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

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Project ID SA169

Overview: Fuel Cell M/HD Vehicle Market Segmentation

Timeline	Barriers (4.5)
Start: September, 2017 End: September, 2020 80% 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: $450k • FY18: $250k • FY19: $100k • FY20: $100k Total DOE funds received to date: $350k	***Modeling*** **(FY18) University of South Carolina -** Dr. Yuche Chen ***External Peer Reviewers*** *(alphabetical)* **Argonne National Laboratory, Bosch, California Air Resources Board (CARB), Center for Transportation and the Environment (CTE), Cummins, Eaton, Energy Independence Now (EIN), FedEx, Toyota, DOE Vehicle Technologies Office**

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

Analysis Framework
- Cost estimation (TCO)
- Stock modeling
- Energy resource utilization
- H_2 infrastructure financial analysis

Models & Tools
- FASTSim
- SERA
- H2A
- H2FAST
- HDRSAM

- FCTO Program Targets
- VTO Program Targets

Studies & Analysis
- Fuel cell M/HDV market analysis
- Framework implementation

- H2@Scale
- VTO/BETO/FCTO Market Segmentation
- TCO Frameworks

Outputs & Deliverables
- Reports
- Online TCO Tool
- Public insights into market potential

- Fuel Cell Technologies Office
- Industry players
- Fuel cell vehicle analysis community

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:

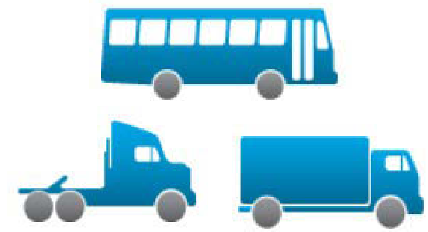
1. To provide industry, government, and non-government ***stakeholders*** a broad scoping ***assessment*** of medium/heavy duty fuel cell vehicle ***market opportunities*** across different classes, vocations, regions, and time

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

Current and Future (2025, Ultimate) Performance and Cost Data[1]

Target year	2018	2025	Ultimate
Batteries			
Battery pack mass [kg/kWh]	4.70	4.03	2.50
HEV battery pack cost [2016$/kWh]	389	275	80
PHEV battery pack cost [2016$/kWh]	389	275	80
PEV battery pack cost [2016$/kWh]	389	275	80
Power Electronics (PE)			
Power electronics with boost & motor [2016$/kW]	53	46	26
FCEV			
Fuel cell specific power [kW/kg]	0.96	1.02	1.02
Fuel cell cost [2016$/kW]	(160-200) 181	113	60
Fuel cell system peak efficiency [% LHV]	63.6%	66%	72%
Storage specific mass [kWh-LHV/kg]	1.48	1.80	2.20
Storage cost [2016$/kWh-LHV]	15.7	11.4	8.0
CNG			
Engine efficency improvement (absolute)	0%	0%	0%
Engine cost [$/kW]	55	55	55
Fuel storage cost [$/usable kWh NG-LHV]	7.47	4.70	3.82
Fuel storage specific mass [kWh/kg]	4.21	4.47	5.10
Conventional			
Engine specific power [kW/kg]	0.27	0.27	0.27
Engine fixed cost [$]	5000	5000	5000
Engine power cost [$/kW]	50	50	50
Engine efficiency improvement (absolute)	0%	2%	10%
Fuel storage specific mass [kWh/kg]	9.88	9.88	9.88

Fleet DNA

NREL's ***Fleet DNA*** database used for drive cycle data

Drive Cycle Data

Performance and Cost Data

FASTSim

FASTSim sizes powertrain components to match acceleration required

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 (2025, ultimate)
- **Powertrains:** Diesel, compressed natural gas (CNG), hybrid-electric (HEV), plug-in hybrid electric (PHEV), battery electric (BEV), fuel cell electric (FCEV)

1. Data source references are provided in the back-up slides

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
Equivalent TL rate, 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

SERA

Total Cost of Ownership for:

Status	Powertrains
2018	Diesel
2025	Diesel Hybrid (HEV)
Ultimate	Compressed Natural Gas (CNG)
	Battery Electric (EV)
	Fuel Cell Electric (FCEV)
	Plug-in Hybrid (PHEV)

***Low/med/high** estimates used for sensitivity analysis

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 (1/13):
FASTSim updates from 2019 AMR *at a glance*

FASTSim

FASTSim Vehicle Modeling Updates

1. Adjusted the interim analysis year from 2020 to 2025
2. Improved vehicle component cost data
   1. Leveraged the latest VTO-Target Setting work (Lustbader, et al., 2019) to update the current battery pack and electric machine costs for heavy-duty vehicle applications
   2. Improved CNG tank cost estimates based on recent FCTO project by SA Inc.
   3. Improved the hydrogen tank cost based on the recent FCTO Program Record (#19008)
3. Improved vehicle performance data
   1. Updated baseline diesel vehicle projections based on the latest VTO-Target Setting work (Lustbader et al., 2019) and FCTO Program Record (#19006)
   2. Updated fuel cell system peak efficiency and specific power based on recent FCTO Program Record (#19006)
4. Added FASTSim runs with regulatory drive cycles for the easier fuel economy comparisons with other projects and public data
5. Completed preliminary FASTSim runs for Class 8 drayage, Class 8 transit bus, Class 8 refuse, Class 6 parcel delivery, Class 6 box truck, and Class 5 van

	Class	Vocation
FY18-20	Class 4	Parcel Delivery
FY19-20	Class 5	Van, Basic Enclosed
FY19-20	Class 6	Box Truck
FY19-20	Class 6	Parcel Delivery
FY19-20	Class 8	Transit Bus
FY19-20	Class 8	Refuse, Garbage Pickup
FY19-20	Class 8	Drayage
FY18-20	Class 8	Short Haul
FY18-20	Class 8	Long Haul

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

This project incorporates the latest work from multiple other DOE projects and peer-reviewed papers

Accomplishments and Progress (2/13): SERA TCO updates from 2019 AMR *at a glance*

SERA

SERA TCO Modeling Updates

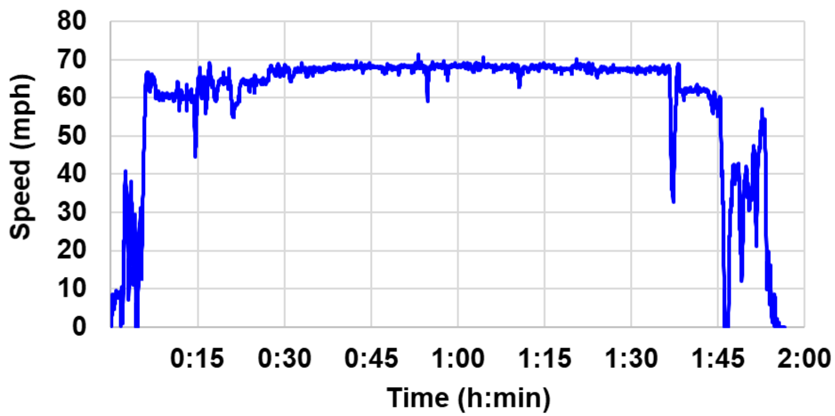
1. Updated CNG fuel prices based on discussion with AFDC data with DOE VTO Clean Cities team
2. Updated HEV O&M costs to better match conventional vehicles and observed data
3. Improved dwell time calculations for PHEV powertrains
4. Updated payload opportunity cost calculations to reflect potential incurred costs rather than lost revenue
5. Added General Operations costs (insurance, permits/licenses, tolls, tires) to allow comparison of TCO across other external studies
6. Added 2,000 lb Federal weight limit exemption for advanced powertrain trucks (up to 82,000 lbs)

Numerous discussions with industry stakeholders, research institutions, and the DOE have improved the modeling data and assumptions

