PROJECT ID: TV032

FUEL CELL ELECTRIC TRUCK (FCET) COMPONENT SIZING

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Project Overview

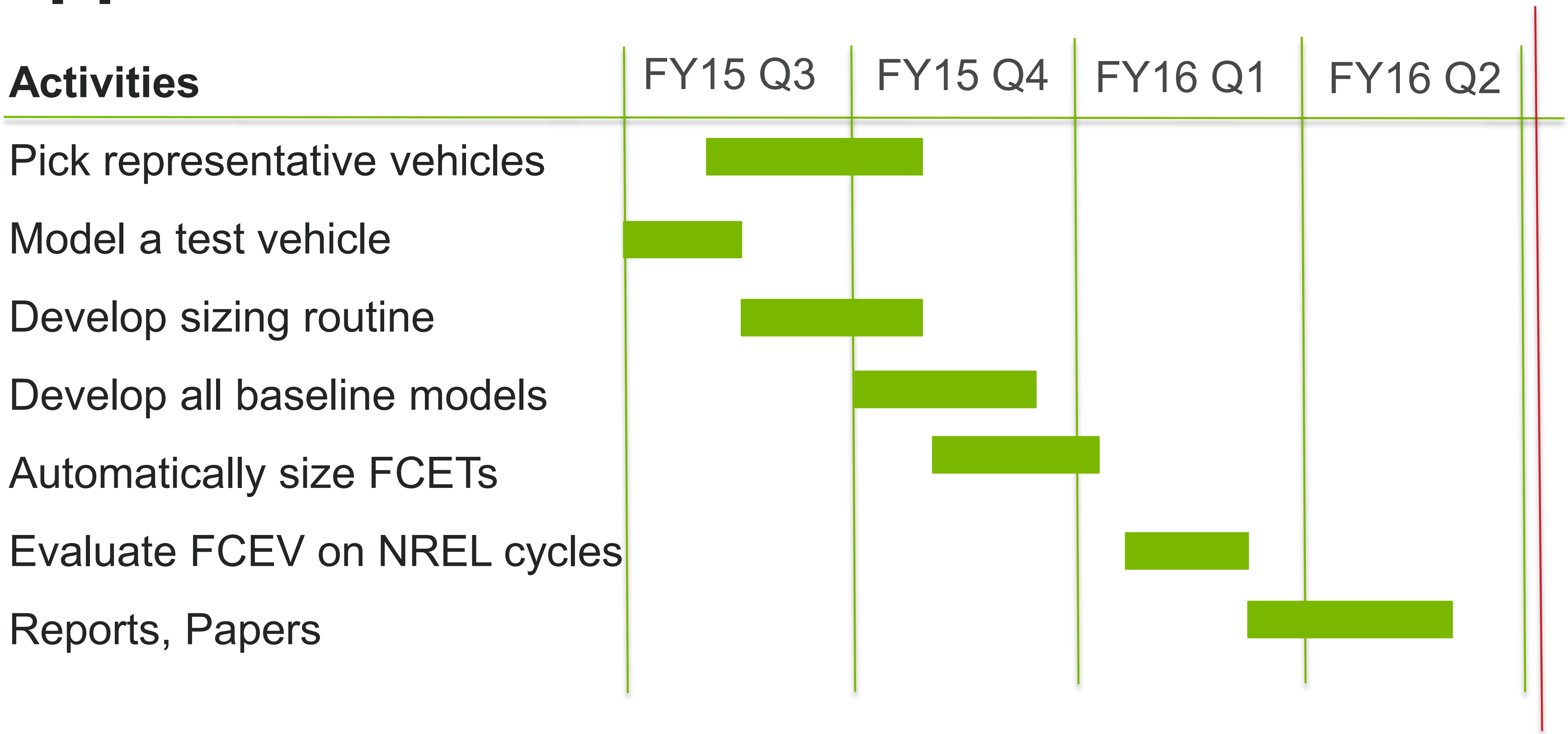
Timeline	Barriers
Start date : July 2015 End date : Feb 2016 Percent complete : 100%	• Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data (A) • Hydrogen Storage (C) http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_tech_valid.pdf
Budget	**Partners**
FY 15 : 100k FY 16 : 50k Percent utilized : 100%	• Fuel Cell Technologies Office • NREL (FleetDNA)

Relevance

Performance & Range Capabilities of Fuel Cell Powered Trucks are not Well Understood

- This project aims to develop design concepts that are functionally equivalent to conventional diesel powered trucks, for multiple classes and vocations.
- How is this different from other fuel cell truck prototypes?
  – Use of fuel cells as the primary source for propulsion power
  – Onboard H_2 storage will provide the entire energy for the drive
  – Battery will be used in a charge sustaining manner.
- Analysis will reveal :
  – Fuel cell and battery power required for trucks
  – Stored H_2 mass and total mass of the fuel cell system
  – Fuel economy and range
  – Verify whether the concept designs meet real world requirements.

