INCREASE YOUR H_2IQ

The #H2IQ Hour

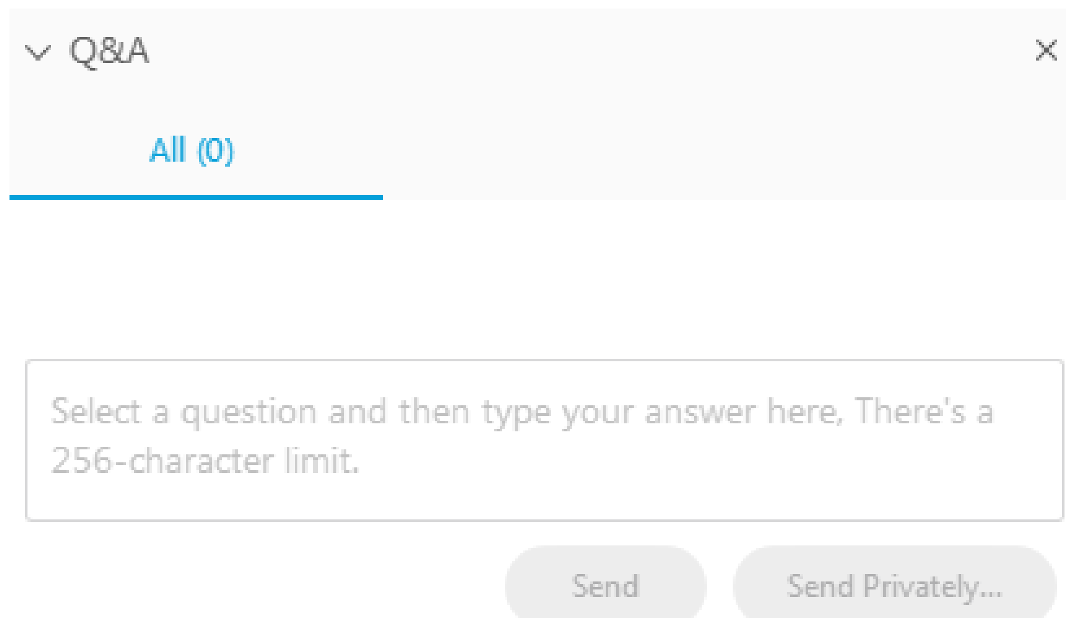
Today's Topic:

Market Segmentation of Medium- and Heavy-Duty Vehicles

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks

Chad Hunter, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, Chen Zhang
National Renewable Energy Laboratory

September 29, 2021

https://www.nrel.gov/docs/fy21osti/71796.pdf

NREL at-a-Glance

2,926

Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

World-class

facilities, renowned technology experts

More than **900**

Partnerships

with industry, academia, and government

Campus

operates as a living laboratory

Thanks to all our peer reviewers and collaborators that have supported this project

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Overview

Executive Summary

Approach

Results

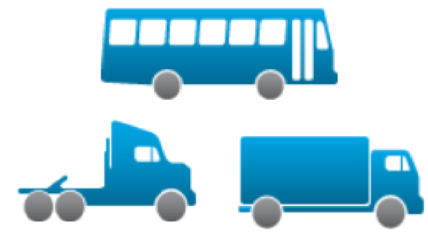
Conclusions

NREL's FASTSim and SERA Models Combined for TCO Analysis

FASTSim

NREL's T3CO Framework

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

Integration with Other Projects:
- Coordinated with VTO/HFTO/BETO transportation decarbonization analysis project

Regional TCO analyzed using established models and OEM specifications

FASTSim data flow combines NREL's Fleet DNA database with EERE technology cost and performance data

Technology Cost Data

Technology Performance Data

Fleet DNA

FASTSim

Results:

- Fuel economy
- Weight
- Vehicle costs and MSRP

NREL's Fleet DNA database used for drive cycle data

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

FASTSim results for:

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

Total cost of ownership modeling in SERA

Cost Data

Vehicle Price
FASTSim

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

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

Payload Capacity 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 (BEV)
	Fuel Cell Electric (FCEV)
	Plug-in Hybrid (PHEV)

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

Scenario design for TCO modeling reflects typical business operating models

SERA

Dry van general freight (e.g., package delivery)

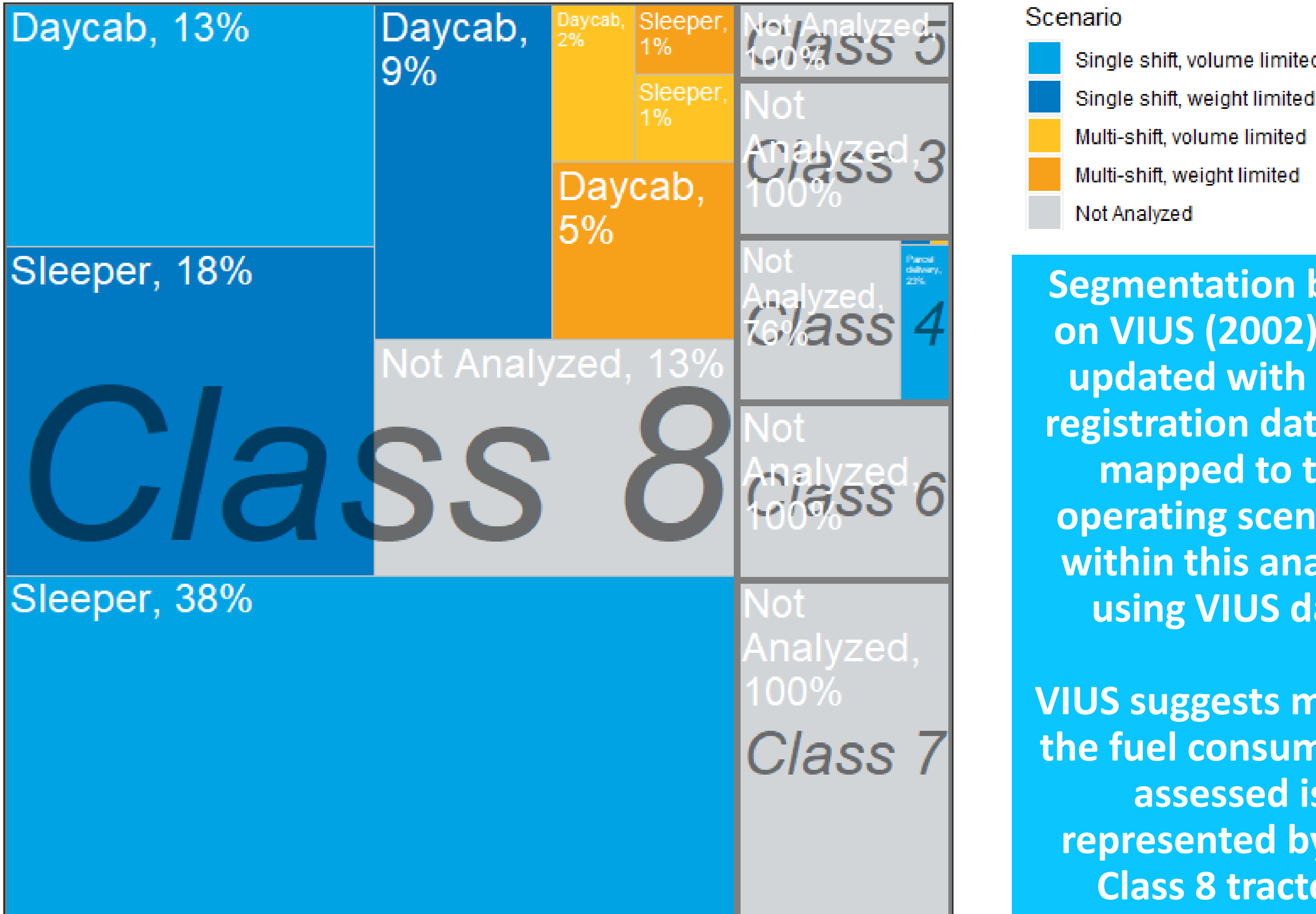
Operating Shift

Payload Limitation	No Dwell Time Cost	Dwell Time Cost Incurred
No Payload Capacity Cost	Single Shift, Volume Limited	Multi-Shift, Volume Limited
Payload Capacity Cost Incurred	Single Shift, Weight Limited	Multi-Shift, Weight Limited

Bulk haulers or heavy haulers with team driving (e.g., beverage delivery, reefers, fuel delivery)

Four scenarios designed to reflect potential industry business operating scenarios and understand which powertrains are most economically attractive for each

Trucks assessed in this report capture a majority of the M/HD fuel consumption



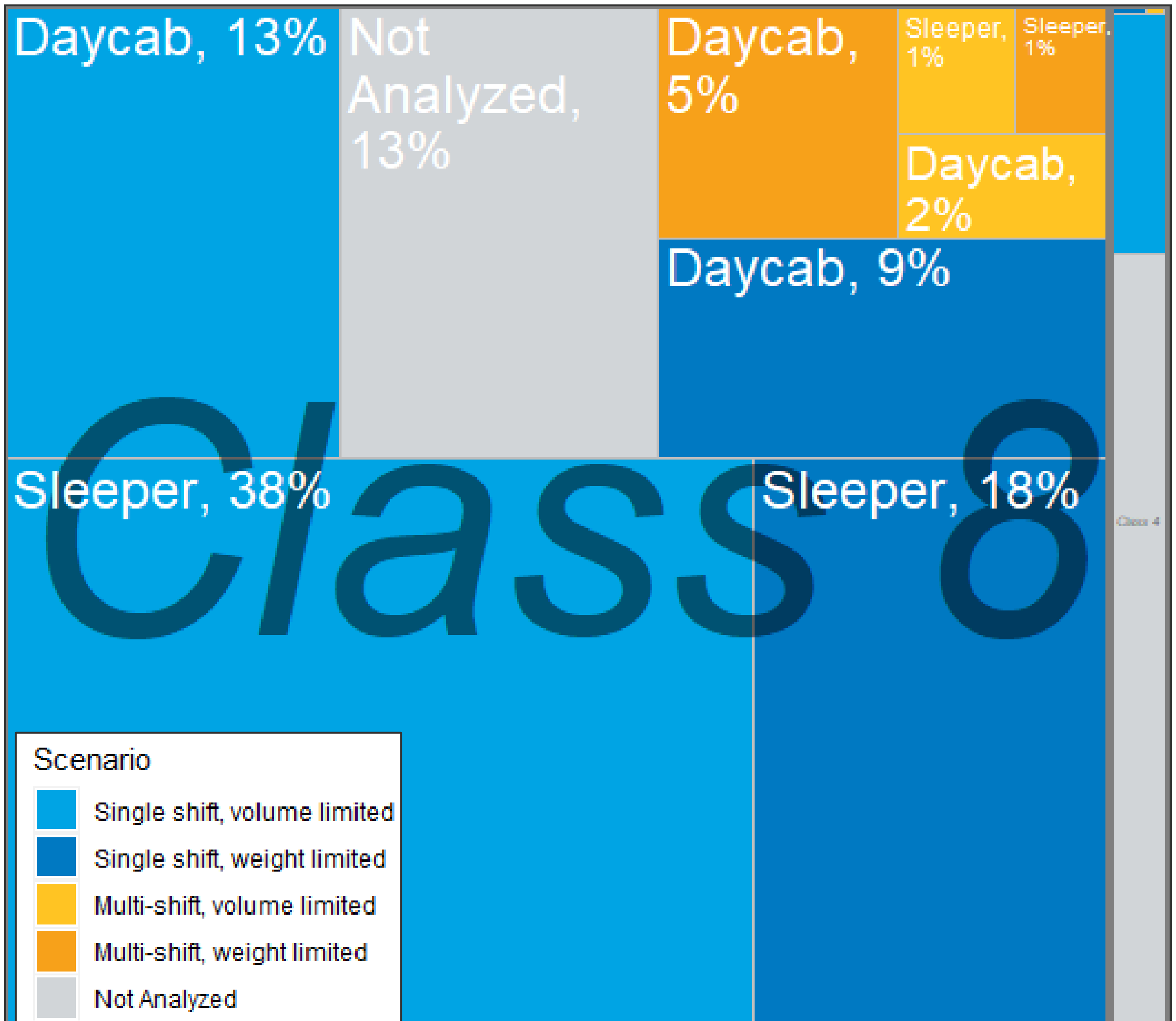
Segmentation based on VIUS (2002) data updated with Polk registration data and mapped to the operating scenarios within this analysis using VIUS data

VIUS suggests most of the fuel consumption assessed is represented by the Class 8 tractors

Trucks assessed in this report capture a majority of the M/HD fuel consumption

Polk adjusted VIUS Scenario Estimation for Class 8 and Class 4 Trucks

- Size = total fuel consumption across Class 8 and Class 4 (slide 55 for all)
- % = scenario's fraction of fuel use by Class



Operation Data Summary:

- Weight-Limited (Class 8 Tractors)
  - Polk adjusted VIUS analysis indicates **33%** of Class 8 tractor fuel usage could be used by tractors that weigh-out
  - NACFE (2015) indicates **2-10%** of Class 8 tractors may weigh-out
  - Schoettle et al. (2016) survey indicates **54.6%** of Class 8 tractors may weigh-out
- Multi-Shift (Class 8 and Class 4)
  - VIUS (2002) indicates **13%** of Class 8 tractor fuel usage could be used by tractors multi-shift; **~1%** for Class 4 Parcel Delivery
  - Schoettle et al. (2016) surveyof Class 8 tractors reports **6.2%** of routes are long-haul team-drivers, **34.4%** are long-haul with overnight stays

Method: Weight and Shift Operation inferred based on VIUS reported truck weight and VMT (mi/yr)

- Class 8 Sleeper (500+mile): Multi-shift is >200k mi/yr
- Class 8 Daycab (300-mile): Multi-shift is > 100k mi/yr
- Class 4 Parcel (120-mile): Multi-shift is >50k mi/yr
- Weight-limited based on GVWR Class limit

Overview

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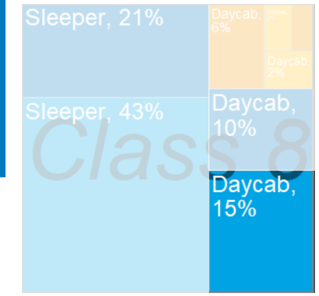
Results – Class 8 Short Haul (300-mile range)

Conclusions

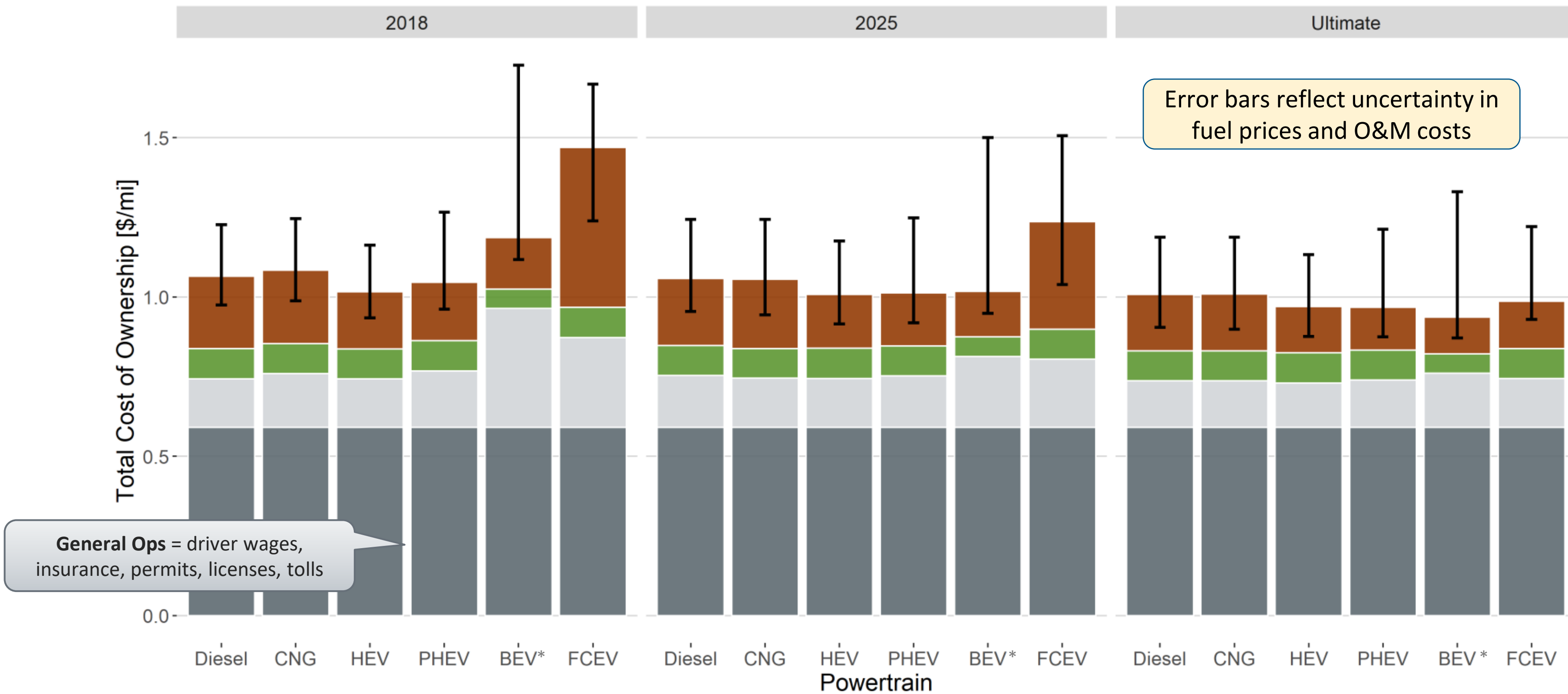
Scenario 1: Single-Shift, Volume-Limited
Class 8 Short Haul (300-mile range) Results



Scenario Parameters

- Class 8 Short Haul (300-mile) in Mid-Atlantic Region
- 60,000 mi/yr (230 mi/day)
- 16.7 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

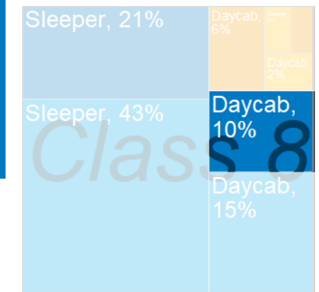
BEVs are lowest cost zero-emission options for short-haul. FCET costs driven by fuel and up-front purchase cost which decrease if targets are achieved



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

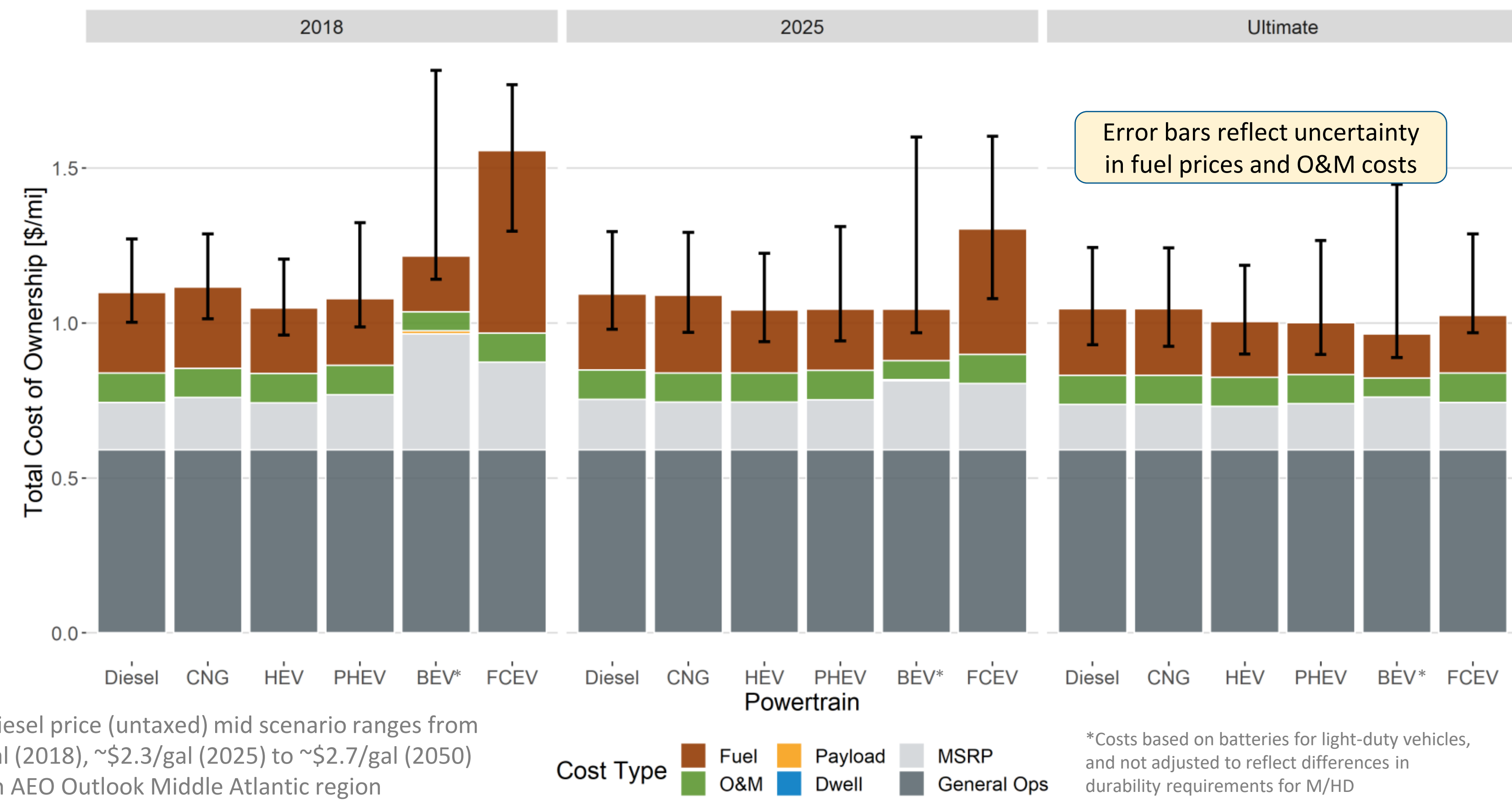
Scenario 2: Single-Shift, Weight-Limited
Class 8 Short Haul (300-mile range) Results



Scenario Parameters

- Class 8 Short Haul (300-mile) in Mid-Atlantic Region
- 60,000 mi/yr (230 mi/day)
- 16.7 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

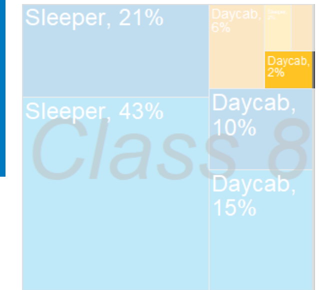
Lost payload capacity costs are not significant for a Class 8 short haul ZEVs due to 2,000lb Federal Exemption for non-diesel powertrains