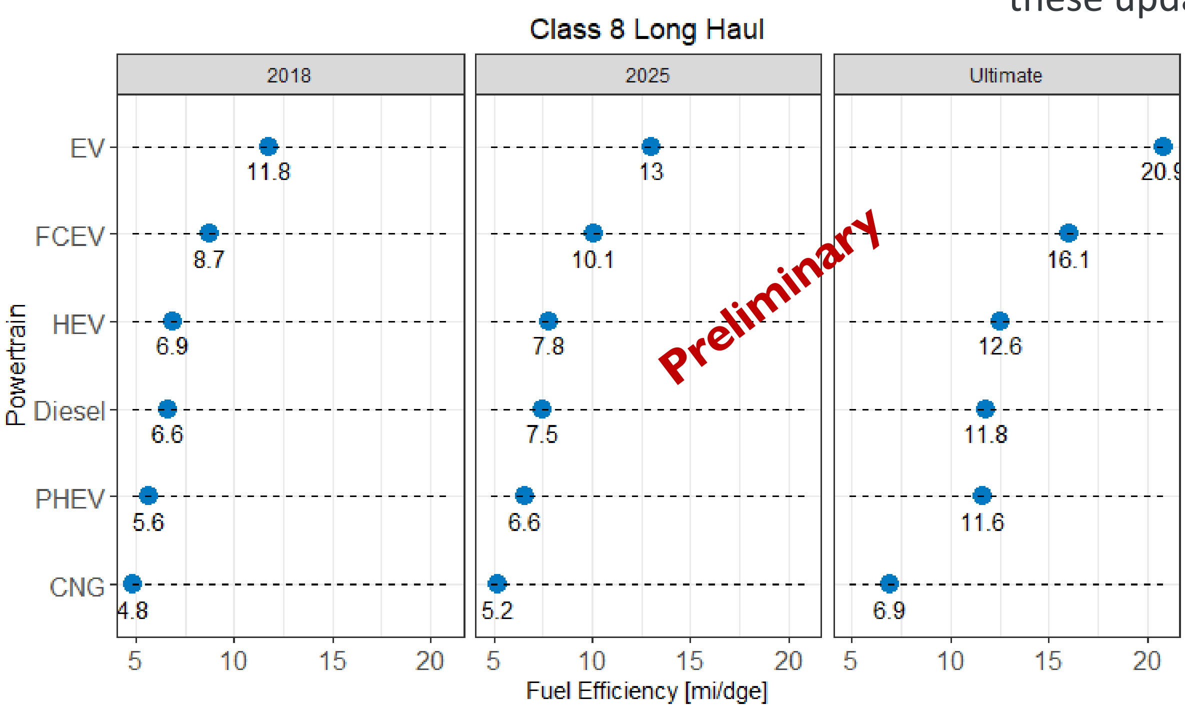
Accomplishments and Progress (3/13): Class 8 Long Haul (750 mile) Vehicle Fuel Economy

FASTSim

Class 8 Tractor Drive Cycle



- Updated baseline diesel vehicle projections based on the latest VTO-Target Setting work (Lustbader et al., 2019) and FCTO Program Record (#19006)
- Updated fuel cell system peak efficiency and specific power based on recent FCTO Program Record (#19006)
- Resulting fuel economy values are shown below for the Fleet DNA real-world drive-cycle with these updated data

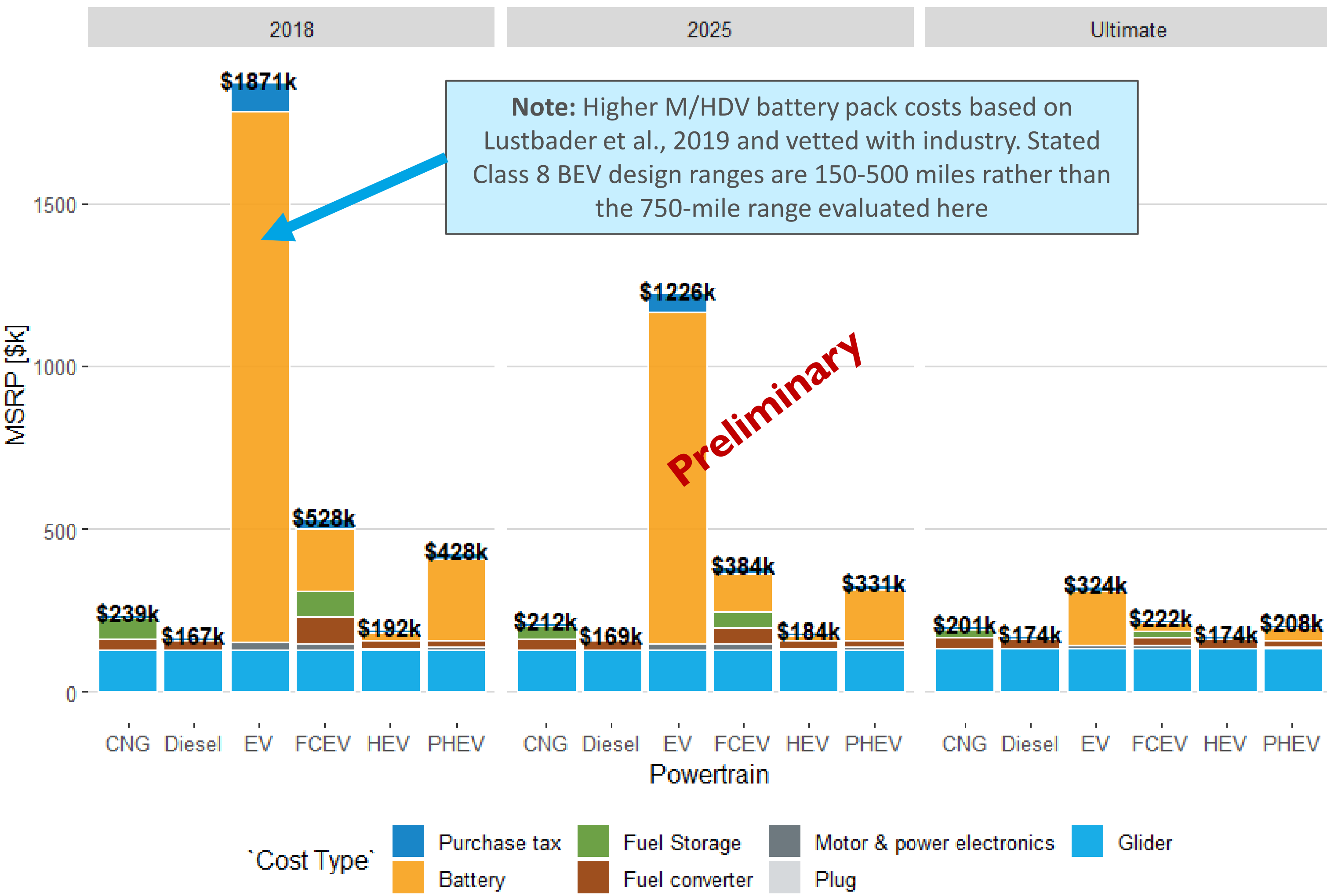


Updated fuel economy estimates better match future diesel truck projections

Accomplishments and Progress (4/13): Class 8 Long Haul (750 mile) Vehicle MSRP Modeling

FASTSim

- Powertrain components sized to meet acceleration needs (0-60 mph, ~60 sec)
- Class 8 Long Haul required range of 750 miles between refueling/recharging
- Vehicle cost/MSRP driven by H_2 storage, H_2 fuel cell stack, and battery



Note: Higher M/HDV battery pack costs based on Lustbader et al., 2019 and vetted with industry. Stated Class 8 BEV design ranges are 150-500 miles rather than the 750-mile range evaluated here