Approach: Milestones



Results are available now. Several papers are accepted at conferences. Completion of analysis and reports are expected by end of FY16

Approach

Build FCET Designs to Match Popular Trucks in Many Major Market Segments

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

- Data & Assumptions
  - Vehicle Inventory and Use Survey (VIUS) was used to identify the largest market segments
  - Representative vehicles are picked from popular models from all major OEMs
    - Based on market share, vehicle & test data availability
- DOE FCTO provided inputs on
  - Fuel cell technology readiness
  - H_2 storage potential in each vehicle based on space available in chassis.
- NREL provided commercial fleet vehicle operating data (FleetDNA) to simulate real world requirements

Approach

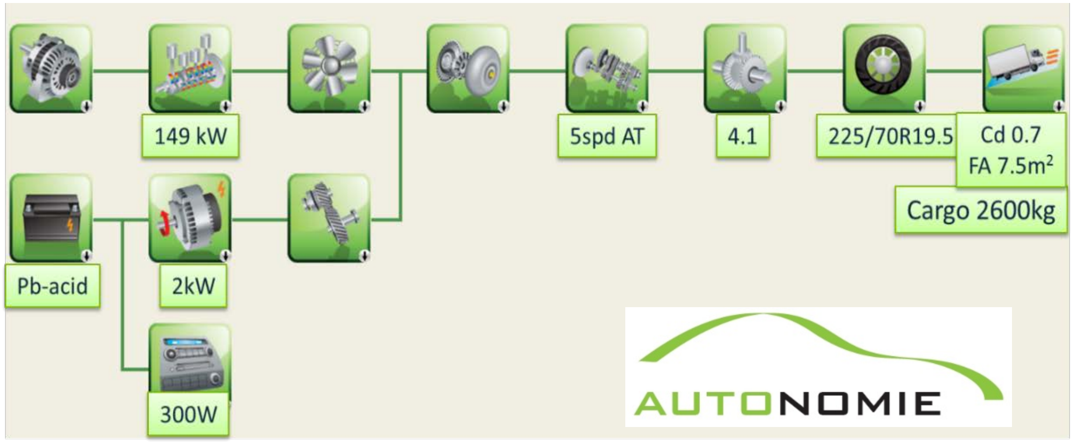
Chosen Representative Vehicles & Vocations

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 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	Tractor Trailer

Approach

Conventional Baseline Vehicle Models Built in Autonomie

Published data from OEMs & suppliers was used for the model. Example shows a Class 4 pickup and delivery van.



- Components in Autonomie library are scaled to match the baseline vehicle
- Cargo weight is adjusted to set the test weight at median value for the class.
- Performance tests
  - Acceleration, Cruise & Grade
- Fuel economy test (EPA cycles)
  - ARB Transient
  - Steady 55mph
  - Steady 65mph

Approach
FCET Sizing Methodology

Powertrain Architecture :

- **Option 1 : Battery Powered Electric Vehicle with a Fuel-cell Range Extender**
  - Depends on battery power for driving performance
  - Fuel cell is sized to meet the minimum power needed to drive the vehicle.
  - All Electric Range is extended by using fuel cell. Once battery depletes, the vehicle may have diminished performance.

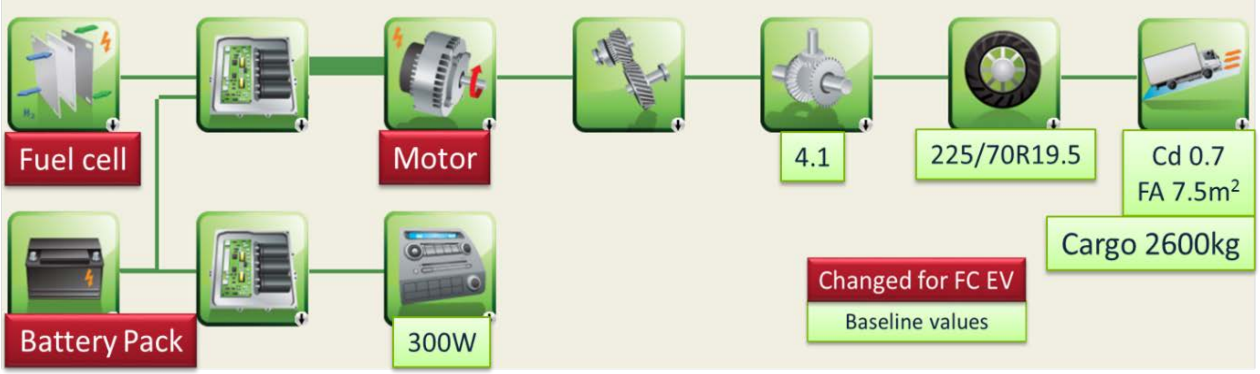
- **Option 2 : Fuel-cell Hybrid Electric Vehicle**
  - Fuel cell provides power for driving performance
    - Rated for continuous requirements (eg. cruise at highway speeds)
  - Does not use any net energy from battery. Uses battery to utilize regen power, and to meet any power demand beyond the FC capability (eg. acceleration).