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

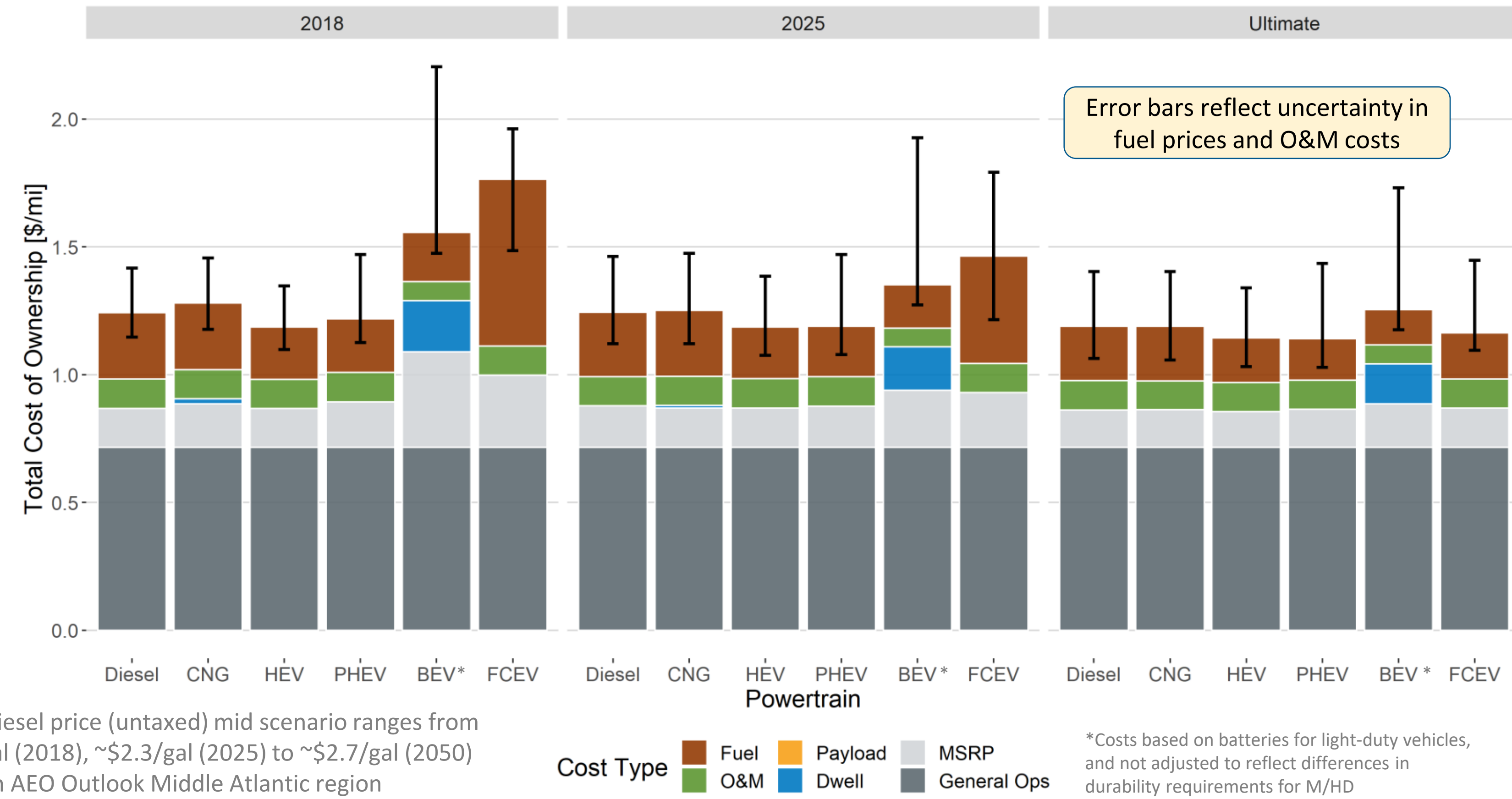
Scenario 3: Multi-Shift, Volume-Limited
Class 8 Short Haul (300-mile range) Results



Scenario Parameters

- Class 8 Short Haul (300-mile) in Mid-Atlantic Region
- 100,000 mi/yr (380 mi/day)
- 10 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

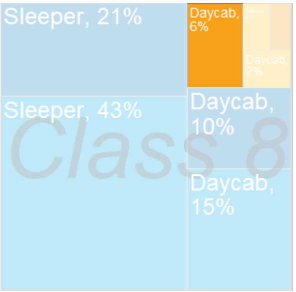
FCET dwell time is not significant, and is less than CNG due to lower onboard storage (higher fuel economy)



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

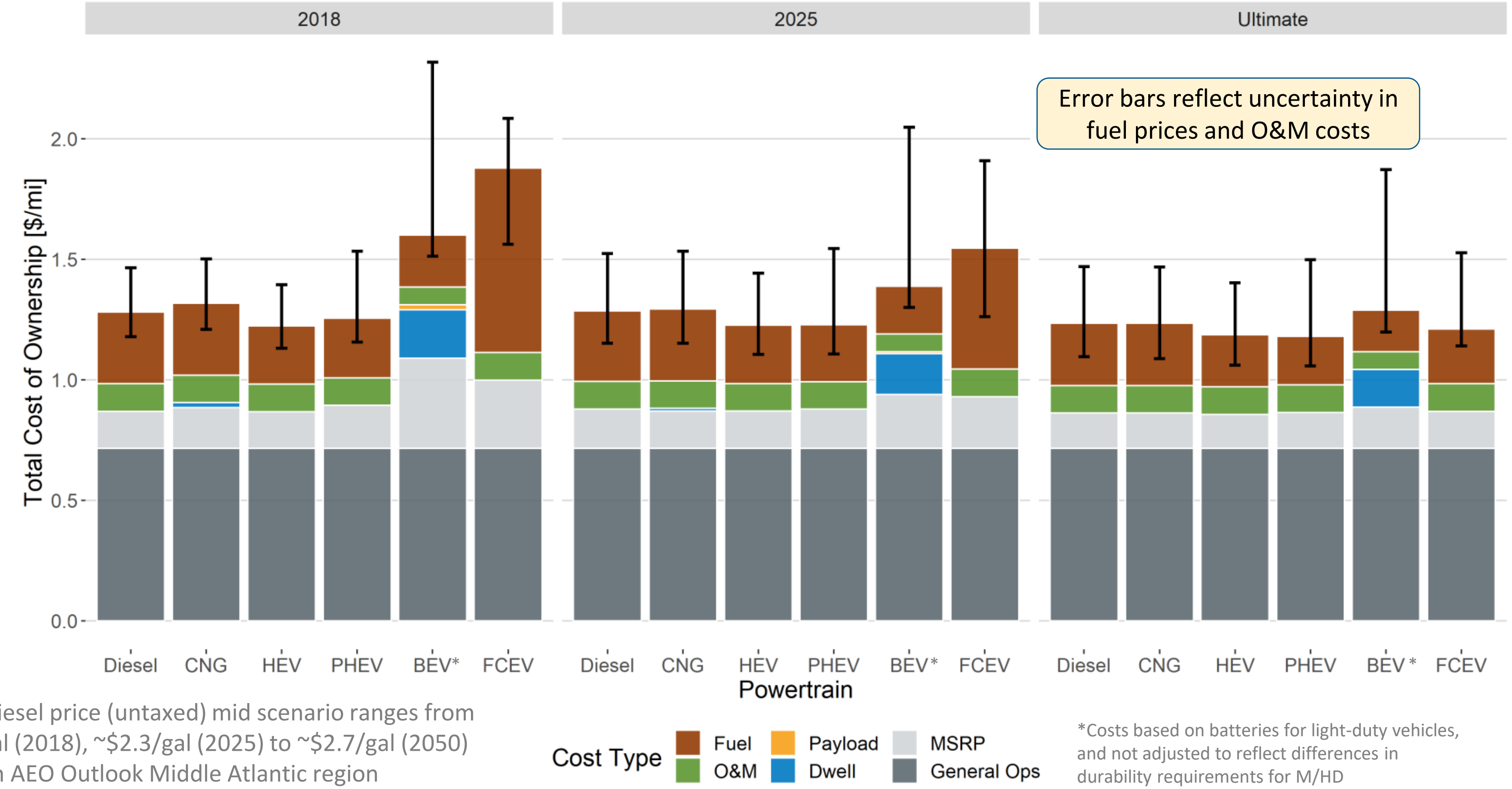
Scenario 4: Multi-Shift, Weight-Limited
Class 8 Short Haul (300-mile range) Results



Scenario Parameters

- Class 8 Short Haul (300-mile) in Mid-Atlantic Region
- 100,000 mi/yr (380 mi/day)
- 10 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

Dwell time costs are only significant for the EV. Lost payload capacity costs are minimal for all powertrains



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

Overview

Executive Summary – Results: Class 8 Long Haul (750-mile range)

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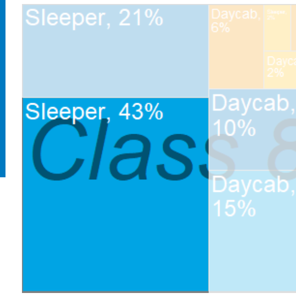
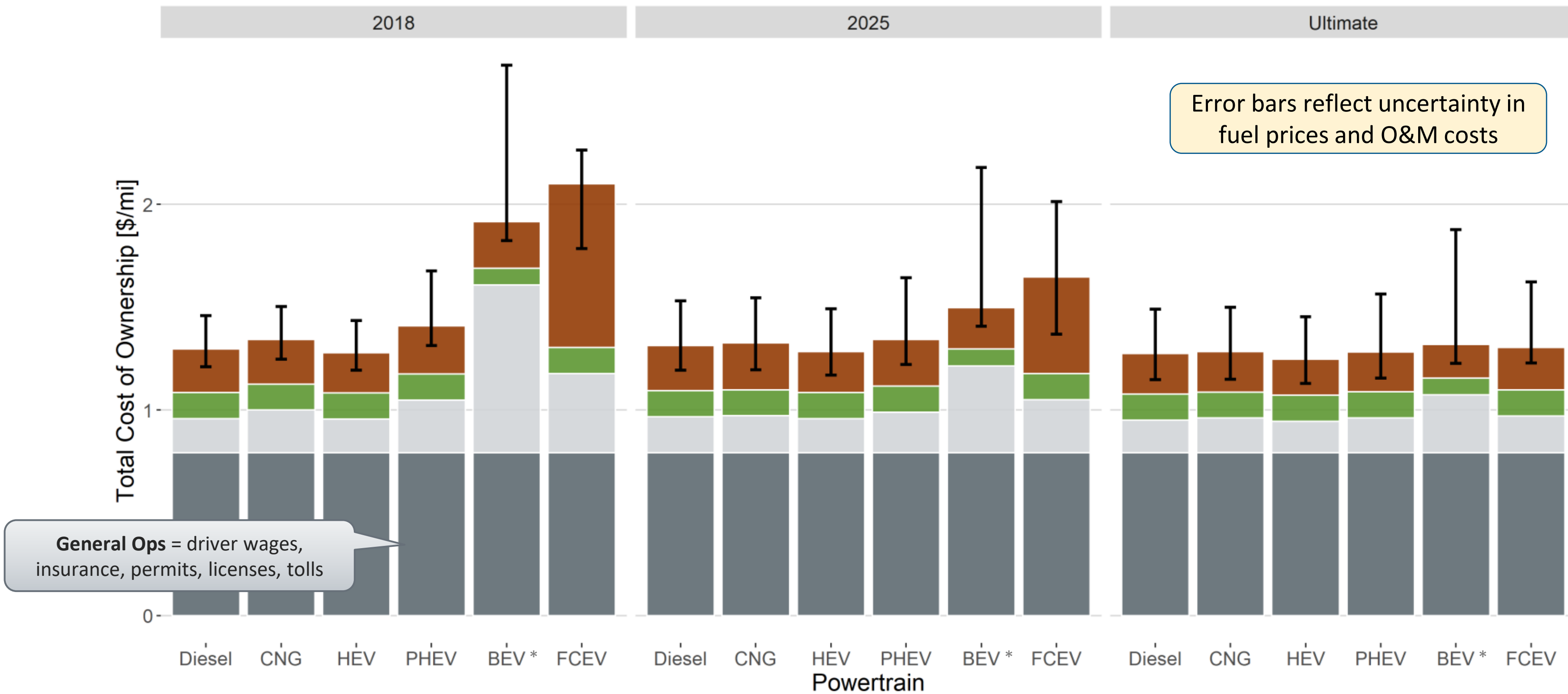
Scenario 1: Single-Shift, Volume-Limited
Class 8 Long Haul (750-mile range) Results



Scenario Parameters

- Class 8 Long Haul (750-mile) in Mid-Atlantic Region
- 150,000 mi/yr (580 mi/day)
- 6.7 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

FCET is lowest cost ZEV for long-haul. BEV MSRP driven by large on-board battery

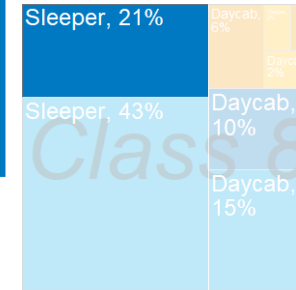


Cost Type: Fuel, O&M, Payload, Dwell, MSRP, General Ops

Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

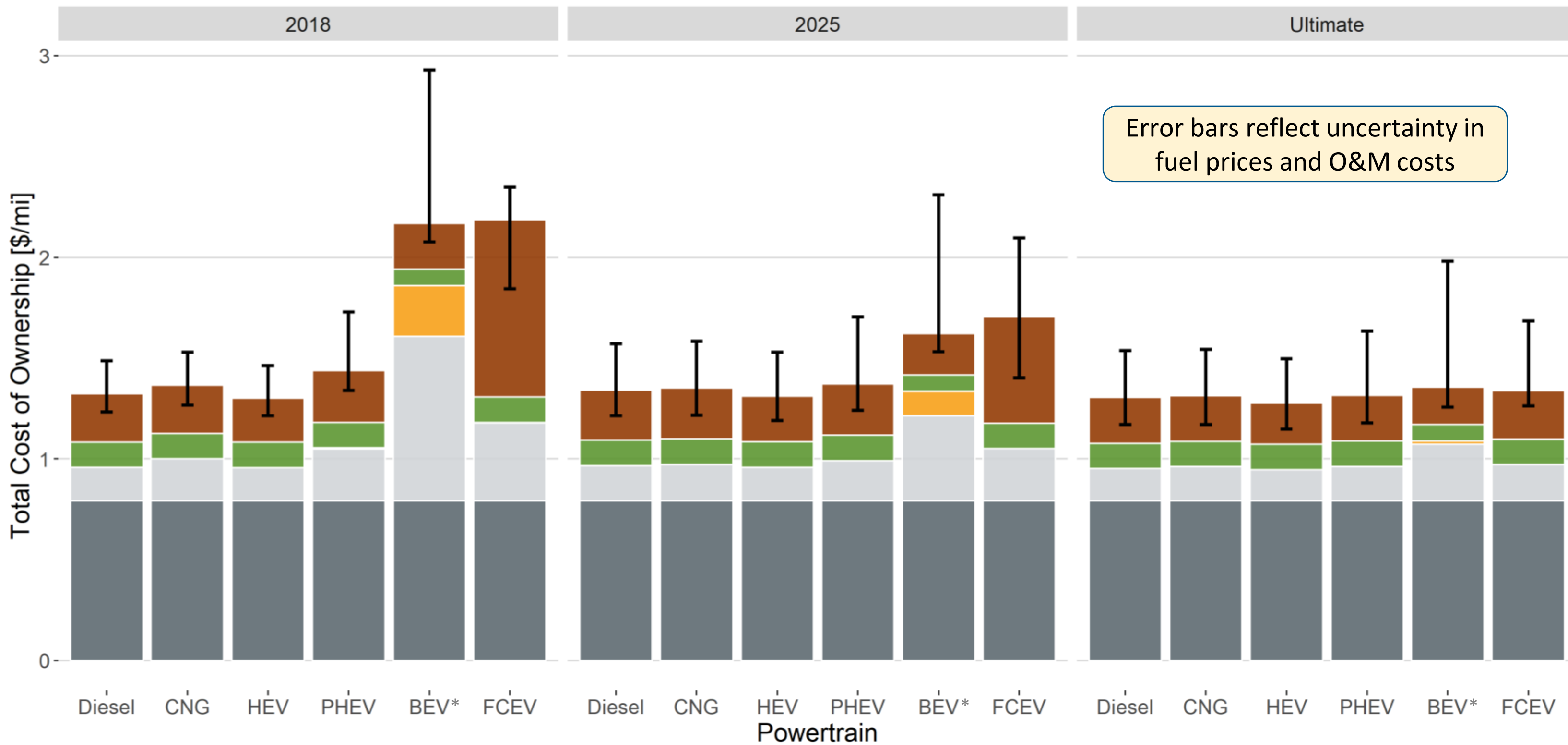
Scenario 2: Single-Shift, Weight-Limited Class 8 Long Haul (750-mile range) Results



Scenario Parameters

- Class 8 Long Haul (750-mile) in Mid-Atlantic Region
- 150,000 mi/yr (580 mi/day)
- 6.7 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

Minimal payload impacts for the FCET due to 2,000lb Federal Exemption for non-diesel powertrains. Battery EV payload capacity cost is minimized if Ultimate battery targets are achieved

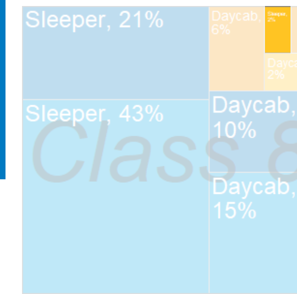


Cost Type: Fuel, O&M, Payload, Dwell, MSRP, General Ops

Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

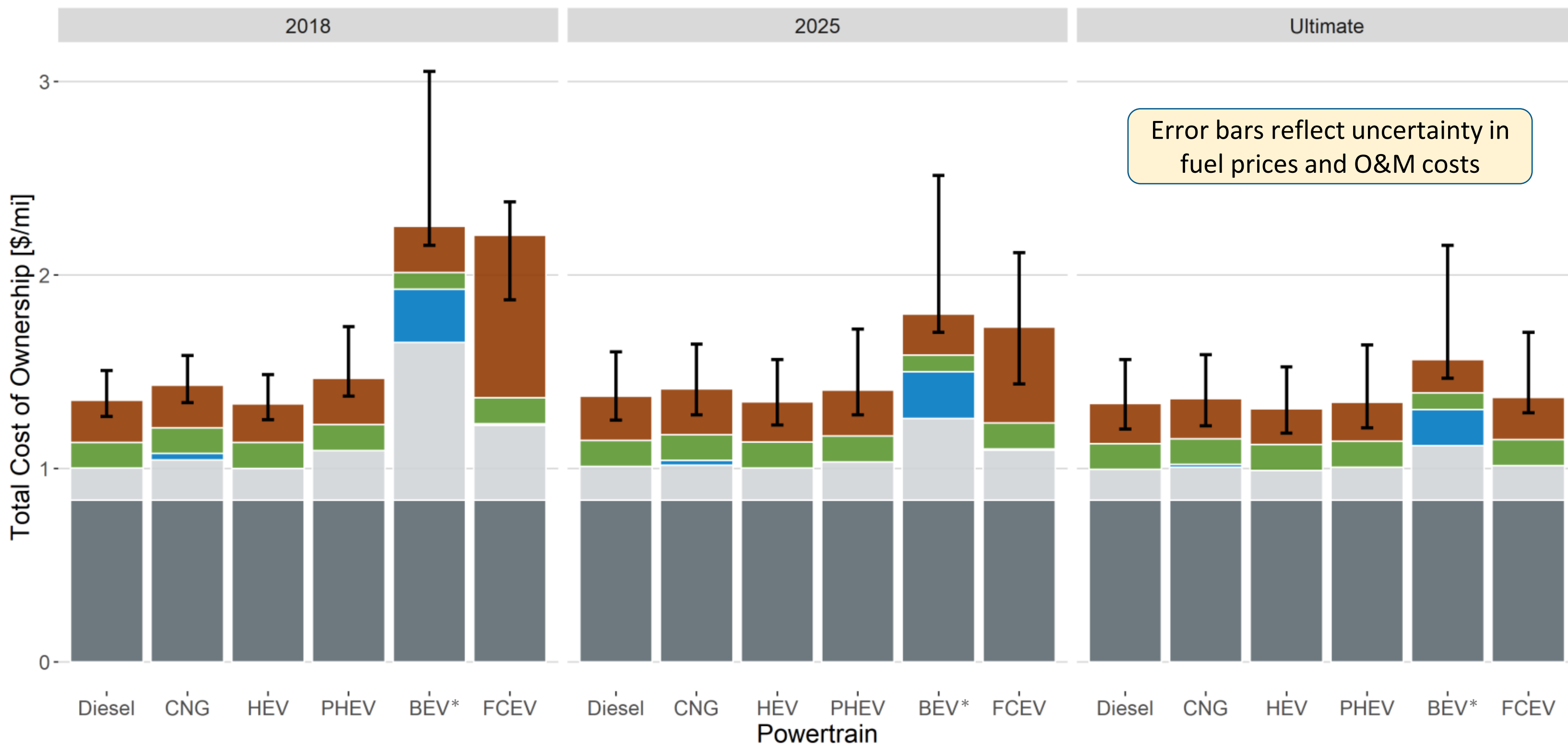
Scenario 3: Multi-Shift, Volume-Limited
Class 8 Long Haul (750-mile range) Results



Scenario Parameters

- Class 8 Long Haul (750-mile) in Mid-Atlantic Region
- 200,000 mi/yr (770 mi/day)
- 5 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

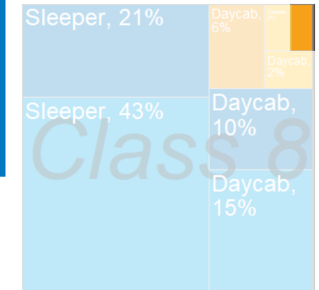
FCET dwell time is not significant, less than CNG due to lower onboard storage (higher fuel economy). Long EV charging time due to large onboard battery



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

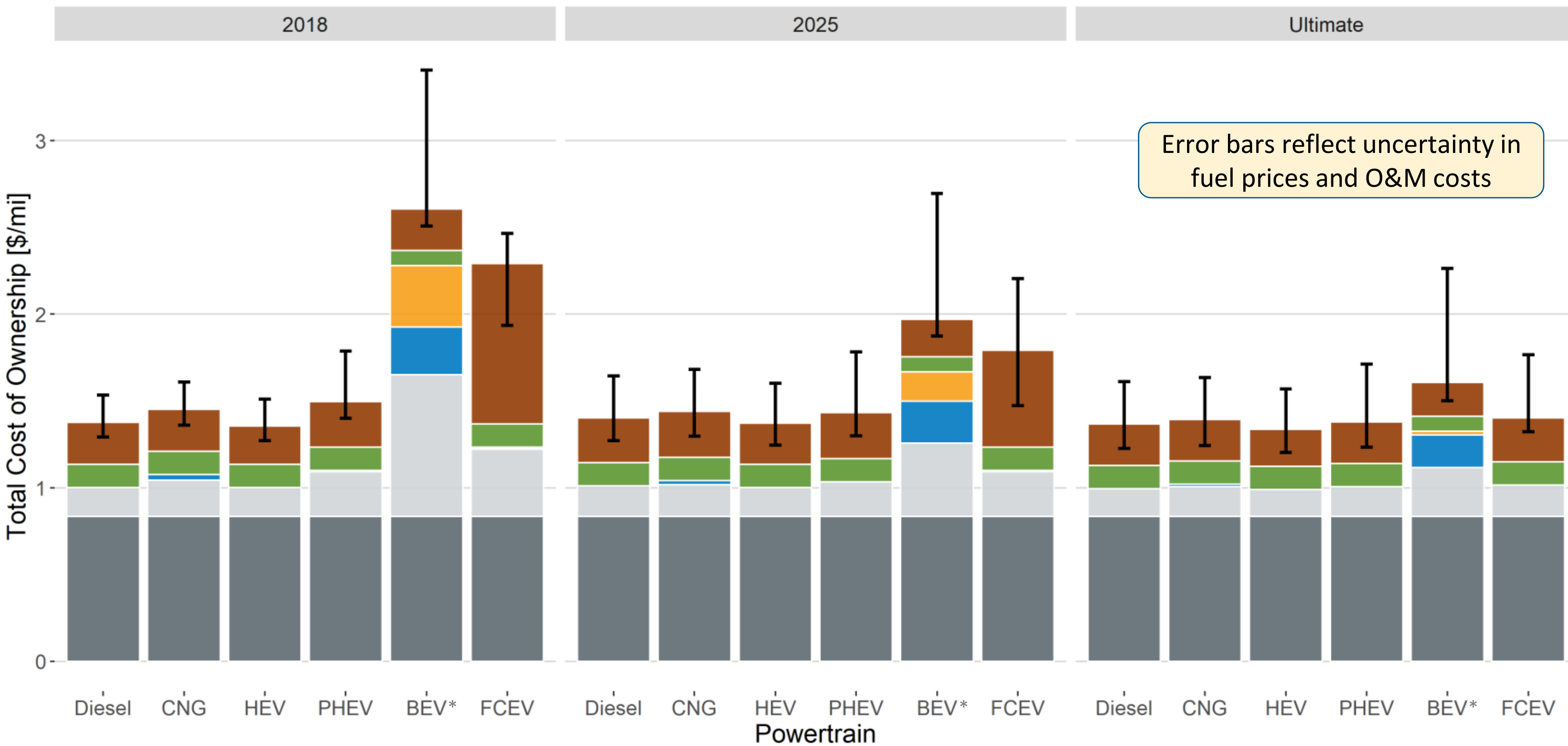
Scenario 4: Multi-Shift, Weight-Limited
Class 8 Long Haul (750-mile range) Results



Scenario Parameters

- Class 8 Long Haul (750-mile) in Mid-Atlantic Region
- 200,000 mi/yr (770 mi/day)
- 5 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

FCET is lowest cost ZEV, due to minimal impact of dwell and lost payload.



