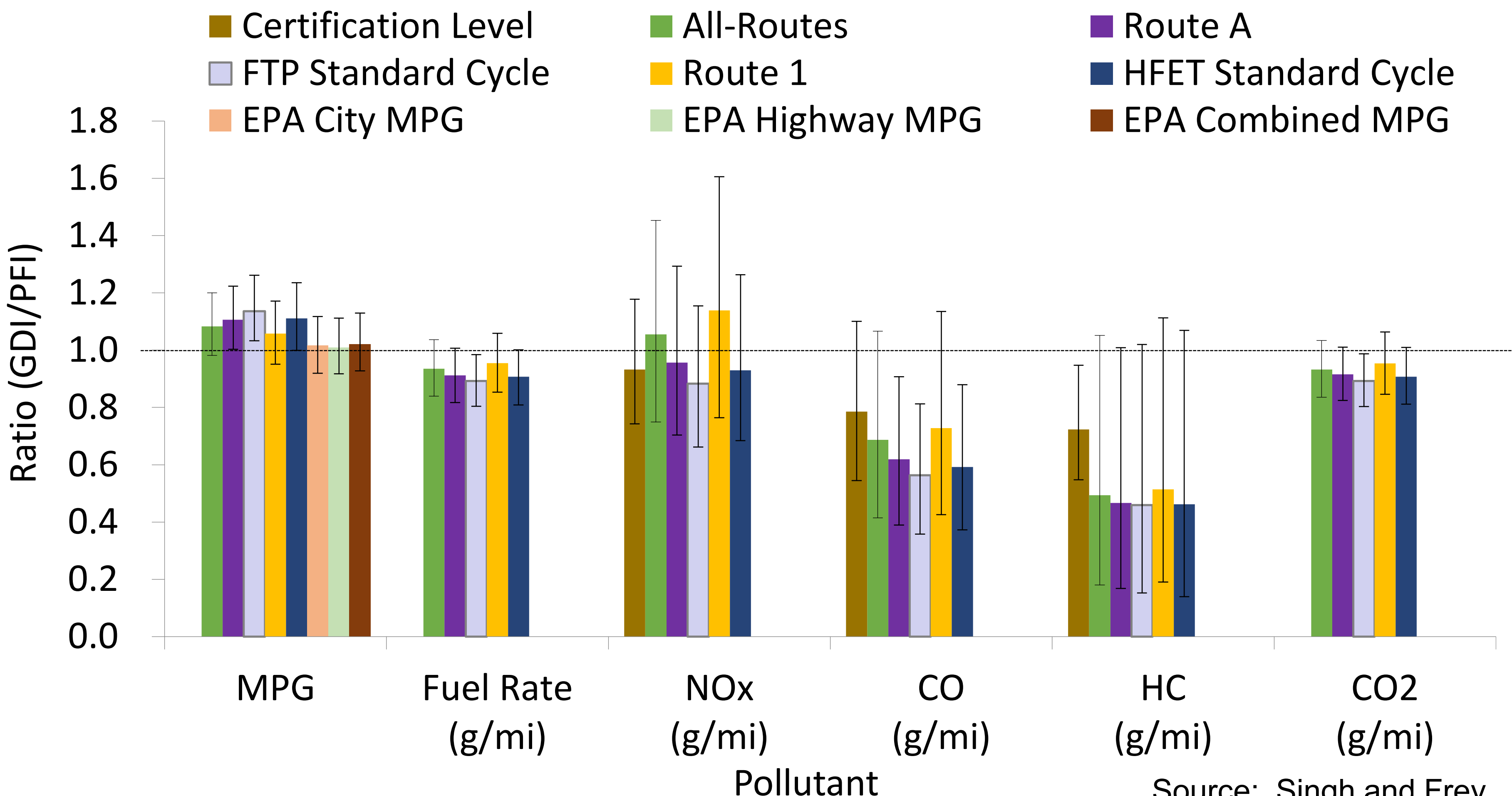
Global Positioning System (GPS) Receivers with Barometric Altimeter

On-board Diagnostic Data Logger (OBD)

Measurement Routes



Results: Real-World Data vs Certification Data



Source: Singh and Frey

Note: Error bars are 95% confidence intervals based on average of 25 "Composite" GDI and "Composite PFI" vehicles, and are estimated using bootstrapping

Flex Fuel Vehicles Production Volume

Model Year	Category	Ford	GM	Jaguar Land Rover	Mercedes	Nissan	Toyota	*FCA†*	*Volkswagen†*	Total
2012	Car	174,597	396,264	-	13,493	-	-	*105,174*	*2,060*	691,588
	Truck	323,563	511,183	-	8,289	24,154	31,670	*453,399*	*-*	1,352,258
	All	498,160	907,447	-	21,782	24,154	31,670	*558,573*	*2,060*	2,043,846
2013	Car	209,988	374,354	321	34,493	-	-	*142,158*	*30,346*	791,660
	Truck	546,695	637,576	-	22,082	13,650	33,203	*431,359*	*20,799*	1,705,364
	All	756,683	1,011,930	321	56,575	13,650	33,203	*573,517*	*51,145*	2,497,024
2014	Car	259,189	282,707	2,754	48,597	-	-	*76,570*	*39,375*	709,192
	Truck	498,245	801,740	32,013	12,079	14,809	56,516	*650,617*	*25,666*	2,091,685
	All	757,434	1,084,447	34,767	60,676	14,809	56,516	*727,187*	*65,041*	2,800,877
2015	Car	140,169	170,959	2,640	12,026	-	-	*183,860*	*28,994*	538,648
	Truck	296,039	313,961	10,795	5,208	13,565	43,060	*585,462*	*31,987*	1,300,077
	All	436,208	484,920	13,435	17,234	13,565	43,060	*769,322*	*60,981*	1,838,725
2016	Car	137,556	125,079	-	24,782	-	-	*115,995*	*21,237*	424,649
	Truck	338,099	139,667	-	9,894	-	69,596	*313,607*	*39,212*	910,075
	All	475,655	264,746	-	34,676	-	69,596	*429,602*	*60,449*	1,334,724

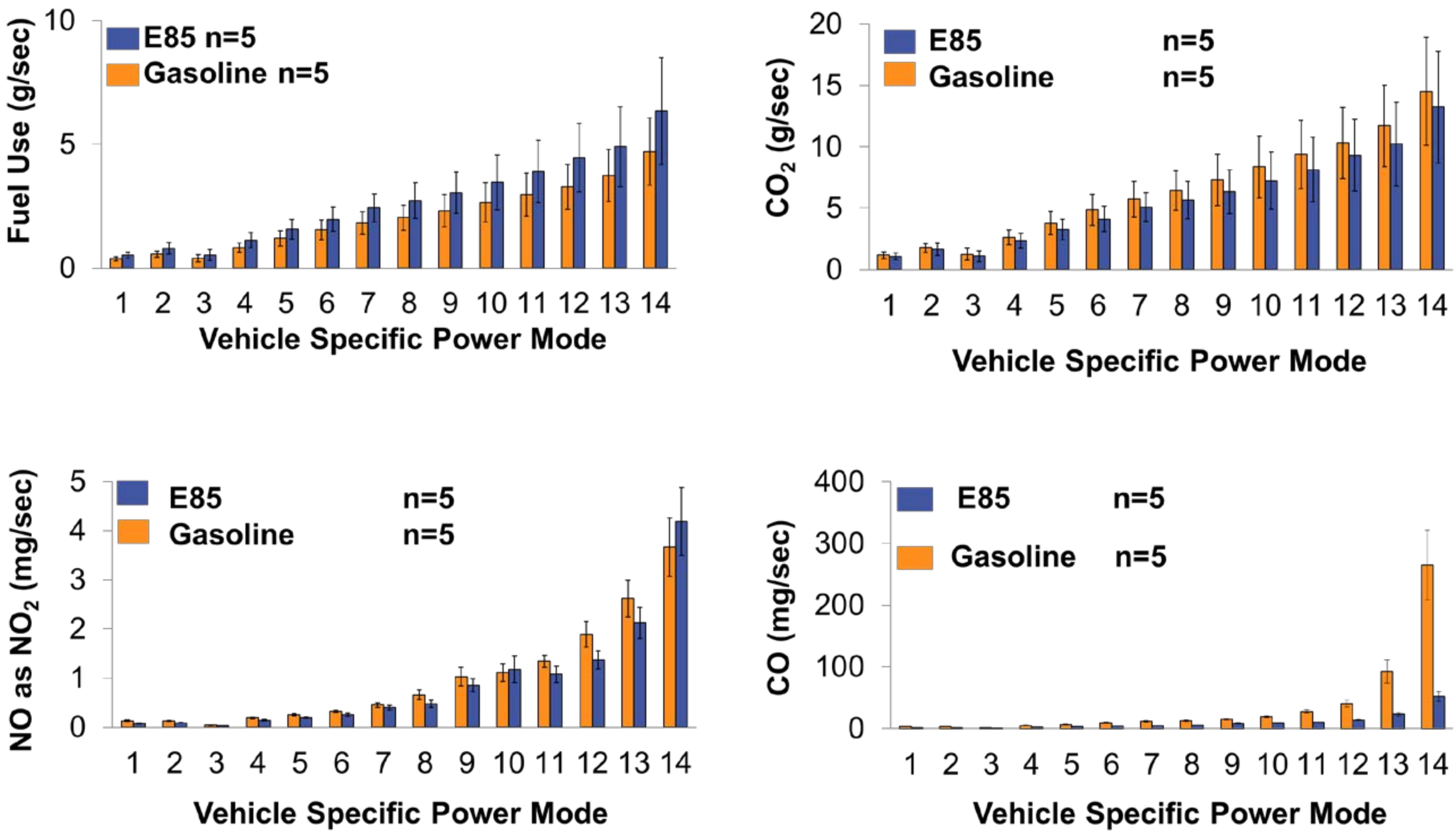
Source: (EPA, 2018)

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., 2002

Comparison of FFVs on E85 vs. E10 Based on PEMS Measurements



Source: Delavarrafiee and Frey, 2018, JAWMA

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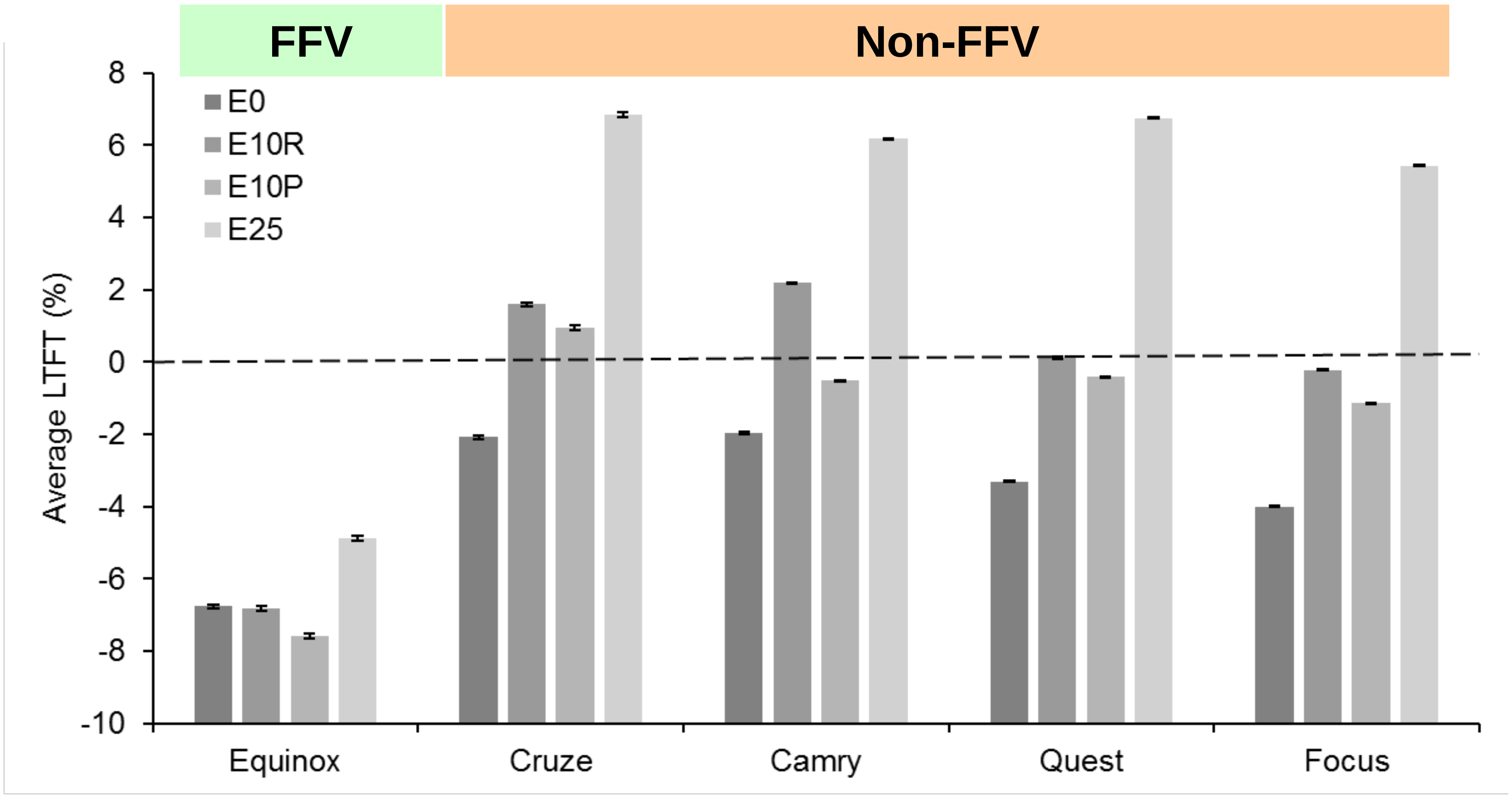
Beyond E10:
Conventional Vehicles Adapt to Ethanol Blends