Many fuel cell vehicle prototypes and studies have used Option 1.
Option 2 is selected because of its relevance to the goal of this project.

Approach

Retrofit fuel cell & electric powertrain on the baseline vehicle

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



- Component weight is estimated from characteristics like power or peak torque.
- Component mass & FCET vehicle mass is also changed when sizing logic updates values like motor power or mass of hydrogen to be stored.
- Baseline test weight of 6809kg is approximately 15000lb, median weight of Class 4.
- FCET may have a different test weight, but the same ‘Cargo weight’

Mass estimates in kg	Baseline	FCHEV
Test weight	6809	6854
Chassis + Body	3417	3417
Cargo	2400	2400
Fuel	100	19
Fuel tank	40	435
Engine	305	
Fuel cell		125
Gearbox	142	10
Motor		145
Battery Low Voltage	83	83
Battery High Voltage		65

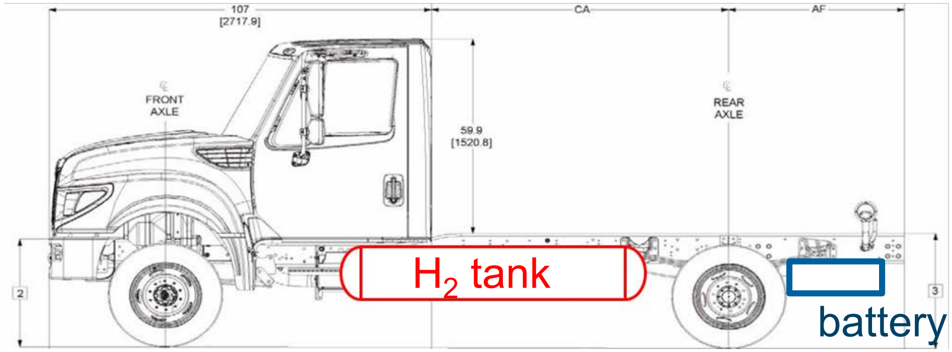
** Refer to backup slides for the survey of components used for mass estimate.*

Technical Accomplishments

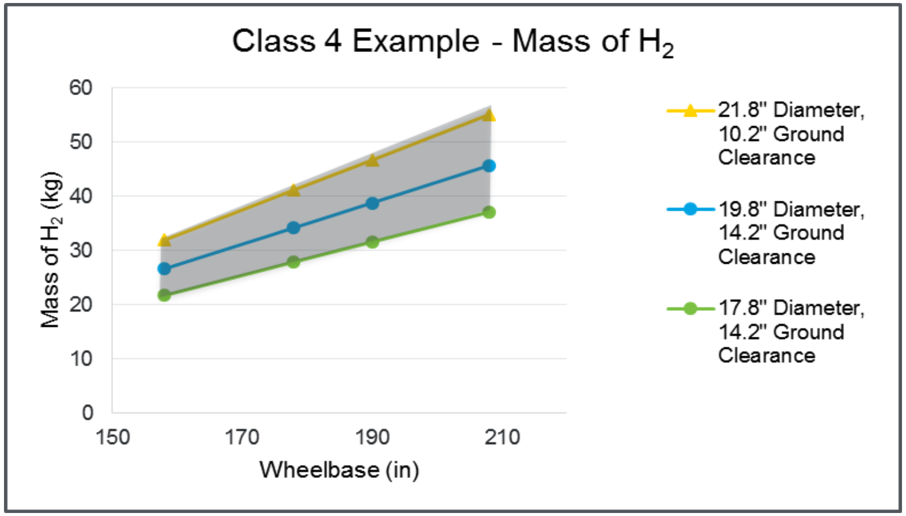
Analysis Shows Available Volume is Sufficient

Existing CNG converted vehicles may be used as reference for hydrogen tank placements

- FCET Proposed Configuration
  - H2 tank along chassis, on one or both sides
  - Battery at conventional fuel tank location under the chassis
  - Fuel cell and motor in place of engine and transmission



(*) Diagram shown does not represent a specific truck or dimensions. Intended for display purposes only.
Hydrogen tank length can be varied for different wheelbase options. Picture is used with permission from "2014 Truck Index"