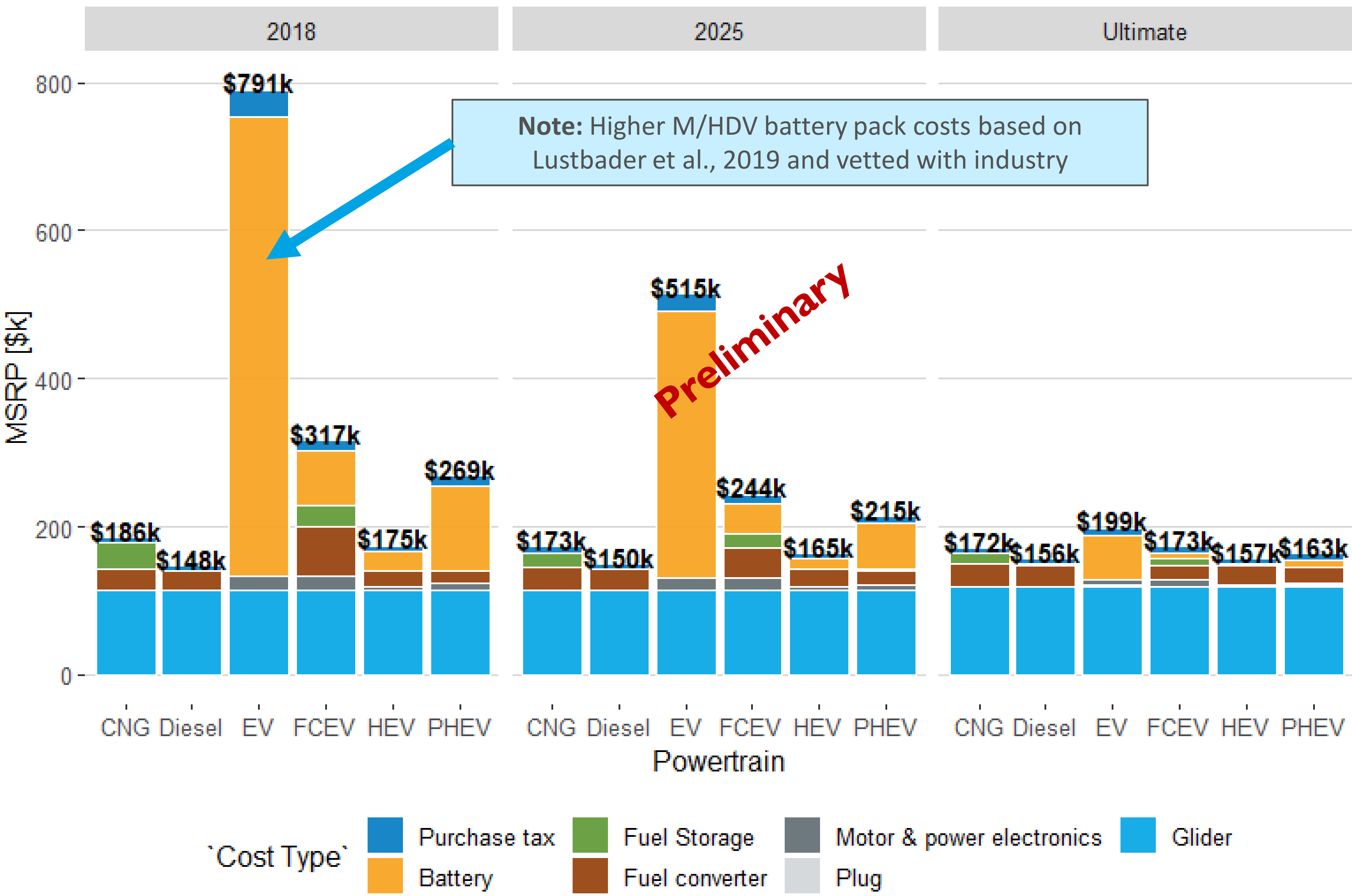
Note:
Fuel Converter = Engine or Fuel Cell

Class 8 Long Haul FCEV MSRP driven by H2 storage, H2 fuel cell stack, and battery

Accomplishments and Progress (5/13): Class 8 Drayage (300 mile) Vehicle MSRP Modeling

FASTSim

- Powertrain components sized to meet acceleration needs
- Class 8 Drayage required range of 300 miles between refueling/recharging



Note: Higher M/HDV battery pack costs based on Lustbader et al., 2019 and vetted with industry

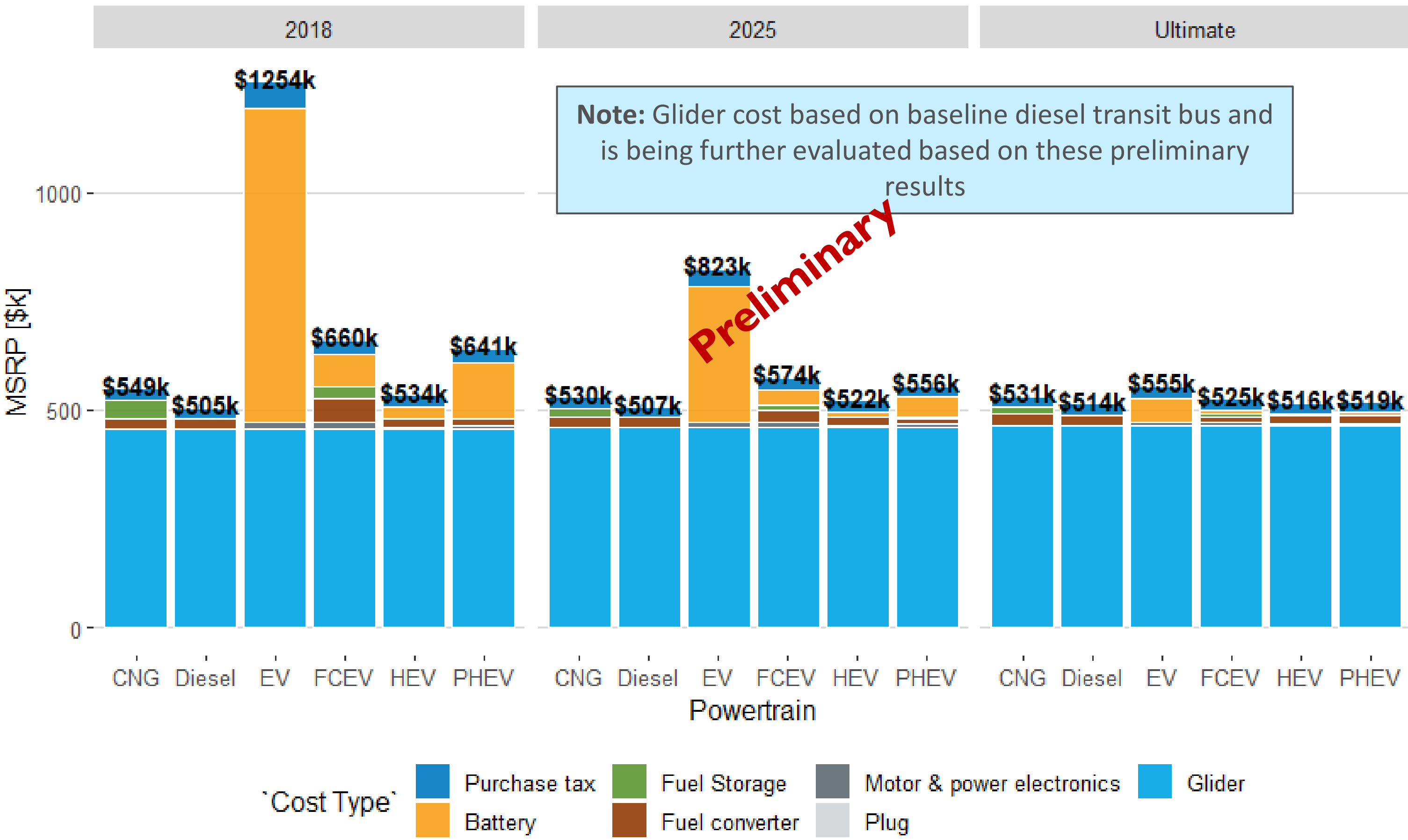
Note:
Fuel Converter = Engine or Fuel Cell

HDV battery costs is also significant for FCEV powertrains

Accomplishments and Progress (6/13): Class 8 Transit Bus (300 mile) Vehicle MSRP Modeling

FASTSim

- Powertrain components sized to meet acceleration needs
- Class 8 Transit Bus required range of 300 miles between refueling/recharging
- Vehicle cost/MSRP driven by the glider based on limited diesel bus data



