Project ID # TA024

Analysis of Fuel Cells for Trucks

R.VIJAYAGOPAL, A.ROUSSEAU

ARGONNE NATIONAL LABORATORY

2019 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

Washington, DC

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Overview

Timeline	Barriers
• Project start date : Sep 2018 • Project end date : Aug 2019 • Percent complete : 50%	• Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data (A) • Lack of Data on Fuel Cells in Real-World Operation (B) • Hydrogen Storage (C) http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_tech_valid.pdf
Budget	**Partners**
• FY18 Funding : $100k • Percent spent : 50%	• Argonne Fuel Cell Team

Objectives & Relevance

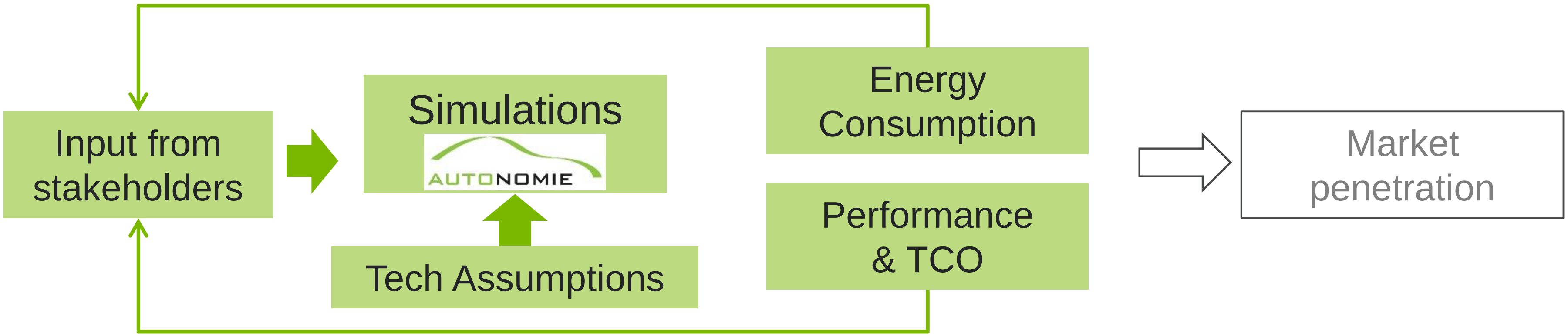
1. Support FCTO medium & heavy duty target settings
   - Develop models for fuel cell electric trucks (FCETs) that would meet or exceed the performance of **present and future** diesel powered trucks
   - Compare energy consumption of FCETs against **best in class** diesel powered class 8 sleeper trucks
     - Estimate total cost of ownership (TCO) based on use case assumptions

2. Quantify the **cooling** system requirements on FCETs
   - Examine the impact of cooling loads on FCETs
     - Can the same system from the conventional truck be electrified to meet the cooling system loads in FCETs?
     - Quantify the power needed to run the cooling system
   - Explore ways to manage cooling loads
     - Have additional battery energy
     - Redesign cooling system
     - Improve fuel cell system efficiency

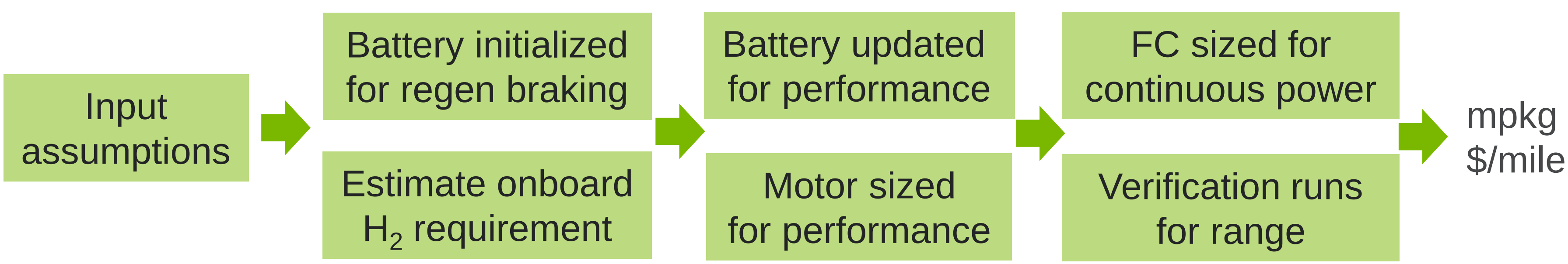
Approach

Develop a path for a better future

- Quantify factors affecting future fuel cell electric trucks viability



- Vehicle technology improvements in ‘interim’ & ‘ultimate’ cases
  - Other DOE activities have developed these future scenarios, sizing procedure and TCO calculation were also developed under TV032,TV150,VAN023 & SA044



Vehicle Assumptions: Class 8 Sleeper

- Two baseline vehicles
  - **Reference technology**: Comparable to 2017-18 trucks.
    Meet regulatory fuel consumption requirements per regulatory test conditions.
    - 6x4 tractor, tested as per regulatory load conditions on EPA65 cycle
  - **Best in class**: Specifications representing fuel economy leaders
    (Ref: NACFE: Run On Less)
    - 6x2 tractor, after market aero improvements, lower payload & tested on EPA55 cycle

- Conventional trucks and corresponding FCETs have similar performances
- Target setting considers the high fuel economy case & thermal model development is done using the higher performance vehicle (worst case scenario)