Long-Term Fuel Trim (which affects fuel/air ratio) adapts to blends from E0 to E25

Ignition timing advance varies with engine load and fuel

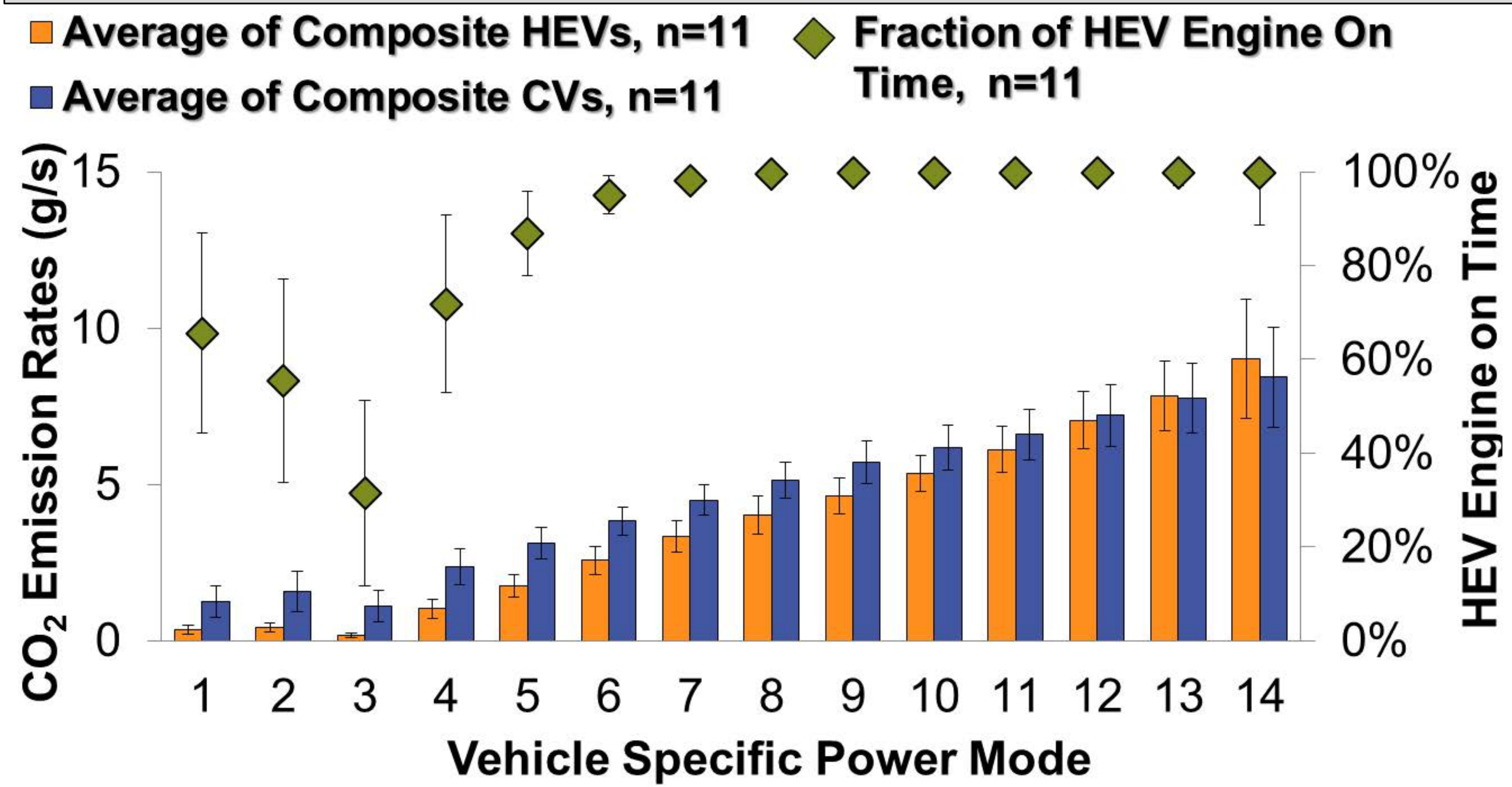
Sales of Alternative Technology Vehicles

Year	Hybrid Electric Vehicles (HEV)	Plug-In Hybrid Electric Vehicles (PHEV)	Battery Electric Vehicles (BEV)	Fuel Cell Electric Vehicle (FCEV)	Sum
2011	250,954	6,966	9,074	19	267,013
2012	387,188	37,558	12,795	30	437,571
2013	536,383	41,376	46,832	19	624,610
2014	441,988	56,548	60,368	49	558,593
2015	365,732	49,118	64,175	75	479,100
2016	336,125	73,146	72,424	1,030	482,725
2017	365,320	91,724	96,261	1,862	555,167
Total	2,689,900	356,058	362,058	3,084	3,411,706
Subtotal: Non-CA	2,002,958	186,303	179,253	9	2,368,523
Market Share	2.64%	0.39%	0.43%	0.00%	3.47%

Source: autoalliance.org

Results: HEV vs. Conventional Vehicle: Average VSP Modal CO_2 Emission Rates

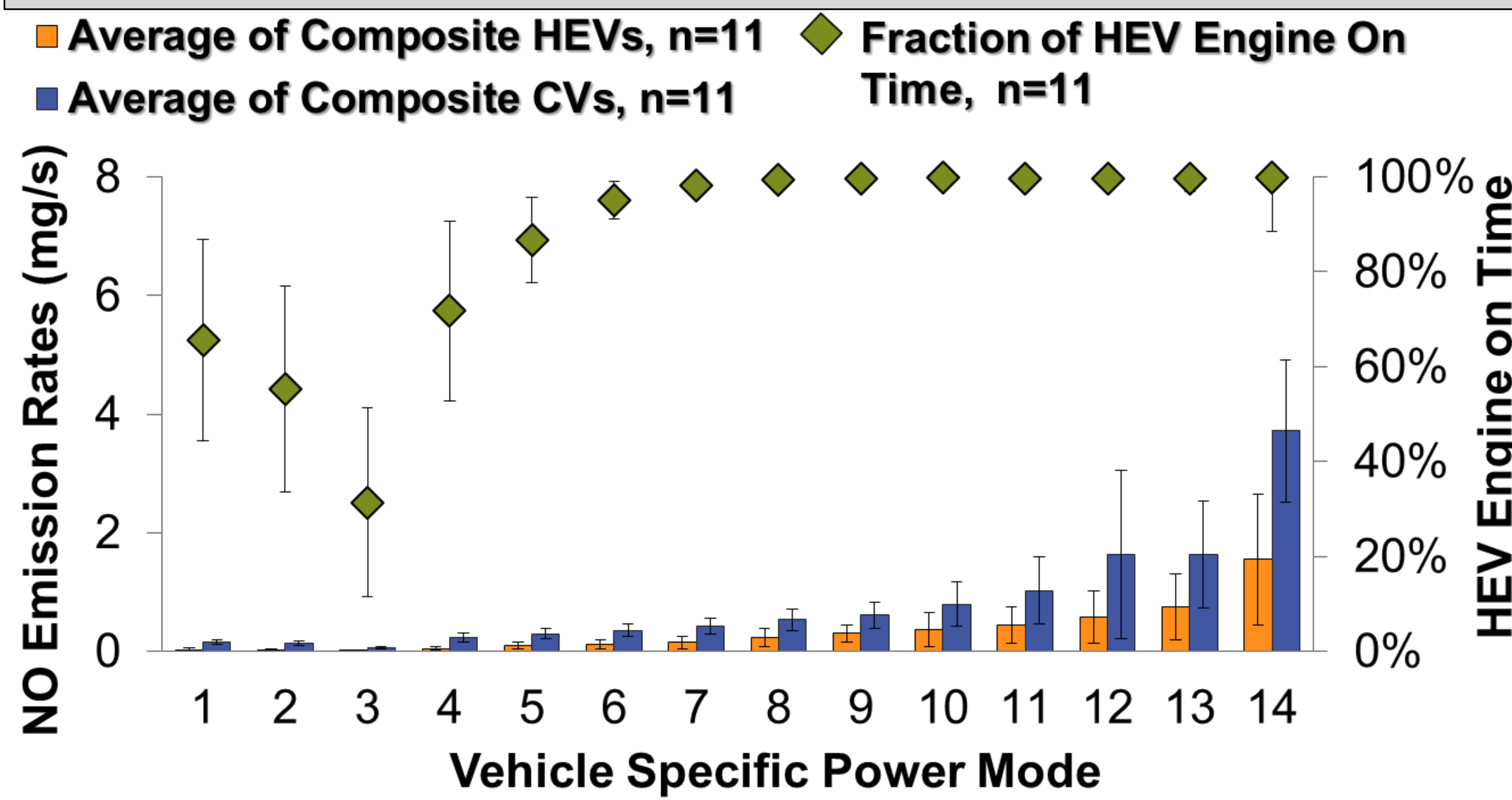
For Modes 1 to 9, HEV CO_2 emission is significantly lower than CV.



*NOTE: Error bars are 95% confidence intervals on mean.
*For the HEVs, modal average VSP fuel use and emission rates are weighted based on the fraction of the time that engine was on.

Results: HEV vs. Conventional Vehicle: Average VSP Modal NO_x Emission Rates

For Modes 1 to 9, HEV NO emission rates are significantly lower than CV.



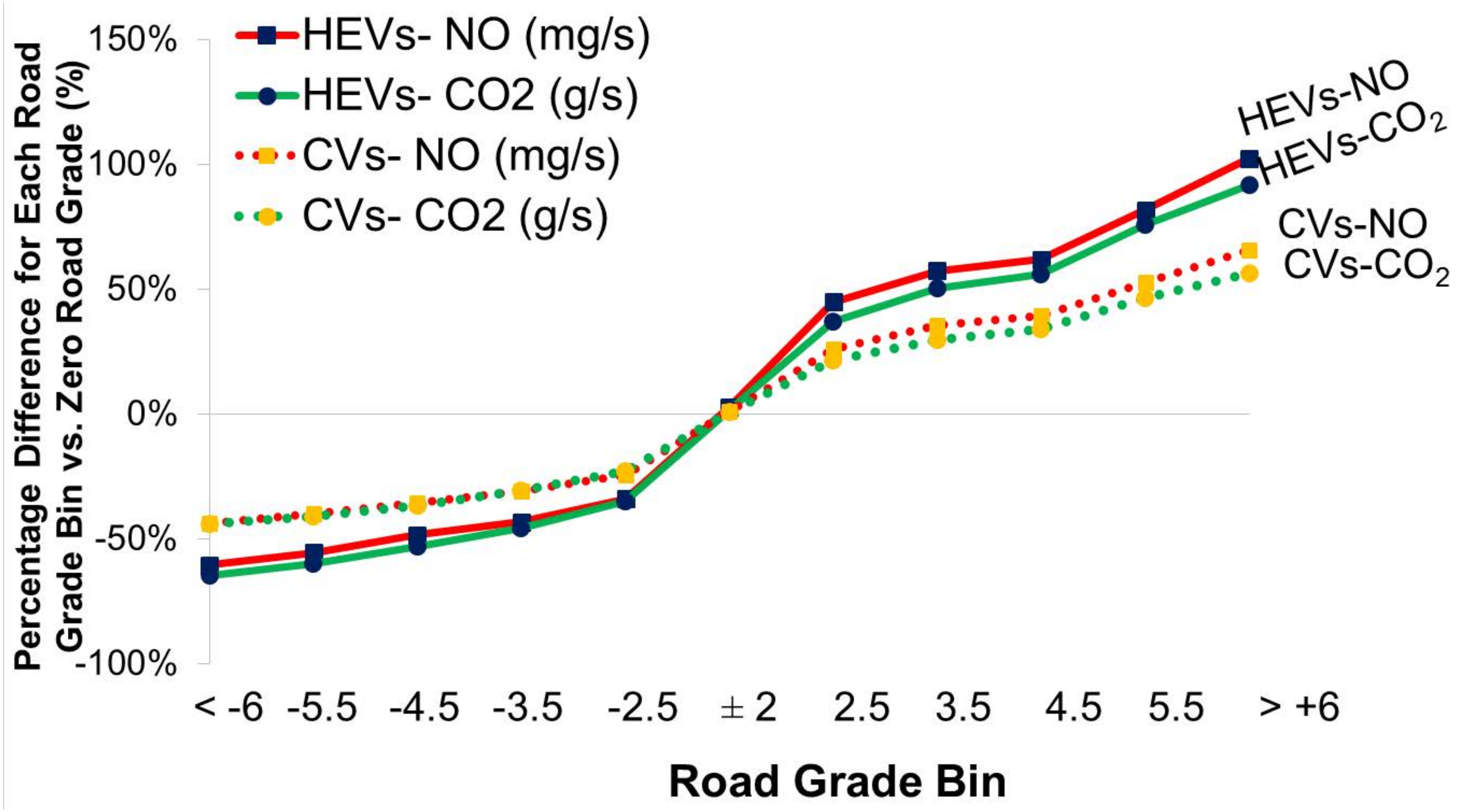
*NOTE: Error bars are 95% confidence intervals on mean.

