Understanding Feasibility of Medium/Heavy-duty Plug-in Hybrid Electric Vehicles from Life-cycle Costs and Emissions Perspectives

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Dr. Greg Shaver

June 5th, 2019

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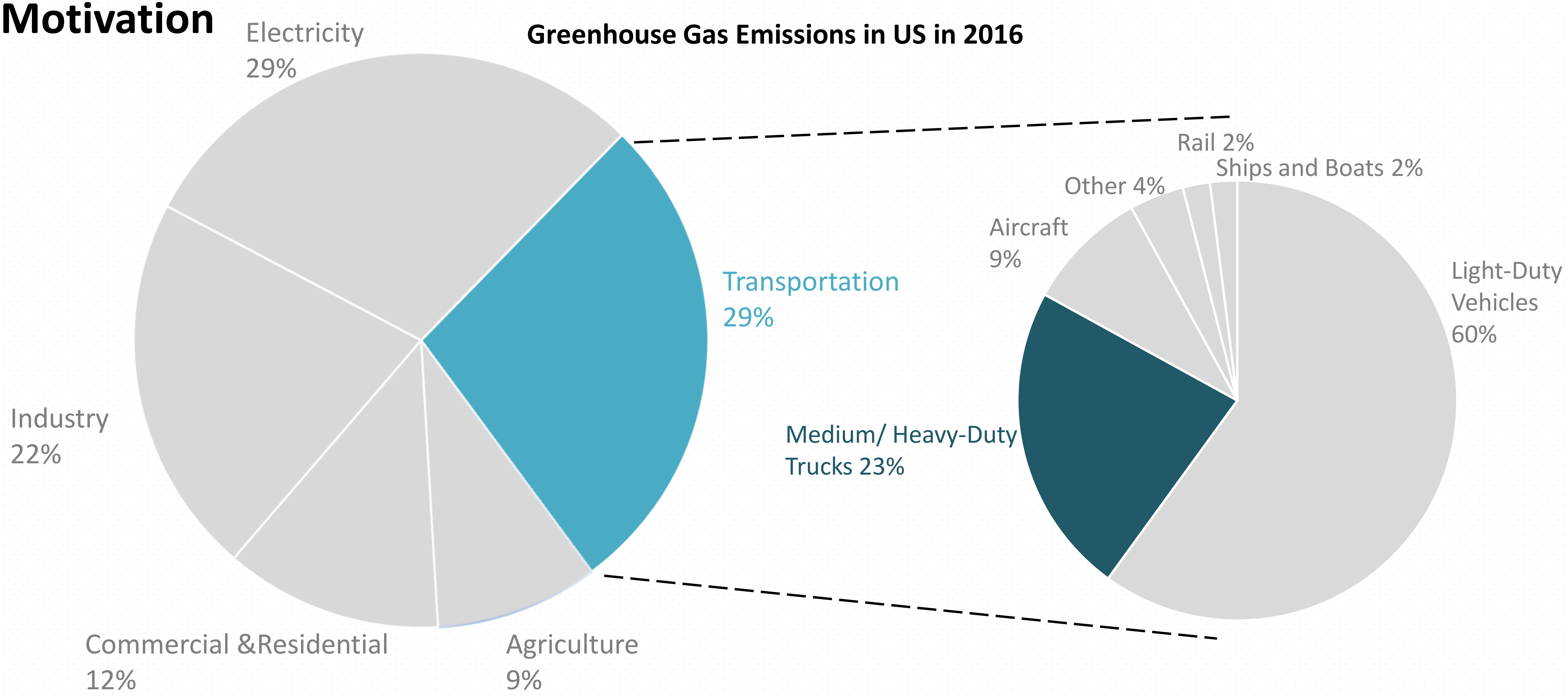
Motivation



US Environmental Protection Agency (2018). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016

Hybridization of vehicles presents a potential to reduce these emissions by reducing fuel consumption
Does plug-in hybridization also have such a potential?

Two Applications of Interest

Transit Bus

Medium-duty Truck

Cost is critical to fleet owners!

Two Applications of Interest

Transit Bus

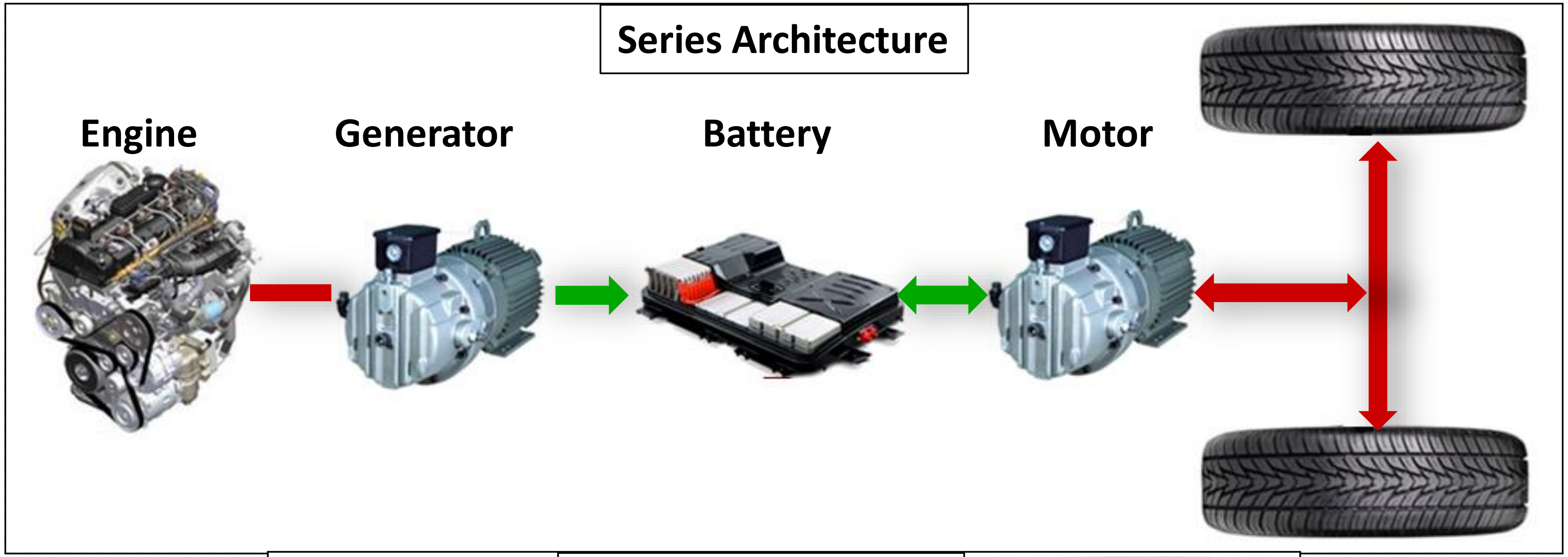
Medium-duty Truck

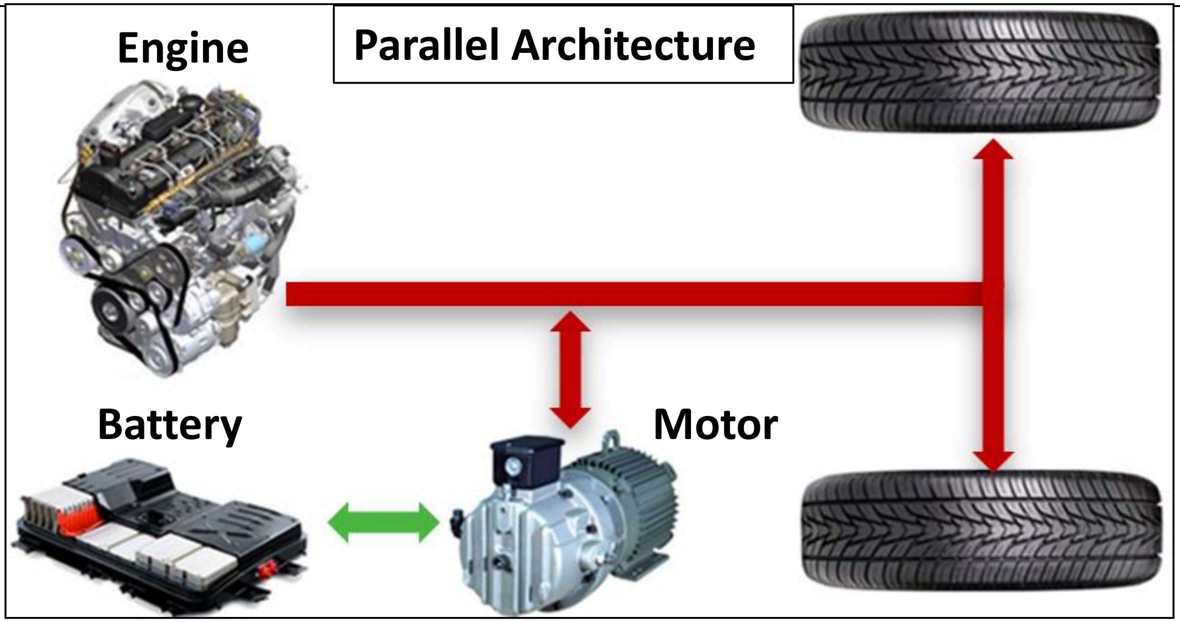
Vehicle Usage Assumptions:

	MD Truck	Transit Bus
Days used/ year	300	300
Annual Vehicle Miles Traveled	25,000	30,000

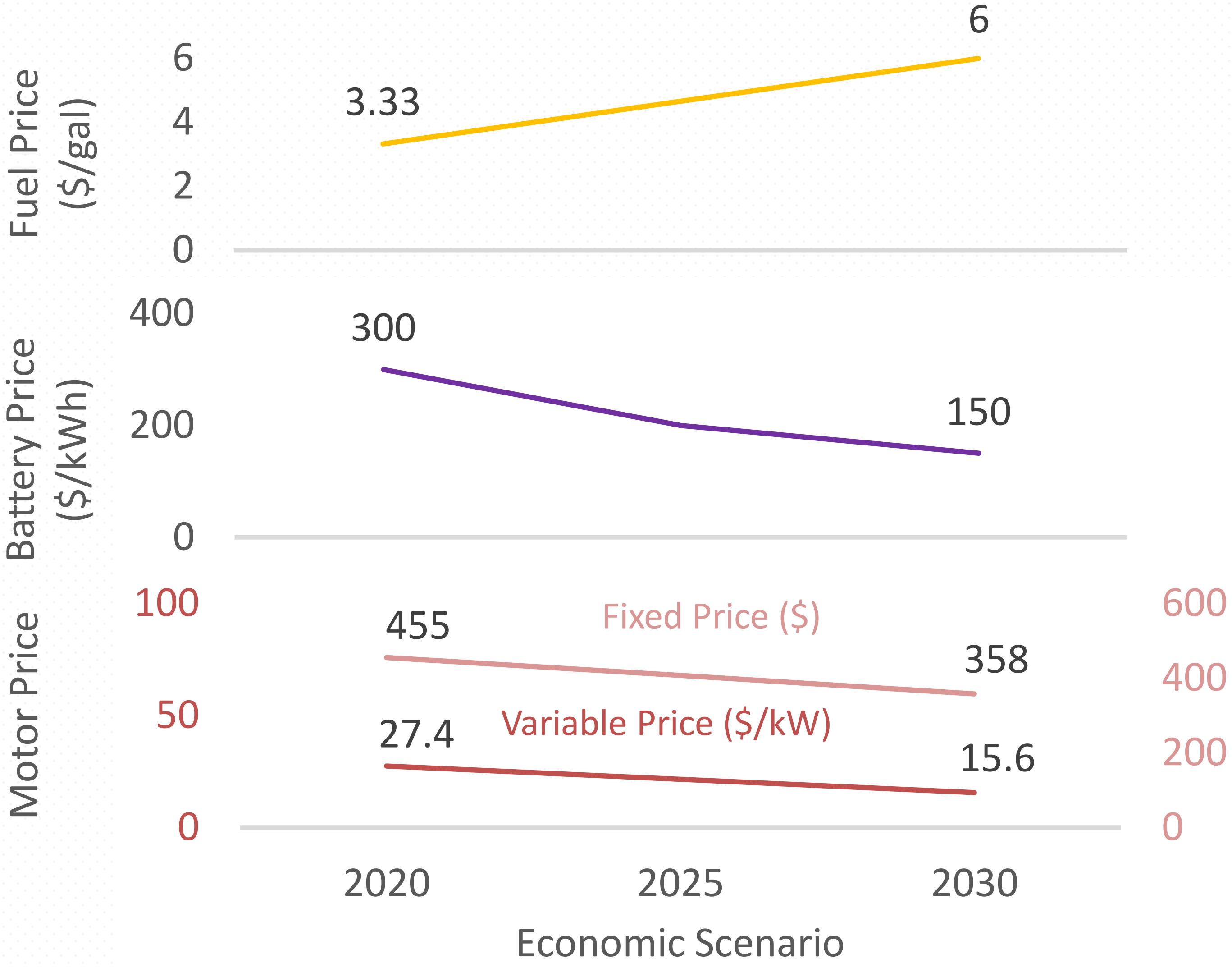
http://www.afdc.energy.gov/data/10309 - US 2015

Hybrid Architectures Considered





Economic Assumptions



Other Constant Economic Assumptions:

Parameter	Value
Electricity Price	$0.1/kWh
Electrical AC Charging Efficiency	90%
Battery End-of-Life capacity	70%
Vehicle Life	12 years

At the end of life of the vehicle, the battery is assumed to have a salvage value proportional to the remaining battery life

U.S. Department of Energy. Annual energy outlook 2015, Tech. rep.; 2013
V.T. Office. Overview of the DOE advanced power electronics and electric motor R & D program APEEM R & D Program Vehicle, Tech. rep.; 2014
B. Nykvist, M. Nilsson, Rapidly falling costs of battery packs for electric vehicles, Nat Clim Change, 5 (4) (2015), pp. 329-332, 10.1038/nclimate2564

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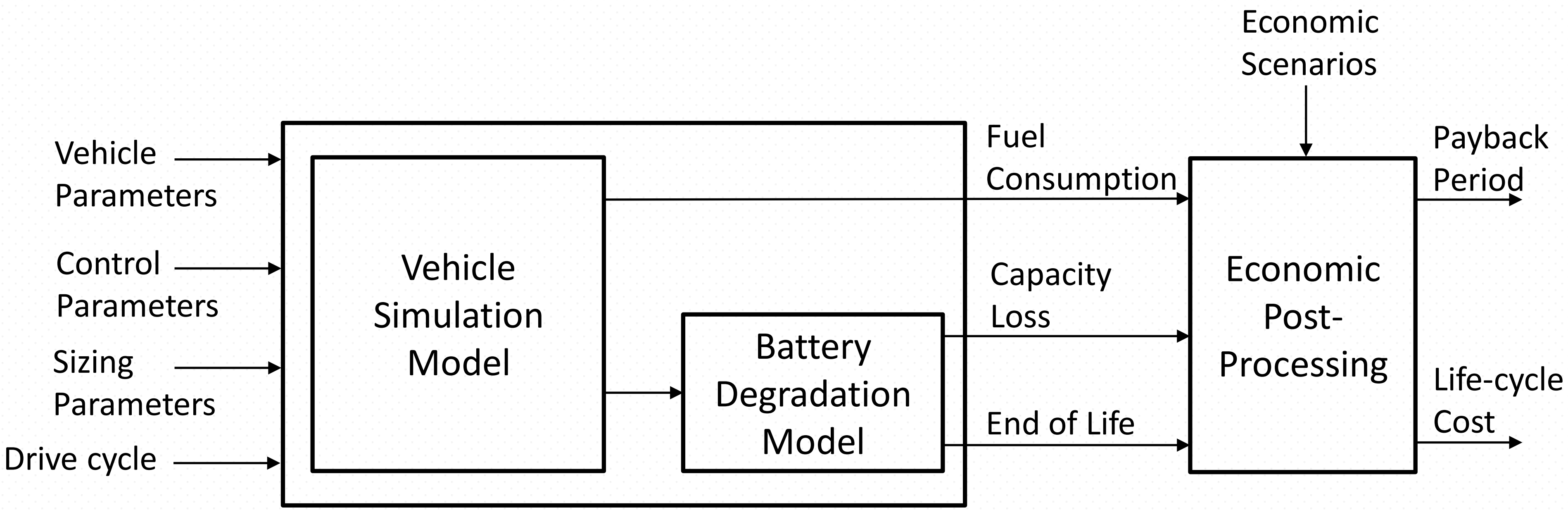
Framework



Constraints for viability

- Drive cycle: (% time trace missed by $>$ 2mph) $<$ 2%
- Gradability (7% at 20 mph)
- Payback Period < 2 years
- Battery Replacements <= 3 (vehicle life = 12 years)

First Scenario of Economic Viability

Application		Drive cycles						
		P&D Class 6	Refuse Truck	NY Comp.	Man-hattan	Orange County	China Normal	China Agg.
Truck	Series	**2030**						
	Parallel							
Bus	Series							
	Parallel							

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	Parallel	**2025**	**2025**	**2025**				
Bus	Series				**2020**	**2025**	**2020**	**2020**
	Parallel				**2020**	**2020**	**2020**	**2020**

Bus application becomes economically viable earlier than Truck.

Constraints for viability

- Drive cycle: (% time trace missed by > 2mph) < 2%
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Bus	Series				2020	2025	2020	2020
	Parallel				2020	2020	2020	2020

Parallel architectures become economically viable earlier. Since they require smaller motor.

