Medium- and Heavy-Duty Electric Drive Vehicle Simulation and Analysis

DOE VTP Annual Merit Review

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Organization: NREL

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Project ID: VSS043

This presentation does not contain any proprietary, confidential or otherwise restricted information.
Project Overview

Timeline

- Project started in FY09
- Project is 75% complete

Budget

- Total DOE project funding
  - FY09: $150k
  - FY10: $150k
  - FY11: $250k
- Total project partner funding:
  - FY10: $37k
- In-kind support received from FedEx Express®, Azure Dynamics®

Barriers Addressed

1. Risk Aversion
2. Cost
3. Computational models, design and simulation methods

Project Partners

- FedEx Express
- Azure Dynamics
- Calstart®, South Coast Air Quality Management District (AQMD)
Project Relevance

Medium Duty (Classes 3-6) Vehicle Segment

- Consumes over 8 billion gallons of fuel per year (U.S.)
- Emits on average 13 tons CO₂ per vehicle per year
- Growing fast: +35% and +49% growth (class 3 and 4) from 1997 to 2002
- Includes short haul delivery  → largest segment group
  - 28% of 16.3M vehicles in 2009

Parcel Delivery is Well-Matched to Electric Drive

1) Transient-intensive drive cycles
2) Fleet vehicles return to base (overnight charging)
3) Operate in densely populated areas
4) Significant potential for per-vehicle emission reductions
### Project Relevance

**OEMs Need to Know**
1. What medium-duty vehicle segments should be targeted?
2. What usage profiles should be designed to?
3. What are the warranty implications?

**End Users Need to Know**
1. What are the best electric drive options?
2. Which routes are best (distance and intensity)?
3. What is the total cost of ownership?
4. How much petroleum and greenhouse gases (GHG) can be avoided?

### Project Objective
Help answer industry and end-user questions, accelerate deployment, magnify impact of plug-in electric vehicles (PEVs), and reduce petroleum consumption.
## Project Milestones

<table>
<thead>
<tr>
<th>Month-Year</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2010</td>
<td>Conference paper: “Model-Based Analysis of Electric Drive Options for Medium-Duty Parcel Delivery Vehicles,” Presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition, November 5–9, 2010, Shenzhen, China</td>
</tr>
<tr>
<td>September 2011</td>
<td>Technical report and/or conference paper summarizing analysis.</td>
</tr>
</tbody>
</table>
1. Drive Cycle Data Collection & Analysis
   - Real-world driving (distance, intensity)
   - Match and bound usage profiles

2. Measure Fuel Consumption
   - NREL ReFUEL Laboratory Chassis Dynamometer

3. Vehicle Modeling
   - Calibrate model using measured fuel consumption by drive cycle
   - Simulate fuel consumption

4. Analysis
   - Sweep range of designs, usage patterns, costs
Project Approach

- 11 FedEx vehicles, 4 depots, 82 route-days, 1 Hz speed-time
### Project Approach

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>HEV Fuel Consumption (liter / 100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTUF4</td>
<td>22.5</td>
</tr>
<tr>
<td>OC Bus</td>
<td>27.3</td>
</tr>
<tr>
<td>NYCC</td>
<td>34.9</td>
</tr>
</tbody>
</table>

Photo credit: Robb Barnitt, NREL

HEV = Hybrid Electric Vehicle
## Project Approach

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FedEx HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_d$</td>
<td>0.7</td>
</tr>
<tr>
<td>Frontal area (m$^2$)</td>
<td>7.02</td>
</tr>
<tr>
<td>Vehicle mass (kg)</td>
<td>4,472</td>
</tr>
<tr>
<td>Engine power (kW)</td>
<td>182</td>
</tr>
<tr>
<td>Motor power (kW)</td>
<td>100</td>
</tr>
<tr>
<td>Battery power (kW)</td>
<td>60</td>
</tr>
<tr>
<td>Battery capacity (kWh)</td>
<td>2.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>Measured Fuel Consumption (L/100km)</th>
<th>Simulated Fuel Consumption (L/100km)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTUF 4</td>
<td>22.5</td>
<td>24.5</td>
<td>8.9%</td>
</tr>
<tr>
<td>OC Bus</td>
<td>27.3</td>
<td>27.4</td>
<td>0.4%</td>
</tr>
<tr>
<td>NYCC</td>
<td>34.9</td>
<td>35.2</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
**Drive Cycles**
- HTUF4
- OC Bus
- NYCC

**Energy and Power**
- +20, 40, 60, 80 kWh
- 30, 60 kW

**Daily Distance Driven**
- 40 km (25 miles)
- 80 km (50 miles)
- 120 km (75 miles)
- 160 km (100 miles)

**Fuel and ESS Cost**
- Current → $3/gallon fuel, $700/kWh ESS
- Midterm → $5/gallon fuel, $300/kWh ESS
- Electricity cost = $0.12/kWh
Technical Accomplishments

