PROJECT ID: TA 024

ANALYSIS OF FUEL CELLS FOR TRUCKS: REAL WORLD BENEFITS

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Project Overview

Timeline	Barriers
Start date : Sep 2019 End date : Aug 2020 Percent complete : 50%	• Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data (A) • Hydrogen Storage (C) http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_tech_valid.pdf
Budget	**Partners**
FY 20 : $60k Percent utilized : 50%	• NREL (FleetDNA, Livewire) • 21CTP

Objective & Relevance

Quantify the real world benefits of fuel cell electric trucks (FCETs) to assist technology target development activities.

- In the past Argonne has demonstrated FCET design solutions that match or exceed conventional vehicle performance
- **What has changed since the earlier assessment?**
  - 21CTP & other OEMs reviewed sizing process and provided additional vehicle requirements.
  - Real world driving cycles (RWDC) are now available from various sources within DOE (CERC Truck, Livewire, FleetDNA)
  - Changes in component technologies & DOE targets.

- **Analysis focuses on:**
  - Range, Fuel cell and Battery power requirements for FCET
  - Stored H_2 mass required for various types of trucks
  - Fuel economy & Total Cost of Ownership (TCO) for real world operation
  - H_2 cost target for achieving TCO parity in MD & HD applications

Approach

Quantify the benefits of vehicle technologies on Medium & Heavy duty (MD & HD) vehicles

Collect component technology forecast from DOE (NREL) → **Size baseline and FCET variants of MD&HD vehicles (Q3,FY20)** → **Estimate fuel economy & TCO** → **Reports & Papers (Q4, FY20)**

Vehicle Technical Specifications (Argonne, Q1 FY20) → **Reviewed by 21CTP Updated sizing code is added to Autonomie (Q2,FY20)** ↑ (to Size baseline and FCET variants)

Guidance on TCO related assumptions. (VTO TCO working group) ↑ (to Estimate fuel economy & TCO)

- Task completed
- In progress
- On track

- **What is new in FY20?**
  - Updated technology progress assumptions (2020 → 2050)
  - Updated assumptions on vehicle specifications, performance targets & sizing methods based on industry feedback
  - Uniform assumptions across multiple studies on TCO estimates

Results from prior work is published (see slide on 'publications' for details)

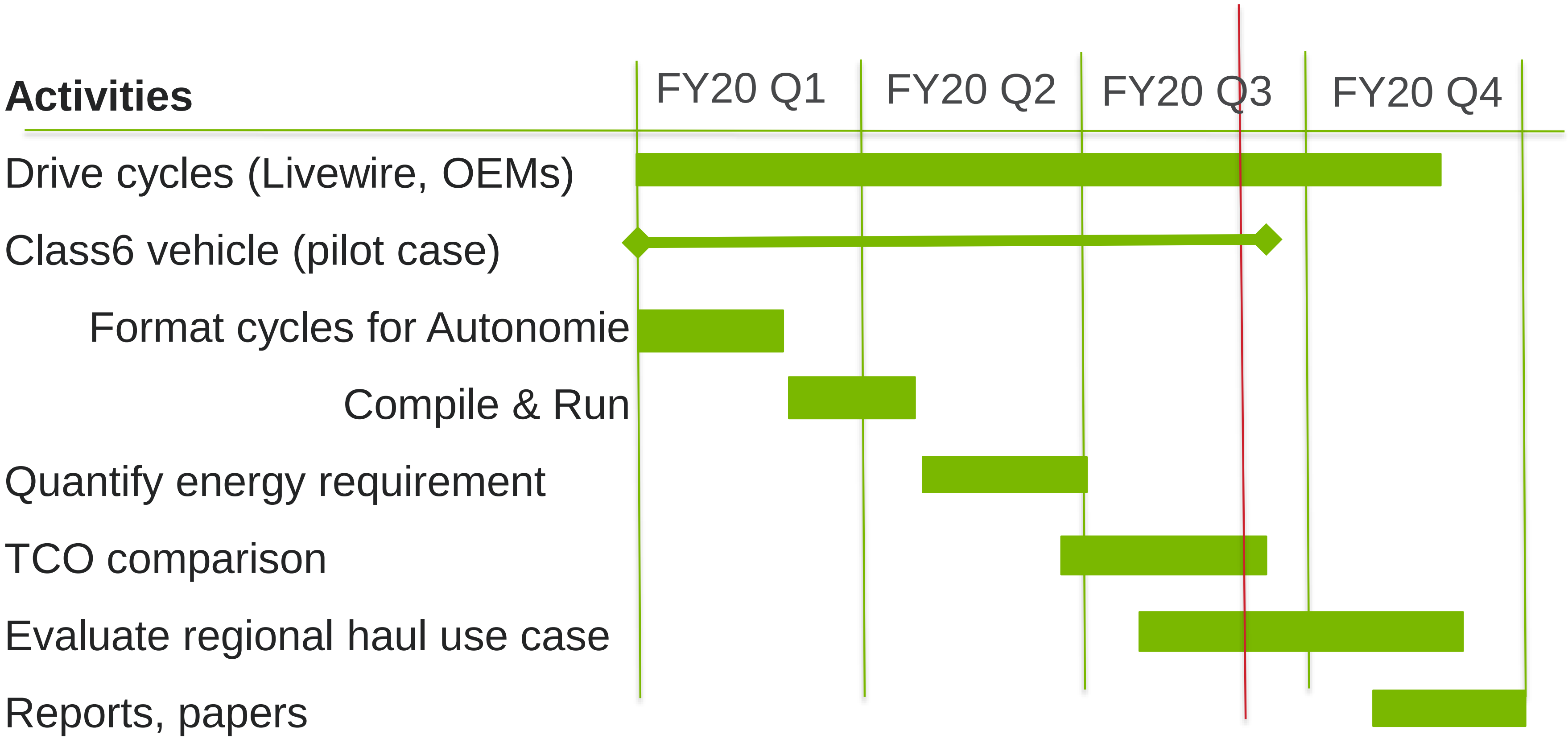
Approach

Focus on two truck classes.