*For the HEVs, modal average VSP fuel use and emission rates are weighted based on the fraction of the time that engine was on.

Cycle Average Gaseous Emission Rates for HEVs vs. Conventional Vehicles

Pollutant	Description	Unit	Observed Driving Cycles in Raleigh, NC	
			Route A	Route 1
CO_2	Percentage Difference (n=11) (Average HEVs vs. Average CVs)	%	-44	-27
	p Value for two paired t-test	-	0.00	0.00
NO_x	Percentage Difference (n=11) (Average HEVs vs. Average CVs)	%	-72	-64
	p Value for two paired t-test	-	0.00	0.01
CO	Percentage Difference (n=9) (Average HEVs vs. Average CVs)	%	-21	-31
	p Value for two paired t-test	-	0.54	0.29
HC	Percentage Difference (n=11) (Average HEVs vs. Average CVs)	%	-47	-43
	p Value for two paired t-test	-	0.04	0.07

Percentage Difference in CO_2 and NO Emission Rates of Each Road Grade Bin Vs. Zero Road Grade



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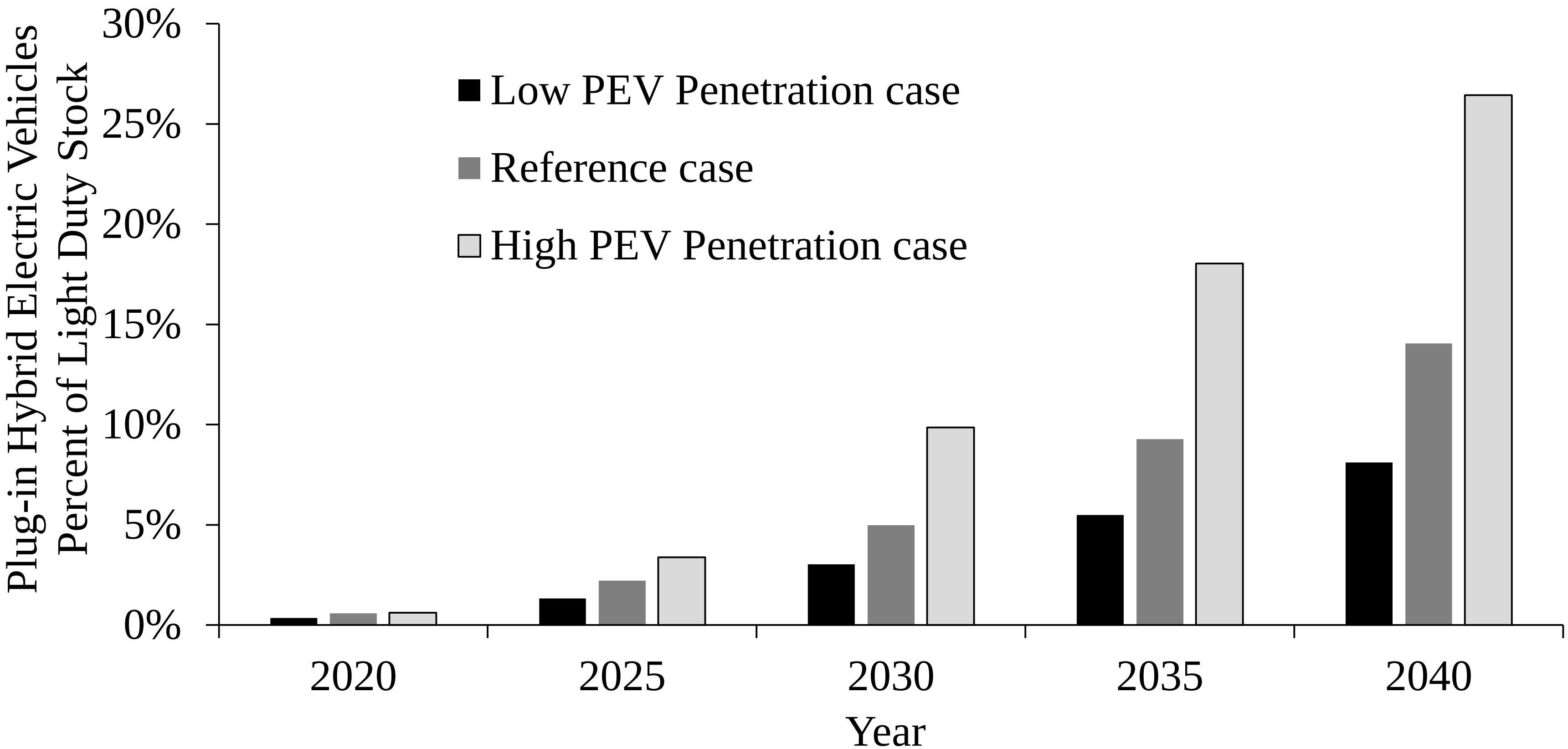
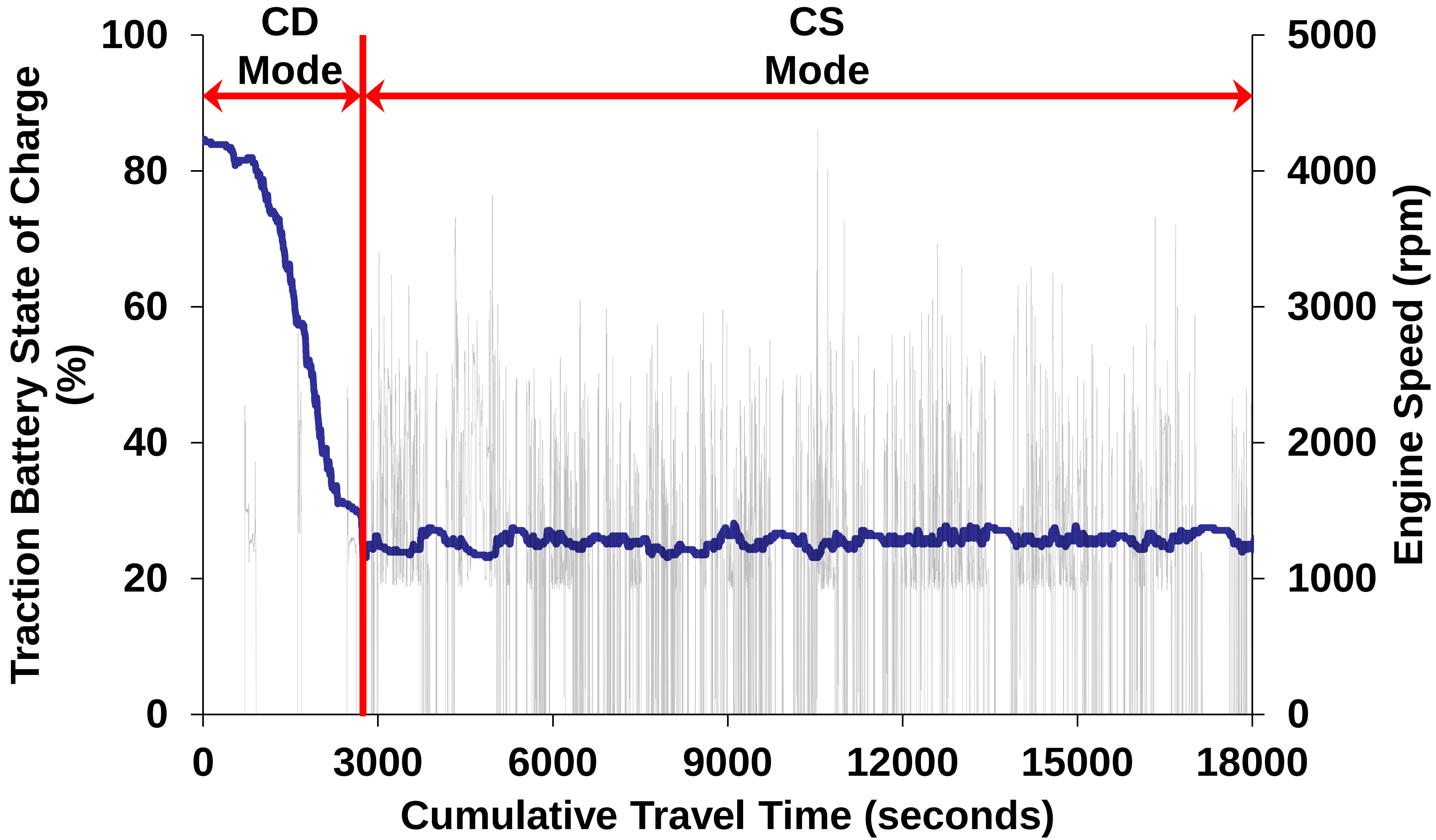
Projected Trend in Global PHEV Vehicle Stock



Projected Trend from 2020 to 2040 in Worldwide Plug-in Electric Vehicles as Percent of Light-Duty Vehicle Stock. Source: (Lynes, 2017)

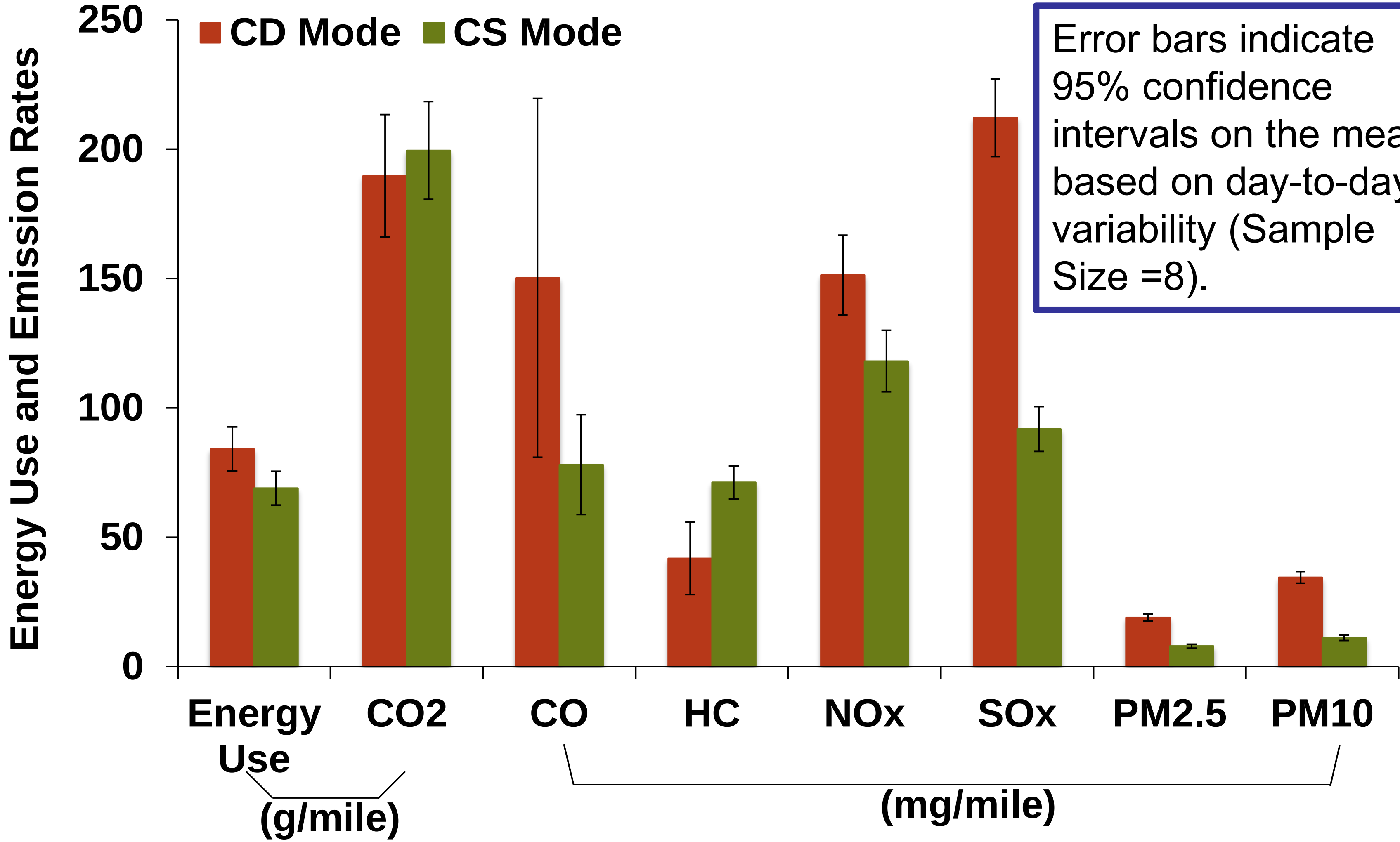
Field Measurements of a 2013 Toyota Prius Plug-In

