Market Segmentation Analysis of Medium and Heavy Duty Trucks with a Fuel Cell Emphasis

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National Renewable Energy Laboratory
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Project ID SA169

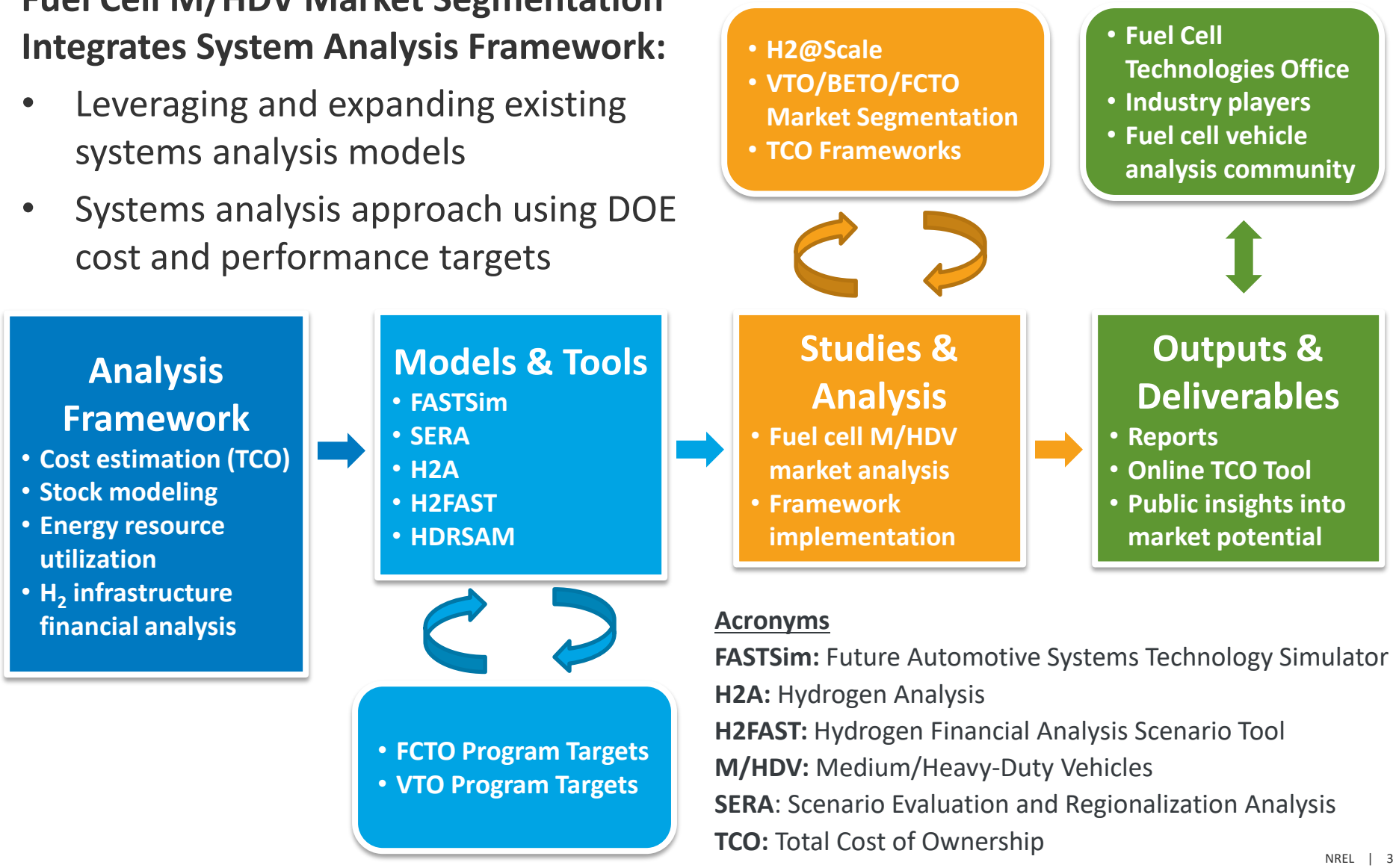
Overview:
Fuel Cell M/HD Vehicle Market Segmentation

Timeline	Barriers (4.5)
Start: September, 2017 End: September, 2019 70% complete	**A. Future Market Behavior** • Assessing competitiveness of fuel cell M/HDVs **C. Inconsistent Data, Assumptions & Guidelines** • Consistent modeling methodology using established DOE cost/price and performance targets **D. Insufficient Suite of Models and Tools** • Expand spatial and temporal analysis tools to M/HDV sector
Budget	**Partners**
Total Project Funding: $350k • FY18: $250k • FY19: $100k Total DOE funds received to date: $350k	***Modeling*** **University of Vanderbilt -** Dr. Yuche Chen ***External Peer Reviewers*** *(alphabetical)* **Bosch, California Air Resources Board (CARB), Center for Transportation and the Environment (CTE), Cummins, Eaton, Energy Independence Now (EIN), FedEx, Toyota**

Relevance (1/2): FCTO Systems Analysis Framework

Fuel Cell M/HDV Market Segmentation Integrates System Analysis Framework:

- Leveraging and expanding existing systems analysis models
- Systems analysis approach using DOE cost and performance targets



Acronyms

FASTSim: Future Automotive Systems Technology Simulator
H2A: Hydrogen Analysis
H2FAST: Hydrogen Financial Analysis Scenario Tool
M/HDV: Medium/Heavy-Duty Vehicles
SERA: Scenario Evaluation and Regionalization Analysis
TCO: Total Cost of Ownership

Relevance (2/2): FCEV Market Segmentation Objectives

Project Objectives:

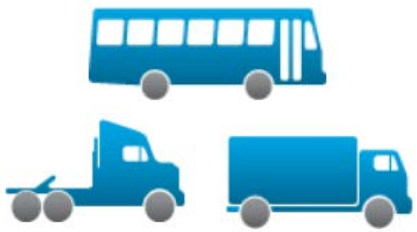
1. To provide industry, government, and non-government ***stakeholders*** a broad scoping ***assessment*** of medium/heavy duty fuel cell vehicle ***market opportunities*** across different classes, vocations, regions, and time

2. Assess technical ***barriers and opportunities*** for improvement in the medium/heavy duty fuel cell vehicle technology space to guide DOE ***investment*** in advanced technologies (MYRDD Milestone 1.16, 1.17)

Approach (1/3): Analysis Approach Overview

FASTSim

SERA



Vehicle Powertrain Cost Modeling

Inputs:
- Vehicle attribute data
- Drive cycle data
- Powertrain technology cost and performance data

Constraints:
- Powertrains meet target acceleration and gradeability

Outputs:
- Vehicle fuel economy, weight
- Component costs & MSRP

Total Cost of Ownership Modeling

Inputs:
- Cost data
  - Vehicle MSRP (FASTSim)
  - Regional fuel prices
  - Operating & Maintenance cost
  - Payload opportunity cost
  - Dwell (refueling) time cost
- Vehicle data
  - Miles travelled, lifetime
  - Fuel economy, weight
- Financial data (discount rate)

Outputs:
- Total cost of ownership

Market Assessment

Impact on FCTO Barriers:
- Identify key drivers to fuel cell truck competitiveness
- Assess fuel cells for commercial applications

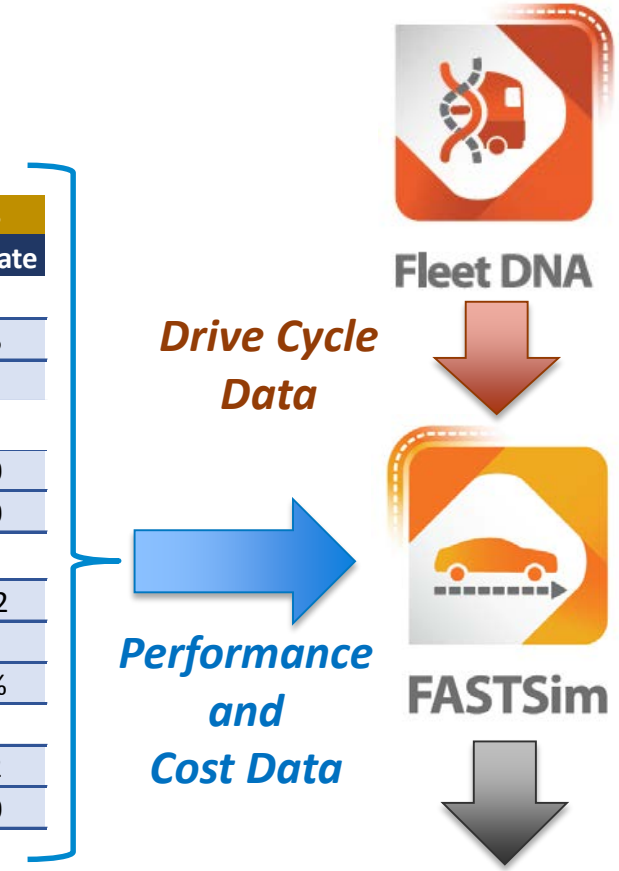
Integration with Other Projects:
- Coordinated with VTO/FCTO/BETO total cost of ownership analysis (ongoing)
- Potentially provide results to future H2@Scale analysis

Regional TCO analyzed using established models and OEM specifications

Approach (2/3): FASTSim used for powertrain optimization

Sample of Current and DOE Target Performance and Cost Data

		Tech Targets	
Target year	**2018**	**2020**	**Ultimate**
Batteries			
Battery Cell Mass [kg/kWh]	4.8	4.2	2.5
BEV Battery Cell Cost [$/kWh]	145	145	80
Power Electronics			
Power electronics & motor (no boost) [$/kW]	22.0	17.0	4.0
Boost Converter [$/kW]	8.5	8.0	2.0
Fuel Cell			
Fuel cell specific power (kW/kg)	1.12	1.12	1.12
Fuel cell cost ($/kW)	205	40	30
Fuel peak efficiency (%)	61%	61%	61%
Fuel storage			
Hydrogen storage (kWh/kg)	1.4	1.5	2.2
Hydrogen tank cost ($/kWh)	36.7	10.0	8.0



NREL's Fleet DNA database used for drive cycle data

FASTSim sizes powertrain components to match acceleration observed in the duty cycle

FASTSim models vehicle fuel economy, weight, and cost for each year and powertrain for direct comparison

Results (by tech status and powertrain):

- **Output:** Fuel economy, weight, costs, MSRP
- **Status:** Current (2018), Tech Targets (2020, ultimate)
- **Powertrains:** Diesel, compressed natural gas (CNG), hybrid-electric (HEV), plug-in hybrid electric (PHEV), battery electric (BEV), fuel cell electric (FCEV)

Approach (3/3):
Total cost of ownership modeling in SERA

Cost Data

Vehicle Price
FASTSim

Fuel Price
AEO Outlook, EPRI, Tesla, HDRSAM, FCTO Targets

O&M Cost
Literature survey, fuel-cell bus evaluations

Payload Opportunity Cost
LTL Carrier Rates, National Research Council, VIUS data

Dwell* Time Cost
ATRI, FMCSA, OOIDA, Nikola, Tesla

**Dwell time = down time for refueling/recharging*

Financial Data

Discount Rate
US Market Data

Vehicle Data

Fuel Economy & Weight
FASTSim

Vehicle Miles Traveled
Transportation Energy Data Book, Fleet DNA

Lifetime
Transportation Energy Data Book, Industry Feedback

Results:

- **Total cost of ownership** by region, technology status (2018, 2020, Ultimate) and Powertrain (Diesel, HEV, CNG, PHEV, EV, FC)
- Each data source has a **low/med/high** estimate
- Sensitivity analysis around low/mid/high cost estimates

Total Cost of Ownership calculated for all Low/Med/High estimates of all input vehicle data and cost data

Emissions benefits were not included in TCO framework but could be added in future analyses

Accomplishments and Progress (1/9): Vehicle modeling and benchmarking

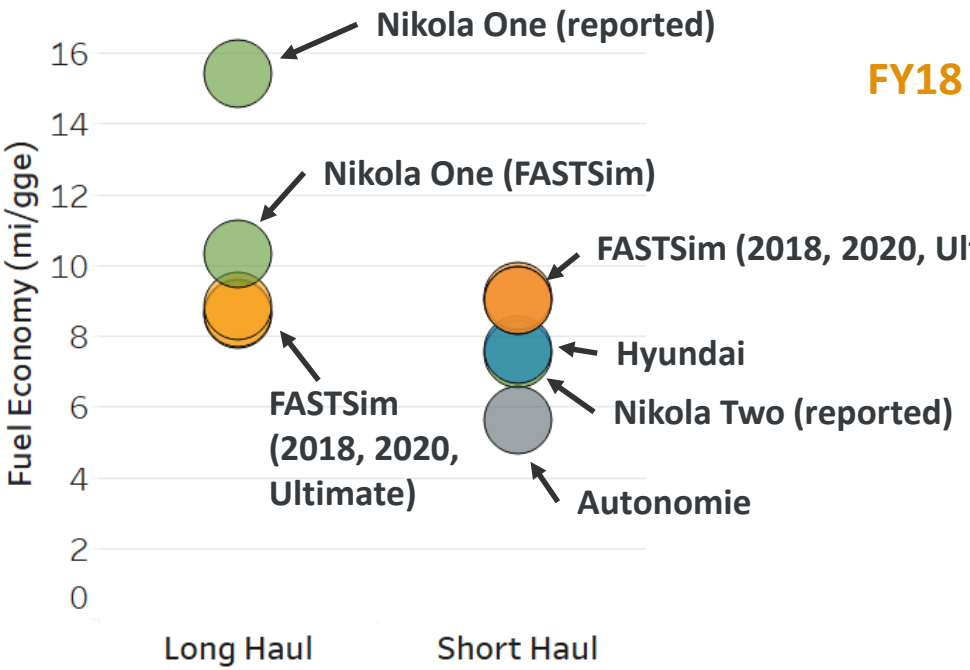
FASTSim

Vehicle Modeling Progress Since 2018 AMR

1. Focused on Class 4 Parcel Delivery and Class 8 Short/Long Haul (FY18)
2. Added plug-in hybrid (PHEV)
3. Added Current (2018) Tech Status
4. Completed FASTSim modeling
5. Benchmarked with Toyota, Hyundai, and Nikola data and Autonomie model

	Vehicle Class	Vocation
FY18	Class 4	Parcel Delivery
FY19	Class 5	Van, Basic Enclosed
	Class 6	Parcel Delivery
	Class 7	Truck Tractor
	Class 8	Transit Bus
	Class 8	Refuse, Garbage Pickup
FY18	Class 8	Short Haul
	Class 8	Long Haul

Vocations with large share of fuel consumption in each Class per VIUS

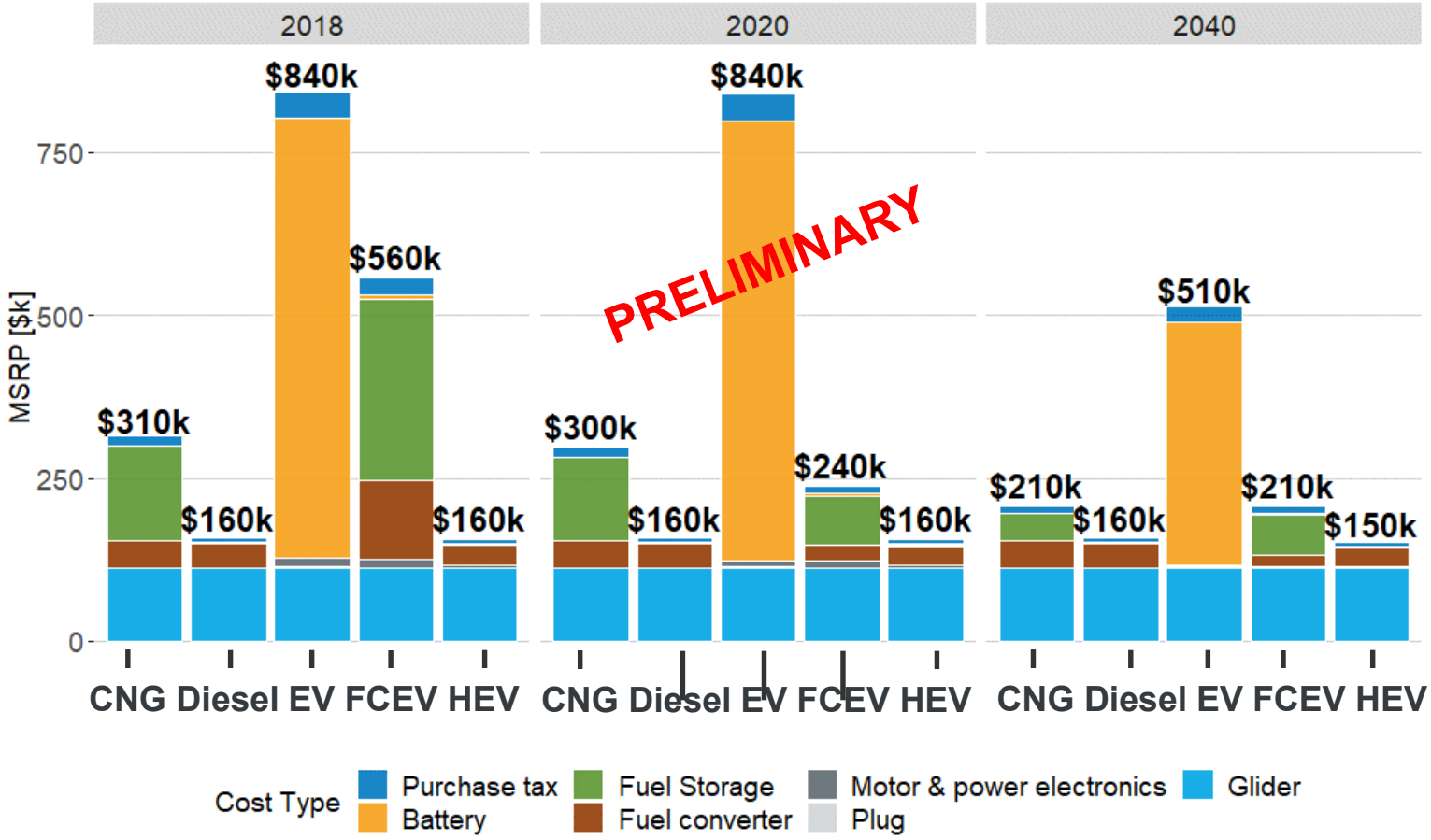


There is a large spread in reported/projected FCET fuel economy and tractor weights. FASTSim estimates are within the spread reported

Accomplishments and Progress (2/9):
Class 8 Long Haul Vehicle MSRP Modeling

FASTSim

- Powertrain components sized to meet acceleration needs (0-60 mph, 45 sec)
- Fuel economy based on representative duty cycle from Fleet DNA
- Class 8 Long Haul required range of 1200 miles between refueling/recharging
- PHEV not modeled for Class 8 Long Haul based on industry feedback



Note:
Fuel Converter = Engine or Fuel Cell

Class 8 Long Haul FCEV MSRP driven by H2 storage and H2 Stack

Class 8 Short Haul and Class 4 Parcel Delivery results are in back-up

Accomplishments and Progress (3/9): Class 8 Long Haul Vehicle Modeling

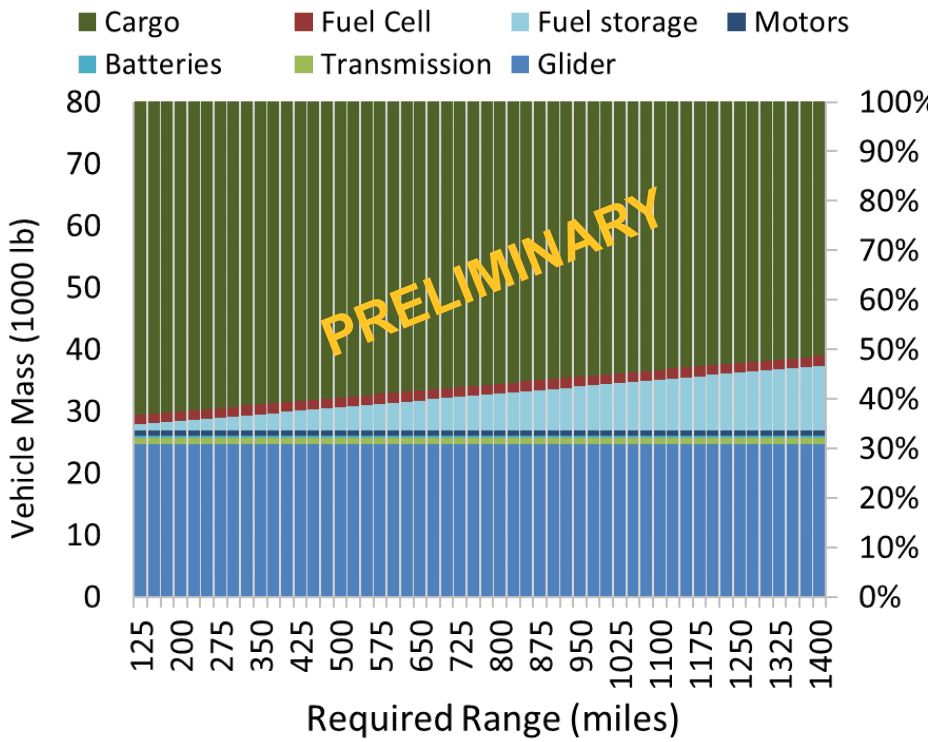
FASTSim

Vehicle Weight and Payload Analysis

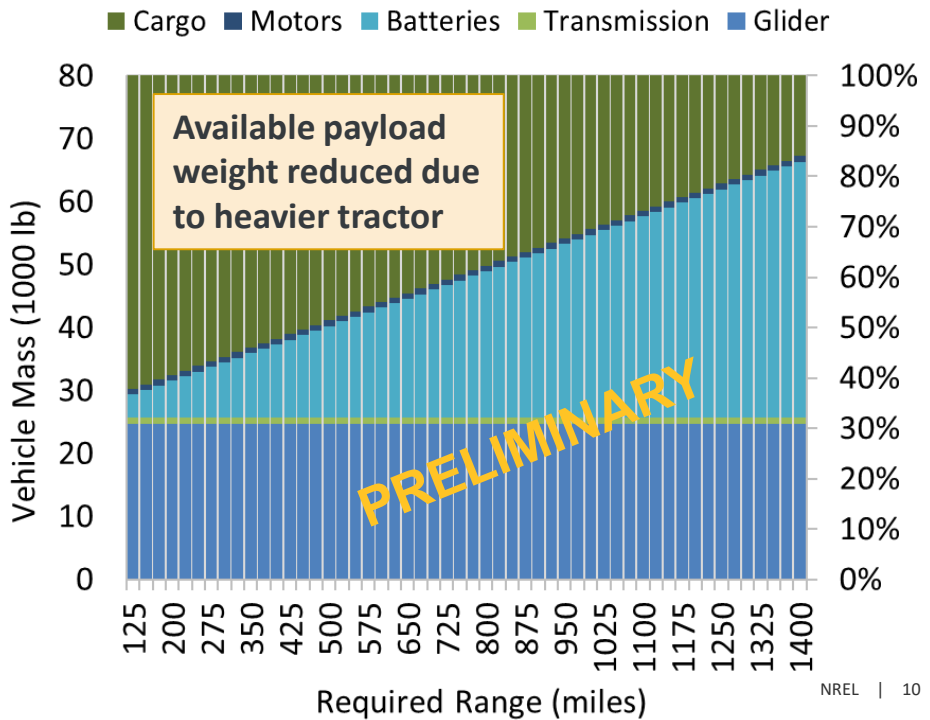
- Theoretical sweep across required range (distance traveled on single refueling/charge) completed
- Tractor mass increases due to larger H2 storage and battery needed