Note:
Fuel Converter = Engine or Fuel Cell

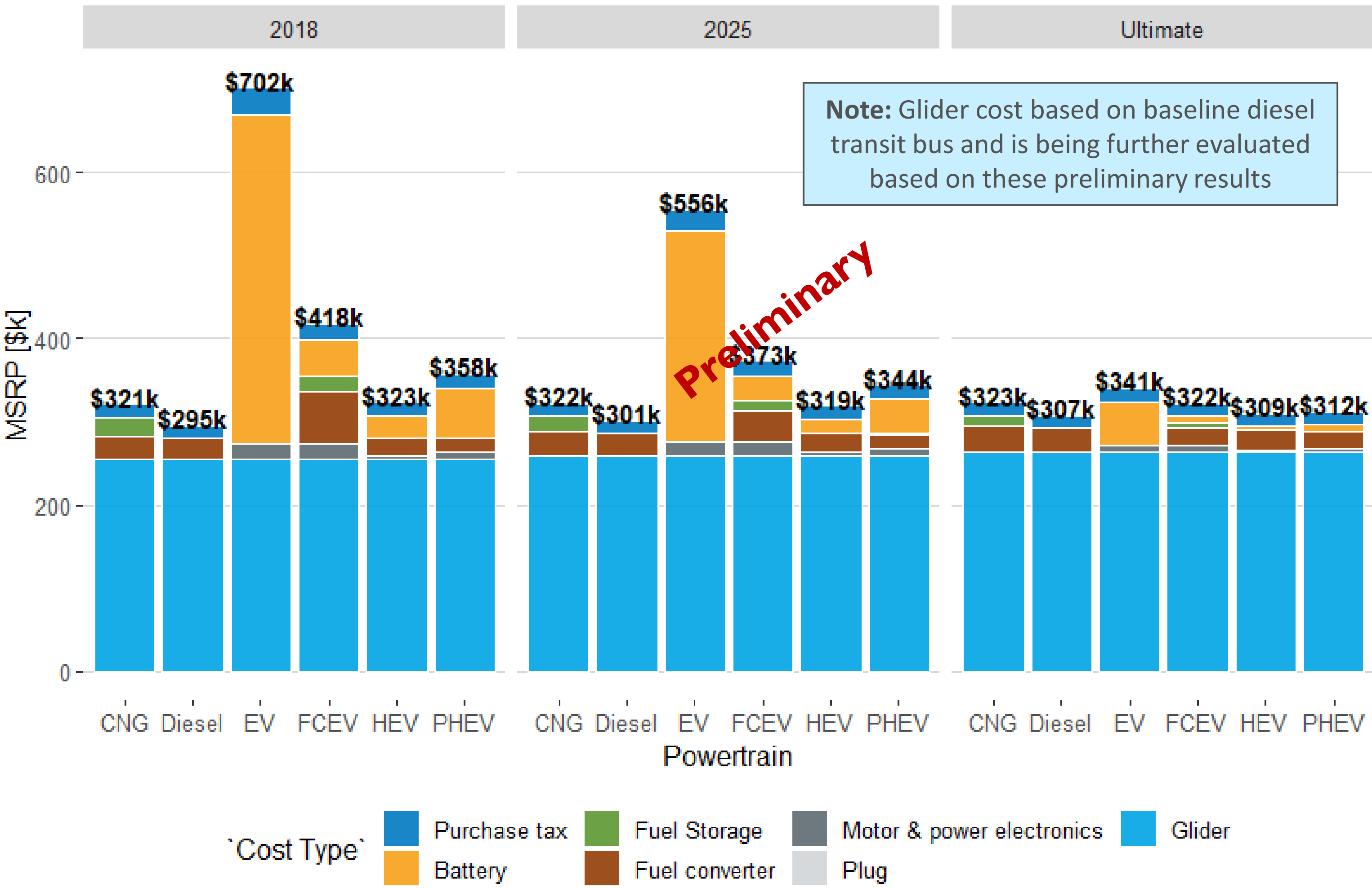
Class 8 Transit Bus costs driven primarily by glider costs

FCEV near parity if the 2025 cost targets are met

Accomplishments and Progress (7/13): Class 8 Refuse (200 mile) Vehicle MSRP Modeling

FASTSim

- Powertrain components sized to meet acceleration needs (0-60 mph, ~60 sec)
- Class 8 Long Haul required range of 750 miles between refueling/recharging
- Vehicle cost/MSRP driven by H_2 storage, H_2 fuel cell stack, and battery



Note: Glider cost based on baseline diesel transit bus and is being further evaluated based on these preliminary results

Note:
Fuel Converter = Engine or Fuel Cell

Class 8 Refuse costs are driven by the glider

FCEV is within ~5% of cost parity with diesel if Ultimate targets are achieved

Accomplishments and Progress (8/13): 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 regimes were defined in the AMR 2019 slides.
Regimes validated since then with conversations with industry

Accomplishments and Progress (9/13): Updated the approach to valuing lost payload

SERA

Lost payload* value based on minimum cost of fleet's four options:

Buy
- Quantify as if fleet would buy a similar truck to meet the needs of the fleet
- Compute levelized cost to purchase additional trucks for the fleet
- E.g. if 10 diesel trucks are needed, and an EV truck has 10% less payload, the fleet would need to buy 11 trucks total

Rent
- Quantify as if fleet would rent a similar truck to meet the needs of the fleet
- Mathematically similar to ***Buy*** option but there are differences in capital depreciation, overhead charges, and taxes

Outsource
- Buying cargo capacity services on the TL/LTL market
- TL rates for marginal cargo capacity are significantly higher than the levelized cost of ownership of a fully-loaded truck

Nothing
- Do nothing and potentially not meet the needs of the fleet/business
- Immediate revenue losses, reduced customer lifetime

	Buy	Rent	Outsource	Nothing
Data:	Levelized TCO	Rental Firm Survey	LTL Rate Survey	Assumed Infeasible
Cost:	~$0.03/klb-mi	~$0.04/klb-mi	~0.3 $/klb-mi	>> ~$0.3/klb-mi

Approach used in these 2020 AMR Slides (Buy, Rent)

Approach used in the 2019 AMR Slides (Outsource)

*Only applies for lost payload above 2,000lb federal exemption, incremental fuel economy impact accounted for within the 2,000lb Federal limit

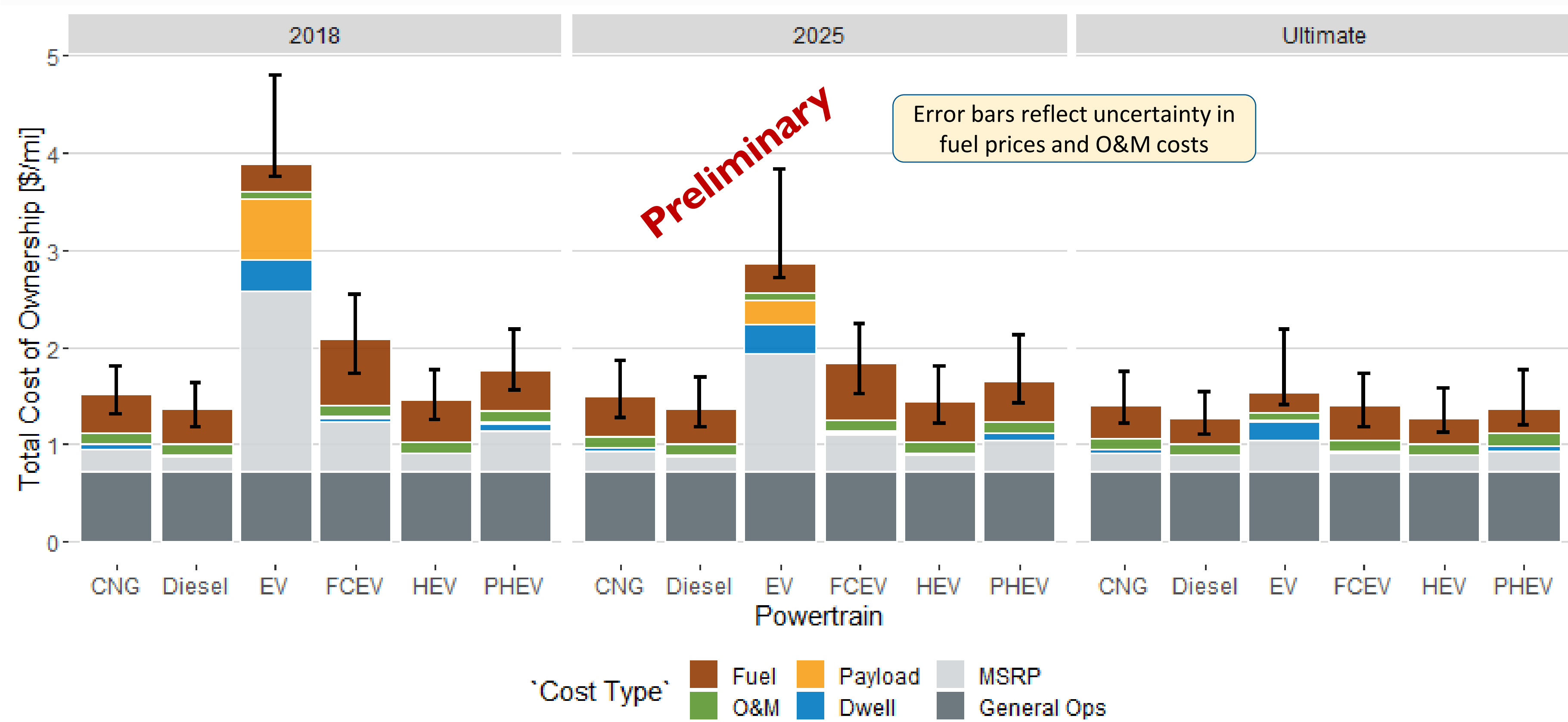
Accomplishments and Progress (10/13): Total Cost of Ownership Scenario Analysis