Results: CD Mode versus CS Mode



Source: Zheng and Frey (in preparation)

Results: CD Mode versus CS Mode



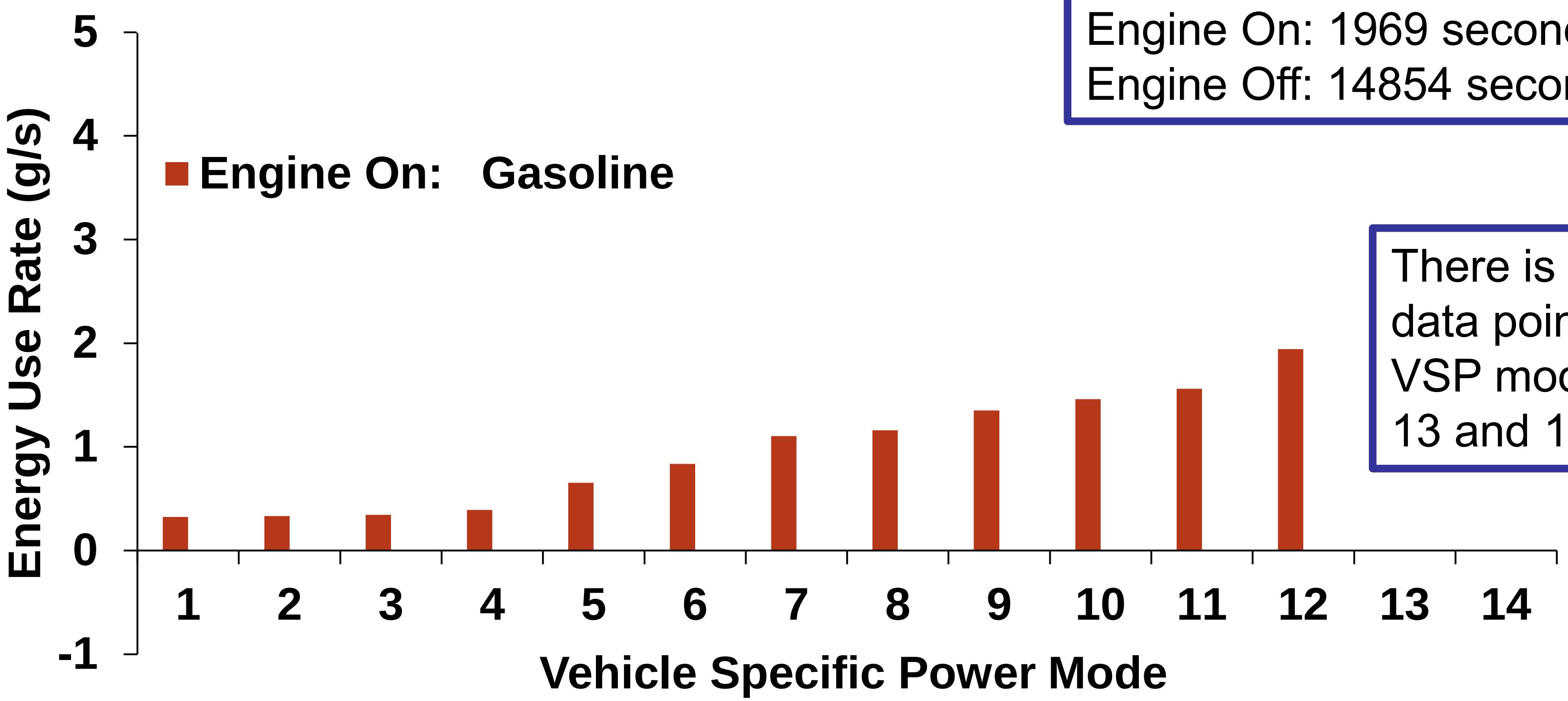
Error bars indicate 95% confidence intervals on the mean based on day-to-day variability (Sample Size =8).

Energy use is gasoline equivalent fuel use.

Results: CD Mode Energy Use

Engine On versus Engine Off

Sample Size
Engine On: 1969 seconds
Engine Off: 14854 seconds



There is no data point in VSP modes 13 and 14.

Error bar indicate 95% confidence intervals on the mean based on second-by-second variability in total energy use rates.

Results: CD Mode Energy Use

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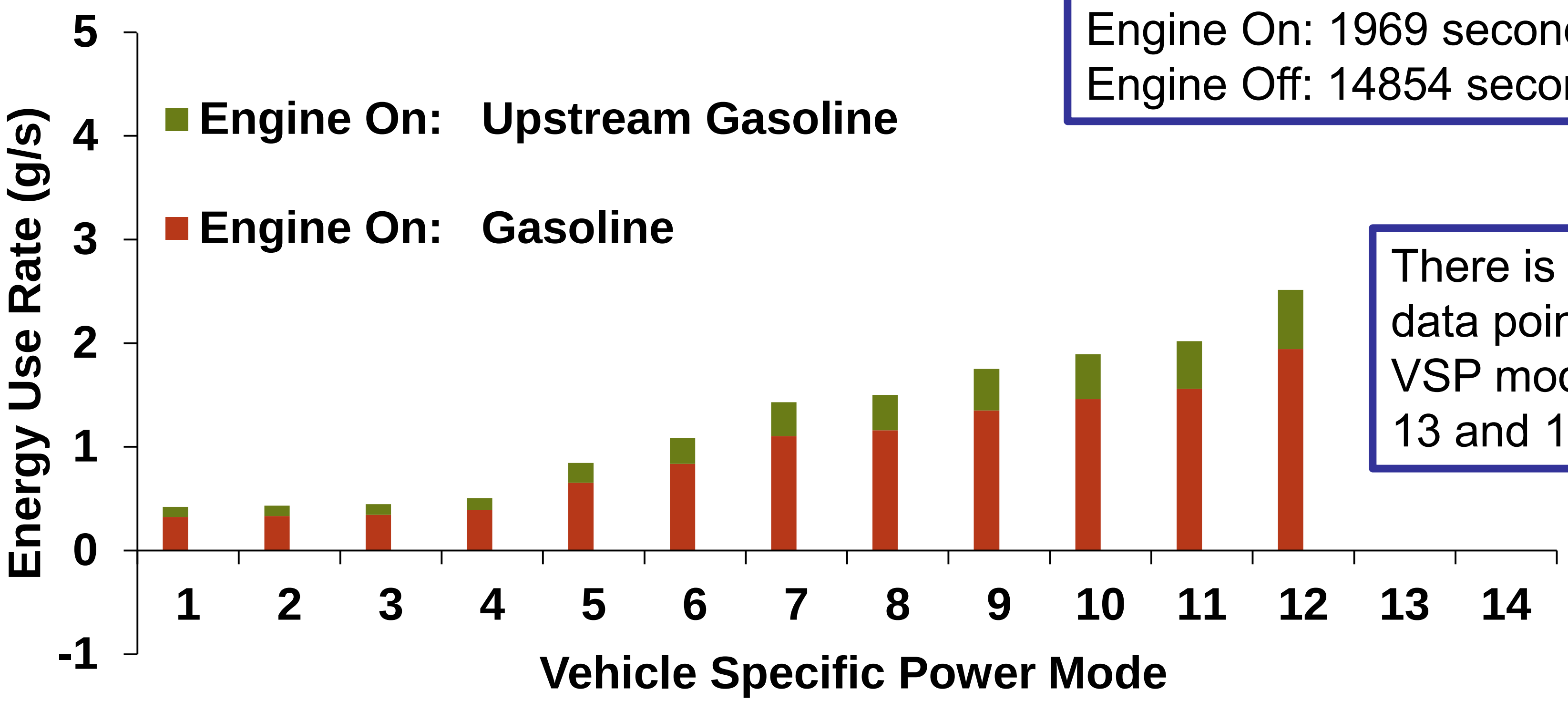

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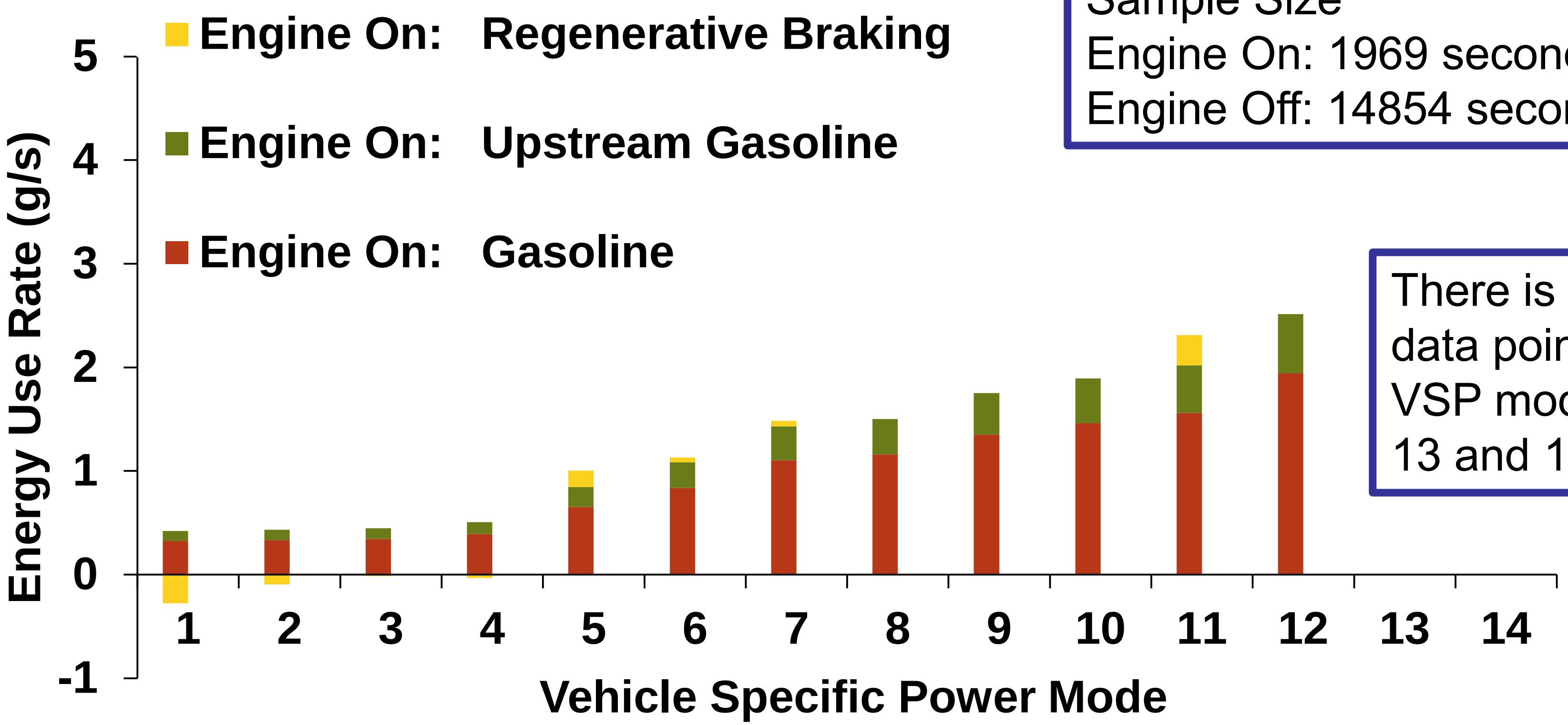