Fuel cell trucks show lower total mass than battery trucks due to large battery needed

Fuel Cell Powertrain (2020 Tech Targets)



Battery Powertrain (2020 Tech Targets)



Accomplishments and Progress (4/9): Total Cost of Ownership Scenario Definition

SERA

Operating Shift (Single vs Multi)

Payload Limitation (Vol vs Wt)

Single Shift, Volume Limited	Multi-Shift, Volume Limited
Single Shift, Weight Limited	Multi-Shift, Weight Limited

Focus of the Class 8 Long Haul results in this presentation

Scenario analysis defined since AMR 2018. Scenarios designed to reflect typical industry business operating scenarios

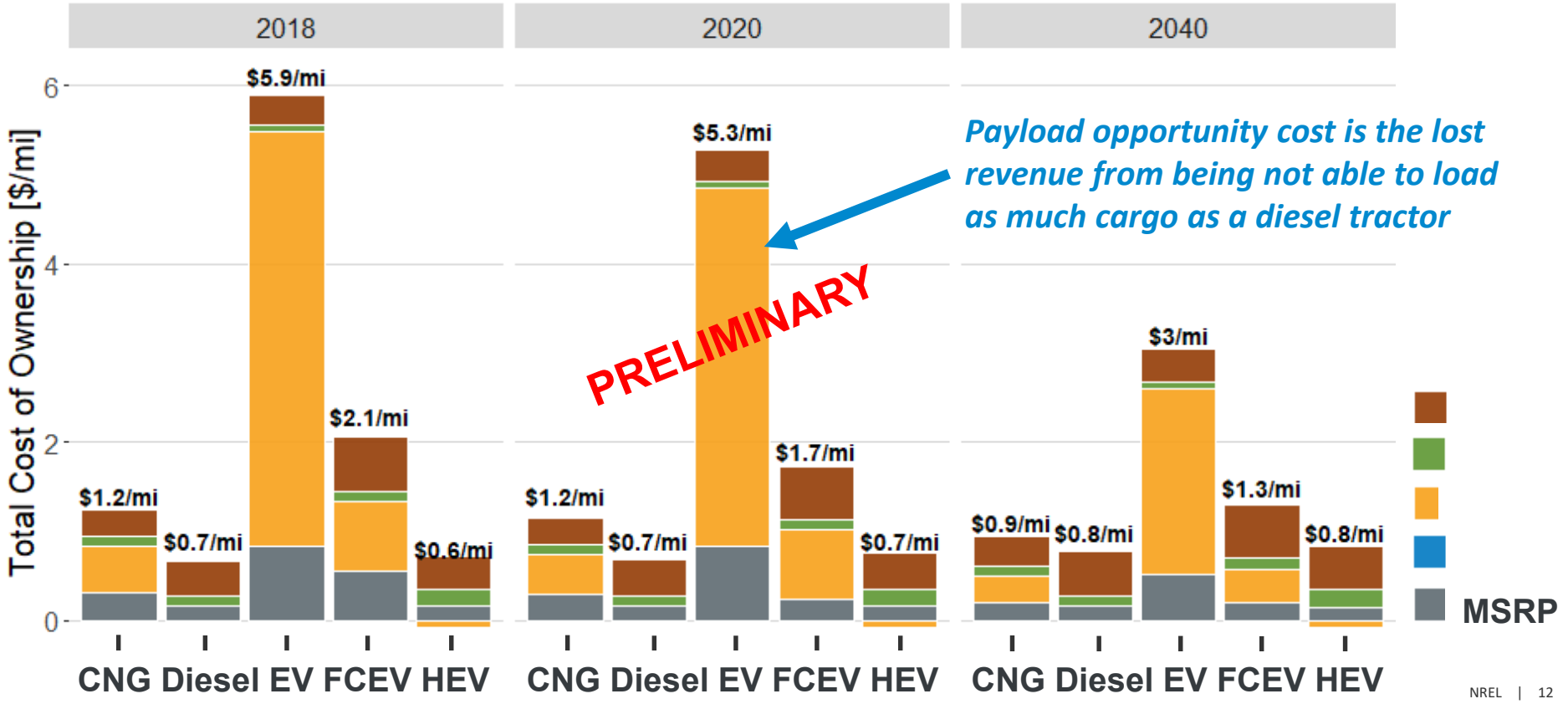
Accomplishments and Progress (5/9): Total Cost of Ownership Scenario Analysis

SERA

Scenario Parameters

- Class 8 Long Haul in Pacific Region
- 100,000 mi/yr, 10 year life
- Payload Cost = High, Dwell Cost = None
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

TCO result in Pacific region. FCET costs driven by fuel ($7/gge H2 in this scenario) and Payload Opportunity Cost

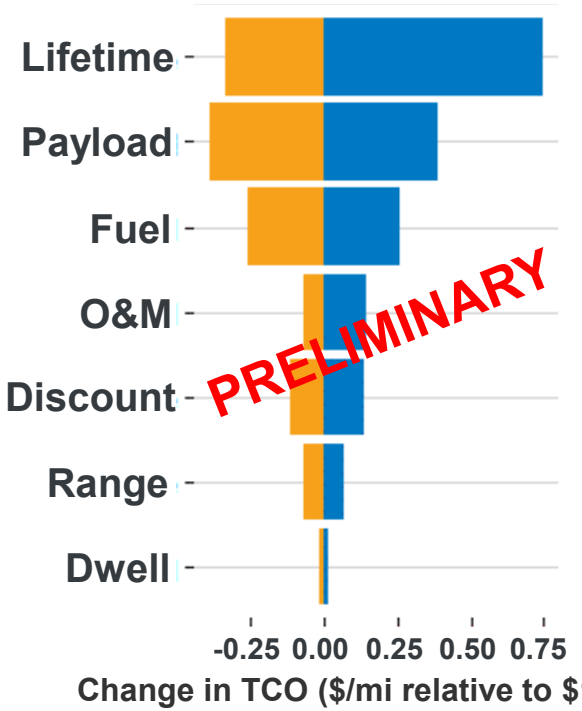


Accomplishments and Progress (6/9):
FCEV Total Cost of Ownership Sensitivity Analysis

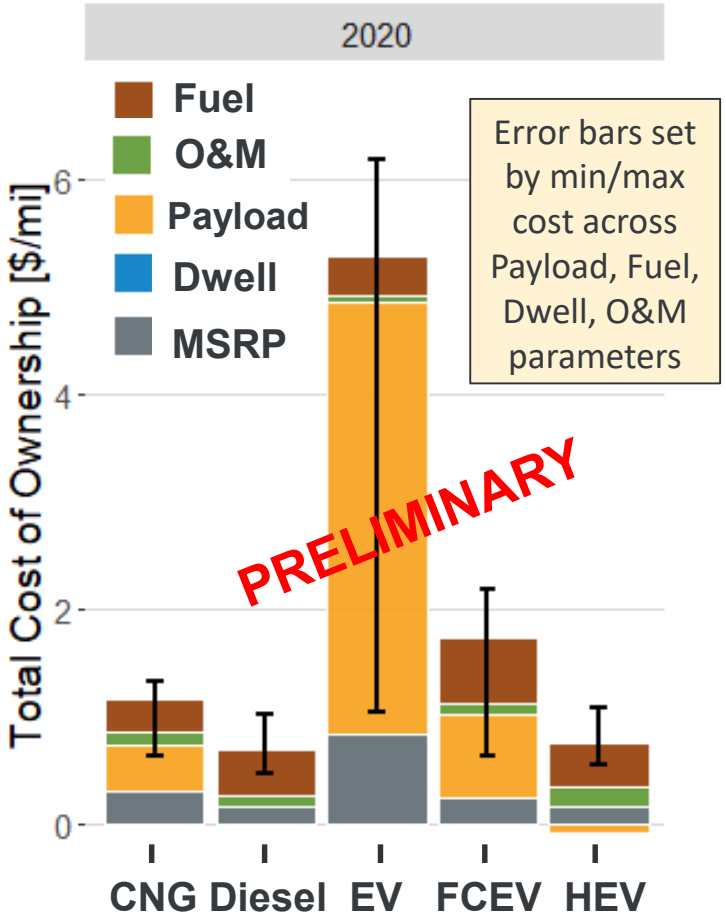
SERA

Scenario Parameters

- Class 8 Long Haul in Pacific Region
- 100,000 mi/yr, 10 year life
- Discount Rate = 7%