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

Overview

Executive Summary – Results: Class 4 Parcel Delivery

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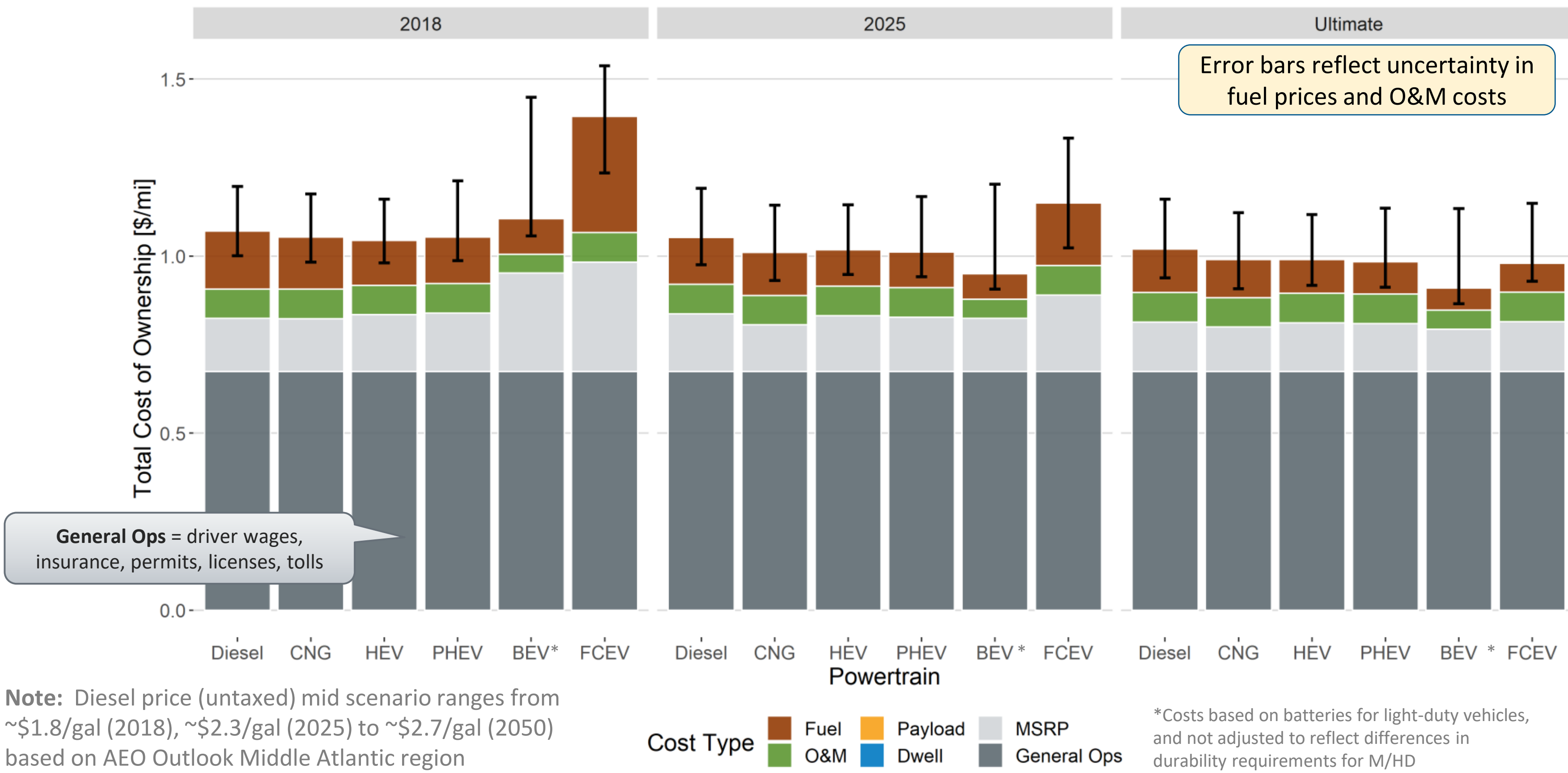
Scenario 1-2: Single-Shift Operation
Class 4 Delivery (120-mile range) Results

Scenario Parameters

- Class 4 Parcel Delivery in Mid-Atlantic Region
- 25,000 mi/yr (80 miles/day)
- 12 year life (300k miles)
- Payload Cost = N/A, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

BEV is lowest cost powertrain. FCET costs driven by fuel, MSRP, and O&M.



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

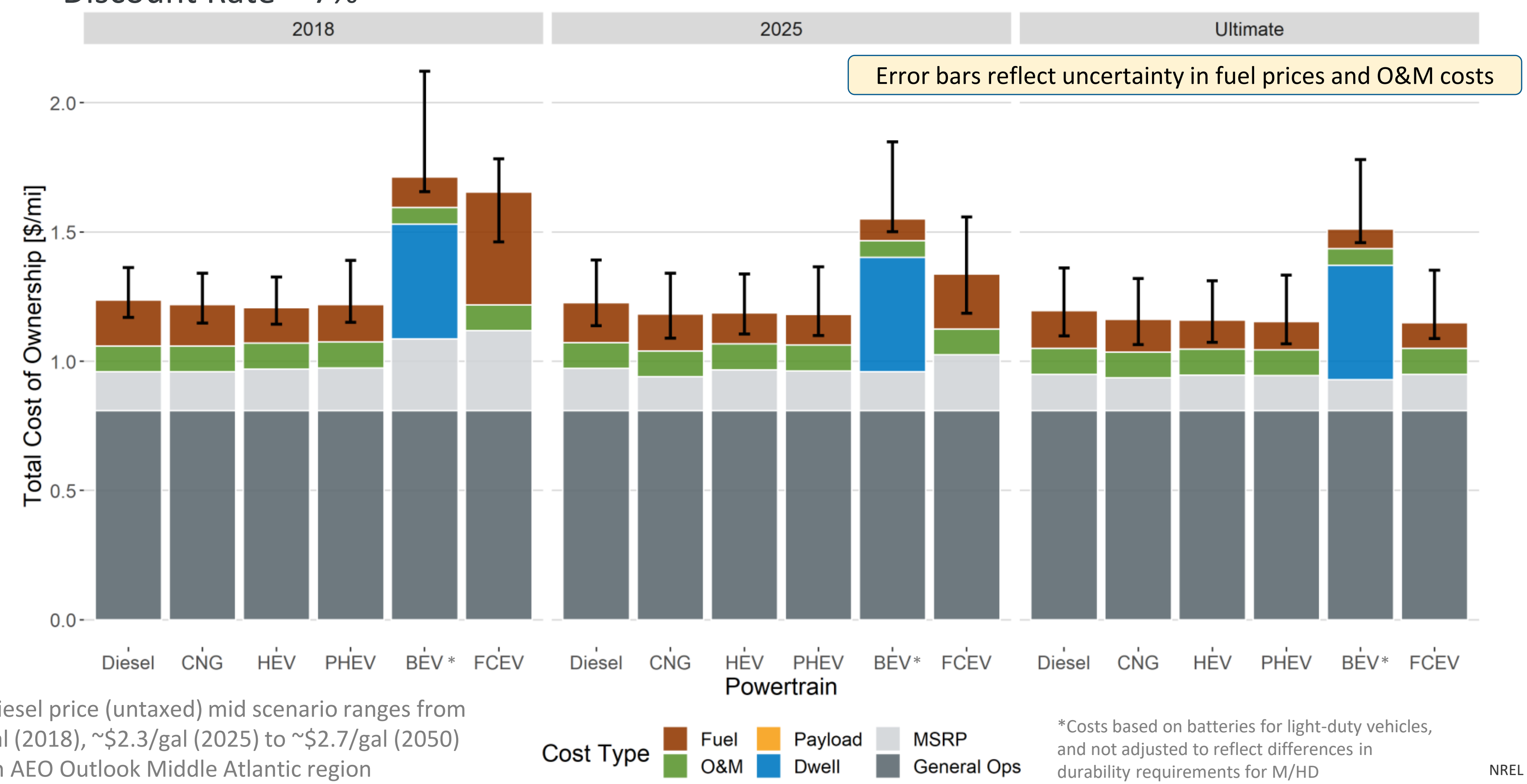
*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

Scenario 3-4: Multi-Shift Operation
Class 4 Delivery (120-mile range) Results

Scenario Parameters

- Class 4 Parcel Delivery in Mid-Atlantic Region
- 50,000 mi/yr (160 miles/day)
- 6 year life (300k miles)
- Payload Cost = N/A, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

FCET is lowest cost zero emission powertrain due to lower dwell time.



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

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BEVs and FCEVs are complementary solutions to deep decarbonization in M/HD segments

T3CO

Overall

- M/HD trucks with battery and fuel cell electric powertrains could be economically competitive with diesel powertrains under several operating scenarios, especially for shorter-range applications (<500-mile Class 8 tractors, 120-mile Class 4 delivery) if high diesel prices (>$3/gal) and low hydrogen/electricity prices are realized
- Battery electric powertrains may be best for shorter range applications or when dwell time is not a concern and are complemented by fuel cell powertrains that may be better for longer ranges or operating scenarios that require higher uptime
- Battery price reduction for BEVs and hydrogen fuel price reduction for FCEVs are key to accelerating M/HD vehicle electrification

Specifics

- **Electricity price and hydrogen fuel price** are key factors to the TCO of all trucks and M/HD refueling/recharging cost reduction/management should be a key focus area for R&D
- **Lost payload capacity cost** for Class 8 long haul (500+ mile) FCEVs or Class 8 short-haul (300-mile) battery EVs is small due to the 2,000 lb exemption for alternative powertrain trucks[1]
- **In the Class 8 short haul (300-mile range) and Class 4 parcel delivery (120-mile range) vocations, BEVs are the lowest cost ZEV** if dwell time costs are not incurred and Ultimate targets are achieved
- **If dwell time costs are incurred, FCEVs are the lowest cost ZEV** for Class 4 parcel delivery, Class 8 short haul (300-mile), and Class 8 long haul (500-mile)
- **In the Class 8 long haul (500-mile range) vocation, FCEVs and BEVs are very competitive with diesel** if targets are met (regardless of dwell and payload costs)
- **In the Class 8 long haul (750-mile range) vocation, FCEVs are the lowest cost ZEV** if targets are met (regardless of dwell and payload costs)

1. Fixing America's Surface Transportation (FAST) Act Truck Size and Weight Provisions. No sunset date currently set. Applies to CNG, EVs. Assume applies to FCEVs.

Thank You

www.nrel.gov

Contact: michael.penev@nrel.gov

Full Report Available Here:
https://www.nrel.gov/docs/fy21osti/71796.pdf

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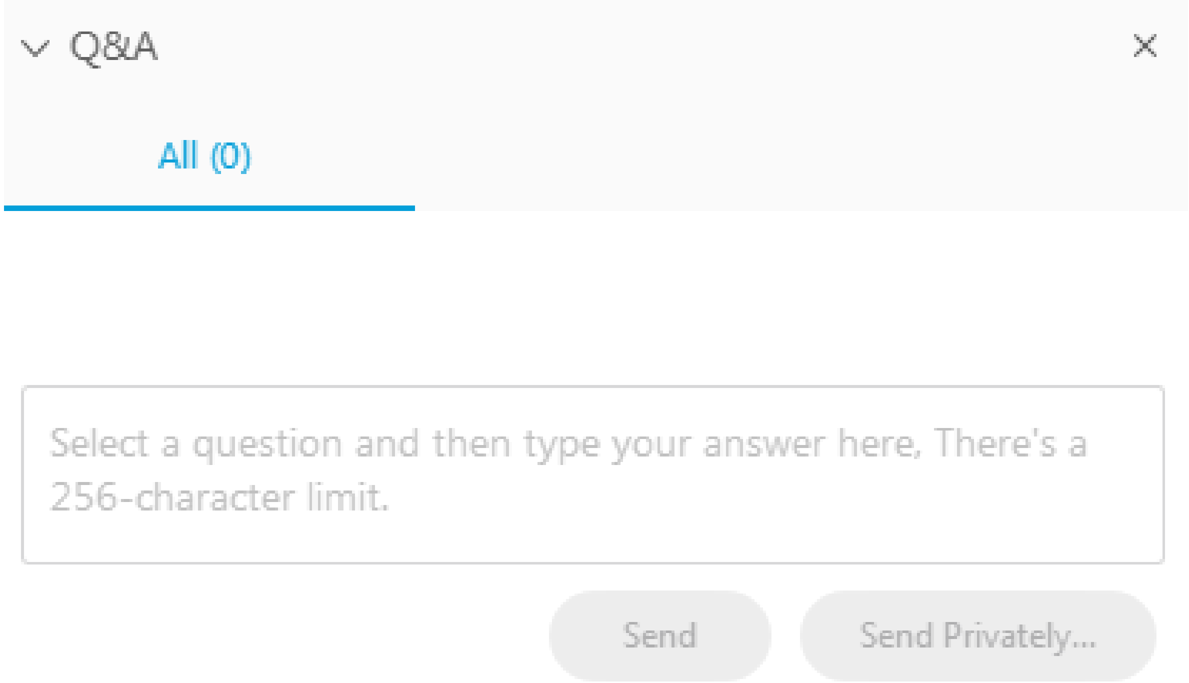
Transforming ENERGY

The #H2IQ Hour
Q&A

Please type your questions into the **Q&A Box**



INCREASE YOUR H_2IQ

The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov

Backup

Context, Constraints, and Limitations

Context

- Input data and assumptions can highly impact the results of any TCO analysis
- M/HD vehicle data has greater uncertainty and less availability than LD vehicle data

Constraints

- Results are dependent on data that is rapidly evolving
- Aiming to use the most updated, VTO/HFTO approved, input assumptions for key data

Limitations

- Key data gaps and challenges are summarized below
- This analysis aims to document these data challenges and help prioritize future R&D

Infrastructure Costs

- Are site-specific, not well studied for M/HD fleets, and non-linear
- On-site storage may be needed to avoid peak demand charges
- **We assume a low/med/high fuel price bounds based on available data**
- Error bars represent spread in fuel costs

Refueling Dwell Time Costs

- Important for fleets (*VTAP Multi-Lab TCO Project Stakeholder Feedback*)
- Lost time could result in lost revenue, larger fleet sizes, or lower driver wages
- **We assume $75/hour for dwell time costs and use average charging or refueling rates to determine vehicle refueling downtime**

Maintenance & Repair Data:

- Limited data available for advanced powertrain trucks
- Most comprehensive data available is for transit buses (demonstration vehicles) with rapid learning and cost reduction
- **Where data is unavailable, we use transit bus data to scale diesel costs**

Lost Payload Capacity Costs

- Top of mind for fleets (*VTAP Multi-Lab TCO Project Stakeholder Feedback*)
- We account for total mass difference between diesel trucks and electrification (engine, aftertreatment, fluids, etc.)
- **We compute levelized cost to purchase additional trucks to meet the fleet's needs**

Vehicles or VMT by Operating Scenario

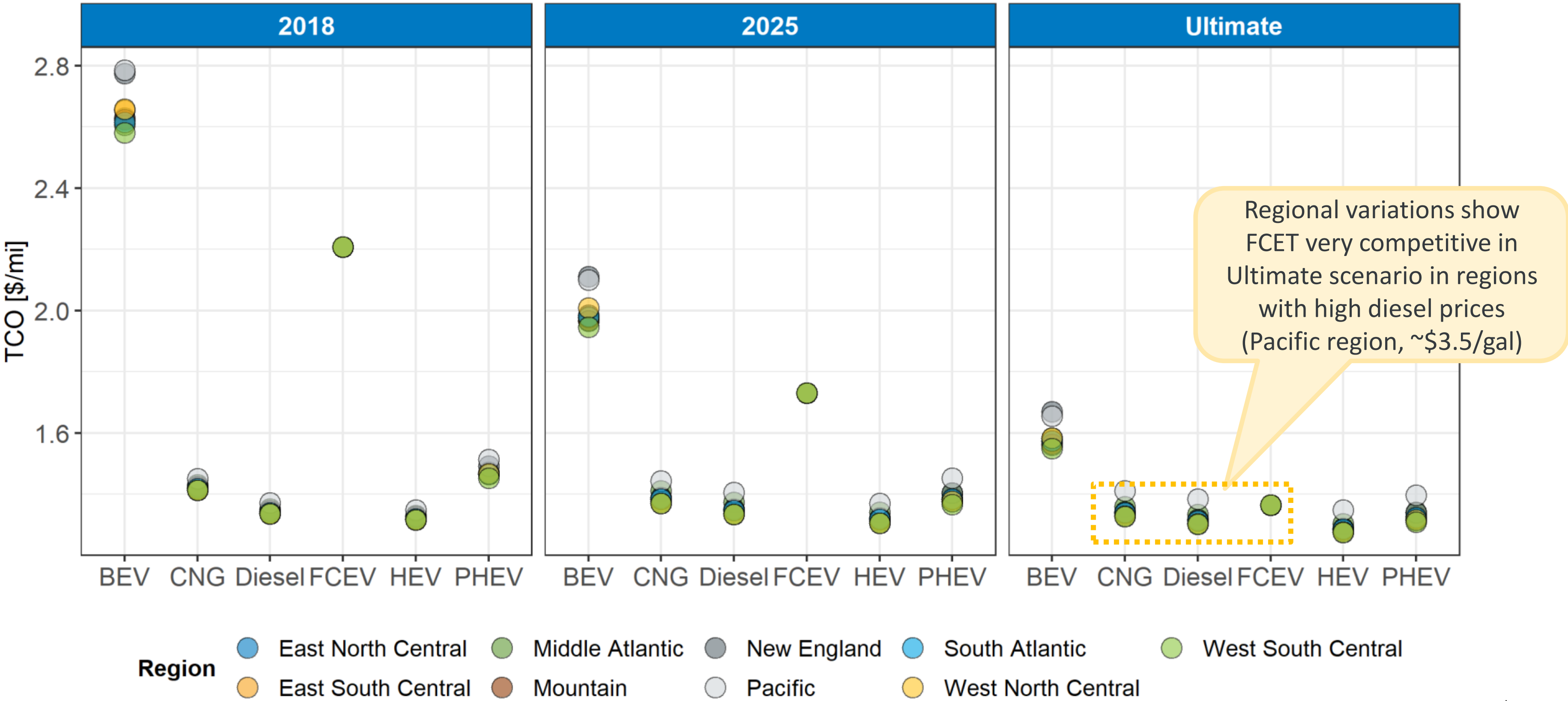
- There is limited data on the number of vehicles or percent of VMT in each operating scenario (single-shift vs multi-shift, cubed-out vs weight-limited)
- VIUS (2002), NACFE (2015), and Schoettle et al. (2016) data used to summarize vehicle and fuel use in each operating scenario but show large uncertainty
- Autonomous vehicles and supply-chain logistics evolution impact on future M/HD duty-cycles is highly uncertain and warrants further research

Scenario 4: Multi-Shift, Weight-Limited Class 8 Long Haul (750 mile range) Results

SERA

Total Cost of Ownership Regional Analysis

- Multi-Shift, Weight-Limited Scenario regional differences in TCO for a Class 8 long haul tractors (750 mile range) traveling 200,000 mile/yr
- FCEV has no regional dependence (fuel prices are regional except for hydrogen)
- Regional variations show FCET competitive in Ultimate scenario in regions with high diesel prices (Pacific region)

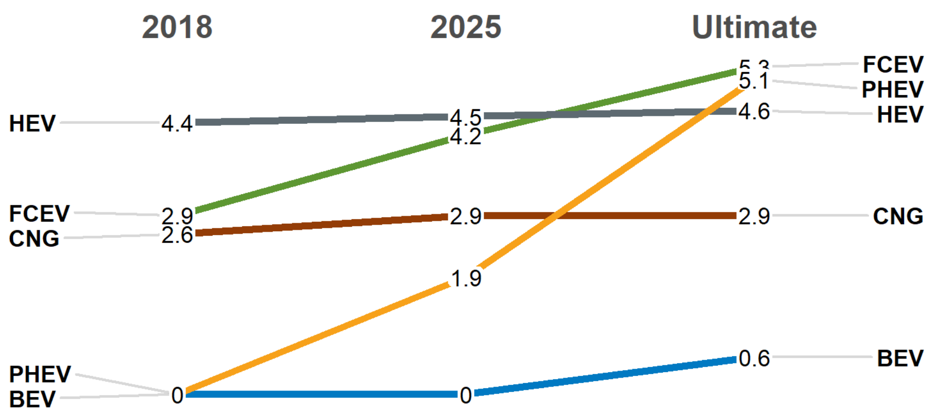


Scenario 4: Multi-Shift, Weight-Limited
Class 8 Long Haul (750 mile range) Results

SERA

Breakeven Fuel or Electricity Price ($/gge)

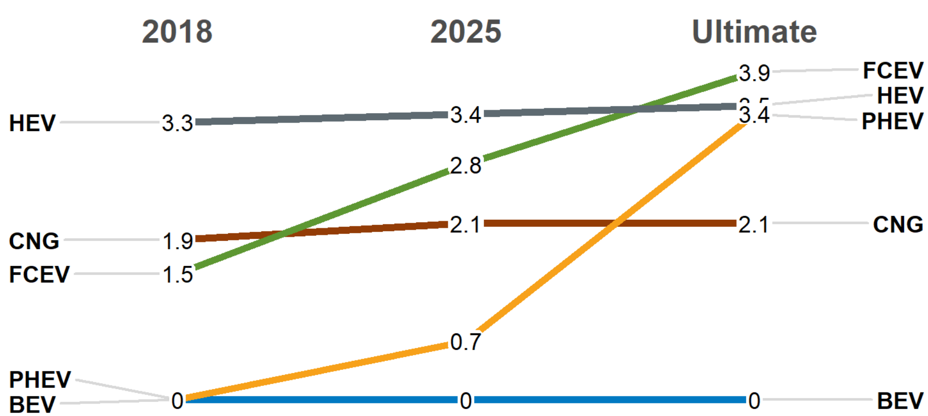
At Diesel Price of $4/gal ($3.52/gge)



In this scenario, 2050 targets must be achieved for FCEVs to achieve TCO parity with diesel