Constraints for viability

- Drive cycle: (% time trace missed by > 2mph) < 2%
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Truck	Series	2030	2030	2025				
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Urban drive cycles prefer hybridization earlier.

Constraints for viability

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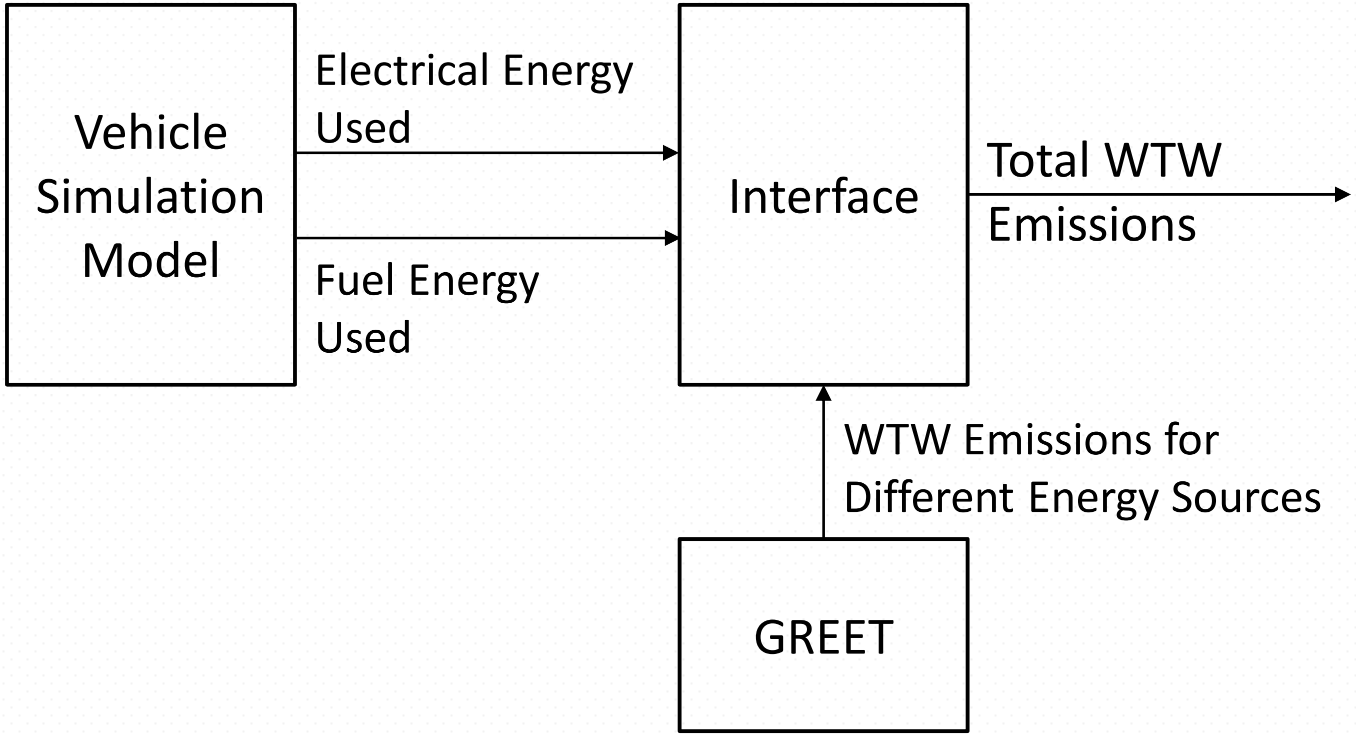
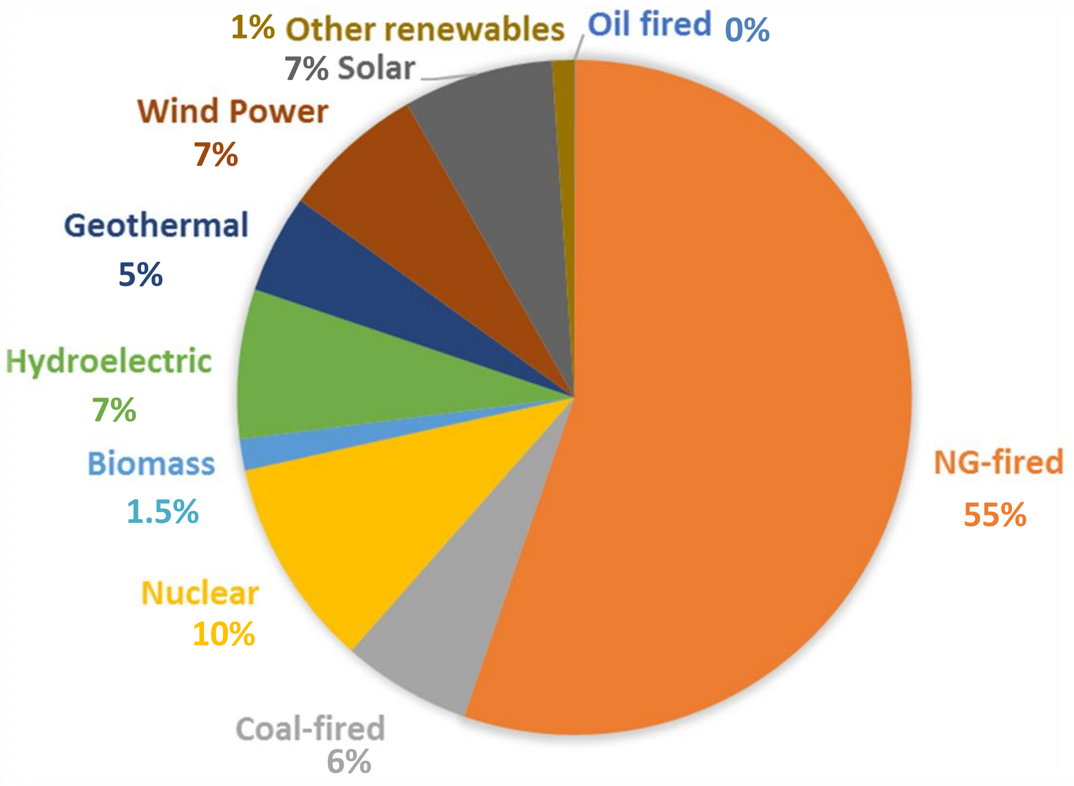
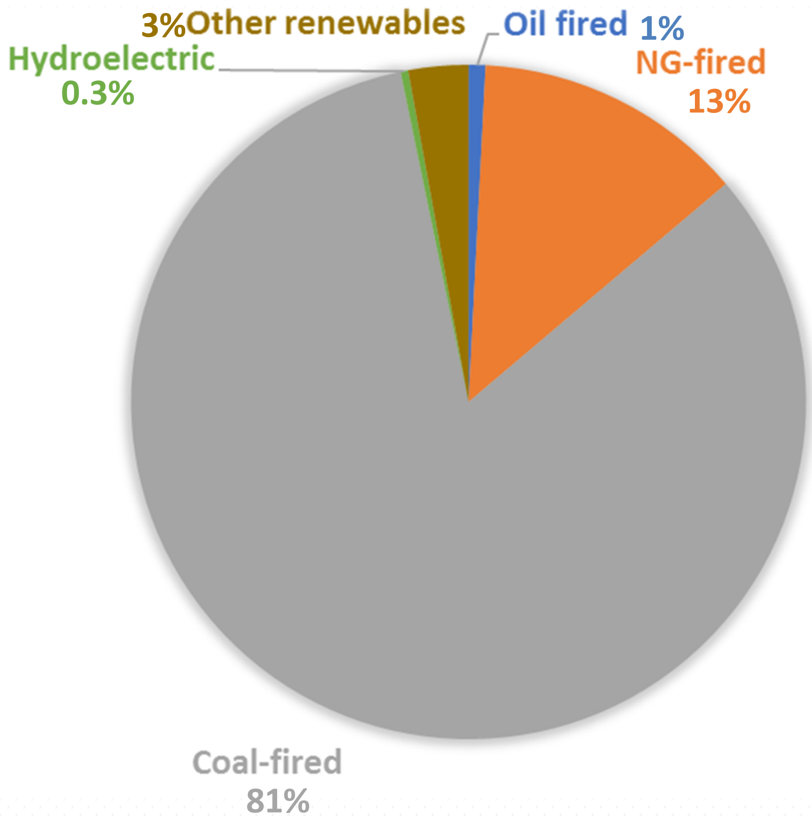


*GREET (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) is a well-to-wheel emissions database and tool developed by Argonne National Labs*

Electricity Sources in California vs Indiana in 2016



California



Indiana

http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html

https://www.energy.gov/sites/prod/files/2016/09/f33/IN_Energy%20Sector%20Risk%20Profile.pdf