SERA

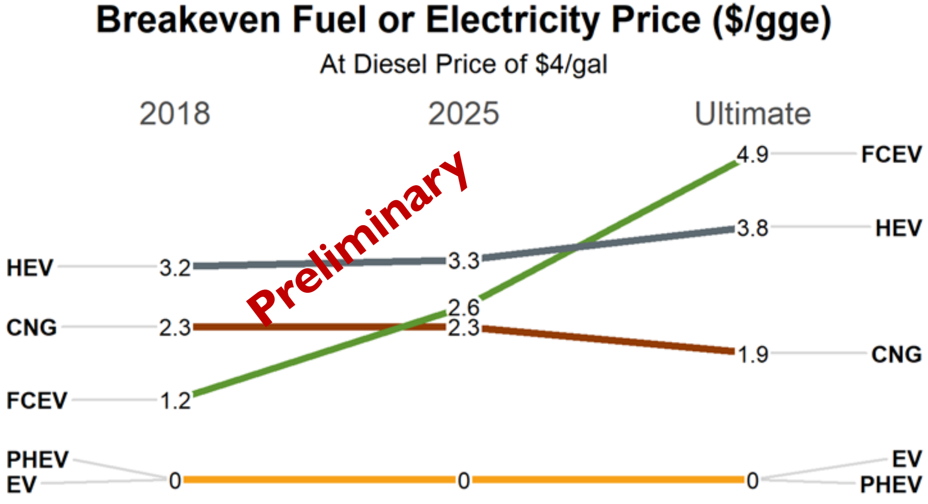
Scenario Parameters

- Class 8 Long Haul in Mid-Atlantic Region
- 100,000 mi/yr, 10 year life
- Payload Cost = **High**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

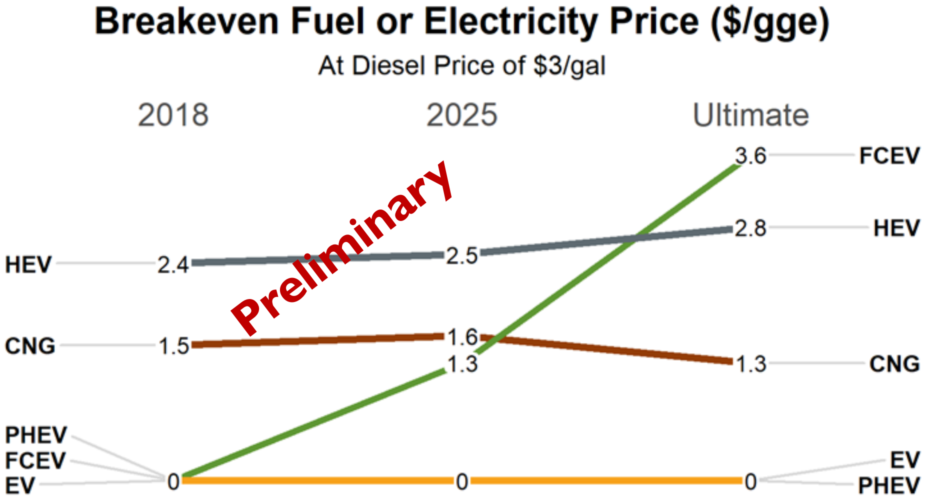
FCET costs driven by fuel ($7/gge H2 in this scenario), while payload and dwell costs are insignificant for FCEV

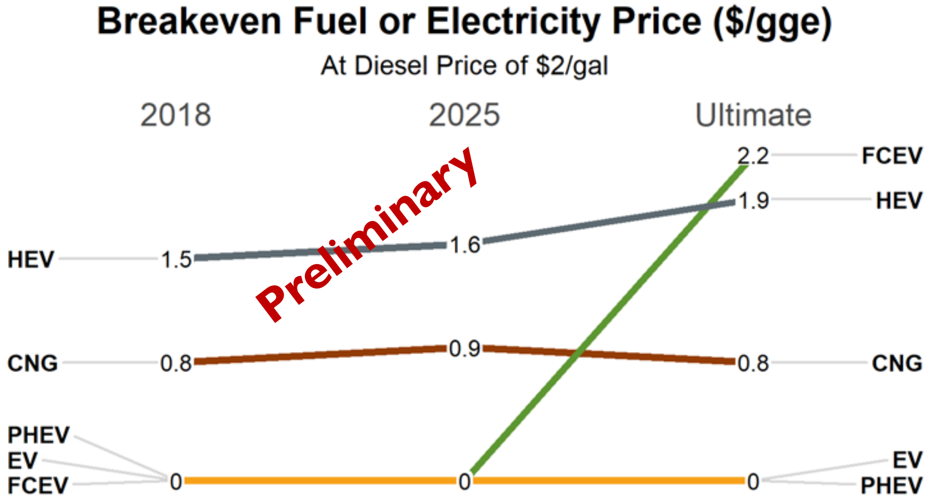


Accomplishments and Progress (11/13): Total Cost of Ownership Scenario Analysis

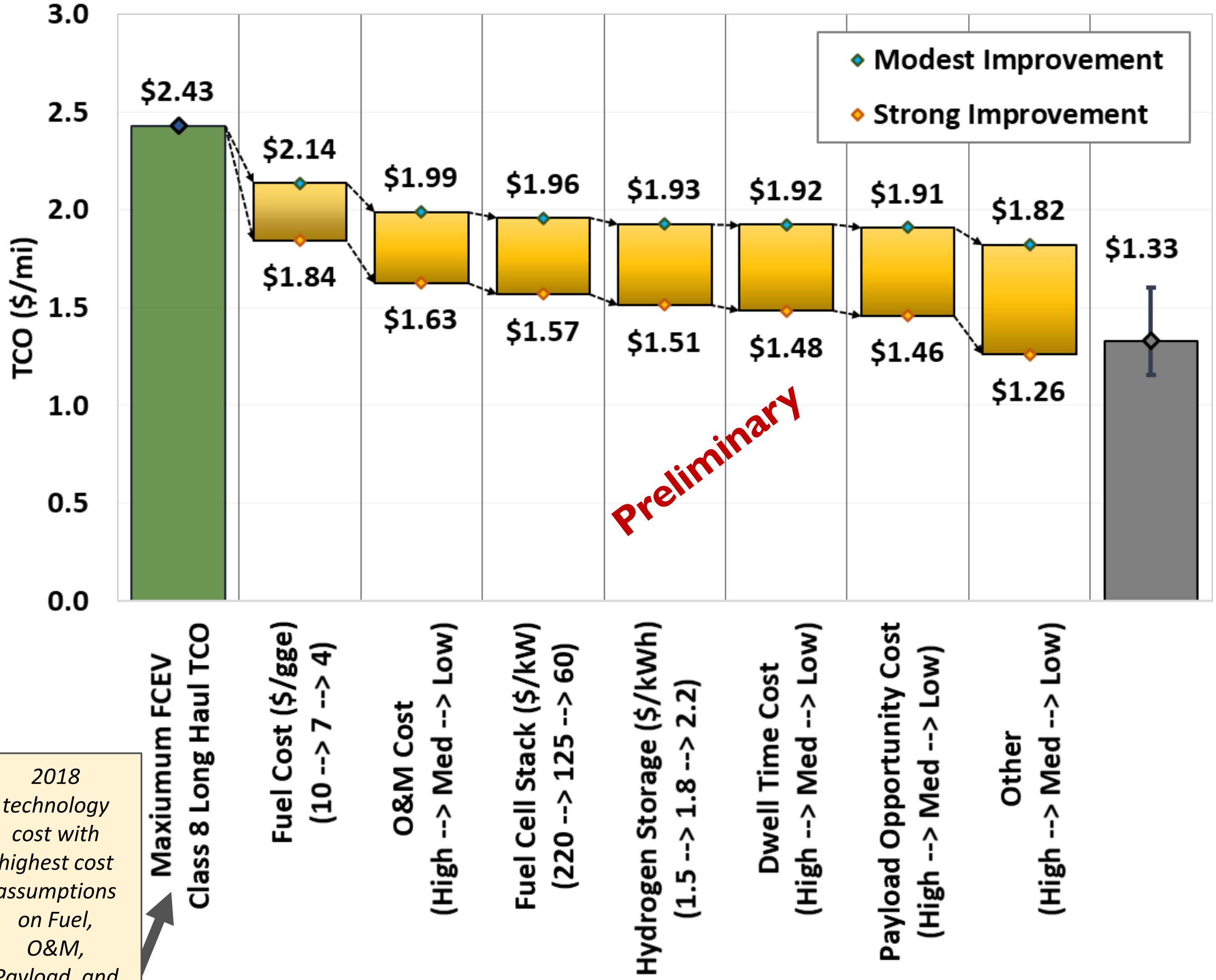


Updated since 2019 AMR Slides. In this scenario, the EERE Ultimate targets must be achieved for FCEVs to achieve TCO parity with diesel