This part of the project was done by FCTO.
Vehicle dimensions are from "2014 truck index"

Technical Accomplishments
Performance Requirements

Goal: Meet or exceed baseline vehicle performance

- Fuel cell is sized to meet all continuous power requirements
  - Cruise
  - 6% Grade for 11 miles
    - Based on Davis Dam cycle
- Motor is sized to for both continuous and peak requirements
  - Acceleration 0-30 mph
  - Acceleration 0-60 mph

Performance Criteria	Class 4 Van
Cargo Mass (lb)	5280
Cruising Speed (mph)	70
Grade Speed (mph)	50
0-30 mph acceleration time (s)	7.2
0-60 mph acceleration time (s)	29.8

- Battery will provide any additional power needed to augment the fuel cell during acceleration events.
- Battery will have enough usable energy to sustain the support through one acceleration event.
- On board hydrogen storage will be sized to drive at least 200 miles.
  - This will be compared against real world requirements from FleetDNA
- Range is estimated for the worst fuel economy observed during the test cycles.

Technical Accomplishments

Power and Energy Requirements Based on Desired Performance

Goal: Meet or exceed baseline vehicle performances

Parameters	Grade	Cruise	0-30	0-60
Motor Power Required (kW)	144	118	-	-
Motor Peak Power Rating (kW)	-	-	224	152
Fuel Cell Power (kW)	164	154	-	-
Battery Power (kW) @60% SOC	-	-	54	9
Usable Battery Energy (Wh)	-	-	29	47
Total Battery Energy (Wh)	-	-	-	235

- Each performance test has its requirements on components.
- The final component size should meet all these requirements.

Technical Accomplishments

Fuel Cell & Battery Sizing Summary

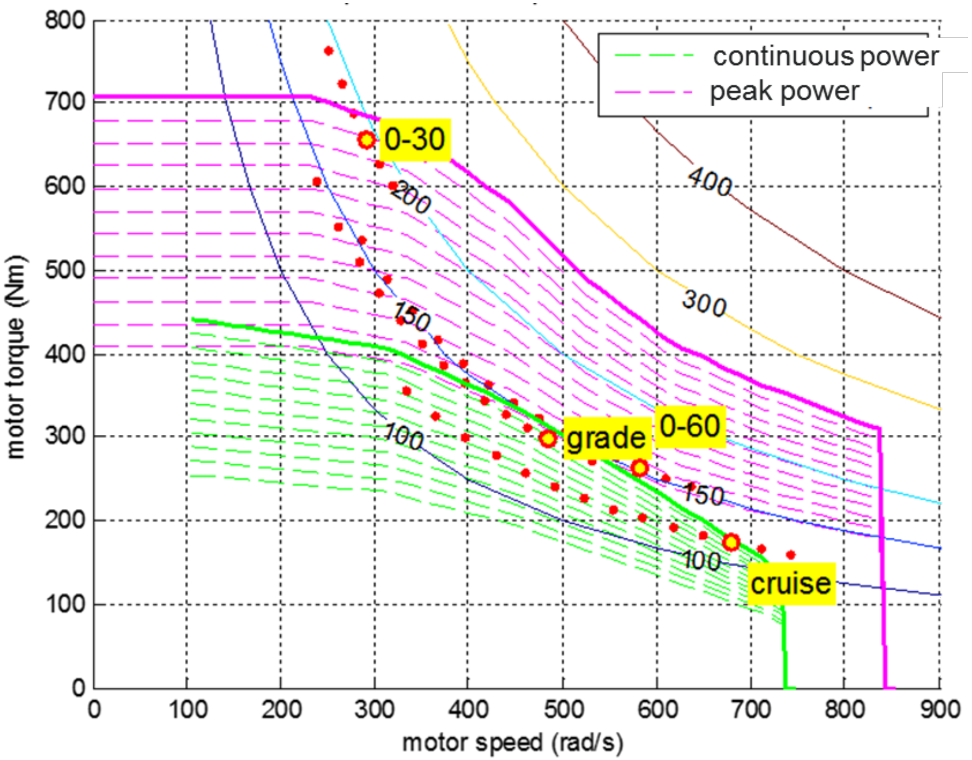
- Fuel Cell
  - Designed to meet continuous power requirement corresponding to grade test
    - **164 kW** of electrical power is needed to accomplish the grade run
- Battery
  - Battery power covers difference between fuel cell power and acceleration power needed by motor. Motor needs 218 kW during 0-30 acceleration test . Fuel cell provides 164 kW.
  - Battery power = 218 - 164 kW = **54 kW**