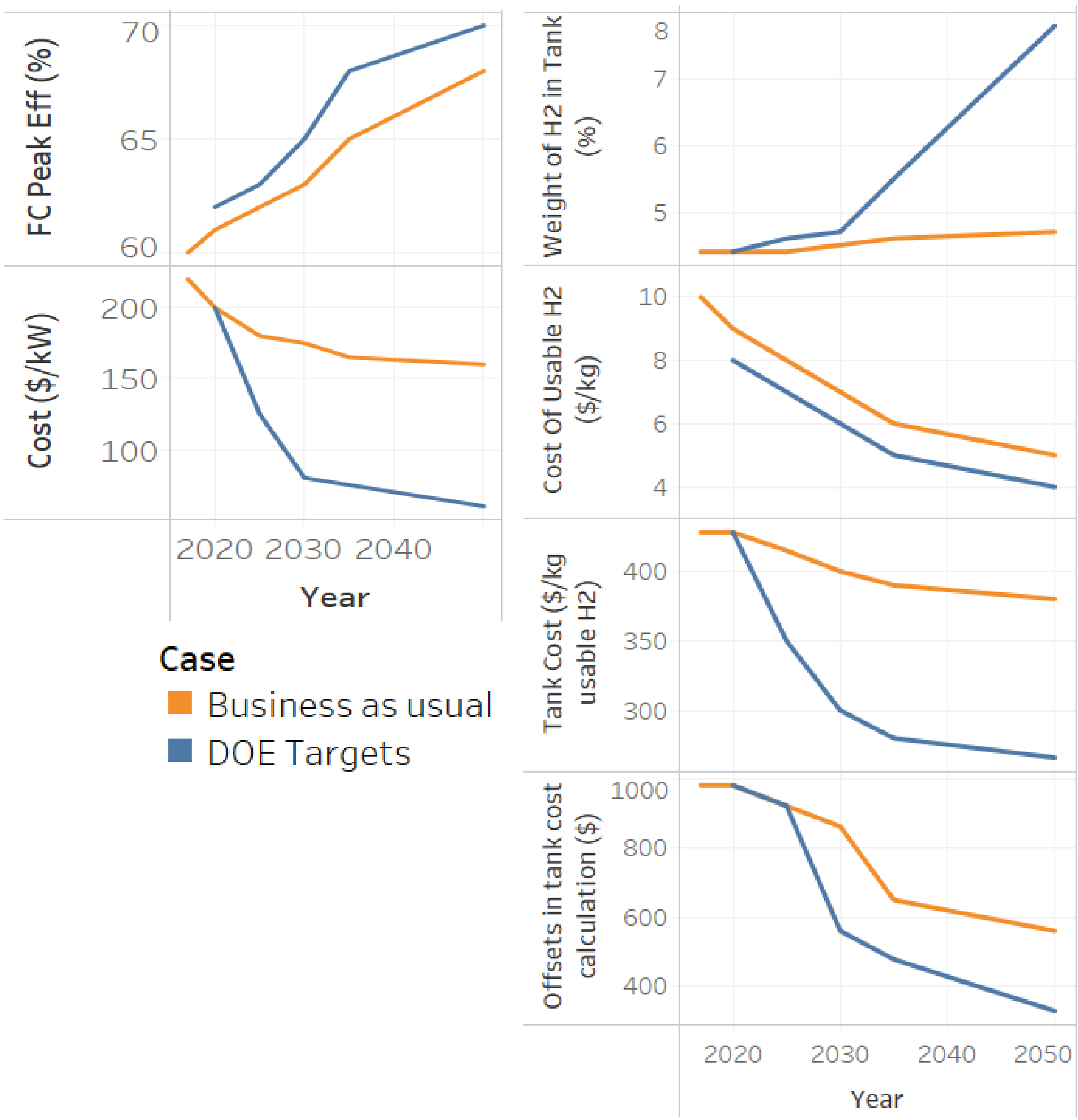
Parameter	Reference truck	Best in class
	Diesel	Diesel
Peak power (kW)	340	305
Highway Fuel Economy (mpg)	7	9.1
Freight Fuel Efficiency (Gallon/1000mile-ton)	8.6	11.9
Test Weight (kg)	30,600	25,000
Cargo (kg)	17,273	9,364