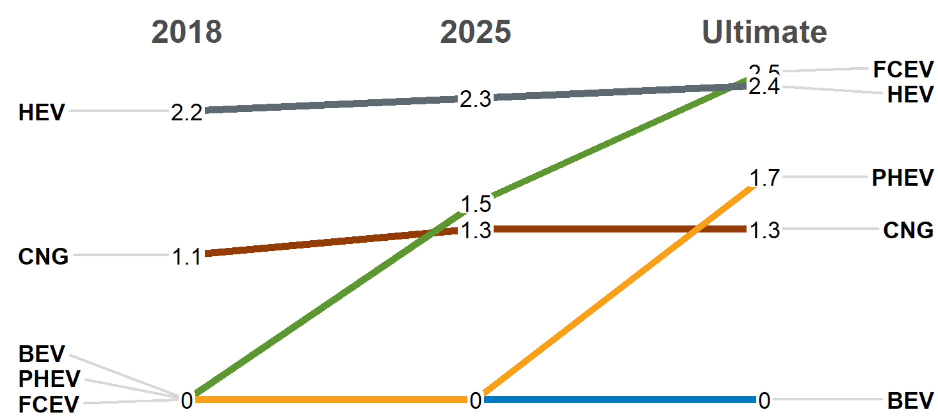
Breakeven Fuel or Electricity Price ($/gge)

At Diesel Price of $3/gal ($2.64/gge)



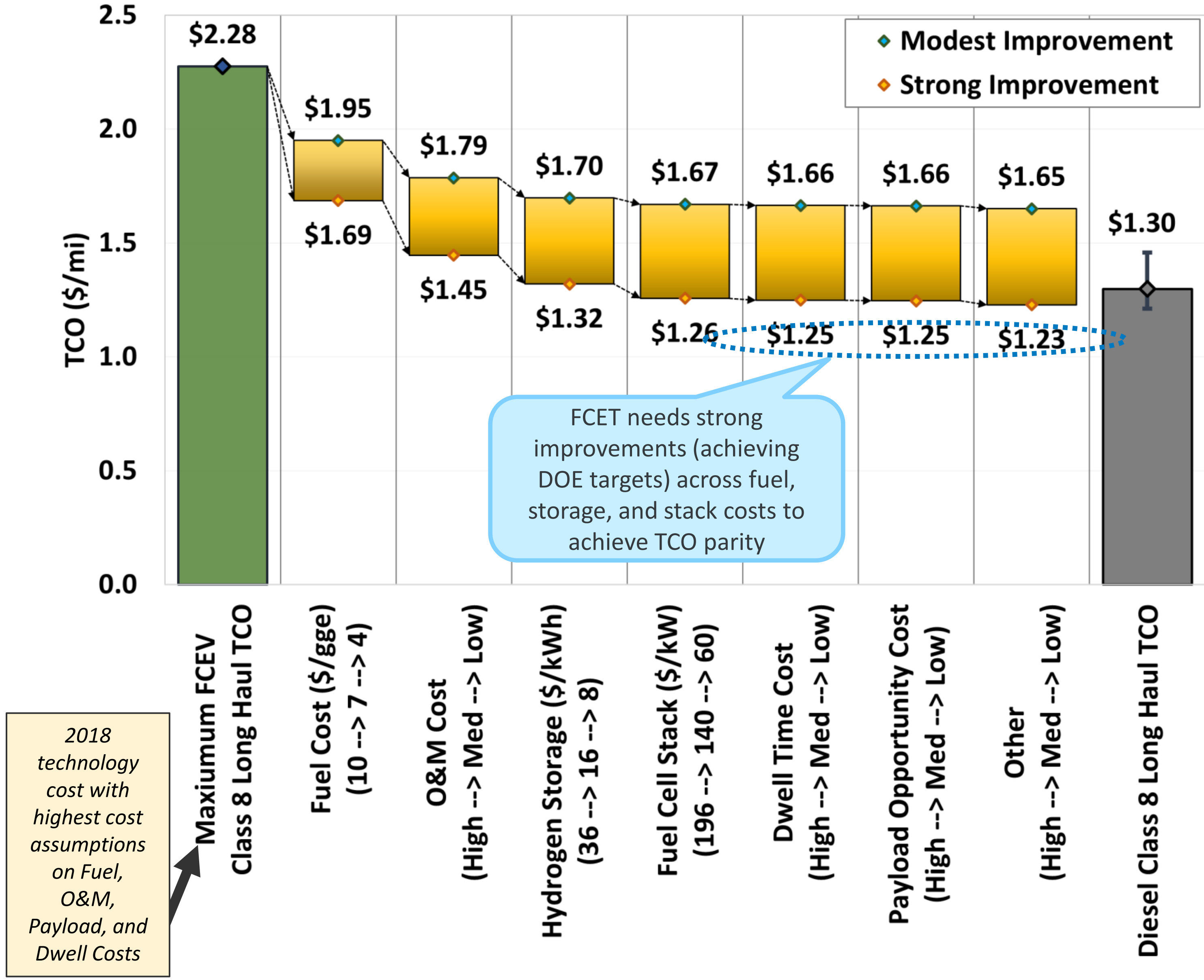
Breakeven Fuel or Electricity Price ($/gge)

At Diesel Price of $2/gal ($1.76/gge)



Note: AEO Outlook diesel prices (untaxed) range from ~$2/gal (Low Oil Case) and ~$6/gal (High Oil Case) in 2050 in some regions

FCEV Sensitivity Analysis
Class 8 Long Haul (750 mile range) Vehicle



SERA

Scenario Parameters

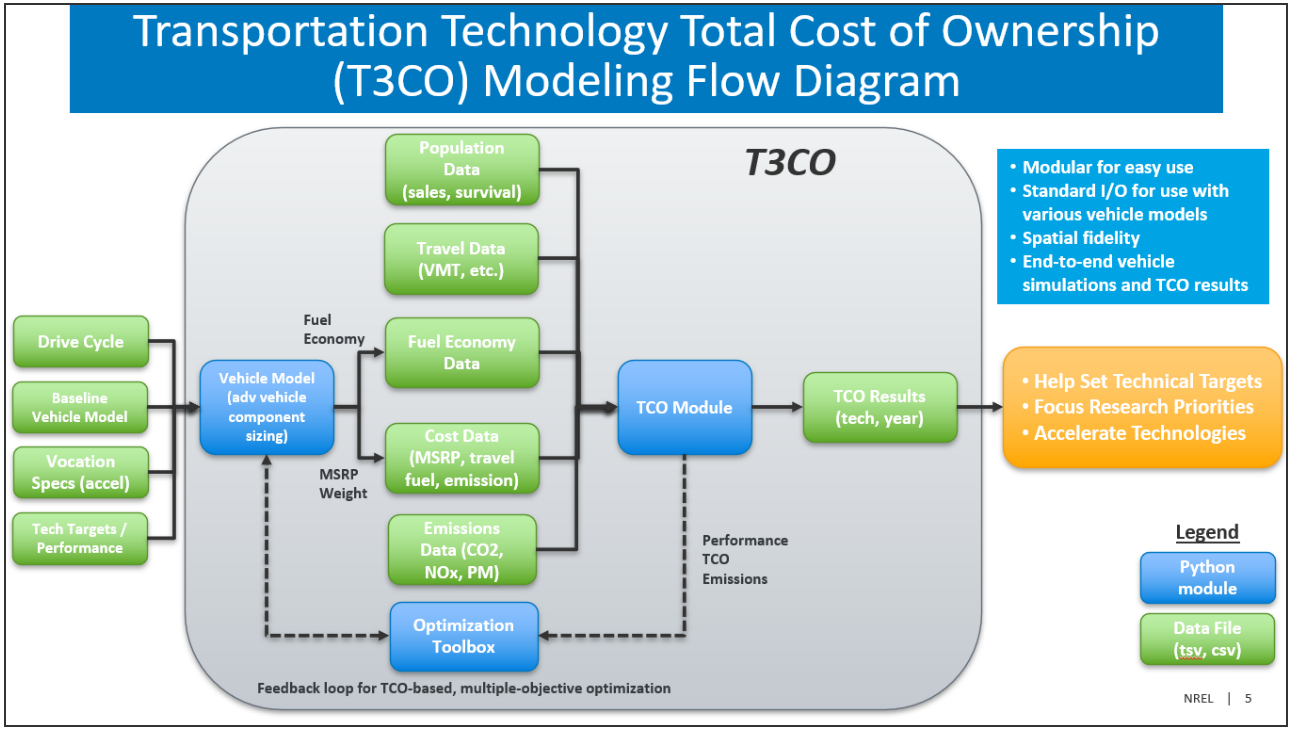
- Class 8 Long Haul
- Mid Atlantic Region
- 2018 Technology
- 200,000 mi/yr
- 5-year life
- Discount Rate = 7%

Strong improvements in hydrogen fuel cost, O&M, storage, stack, and dwell brings FCEV into potential cost parity with diesel powertrain ($1.48/mi)

Developing an integrated, rapid, and unified TCO modeling framework

SERA

T3CO



Relationship to this project

- This project helps provide the TCO modeling approach and datasets
- This work identifies the need for accessible assumption database and manager
- Basic T3CO capabilities will be used for the next phase of this project

Timeline (Current HFTO Funding)

- FY21, Q2 – Develop basic TCO end-to-end analysis with FASTSim + SERA/TCO module

Timeline (If Funded)

- *+3 months* - Circulate with 21CTP for feedback on assumptions, data, approach, and tool usability
- *+6 months* - Apply advanced multi-objective Pareto-front optimization and sensitivity analysis
- *+9 months* - Provide accessible assumption database through GUI or assumption manager

Overview

Executive Summary

Approach – FASTSim Modeling

Results

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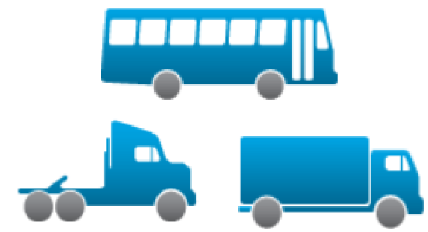
NREL's FASTSim and SERA Models Combined for TCO Analysis

FASTSim | NREL's T3CO Framework | SERA



Vehicle Powertrain Cost Modeling	Total Cost of Ownership Modeling	Market Assessment

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 HFTO Barriers:

- Identify key drivers to fuel cell truck competitiveness
- Assess fuel cells for commercial applications

Integration with Other Projects:

- Coordinated with VTO/HFTO/BETO total cost of ownership analysis (ongoing)
- Potentially provide results to future H2@Scale analysis

Regional TCO analyzed using established models and OEM specifications

FASTSim data flow combines NREL's Fleet DNA database with EERE technology cost and performance data

Technology Cost Data

Technology Performance Data

Fleet DNA

FASTSim

Results:

- Fuel economy
- Weight
- Vehicle costs and MSRP

NREL's Fleet DNA database used for drive cycle data

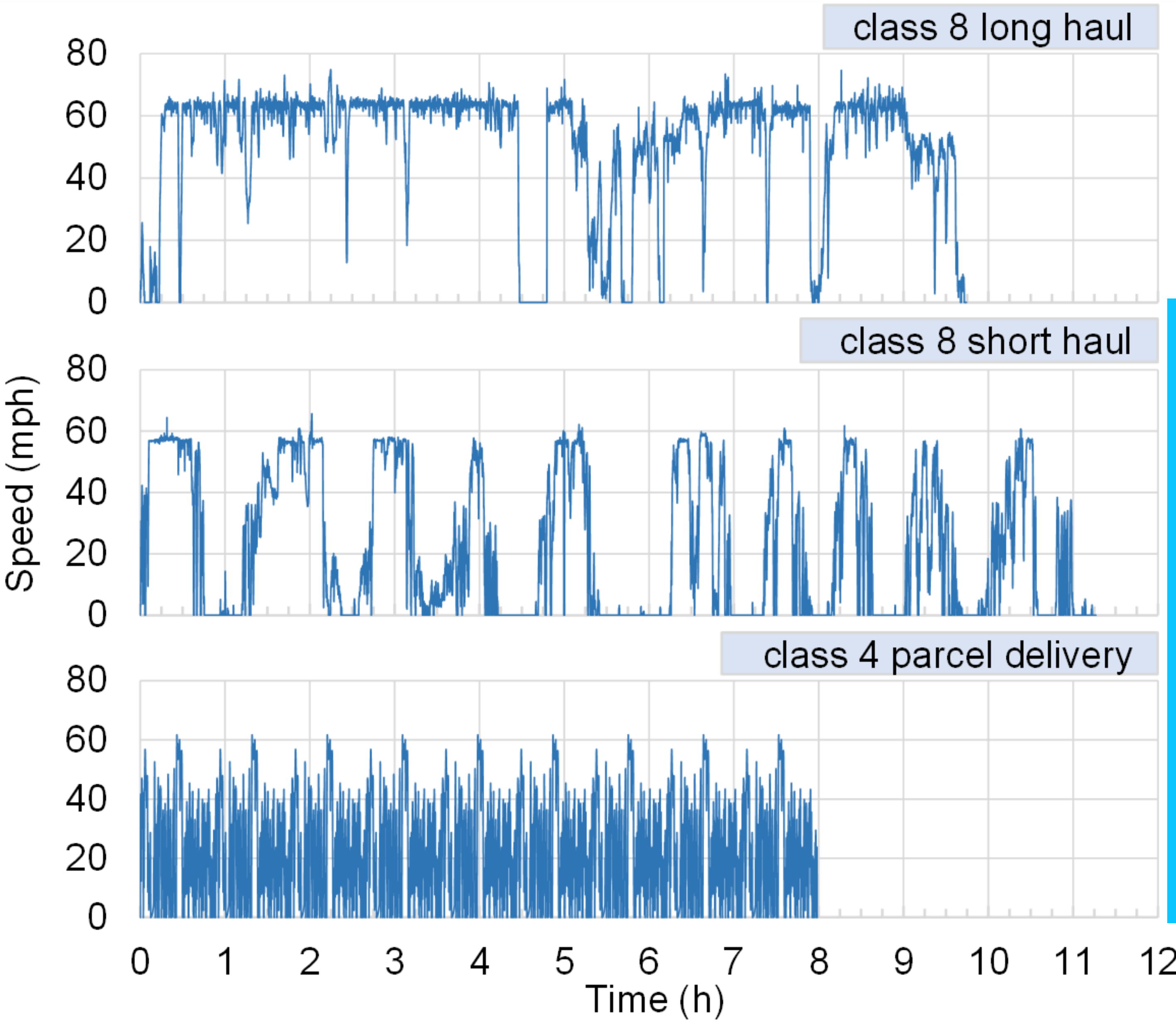
FASTSim sizes powertrain components to match acceleration observed in the duty cycle

FASTSim results 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)

NREL's Fleet DNA real-world drive cycles used for fuel economy estimation

Fleet DNA



Representative drive cycles (Lustbader et al., 2021) from NREL's Fleet DNA database were selected that reflect typical operation of these vehicle/vocations

Drive cycles used in FASTSim to estimate an average, real-world fuel economy used in the TCO analysis

Key FASTSim Modeling Assumptions References

T3CO

Target year (2025, Ultimate are Lab Years)	2018	2025	Ultimate	References	Notes
Batteries					
Battery pack mass [kg/kWh]	4.70	4.03	2.50	VTO Light-Duty Vehicle Targets	2018 battery cost based on GPRA targets for energy storage (official VTO numbers; email from Jake Ward on 8/4/20). 2025 value based on VTO's LDV target of $100/kWh (email from Brian Cunningham on 1/11/21). 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). For reference, 2020 GPRA Analysis battery costs are $302/kWh, $175/kWh, and $50/kWh for 2021, 2027, and 2050, respectively **Assumed:** 2016$ and *Pack Costs = System Costs* (includes all cooling/structural components included for vehicle glider integration)
HEV battery pack cost [$/kWh-total]	197	100	80		
PHEV battery pack cost [$/kWh-total]	197	100	80		
PEV battery pack cost [$/kWh-total]	197	100	80		
Power Electronics (PE)					
Power electronics with boost & motor [$/kW]	8-49.2	6-41.7	4-20.9	**Low Bounds:** US Drive Electrical and Electronics Technical Team Roadmap (2017) **High Bound:** 2020 GPRA Benefits Analysis	Low bound based on LDVs. Ultimate value set at $4/kW and completed sensitivity analysis on it (see slide 58-59). M/HD costs are currently being evaluated at VTO. High bound for sensitivity analysis based on 2020 GPRA Benefits Analysis using $49/kW, $41/kW, and $21/kW in 2021, 2027, and 2050, respectively.
FCEV					
Fuel cell specific power [kW/kg]	0.96	1.02	1.08	SA Inc. 2018, Supplemental data	SA Inc. report does not include Ultimate value. Email from Elliot Padgett (HFTO) on 7/28/20 recommending 1.08 kW/kg for Ultimate Value. HFTO approved on 11/19/20
Fuel cell cost [$/kW]	196	140	60	2019 HFTO Record #19006 (Class 8 Truck Targets)	2018 value of $196/kW (2016$) based on HFTO guidance per SA Inc. analysis (3/22/21). HFTO Record #19006 shows $190/kW assuming 1,000 units/yr (237,000 kW/yr) 2025 value of $140/kW based HFTO guidance (3/23/21) HFTO approved on 3/23/21
Fuel cell system peak efficiency [% LHV]	64%	66%	72%		Uses High Target for System Peak Efficiency
Storage specific mass [kWh-LHV/kg]	1.48	1.80	2.20	2019 HFTO Record #19008 (Onboard Storage Cost)	
Storage cost [$/kWh-LHV]	36	16.0	8.0		Consistent with 2019 HFTO Record #19006 for LDVs. Current value in 2016$ and assumes 1,000 systems/yr mfg vol (5,600 kg/yr which is ~70-100 systems for HD trucks)
Hydrogen Cost ($/kg)	10	7	4	Eudy, L. 2019, HFTO Targets	2018 value based on average fuel prices experienced at FCEB stations (Eudy, L. 2019; see slide 48) 2025 and Ultimate based on targets for LDVs (M/HD Targets currently under development by ANL)

Key Market Segmentation Assumptions References

T3CO

Target year (2025, Ultimate are Lab Years)	2018	2025	Ultimate	References	Notes
CNG					
CNG engine peak efficiency	38%	41%	46%	2020 EERE NG Report (Curran and Graves (personal communication, January 2021)	Kevin Stork (DOE VTO) provided data on 1/11/21 from 2020 EERE NG Report by Curran and Graves. Assumes HD CNG engine efficiency has a 20% efficiency penalty compared to a HD diesel engine.
Engine cost [$/kW]	55	55	55	FASTSim	
Fuel storage cost [$/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]	0.275	0.275	0.275	FASTSim	
Engine cost a_0 coefficient [$][a]	7,617	7,617	7,617	2020 GPRA Benefits Analysis	Based on 2020 GPRA Benefits Analysis which has been reviewed and approved by VTO
Engine cost a_1 coefficient [$/kW][a]	15.1	15.1	15.1		
Engine cost a_2 coefficient [$/kW^2][a]	0.1	0.1	0.1		
Waste heat recovery cost increase [$][b]	0	10,000	5,000	2019 HFTO Record #19006 (Class 8 Truck Targets)	Data not reported in published DOE Record but provided by Jason Marcinkoski (HFTO)
Transmission cost reduction [$][b]	0	1,100	1,800		
Engine advancement cost increase [$][b]	0	1,500	-6,000		
Class 8 engine peak efficiency	47.3%	51.8%	57.0%	2020 GPRA Benefits Analysis	FY19 GPRA Analysis and Class 8 Truck Record (2019 HFTO Record #19006) used 59% as peak efficiency for Class 8 tractor engines
Class 4 engine peak efficiency	42.1%	45.7%	49.6%		
Fuel storage specific mass [kWh/kg]	9.88	9.88	9.88	FASTSim	

a: Conventional engine cost curve fit (P = power [kW]):

$$Cost = a_0 + a_1 * P + a_2 * P^2$$

b: Costs based on Class 8 sleeper and applied proportionally to drivetrain power

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

T3CO

- **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 reduce 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)** – based on Toyota Prius (2015) with 60% of range in charge-depleting mode

Vehicle[a]	Powertrain	Motor[b] (kW)	Engine[b] (kW)	Fuel Cell[b] (kW)	Battery (kWh)
C8 long-haul (750)	Diesel		317, 309, 300		
C8 long-haul (750)	CNG		317, 309, 300		
C8 long-haul (750)	HEV	78, 76, 74	235, 229, 223		25, 20, 16
C8 long-haul (750)	BEV	309, 302, 294			2,200, 1,800, 1,200
C8 long-haul (750)	FCEV	303, 295, 288		303, 295, 288	20, 20, 20
C8 long-haul (750)	PHEV	140, 136, 133	170, 166, 161		336, 265, 182
C8 long-haul (500)	Diesel		317, 309, 300		
C8 long-haul (500)	CNG		317, 309, 300		
C8 long-haul (500)	HEV	78, 76, 74	235, 229, 223		25, 20, 16
C8 long-haul (500)	BEV	309, 302, 294			1,436, 1,173, 789
C8 long-haul (500)	FCEV	303, 295, 288		303, 295, 288	20, 20, 20
C8 long-haul (500)	PHEV	140, 136, 133	170, 166, 161		218, 173, 120
C8 short-haul	Diesel		340, 331, 320		
C8 short-haul	CNG		340, 331, 320		
C8 short-haul	HEV	84, 82, 79	253, 245, 238		27, 22, 17
C8 short-haul	BEV	332, 323, 314			823, 682, 452
C8 short-haul	FCEV	325, 316, 307		325, 316, 307	20, 20, 20
C8 short-haul	PHEV	150, 146, 142	182, 177, 171		128, 124, 128
C4 parcel delivery	Diesel		155, 143, 140		
C4 parcel delivery	CNG		155, 143, 140		
C4 parcel delivery	HEV	38, 35, 34	115, 106, 103		17, 12, 10
C4 parcel delivery	BEV	146, 135,132			231, 155, 109
C4 parcel delivery	FCEV	146, 135, 132		146, 135, 132	4, 4, 4
C4 parcel delivery	PHEV	68, 62, 61	82, 76, 74		33, 24, 17

a: Class 8 max weight = 80,000lb. Class 4 max weight = 16,000lb

b: Max weight 0-60mph acceleration (s): C8 sleeper = 59, C8 day cab = 55, C4 delivery = 30

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Total cost of ownership modeling in SERA

Cost Data

Vehicle Price
FASTSim

Fuel Price
AEO Outlook, EPRI, Tesla, HDRSAM, HFTO 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)

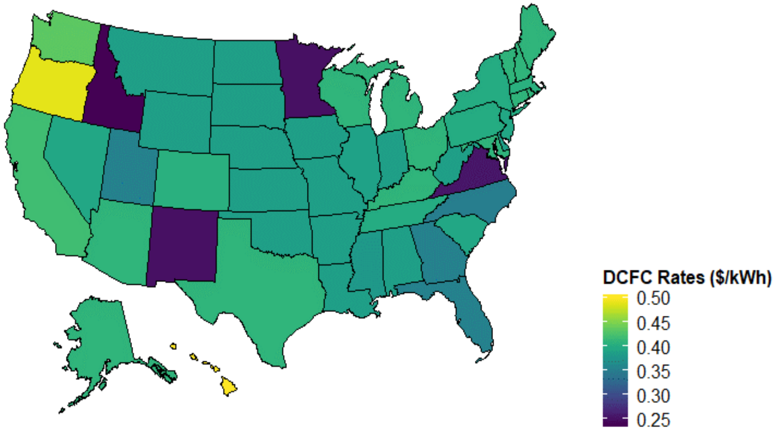
Total Cost of Ownership calculated for all Low/Med/High estimates of all input vehicle data and cost data

