Cost Benefits Analysis of Technology Improvements in Medium & Heavy Duty Fuel Cell Vehicles

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## Project Overview

### Timeline
- Project start date: Oct 2018
- Project end date: Sept 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
- FY19 Funding: $40k
- Percent spent: 50%


### Partners
- Argonne Fuel Cell Team
Objectives & Relevance

- What are the benefits of fuel cell electric trucks (FCETs)?
  - Quantify FCETs benefits compared to other powertrains

- What are the impacts of meeting the targets?
  - Develop scenarios for technology improvements, Business as usual & DOE/VTO/FCTO targets

- What is the impact of FCTO targets on the fuel weight, power, cost of various components?
  - Size vehicles for comparable performance & examine component requirements

- What is the point of diminishing returns for technology improvements?
  - Evaluate how technology improvements in FCETs & other powertrains will affect economic viability
    - Compare fuel economy (mpgde)
    - Compare total cost of ownership (TCO)
Approach

Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost

Analysis Framework
- Technical Targets from DOE & stake holders

Models & Tools
- Autonomie GC Tool

Studies & Analysis
- Fuel cell system design impact on vehicle benefits for different classes & vocations on standard driving cycles

Outputs & Deliverables
- Report
  - Improved understanding of fuel cell system design impact on fuel efficiency and cost compared to competing powertrain options

Argonne Energetics

National Labs ANL

FCT Office, & External Reviews
Approach
Size FCETs using assumptions developed through DOE & industry interactions

- Additional DOE activities supported this process: sizing procedure and TCO calculation developed under TV032, TV150, VAN023.
- This work supports FC target setting activities presented in TA024
Vehicle & Powertrain Assumptions

- **Reference technology**: Comparable to 2017-18 trucks. Simulated per regulatory load conditions on ARB Transient, EPA 55 & EPA65 cycles
- All powertrain variants are sized for similar performance capability

<table>
<thead>
<tr>
<th>Performance requirements</th>
<th>Class 4 Delivery</th>
<th>Class 6 Delivery</th>
<th>Class 8 Sleeper</th>
<th>Class 8 Day Cab</th>
<th>Class 8 Vocational</th>
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<tbody>
<tr>
<td>Cargo (kg)</td>
<td>2,590</td>
<td>5,091</td>
<td>17,273</td>
<td>17,273</td>
<td>6,818</td>
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<tr>
<td>6% grade speed (mph)</td>
<td>50</td>
<td>37</td>
<td>32</td>
<td>31</td>
<td>28</td>
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<tr>
<td>Cruise speed (mph)</td>
<td>70</td>
<td>70</td>
<td>65</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>Acceleration 0-30mph (s)</td>
<td>9</td>
<td>14</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Acceleration 0-60mph (s)</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>66</td>
<td>66</td>
</tr>
</tbody>
</table>

- **Additional Powertrain Considered**
  - Conventional
  - Start-stop (ISG)
  - Hybrid (HEV)
  - Series plug in hybrid (PHEV)
  - Battery electric vehicles (BEV)

*Conv and HEVs are diesel powered. CNG variants will be added later*
Performance Based Sizing Ensures Fair Comparison

Sizing Assumptions

- No trade off on payload or performance
  - Fixed payload across all powertrains
  - Match or better conventional vehicles performance
- BEVs range depend on the application.
  - Fleet DNA, VIUS are used as reference for range.
- PHEVs sized for 50% of BEV electric range.

As performance parameters are not widely published for heavy vehicles, the baseline values have been estimated through simulations.
Technology Progress Assumptions

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

Table is provided in backup slides
Technical Accomplishments

Impact of targets on fuel cell & H₂ tank

Preliminary results

- Grade climbing requirement dictates fuel cell power for FCETs. Weight reduction helps reduce the power requirements.
- Cost targets have a more appreciable impact in reducing system cost.
Technical Accomplishments

Fuel consumption comparison across various powertrains

- FCETs are most beneficial for Urban driving scenarios
- Class 8 Sleepers are already very efficient for highway driving.

* Charge sustaining operation is shown for PHEV.
Technical Accomplishments

Truck purchase price comparison across powertrains

- Battery and FC system costs are expected to drop. Engine cost will increase due to stricter emission norms and cost of improving efficiency.

* All powertrains are simulated with same body & glider properties as that of conventional truck.
Technical Accomplishments

If DOE targets are not met, none of the truck segments evaluated in this case will achieve cost parity with diesel by 2050.
Collaboration and Coordination with Other Institutions

- **Vehicle Assumptions**
  - DOE VTO
  - 21CTP partners
  - FC Workshop @ Argonne

- **Components**
  - FCTO
  - Ballard
  - SA Inc

- **Reviews**
  - VTO & FCTO
  - Argonne FC team
  - GREET team

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

- Provide information to estimate market penetration
  - Fuel consumption & vehicle cost estimates

- Expand the analysis to include TCO ($/mile) to conduct techno-economic impact
  - When will FCETs achieve cost parity with diesels?
  - Which vocations will first achieve cost parity with current technology targets?