- Higher cumulative fuel consumption with increasing drive cycle intensity, battery capacity and mass

![Graph showing cumulative fuel consumption vs. daily vehicle distance traveled for different battery capacities and drive cycles.](image-url)
Technical Accomplishments

• Drive cycle intensity impacts CD range and cumulative fuel consumption

Example: a PHEV with 40 kWh battery must drive <80 km (~50 miles) between charges to consume less fuel than an HEV with 2.5 kWh battery.
Technical Accomplishments

- Battery capacity and mass impact CD range and cumulative fuel consumption

Example: a PHEV with 80 kWh battery sustains the lowest cumulative fuel consumption for the longest distance (~25 km / 15 miles), but due to large battery mass, consumes the most fuel if driven >60 km (~37 miles) between charges.
Technical Accomplishments

Incremental PHEV lifetime operating costs are not currently HEV-competitive ($3/gallon fuel, $700/kWh ESS; 40 km/day)
Incremental PHEV lifetime operating costs can be HEV-competitive ($5/gallon fuel, $300/kWh ESS; 40 km/day)
Technical Accomplishments

- Incremental lifetime operating costs ($5/gallon fuel, $300/kWh battery) for most cost-effective configuration compared to HEV baseline
- Drive cycle intensity and daily distance important factors
- Fleets could balance incremental cost against purchase incentives

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Drive Cycle</th>
<th>40 km/day</th>
<th>80 km/day</th>
<th>120 km/day</th>
<th>160 km/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV+20 (30kW)</td>
<td>HTUF4</td>
<td>$6,568</td>
<td>$7,525</td>
<td>$9,018</td>
<td>$10,473</td>
</tr>
<tr>
<td>PHEV+20 (60kW)</td>
<td>HTUF4</td>
<td>$7,944</td>
<td>$9,247</td>
<td>$11,150</td>
<td>$13,029</td>
</tr>
<tr>
<td>PHEV+20 (30kW)</td>
<td>OC Bus</td>
<td>$6,154</td>
<td>$7,600</td>
<td>$9,200</td>
<td>$10,854</td>
</tr>
<tr>
<td>PHEV+20 (60kW)</td>
<td>OC Bus</td>
<td>$7,661</td>
<td>$9,719</td>
<td>$11,880</td>
<td>$14,149</td>
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<tr>
<td>PHEV+20 (30kW)</td>
<td>NYCC</td>
<td>$7,620</td>
<td>$9,678</td>
<td>$11,838</td>
<td>$14,049</td>
</tr>
<tr>
<td>PHEV+20 (60kW)</td>
<td>NYCC</td>
<td>$9,311</td>
<td>$12,040</td>
<td>$14,924</td>
<td>$17,927</td>
</tr>
</tbody>
</table>
Technical Accomplishments

PHEV configurations have significant fuel displacement potential

40 km/day; compared to HEV
Technical Accomplishments

PHEV fuel displacement advantage depends upon route selection

Negative fuel displacement with larger battery, longer daily distance over more intense cycle

80 km/day; compared to HEV
Collaborations

FedEx Express
• Industry partner, outside VTP
• Supplied drive cycle data and a test vehicle

Azure Dynamics
• Industry partner, outside VTP
• Supplied vehicle model inputs and data acquisition support

Calstart and South Coast AQMD
• Industry, regulatory partners outside VTP
• Provided added financial support
Summary

Medium duty vehicles are excellent candidates for electric drive application by virtue of usage profiles, fleet logistics, and fleet-specific value proposition.

**BUT, battery and fuel costs dominate economics**
- As we know, lowering battery costs is critical to electric drive penetration.
- $5/gallon fuel and $300/kWh battery still not lifetime operating cost-competitive with HEV.

**SO, targeted design and strategic deployment are critical**
- Maximizing petroleum reduction, minimizing cost are best achieved by careful route (intensity and distance) selection.
- Shorter, less intense routes are best suited to lower power motor/battery and less battery capacity (and mass).
Proposed Future Work

1. Develop additional models of Class 4 parcel delivery vehicles
   - Conventional vehicle (diesel)
   - Diesel HEV (EPA 2007 and 2010)
   - Diesel PHEV (EPA 2007 and 2010)
   - EV

2. Simulate performance using matrix of designs and usage patterns
   - Use real drive cycles
   - Battery sized for 0–2 replacements over life of vehicle
   - Apply battery life model
   - Ambient temperature variation
   - Overnight and opportunity charging
   - Charging profiles (Level 2 and Level 3)

3. Analysis
   - Total Cost of Ownership
     - Range of liquid fuel and battery costs
     - Impact of battery replacements
   - Lifetime petroleum reduction
   - Lifetime GHG reduction
Special thanks to:
Lee Slezak and David Anderson – DOE Vehicle Technologies Program

Questions?