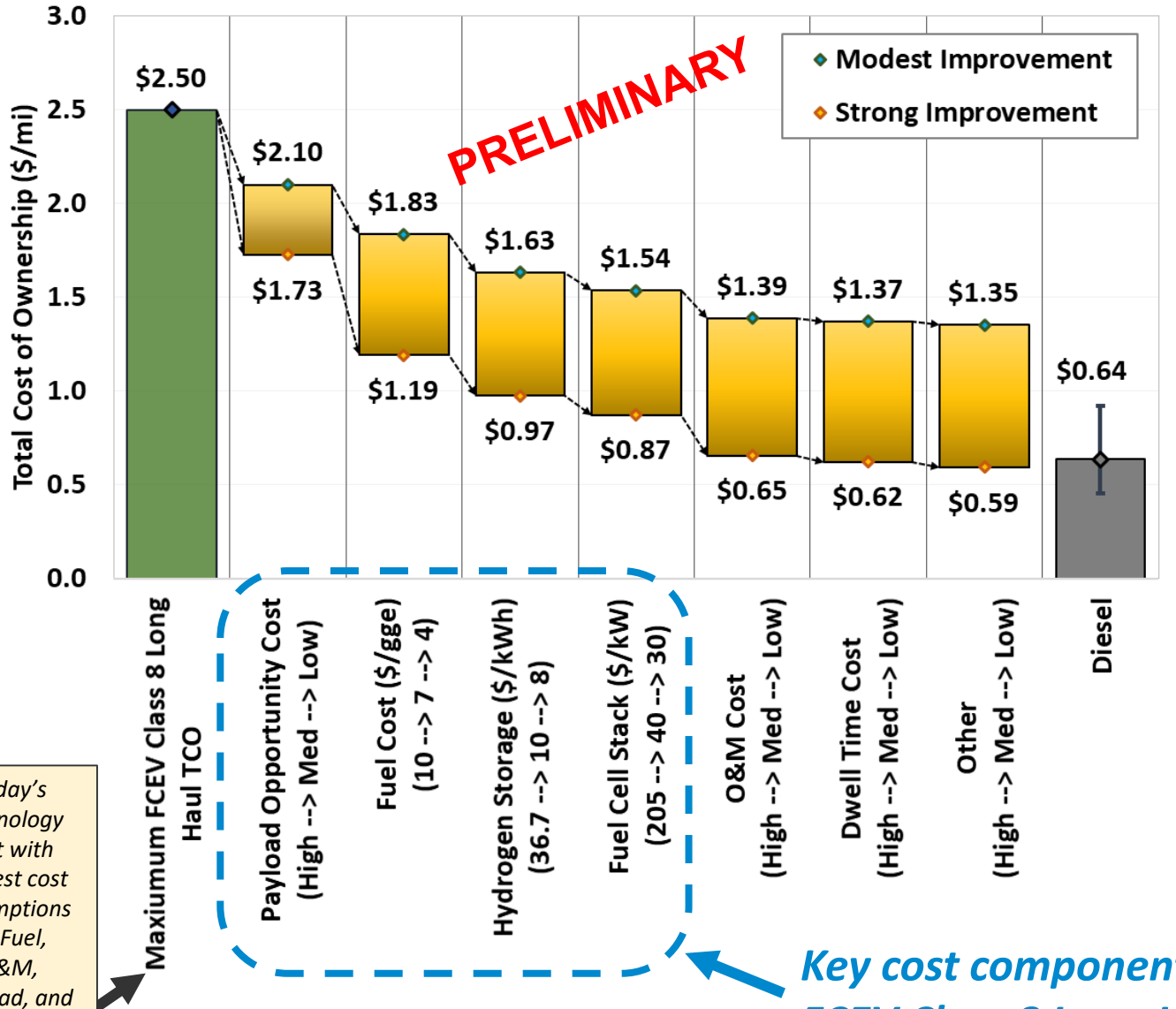


Large uncertainty in TCO for each powertrain indicates economic competitiveness depending on how scenarios are defined



Accomplishments and Progress (7/9):
Total Cost of Ownership Sensitivity Analysis

SERA



Scenario Parameters

- Class 8 Long Haul
- Pacific Region
- 2018 Technology
- 100,000 mi/yr
- 10 year life
- Discount Rate = 7%

Sensitivity analysis on FCEV Class 8 Long Haul shows pathway to TCO parity with Diesel Technology

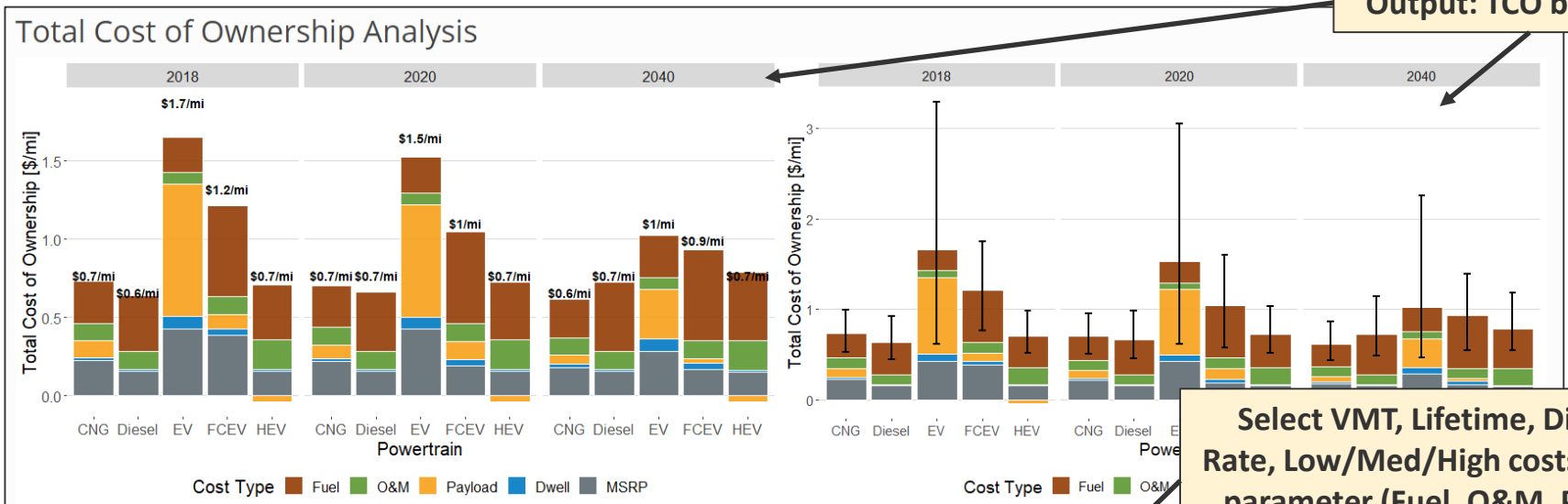
Today's technology cost with highest cost assumptions on Fuel, O&M, Payload, and Dwell Costs

Key cost components for FCEV Class 8 Long Haul

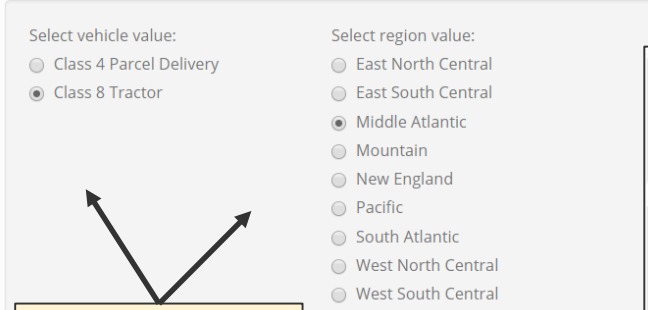
Accomplishments and Progress (8/9): Total Cost of Ownership Online Tool

Online Tool prototype built for users to explore their own scenarios and parameter combinations. Final tool will be published with report

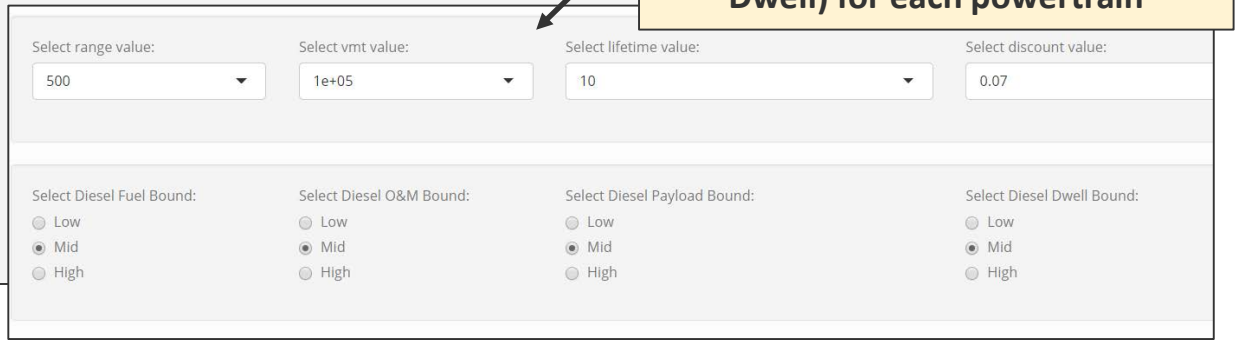
Output: TCO bar charts



Select VMT, Lifetime, Discount Rate, Low/Med/High costs for each parameter (Fuel, O&M, Payload, Dwell) for each powertrain



Select Vehicle and Region



Accomplishments and Progress (9/9)
Responses to Reviewers' Comments

Include Current Tech Status: The team should include today's costs in addition to evaluating future technical cost and performance targets.

Great suggestion and we have incorporated this into our analysis.

Include PHEV: The team should include plug-in hybrid (PHEV) technology in addition to the existing powertrain technologies (Diesel, hybrid, CNG, Battery, Fuel Cell) in this analysis.

We have incorporated PHEV technology in our Class 4 Parcel Delivery vehicle analysis. After discussing with industry stakeholders, PHEV is not a likely candidate for Class 8 Short and Long Haul so it was not included there. The vehicles/vocations evaluated in FY19 are expected to include PHEV.

Use Autonomie and/or Validate Against It: The team should consider using Autonomie rather than FASTSim or benchmark against it.

Autonomie and FASTSim are both peer-reviewed, industry-used models for vehicle modeling. FASTSim was primarily used in this analysis to be consistent with a parallel, ongoing multi-EERE office (VTO/FCTO/BETO) project. A benchmarking analysis was completed.

Sensitivity Analysis: The team should complete a sensitivity analysis as discussed by the presenter but not clear from the slides.

Sensitivity analysis has been completed as detailed in FY18. Additionally, a online tool is expected to be published with the report to allow users to explore the uncertainty by creating their own "what-if" scenarios.

Collaboration and Coordination

Modeling

- **Vanderbilt University**
  - Dr. Yuche Chen supported vehicle stock model development and operating and maintenance data review

External Peer Reviewers (Thank You!)

- **Bosch**
- **California Air Resources Board (CARB)**
- **Center for Transportation and the Environment (CTE)**
- **Cummins**
- **Eaton**
- **Energy Independence Now (EIN)**
- **FedEx**
- **Toyota**

The mix of industry, state agency, and non-profit organizations has been very helpful in defining the scenarios and visualizations that are the most useful to see

Remaining Challenges and Barriers

Data Certainty

- There is limited public, robust data on many of the total cost of ownership parameters
- Large uncertainty ranges impacts the ability to segment the M/HD market as multiple powertrain technologies can compete under different conditions

Modeling Actual Vehicle Ownership Behavior

- Total cost of ownership over the lifetime of the vehicle may not represent how industry owns vehicles. For example, Class 8 Long Haul first owners typically own them for ~2-4 years before selling in secondary market. Resale value of Battery and Fuel Cell powertrains is unknown and difficult to estimate

Future Work and Potential Work

FASTSim Cost Modeling (FY19)

- Complete FASTSim vehicle modeling for remaining vehicles in this study (Class 4 Delivery and Class 8 Short/Long Haul completed)

SERA TCO Modeling (FY19)

- Integrate FASTSim outputs for remaining FY19 vehicles into SERA for TCO analysis
- Complete TCO analysis including Sensitivity and Scenario analysis for all vehicles/vocations

Knowledge Transfer (FY19)

- Obtain feedback on prototype Online Tool and update based on feedback
- Publish the Journal Article and NREL Report on Class 4 Parcel Delivery and Class 8 Short/Long Haul along with Online Tool
- Draft report on remaining vehicles/vocations (AOP milestone)

Potential Future Scope (FY20+)

- Integrate with **H2@Scale** through temporal and spatial supply, demand, and storage requirements
- Integrate TCO data into ADOPT vehicle choice model
- Evaluate other vehicle segments (rail, marine)

Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

- ***FASTSim*** is currently available (LDV) and the updated version (with M/HDV capabilities) will be made available after project completion
  - https://www.nrel.gov/transportation/fastsim.html

- Licensing of ***SERA*** model is being considered. Please inquire if you are interested in using it.

