Analysis of Fuel Cells for Trucks

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## Project Overview

### Timeline
- Project start date: Sep 2018
- Project end date: Aug 2019
- Percent complete: 50%

### Barriers
- 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)

### Budget
- FY18 Funding: $100k
- Percent spent: 50%

### Partners
- 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

**Diagram: Simulations Flowchart**

1. Input from stakeholders
2. Tech Assumptions
3. Simulations
4. Energy Consumption
5. Performance & TCO
6. Market penetration

- Input assumptions:
  - Battery initialized for regen braking
  - Battery updated for performance
  - FC sized for continuous power
- Output assumptions:
  - Estimate onboard \( H_2 \) requirement
  - Motor sized for performance
  - Verification runs for range
  - mpkg $/mile
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)

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

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
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
Objectives & Relevance

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   – 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.

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


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

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

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

**Q/ΔT Limits for Diesel Trucks**

- Hill climbing: \( Q/\Delta T = 4.5 \text{ kW/}^\circ\text{C} \), 25°C ambient temperature, radiator fan on
- Highway cruising: \( Q/\Delta T = 2.6 \text{ kW/}^\circ\text{C} \), radiator fan off
- Highway cruising: \( Q/\Delta T = 5.4 \text{ kW/}^\circ\text{C} \), radiator fan on

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

<table>
<thead>
<tr>
<th>Speed</th>
<th>Climb at 6% grade</th>
<th>Highway Cruising</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan On Off</td>
<td>30 mph</td>
<td>60 mph</td>
</tr>
<tr>
<td>Maximum/desired coolant temperature</td>
<td>105°C</td>
<td>95°C</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>25°C</td>
<td>50°C</td>
</tr>
<tr>
<td>Fan</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>Propulsion Power</td>
<td>330 kW</td>
<td>150 kW</td>
</tr>
</tbody>
</table>
Fuel Cells for Linehaul Heavy-Duty Trucks
Envelope of Operating Potentials and Temperatures

Stand-alone stack needs to operate at 700 mV cell voltage and 95°C 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 kWₑ) with higher power density (lower cell voltage, 675 mV)
- Improved durability because of lower operating temperature (75-85°C coolant exit T)
- Possible trade-off between power density (cell voltage) and durability (temperature)

### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion Power</td>
<td>kWₑ</td>
<td>330</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>From FCS</td>
<td>kWₑ</td>
<td>330</td>
<td>256</td>
<td>208</td>
</tr>
<tr>
<td>From Battery</td>
<td>kWₑ</td>
<td>0</td>
<td>74</td>
<td>122</td>
</tr>
<tr>
<td>Fan Power</td>
<td>kWₑ</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>FCS Net Power</td>
<td>kWₑ</td>
<td>360</td>
<td>286</td>
<td>238</td>
</tr>
<tr>
<td>Stack Power</td>
<td>kWₑ</td>
<td>400</td>
<td>320</td>
<td>265</td>
</tr>
<tr>
<td>ESS Usable Energy</td>
<td>kWh</td>
<td>0</td>
<td>27</td>
<td>45</td>
</tr>
<tr>
<td>ESS Rated Energy</td>
<td>kWh</td>
<td>0</td>
<td>39</td>
<td>64</td>
</tr>
<tr>
<td>Coolant Temp.</td>
<td>°C</td>
<td>&gt;90</td>
<td>85</td>
<td>75</td>
</tr>
</tbody>
</table>

Climbing 6% Grade at 30 mph
25°C Ambient, Fan On
330 kWₑ Propulsion Power
Q/ΔT = 4.5 kW/°C

Stack: 320 kWₑ
ESS: 40kWh
Cell V: 675 mV
Coolant: 85°C

Stack: 265 kWₑ
ESS: 65kWh
Cell V: 675 mV
Coolant: 75°C

Stack: 400 kWₑ
Cell V: 700 mV
Coolant T: 95°C
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.

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

- **Fuel Cell System Performance**
- **Component & Vehicle Assumptions**
- **Fuel Consumption & Cost**
- **Market Acceptance of Advanced Automotive Technologies**
- **DOE vehicle life cycle cost analysis**

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**GREET**
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 Line haul requirements exceed the needs of trucks used for other purposes.

- 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 H₂ 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

Sizing process was developed in prior work (TV032)
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.

\[ RCO = \text{Cost}_{\text{inv}} + \text{Cost}_{\text{pv\_energy}} + \text{Cost}_{\text{pv\_maint}} + \text{Cost}_{\text{pv\_batt\_replace}} + \text{Cost}_{\text{residual}} \]

- Total investment: \( \text{Cost}_{\text{inv}} = \text{Cost}_{\text{purchase}} + \text{Cost}_{\text{init\_registr}} + \text{Cost}_{\text{home\_EVSE}} - \text{Cost}_{\text{PEV\_incentive}} \)
  - \( \text{Cost}_{\text{purchase}} = \text{Cost}_{\text{manuf}} \times (1 + \text{profit\_margin} + \text{tax\_added}) \)
  - \( \text{Cost}_{\text{init\_registr}} = 186 \text{ [$]} \) \( \text{Cost}_{\text{home\_EVSE}} = 0 \text{ [$]} \) \( \text{Cost}_{\text{PEV\_incentive}} = 0 \text{ [$]} \)

- Present value energy cost: \( \text{Cost}_{\text{pv\_energy}} = (\text{on\_road\_kWh/km} \times \$_{\text{elec/kWh}} + \text{baseline liter/km} \times \$_{\text{gas/liter}}) \times \text{distance}_{\text{trvl\_yr}} / f_{\text{cap\_reco}} \)
  - \( \$_{\text{elec/kWh}} = 0.135, \$_{\text{gas/liter}} = 0.793 = 3 \text{ [$/gasoline\_equivalent\_gallon]} \) \( (\$_{H_2/kg} = 4) \)
  - \( \text{distance}_{\text{trvl\_yr}} = 22530.823 \text{ km} = 14000 \text{ mile} \)

- Present value maintenance: \( \text{Cost}_{\text{pv\_maint}} = (\text{Cost}_{\text{maint}} \times \text{distance}_{\text{trvl\_yr}} + \text{Cost}_{\text{ownership\_registr}}) / f_{\text{cap\_reco}} \)
  - \( \text{Cost}_{\text{maint}} = 0.08 / 1.60934 \text{ [$/km]} \) \( \text{Cost}_{\text{ownership\_registr}} = 46 \text{ [$]} \)

- Present value battery replacement cost: \( \text{Cost}_{\text{pv\_batt\_replace}} = 0 \)

- Residual value: \( \text{Cost}_{\text{residual}} = -\text{Cost}_{\text{inv}} \times (1 - 15 \times 10^{-7} \times \text{time}_{\text{service}} \times \text{distance}_{\text{trvl\_yr}} - 0.476) \times (1 + \text{rate\_discount})^{-\text{time}_{\text{service}}} \)
  - \( \text{time}_{\text{service}} = 5 \text{ [yr]} \) \( \text{rate\_discount} = 0.05 \)

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 stakeholders.
  - 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.
Response to Reviewer Comments

- This project was not reviewed last year