Accomplishments and Progress (12/13): Updated TCO waterfall chart with latest data



2018 technology cost with highest cost assumptions on Fuel, O&M, Payload, and Dwell Costs

SERA

Scenario Parameters

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

Strong improvements in just hydrogen fuel cost and O&M costs allows the FCEV to achieve cost parity with diesel

Accomplishments and Progress (13/13)
Responses to Reviewers' Comments

Fuel Cell Stack Costs: The text suggests that the values are from DOE targets, but the peak fuel cell system efficiency shown for 2020 and the ultimate efficiency do not match the DOE Fuel Cell Technologies Office (FCTO) targets for fuel cell system peak efficiency.

This has been updated based on the 2019 FCTO Program Record for Hydrogen Class 8 Long Haul Truck Targets (#19006).

Fuel and Refueling Infrastructure Costs: It is recommended the team reach out to infrastructure providers to better understand these costs.

Explicit, detailed infrastructure analysis is outside the scope of this current project and being completed by other DOE FCTO Projects.

Industry Peer Reviewers: An expanded list of fleet users in the collaborators and reviewers could be beneficial

The team has engaged with additional fleet stakeholders (e.g. NACFE) and DOE collaborators investigating M/HD TCO aspects since the 2019 AMR. Those conversations have informed the development of this project, but they have not officially reviewed the project/report and thus are not listed in this deck.

Online Tool: The project team is strongly, strongly encouraged to publish a version of this model that any stakeholder can use.

While an online tool was originally being developed, the team is working with other national labs and the DOE Vehicles Technology Office to support a more wholistic TCO tool for all on-road vehicles. It is expected that this tool will be publicly available near the end of 2020.

Collaboration and Coordination

DOE	National Labs

Fuel Cell Technologies Office
 	
Vehicle Technologies Office
• Jake Ward
• Madhur Boloor
• Clean Cities Team
    • Dennis Smith
    • Mark Smith
    • Linda Bluestein
	ANL
	• Ram Vijayagopal
	• Amgad Elgowainy
	• Aymeric Rousseau
	
	NREL
	• Jason Lustbader
	• Matteo Muratori
	• Mike Lammert

Other Peer Reviewers

Bosch
California Air Resources Board (CARB)
Center for Transportation and the Environment (CTE)
Cummins
Eaton
Energy Independence Now (EIN)
FedEx
SA, Inc.
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

FY20 Project Plan

FASTSim Cost Modeling

- Complete modeling for remaining vehicles

SERA TCO Modeling

- Integrate remaining vehicle FASTSim outputs into SERA
- Complete TCO sensitivity and scenario analysis

Knowledge Transfer

- Obtain feedback on Online Tool
- Publish NREL report on FY18 vehicles
- Publish NREL report for FY19 vehicles

FASTSim Cost Modeling (FY20)

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

SERA TCO Modeling (FY20)

- Integrate FASTSim outputs for remaining FY20 vehicles into SERA for TCO analysis
- Complete TCO analysis including Sensitivity and Scenario analysis for all vehicles/vocations

Knowledge Transfer (FY20)

- Publish the NREL Report on Class 4 Parcel Delivery and Class 8 Short/Long Haul
- Publish NREL Report on remaining vehicles/vocations

Potential Future Scope (FY20+)

- Integrate with **H2@Scale** through temporal and spatial supply, demand, and storage requirements
- Integrate TCO data into ADOPT-HD 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.

- Two NREL Reports will be published detailed the modeling methods, assumptions, and results

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 FY19

- Improved vehicle component cost data (battery costs, electric machine costs, CNG tank costs, H2 tank costs) based on the most recent data available to improve the integrity of the results
- Improved vehicle performance data (baseline diesel vehicle improvements, fuel cell system peak efficiencies, fuel cell specific power) based on the most recent data available
- Completed preliminary FASTSim runs for Class 8 drayage, Class 8 transit bus, Class 8 refuse, Class 6 parcel delivery, Class 6 box truck, and Class 5 van
- Updated relevant TCO data (CNG fuel prices, HEV O&M costs, general operations costs) and TCO calculations (dwell time, payload valuation) to more accurately estimate the TCO of advanced powertrains
- Coordinated and collaborated with stakeholders across industry, DOE, non-profits, and the national labs

FY20 Ongoing and Planned Work

- Publish NREL Report on Class 4 Parcel Delivery and Class 8 Long/Short Haul vehicles
- Complete vehicle modeling and TCO scenario/sensitivity analysis on remaining M/HD vehicles (Class 8 drayage, Class 8 transit bus, Class 8 refuse, Class 6 parcel delivery, Class 6 box truck, and Class 5 van)
- Publish NREL Report on Class 8 drayage, Class 8 transit bus, Class 8 refuse, Class 6 parcel delivery, Class 6 box truck, and Class 5 van

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

Thank You

www.nrel.gov

NREL/PR-5400-77834

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NREL Transforming ENERGY

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

- Cost and Performance Data – Slide 30
- Acceleration Target: Slide 31 for Class 8 Tractors
- 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 32
- Payload Opportunity Cost – Slide 35-36
- O&M Cost – Slide 33
- Dwell Cost – Slide 34
- 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

Key Market Segmentation Assumptions

Target year	2018	2025	Ultimate	References	Notes
Batteries					
Battery pack mass [kg/kWh]	4.70	4.03	2.50	ARB 2016 (Lustbader, et al. 2019) VTO LDV Targets	2018 values based on the 2019 VTO Truck Target Setting Work completed by Lustbader et al. (Advance Scenario)
HEV battery pack cost [2016$/kWh]	389	275	80		Ultimate value $80/kWh (pack) are based on VTO's suggestion to use LDV targets while M/HDV targets are being set (email on 5/22/20). Interim set by calculating a constant %4.8 YoY improvement rate between 2018 and 2050
PHEV battery pack cost [2016$/kWh]	389	275	80		Original source does not have dollar year so reported as nominal. Assume equal to 2016$
PEV battery pack cost [2016$/kWh]	389	275	80		**Assumed:** *Pack Costs = System Costs* (includes all cooling/structural components included for vehicle glider integration)
Power Electronics (PE)					
Power electronics with boost & motor [2016$/kW]	53	46	26	Lustbader, et al. 2019	2019 VTO Truck Target Setting Work completed by Lustbader et al. (Advance Scenario)
FCEV					
Fuel cell specific power [kW/kg]	0.96	1.02	1.02	SA Inc. 2018, Supplemental data	Ultimate uses 2025 value since reference did not propose an Ultimate value
Fuel cell cost [2016$/kW]	(160-200) 181**	113	60	2019 FCTO Record #19006 (Class 8 Truck Targets)	**Assumes $170/kW in 2019 based on 1,000 units/yr (237,000 kW/yr)
Fuel cell system peak efficiency [% LHV]	63.6%	66%	72%		Uses High Target for System Peak Efficiency
Storage specific mass [kWh-LHV/kg]	1.48	1.80	2.20	2019 FCTO Record #19008 (Onboard Storage Cost)	
Storage cost [2016$/kWh-LHV]	15.7	11.4	8.0		Consistent with 2019 FCTO Record #19006 Assumes 100,000 systems/yr mfg vol (560,000 kg/yr which is ~7,000 systems for HD trucks)
CNG					
Engine efficency improvement (absolute)	0%	0%	0%	FASTSim (multiple data sources)	
Engine cost [$/kW]	55	55	55		
Fuel storage cost [$/usable kWh NG-LHV]	7.47	4.70	3.82	SA Inc. 2017 estimate (currently unpublished)	Uses 1k, 30k, 500k systems/year production volumes
Fuel storage specific mass [kWh/kg]	4.21	4.47	5.10	FY15 GPRA Benefits Analysis	Limited data available
Conventional					
Engine specific power [kW/kg]	0.27	0.27	0.27	FASTSim (multiple data sources)	
Engine fixed cost [$]	5000	5000	5000		
Engine power cost [$/kW]	50	50	50		
Engine efficiency improvement (absolute)	0%	2%	10%	(Lustbader, et al. 2019)	Applies to Class 8 trucks, consistent with 2019 FCTO Record #19006
Fuel storage specific mass [kWh/kg]	9.88	9.88	9.88	FASTSim (multiple data sources)	