Argonne NATIONAL LABORATORY

NACFE – North American Council for Freight Efficiency

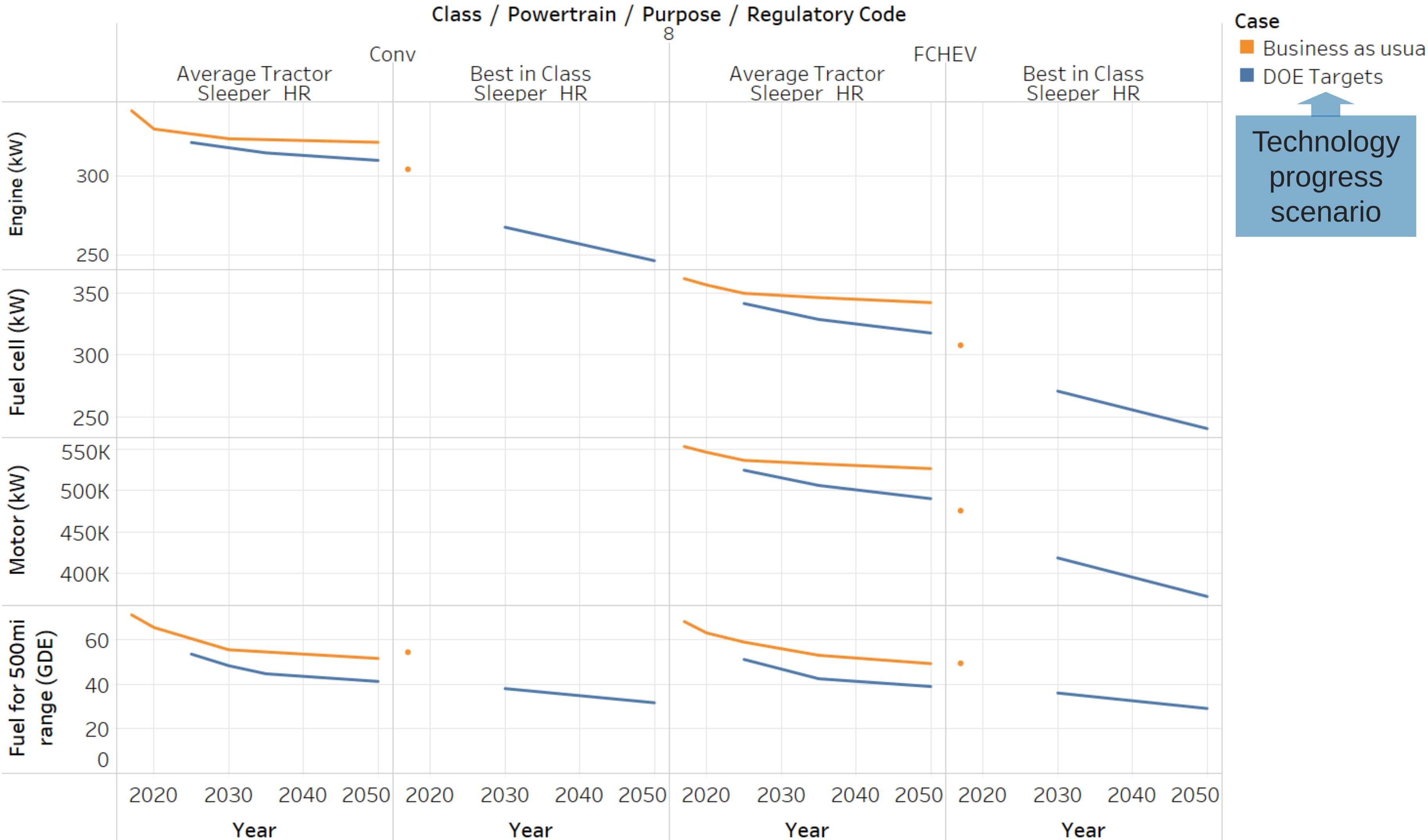
Technology Progress Assumptions

- Interim & ultimate targets are expected to be achieved by 2030 and 2050 respectively.
- Additional vehicle technologies will improve as well.
  - >30% reduction for Cd, Cr & glider weight
- Conventional vehicles will be more efficient
  - Diesel engine efficiency target for 2050 is 59%
- Two technology progress cases are considered to account for uncertainties.