Vehicle Class	Vocation/ Description
class 2b, 6000 – 10000 lbs	Small Van
class 3, 10001 – 14000 lbs	Enclosed Van
class 3, 10001 – 14000 lbs	School Bus
class 3, 10001 – 14000 lbs	Service, Utility Truck
class 4, 14001 – 16000 lbs	Walk In, Multi Stop, Step Van
class 5, 16001 – 19500 lbs	Utility, Tow Truck
class 6, 19501 – 26000 lbs	Construction, Dump Truck
class 6, 19501 – 26000 lbs	**Delivery Truck** 1
class 7, 26001 – 33000 lbs	School Bus
class 8, 33001 lbs or heavier	Construction, Dump Truck
class 8, 33001 lbs or heavier	Line haul
class 8, 33001 lbs or heavier	Refuse, Garbage Pickup, Cab over type
class 8, 33001 lbs or heavier	**Regional Haul** 2

More cases will be analyzed as real world data is added to Livewire

Milestones



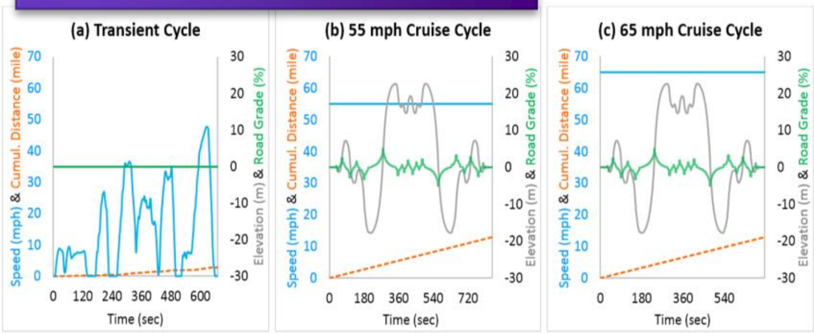
Preliminary results are available for energy and power requirements for Class6 Delivery cycles provided by an industry partner. More cycles are expected from NREL through Livewire.

Completion of analysis and reports are expected by end of FY20

Vehicle Energy Consumption Evaluation Example

Vehicles are sized to match or exceed the requirements.

EPA's regulatory cycles



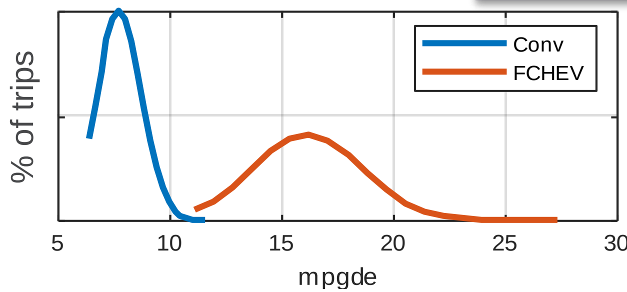
Vehicle Requirements

Cargo, Cruising speed, Acceleration, Startability, Gradeability

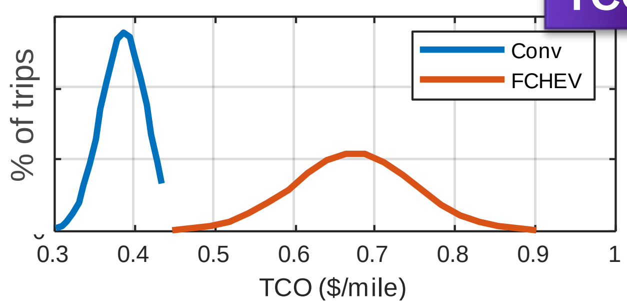
AUTONOMIE

Fuel economy, vehicle cost & TCO estimates

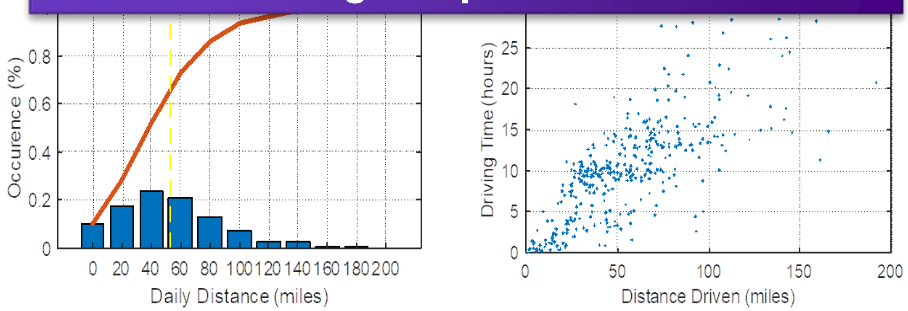
MPGDE



TCO



Real world range requirements for trucks



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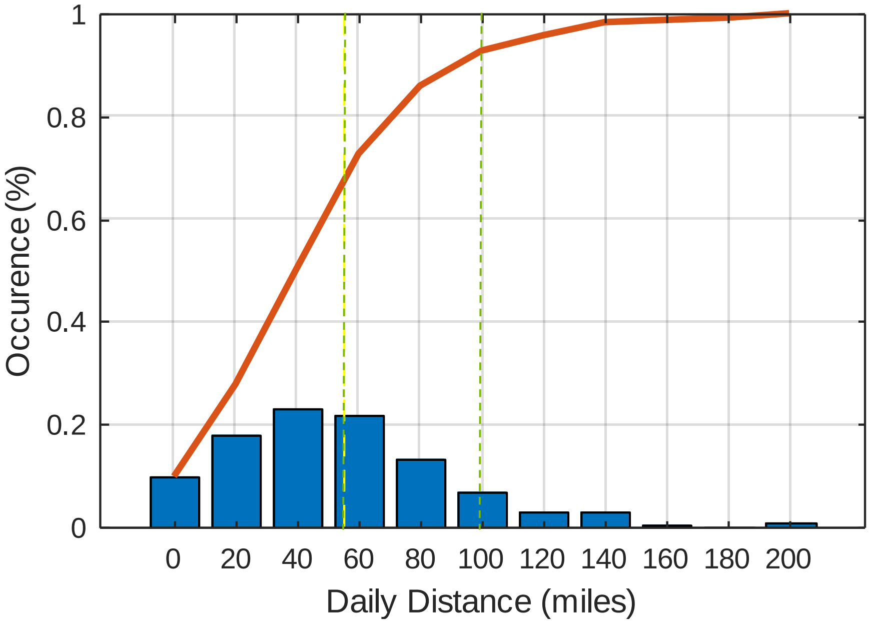
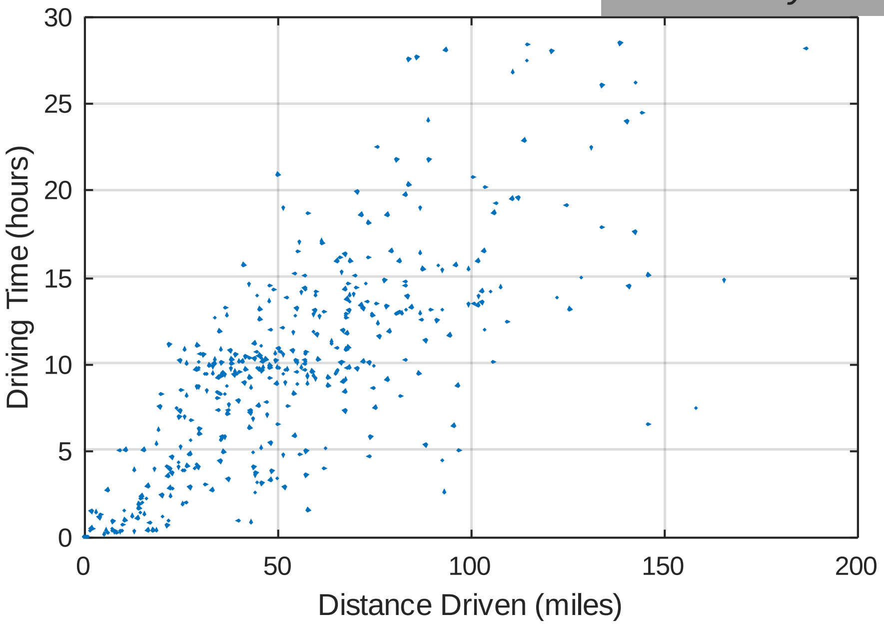
Class 6 delivery truck: 150 mile driving range is needed for most real world daily driving.