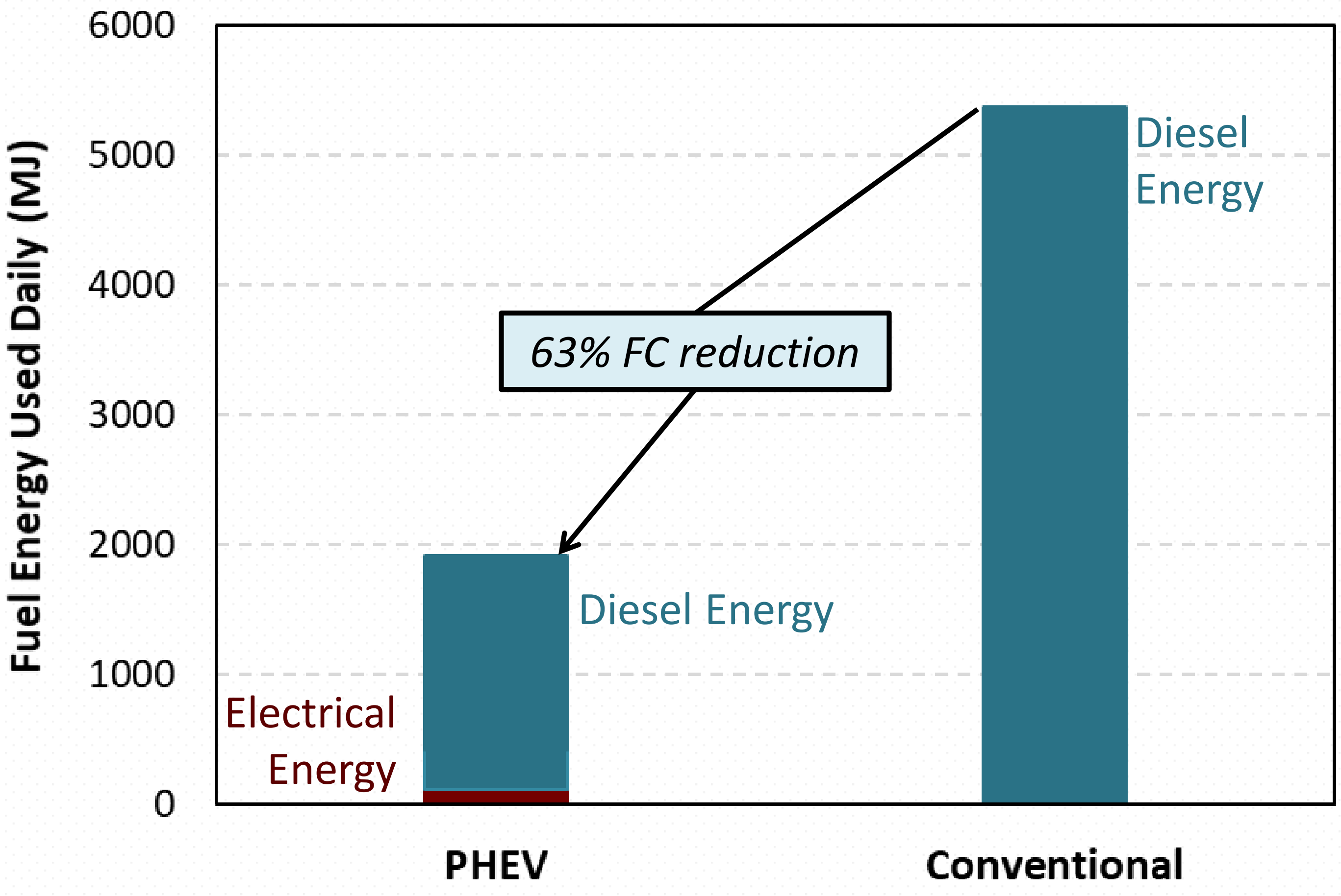
A majority of California's electricity comes from Natural gas-fired plants whereas that for Indiana comes from Coal-fired power plants.

Example: Series Transit Bus Solution on Manhattan Cycle

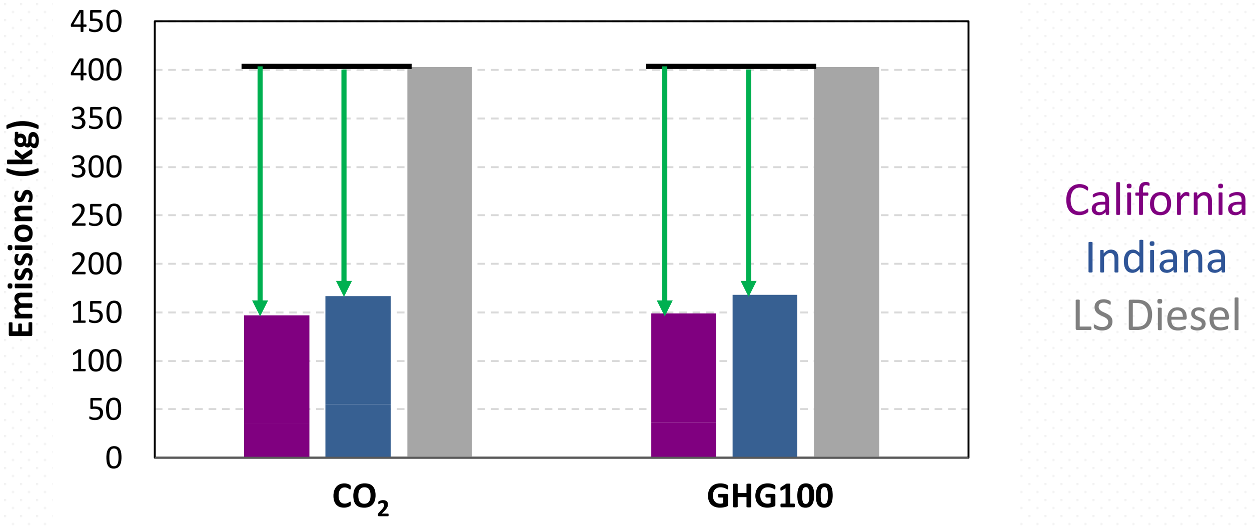
Application		Drive cycles						
		P&D Class 6	Refuse Truck	NY Comp.	Man-hattan	Orange County	China Normal	China Agg.
Truck	Series	2030	2030	2025				
	Parallel	2025	2025	2025				
Bus	Series				2020	2025	2020	2020
	Parallel				2020	2020	2020	2020

MJ of fuel energy used per day

Daily VMT = 100



Daily Emissions (kg) from Operation of Series Transit Bus PHEV on Manhattan Cycle



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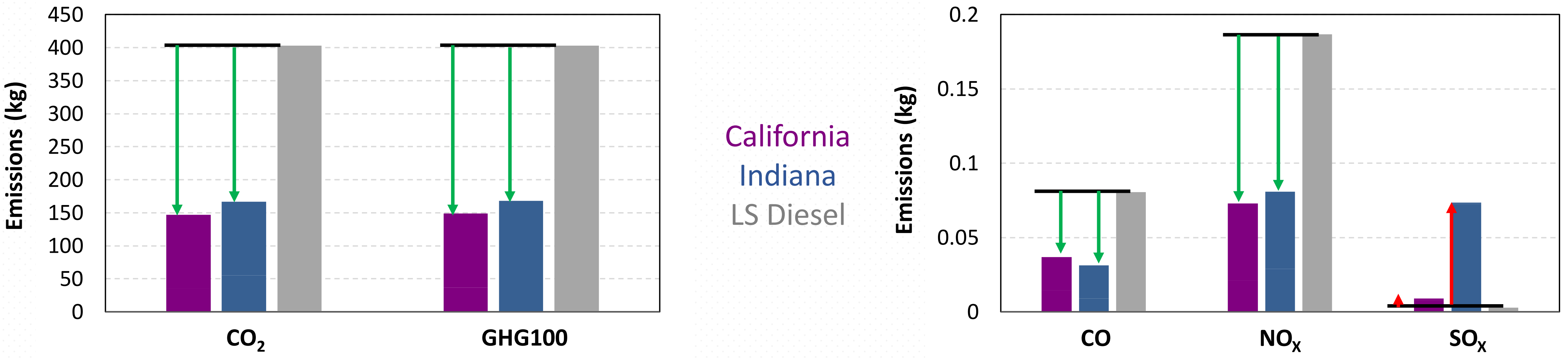