- Minimum energy needed from battery to sustain one 0-60mph acceleration event is 47Wh (as the duration of battery assist is only a few seconds).
- Li-nano phosphate cells have power & energy density values of 2.7 kW/kg & 70 Wh/kg respectively
  - The pack in this vehicle will have a total energy of 1.4kWh
    - Ni-MH cells may be a cheaper option that satisfies the requirements
    - Ultra capacitors too could be explored

Technical Accomplishments

Electric Powertrain Sizing

Sweep of final drive and motor power options to find the smallest motor that can provide the necessary speed and torque



Motors might vary in their continuous and peak operating capability. Hence this step is specific for the motor considered in this study

Selected component sizes	
Motor Continuous Power (kW)	151
Motor Rated Power (kW)	260
Fuel Cell Power (kW)	164
Battery Power (kW)	54
Battery Total Energy (Wh)	1426
Battery Volume (L)	53.4
Motor Speed Ratio	8.9

Discrete steps were used for the parameter sweep*
Motor power range = [100 : 10 : 300]
Over all ratio range = [5 : 0.1 : 20]

A finer step size could yield better solutions.

Technical Accomplishments
Fuel Economy & Onboard H2 storage

H_2 mass requirement is estimated for 200 mile range with the worst case fuel economy.

Fuel economy	Baseline (mpg)	FCET (mpkg)
ARB Transient	17	30.4
Mild 55	12.4	14.2
Mild 65	9.6	**10.4**
Vocational Fuel economy		
Regional	14.1	21.5
Multi use	16.1	27.4
Urban	16.7	29.4

- Onboard H_2 storage *(for the Class 4 truck considered here)*
  - requirement for a 200 mile run is 19.2 kg
  - storage potential is between 20- 55 kg (depending on wheel base)*

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** Refer to 'reviewer only' slides for the details of this analysis*

Technical Accomplishments

No Trade off in Performance & Payload

Better acceleration due to electric powertrain

Performance Criteria	Baseline	FCET
Cargo Mass (lb)	5280	5280
Cruising Speed (mph)	70	69
Grade Speed (mph)	50	50
0-30mph acceleration time (s)	7.2	6.8
0-60mph acceleration time (s)	29.8	22.2

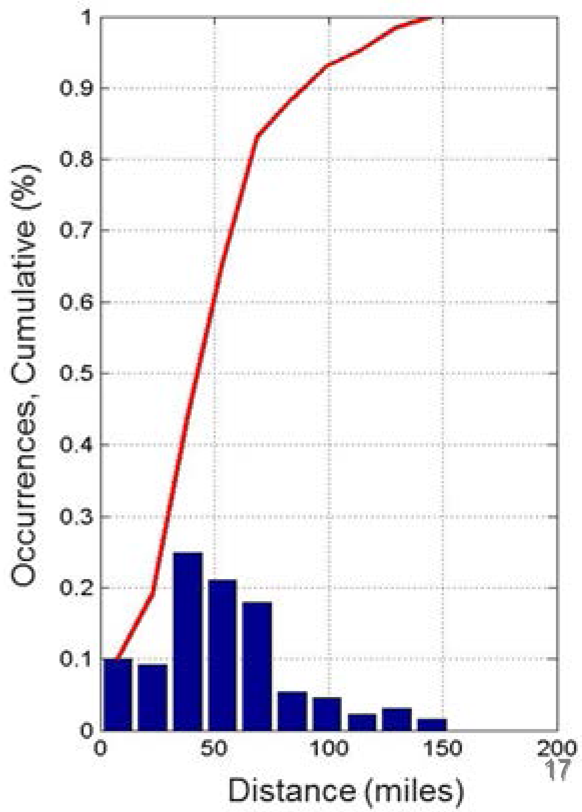
- Cruising and grade power requirements were critical in this sizing process.
- The iterative sizing process has a 2% tolerance. This results in the difference in cruising speed.