Similar to the prior assumption based on VIUS & FleetDNA.

- Each cycle represents one ‘work’ day of driving for one vehicle (510 cycles total).
- A downtime of at least 4 hours is taken as the ‘end of day’. Some cycles show over 30 hours of operation over multiple shifts, with less than 4 hour gap between shifts
- For this data set,
  - A 125 miles range is sufficient for 95% of the daily trips.
  - 80% of daily trips are less than 75 miles.

Preliminary results





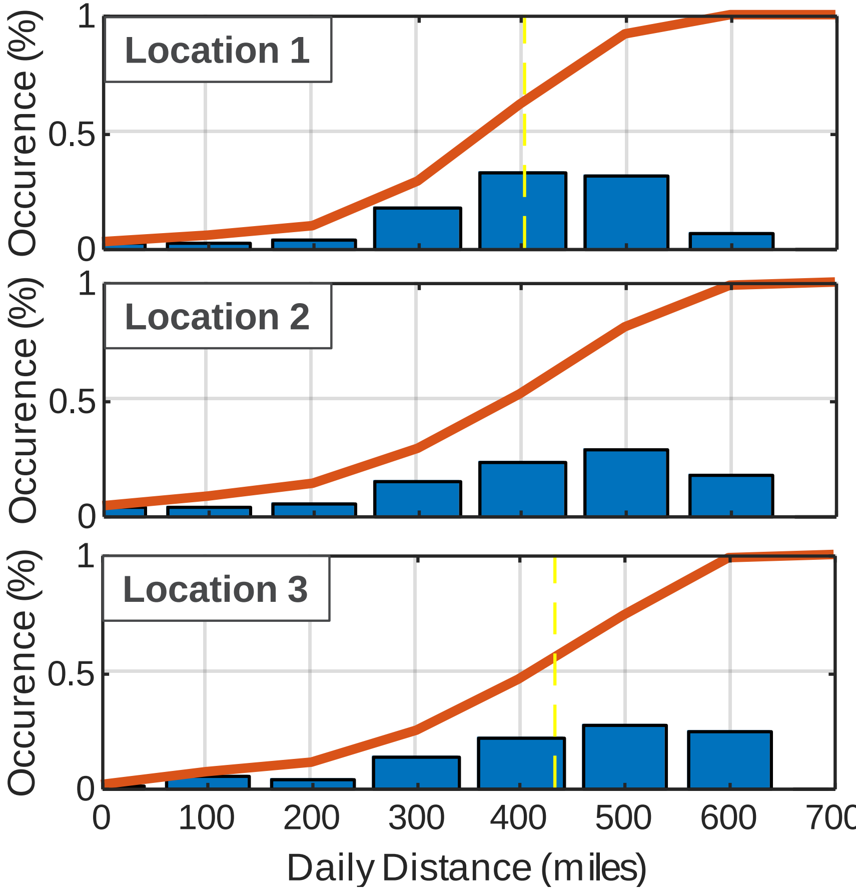
Note: Many BEV delivery truck prototypes too use similar driving range

Class 8 regional haul: 500 mile range sufficient for 80-90% of the trips.

Prior work used two tractor models. Daycab with 250 mile & a longer range sleeper with 500 mile range.

Preliminary results

- One of the locations had 20% trips that exceeded 500 mile.
- NACFE estimates 7% of trips are over 500 miles.
- Will continue to review drive cycle data from more locations to determine whether daily driving distance should be increased.
- This work will use the 500 mile range tractor (sleeper) model for analysis.
  – A daycab model with similar range will also be added to the analysis



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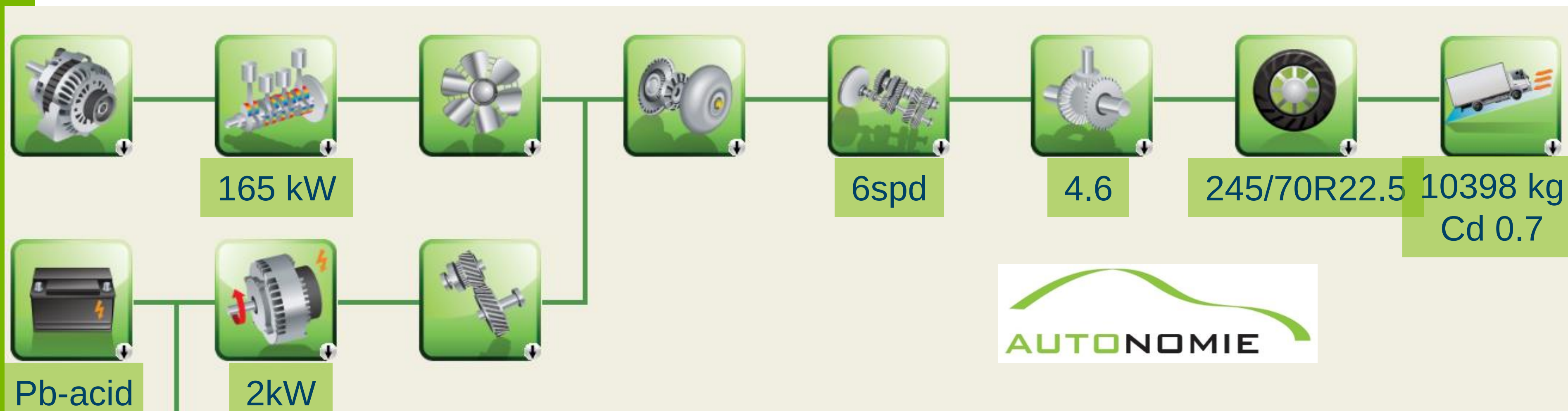
Conventional vehicle used as baseline