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

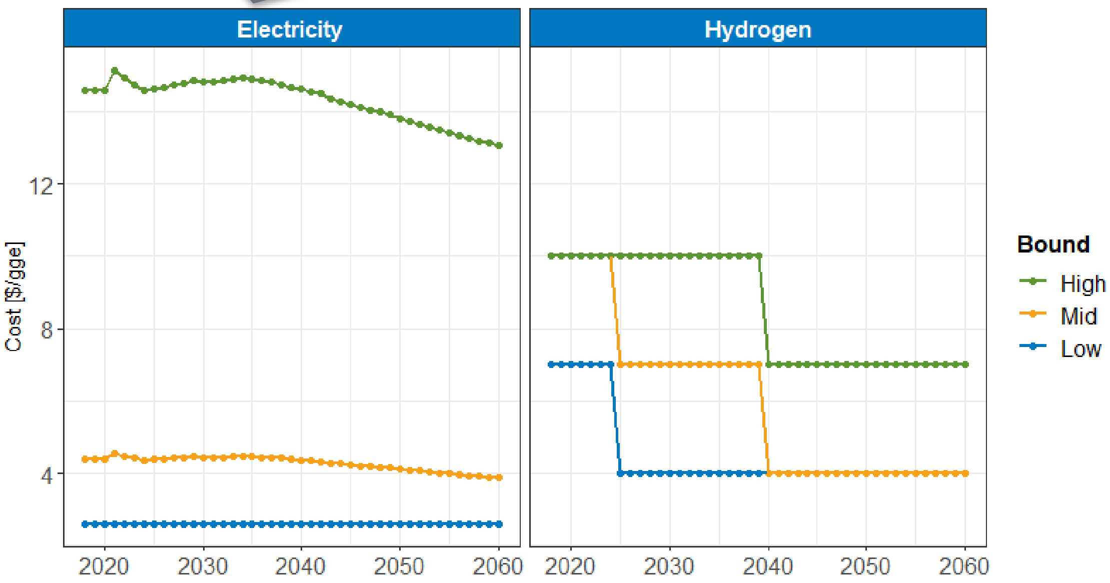
Fuel prices based on various sources including EIA Energy Outlook, Tesla, DOE Targets, HDRSAM, H2FAST, and EPRI

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, Muratori 2019 ($0.07/kWh)	AEO Reference - Transportation	EPRI Reported DCFC Prices (~$0.5/kWh)
Hydrogen	HFTO Target Price ($4/kg)	HFTO Interim ($7/kg)	FCEB Evaluations ($10/kg)

EPRI Reported DCFC Charging Prices



Borlaug (2020) Levelized Cost of Charging analysis shows LCOC = $0.08/kWh – 0.27/kWh ($2.7/gge-$9/gge) but only evaluate LDV stations up to 150kW. Muratori (2019) shows DCFC costs for depot-like scenarios (400kW) could be $0.07/kWh-$2/kWh

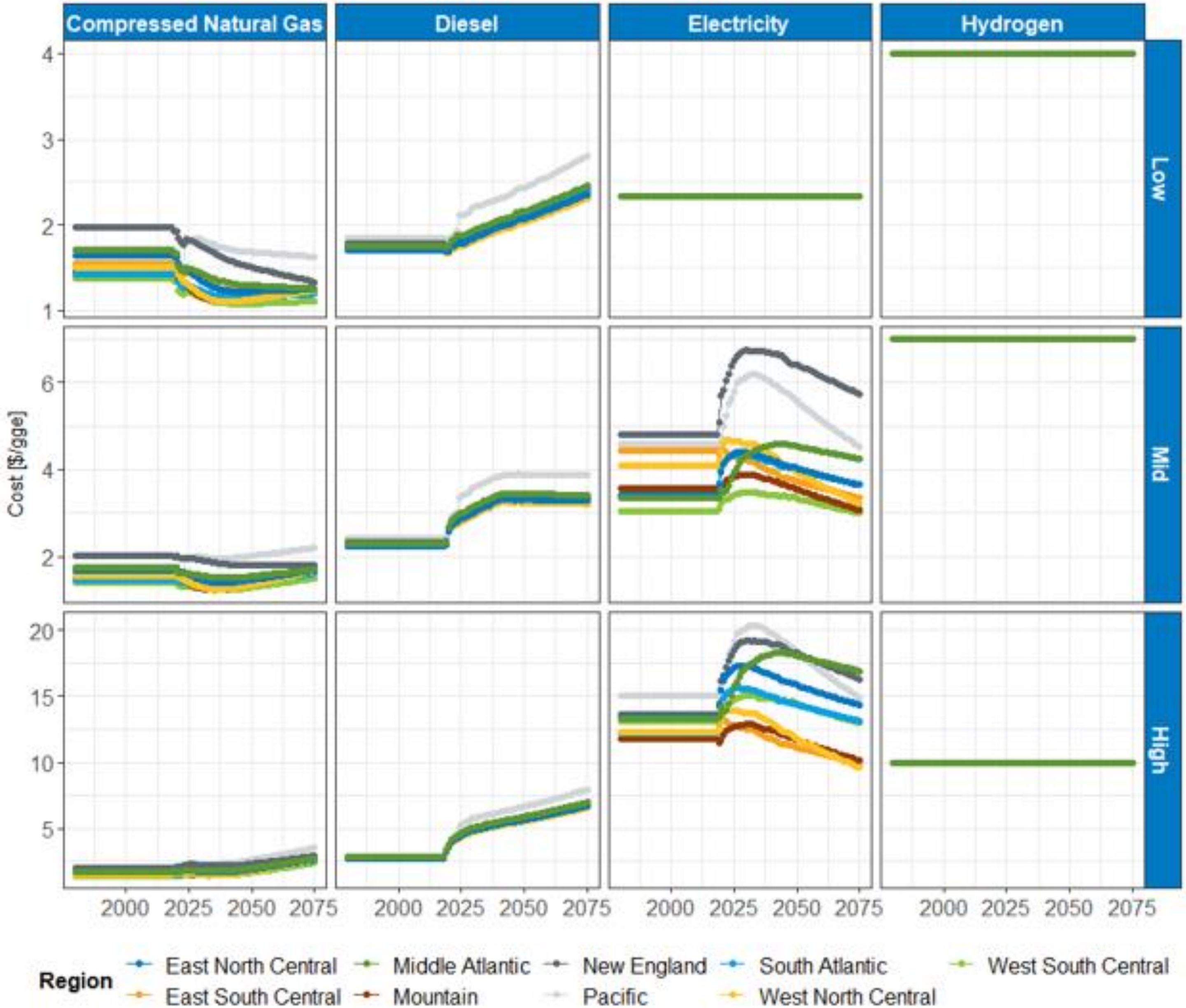


AEO Outlook CNG prices are ~25-30% lower than reported in AFDC for the same location

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

Summary of regional fuel prices used in this analysis



Note: Diesel prices are untaxed. Values shown are based on AEO data adjusted by an average tax rate

FCEB Evaluations Provide the Data for M/HD Hydrogen Fuel Prices

Slide from: Eudy, L. 2019. Annual Merit Review and Peer Evaluation Meeting.
https://www.nrel.gov/docs/fy19osti/73407.pdf

Accomplishments and Progress
Hydrogen Cost Data Summary, \$/mi

	AC Transit[a]	SunLine[b]	OCTA[c]	SARTA[d]
Data period	2/13–7/17	3/12–12/18	3/16–12/18	2/18–12/18
Number of months	54	82	34	11
Average H_2 cost, \$/kg	8.39	10.17	13.95	5.14
Maximum H_2 cost, \$/kg	10.26	26.02	16.99	5.88
Minimum H_2 cost, \$/kg	6.49	2.53	12.99	5.00
Overall FCEB fuel cost, \$/mile	1.41	1.83	2.21	1.04
Baseline technology	Diesel	CNG	CNG	CNG/diesel hybrid
Average fuel cost, \$/gal or \$/gge	2.43	0.96	1.15	1.89/2.30
Overall baseline fuel cost, \$/mile	0.57	0.32	0.32	0.45/0.51

Overall cost comparison to baseline

Hydrogen cost for buses with dedicated fleets ranges from \$2-\$26/kg, typical value around \$10/kg for dedicated refueling stations

Fuel cost is based on data provided by agencies; not all are equal comparisons

[a] Delivered cost

[b] Includes station operating and maintenance (O&M) costs

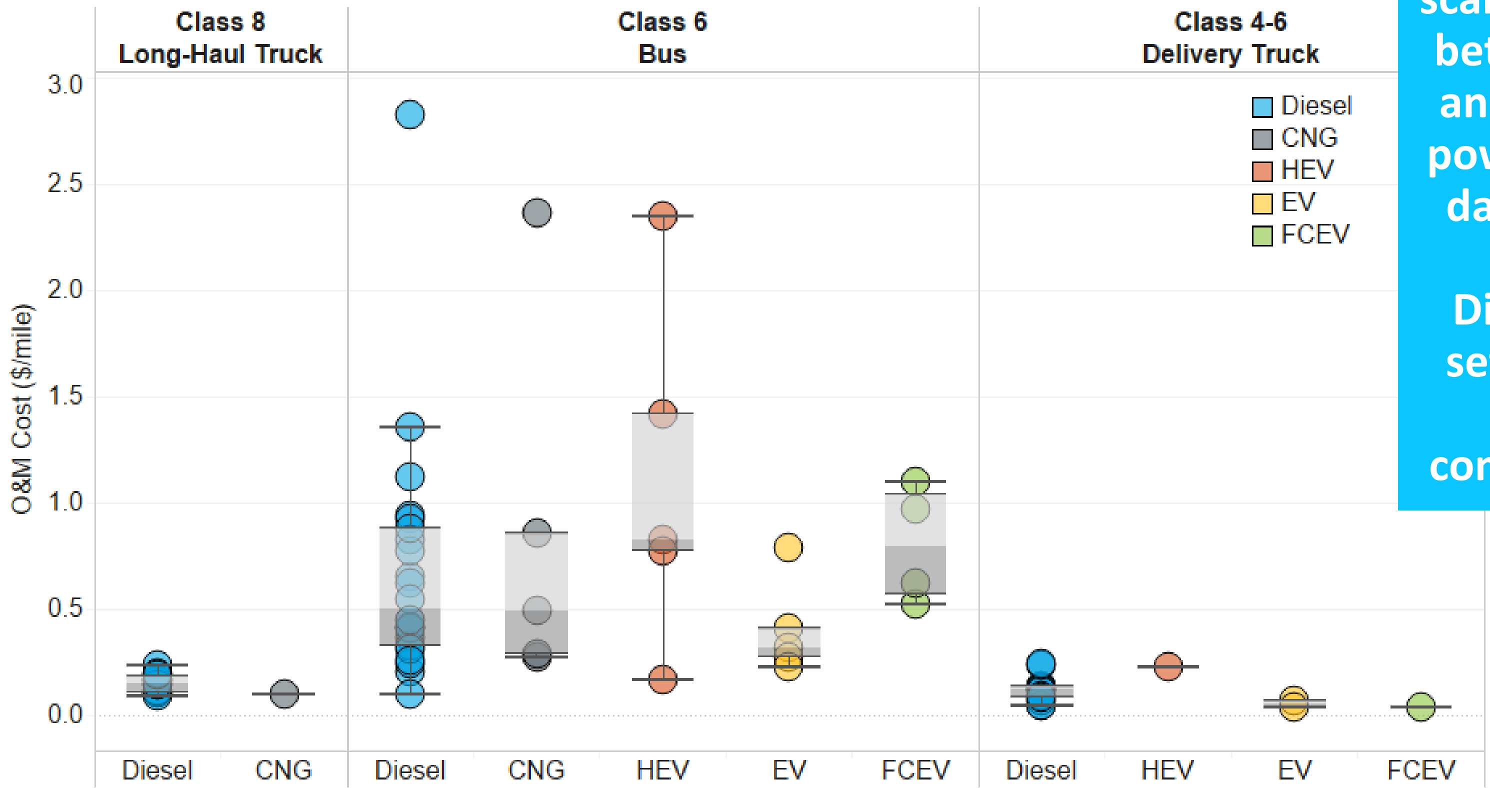
[c] Retail cost from local public stations

[d] Delivered cost

NREL | 10

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	0.153
	High	0.301	0.298	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

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

DOE VTO currently does not have a Tech Target for charging rates. VTO funded NREL analysis evaluating 1MW charging provides higher charge rate assumption. *High Cost* case of 500 kW is assumed

Lower Limits on Refueling Times

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

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

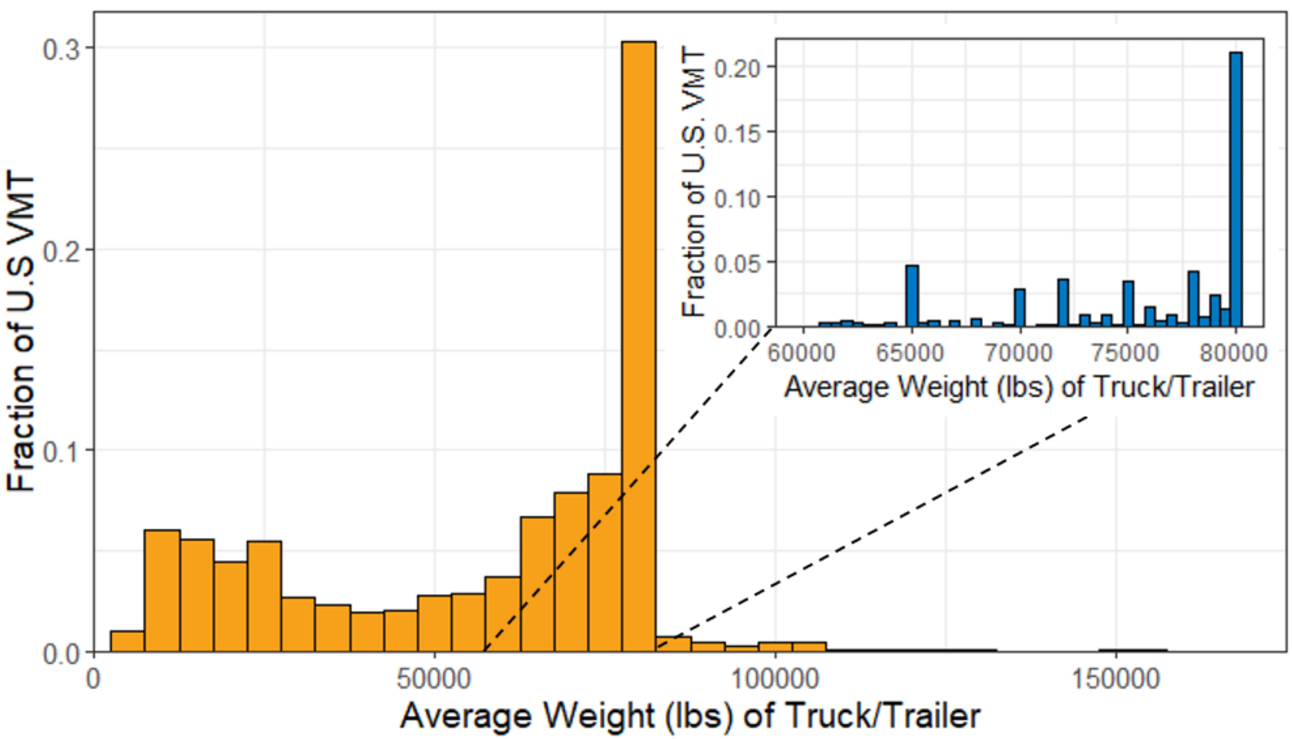
A constant rate of $75/hr was used in this analysis

Dwell time is based on peak refueling/recharging rates. Lower limits accommodate for non-linear charging/refueling (CNG, H2) behavior

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[1] 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

Fixing America's Surface Transportation (FAST) Act Truck Size and Weight Provisions.

- *There is currently no sunset time.*
- *FCEVs are not explicitly called out in it.*

Note: marginally higher payload will marginally reduce fuel economy which is accounted for in the Weight-Limited Scenarios in this analysis

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	-0.002	0	0.819 to -0.844	0
	High	-0.001	0	0.286 to -0.318	0
2025	Low	0	0	0	0
	Mid	-0.003	0	0.255 to -0.266	0
	High	-0.002	0	0.133 to -0.149	0
Ultimate	Low	0	0	0	0
	Mid	-0.003	0	0.027 to -0.028	-0.002
	High	-0.002	0	0.016 to -0.018	-0.002

Class 8 Short 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	-0.001	0	0.049 to -0.05	-0.002
	High	-0.001	0	0.013 to -0.113	-0.001
2025	Low	0	0	0	0
	Mid	-0.002	0	0.013 to -0.013	-0.004
	High	-0.001	0	0.005 to -0.006	-0.001
Ultimate	Low	0	0	0	0
	Mid	-0.002	0	0	-0.006
	High	-0.001	0	0	-0.002

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

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Scenario design for TCO modeling reflects typical business operating models

SERA

Dry van general freight (e.g., package delivery)

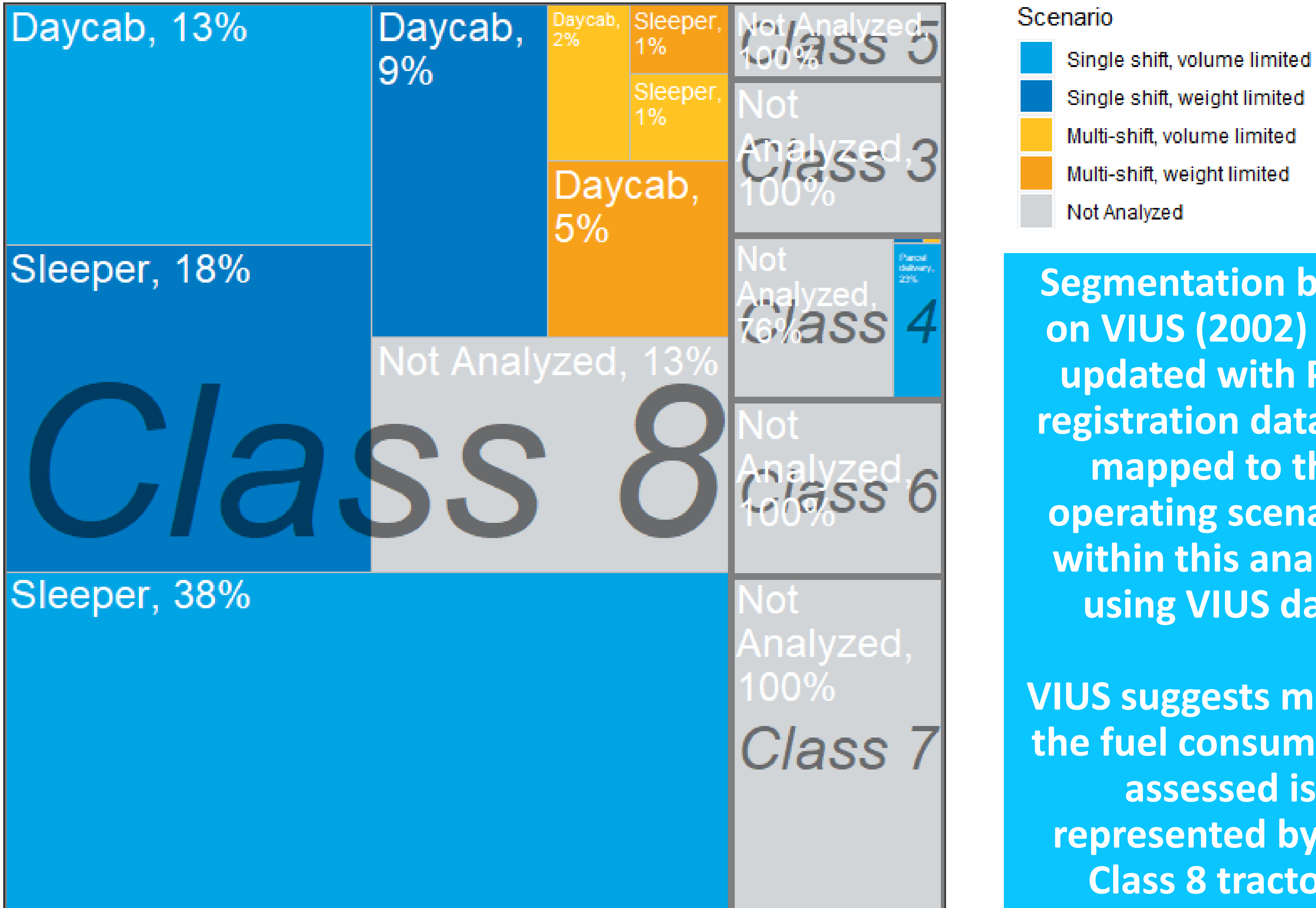
Operating Shift

Payload Limitation		No Dwell Time Cost	Dwell Time Cost Incurred
	No Payload Capacity Cost	Single Shift, Volume Limited	Multi-Shift, Volume Limited
	Payload Capacity Cost Incurred	Single Shift, Weight Limited	Multi-Shift, Weight Limited

Bulk haulers or heavy haulers with team driving (e.g., beverage delivery, reefers, fuel delivery)

Four scenarios designed to reflect potential industry business operating scenarios and understand which powertrains are most economically attractive for each

Trucks assessed in this report capture a majority of the M/HD fuel consumption



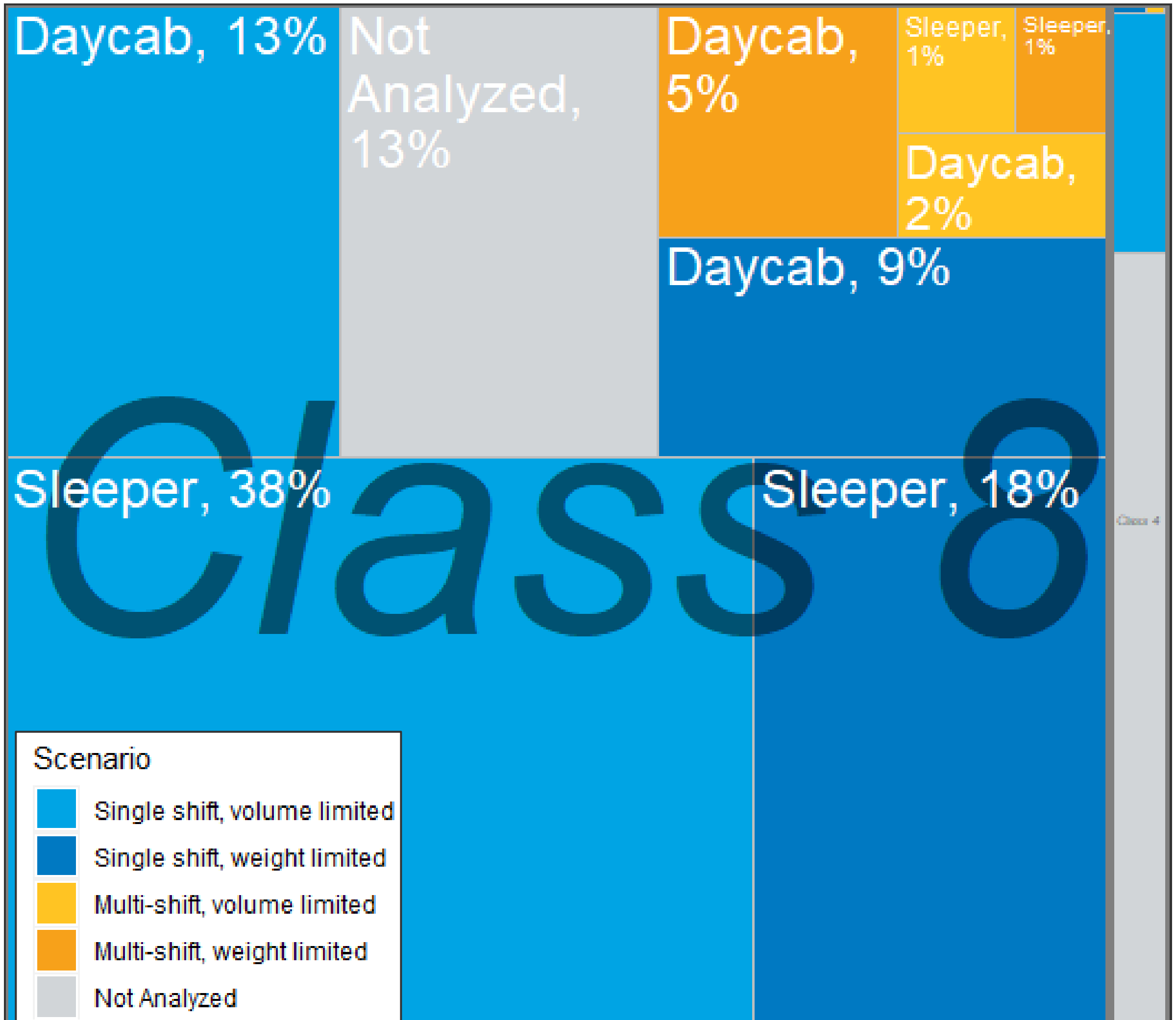
Segmentation based on VIUS (2002) data updated with Polk registration data and mapped to the operating scenarios within this analysis using VIUS data