- Evaluate TCO sensitivity to changes in Fuel Cell & Storage technologies
  - Similar analysis was performed for light duty vehicles in FY18

- Add more vehicle types to this analysis, include real world conditions to estimate operating costs
Summary

- What are the benefits of fuel cell electric trucks (FCETs)?
  - FCETs demonstrated over 50% fuel savings in urban driving scenario.
  - Conventional Class 8 Sleeper trucks are the toughest competition for FCETs

- What are the impacts of meeting the targets?
  - FCETs can achieve cost parity with diesel trucks only if the targets are met.
  - Fuel cost parity and fuel availability are other considerations affecting consumer acceptance

- What is the impact of FCTO targets on the fuel weight, power, cost of various components?
  - Power requirements will reduce marginally due to light weighting.
  - Cost targets play a critical role in reducing overall ownership costs

- What is the point of diminishing returns for technology improvements?
  - TCO comparison will be analyzed next
Architectures considered in this study

Each powertrain has its own sizing logic. This is being integrated to AMBER

Conventional

Pre-Trans Hybrid (HEV)

Mild Hybrid (ISG)

Series Plug In Hybrid (PHEV)

Battery Electric (BEV)

Fuel cell electric trucks (FCET)
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>MD HD</td>
<td>Medium Duty &amp; Heavy Duty</td>
</tr>
<tr>
<td>FCET</td>
<td>Fuel cell electric truck</td>
</tr>
<tr>
<td>FCHEV</td>
<td>Fuel cell hybrid electric vehicle</td>
</tr>
<tr>
<td>Light_HD</td>
<td>EPA uses this terms to denote Class 3-4 vehicles</td>
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<tr>
<td>Medium_HD</td>
<td>EPA uses this terms to denote Class 5-6 vehicles</td>
</tr>
<tr>
<td>Sleeper_HR</td>
<td>HR stands for high roof configuration. Mid and low roof designs are other variants</td>
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<tr>
<td>mpgde</td>
<td>Miles per gallon diesel equivalent.</td>
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<tr>
<td>ARB Transient</td>
<td>Regulatory transient driving cycle used by EPA</td>
</tr>
<tr>
<td>EPA 55, EPA 65</td>
<td>55mph and 65mph regulatory cycles used by EPA</td>
</tr>
<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
</tr>
<tr>
<td>PnD</td>
<td>Pickup and Delivery</td>
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</table>
**FC & H₂ Assumptions**

- The ‘Low’ assumptions refer to the Business as Usual scenario. ‘High’ case reflects the impact of DOE funding.

- An excel sheet with all assumptions (across all powertrains and components) was shared with DOE earlier.
- It will be available from Argonne website by end of FY19.

<table>
<thead>
<tr>
<th>Year</th>
<th>Case</th>
<th>FC Peak Eff (%)</th>
<th>FC specific power (W/kg)</th>
<th>FC cost ($/kw)</th>
<th>H₂ in 100kg tank (kg)</th>
<th>Tank variable cost ($/usable H₂)</th>
<th>Tank fixed cost ($)</th>
<th>Cost of Usable H₂ ($/kg)</th>
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<td>Low</td>
<td>0.6</td>
<td>650</td>
<td>220</td>
<td>4.4</td>
<td>428</td>
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<tr>
<td>2020</td>
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<td>200</td>
<td>4.4</td>
<td>428</td>
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<td>9</td>
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<tr>
<td>2020</td>
<td>High</td>
<td>0.62</td>
<td>650</td>
<td>200</td>
<td>4.4</td>
<td>428</td>
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<td>Low</td>
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<td>650</td>
<td>180</td>
<td>4.4</td>
<td>415</td>
<td>923</td>
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<td>125</td>
<td>4.6</td>
<td>350</td>
<td>923</td>
<td>7</td>
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<td>2030</td>
<td>Low</td>
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<td>659</td>
<td>175</td>
<td>4.5</td>
<td>400</td>
<td>863</td>
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<td>2030</td>
<td>High</td>
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<td>80</td>
<td>4.7</td>
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<td>659</td>
<td>165</td>
<td>4.6</td>
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<td>75</td>
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<td>Low</td>
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<td>4.7</td>
<td>380</td>
<td>559</td>
<td>5</td>
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<tr>
<td>2050</td>
<td>High</td>
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<td>60</td>
<td>7.8</td>
<td>266</td>
<td>326</td>
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Sizing process:
All trucks are based on popular production vehicles.

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
   • H₂ requirement

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

Argonne has developed models for over 20 class vocation combinations
   – Simulation models and assumptions are available to support any DOE funded activity.

Sizing process was developed in prior work (TV032)
Cost estimation process:

- Developed under a VTO’s VAN023 project.
  - Retail price of trucks were collected from dealers and OEMs.
  - 20% margin is assumed to estimate the cost of manufacturing the truck.
  - Cost of mature components such as engine & transmission are computed based on the mass of those components.
    - There is additional cost assumed for improvement in efficiency.
    - All these assumptions and cost calculations will be made available in a detailed report by end of FY19.

- MD&HD components with new technologies are assumed to have an additional cost multiplication factor during the initial years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Engine</th>
<th>Light weighting</th>
<th>Motor</th>
<th>Battery</th>
<th>Fuel cell</th>
<th>H2 tank</th>
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<tr>
<td>2017</td>
<td>1.24</td>
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<td>2025</td>
<td>1.10</td>
<td>1.05</td>
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<td>1.00</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>2050</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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