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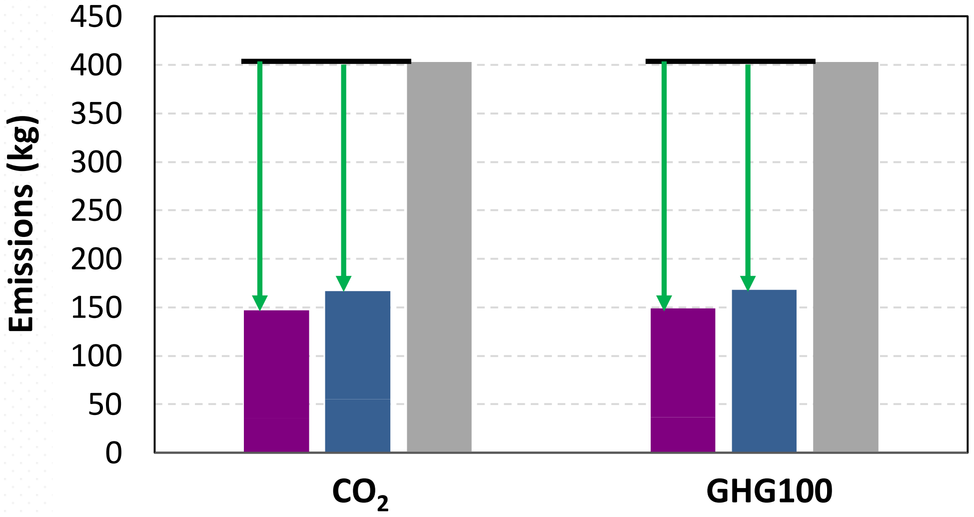
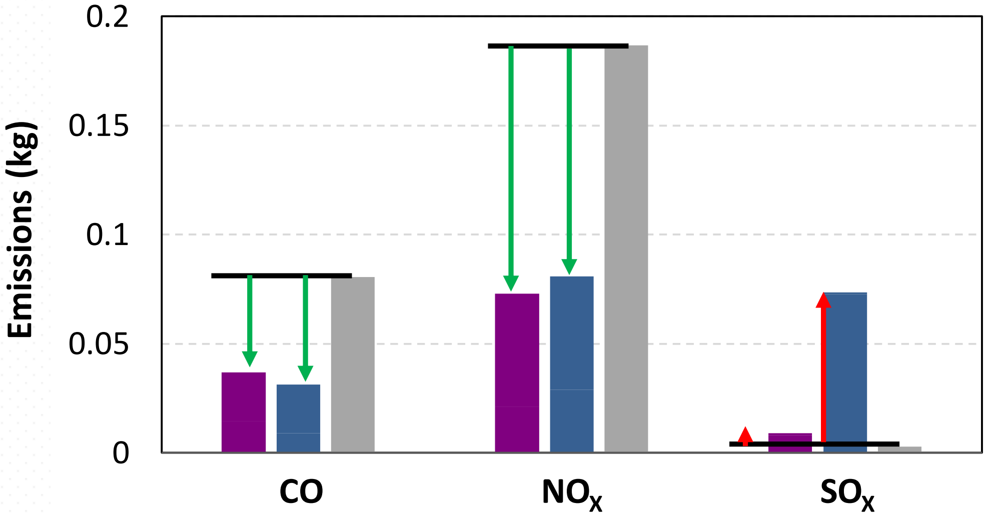


California
Indiana
LS Diesel



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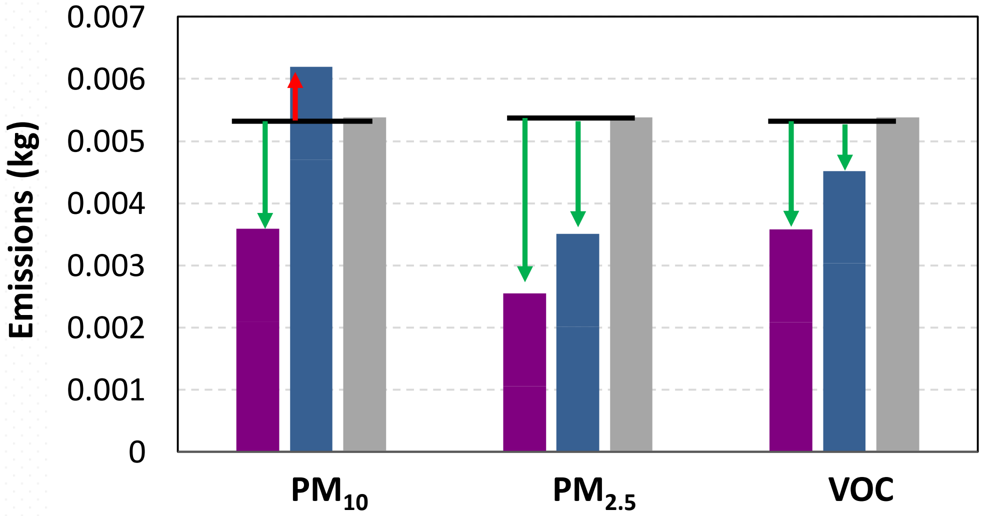

Conclusions

Economic Viability Analysis

- Parallel architectures become viable for hybridization earlier than the series architecture.
- Transit buses become viable earlier than MD truck.
- Urban drive cycles are more favorable for hybridization

WTW Emissions from a Transit Bus PHEV in Indiana and California (not considering battery manufacturing)

- CO_2 and GHG emissions reduce by about 60% in both the states
- A reduction in CO, NO_x , $PM_{2.5}$, VOC is shown
- PM_{10} and SO_x emissions are shown to increase

Thank You!

Back-up

Economic Viability Analysis

- Parallel architectures become viable for hybridization earlier than the series architecture.
- Transit buses become viable earlier than MD truck.
- Urban drive cycles are more favorable for hybridization

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Truck	Series	2030	2030	2025				
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Bus	Series				2020	2025	2020	2020
	Parallel				2020	2020	2020	2020

Constraints for viability

- Drive cycle: (% time trace missed by > 2mph) < 2%
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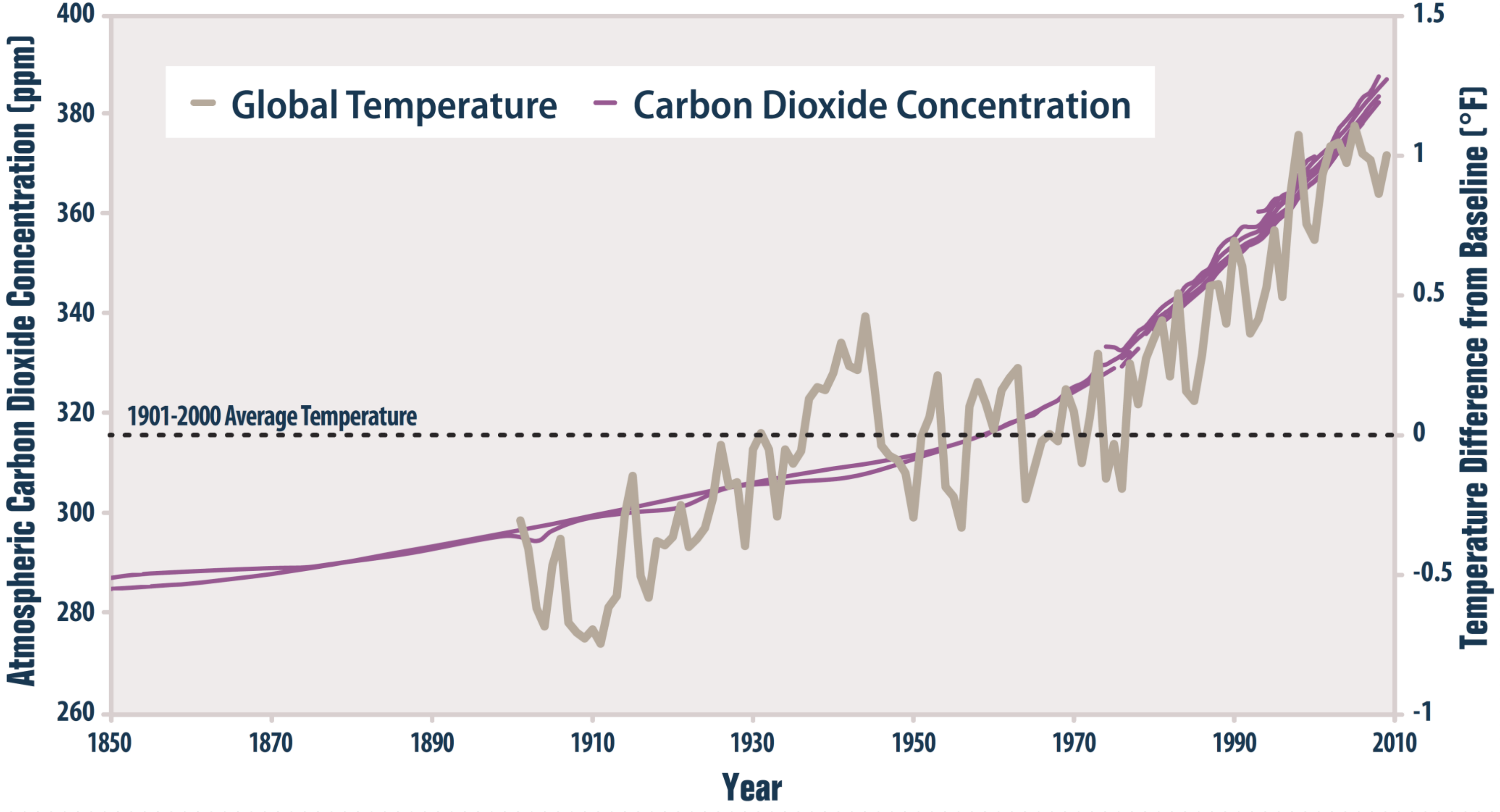
- Battery Replacements <= 3 (vehicle life = 12 years)