Technical Accomplishments

Developed vehicles for present, interim and ultimate scenario

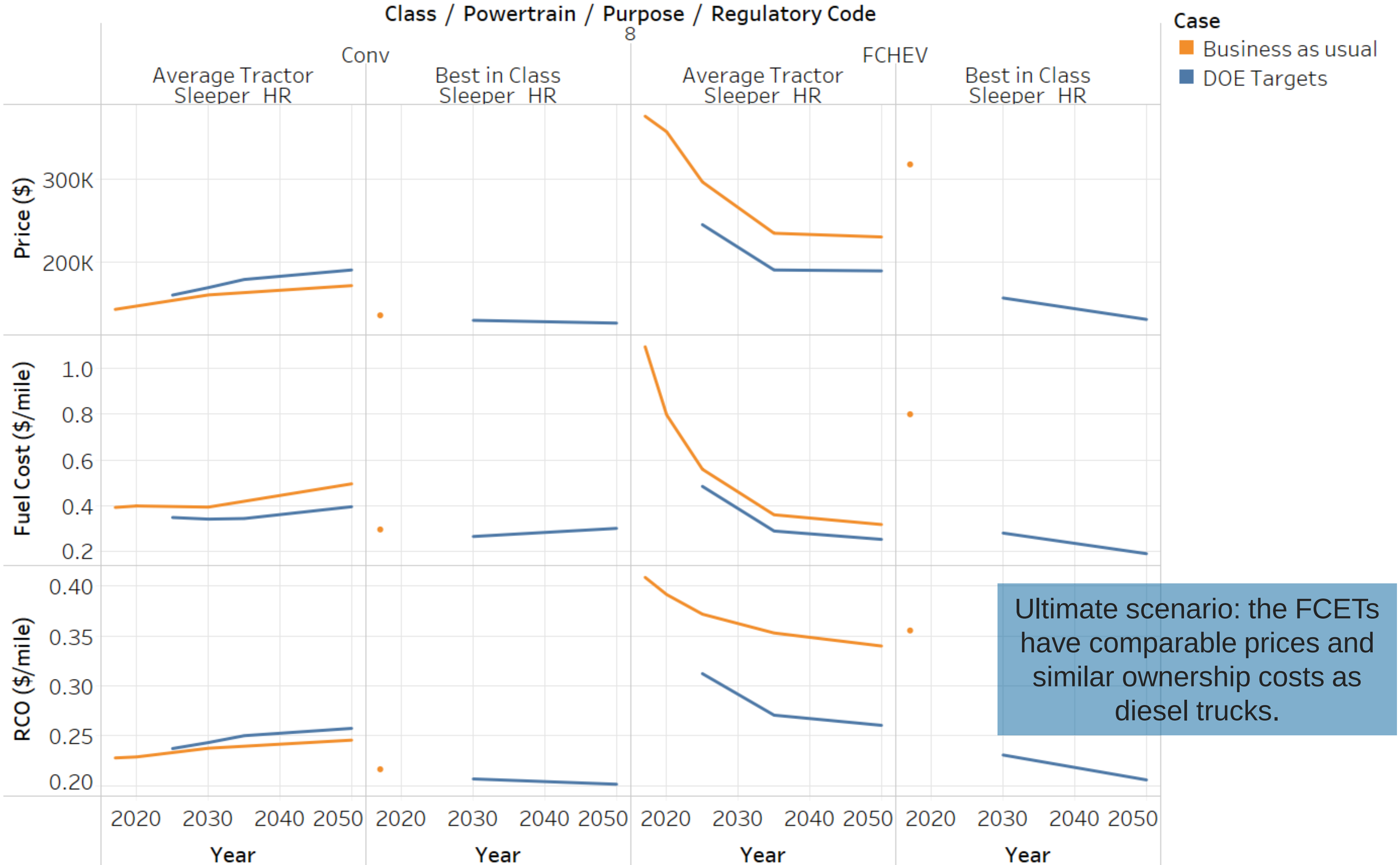


Preliminary results

Argonne NATIONAL LABORATORY

Technical Accomplishments

Estimated cost of owning and operating vehicles



Ultimate scenario: the FCETs have comparable prices and similar ownership costs as diesel trucks.

Preliminary results

Argonne NATIONAL LABORATORY

Objectives & Relevance

1. Support FCTO in medium & heavy duty target setting activities
   - Develop models for FCETs that would meet or exceed the performance of present and future diesel powered trucks
   - Compare energy consumption of FCETs against best in class diesel powered class 8 sleeper trucks
     - Estimate total cost of ownership (TCO) based on use case assumptions

2. Quantify the **cooling** system requirements on FCETs
   - Examine the impact of cooling loads on FCETs
     - Can the same system from the conventional truck be electrified to meet the cooling system loads in FCETs?
     - Quantify the power needed to run the cooling system
   - Explore ways to manage cooling loads
     - Have additional battery energy
     - Redesign cooling system

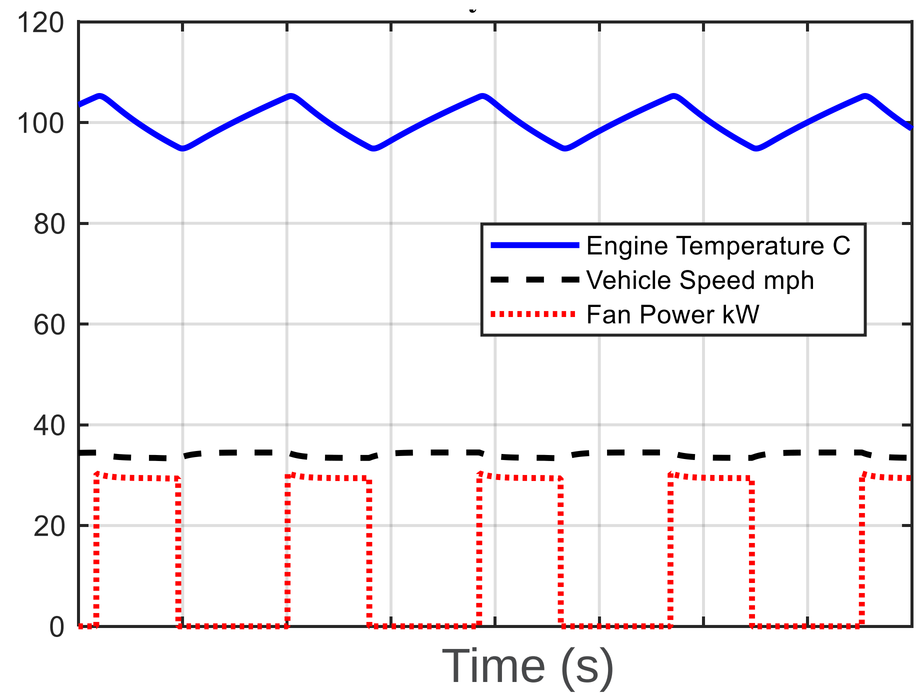
Approach: FCETs Thermal Behavior Modeling

- Develop conventional and fuel cell vehicle models with thermal characteristics.
- Validate the conventional cooling system model against test data
- Integrate cooling model to a FCETs
  - Electric fans and water pumps
- Explore various methods to maintain fuel cell temperature under the desired operational limits.
  - Use battery to supplement propulsion power
    - Quantify battery requirements
  - Use larger radiator (not necessarily more frontal area)
    - Quantify additional cooling load

Technical Accomplishments

Developed diesel engine cooling system

- Considers
  - Heat generation by engine
  - Heat transfer through coolant
  - Heat rejection in Radiator
  - Fan, water pump & thermostat
- Fan operation is intermittent and consumes up to 30kW [1]
- Water pump consumes ~3kW
- The frequency and duration of fan use is consistent with test data observed from Davis Dam tests
- Fan is used for <50% of the time even during the worst case scenario.



Preliminary results

This study examines cooling loads for FCETs using a similar approach.

[1] Larry Slone, and Jeffrey Birkel. *Advanced Electric Systems and Aerodynamics for Efficiency Improvements in Heavy Duty Trucks*. United States: N. p., 2007. Web. doi:10.2172/934589.