Class 6 delivery vehicle is shown as example
Sizing is based on process reviewed by industry partners*



- Components in Autonomie library are scaled to match the requirements of baseline vehicle
- Cargo weight is from EPA's regulatory impact analysis example.
- Performance tests
  - Acceleration, Cruise & Grade
- Fuel economy test : EPA cycles & Real world cycles

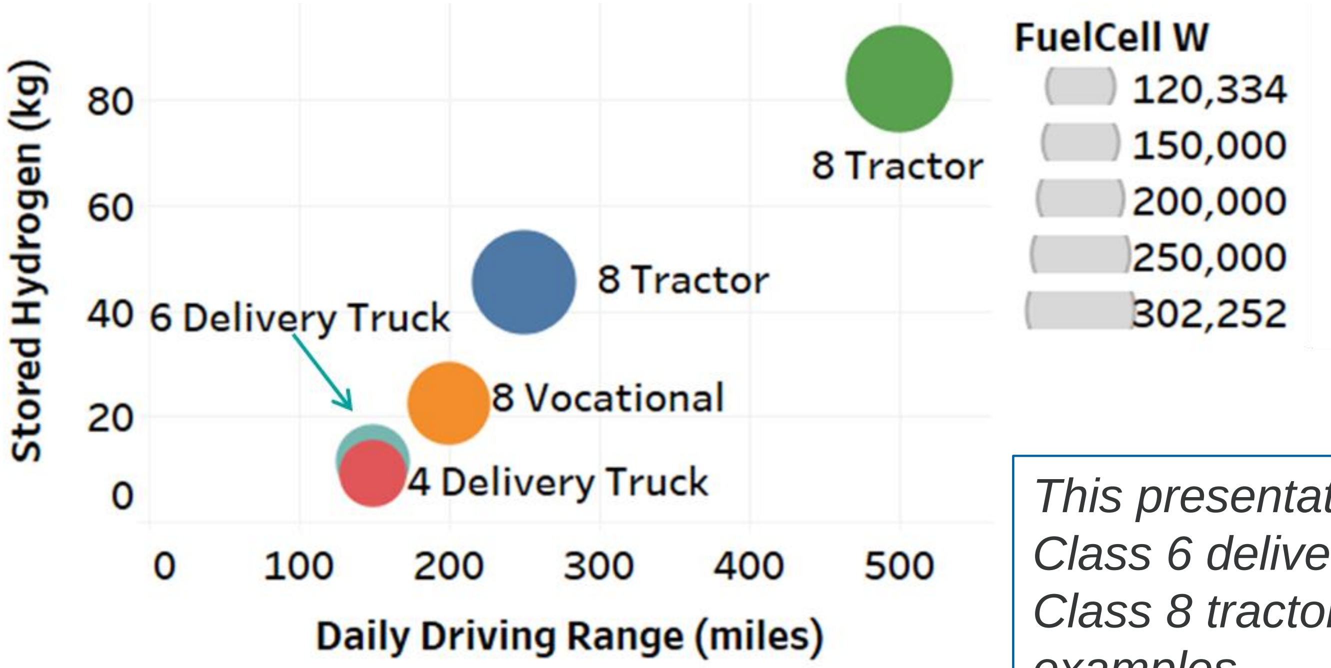
*sizing procedure details are available in backup

FCET Sizing Approach

Fuel cell dominant hybrid electric vehicle (FCHEV)

Vehicle chassis, axle, wheels are unchanged to retain the same GVWR

- FCHEVs are sized for multiple classes and vocations
  - Fuel cell dominant design is followed for this project.
- Examples for vehicles & sizing process are integrated to Autonomie and is available for wider research community.



This presentation will use Class 6 delivery truck and Class 8 tractor (500 mile) as examples.

Technical Accomplishments

FCET sizing details: Class 6 truck example

Goal: Meet or exceed baseline vehicle performance at max GVWR

- Fuel cell is sized to meet all continuous power requirements
  - Cruise & Grade
- Motor is sized to for both continuous and peak requirements
- Battery will provide any additional power needed to augment the fuel cell during transient events.

Basic Performance Criteria	Class 6 Delivery Truck
Max Cruising Speed (mph)	70
6% Grade Speed (mph)	37
0-30 mph acceleration time (s)	14
0-60 mph acceleration time (s)	50
* Sustained Grade at 65mph (%)	1.5
* Launch capability (%)	20
*New requirements being added based on industry feedback	

Sizing Summary	2017	2020 sizing	change
Range (miles)	150	150	--
Onboard H_2 (kg)	16.6	**11.4**	↓
FC Power (kW)	160	150	↓
Motor Power (kW)	290	302	↑
Cargo for Fuel Economy runs (lb)	11300	4500	↓
Test weight for Fuel Economy runs (lb)	22800	16200	↓
Test weight for Performance sizing (lb)	22800	26000	↑

FC efficiency & vehicle improvements results in reduced FC power and onboard storage requirement compared to prior work

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Identify Real World Fuel Economy of Conventional and FCETs

Class 6 delivery truck (MD) example using real world drive cycles*.

- Regulatory cycles provide a good way to compare energy consumption of vehicles
- Real world drive cycle analysis will show the potential fuel saving benefits for actual users on their specific routes.