Motivation



- Global earth surface temperature has increased by 1°F since the 1970s.
- Carbon dioxide constitutes 81% of the greenhouse gas emissions in the US

Carbon Dioxide Information Analysis Center. 2010. http://cdiac.ornl.gov/
National Oceanic and Atmospheric Administration. 2010. www.noaa.gov

Design of Experiments – Series Bus Example

- 10 parameters; Sparse-sampled DOE size = 1300
- Latin Hyper-Cube (LHC) design with "maximin distance" criterion

Parameter	Units	Min. Value	Max. Value
Coefficient of drag	-	0.58	0.88
Coefficient of rolling resistance	-	0.005	0.007
Vehicle mass	kg	12000	18000
M/G peak power	kW	150	300
Battery energy capacity	kWh	31	198
Engine/generator peak power	kW	50	150
Maximum allowed C-Rate for Battery charge/discharge	-	1	4
Power filter parameter T1	-	0	0.5
Slope of Battery SOC regulation power demand (CSHEV mode)	W/SOC	200	20000
% Power demand over which engine is requested (CDHEV mode)	-	0.3	0.9

3 vehicle parameters

3 sizing parameters

Powertrain Solution

4 control strategy parameters

Scope

Application		Drive cycles						
		P&D Class 6	Refuse Truck	NY Comp.	Man-hattan	Orange County	China Normal	China Agg.
Truck	Series (T=1300)	✓	✓	✓				
	Parallel (T=800)	✓	✓	✓				
Bus	Series (T=1000)				✓	✓	✓	✓
	Parallel (T=1300)				✓	✓	✓	✓

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Bus	Series							
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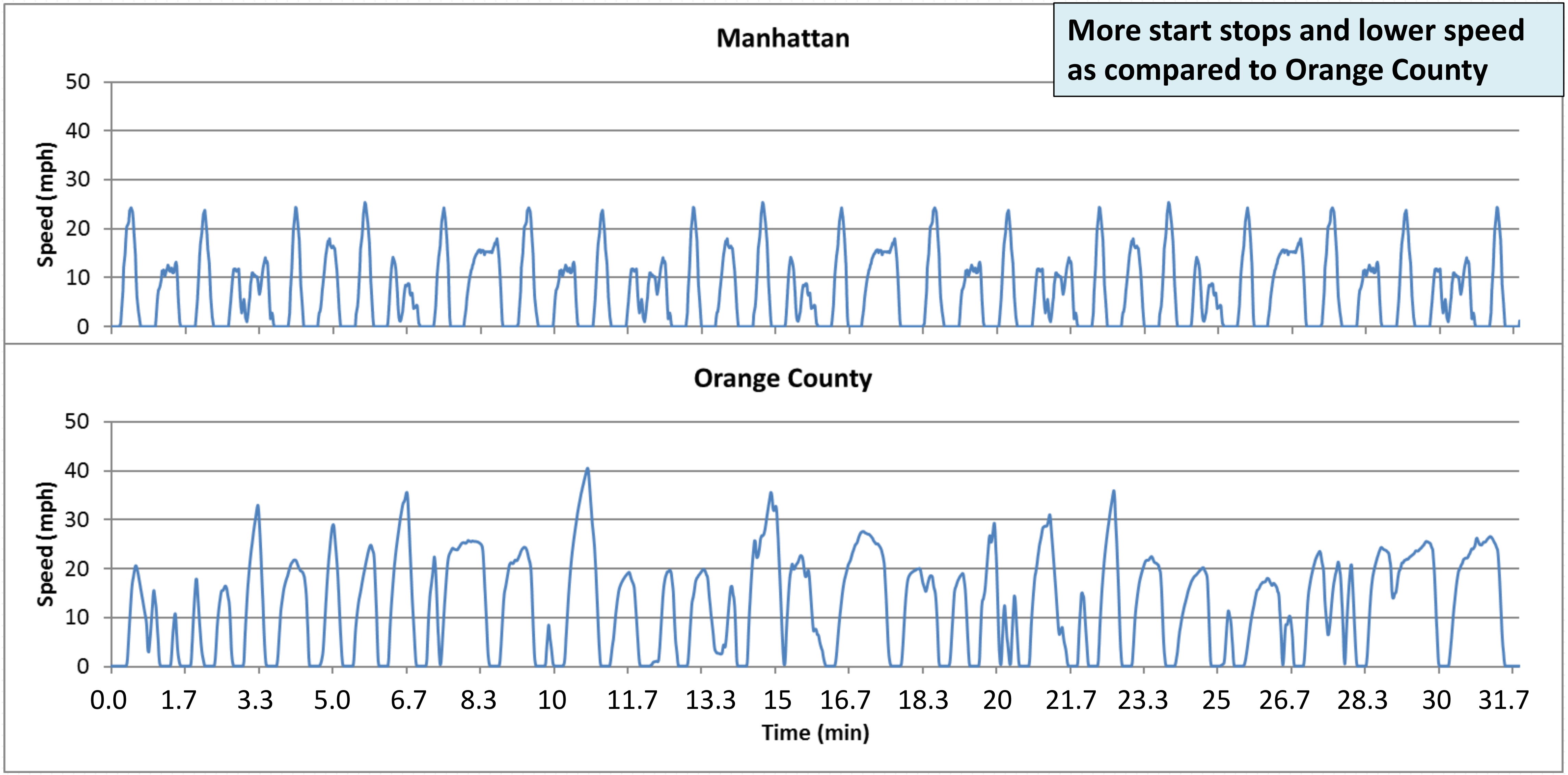
Simple Comparison of Drivecycles