3. Fuel Cell Systems for Heavy-Duty Vehicles: Heat Rejection in Class 8, Linehaul Trucks

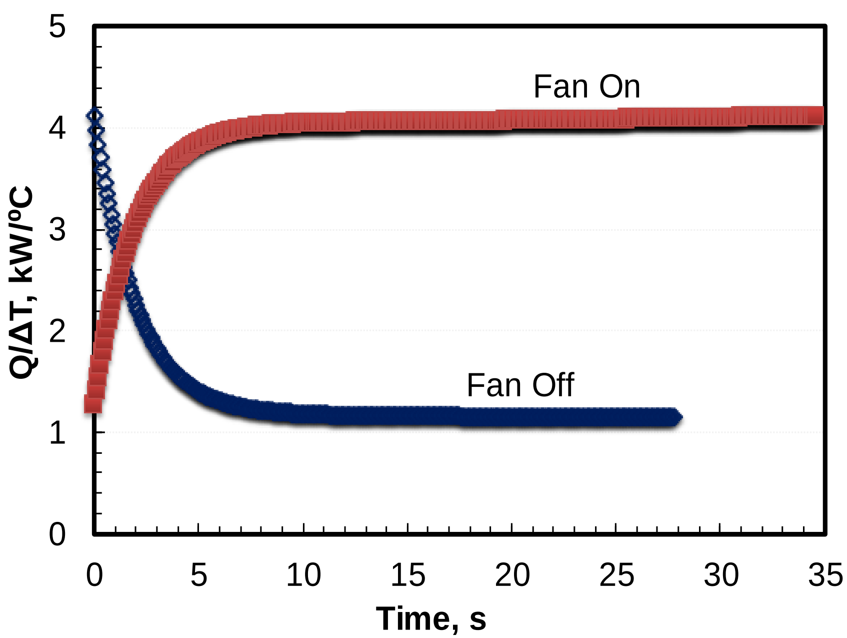
FC-017

Continuous duty cycles that are critical in determining heat rejection requirement

- For traffic safety, must maintain 30 mph on 6% grade (infrequent occurrence)
- For >1,000,000 mile durability, limit stack temperature on 60-mph cruising speed
- To facilitate adoption of new technology, minimal changes to heat rejection equipment

Autonomie simulation of radiator heat transfer on 6% grade, 330-kW baseline power

- Single speed, 30-kW radiator fan turned on when coolant temperature >105ºC
- Radiator fan turned off when coolant temperature < 95ºC



Q/ΔT Limits for Diesel Trucks

- Hill climbing: Q/ΔT = 4.5 kW/ºC, 25ºC ambient temperature, radiator fan on
- Highway cruising: Q/ΔT = 2.6 kW/ºC, radiator fan off
- Highway cruising: Q/ΔT = 5.4 kW/ºC, radiator fan on

Heat Rejection Metrics for Diesel Engines in Class-8 Long Haul Trucks

	Climb at 6% grade	Highway Cruising
Speed	30 mph	60 mph
Maximum/desired coolant temperature	105ºC	95ºC
Ambient temperature	25ºC	50ºC
Fan	On	Off
Propulsion Power	330 kW	150 kW

Argonne NATIONAL LABORATORY

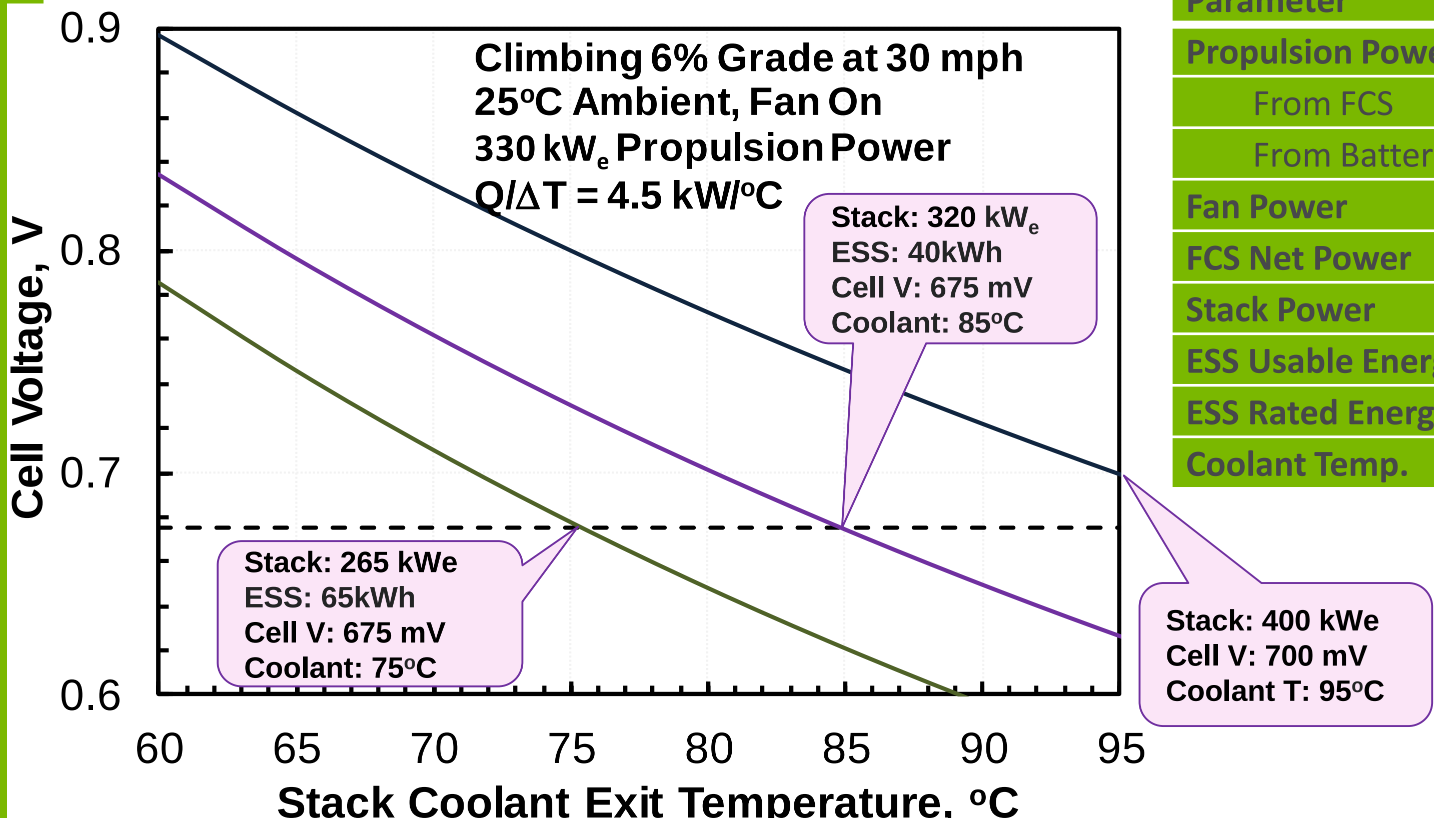
Fuel Cells for Linehaul Heavy-Duty Trucks
Envelope of Operating Potentials and Temperatures