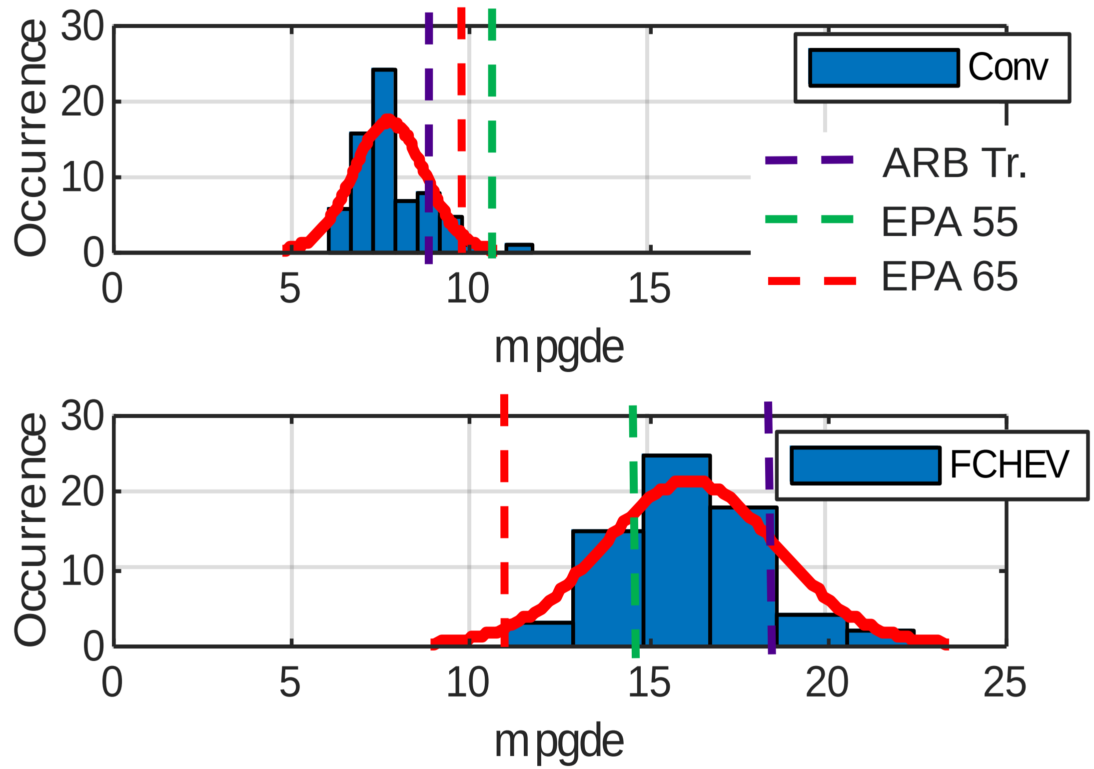
Regulatory cycles

mpgde	Conv	FCHEV
ARB Transient	9.1	18
EPA 55	11.2	14.5
EPA 65	9.7	11

- Relative advantage of FCHEVs depends on the drive cycles
- This data set has a lot of high speed driving (>70mph) and idle time. This adversely affects the observed fuel economy.

Real world cycles

Preliminary results



* Each real world cycle depicts vehicle usage for one or more shifts.
A vehicle down time of at least 4 hours is considered as an end of the work day.

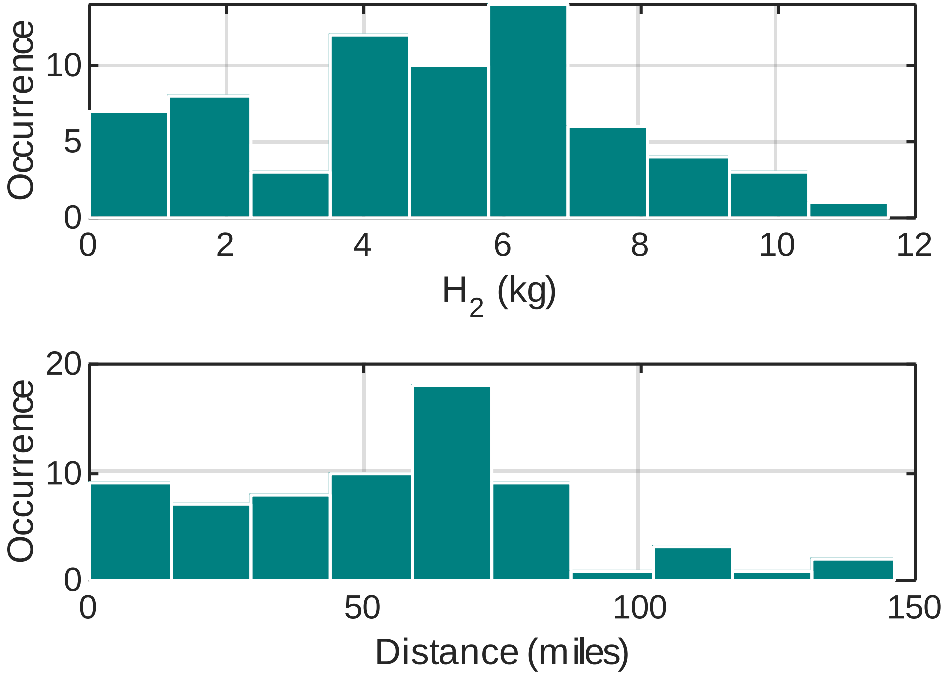
Autonomie sizing process provides FCETs that meet real world requirements

Longer cycles tend to be mostly on highways, and have similar energy consumption as EPA65.

- Based on the real world cycle samples in this work, ~11kg of H_2 will be sufficient.
  - More samples are being evaluated from various parts of the country

Preliminary results

- Other DOE funded activities support this finding.
  - MT017 – Fedex (150 miles)
  - TV034 – UPS, CTE (125 miles)
  - FleetDNA data shows 97% cycles are under 125 miles
- They report similar energy consumption levels
  - 10kg H_2 & 30-80kWh battery



This gives us a good simulation model to evaluate fuel consumption impact of component technology improvements

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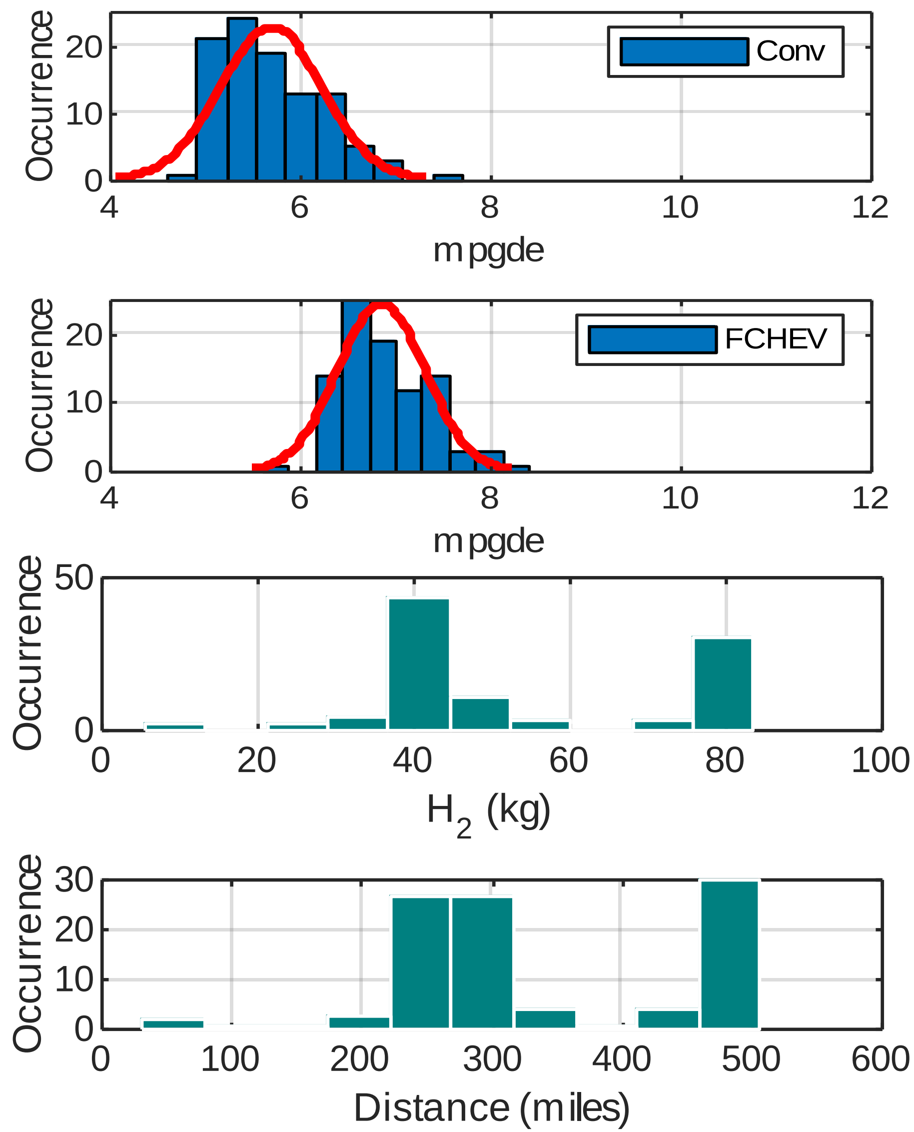
Real world fuel consumption is quantified for Class 8 regional haul trucks