VIUS suggests most of the fuel consumption assessed is represented by the Class 8 tractors

Trucks assessed in this report capture a majority of the M/HD fuel consumption

Polk adjusted VIUS Scenario Estimation for Class 8 and Class 4 Trucks

- Size = total fuel consumption across Class 8 and Class 4 (slide 55 for all)
- % = scenario's fraction of fuel use by Class



Operation Data Summary:

- Weight-Limited (Class 8 Tractors)
  - Polk adjusted VIUS analysis indicates **33%** of Class 8 tractor fuel usage could be used by tractors that weigh-out
  - NACFE (2015) indicates **2-10%** of Class 8 tractors may weigh-out
  - Schoettle et al. (2016) survey indicates **54.6%** of Class 8 tractors may weigh-out
- Multi-Shift (Class 8 and Class 4)
  - VIUS (2002) indicates **13%** of Class 8 tractor fuel usage could be used by tractors multi-shift; **~1%** for Class 4 Parcel Delivery
  - Schoettle et al. (2016) surveyof Class 8 tractors reports **6.2%** of routes are long-haul team-drivers, **34.4%** are long-haul with overnight stays

Method: Weight and Shift Operation inferred based on VIUS reported truck weight and VMT (mi/yr)

- Class 8 Sleeper (500+mile): Multi-shift is >200k mi/yr
- Class 8 Daycab (300-mile): Multi-shift is > 100k mi/yr
- Class 4 Parcel (120-mile): Multi-shift is >50k mi/yr
- Weight-limited based on GVWR Class limit

Overview

Executive Summary

Approach

Results – Additional Results/Analysis

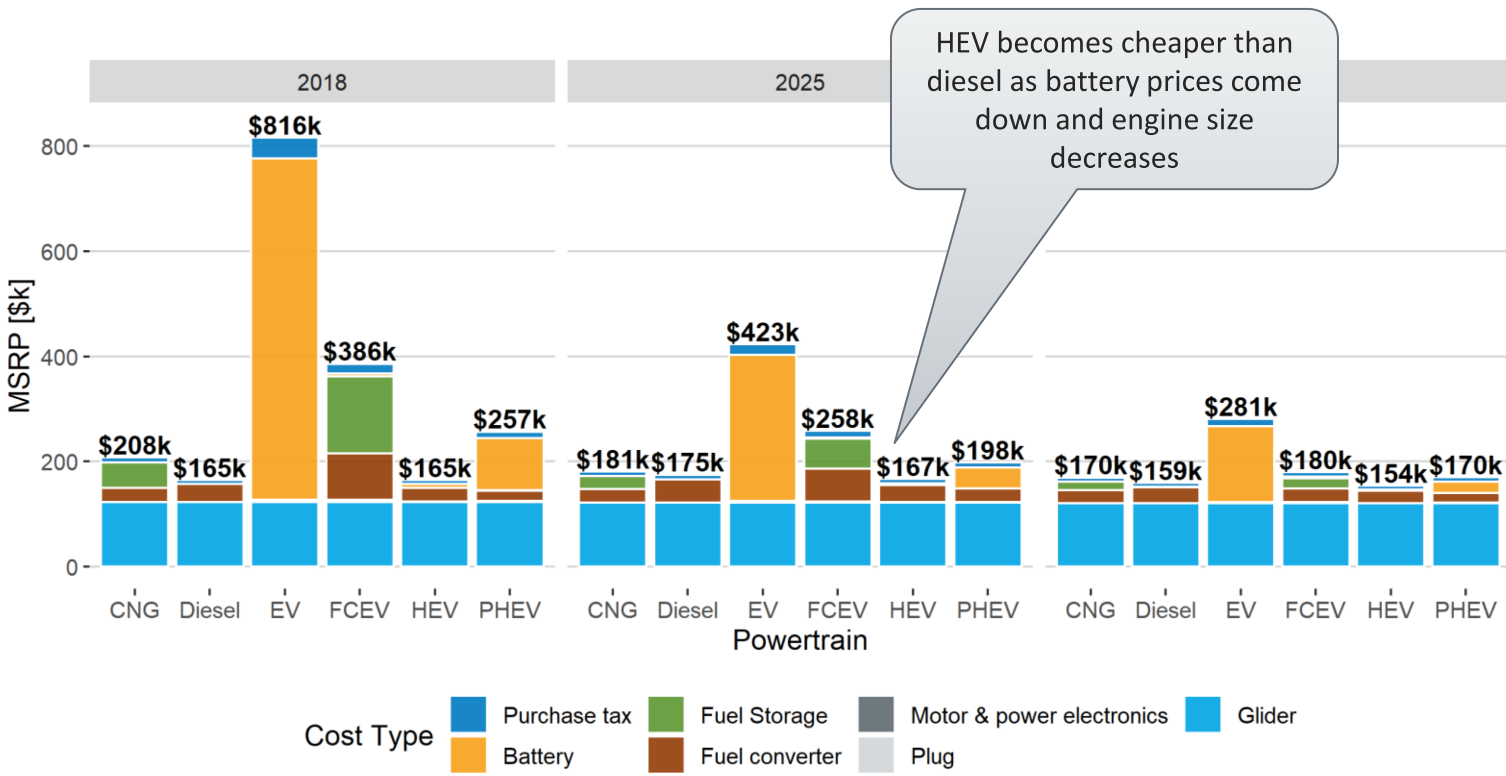
Conclusions

Class 8 Long Haul (750 mile range) Vehicle MSRP Modeling

T3CO

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

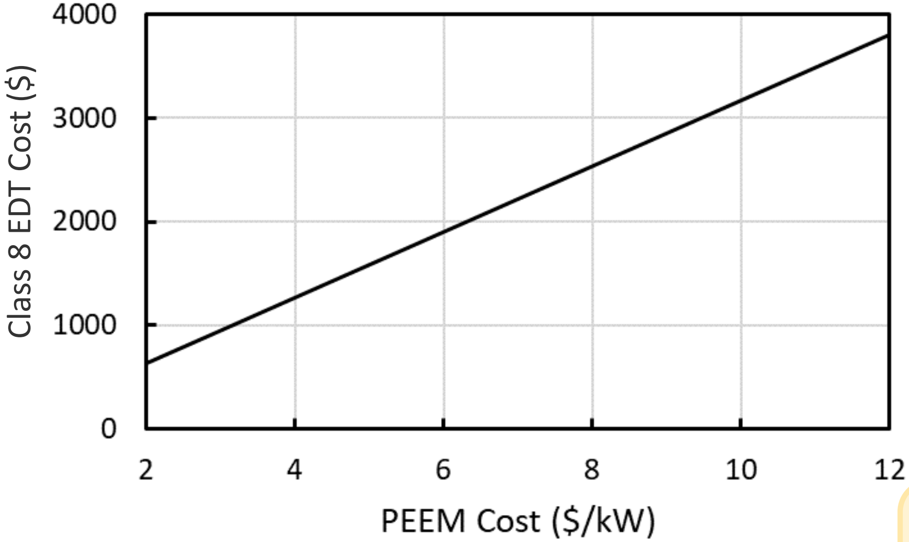
Note:
Fuel Converter = Engine or Fuel Cell



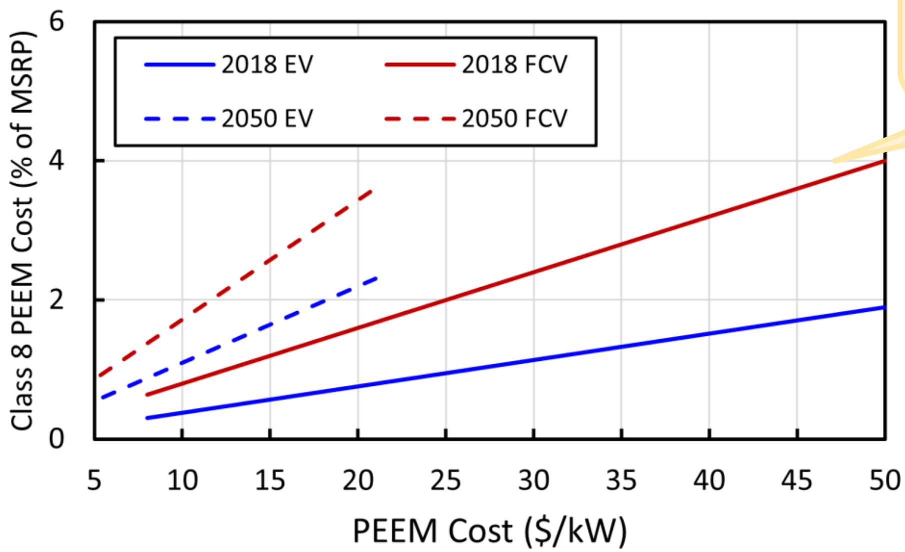
Class 8 Long Haul FCEV MSRP driven by H2 storage and H2 fuel cell stack

Electric drive technologies (EDT) cost impact on MSRP for Class 8 Long Haul (750-mile range)

T3CO



- Class 8 tractor has ~317 kW motor
- At $8/kW, EDT accounts for 0.25 – 1.5% of total MSRP
- At $2/kW, EDT accounts for less than 0.5% of MSRP



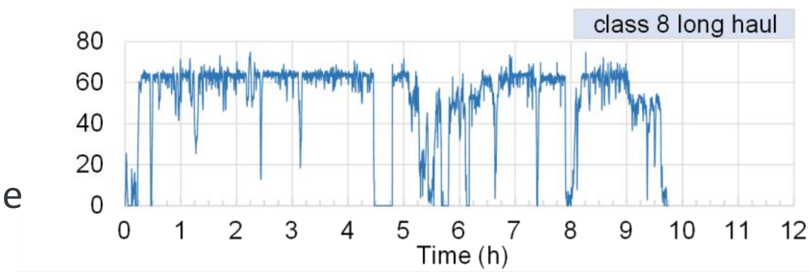
Moving from $6/kW to $2/kW will reduce MSRP by <0.5% for battery electric trucks

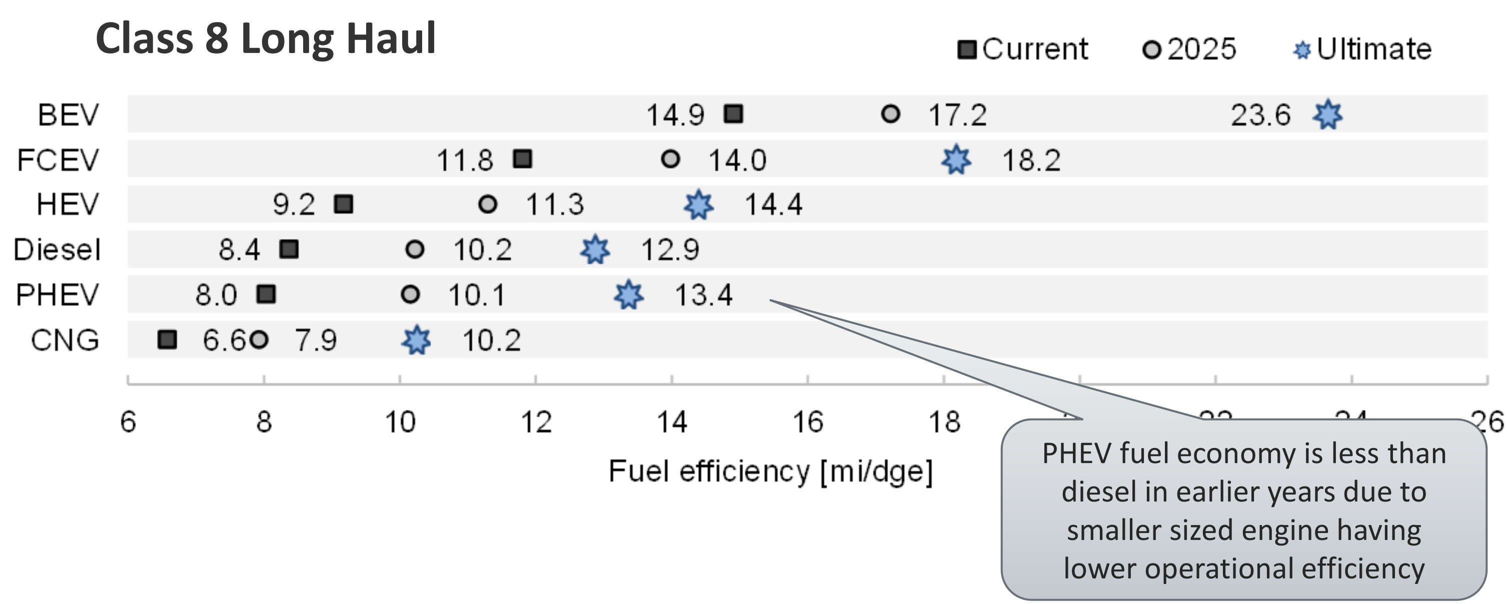
Small changes in EDT cost within $2/kW - $8/kW have a very minor impact on MSRP and a negligible impact on TCO

Real-World Fuel Economy Results for Class 8 Long Haul (750 mile)

T3CO

- FASTSim models each vehicle's fuel economy based on the input drive cycle along with the vehicle specifications input (e.g. drag coefficient, frontal area, etc.)
- Fuel economy modeled with a typical payload of ~32,500lb (or the max hauling capacity in the case of the battery electric powertrain)
- Class 8 long haul FCEV fuel economy is 30% more than current diesel technology, allowing for energy savings over the vehicle's lifetime

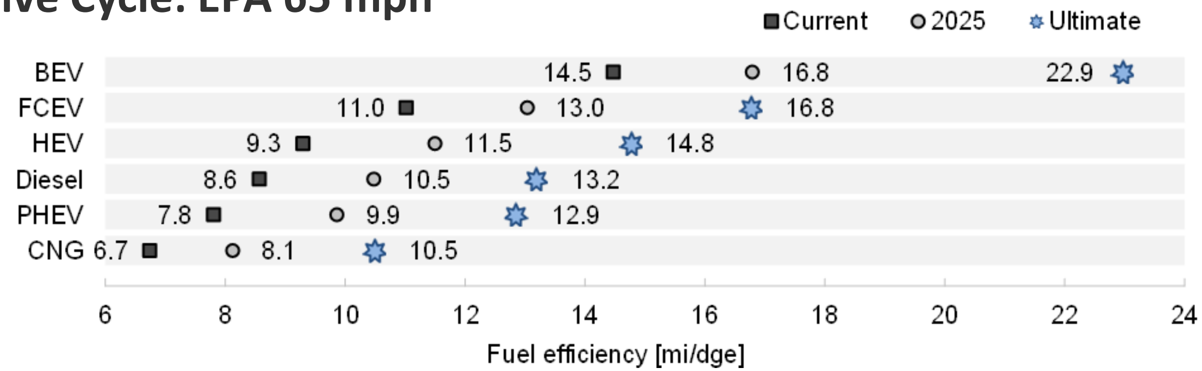




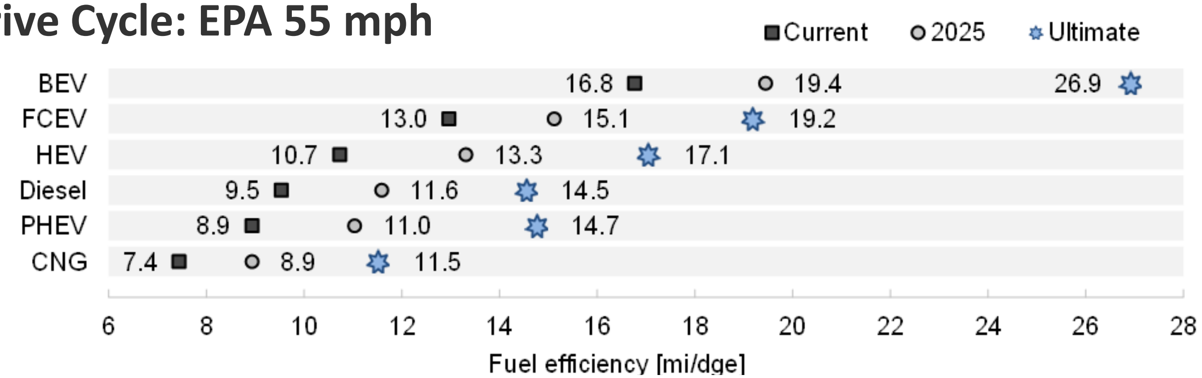
Regulatory Cycle Fuel Economy Results for Class 8 Long Haul (750 mile)

T3CO

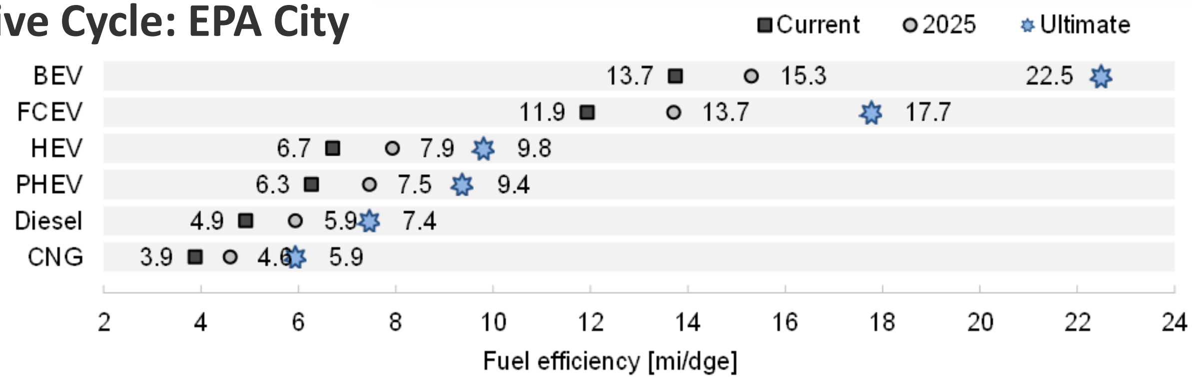
Drive Cycle: EPA 65 mph



Drive Cycle: EPA 55 mph



Drive Cycle: EPA City



Class 8 Long Haul (750 mile range) Vehicle Weight Modeling

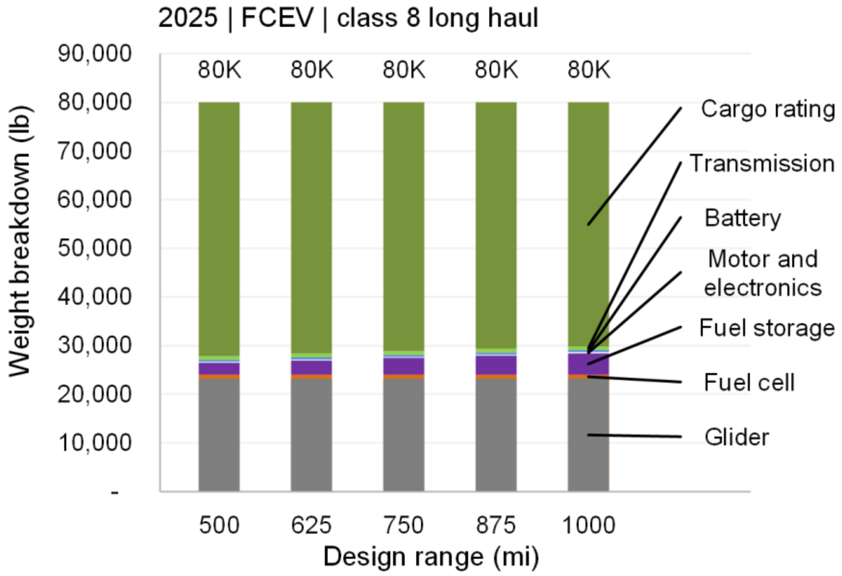
T3CO

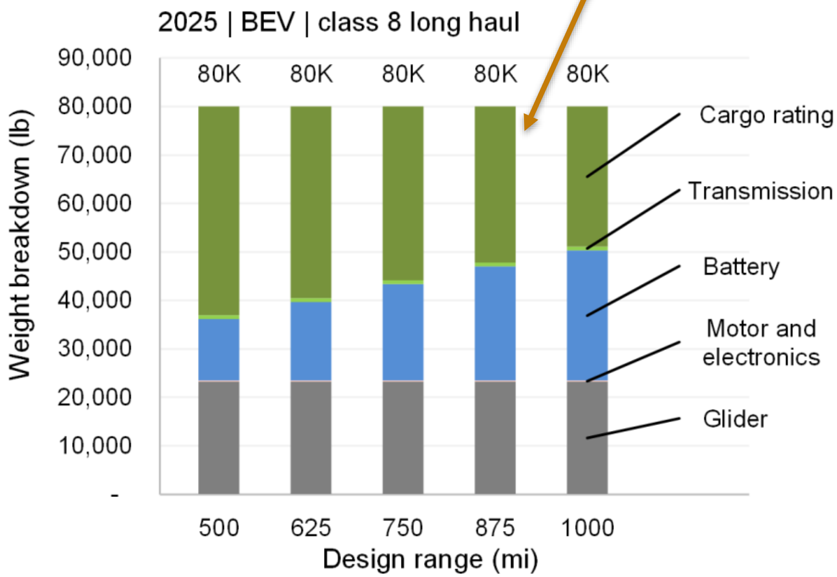
Vehicle Weight and Payload Analysis

- Theoretical sweep across required range (distance traveled on single refueling/charge) completed
- Tractor mass increases due to larger H_2 storage system and battery needed