FC-017

Stand-alone stack needs to operate at 700 mV cell voltage and 95ºC coolant exit temperature at rated power to meet the Q/ΔT constraint.

Benefits of hybridizing fuel-cell dominant propulsion system with energy storage battery

- Smaller stack (330-265 kW_e) with higher power density (lower cell voltage, 675 mV)
- Improved durability because of lower operating temperature (75-85ºC coolant exit T)
- Possible trade-off between power density (cell voltage) and durability (temperature)

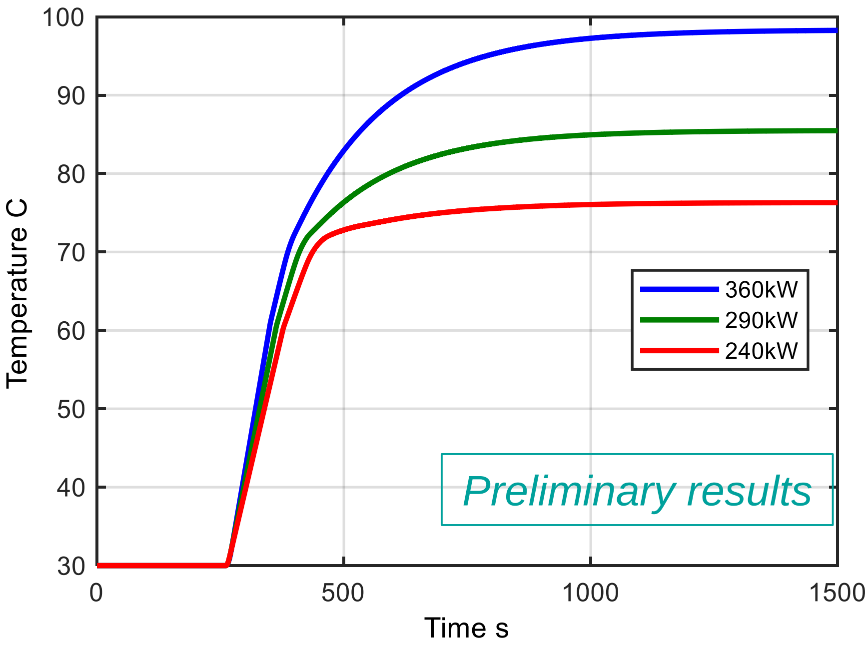


Parameter	Unit	#1	#2	#3
Propulsion Power	kW_e	330	330	330
From FCS	kW_e	330	256	208
From Battery	kW_e	0	74	122
Fan Power	kW_e	30	30	30
FCS Net Power	kW_e	360	286	238
Stack Power	kW_e	400	320	265
ESS Usable Energy	kWh	0	27	45
ESS Rated Energy	kWh	0	39	64
Coolant Temp.	ºC	>90	85	75

Technical Accomplishments

Option 1: Battery to supplement FC power

- FCETs simulated with varying battery sizes to reduce the power requirement on fuel cell.
- Observation from vehicle level simulations consistent with fuel cell team estimates.
- Fans, pumps and battery packs needed for cooling systems will have an impact on fuel consumption as well.
  - Fan results in ~30kW electric loads. Alternate fan designs are being evaluated [2]

