FUEL CELL ELECTRIC TRUCK (FCET) COMPONENT SIZING

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## Project Overview

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start date</td>
<td>July 2015</td>
</tr>
<tr>
<td>End date</td>
<td>Feb 2016</td>
</tr>
<tr>
<td>Percent complete</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>• Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data (A)</td>
</tr>
<tr>
<td></td>
<td>• Hydrogen Storage (C)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Budget</th>
<th>Partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY 15</td>
<td>• Fuel Cell Technologies Office</td>
</tr>
<tr>
<td>FY 16</td>
<td>• NREL (FleetDNA)</td>
</tr>
<tr>
<td>Percent utilized</td>
<td>100%</td>
</tr>
</tbody>
</table>
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 H₂ 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 H₂ 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

- 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
  - H₂ 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**

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vocation/ Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 2b, 6000 – 10000 lbs</td>
<td>Small Van</td>
</tr>
<tr>
<td>class 3, 10001 – 14000 lbs</td>
<td>Enclosed Van</td>
</tr>
<tr>
<td>class 3, 10001 – 14000 lbs</td>
<td>School Bus</td>
</tr>
<tr>
<td>class 3, 10001 – 14000 lbs</td>
<td>Service, Utility Truck</td>
</tr>
<tr>
<td>class 4, 14001 – 16000 lbs</td>
<td>Walk In, Multi Stop, Step Van</td>
</tr>
<tr>
<td>class 5, 16001 – 19500 lbs</td>
<td>Utility, Tow Truck</td>
</tr>
<tr>
<td>class 6, 19501 – 26000 lbs</td>
<td>Construction, Dump Truck</td>
</tr>
<tr>
<td>class 7, 26001 – 33000 lbs</td>
<td>School Bus</td>
</tr>
<tr>
<td>class 8, 33001 lbs or heavier</td>
<td>Construction, Dump Truck</td>
</tr>
<tr>
<td>class 8, 33001 lbs or heavier</td>
<td>Line haul</td>
</tr>
<tr>
<td>class 8, 33001 lbs or heavier</td>
<td>Refuse, Garbage Pickup, Cab over type</td>
</tr>
<tr>
<td>class 8, 33001 lbs or heavier</td>
<td>Tractor Trailer</td>
</tr>
</tbody>
</table>
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’

* 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
- 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.

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Class 4 Van</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo Mass (lb)</td>
<td>5280</td>
</tr>
<tr>
<td>Cruising Speed (mph)</td>
<td>70</td>
</tr>
<tr>
<td>Grade Speed (mph)</td>
<td>50</td>
</tr>
<tr>
<td>0-30 mph acceleration time (s)</td>
<td>7.2</td>
</tr>
<tr>
<td>0-60 mph acceleration time (s)</td>
<td>29.8</td>
</tr>
</tbody>
</table>
Technical Accomplishments
Power and Energy Requirements Based on Desired Performance

Goal: Meet or exceed baseline vehicle performances

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

- 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.

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.

Selected component sizes

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Continuous Power (kW)</td>
<td>151</td>
</tr>
<tr>
<td>Motor Rated Power (kW)</td>
<td>260</td>
</tr>
<tr>
<td>Fuel Cell Power (kW)</td>
<td>164</td>
</tr>
<tr>
<td>Battery Power (kW)</td>
<td>54</td>
</tr>
<tr>
<td>Battery Total Energy (Wh)</td>
<td>1426</td>
</tr>
<tr>
<td>Battery Volume (L)</td>
<td>53.4</td>
</tr>
<tr>
<td>Motor Speed Ratio</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Technical Accomplishments

Fuel Economy & Onboard H₂ storage

H₂ mass requirement is estimated for 200 mile range with the worst case fuel economy.

<table>
<thead>
<tr>
<th>Fuel economy</th>
<th>Baseline (mpg)</th>
<th>FCET (mpkg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARB Transient</td>
<td>17</td>
<td>30.4</td>
</tr>
<tr>
<td>Mild 55</td>
<td>12.4</td>
<td>14.2</td>
</tr>
<tr>
<td>Mild 65</td>
<td>9.6</td>
<td>10.4</td>
</tr>
</tbody>
</table>

**Vocational Fuel economy**

<table>
<thead>
<tr>
<th></th>
<th>Baseline (mpg)</th>
<th>FCET (mpkg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>14.1</td>
<td>21.5</td>
</tr>
<tr>
<td>Multi use</td>
<td>16.1</td>
<td>27.4</td>
</tr>
<tr>
<td>Urban</td>
<td>16.7</td>
<td>29.4</td>
</tr>
</tbody>
</table>

- **Onboard H₂ 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)*

* 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

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Baseline</th>
<th>FCET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo Mass (lb)</td>
<td>5280</td>
<td>5280</td>
</tr>
<tr>
<td>Cruising Speed (mph)</td>
<td>70</td>
<td>69</td>
</tr>
<tr>
<td>Grade Speed (mph)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>0-30mph acceleration time (s)</td>
<td>7.2</td>
<td>6.8</td>
</tr>
<tr>
<td>0-60mph acceleration time (s)</td>
<td>29.8</td>
<td>22.2</td>
</tr>
</tbody>
</table>

- 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
Technical Accomplishments
Accomplishments and Progress

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

- This analysis shows that about 20kg onboard H₂ 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.
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
CLASS 4 BASELINE VEHICLE

Curb weight : 9,700 lb  Max Cargo : 6300 lb
Tires : 225/70/R19.5
Cd : 0.7
FA : 7.5 m²
FD ratio : 4.1
Test Cargo : 5,300 lb
Test weight : 15,000 lb (Class 4 median)

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

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

FCHEV will keep these properties unchanged
POWER REQUIREMENT: ACCELERATION TEST
POWER REQUIREMENT: CRUISE & GRADE

6% Grade test

Cruise test

0 200 400 600 800 1000 1200 1400

0 200 400 600 800 1000 1200 1400

0 50

0 0.1 0.05

0 0

0 120 140 160 180

0 60 80 100

0 100

Motor
Fuel Cell

Motor power
fuelcell power
actual speed
driver demand

0 1000 2000 3000 4000 5000 6000 7000 8000

Time(s)