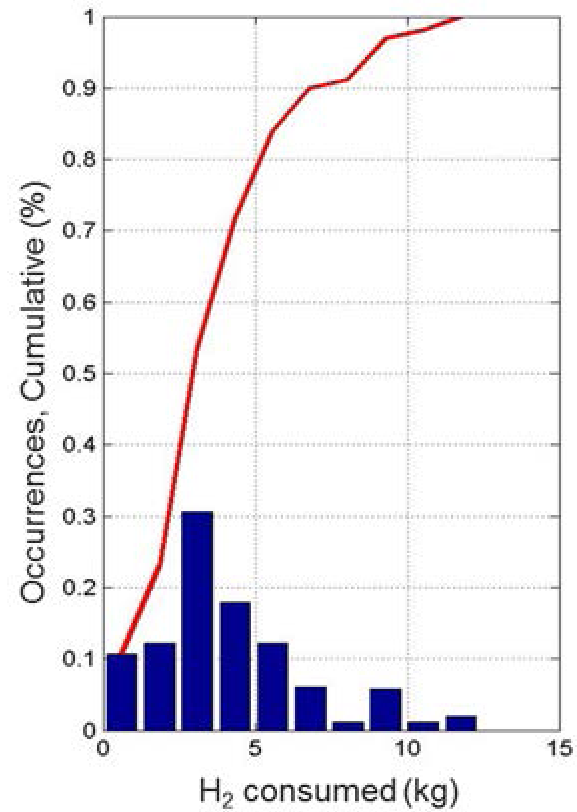
Technical Accomplishments

No Tradeoff in Real World Usage

261 daily cycles from Class 4 ‘pickup and delivery’ vehicles in FleetDNA

- Real world fuel economy varies between 10 – 18 miles/kg
- Real world onboard H_2 requirement is about 12 kg
- Proposed FCET will perform well under real world circumstances
  - A few thousand cycles were used for all the vehicles classes & vocations





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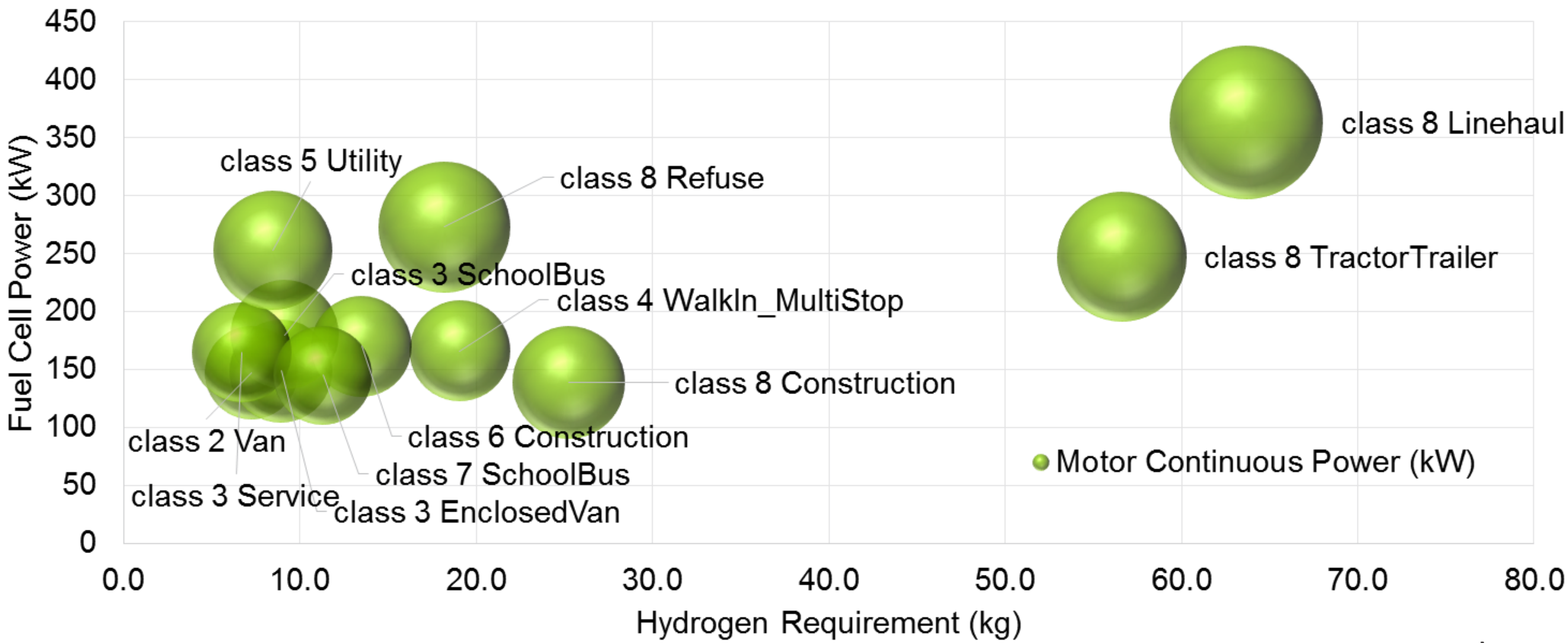
Technical Accomplishments
Accomplishments and Progress

Sizing logic was automated.
Multiple classes and vocations were analyzed.

- This analysis shows that about 20kg onboard H_2 storage and a 180kW fuel cell can cater to many types of medium duty trucks
- Class 8 trucks that run longer distances on highway require a lot more hydrogen storage than the urban & regional duty trucks



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Collaboration

- The baseline vehicles developed during this project are now included in the public version of Autonomie

- NREL provided the cycles from FleetDNA

- A general process to convert FleetDNA cycles to Autonomie readable format was developed and shared with NREL.