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

Available payload weight reduced due to heavier tractor





Class 8 Long Haul (750 mile range) Vehicle Weight Modeling

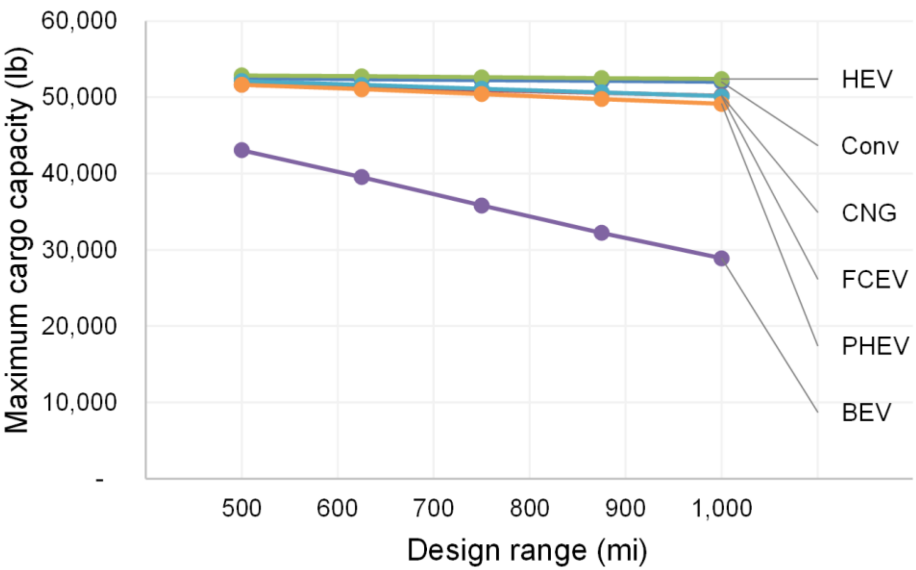
T3CO

Vehicle Weight and Payload Analysis

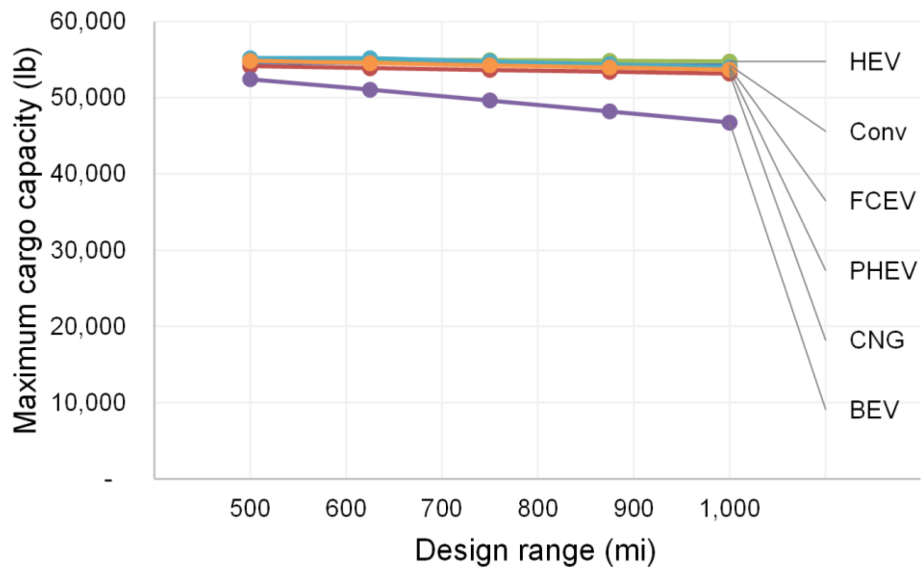
- FCEV and CNG have comparable payload reductions
- Battery EV experiences significant payload reductions at a range greater than 300 miles even if Ultimate targets are achieved

Achieving EERE Ultimate targets allows CNG, FCEV to have comparable payload capacity to diesel with up to ~750 miles of range

Max Cargo Capacity (2025 Tech Targets)

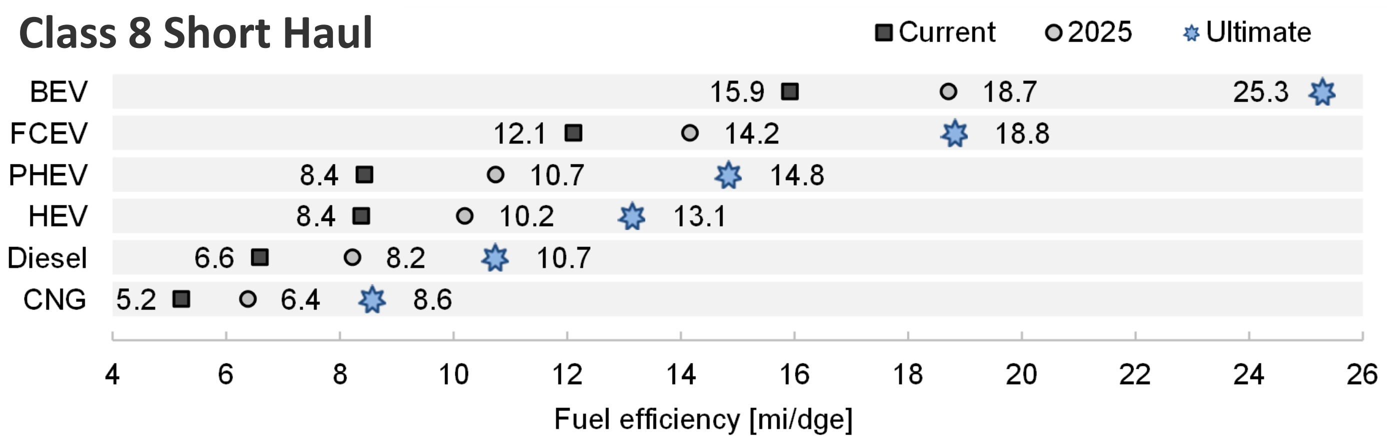


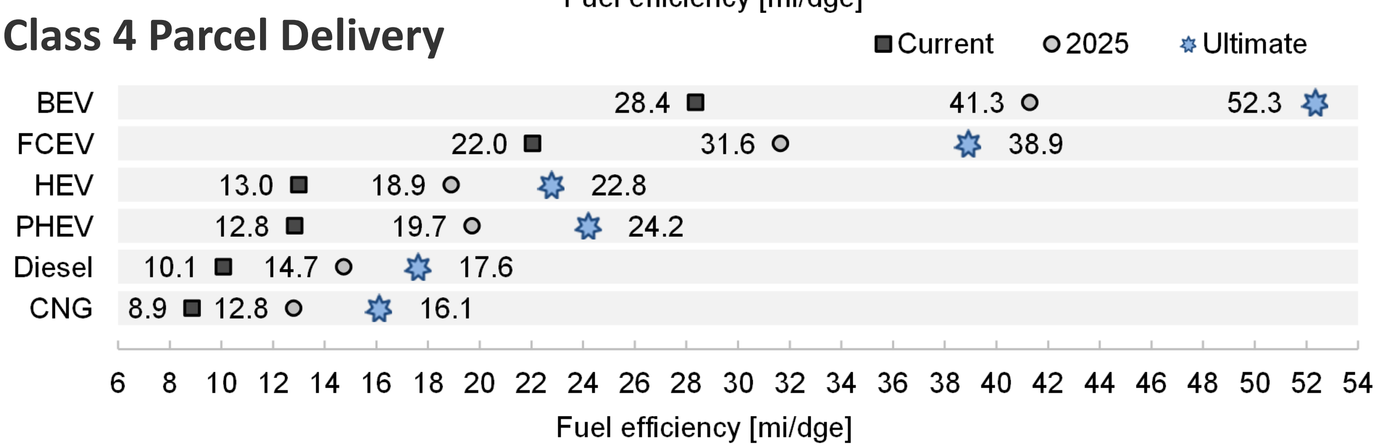
Max Cargo Capacity (Ultimate Tech Targets)



Real-World Fuel Economy Results for Class 8 Short Haul (300 mile) and Class 4 Parcel Delivery

- FASTSim models each vehicle's fuel economy based on the input drive cycle along with the vehicle specifications input (e.g. drag coefficient, frontal area, etc.)
- Fuel economy modeled with a typical payload of ~32,500lb (or the max hauling capacity in the case of the battery electric powertrain for the Class 8 Short Haul)





Fuel Converter (engine, fuel cell) Average Operational Efficiency and Peak Efficiency on Fleet DNA Cycle

- FASTSim models each vehicle's fuel economy based on the input drive cycle along with the vehicle specifications input (e.g. drag coefficient, frontal area, etc.)
- Operation modeled with a typical payload of ~32,500lb (or the max hauling capacity in the case of the battery electric powertrain)

	C8 truck sleeper		C8 truck day cab		C4 delivery	
	Average fuel converter efficiency	Peak efficiency	Average fuel converter efficiency	Peak efficiency	Average fuel converter efficiency	Peak efficiency
Current Diesel	46.3%	47.3%	46.7%	47.3%	38.9%	42.0%
2025 Diesel	50.4%	51.8%	51.0%	51.8%	42.9%	45.7%
Ultimate Diesel	55.1%	57.0%	55.8%	57.0%	47.0%	49.6%
Current CNG	36.4%	38.0%	36.9%	38.0%	37.5%	38.0%
2025 CNG	39.1%	41.0%	39.6%	41.0%	40.4%	41.0%
Ultimate CNG	43.7%	46.0%	44.3%	46.0%	45.3%	46.0%
Current HEV	46.8%	47.3%	46.8%	47.3%	38.2%	42.0%
2025 HEV	51.1%	51.8%	51.2%	51.8%	42.1%	45.7%
Ultimate HEV	56.1%	57.0%	56.2%	57.0%	46.2%	49.6%
Current FCEV	62.1%	64.0%	62.3%	64.0%	61.8%	64.0%
2025 FCEV	64.4%	66.0%	64.6%	66.0%	63.9%	66.0%
Ultimate FCEV	70.8%	72.0%	71.0%	72.0%	70.0%	72.0%

Overview

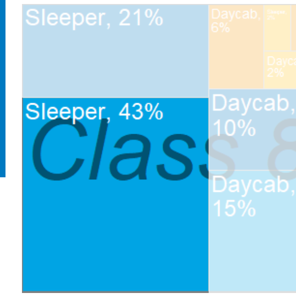
Results: Class 8 Long Haul (500-mile range)

Approach

Results

Conclusions

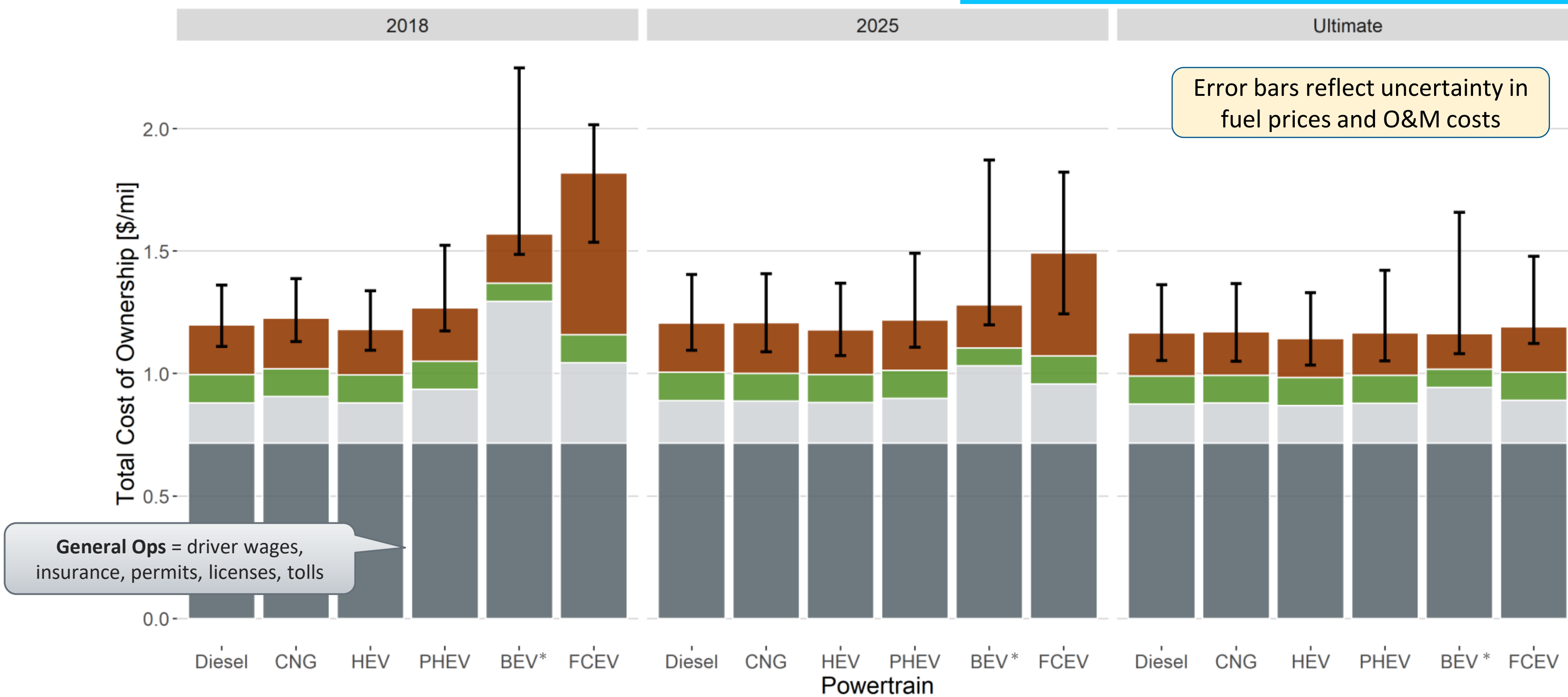
Scenario 1: Single-Shift, Volume-Limited
Class 8 Long Haul (500-mile range) Results



Scenario Parameters

- Class 8 Long Haul (500-mile) in Mid-Atlantic Region
- 100,000 mi/yr (380 mi/day)
- 10 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

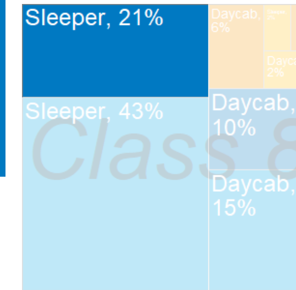
FCET costs driven by fuel and upfront purchase price. FCEV TCO within bounds of diesel TCO uncertainty by 2025



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

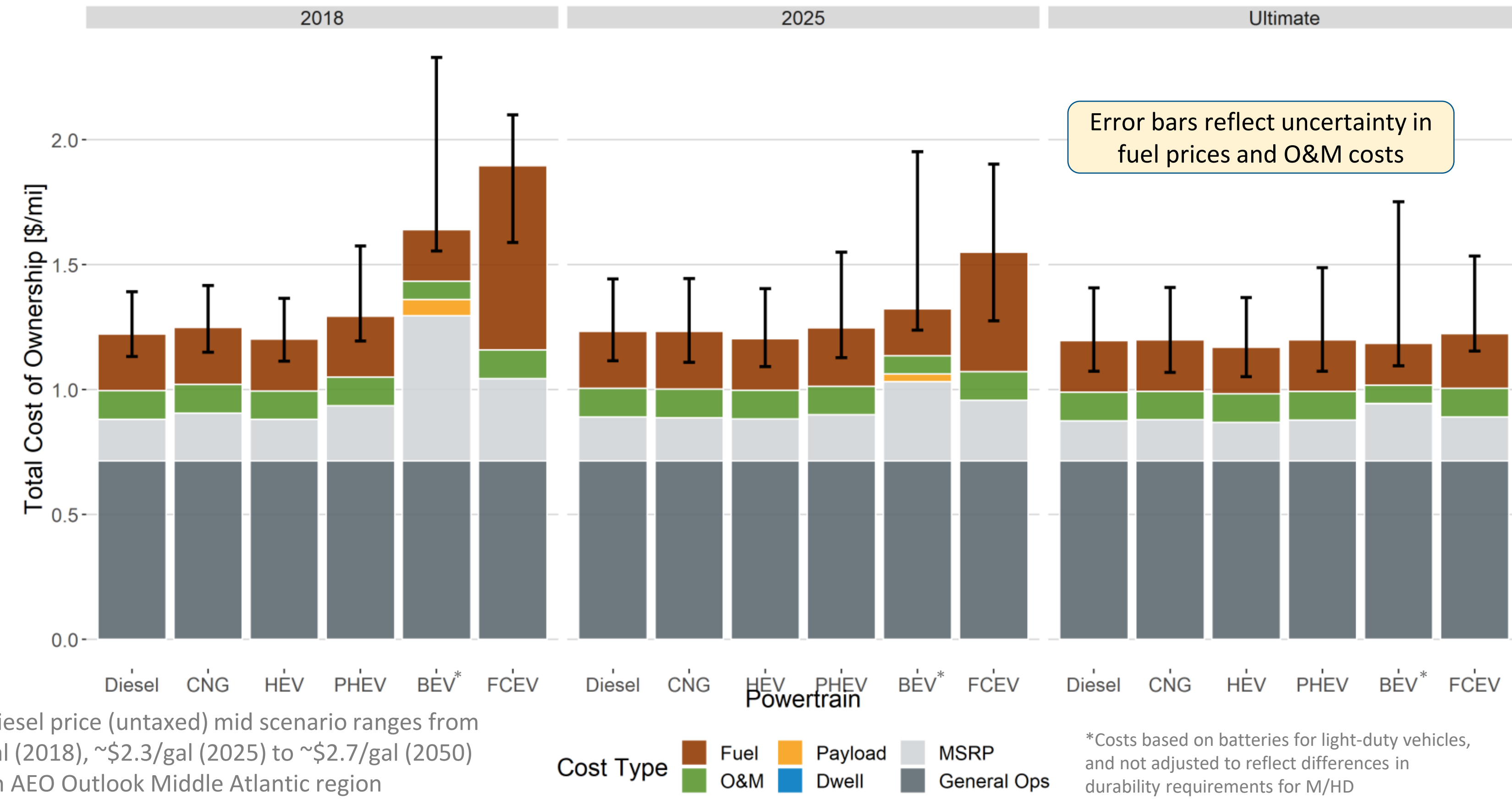
Scenario 2: Single-Shift, Weight-Limited Class 8 Long Haul (500-mile range) Results



Scenario Parameters

- Class 8 Long Haul (500-mile) in Mid-Atlantic Region
- 100,000 mi/yr (380 mi/day)
- 10 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **None**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

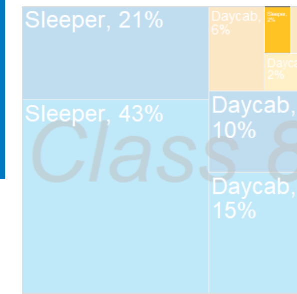
Lost payload capacity costs are not significant for a Class 8 short haul ZEVs due to 2,000lb Federal Exemption for non-diesel powertrains



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

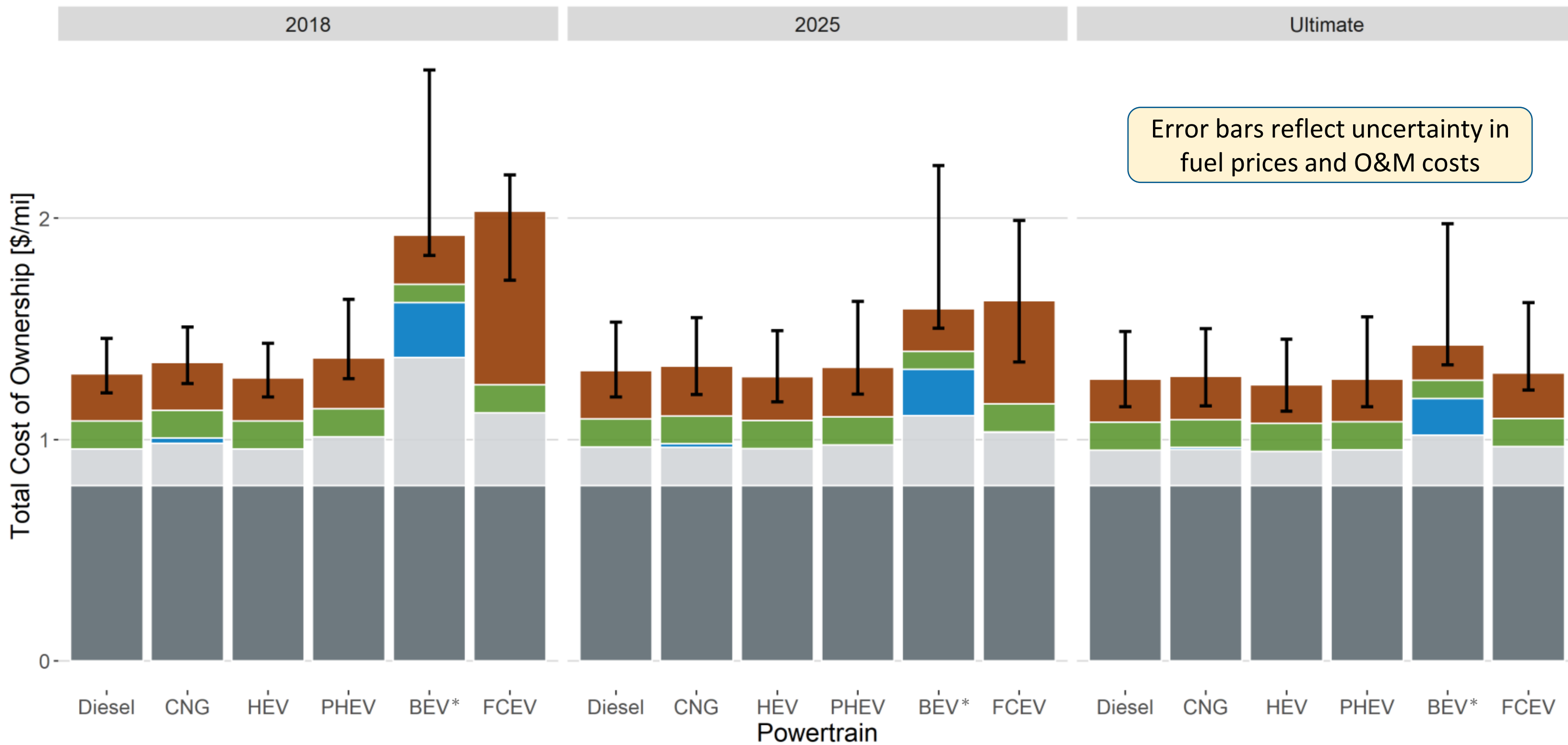
Scenario 3: Multi-Shift, Volume-Limited
Class 8 Long Haul (500-mile range) Results



Scenario Parameters

- Class 8 Long Haul (500-mile) in Mid-Atlantic Region
- 150,000 mi/yr (580 mi/day)
- 6.7 year life (1M miles)
- Payload Cost = **None**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

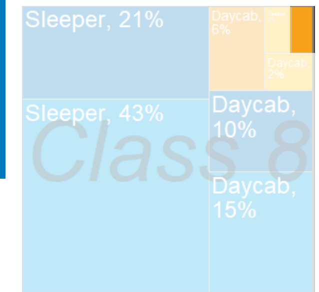
FCET dwell time is not significant, less than CNG at 5 kg/min due to lower onboard storage (higher fuel economy). Long EV charging time due to large onboard battery