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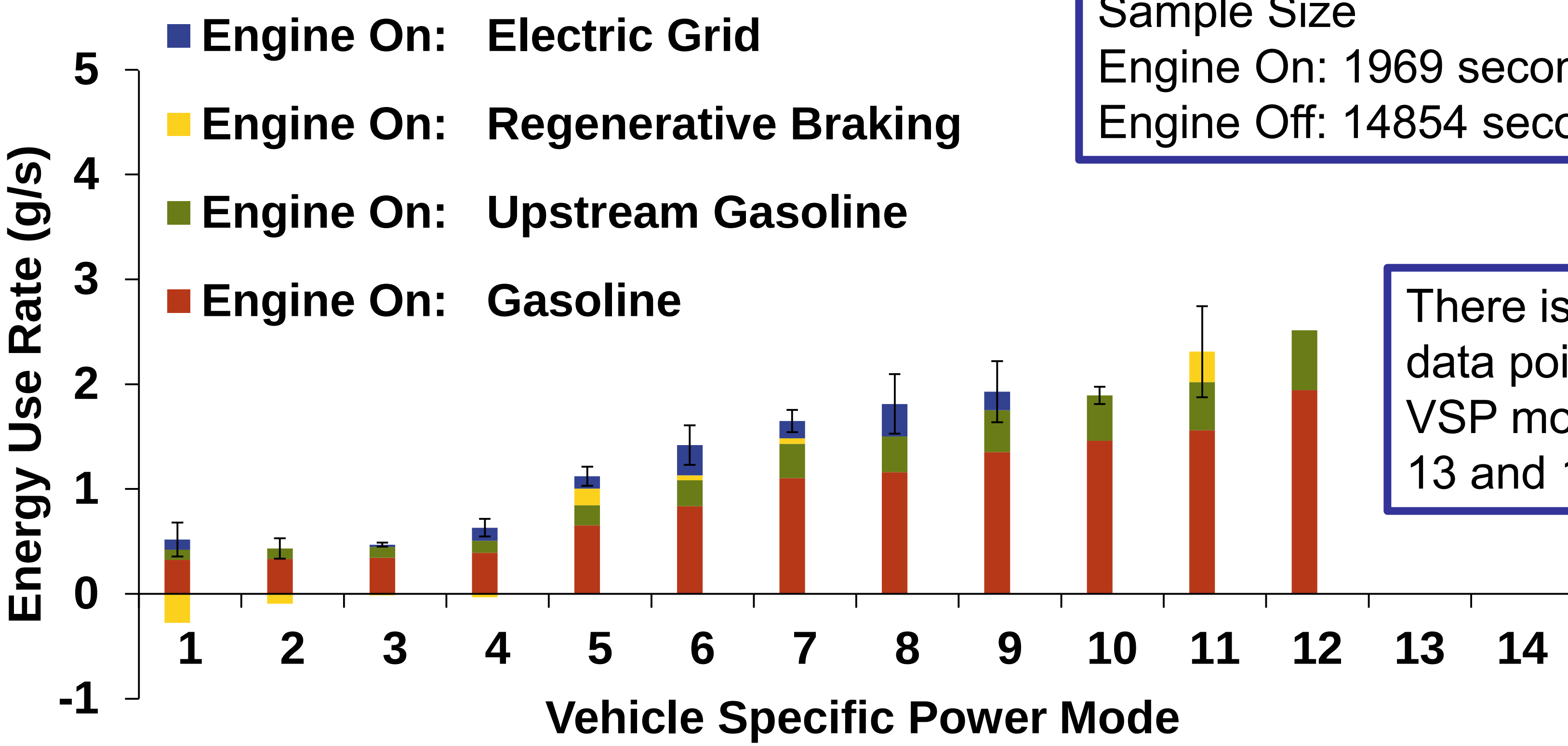

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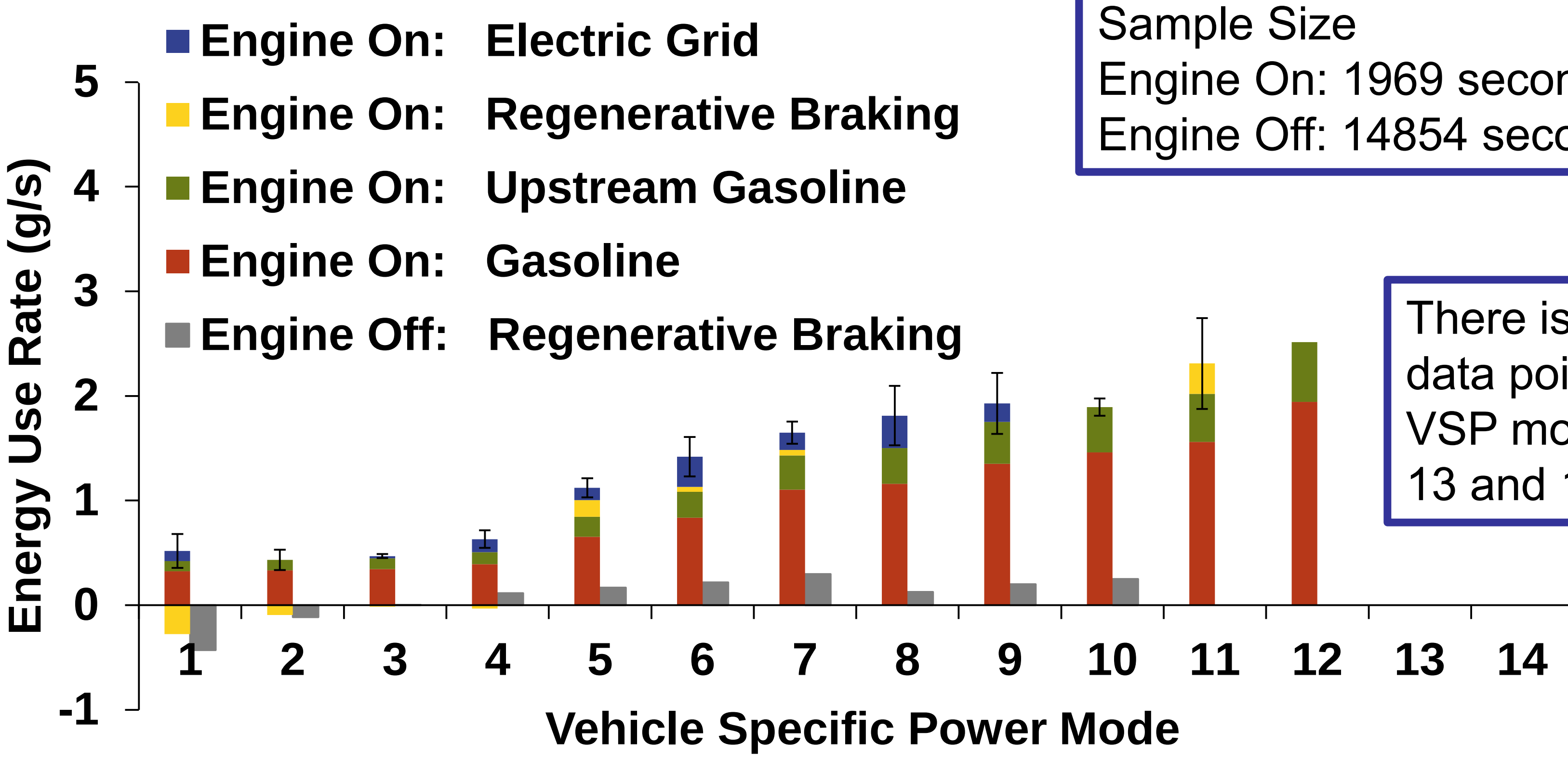

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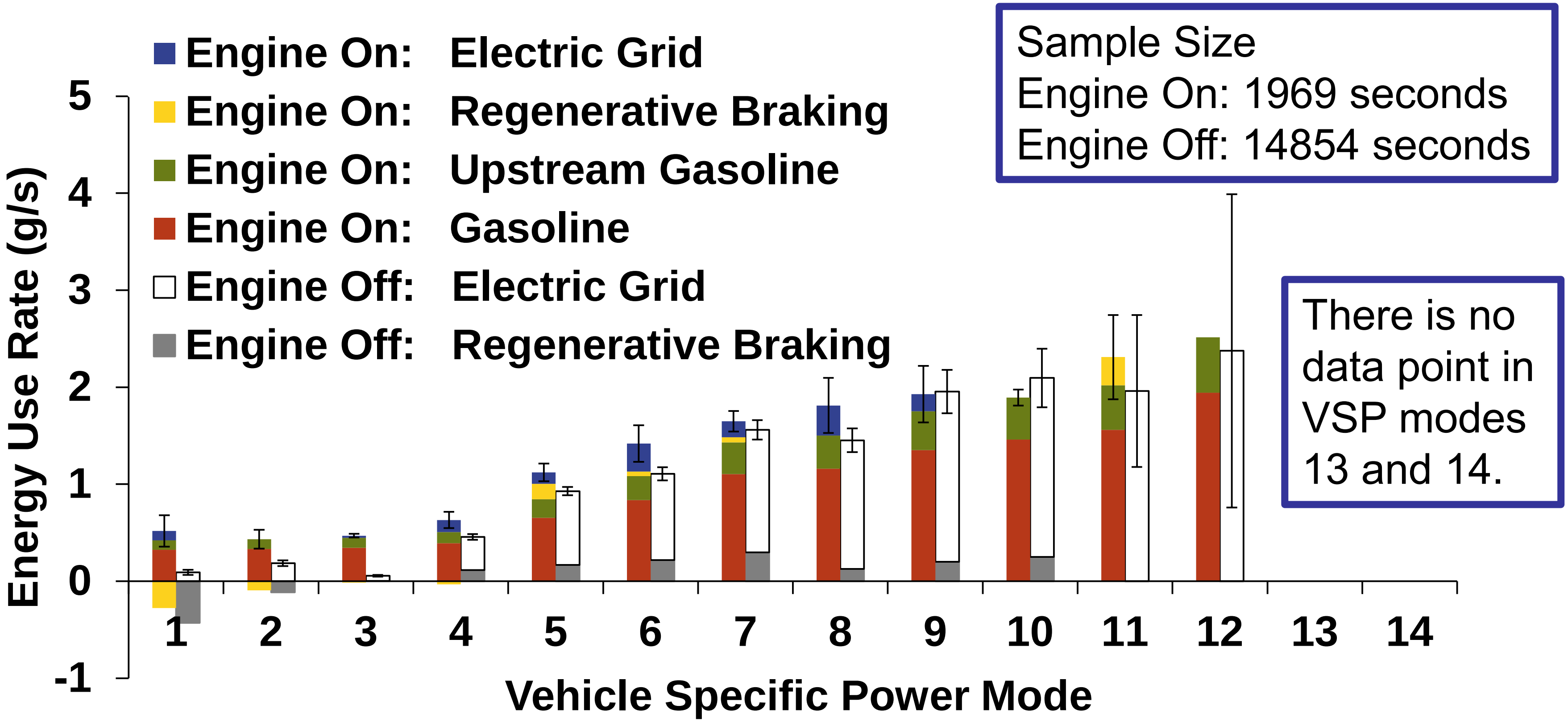
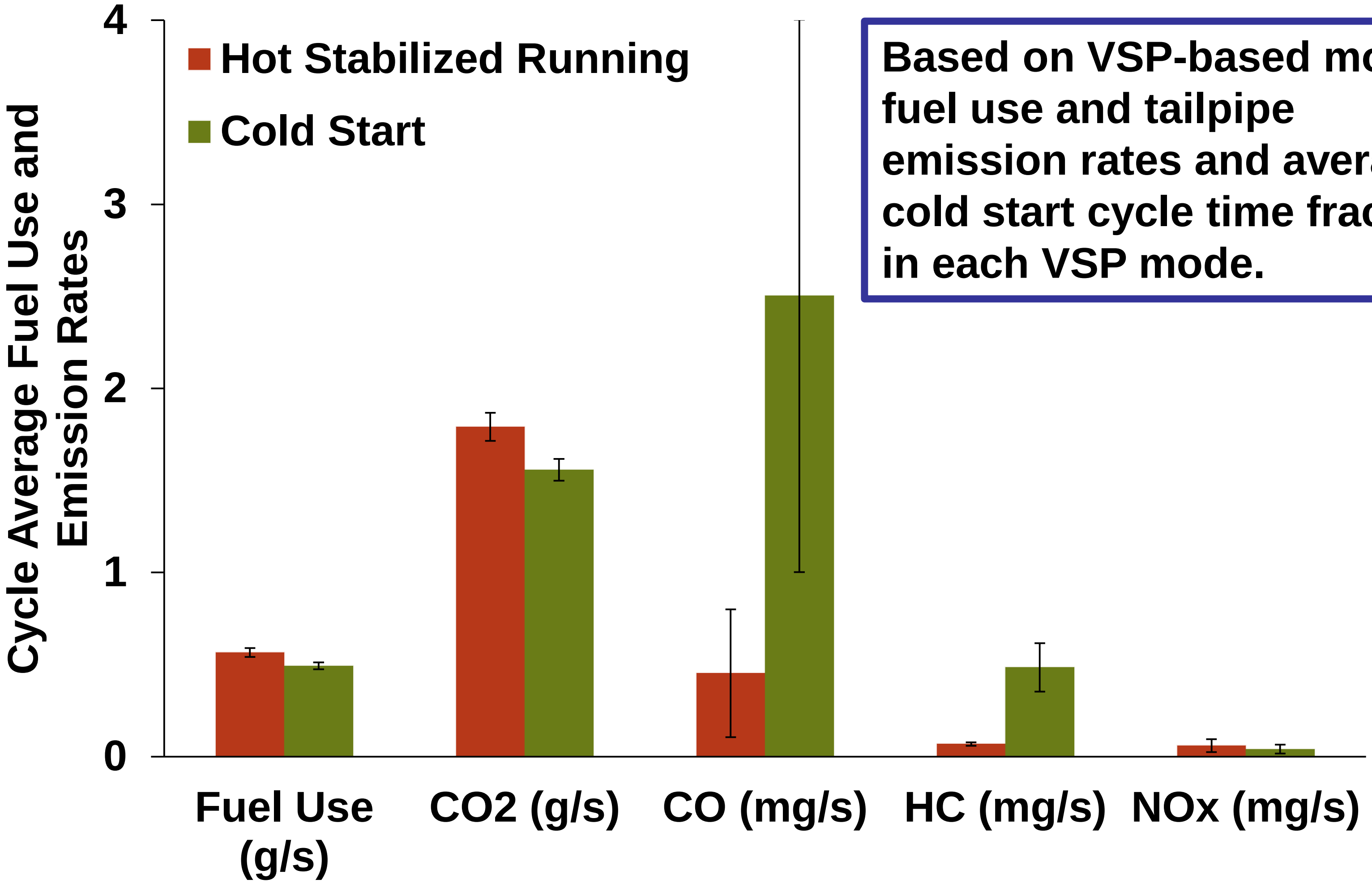


Error bar indicate 95% confidence intervals on the mean based on second-by-second variability in total energy use rates.