- Online Tool is being developed for external users to explore "what-if" scenarios of their choosing. Goal is to publish in parallel with NREL Report

Any proposed future work is subject to change based on funding levels

Summary

Relevance

- Completed analysis of program performance and cost status for the potential use of fuel cells for commercial applications and to help enable them (MYRDD Milestone 1.16, 1.17)

Approach

- FASTSim for vehicle optimization to obtain vehicle cost, fuel economy, and weight
- SERA TCO modeling direct costs (MSRP, fuel, O&M) and indirect costs (payload, dwell)

Accomplishments and Progress since FY18

- Incorporated 2018 AMR Reviewer Feedback to include Current Technology costs and PHEVs
- Completed TCO analysis of Class 8 Short Haul, Class 8 Long Haul, and Class 4 Parcel Delivery
- Identified key cost parameters and demonstrated path to TCO parity with Diesel (presented example for Class 8 Long Haul)
- Analyzed cost and performance improvements effect on Class 8 Long Haul FCEV TCO:
  - Fuel Price: $10/gge → $4-7/gge ($0.27-0.53/mi)
  - Hydrogen Storage: $36.7/kWh → $8-10/kWh ($0.20-0.22/mi)
  - Fuel Cell Stack: $205/kW → $30-40/kW ($0.10/mi)
  - TCO reductions are specific to the 10 year, 100,000 mi/yr scenario assumptions presented here
- Created prototype Online Tool for users to explore TCO data and create “what-if” scenarios

FY19 Ongoing and Planned Work

- Publish Report and Journal Article on Class 4 Parcel Delivery and Class 8 Long/Short Haul vehicles
- Obtain feedback on Online Tool, update, and publish tool for users to explore TCO data
- Complete vehicle modeling and TCO scenario/sensitivity analysis on remaining M/HD vehicles and draft report (AOP Milestone)

Any proposed future work is subject to change based on funding levels

Thank You

www.nrel.gov

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Technical Back-Up Slides

Acronyms

ATRI: American Transportation Research Institute
BETO: Bioenergy Technologies Office
BEV: Battery Electric Vehicle
CNG: Compressed Natural Gas
EPRI: Electric Power Research Institute
FASTSim: Future Automotive Systems Technology Simulator
FCEV: Fuel Cell Electric Vehicle
FCTO: Fuel Cell Technologies Office
FMCSA: Federal Motor Carrier Safety Administration
H2A: Hydrogen Analysis
H2FAST: Hydrogen Financial Analysis Scenario Tool
HDRSAM: Heavy-Duty Refueling Station Analysis Model
HEV: Hybrid-Electric Diesel Vehicle
LTL: Less than truckload
M/HDV: Medium/Heavy-Duty Vehicles
MSRP: Minimum Suggested Retail Price
MYRDD: Multi-Year Research, Development, and Demonstration Plan
OOIDA: Owner Operator Independent Drivers Association
PHEV: Plug-in Hybrid Electric Vehicle
SERA: Scenario Evaluation and Regionalization Analysis
TCO: Total Cost of Ownership
VIUS: Vehicle Inventory and Use Survey
VTO: Vehicle Technologies Office

Assumptions

FASTSim Modeling

- Drive Cycles – Class 8 Tractor (Slide 32), Class 4 Parcel Delivery (Slide 33)
- Cost and Performance Data – Slide 26
- Acceleration Target: 0-60mph in 45 seconds
- Vehicle Weight based on Sum of Component Weights multiplied by 1.2 factor (EPA M/HDV Final Rulemaking)[1]
- Vehicle Price (MSRP) based on Sum of Component Costs multiplied by 1.5 factor (peer-reviewed FASTSim value)

SERA TCO Modeling

- Fuel Prices – Slide 27-28
- Payload Opportunity Cost – Slide 29
- O&M Cost – Slide 30
- Dwell Cost – Slide 31
- Vehicle Miles Traveled – Based on Transportation Energy Data Book and Fleet DNA
- Vehicle Lifetime – Based on Transportation Energy Data Book and Industry Feedback
- Discount Rate – Based on Long Term Treasury Rates (3%), historical S&P 500 Performance (7-10%)

General

- Designed new powertrains to meet the performance of conventional (diesel) technology so a 1-1 vehicle displacement is implicitly assumed
- Durability and longevity of new powertrains is assumed to be the same as diesel technology which assumes vehicle manufacturers will create products that meet these requirements
- Assumed no incentives for zero or near-zero emission vehicles
- Assumed no value for emission reductions

1. "Final Rulemaking to Establish Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," Office of Transportation and Air Quality U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, Policies and Guidance EPA-420-R-11-901, Aug. 2011

FASTSim input performance and cost assumptions

Target year	Today	2020	Long Term
Batteries			
Battery Cell Mass [kg/kWh]	4.80	4.24	2.50
Battery Cell Price HEV ($/kW)	20	20	13
HEV Battery Cell Cost [$/kWh]	145	145	80
PHEV Battery Cell Cost [$/kWh]	145	145	80
PEV Battery Cell Cost [$/kWh]	145	145	80
Power Electronics			
Power electronics & motor (no boost) [$/kW]	22.00	17.00	4.00
Boost Converter [$/kW]	8.50	8.00	2.00
DC/DC Buck Converter [$/kW]	65.0	65.0	18.0
Plug Cost (On Board Charger) [$]	125	125	18.0
FCEV			
Fuel Cell			
Fuel cell specific power (kW/kg)	1.12	0.65	0.65
Fuel cell cost ($/kW)	205	40	30
Fuel peak efficiency (%)	61%	61%	61%
Fuel storage			
Hydrogen storage (kWh/kg)	1.4	1.50	2.20
Hydrogen tank cost ($/kWh)	36.68	10.00	8.00
Hydrogen fuel price ($/kg)	15.7	4.00	4.00
CNG			
CNG Storage [$/Usable kWh NG]	8.97	8.97	3.00
CNG fuel storage mass (kWh/kg)	4.67	4.67	5.83
Engine cost ($/kW)	55	55	55
CONVENTIONAL			
Engine			
Engine specific power (kW/kg)	0.23	0.23	0.23
Engine fixed cost ($)	5,000	5,000	5,000
Engine cost ($/kW)	50	50	50
Fuel storage			
Fuel and storage sepcific mass (kWh/kg)	9.88	9.88	9.88
Fuel storage cost ($/kWh)	0.07	0.07	0.07

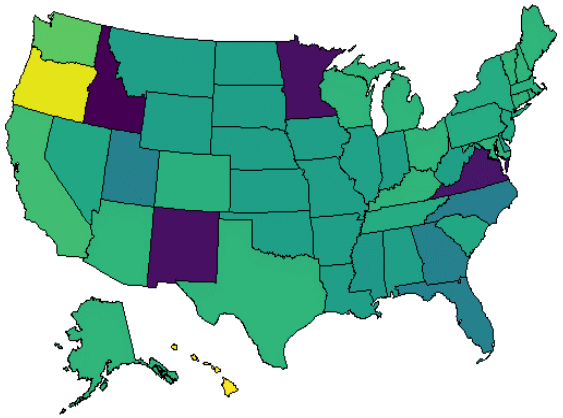
Current costs were estimated for various powertrain technologies.

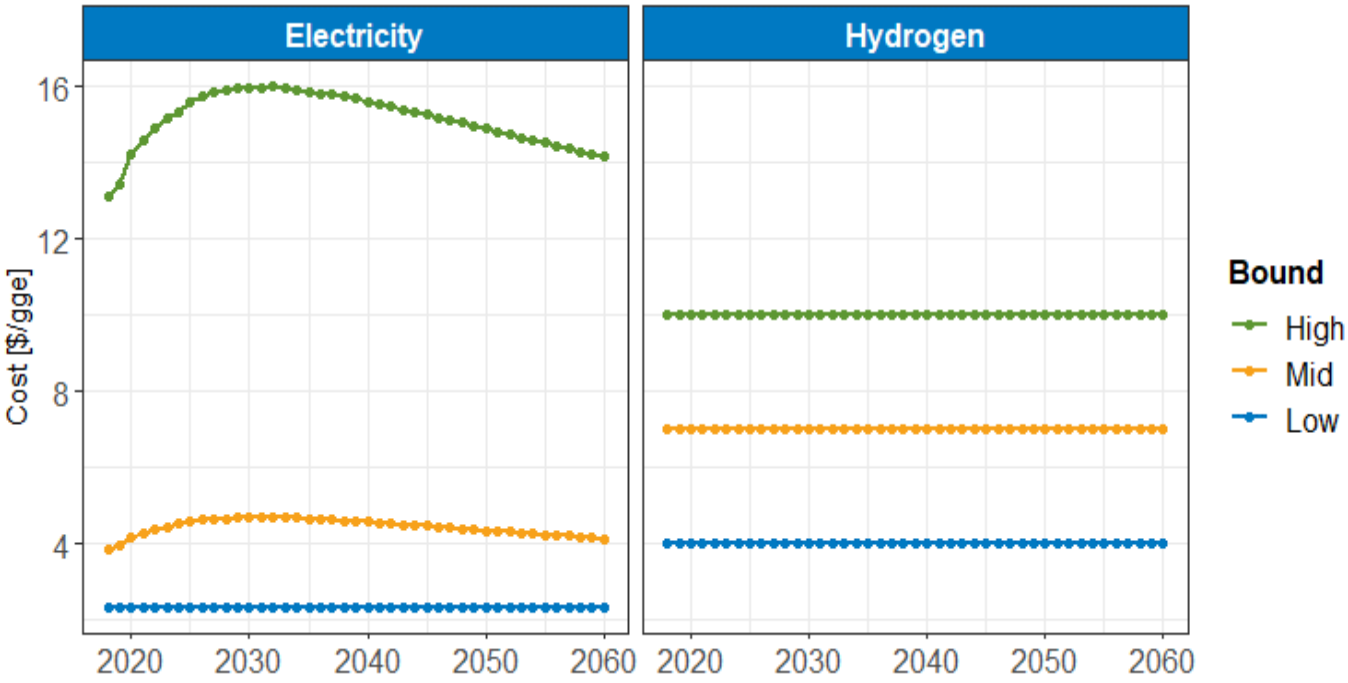
Future cost and performance values are based on DOE Targets (2020 and Ultimate)

Fuel priced based on various sources including EIA Energy Outlook, Tesla, DOE Targets, HDRSAM, H2FAST, and EPRI

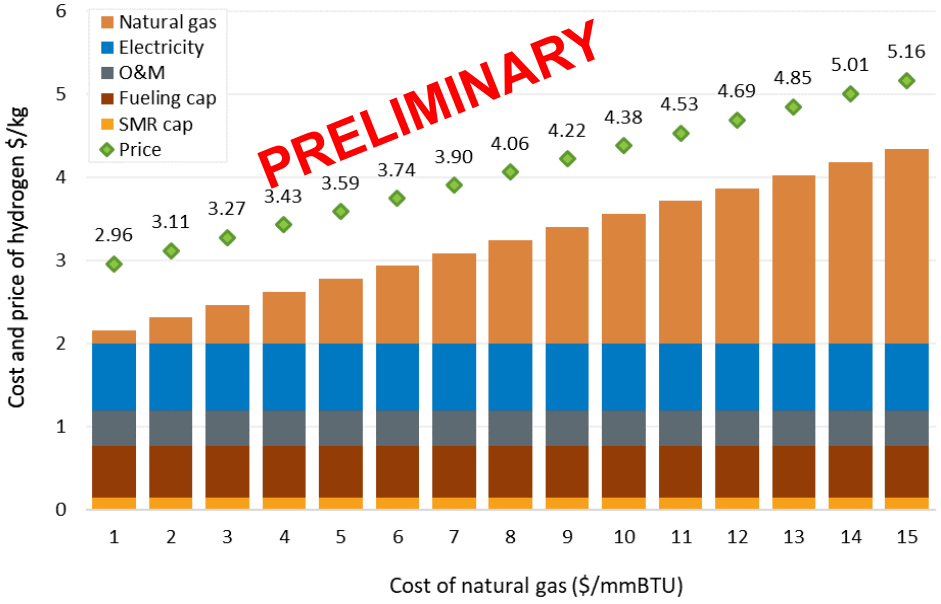
Fuel	Low	Mid	High
Diesel	AEO Low Oil	AEO Reference	AEO High Oil
Natural Gas	AEO High Oil and Gas Resource Technology	AEO Reference	AEO Low Oil and Gas Resource Technology
Electricity	Tesla quoted electricity price ($0.07/kWh)	AEO Reference - Transportation	EPRI Reported DCFC Prices
Hydrogen	DOE Hydrogen Price Target ($4/kg)	HDRSAM/H2FAST ($7/kg)	HDRSAM/H2FAST ($10/kg)