More start stops and lower speed as compared to Orange County



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Constraints for viability

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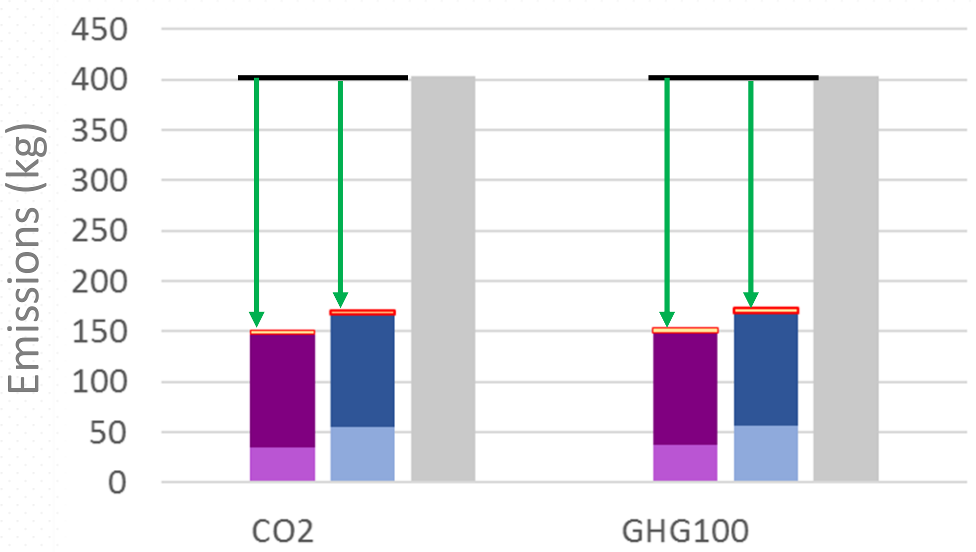
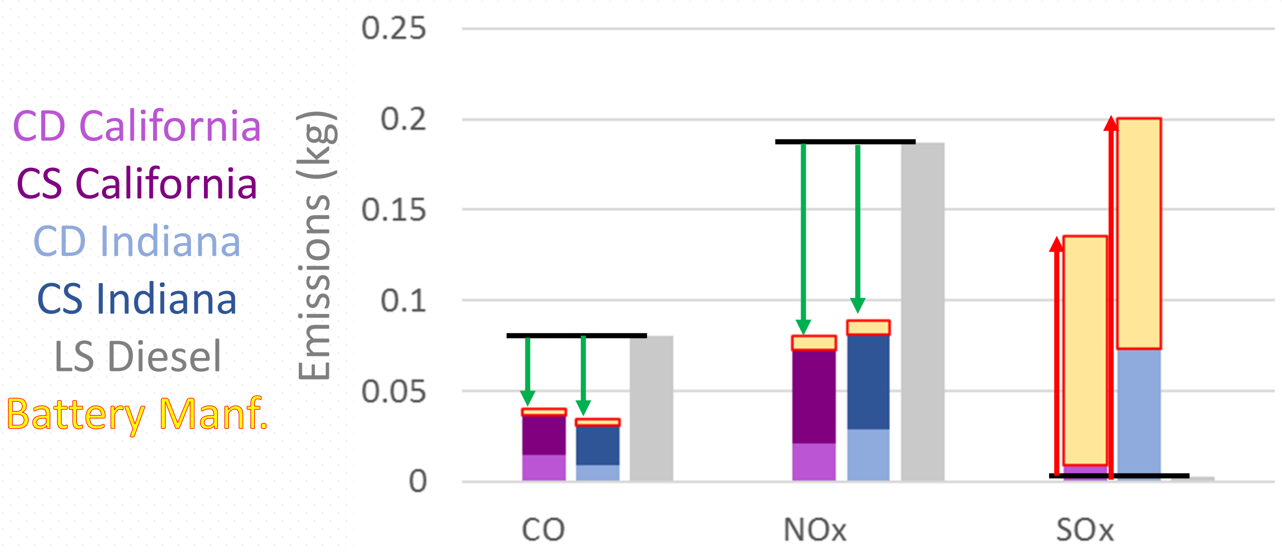
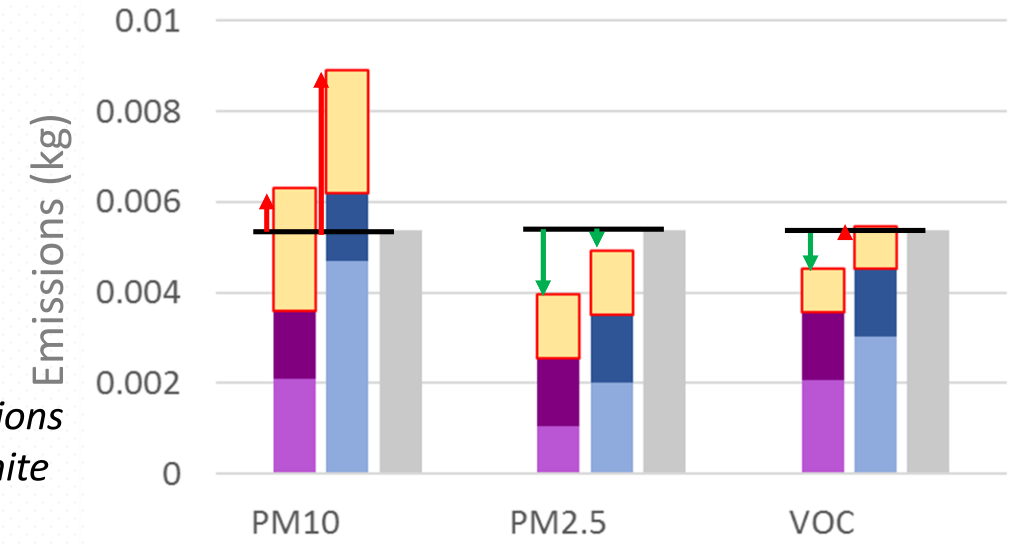
Additional Daily Emissions from Battery Manufacturing



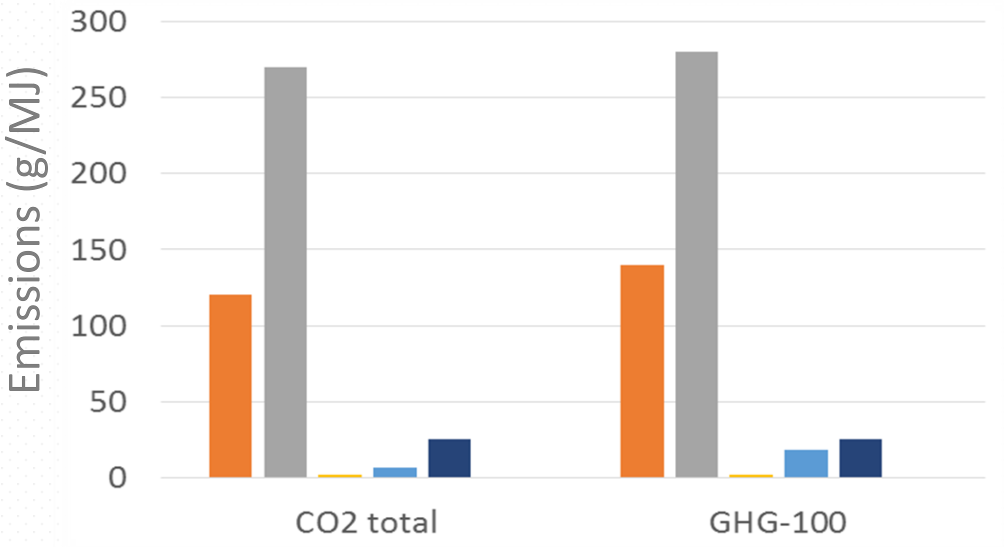


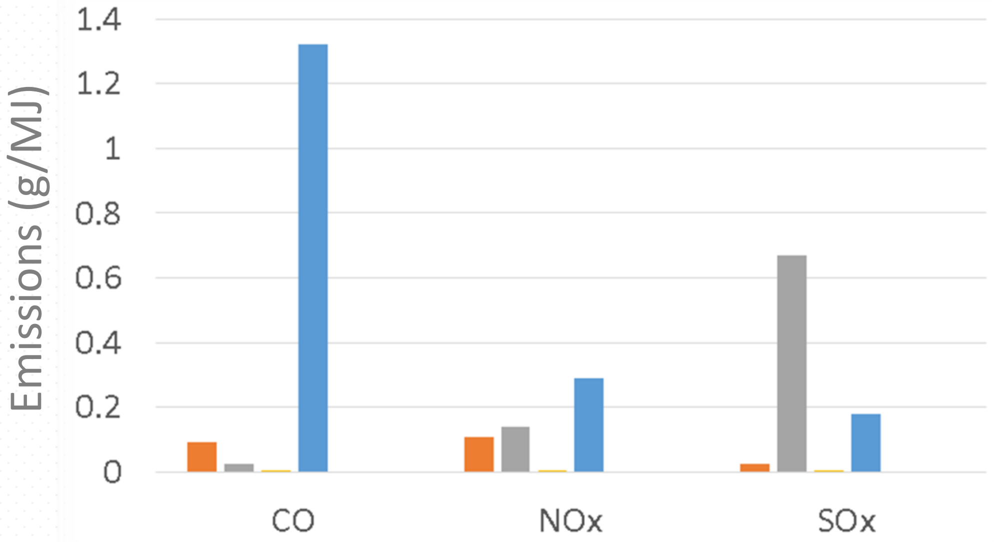
Daily VMT = 100
Battery
Replacements = 3

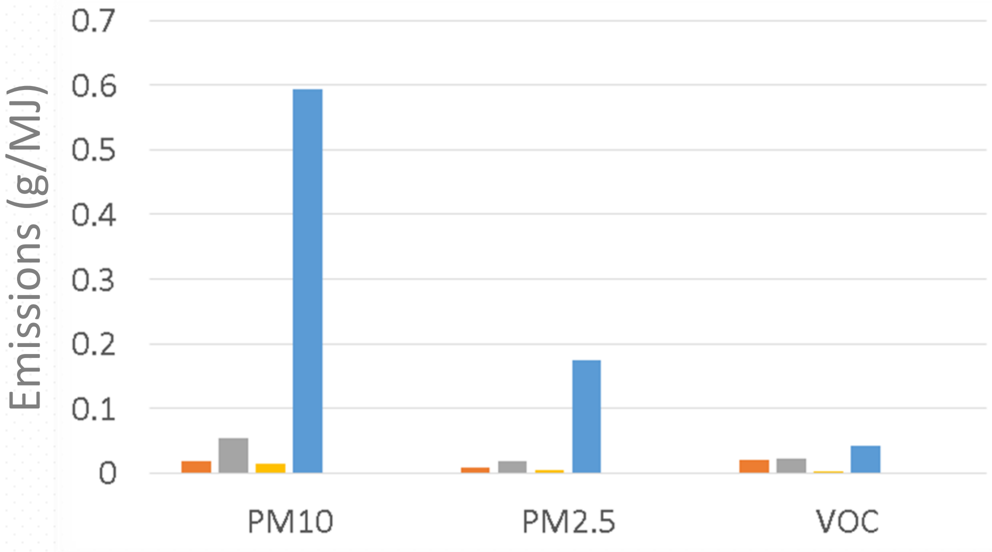


Note: The battery manufacturing emissions data available in GREET for NMC/Graphite was used. This does not consider the emissions due to battery recycling.