Remaining Challenges & Barriers

Cost & Durability

- Durability was not considered in this study
- Cost competitiveness may present challenges until markets are established and economies of scale reduce the cost of producing fuel cell systems.

- Future Steps
  - add the ownership cost component into this study to examine the economic feasibility of these vehicles

Future Steps

Evaluate ownership cost of FCETs

- Adding ownership cost component into this study can examine the economic feasibility of these vehicles

- At present the conventional trucks are mostly diesel powered. CNG vehicles, or even gasoline hybrids could be considered as competing technologies in some segments.

- The process for doing such analysis exists, as demonstrated earlier (Project ID # SA044). It could be applied to this study too.

Summary

FCETs is shown to be technically feasible for many MD & HD applications

- An automated sizing process was developed for FCETs
- FCETs sized through this process can match or better the performance of conventional trucks
- FCETs performed well on real world use cases based on data collected from major fleet operators in US.

BACKUP SLIDES

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CLASS 4 BASELINE VEHICLE

Curb weight	:	9,700 lb Max Cargo : 6300 lb
Tires	:	225/70/R19.5
Cd	:	0.7
FA	:	7.5 m^2
FD ratio	:	4.1
Test Cargo	:	5,300 lb
Test weight	:	15,000 lb (Class 4 median)

FCHEV will keep these properties unchanged (Tires, Cd, FA, FD ratio, Test Cargo)