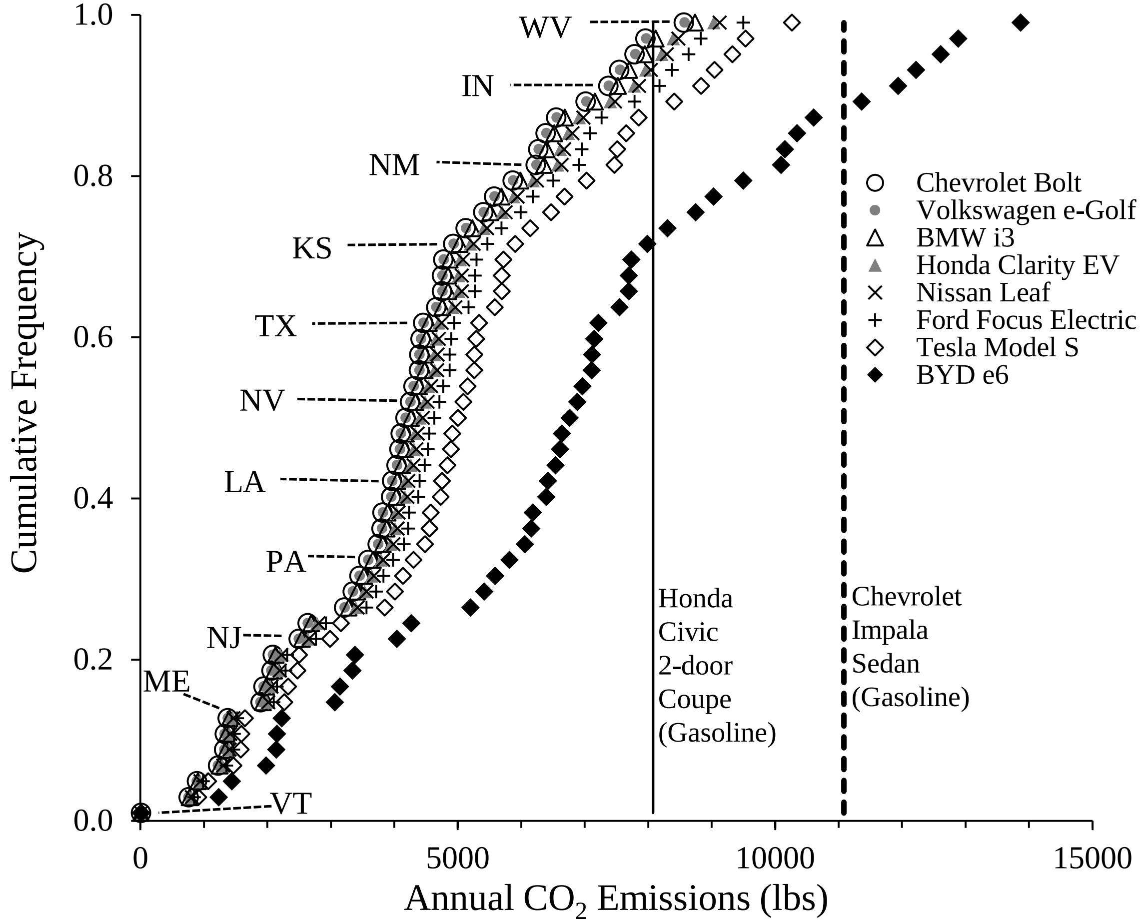
Results: Cold Start versus Hot Stabilized Running



Based on VSP-based modal fuel use and tailpipe emission rates and average cold start cycle time fraction in each VSP mode.

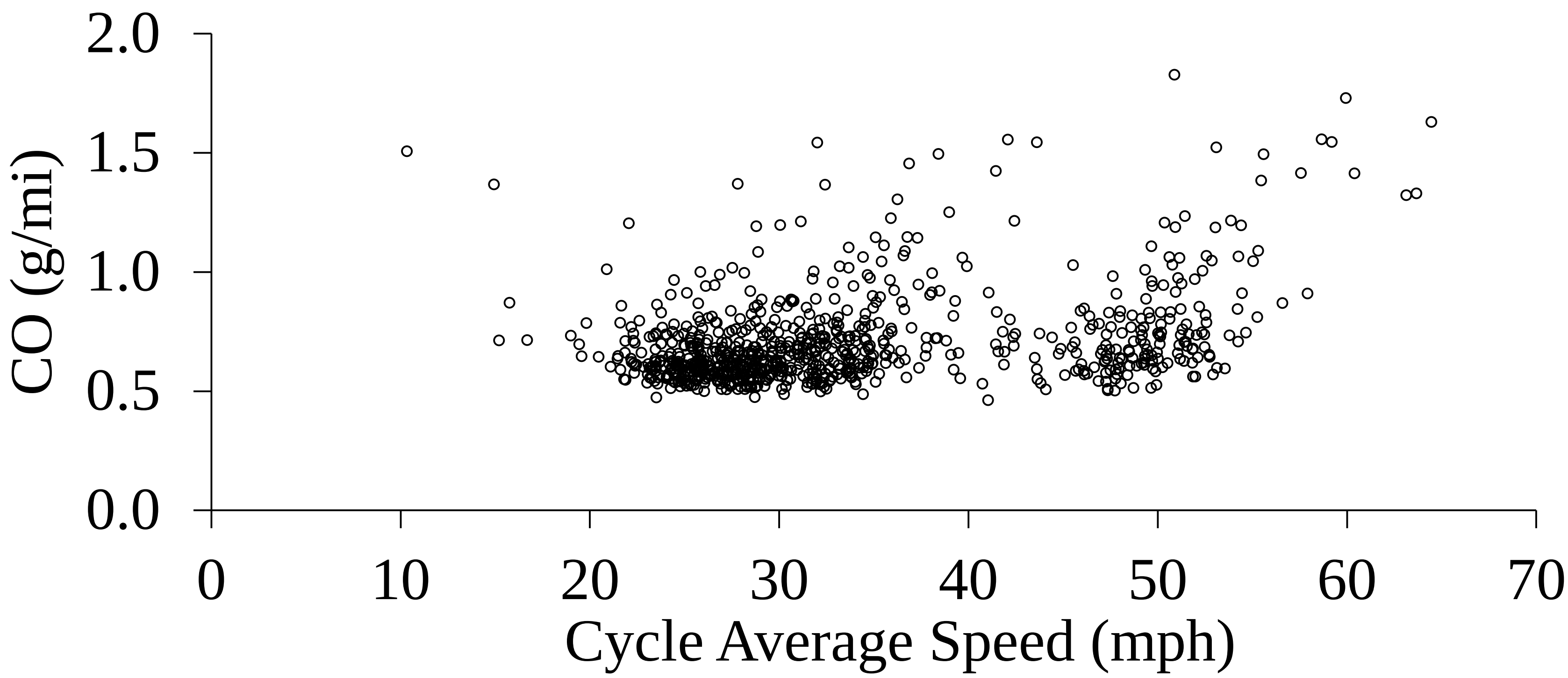
Error bar indicate 95% confidence intervals on the mean.

Comparison of Annual Inter-State Variability in Indirect Power Generation



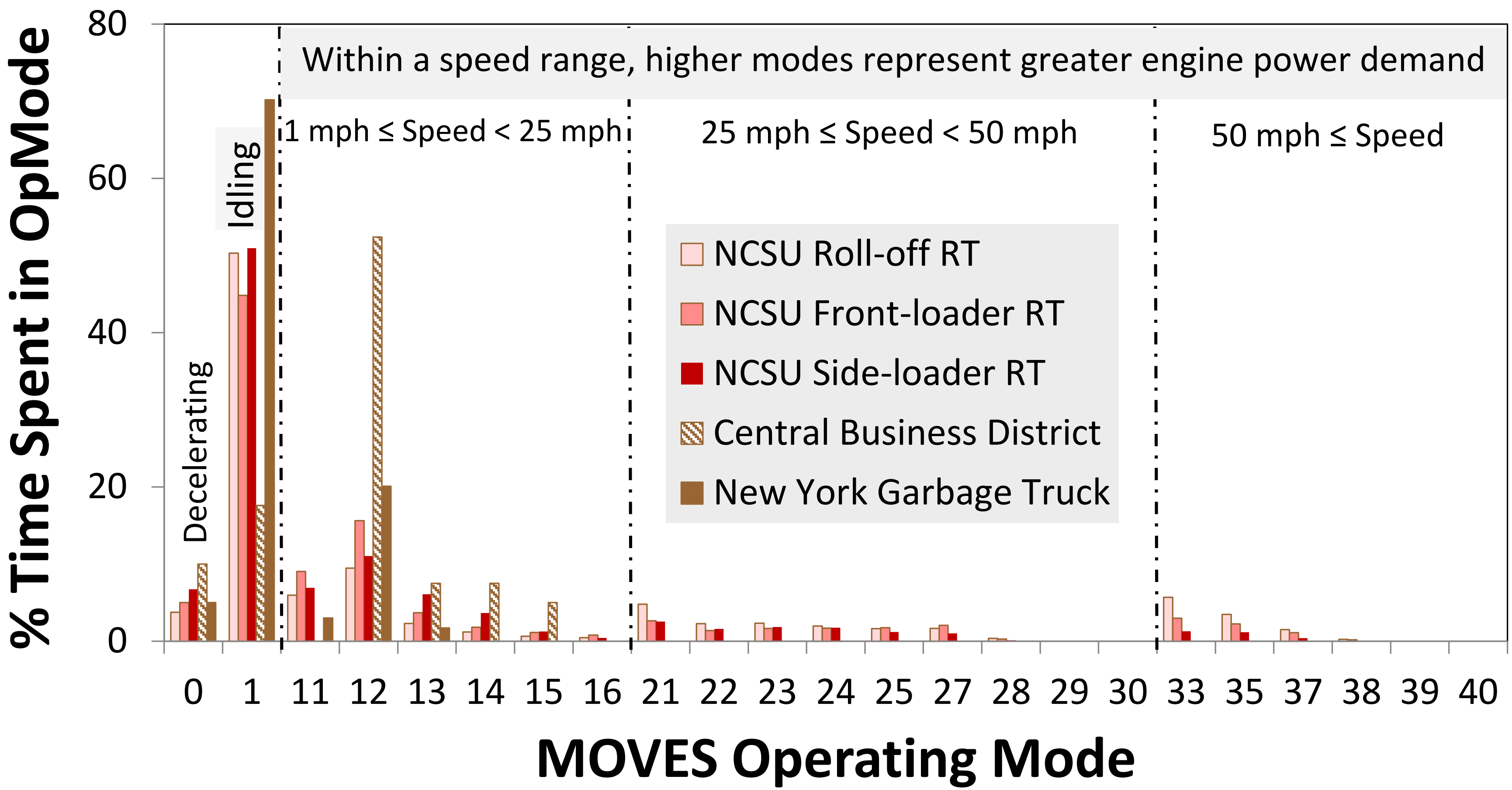
Comparison of Annual Inter-State Variability in Indirect Power Generation CO2 Stack Emissions for Electricity Consumed by Selected Electric Vehicles and Tailpipe Exhaust CO2 Emissions from Selected Gasoline Vehicles. Based on 2017 Model Year Vehicles. Source: Alternative Fuel Data Center, U.S. Department of Energy

Move Beyond Default Cycles: CO Emission Rates Based on 800+ Real-World Cycles



Source: Frey

Comparison of Duty Cycles: NCSU vs Literature



Source: Sandhu, Frey, Bartelt-Hunt, and Jones 2014, AWMA Annual Meeting

Effect of Driving Cycle

Duty Cycle	Fuel g/s	CO_2 g/s	CO mg/s	HC mg/s	NO_x mg/s	PM mg/s
RO-Avg	3.1	10	21	5.8	56	0.8
MOVES2014	5.5	17	26	8.8	90	1.3
%Diff	76	77	23	53	60	60

Duty Cycle	Fuel g/s	CO_2 g/s	CO mg/s	HC mg/s	NO_x mg/s	PM mg/s
SL-Avg	3.0	10	30	4.2	58	0.8
MOVES2014	5.3	17	34	7.0	86	1.1
%Diff	74	75	15	65	48	35