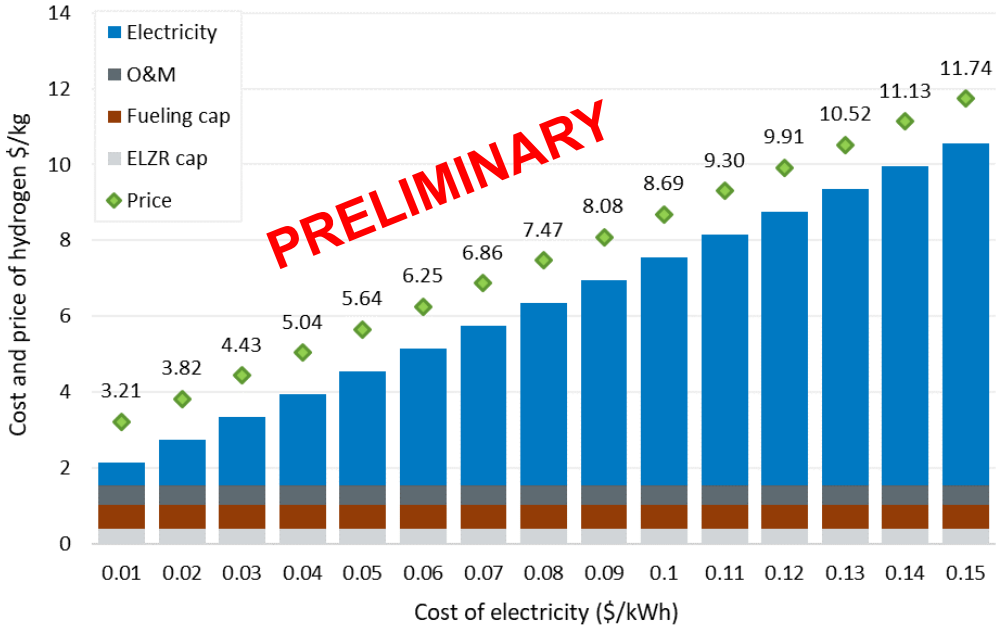
EPRI Reported DCFC Charging Prices





M/HD fleet hydrogen fuel price analysis with H2FAST and HDRSAM





H2FAST financial analysis of unsubsidized Onsite SMR and Onsite Electrolysis for H2 fuel generation using HDRSAM data

Results suggest that for natural gas prices < $8/mmBTU, $4/gge dispensed hydrogen is achievable without incentives

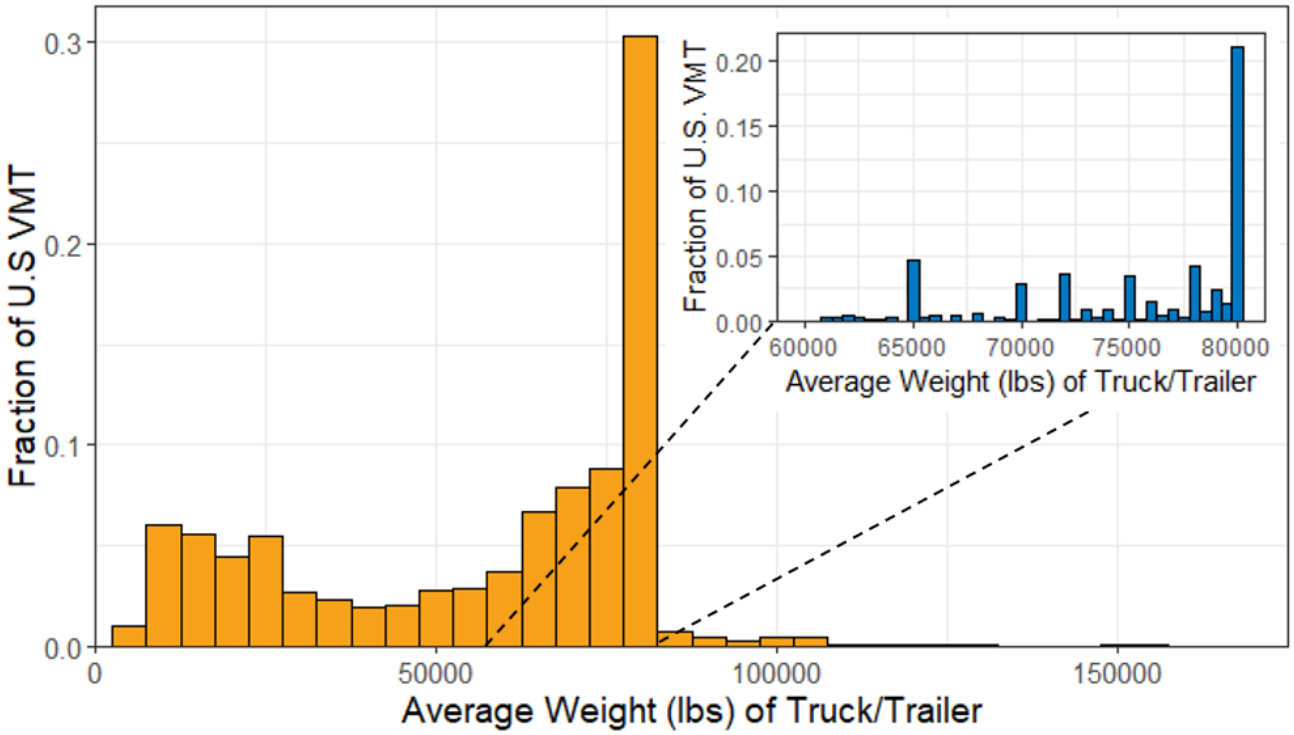
Onsite Electrolysis requires electricity prices < $0.03/kWh to achieve $4/gge

Analysis assumes selling H2 is primary revenue stream (fleet operations) whereas public refueling stations (e.g. gas stations) obtain most of their profit from selling food/drinks/merchandise.

Payload opportunity cost analysis

Bound	Payload Opportunity Cost ($/lb mile)	Industry Scenario
Low	0	Volume limited LTL shipment
Mid	0.0003	Typical freight class, origin/destination, and weight break
High	0.0006	High freight class, unattractive origin/destination, and low weight break

2002 VIUS showing VMT fraction by typical payload indicates strong possibility of being weight-limited



Payload $/lb-mi costs based on survey of LTL Carrier Rates

Expected value of payload opportunity costs based on 30% probability of being weight-limited [1]

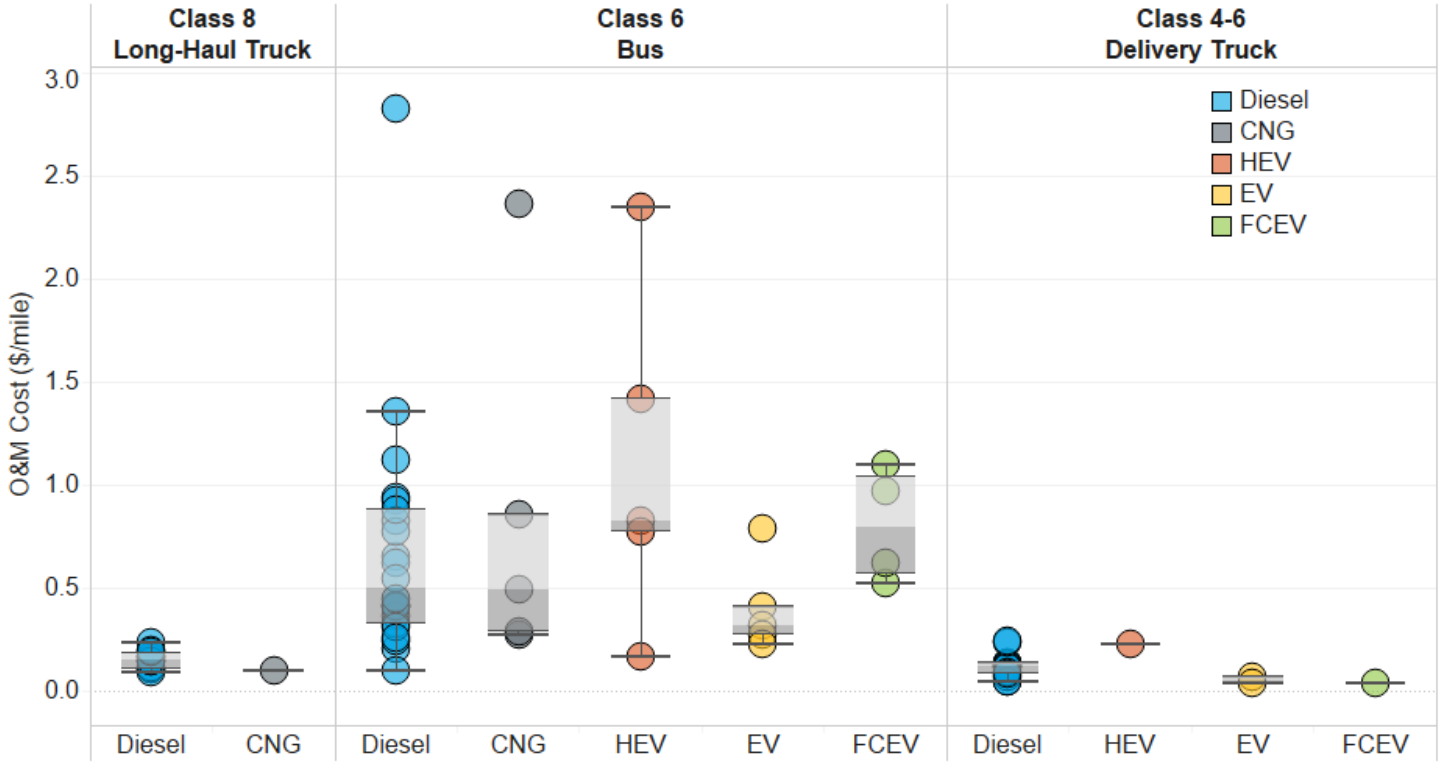
[1] https://www.nap.edu/catalog/12845/technologies-and-approaches-to-reducing-the-fuel-consumption-of-medium-and-heavy-duty-vehicles

Operating and Maintenance costs based on extensive literature survey and FC Bus Evaluations (NREL)

Cost ($/mi)	Bound	Diesel / PHEV	HEV	CNG	EV	FCEV
Class 4 Parcel Delivery	Low	0.058	0.134	0.049	0.047	0.047
	Mid	0.120	0.199	0.119	0.077	0.120
	High	0.234	0.385	0.233	0.111	0.272
Class 8 Tractor	Low	0.076	0.176	0.065	0.061	0.061
	Mid	0.155	0.258	0.153	0.100	0.155
	High	0.306	0.503	0.304	0.146	0.356

O&M costs based on literature data as available.