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

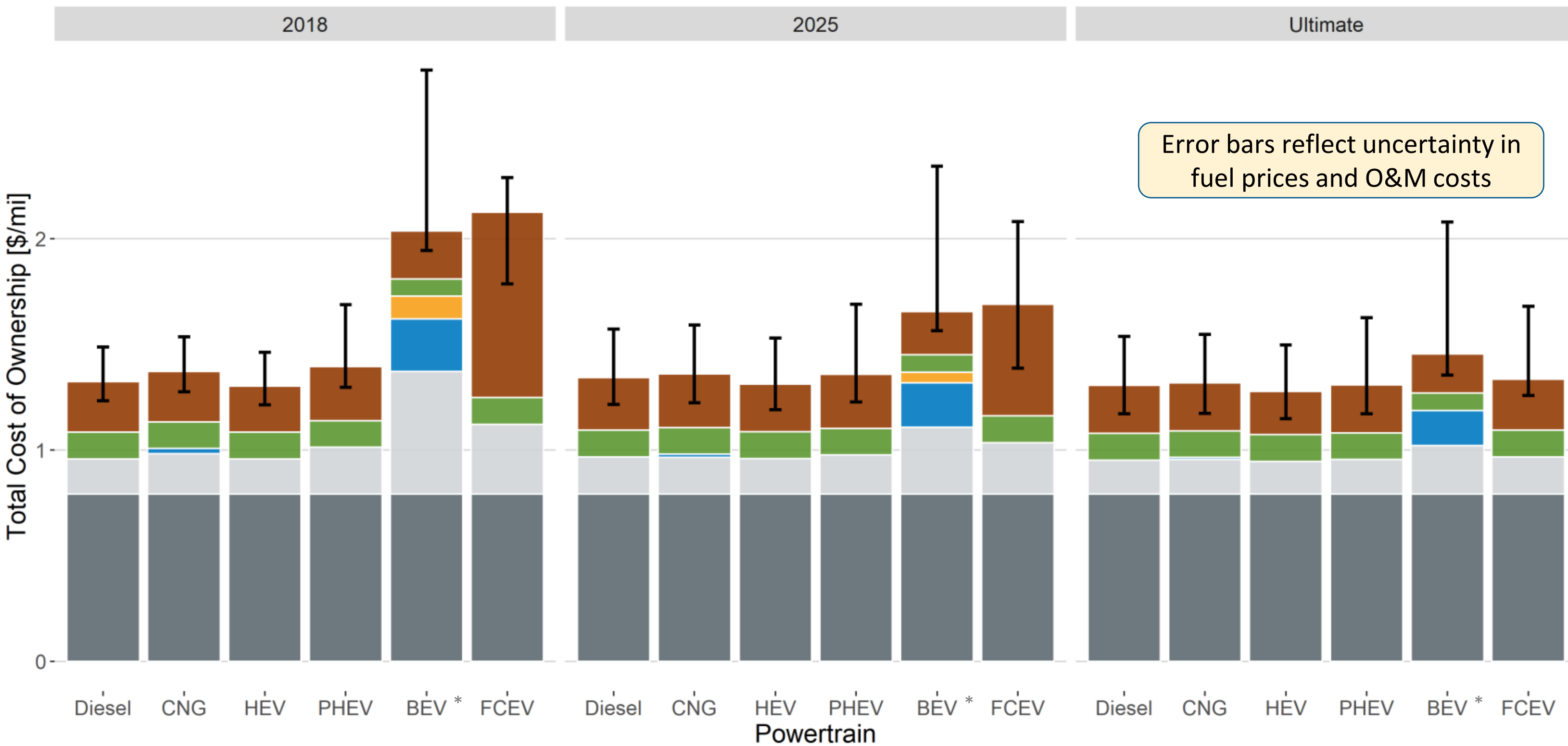
Scenario 4: Multi-Shift, Weight-Limited
Class 8 Long Haul (500-mile range) Results



Scenario Parameters

- Class 8 Long Haul (500-mile) in Mid-Atlantic Region
- 150,000 mi/yr (580 mi/day)
- 6.7 year life (1M miles)
- Payload Cost = **High**, Dwell Cost = **High**
- Fuel, O&M Costs = Mid
- Discount Rate = 7%

FCET costs driven by fuel cost which is higher when payload is maxed out (lower fuel economy), minimal impact of dwell and lost payload



Note: Diesel price (untaxed) mid scenario ranges from ~$1.8/gal (2018), ~$2.3/gal (2025) to ~$2.7/gal (2050) based on AEO Outlook Middle Atlantic region

*Costs based on batteries for light-duty vehicles, and not adjusted to reflect differences in durability requirements for M/HD

Thank You

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NREL Transforming ENERGY

Updates since DAS-T Review on Jan 12, 2021

- **Timeline**
  - Review with DAS-T on 1/12/21
  - DAS-T office and NREL internal reviewers provided comments by 2/9
  - Internal NREL review completed on 2/11
  - HFTO provided updated fuel cell cost assumptions 3/22

- **Major Updates**
  - Vehicle miles travelled (VMT; mi/yr) assumptions are now dependent on scenario analyzed and vehicle definition to better reflect operating scenarios
  - Quantified the percentage of vehicles, miles travelled, and fuel usage in operating each scenario based on available literature and VIUS data
  - Added a 500-mile Class 8 sleeper vehicle to the analysis to better represent current market trends for ZEVs

- **Summary changes to results**
  - TCO is slightly higher than previously due to VMT changes (less discounting)
  - 500-mile range Class 8 Sleeper ZEV MSRP significantly less than 750-mile version
  - Analysis still shows complementarity between ZEV powertrain options

Updates since DAS-T Review on Jan 12, 2021 (full list)

- PHEV:
  - We will keep this powertrain in the analysis
  - We will caveat it heavily that we are not optimizing the powertrain design and further work is needed to fully understand the opportunity for PHEVs in the M/HD market

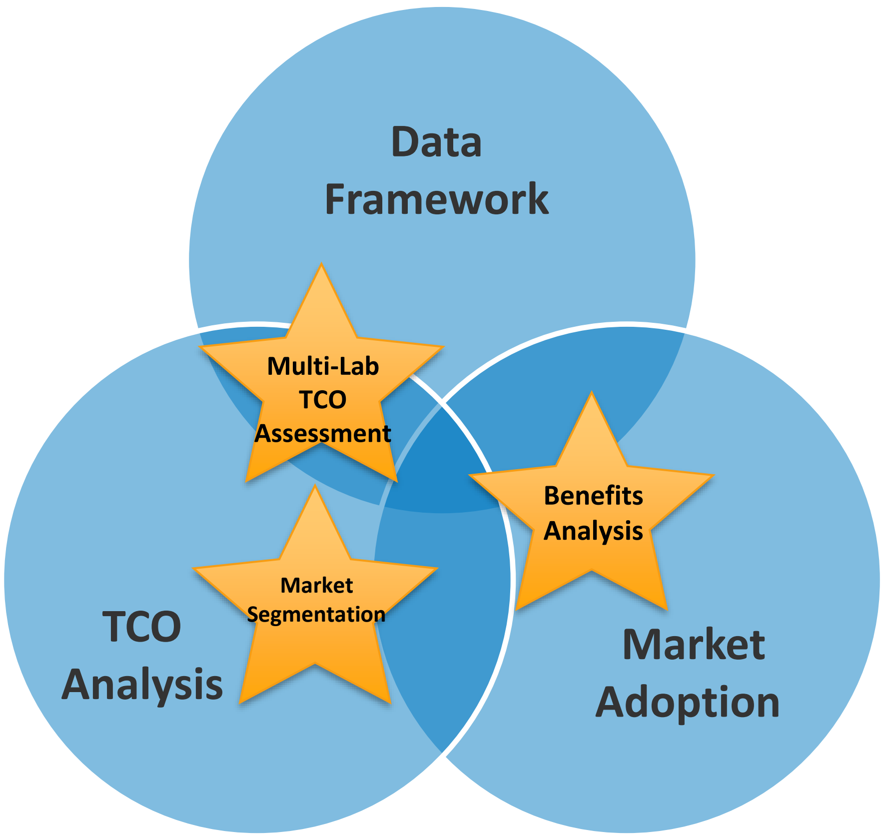
- Estimating Vehicles/VMT in Each Operating Scenario:
  - We will use the existing, limited data with lots of caveats
  - Weight-Limited Operation
    - NACFE (2015) indicates 2-10% of vehicles may be weight-limited
    - VIUS (2002) indicates >20% of VMT
    - Schoettle et al. (2016) survey indicates >50% (54.6%) of Class 8 tractor trailers may weigh-out
  - Multi-Shift Operation
    - Schoettle et al. (2016) survey indicates 6.2% of trucks being long-haul team drivers (40.6% long-haul with overnight stay or team, 34.4%)
    - VIUS (2002) indicates ~5-15% of sleeper cabs VMT > 150k mi/yr
    - VIUS (2002) indicates ~15-25% of day cabs VMT > 100k mi/yr
    - VIUS (2002) indicates ~<10% of Class 4 parcel delivery trucks >50k mi/yr

- Vehicle Range:
  - We will add a 500-mile Class 8 sleeper vehicle range in addition to the 750-mile Class 8 sleeper
  - So the vehicles we will assess in this report are:
    - Class 8 Sleeper – 750 mile range
    - Class 8 Sleeper – 500 mile range **(new)**
    - Class 8 Day Cab – 300 mile range
    - Class 4 Parcel Delivery – 120 mile range

- Scenario Design:
  - We will be adjusting the annual VMT to depend on the scenario (Single-Shift vs Multi-Shift)
  - The VMT assumptions are summarized in the table below and are based on VIUS data (e.g., median vs right-tail)
  - Total lifetime miles of the diesel engine remains constant and consistent with what we had before, so this simply accelerates the driving to earlier years
    - Class 8 tractor lifetime miles = 1 million
    - Class 4 truck lifetime miles = 300k
- Other:
  - Updated to AEO Outlook 2021
  - Update drive-cycles to be consistent with Lustbader et al. (2021) methodology for selecting representative drive-cycles per vocation
  - Added BEV $250/kWh sensitivity analysis
  - Clarified EVSE mid case results in High costs
  - No payload costs for non-Class 8 trucks
  - Changed references of “power electronics and electric machine (PEEM)” to “electric drive technologies (EDT)”

	Class 8 Sleeper (750 mile range)		Class 8 Sleeper (500 mile range)		Class 8 Day Cab (300 mile range)		Class 4 Parcel Delivery (120 mile range)	
Scenario	Annual	Daily (260 workdays)	Annual	Daily (260 workdays)	Annual	Daily Workday (260 days)	Annual	Daily Workday (300 days)
Single-Shift	150000	580	100000	380	60000	230	25000	80
Multi-Shift	200000	770	150000	580	100000	380	50000	170

VTO/HFTO Projects Compliment Each Other



Multi-Lab TCO Assessment (VTO)

- Goal: Identify *and fill* data gaps related to total cost of vehicle ownership
- L/M/HDV focus

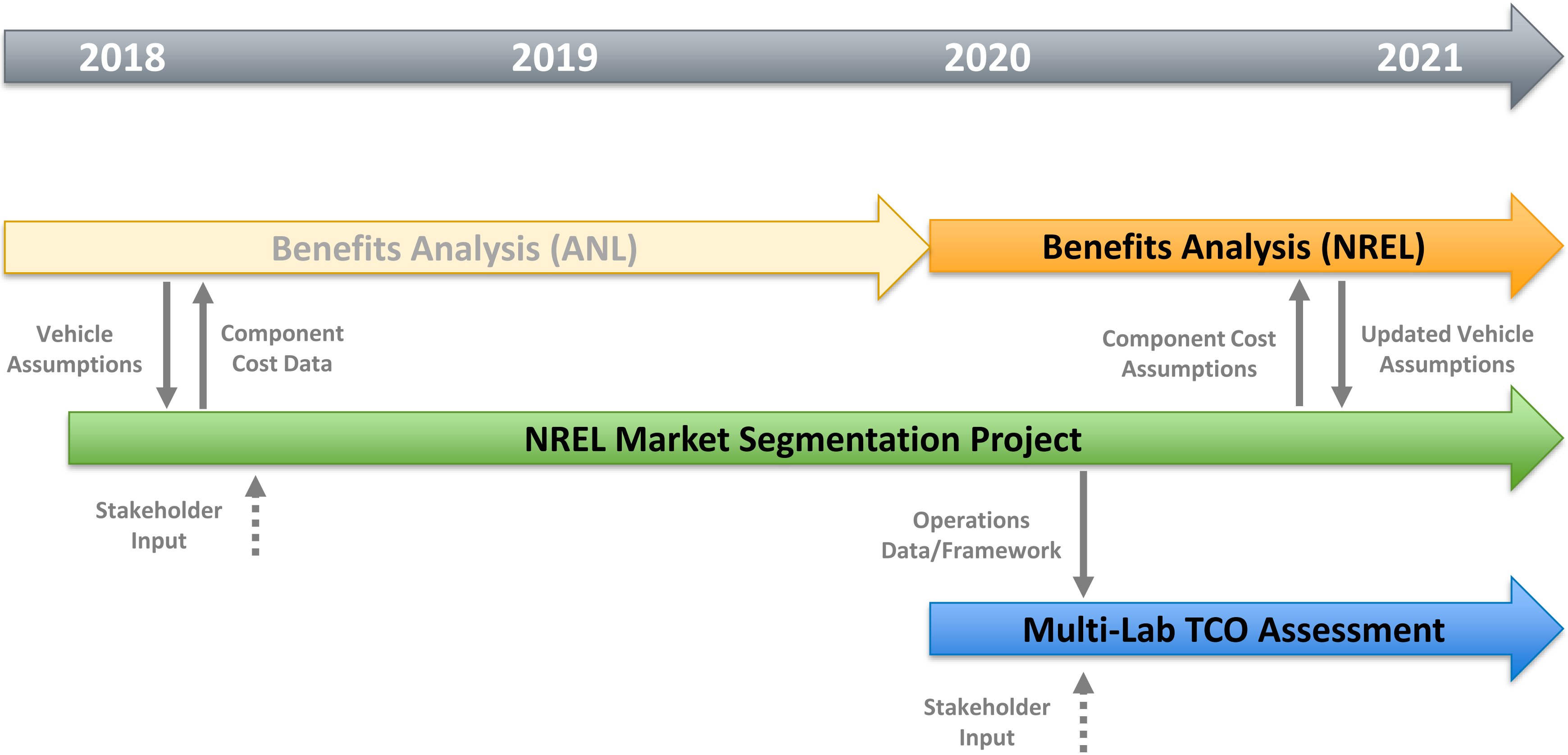
Market Segmentation (HFTO)

- Goal: Provide a detailed TCO assessment to identify tipping points / break-even points
- M/HDV focus

Benefits Analysis (VTO/HFTO)

- Goal: Quantify the on-road petroleum and emissions benefits from VTO/HFTO R&D
- L/M/HDV focus

VTO/HFTO Projects Have Supported Each Other On Key Data Inputs and Methods



Primary Updates Since HFTO Review on 7/9

HFTO Technology Targets Updated To Match GPRA Benefits Analysis Project

- Small changes to fuel cell cost in 2018 (durability adjustment to SA Inc. data) and 2025 (interpolation)
- Ultimate FCEV gross specific power updated to 1.08 kW/kg per HFTO review
- Hydrogen fuel price
  - 2018: $10/kg (lower bound of $7/kg based on FCEB data)
  - 2025: $7/kg (upper bound of $10/kg, lower bound of $4/kg)
  - Ultimate: $4/kg (upper bound of $7/kg)

Baseline Future Diesel Class 8 Tractor Specs Updated

- Diesel truck model (2018, 2025, Ultimate) updated to be consistent with FY20 GPRA Benefits Analysis approved assumptions (e.g., Ultimate diesel fuel economy of ~10-15 mpdge*)
  - Updated diesel engine and aftertreatment costs to match FY20 GPRA Project (latest data available)
  - Added costs for waste heat recovery in 2025, Ultimate (matching Class 8 FCET target setting work)
- Diesel engine cost curve updated based on latest GPRA Benefits Analysis Project
- Diesel prices converted to untaxed for consistent comparison

Component Cost and Performance Data Updated

- Battery cost of $197/kW (2018), 170 $/kW (2025) based on feedback from VTO
- Power electronics cost of $8/kW (2018), $6/kW (2025) based on LDVs with sensitivity up to preliminary HDV BEV estimates per feedback from VTO/ORNL

Communication / Slide Updates

- Added engine / fuel converter sizes over time
- Added caveats, references to assumptions table (e.g., LD battery prices)
- Added fuel price ranges to slides with plots
- Added qualitative text on edge-case scenario design

*Fuel economy depends on vehicle improvement year (2025/Ultimate), drive cycle, and assumed payload

FY20 Benefits Analysis Coordination

	FY20 Benefits Analysis	HFTO Market Segmentation (This Project)
Vehicles	Class 8 sleeper Class 8 day cab Class 8 box (vocational) Class 6 box (vocational)	**Class 8 sleeper** **Class 8 day cab** **Class 4 parcel delivery** } **1st Report (this presentation)** Class 8 drayage Class 8 transit bus Class 8 refuse Class 6 box Class 6 parcel delivery Class 5 basic van } 2nd Report (draft in progress)
Scope	TRUCK adoption model based on TCO	TCO comparison
Scenarios	Direct TCO	Enhanced TCO with dwell time costs and lost payload costs

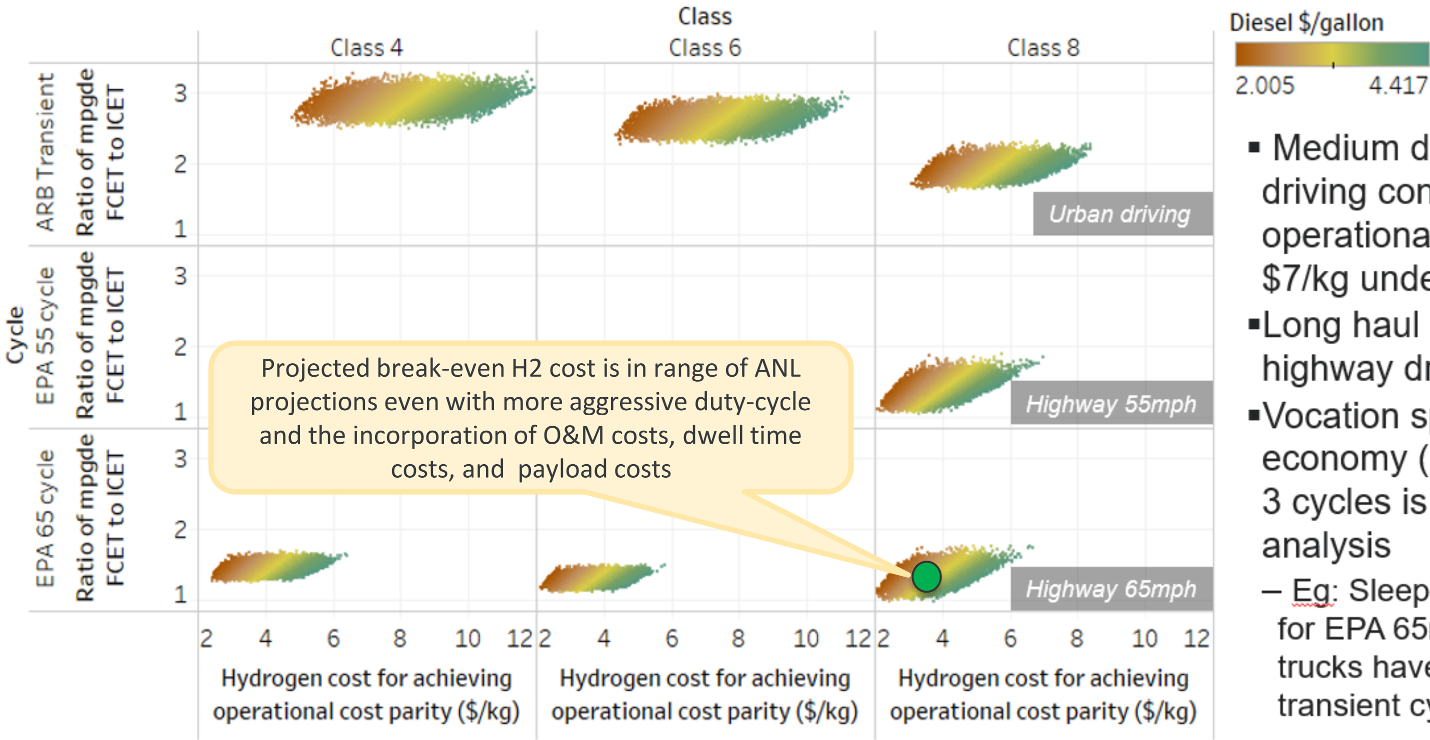
The 2nd Market Segmentation Report uses many of the vehicle / TCO assumptions as the FY20 Benefits Analysis Project

Breakeven analysis compared with ongoing ANL analysis for M/HD Target H2 Prices

Slide from Ram Vijayagopal's 11/23/20 presentation to HFTO on *Hydrogen cost target: Process overview and results*

Type of truck and driving behavior are the next most prominent factors that influence the hydrogen cost target.

On urban conditions FCETs are 2-3 times better than ICETs in their fuel economy, but this advantage is considerably diminished for Longhaul trucks driving on highways



- Medium duty trucks on urban driving conditions can achieve operational cost parity even at $7/kg under ultimate scenario.
- Long haul trucks need <$4/kg on highway driving
- Vocation specific weighted fuel economy (EPA's process) on these 3 cycles is used for further analysis
  - Eg: Sleeper trucks have 86% weight for EPA 65mph cycle. Urban delivery trucks have 90% weightage for ARB transient cycle

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CNG Tank Cost Update

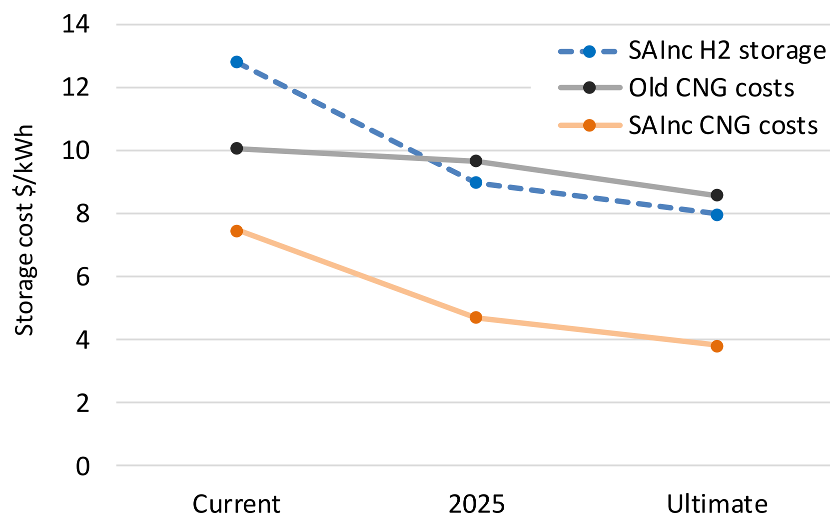
Annual System Production Rate	system/yr	HDV System					
		1,000	10,000	30,000	80,000	100,000	500,000
Balance of Plant	$/system	$3,505.46	$1,534.91	$1,090.83	$866.92	$816.09	$583.25
Fiber Winding	$/system	$3,899.70	$3,899.70	$3,899.70	$3,690.70	$3,561.15	$3,483.53
Liner Annealing	$/system	$35.96	$27.38	$11.27	$6.23	$8.04	$6.59
B-Stage Cure (Cure #1)	$/system	$48.97	$26.64	$6.17	$6.71	$7.04	$5.99
Tank Shoulder Foam	$/system	$58.79	$8.62	$4.90	$3.74	$3.60	$3.27
Full Cure	$/system	$207.20	$109.53	$11.84	$5.64	$4.75	$3.46
Boss	$/system	$54.27	$35.70	$28.69	$26.00	$25.66	$24.54
Hydro Test	$/system	$113.22	$16.43	$9.26	$8.37	$7.83	$7.83
He Fill & Leak Test	$/system	$47.87	$25.46	$12.23	$10.58	$9.59	$9.59
Liner Blow Mold	$/system	$186.57	$93.61	$66.00	$57.37	$56.33	$54.68
System Assembly	$/system	$33.71	$10.49	$9.63	$9.52	$9.46	$9.35
Sum	$/system	$8,192	$5,788	$5,151	$4,692	$4,510	$4,192

- Cost estimate source: SAInc (Uses same methodology as H2 storage tank estimates)
- 15% CNG storage system manufacturer markup
- Max pressure = 3,600 psig
- Min pressure = 300 psig
- Usable tank storage cost results:

Storage cost $/kWh	Current	2025	Ultimate
Prior values	10.08	9.66	8.59
SAInc values	7.47	4.70	3.82

CNG tank cost estimate from SAInc was used
- **Same methodology as H2 tank storage cost estimation**

Applied 15% manufacturing markup
Resulting costs are lower ($/kWh): 7.47, 4.70, 3.82



Collaboration and Coordination

Literature Review and Modeling

- **South Carolina University**
  - Dr. Yuche Chen completed the operating and maintenance cost data literature 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

Additional Assumptions

FASTSim Modeling

- 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

- 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 (e.g. one fuel cell truck can do the same work as one diesel truck)
- 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 at the cost levels evaluated
- Assumed no incentives for zero or near-zero emission vehicles
- Assumed no value/benefits 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

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
HFTO: Hydrogen and 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