Source: Sandhu, Frey, Bartelt-Hunt, and Jones 2014, AWMA Annual Meeting

Field Study

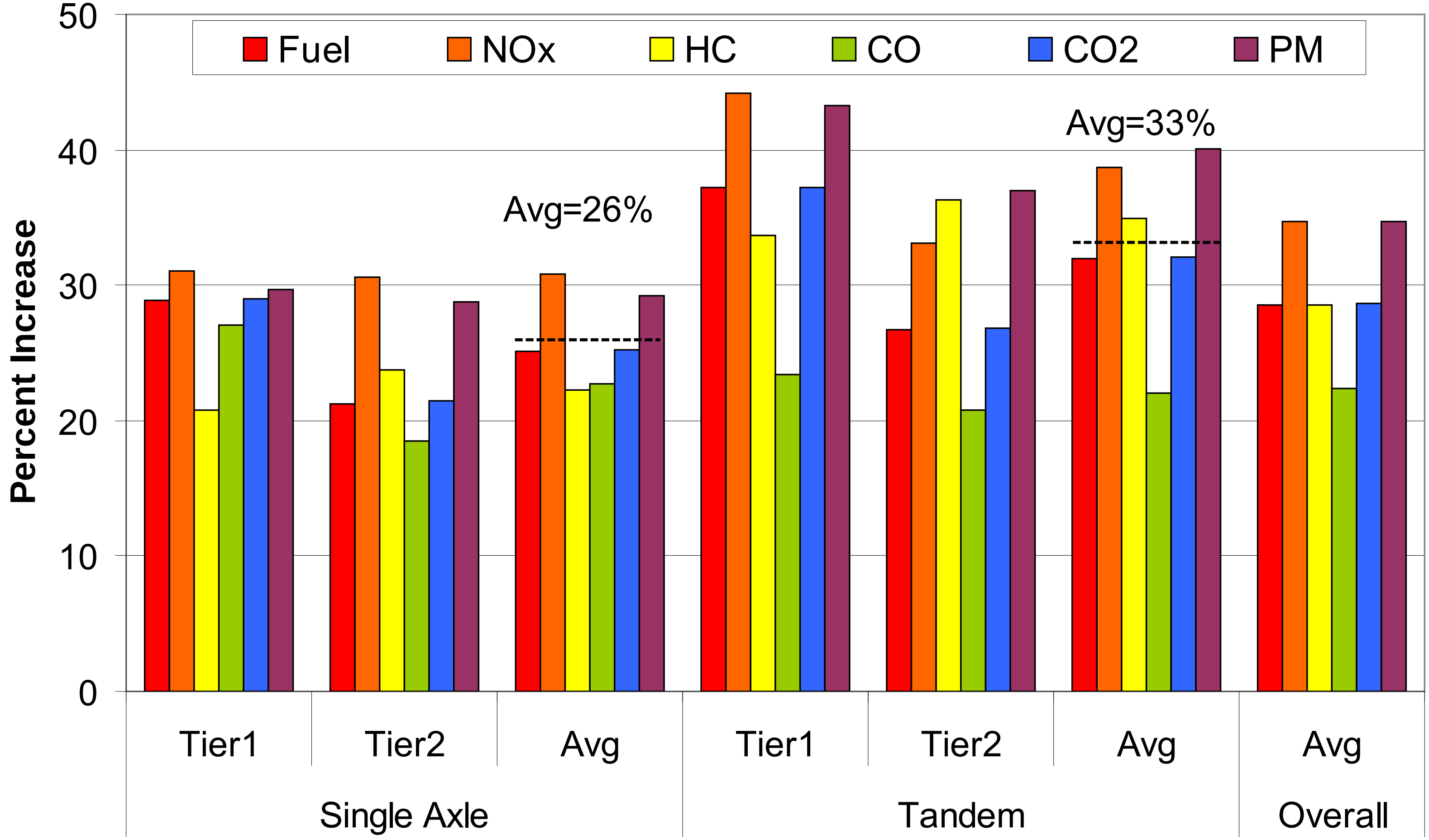
- Portable Emission Measurement System
- NCDOT in-use dump trucks
  - Single rear axle – “Single”
  - Double rear axle – “Tandem”
  - Tier 1 and Tier 2 engines
- Drivers – NCDOT
- Duty cycles – real world activity

“Single”

“Tandem”

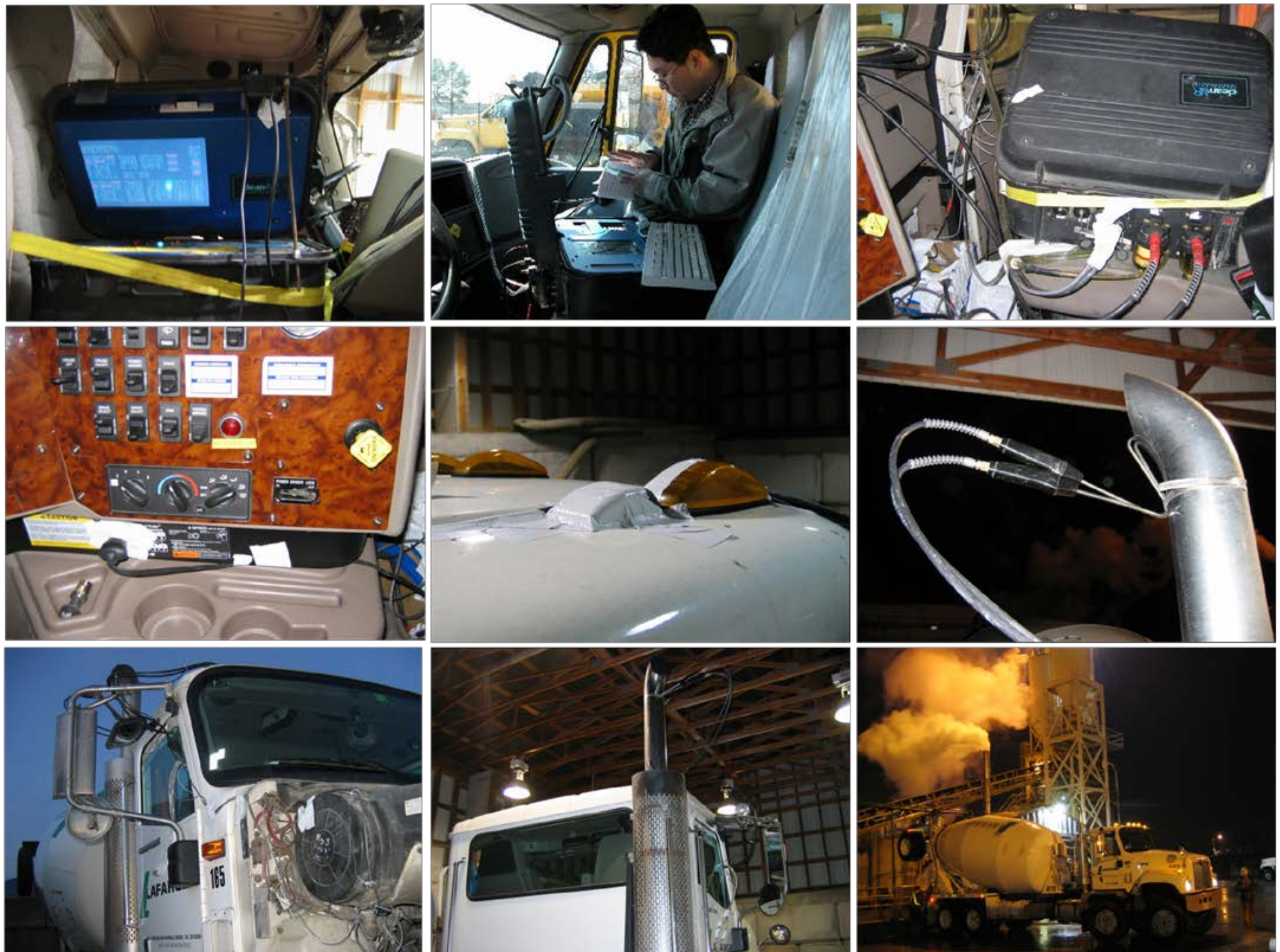
Source: Frey and Kim, 2006, Transportation Research Record

Overall Comparison of Loaded Versus Unloaded Fuel Use and Emissions: Petroleum Diesel



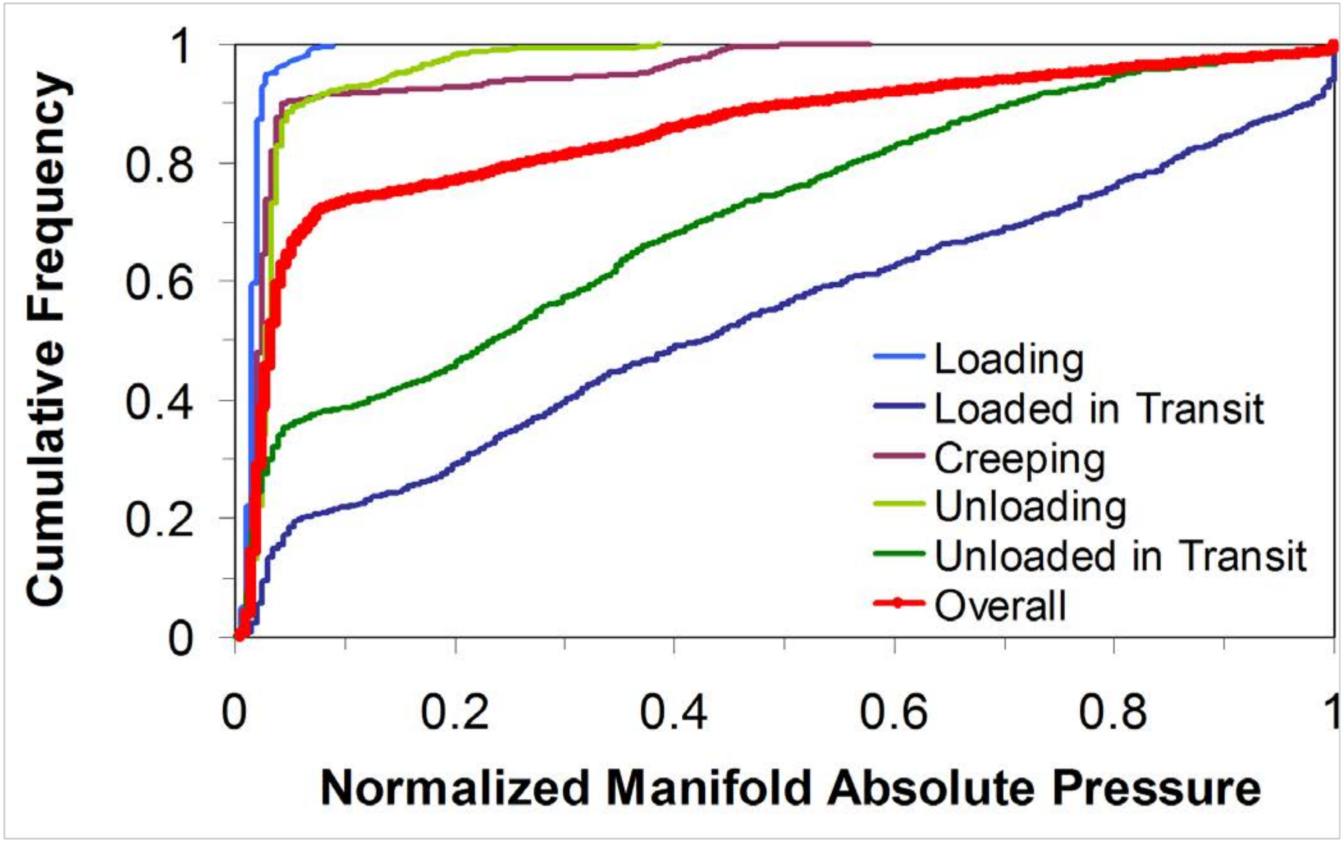
Source: Frey and Kim, 2006, Transportation Research Record

Field Data Collection on Concrete Mixer Trucks



Source: Frey and Kim, 2009, Transportation Research – Part D

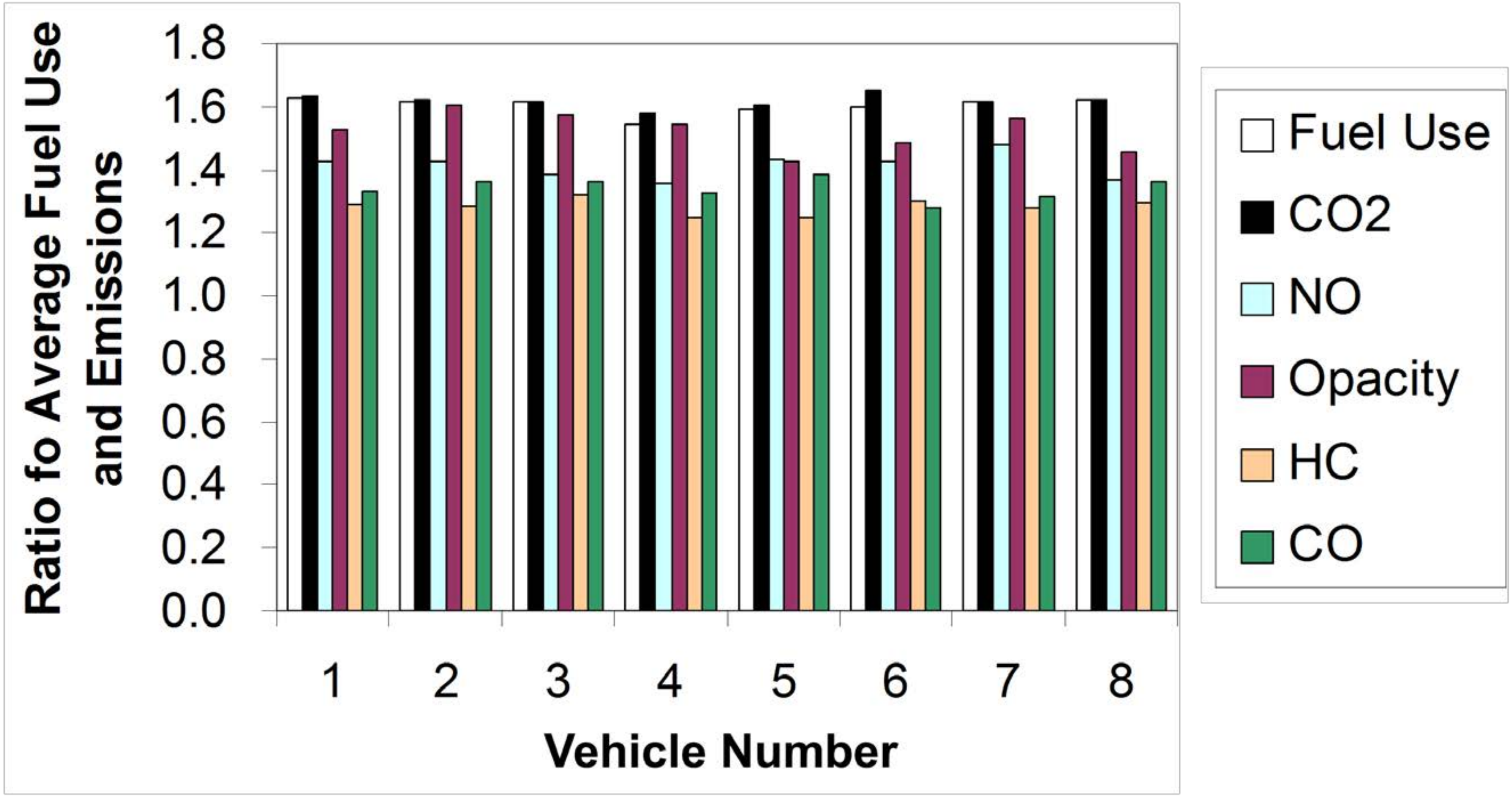
Frequency Distribution of Engine Loads for Components of Concrete Mixer Truck Duty Cycle