80kg storage is found sufficient for 500 mile range

- There are lot of use cases that can be met with a 50kg storage.
- The peak for 80kg is observed only because the designed range of the vehicle is limited to 500 miles, and simulation is stopped when the vehicle runs out of stored H_2.
- This shows the need for having two types of models having,
  a. 250-300 mile range
  b. 600-700 mile range

After reviewing data from more locations, these requirements will be updated.



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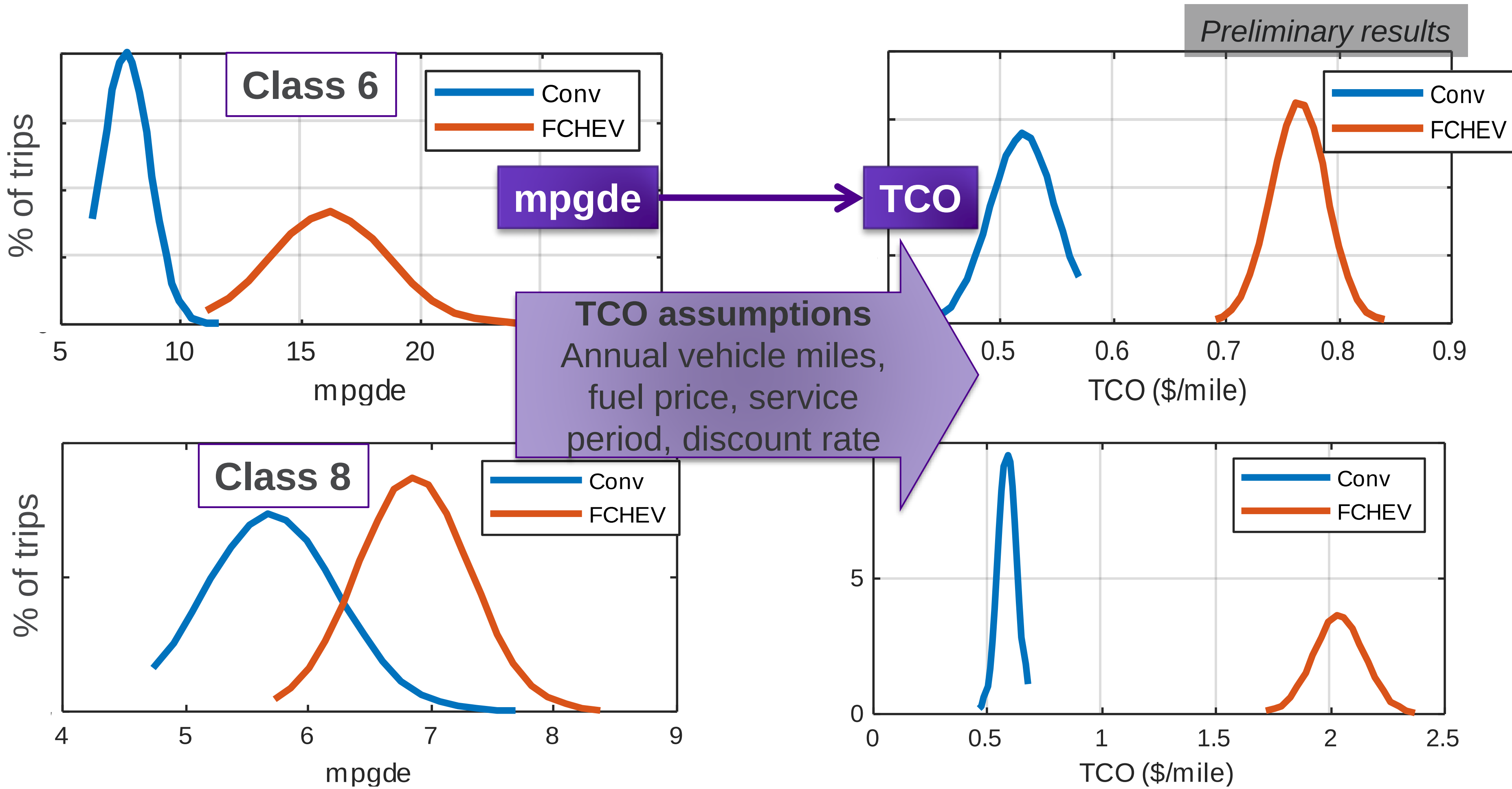
Work in progress: Compute TCO from vehicle cost and fuel consumption

Awaiting new TCO assumptions from VTO working group.