Emissions According to Source of Electricity
(in g/MJ of electricity generated)







Electricity generation from coal produces most CO_2 GHG and SO_x emissions.
Electricity generation from biomass produces most PM, CO and NO_x emissions.

Battery Degradation Model

– **NMC+LMO/Graphite** chemistry

$$Q_{\text{loss},\%} = (aT^2 + bT + c)\, exp[(dT + e)I_{\text{rate}}] \times Ah_{\text{throughput}} + f t^{0.5} exp[-E_{\text{a}}/RT]$$

Cyclic Aging

Calendar Aging

Combined **calendar-life + cycle-life** prediction model description – *Wang et al. (JPS 2014)*

– Paper presents validation up to 6.5 C, model is used below 4C in our simulations to predict battery life with confidence

– We assume slow overnight charging at C-rates < 2C (No fast charging)

Scope

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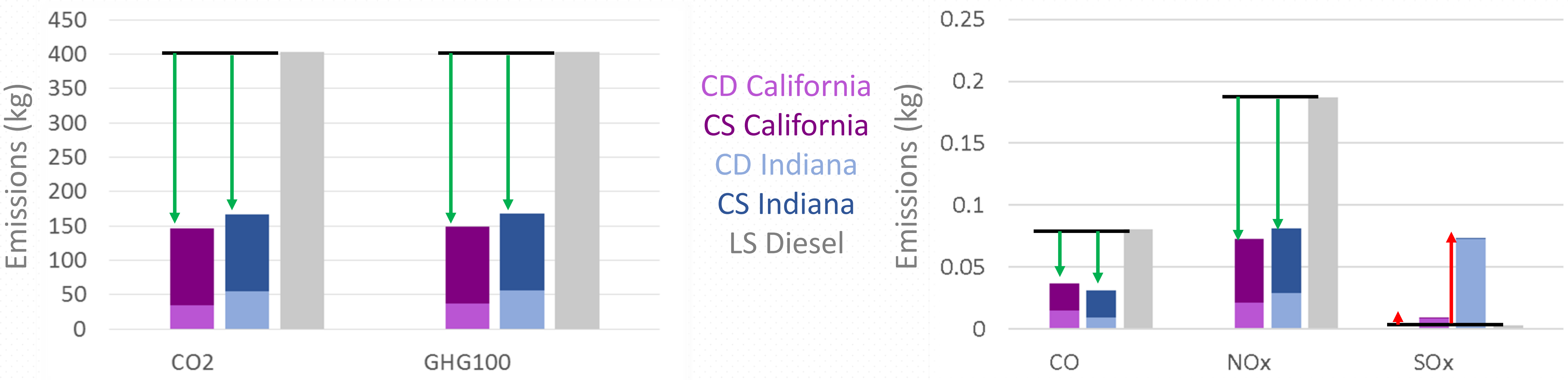
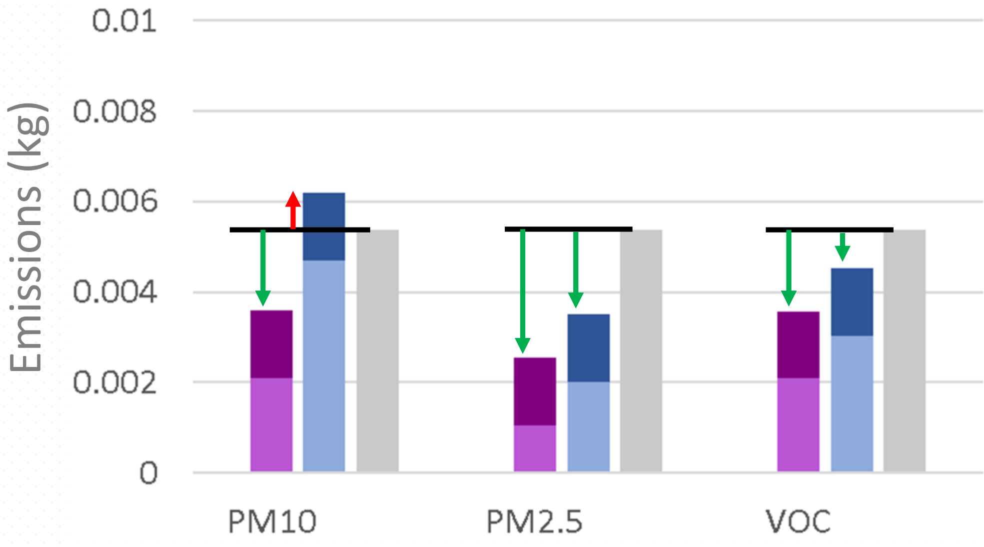
Truck	Series (T=1300)	✓	✓	✓				
	Parallel (T=800)	✓	✓	✓				
Bus	Series (T=1000)				✓	✓	✓	✓
	Parallel (T=1300)				✓	✓	✓	✓

**T = Total simulations*

Daily Emissions (kg) from Operation of Series Transit Bus PHEV on Manhattan Cycle



Daily VMT = 100



Although electricity by itself produces more WTW emissions than diesel per MJ of usage, FC reduction combined with little electrical energy used for battery charging enables significant WTW emissions reduction.

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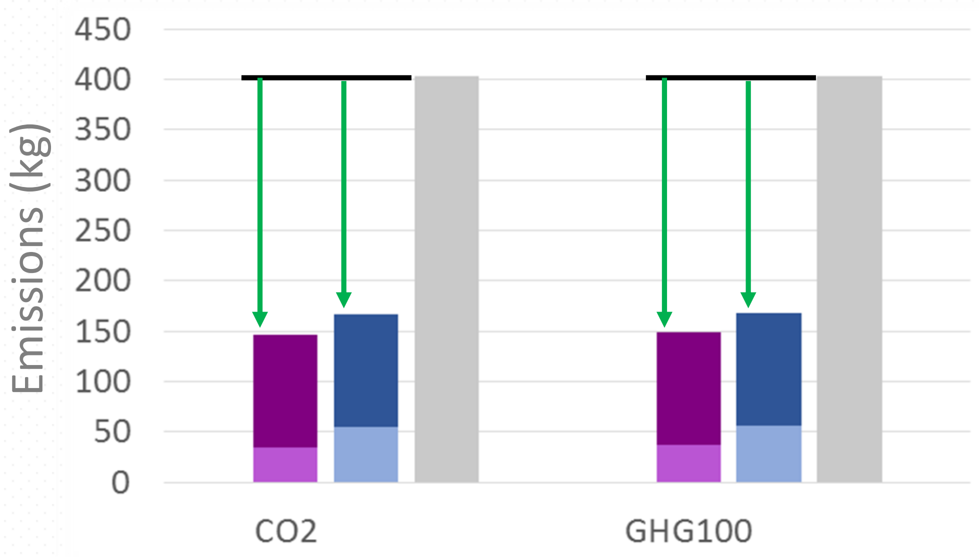

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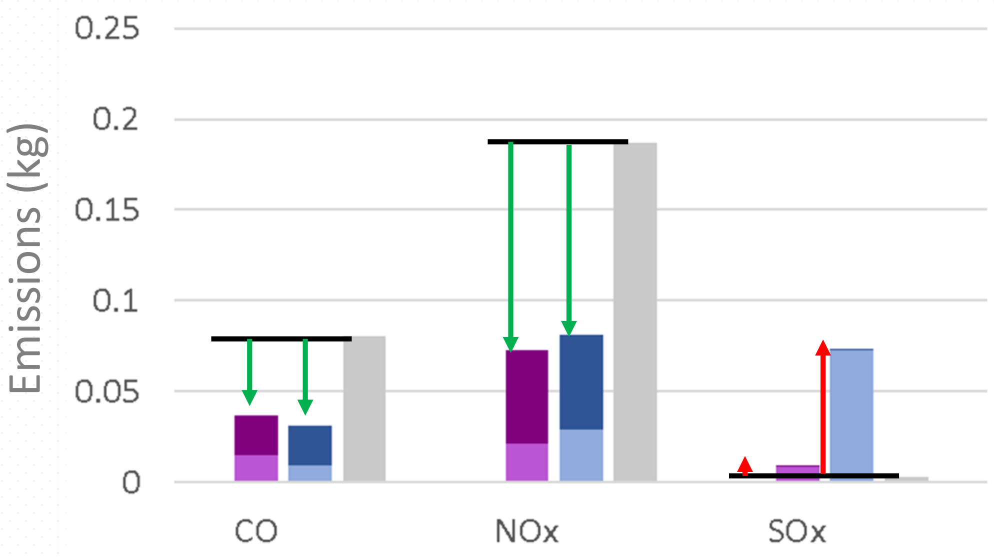

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