n_{LO}	=	205
n_{LOTR}	=	948
$n_{Creeping}$	=	3,589
n_{UN}	=	1,304
n_{UNTR}	=	1,183
$n_{Overall}$	=	7,229

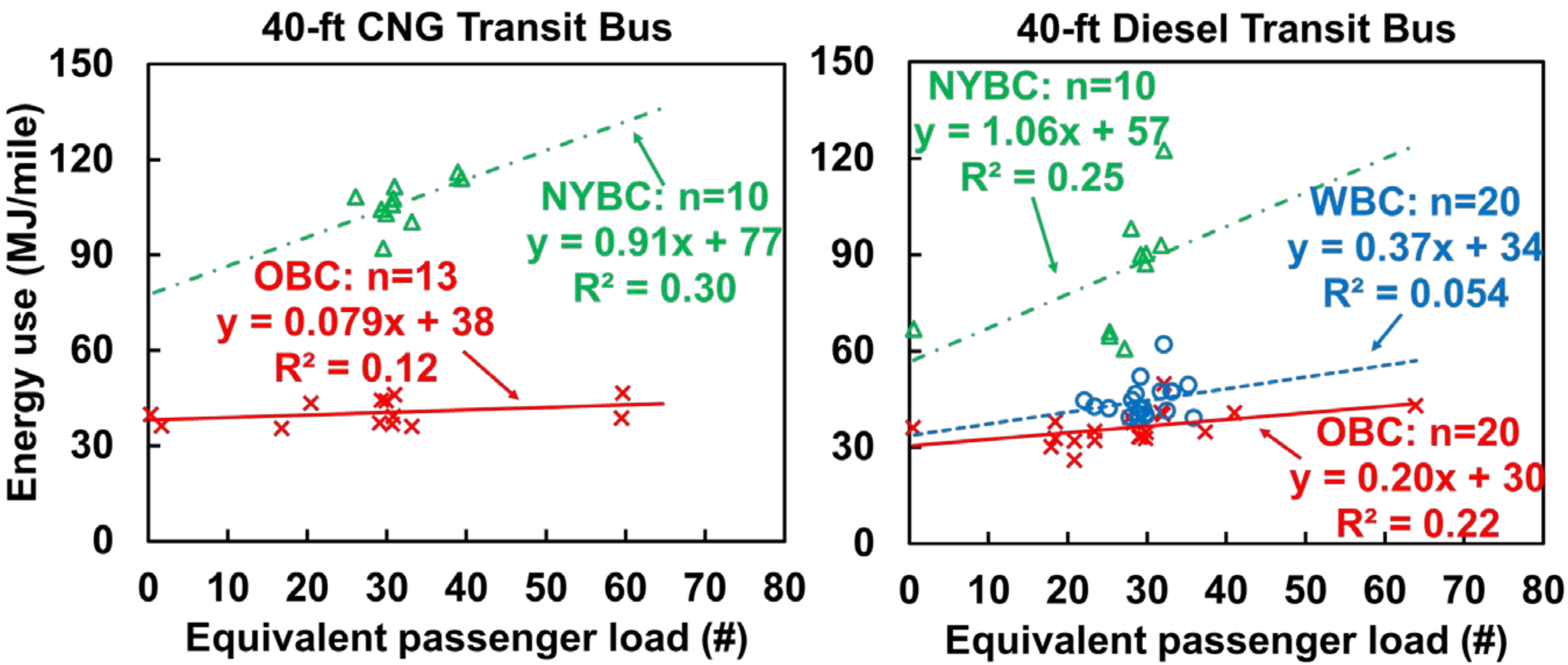
Source: Frey and Kim, 2009, Transportation Research – Part D

Ratio of Loaded to Unloaded Fuel Use and Emission Rates for Concrete Mixer Trucks



Source: Frey and Kim, 2009, Transportation Research – Part D

Transit Bus Energy Use Rate Versus Passenger Load

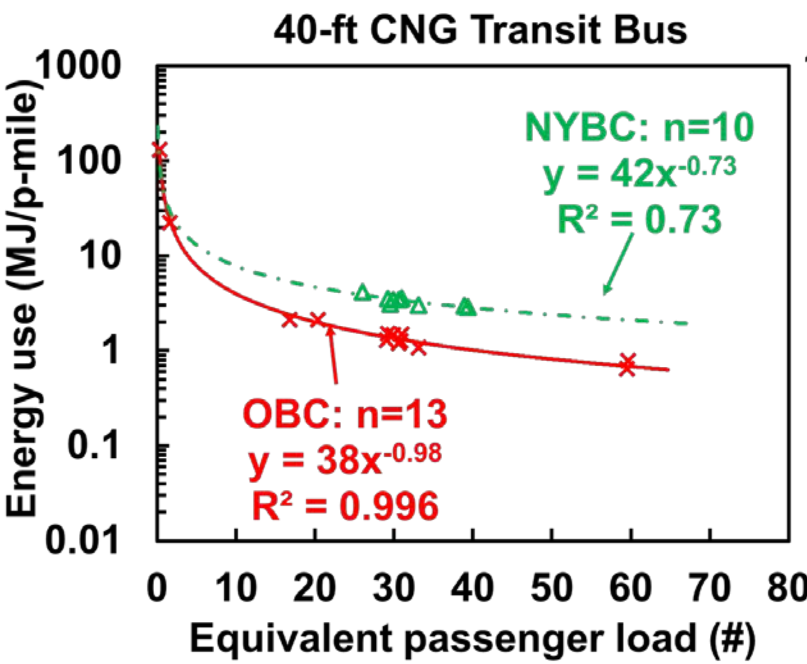


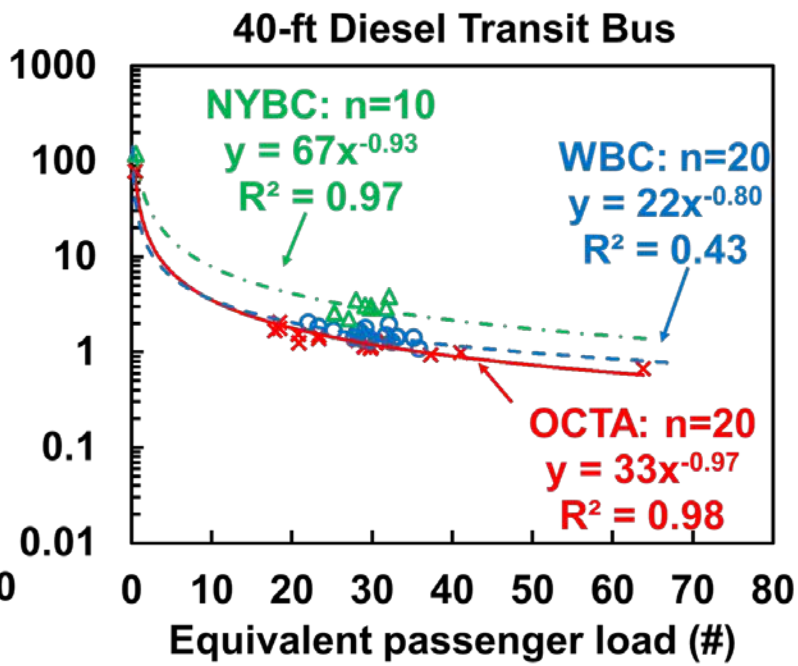
Source: Wei and Frey, 2018, TRB Annual Meeting

MOVES Transit Bus

- These data do not =correspond to any particular size of transit bus
- Categorized by regulatory class (weight)
- Common sizes are 30 foot, 40 foot, and 60 foot long (with variations)
- Better documentation of basis
- Categorize by regulatory class and size

Implications: Energy Use Rate Per Passenger Mile





Source: Wei and Frey, 2018, TRB Annual Meeting

Other Needs: Secondary Organic Aerosol (SOA) Precursors

- IVOC and SVOC from gasoline and diesel vehicles leads to SOA formation (Gentner et al., 2017)
- Ratio of SOA-precursors to primary PM from LDGVs ranged from 20 to 90 for measurements that included cold starts (May et al., 2014)
- SOA yield is likely higher for gasoline than diesel vehicles (McDonald et al., 2015)
- Decreases in aromatics can decrease SOA (Zhu et al. 2017)
- Intermediate VOCs (IVOCs) (13 to 19 carbon atoms)
- Semi-Volatile Organic Compounds (SVOCs) (20 to 26 carbon atoms)
- Formatting MOVES output for SOA precursors, and for ratio of precursors to primary organic aerosol emissions, would be helpful.
- Actual SOA formation also depends on atmospheric concentration of peroxy radicals and other factors.

Other Needs: Role of Lubricating Oil

- Not well-characterized
- E.g., SOA precursor
- Factor in cold starts
- Factor in primary organic aerosol emissions (e.g., Li et al., 2016)
- Factor in UFP emissions (e.g., Pirjola et al., 2015)
- Implicated in self-pollution of diesel school buses (i.e. crankcase gases) (e.g., Ireson et al., 2011)
- Needs more research

Other Needs: Ultrafine Particles

- More attention to this in Europe
- Solid Particle Number (SPN) method used in Europe
- Role of volatile UFPs, especially at size less than 23 nm

Other Needs: Brake and Tire Wear

- Brake and tire wear likely to exist for all vehicles as long as there are friction brakes and tires
- Vehicles with batteries tend to be heavier – more wear emissions (e.g., Timmers and Achten, 2016).
- Some of these particles are large (>2.5 micrometers) (e.g., Sanders et al., 2003) and are of less health concern
- Brake UFP emissions seem to increase with brake temperature (e.g., Nosko et al., 2017; Alemani et al., 2018)
- Evidence of UFP emissions from tires (Dahl et al., 2006), which include more organics than brake wear (Thorpe and Harrison, 2008)
- Needs more investigation

Other Needs: Air Conditioning

- Based on MOVES, air conditioning imposes an energy use penalty of approximately 10 to 15 percent, depending on the cycle.
- Based on data collected in 1997 and 1998
- Current GHG emission standards offer incentives for AC efficiency
- Lack of adequate quantification of AC energy consumption based on recent data and trends

Autonomous Vehicles

- Potentially very ‘disruptive’
- More trip taking?
- “right-sized” vehicles?
- More efficient trajectories? Or higher performance trajectories?
- Will pricing models adapt to potentially large increases in energy demand from AVs?
- Possible market share of 2 to 15 percent by 2030… (?)
- Full autonomy less likely until mid-century or later
- When, how, should MOVES start to account for AVs…

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Summary

- LDGV is in technology transition from PFI to GDI
- Significant number of FFVs
- LDGVs adapt to ethanol blends
- Growing numbers of HEVs, PHEVs, BEVs
- HEVs can likely be modeled with existing opmodes as long as fraction of engine off time is accounted for.
- Grid-based emissions for PHEVs and BEVs should be taken into account
- With the growing number of available real-world cycles, should move away from "default cycles" to distributions of cycles, and assess mean trends rather than interpolate
- While beyond detail needed for aggregated inventories, libraries of vocational duty cycles could be helpful to some users
- Vehicle load is not a variable in MOVES. Fuel use and emissions are sensitive to vehicle load.
- Other needs include accounting for SOA-precursors, UFP characteristics, role of lubricating oil w.r.t. particle emissions, improved brake and tire wear estimates, and updating air conditioning adjustments