FCEV costs scaled based on spread between Diesel Bus and FC Bus if no FC data was available



Dwell time cost based on estimated refueling time and typical hourly dwell time cost

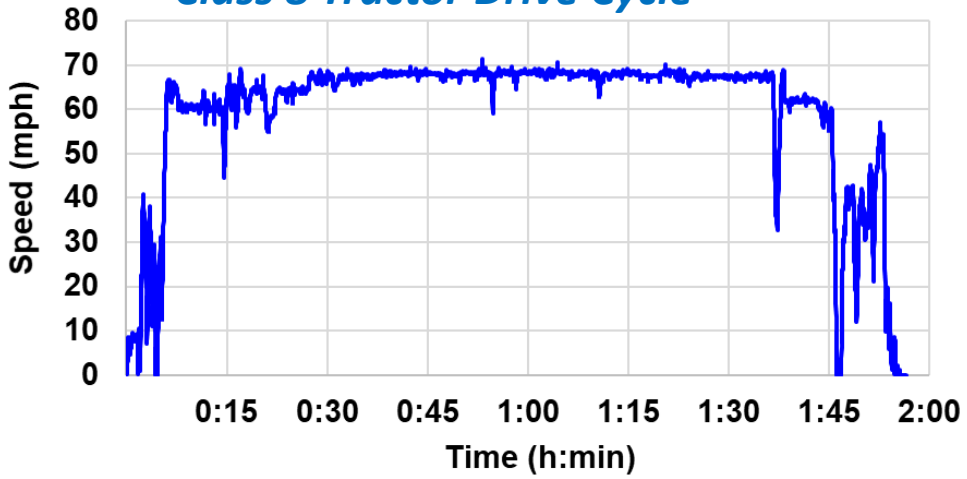
	Diesel/HEV /PHEV (min)	CNG (min)	FCEV (min)	BEV (min)	Industry Scenario
Low	-	-	-	-	Day trip with refueling/recharging overnight
Mid	5	10	20	40	Continuous (team) driving, refueling/recharging as needed. Ideal refueling/recharging time
High	10	20	40	80	Continuous (team) driving, refueling/recharging as needed. Unideal refueling/recharging time

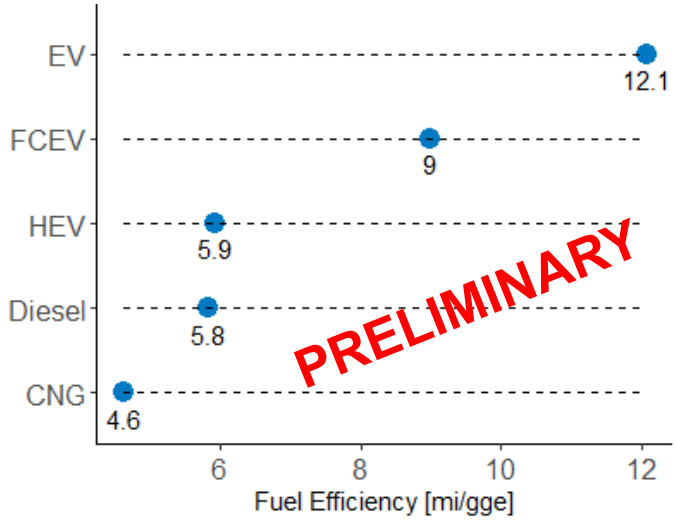
Dwell (refueling or recharging) time based on industry reported values and/or targets (Nikola, Tesla). Constant rate of $75/hr was used in this analysis.

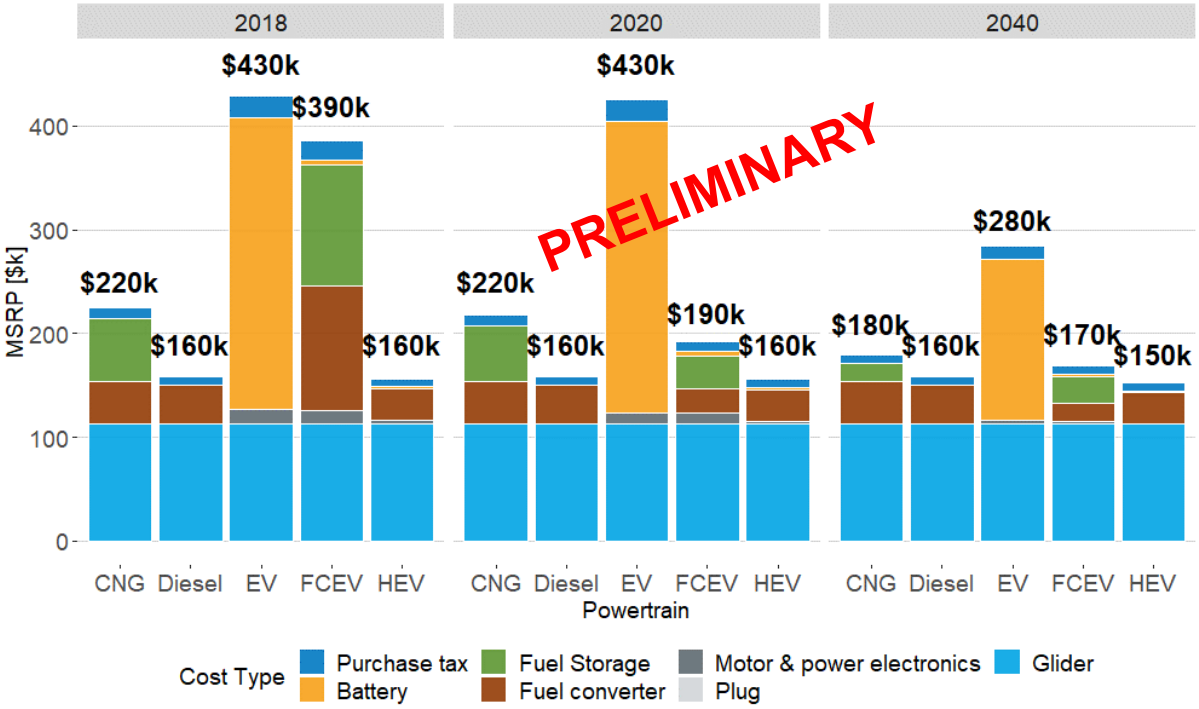
Accomplishments and Progress:
Class 8 Short Haul Vehicle Modeling

FASTSim

Class 8 Tractor Drive Cycle





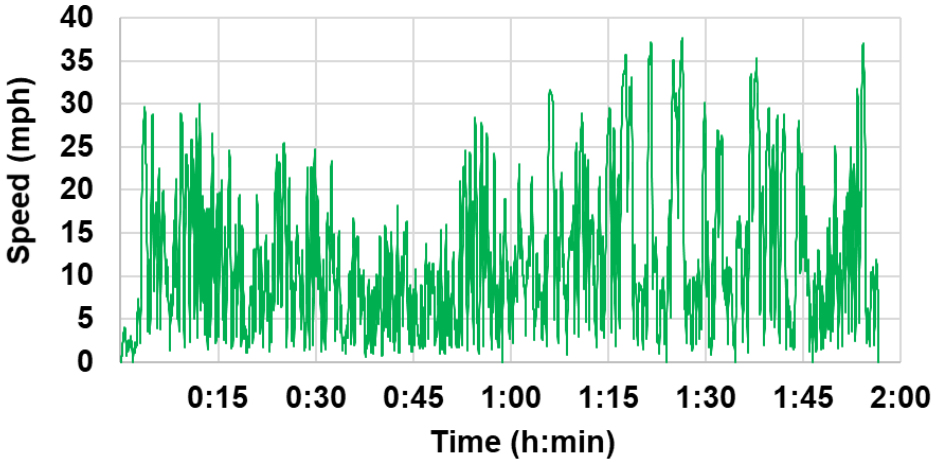


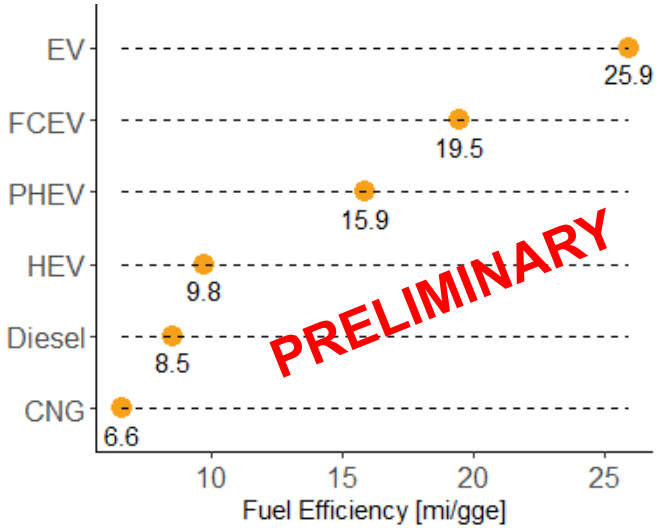
Class 8 Short Haul costs by powertrain. FCEV costs drop dramatically when 2020 and Ultimate DOE Targets are met

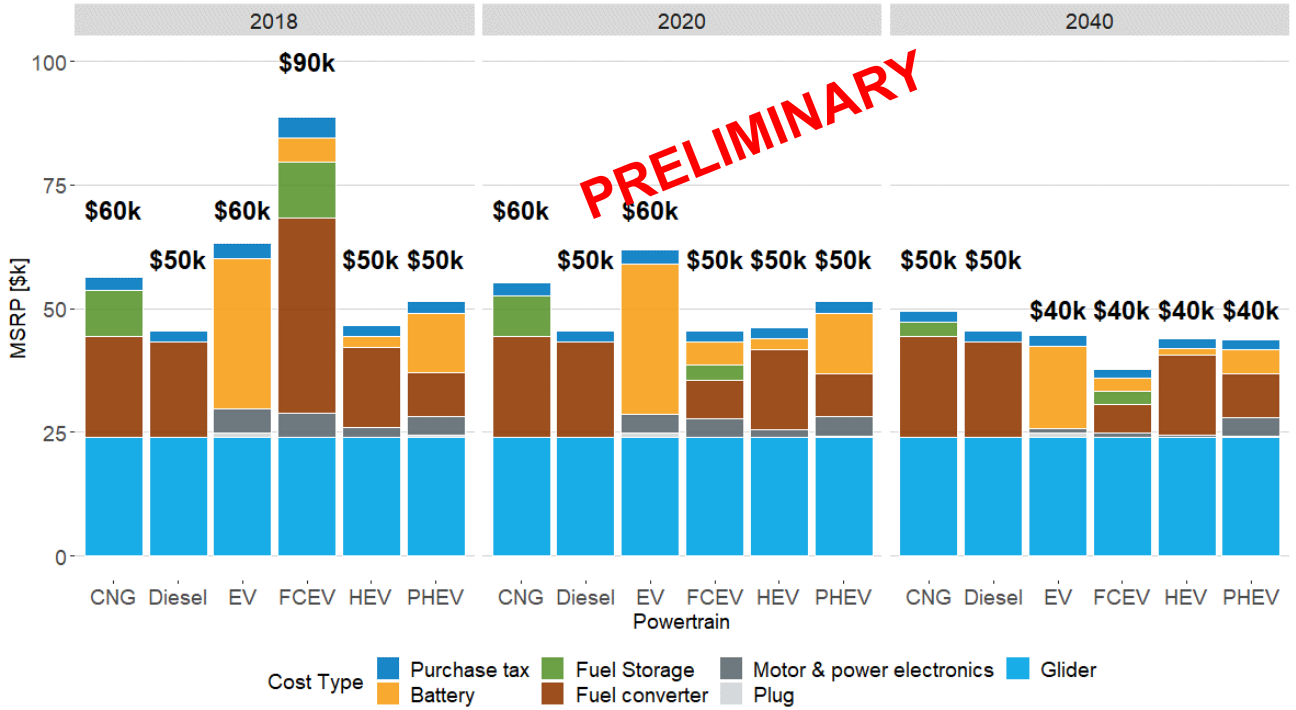
Accomplishments and Progress:
Class 4 Parcel Delivery Vehicle Modeling