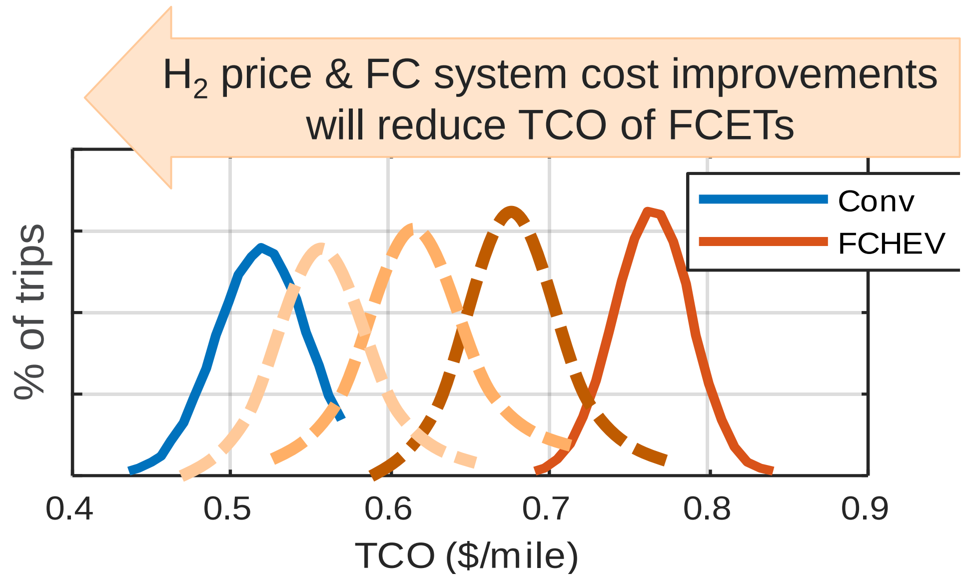
- With present day vehicle price and fuel cost, FCET is more expensive to own and operate.

Next Step: Explore ways to achieve TCO parity

1. **FC & storage cost target will reduce initial price**
2. **FC efficiency improvements will reduce H_2 consumption**
3. **H_2 price reduction will directly reduce fuel cost**

Technology	Present	Interim	Ultimate
FC ($/kw)	200	80	60
Storage Cost ($/kWh)	17	10	8
FC Efficiency (%)	62	68	72
H_2 price($/kg)	12	6	4

** Cost target values are under revision by HFTO. New values will be updated in this analysis too.*



- TCO of Class 6 FCETs is about 1.5 times that of diesel trucks
- For Class 8 regional haul, FCETs are ~4 times more expensive than diesel trucks.
  - For H_2 target setting activities, the regional haul use case presents a more challenging scenario

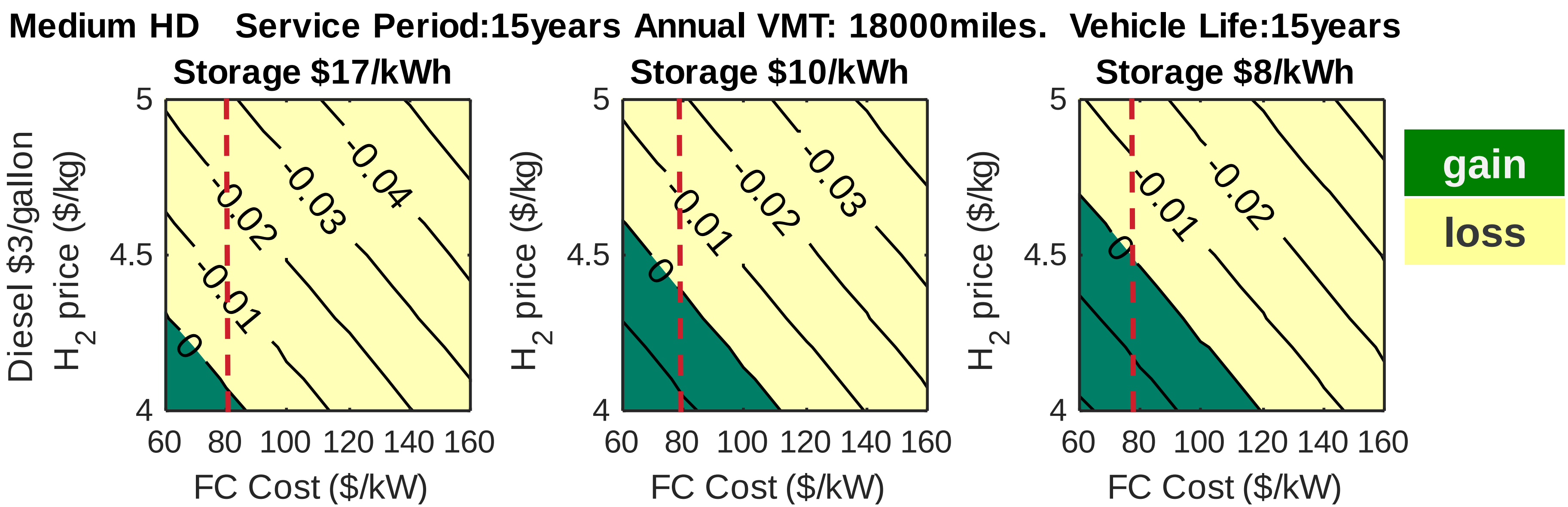
FCHEVs can be competitive in medium duty segment even at H_2 cost > $4/kg, if technology progresses as expected.

Evaluating the change in TCO when a diesel truck is replaced with FCET

TCO Differential = (TCO of Conv – TCO of FCHEV) = **$/mile** savings for fleet operator

Illustrative Example: Class 6 Delivery Trucks TCO Differential

Preliminary results



- Achieving interim goals (2030 high) for FC cost, efficiency & storage cost will bring the initial price down. This will help achieve TCO parity at H_2 prices around $4.5/kg

This illustration is based on assumptions from FY19 analysis. This will be updated for new cost targets & vehicle assumptions in FY20

Collaborations

NREL, 21CTP, CERC, EEMS, Navistar

- CERC Truck project (G.Singh, VTO) has real world driving data for class 6 delivery vehicles and two other vocations.
- NREL is collecting, verifying and sharing real world data collected under various programs. Regional haul data is already available from 3 locations.
- EEMS (D.Anderson, E.Boyd, VTO) is facilitating the data sharing using Livewire platform.
- Navistar provided additional grade and launch requirements to be used as sizing assumption for each vocation. Helping with cooling system modelling as well.
- 21CTP has setup Powertrain System Analysis working group where both Argonne and NREL are working with OEMs to establish common assumptions for truck modelling and technology evaluation.
  - This working group reviewed the sizing assumptions & methodology.
  - Provides guidance on assumptions used for feasibility analysis
- Argonne has shared all vehicle and sizing assumptions. The powertrain sizing logics are now publicly available through AMBER/Autonomie.

Future Work

- Develop validated vehicle models for additional classes and vocations.
  - Argonne and NREL are collaborating with 21CTP on roadmap development. This project has identified multiple truck categories for detailed simulation
  - Fuel cell powered trucks too are part of this initiative.
- Support target setting activities of FCTO
  - Work is in progress on truck specific interim price target for H_2.
- As more real world cycles become available, rigorous check for real world applicability of FCHEVs will be carried out for all those types of trucks
  - Regional haul analysis is in progress
- Integrate thermal models for FC systems to Autonomie and develop vehicle models for various representative trucks to evaluate cooling system requirements.
  - Collaborating with fuel cell team in Argonne and OEMs
- Collaborate with NREL on volume requirements and restrictions in each type of vehicle.