FASTSim designs alternative powertrains to match the performance of the diesel vehicle

FASTSim

Diesel - acceleration (0-60 mph) based on public data and industry feedback

Diesel hybrid (HEV) – designed to have 75% of propulsion power from the engine to redu... reliance on its battery for extended road grade climbs

Fuel cell (FCEVs) - designed to be able to fully power the motor for grade operation while the hybrid battery was used for regenerative breaking

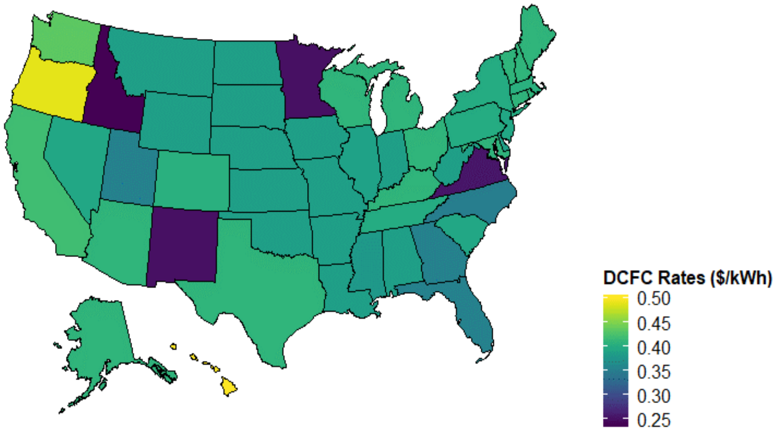
Plug-in hybrid (PHEV) – (Class 4 only) powertrain sized proportionally to Workhorse E-Gen

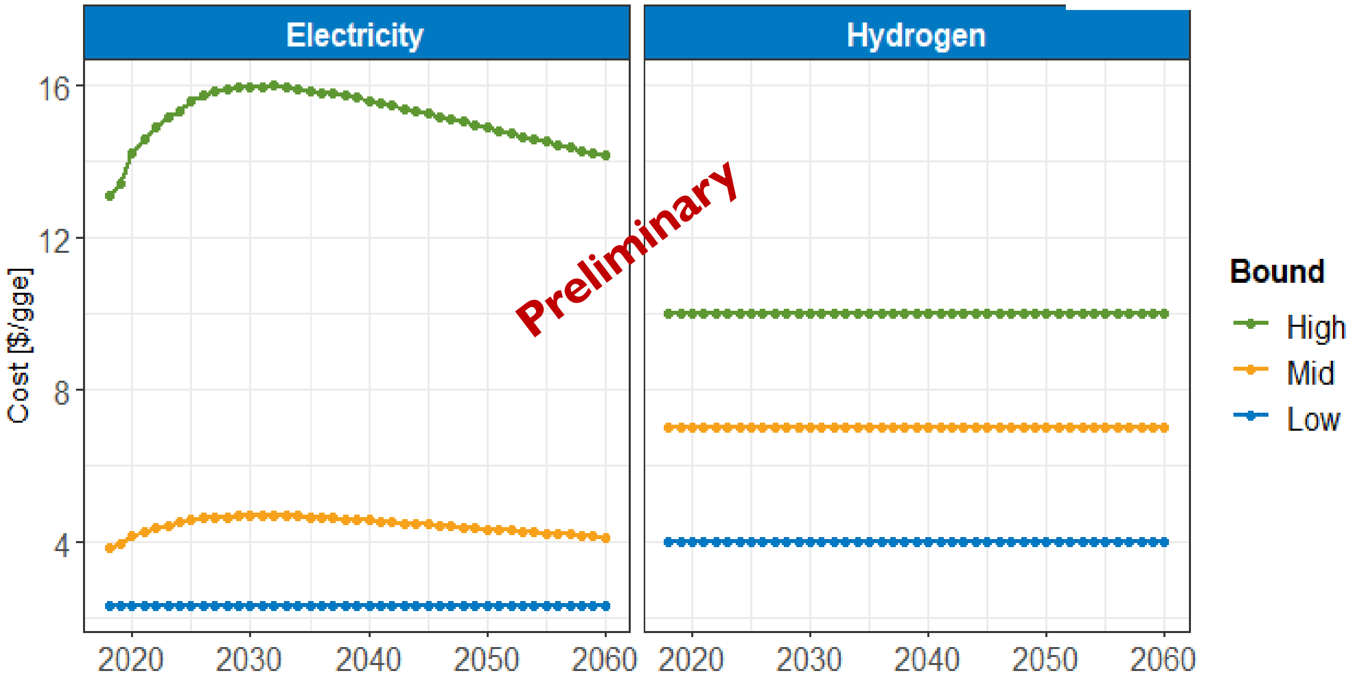
Vehicle	Drivetrain	Motor (kW)	Engine (kW)	Fuel Cell (kW)	Max weight (lb)	Acceleration 0-60 mph (s)
Class 8 truck	Diesel		317		80,000	60
Class 8 truck	CNG		327		80,000	58
Class 8 truck	HEV	79	235		80,000	60
Class 8 truck	EV	361			80,000	49
Class 8 truck	FCEV			328	80,000	55
Class 4 parcel delivery	Diesel		155		16,000	30
Class 4 parcel delivery	CNG		155		16,000	30
Class 4 parcel delivery	HEV	38	115		16,000	30
Class 4 parcel delivery	EV	146			16,000	30
Class 4 parcel delivery	FCEV			144	16,000	30
Class 4 parcel delivery	PHEV	68	82		16,000	30

Fuel prices 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	Anchored to Diesel prices and adjusted by reported CNG/Diesel price spread based AFDC data from 2016-2020*		
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





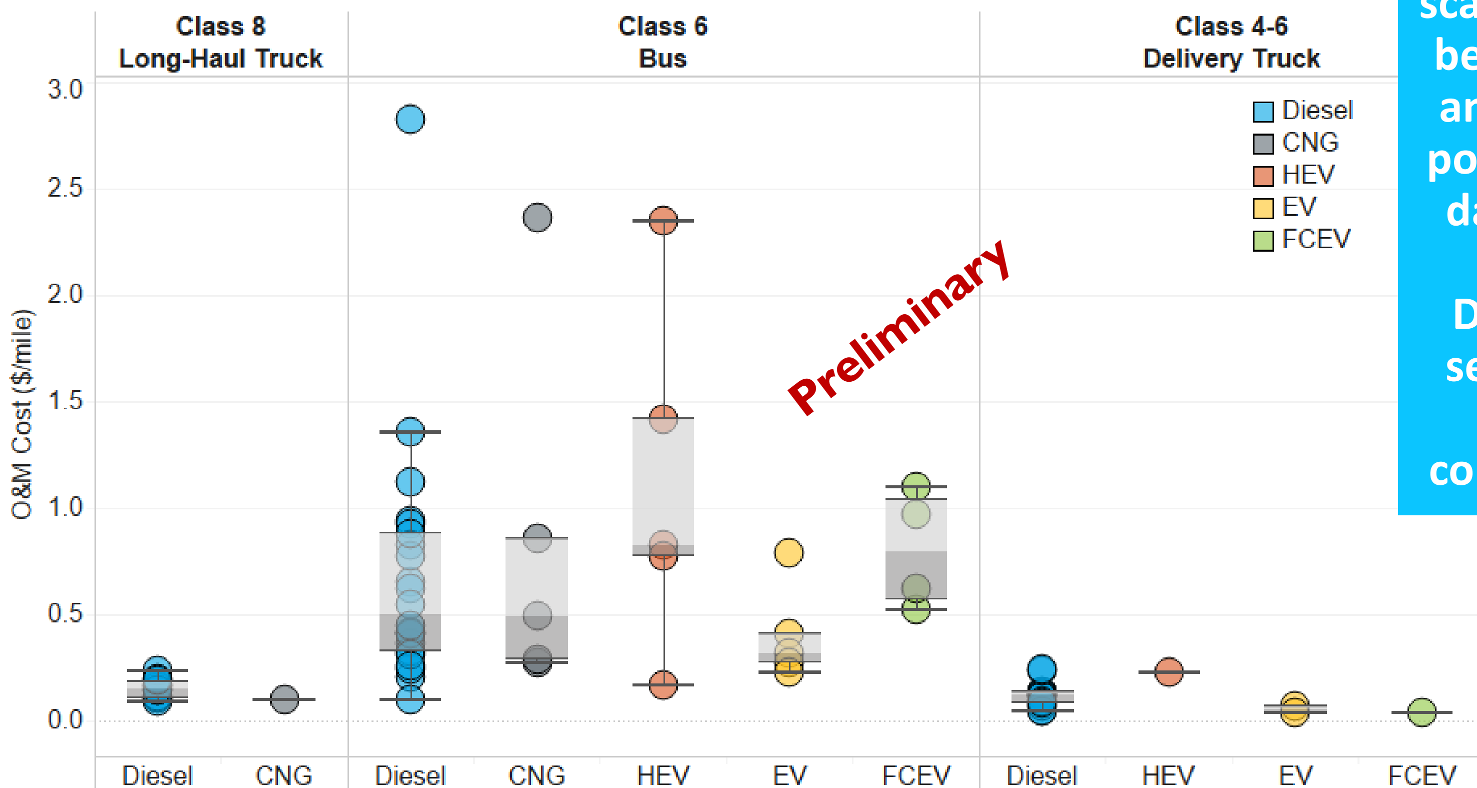
AEO Outlook CNG prices are ~25-30% lower than reported in AFDC for the same location