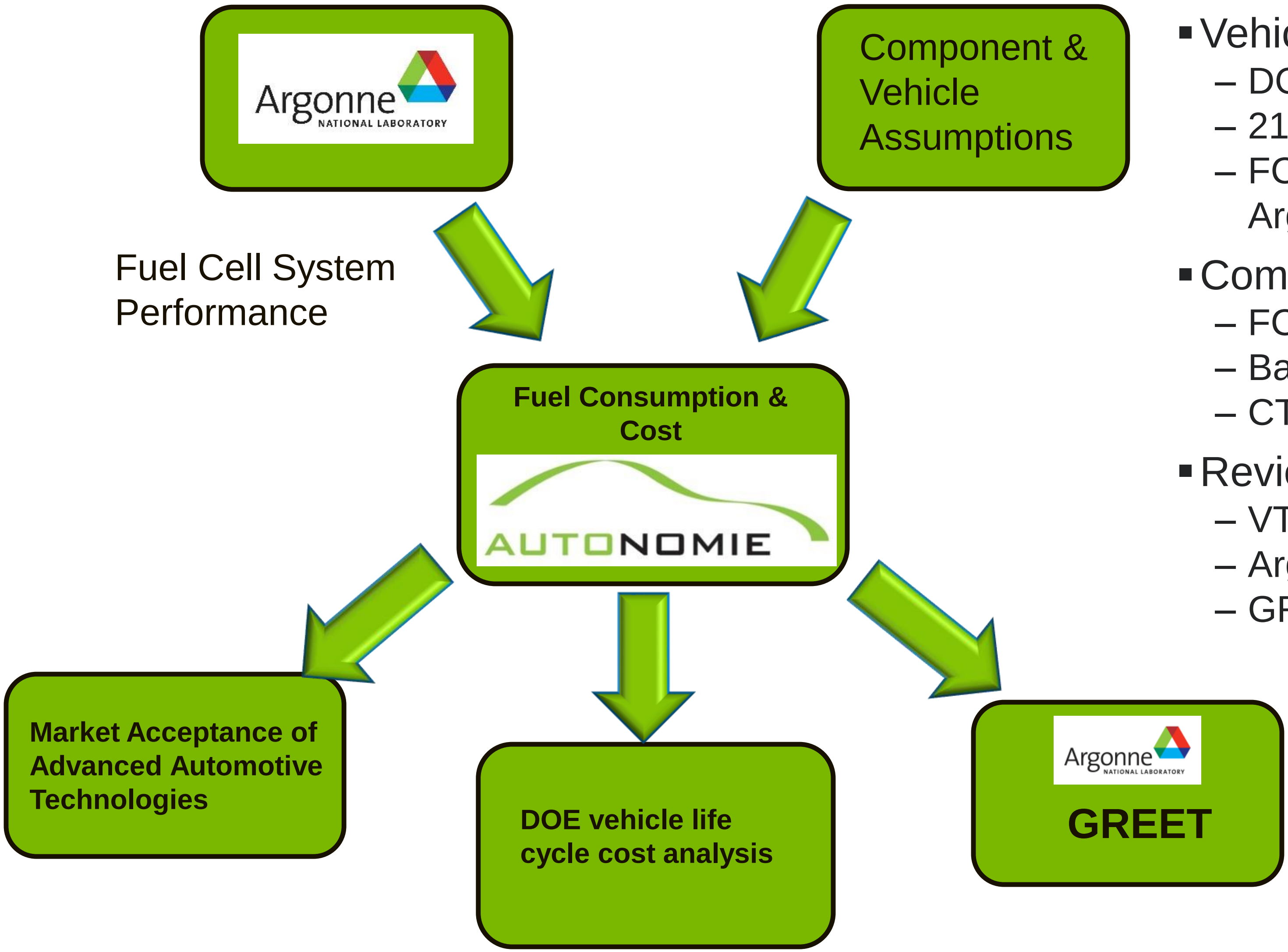


Option 2: Improved radiator design

- Increasing the surface area of radiator improves cooling, but it will increase the fan load.
- Models are being developed to quantify these effects.

[2] Fan performance data from Multiwing Optimizer, www.multi-wing.com

Collaboration and Coordination with Other Institutions



- Vehicle Assumptions
  - DOE VTO
  - 21CTP partners
  - FC Workshop @ Argonne
- Components
  - FCTO
  - Ballard
  - CTE & Univ of Texas
- Reviews
  - VTO & FCTO
  - Argonne FC team
  - GREET team

Proposed Future Work

1. Continue to support the target development process
   - Verify whether the class 8 targets will meet the needs of all other use cases

2. Explore better radiator designs to account for cooling system requirements of FCETs. Find the solution that minimizing the RCO of FCETs

Long term goal is to make the thermal characteristics an integral part of the vehicle sizing algorithm for all powertrains.

Summary

- Supported FCTO fuel cell target settings for medium and heavy duty vehicles through system simulation.
  - Workshop conducted at Argonne in 2018 informed the assumptions used for this work.
  - All assumptions, model and results are made available for review/comments.

- Worked with Argonne Fuel Cell team to quantify the fuel cell heat rejection
  - Developed cooling system model and verified against test data
  - Developed battery sizing algorithm to include FCET cooling requirements.
  - Currently developing model for several radiator properties and estimating the changes in fan load.

Backup Slides

Why are Class 8 trucks chosen for this?

Class 8 Linehaul requirements exceeds the needs of trucks used for other purposes.