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

Summary

Real world cycles are used to estimate daily driving range & fuel economy of FCHEVs

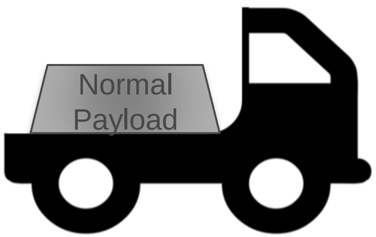
- Real world requirements of Class 6 delivery trucks were analysed. For Class 6 delivery truck, we quantified
  - Range, Fuel cell and Battery power requirements
  - Onboard H_2 storage requirements (verified against results observed from field demonstrations)
  - Fuel economy & Total Cost of Ownership (TCO) for real world operation
- Class 8 regional haul is been added to the analysis.
- Autonomie powertrain sizing provides design solutions that meet real world driving requirements.
  - Collaborated with 21CTP to implement an improved sizing logic
  - Updated analysis with newer truck specific technology improvement & TCO assumptions
- Shown that TCO parity can be achieved only with further improvements in component technology and cost.

BACKUP SLIDES

Sizing & Fuel Consumption Measurement

Assumptions were updated based on feedback from 21CTP

Sizing → **Analysis**



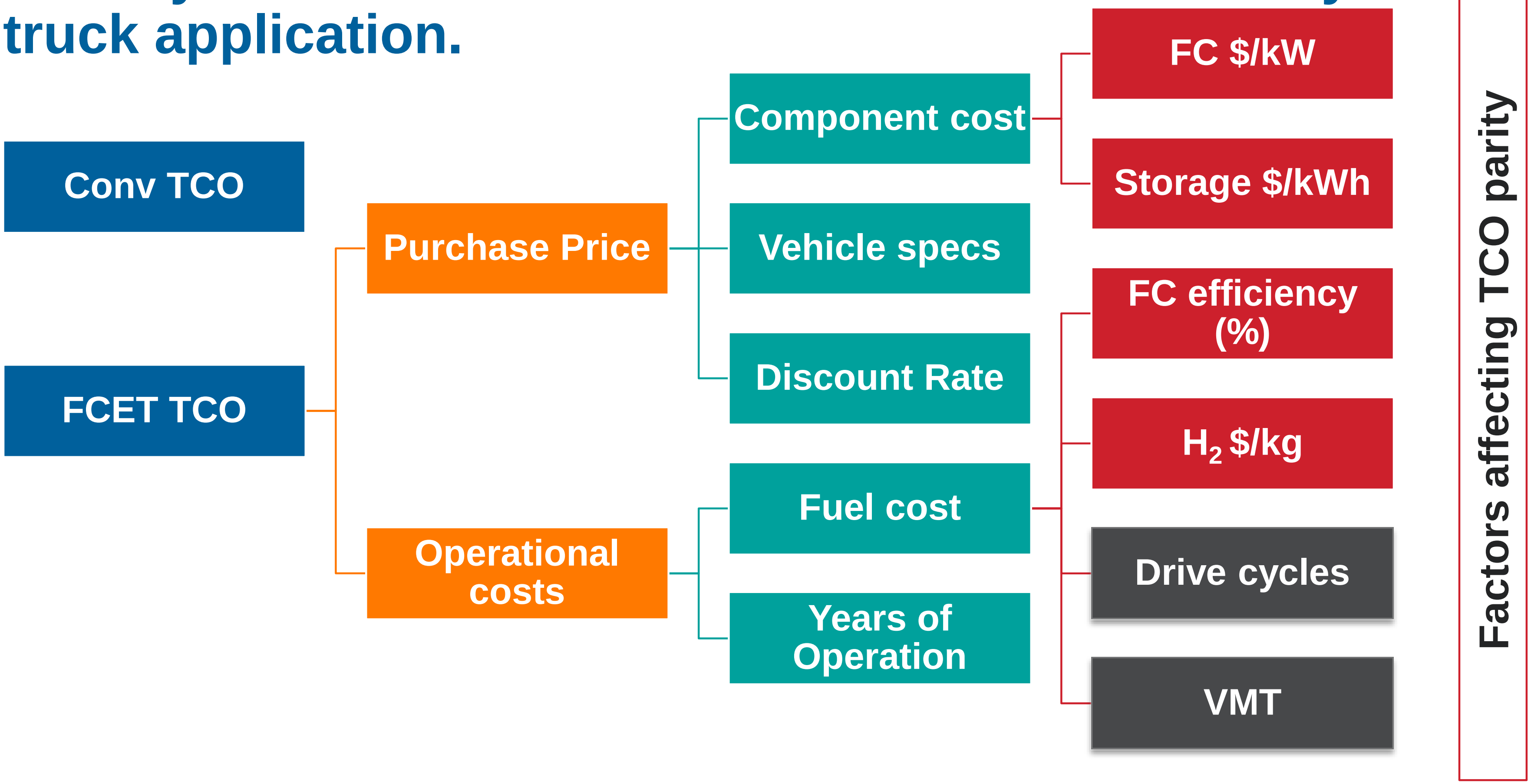
- Performance tests @ max GVWR
  - Cruising speed @ 0% grade
  - 1.5% Grade @ 55mph
  - 6% Grade climb for 11 miles
  - Launch @ 20% grade
  - Acceleration
    - 0-30mph
    - 0-60mph*
  - All Electric/Driving Range
  - Passing*

- Fuel economy tests @ regular load
  - EPA regulatory cycles
  - Raw Real World Cycles (Livewire, FleetDNA, CERC)
- TCO/LCOD
  - Component Cost:
    - DOE targets
    - ML based estimates
  - Fuel Cost: IEA projections

** Not applicable for certain vocational trucks*

Factors that affect TCO and their sensitivity to each truck application

Identify factors that affect TCO and their sensitivity to each truck application.



- By fixing the values/range for some of the parameters, we can find the sensitivity of TCO parity to various technology targets

Publications

Reports submitted to DOE

- ANL-19/58, “Vehicle Technologies and Fuel Cell Technologies Office Research and Development Programs: Prospective Benefits Assessment for Medium and Heavy Duty Vehicles”,
  T.Stephens, R.Vijayagopal, M.Dwyer, A.Birky, A.Rousseau

- ANL/ESD-19/10 “A Large-Scale Vehicle Simulation Study To Quantify Benefits & Analysis of U.S. Department of Energy VTO & FCTO R&D Goals”
  E.Islam, A.Moawad, R.Vijayagopal, A. Rousseau

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