An actual-market-conversion-multiplier of 1.25 is used to scale the AEO Outlook CNG prices

*Recommended approach from VTO Clean Cities team that oversees AFDC database and CNG fuel prices

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

Cost ($/mi)	Bound	Diesel, HEV, PHEV	CNG	EV	FCEV
Class 4 Parcel Delivery	Low	0.057	0.049	0.046	0.046
	Mid	0.118	0.117	0.076	0.118
	High	0.233	0.231	0.111	0.270
Class 8 Tractor	Low	0.075	0.064	0.060	0.060
	Mid	0.152	0.151	0.098	0.152
	High	0.301	0.301	0.143	0.349



O&M costs based on literature data as available

Alternative powertrain costs scaled based on ratio between Diesel Bus and the alternative powertrain Bus if no data was available

Diesel, HEV, PHEV set to be the same based on comparative studies

Dwell time cost based on refueling rates, fuel storage size, and hourly dwell time cost

Refueling Rates for CNG, FCEV, and EV

	CNG (gge/min)	FCEV (kg/min)	EV (kW)	Industry Scenario
Low	-	-	-	Day trip with refueling/recharging overnight
Mid	8	10	1000	Continuous (team) driving, refueling/recharging as needed. Ideal refueling/recharging rate
High	4	5	500	Continuous (team) driving, refueling/recharging as needed. Unideal refueling/recharging rate

Lower Limits on Refueling Times

	Diesel, HEV, CNG, FCEV (min)	EV and PHEV (min)
Low	-	-
Mid	5	30
High	10	60

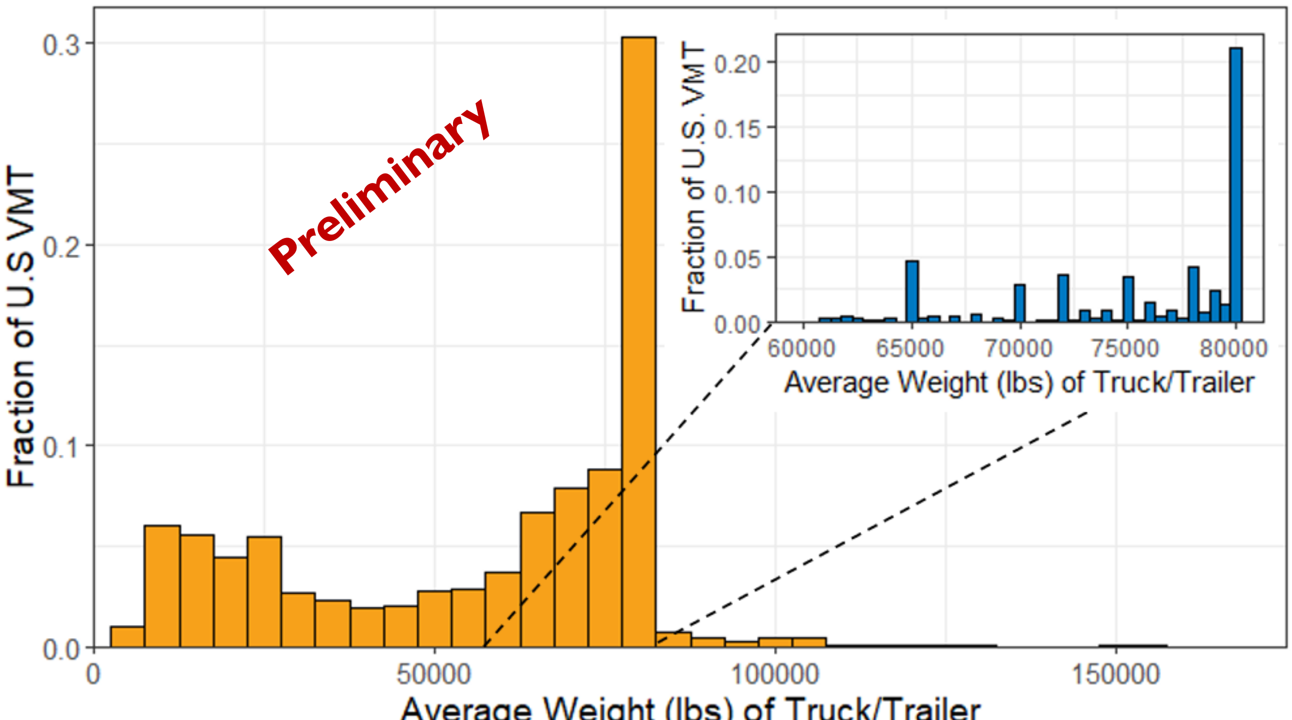
Dwell (refueling or recharging) time based on industry reported values, NREL research, and claimed targets (Nikola, Tesla).

A constant rate of $75/hr was used in this analysis.

Payload opportunity costs estimated to account for lost cargo capacity from heavier powertrains

Bound	Industry Scenario
Low	No cost, volume limited LTL shipment
Mid	Typical freight class, origin/destination, and weight break
High	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 costs account for Federal Law allowing 2,000lb capacity exceedance on Class 8 GVWR (up to 82,000lbs)

Cost of lost payload based on $/lb-mi costs estimated for each vehicle based on that vehicle's total operating cost

Levelized cost of "buying" an additional, equivalent truck is used to estimate lost payload costs

Class 8 Long Haul (750 mile range) Payload Cost Range

Model Year	Bound	HEV ($/mile)	CNG ($/mile)	EV ($/mile)	FCEV ($/mile)
2018	Low	0	0	0	0
	Mid	0	0.002-0.004	1.745-3.948	0.06-0.12
	High	0	0.002-0.004	1.877-4.097	0.067-0.126
2025	Low	0	0	0	0
	Mid	-0.001--0.001	0 - -0.001	0.477-1.055	0.019-0.036
	High	-0.001--0.001	0 - -0.001	0.527-1.12	0.022-0.038
Ultimate	Low	0	0	0	0
	Mid	-0.003--0.002	0	0.028-0.054	0
	High	-0.003--0.002	0	0.034-0.061	0

Class 8 Long Haul (300 mile range) Payload Cost Range

Model Year	Bound	HEV ($/mile)	CNG ($/mile)	EV ($/mile)	FCEV ($/mile)
2018	Low	0	0	0	0
	Mid	0	0	0.167-0.357	0
	High	0	0	0.192-0.385	0
2025	Low	0	0	0	0
	Mid	-0.002--0.001	0	0.044-0.09	0
	High	-0.002--0.001	0	0.052-0.101	0
Ultimate	Low	0	0	0	0
	Mid	-0.003--0.002	0	0	-0.008--0.005
	High	-0.004--0.002	0	0	-0.009--0.006

Payload costs based on cost to buy an equivalent truck in that region

Payload costs thus depend on region since fuel price depends on region

Payload costs decrease over time as advanced powertrain weight decreases