FASTSim

Class 4 Parcel Delivery Drive Cycle



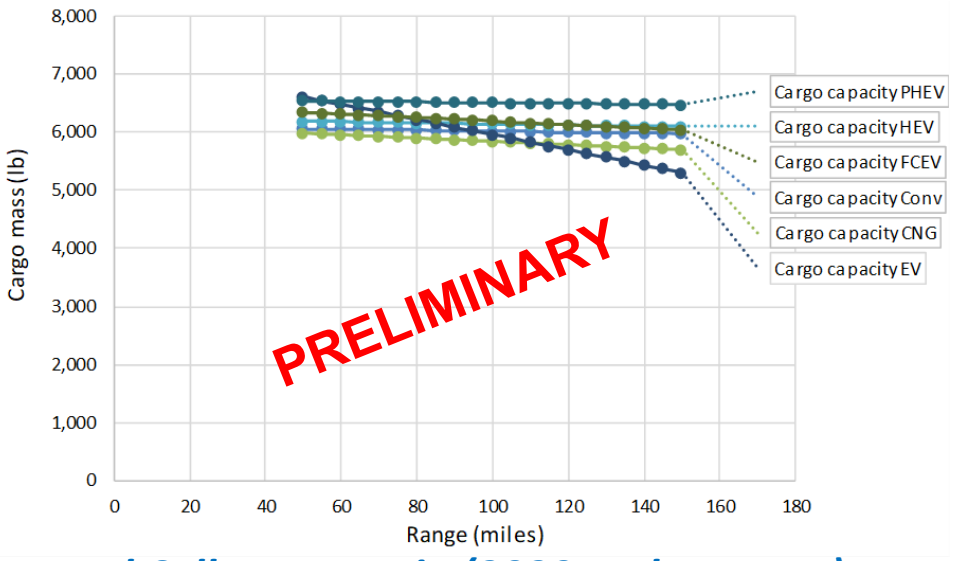




Class 4 Parcel Delivery vehicle shows FCEV MSRP more expensive with today's costs, but competitive with Diesel and HEV with 2020 cost targets

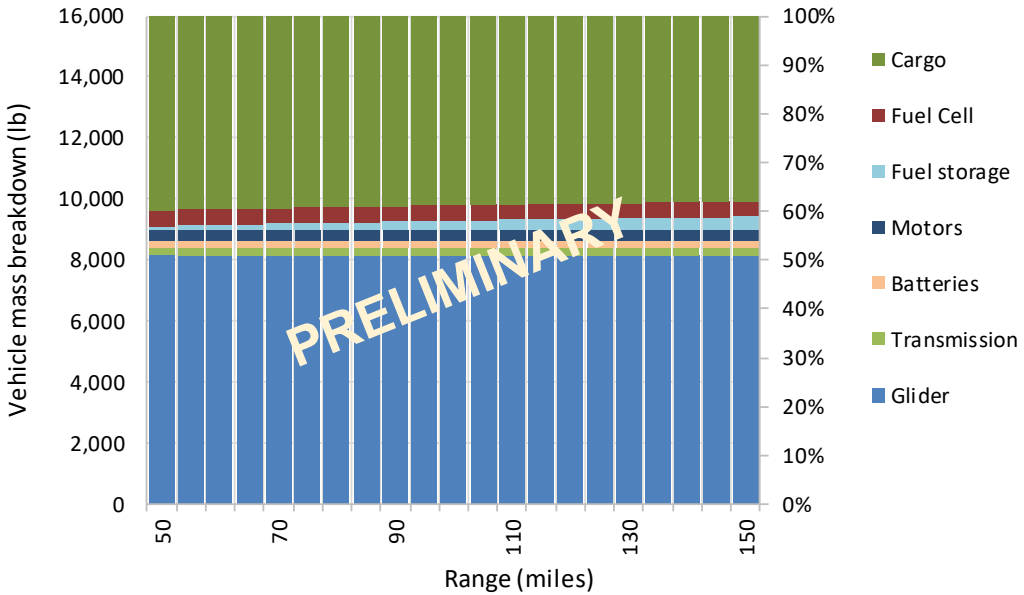
Accomplishments and Progress:
Class 4 Parcel Delivery Vehicle Modeling

FASTSim

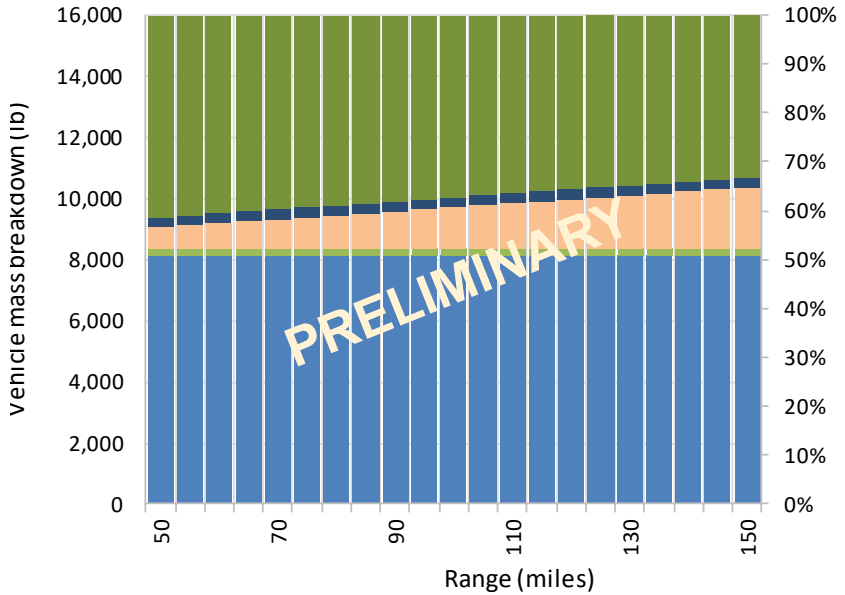


Cargo capacity (weight) is reduced by battery weight as range requirement increases

Fuel Cell Powertrain (2020 Tech Targets)



Battery Powertrain (2020 Tech Targets)

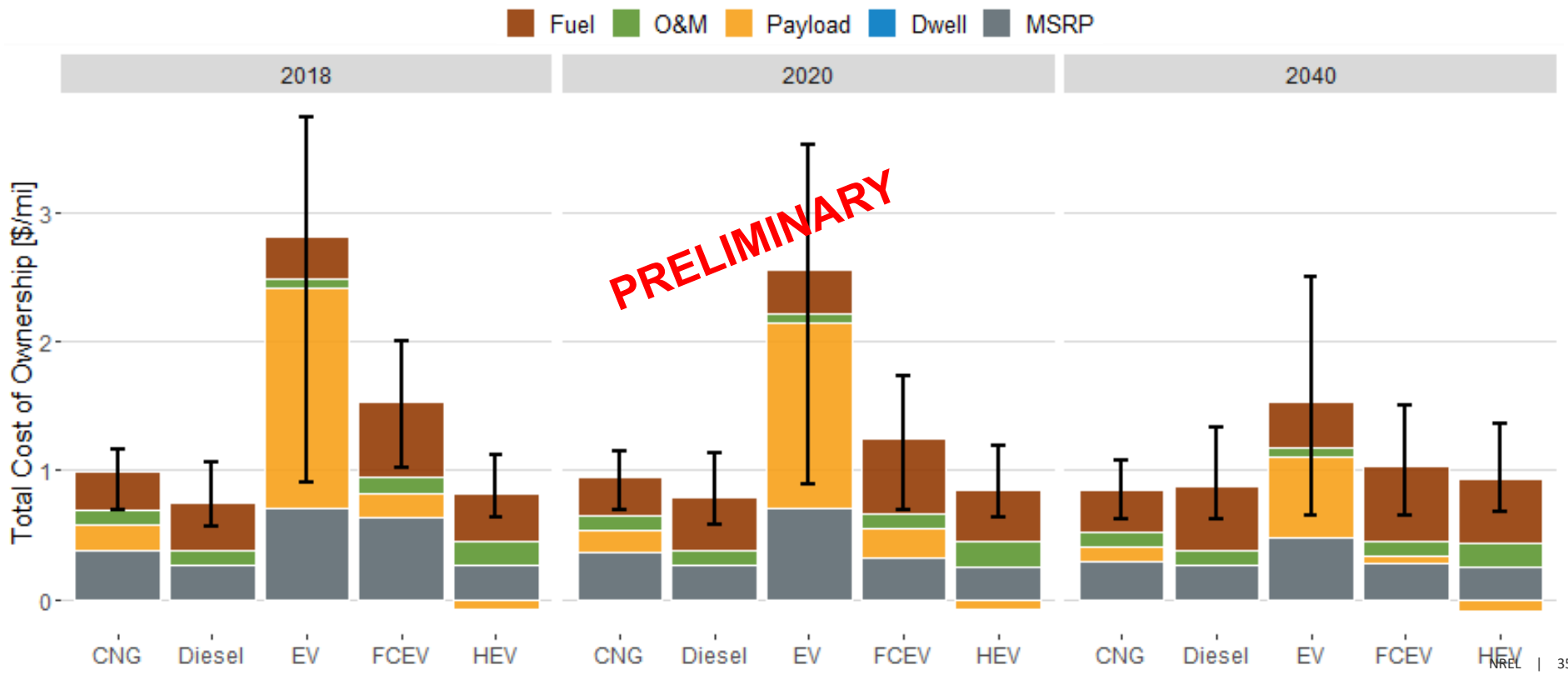


Total Cost of Ownership Scenario Analysis: Class 8 Short Haul

Scenario Parameters

- Class 8 Short Haul in Pacific Region
- 60,000 mi/yr, 10 year life
- Payload Cost = **High**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

TCO result in Pacific region. FCET costs driven by fuel ($7/gge H2 in this scenario) and Payload Opportunity Cost. At $4/gge H2, TCO of FCEV is lower than Diesel



Total Cost of Ownership Scenario Analysis: Class 4 Parcel Delivery

SERA

Scenario Parameters

- Class 4 Parcel Delivery in Pacific Region
- 30,000 mi/yr, 10 year life
- Payload Cost = **None**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

TCO result in Pacific region. FCET costs driven by fuel ($7/gge H2 in this scenario) and O&M Opportunity Cost