GVWR : 14,140 lb SRW – 19,500lb for DRW *

* Chassis capability

Baseline Powertrain

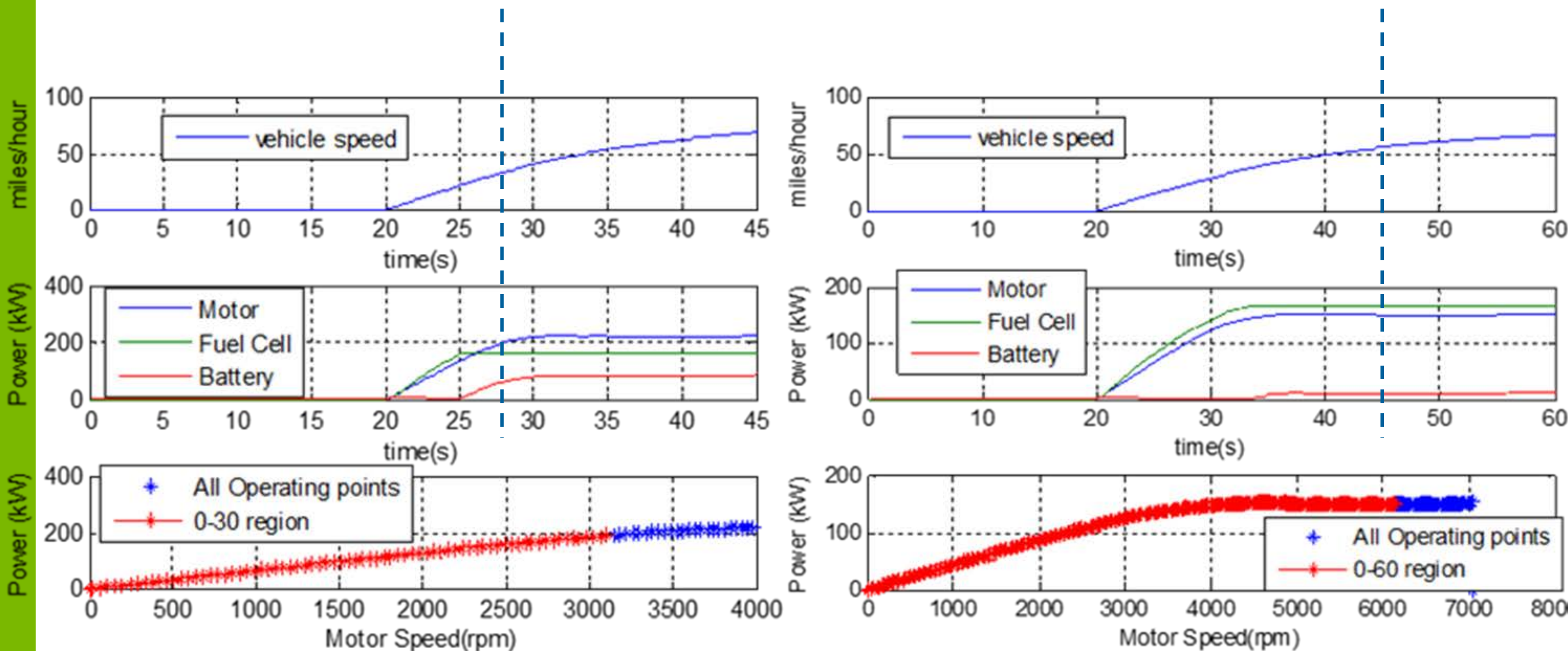
Engine : 149kW, 6.7L Cummins ISB

Gearbox : 6spd AT, Allison 1000 HS

Baseline performance

- 0-30mph in 7.1s
- 0-60 mph in 30s
- 50 mph @ 6% grade

POWER REQUIREMENT : ACCELERATION TEST



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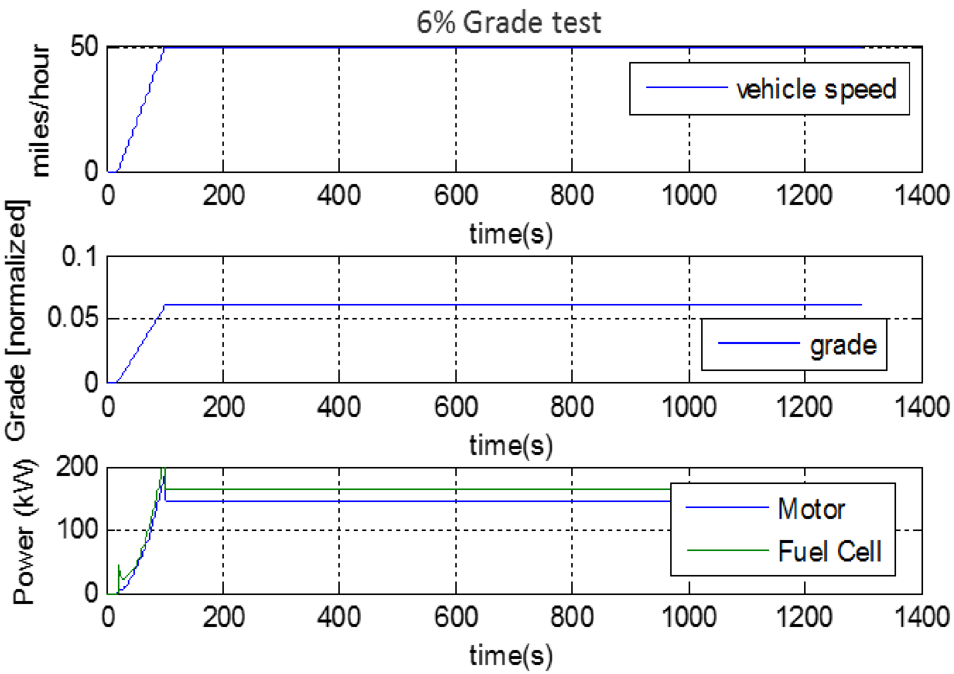
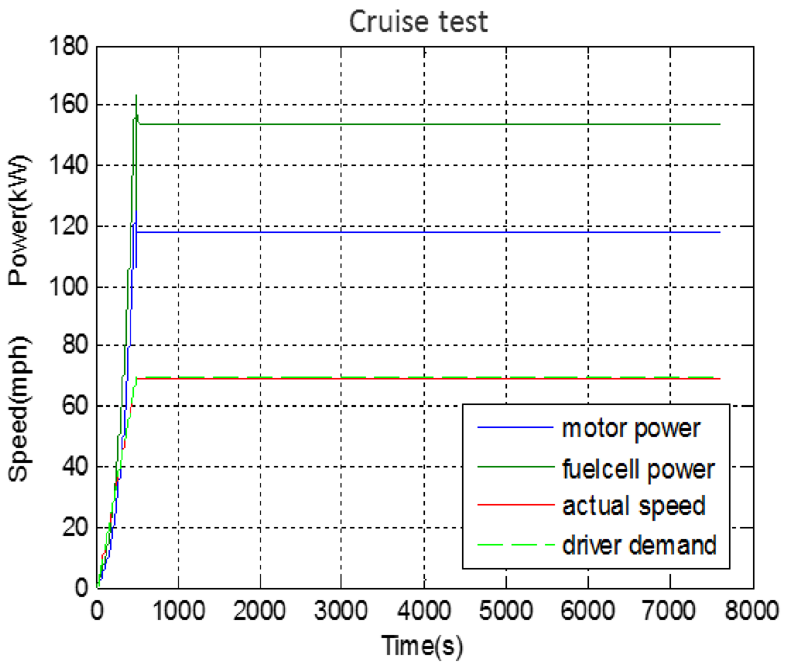
POWER REQUIREMENT : CRUISE & GRADE





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