1. Representative Trucks
- Based on market data.
- Vehicle data is from OEMs & other sources

2. Develop Baseline Model
- Determine performance capabilities and fuel economy

3. FCET Sizing
- Determine component sizes to meet performance
- H_2 requirement

4. Simulate Truck Performance
- Verify performance
- Verify range
- Verify real world usage

Sizing process was developed in prior work (TV032)

- Class 8 Line haul is the primary candidate for target setting process
  - 75% of diesel usage in US is for tractor trailers.
  - Challenging requirements
    - power output, onboard H_2 storage, refueling time, cooling requirements
  - Very sensitive to cost of ownership
  - Sensitive to cargo capability (weight and volume)

- Argonne can now evaluate over 20 class vocation combinations
  - Simulation models are available. Analysis will require additional effort

Full RCO Assumptions

- Relevant Cost of Ownership (RCO) depends on initial cost, residual cost and recurrence cost involved in owning and operating the vehicle over its service period.

$$RCO = Cost_{inv} + Cost_{pv\_energy} + Cost_{pv\_maint} + Cost_{pv\_batt\_replace} + Cost_{residual}$$

– Total investment: $Cost_{inv} = Cost_{purchase} + Cost_{init\_registr} + Cost_{home\_EVSE} - Cost_{PEV_{incentive}}$
  - $Cost_{purchase} = Cost_{manuf} \times (1 + profit_{margin} + tax_{added})$
  - $Cost_{init\_registr} = 186\ [\$]$ $Cost_{home\_EVSE} = 0\ [\$]$ $Cost_{PEV_{incentive}} = 0\ [\$]$

– Present value energy cost: $Cost_{pv\_energy} = (on\_road\_kWh/km \times \$_{elec/KWh} + baseline\ liter/km \times \$_{gas/liter}) \times distance_{trvl\ yr}/f_{cap\_recov}$
  - $\$_{elec/KWh} = 0.135$, $\$_{gas/liter} = 0.793 = 3\ [\$/gasoline\ equivalent\ gallon]\ (\$_{H_2/kg} = 4)$
  - $distance_{trvl\ yr} = 22530.823\ \text{km} = 14000\ \text{mile}$

– Present value maintenance: $Cost_{pv\_maint} = (Cost_{maint} \times distancev_{trvl\ yr} + Cost_{ownership\_registr})/f_{cap\_recov}$
  - $Cost_{maint} = 0.08/1.60934\ [\$/km]$ $Cost_{ownership\_registr} = 46\ [\$]$

– Present value battery replacement cost: $Cost_{pv\_batt\_replace} = 0$

– Residual value: $Cost_{residual} = -Cost_{inv} \times (1 - 15 \times 10^{-7} \times time_{service} \times distance_{trvl\ yr} - 0.476) \times (1 + rate_{discount})^{-time_{service}}$
  - $time_{service} = 5\ [yr]$ $rate_{discount} = 0.05$

Ref: A. Rousseau, et al., "Comparison of Energy Consumption and Costs of Different Plug-in Electric Vehicles in European and American Context," EVS28, 2015

Interaction with other institutions

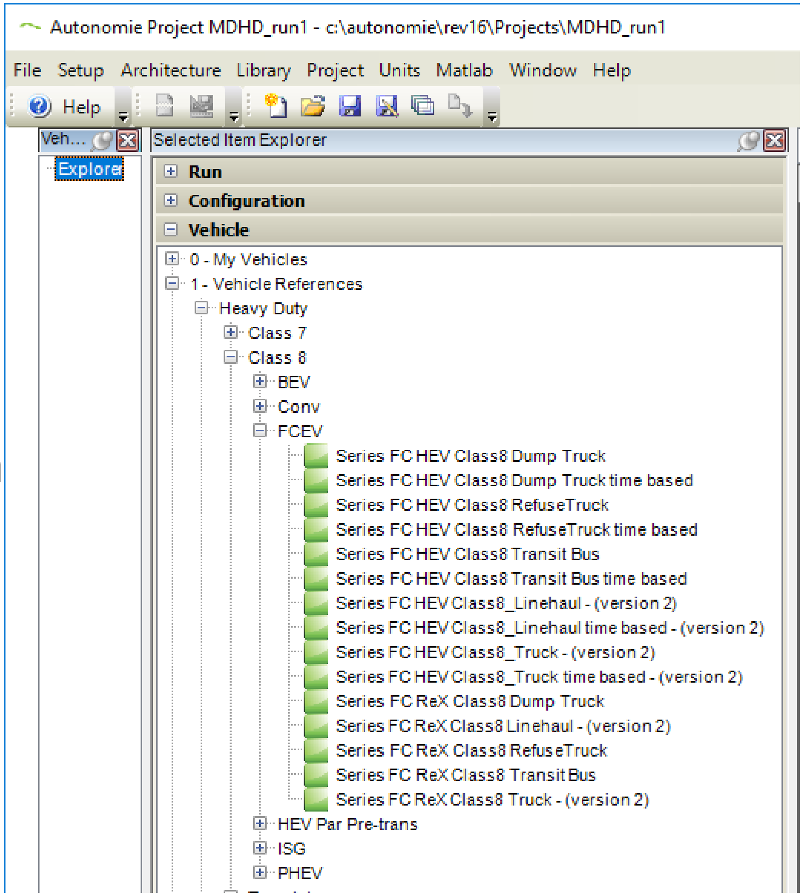
- CTE & Univ of Texas were helpful in sharing the cooling system details from their class4 truck prototype. It served as a validating point for our model development.
- Workshop conducted at Argonne was very useful to get feedback from a lot of stake holders.
  - Several large fleet operators provided feedback on the range expected on different types of trucks.
  - Ballard provided feedback on FC cost and efficiency status as well as how it is expected to improve

Data management plan

Sharing the models & results with everybody for future work.

- All vehicle models, and test procedures are integrated to the simulation tool, Autonomie.
  - It is freely available for all US government funded activities.
  - Rev16 has example for multiple vehicle classes, vocations & powertrains.
- More vehicle variants are added to upcoming releases of Autonomie.
- Results from the simulation are available from the tableau server setup by Argonne, and as an excel sheet to support other projects

AUTONOMIE



Response to Reviewer Comments

- This project was not reviewed last year