2015 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

**Multi-Speed Transmission for Commercial Delivery Medium Duty Plug-In Electric Drive Vehicles**

Project ID: VSS161

**Principal Investigator: Bulent Chavdar**

Eaton Corporation

June 11, 2015

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

Timeline
• Project Start Date: October 1, 2014
• Project End Date: October 31, 2017
• % Complete: 20%

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10/1/2014</td>
<td>10/31/2015</td>
</tr>
<tr>
<td>2</td>
<td>11/1/2015</td>
<td>10/31/2016</td>
</tr>
<tr>
<td>3</td>
<td>11/1/2016</td>
<td>10/31/2017</td>
</tr>
</tbody>
</table>

Barriers & Technical Targets:
• The public acceptance of electric vehicles will be increased with a transmission
• The performance gap between EVs and ICDVs will be reduced with a transmission
• The concept transmission will be reliable, affordable, scalable and low weight

Budget
• Project Value: $3,749,713
  • DOE Share: $2,999,770
  • Cost Share: $749,943 (20%)
• Funding received in FY14: $82,066
• Funding for FY15: $622,748

Partners
• Prime: Eaton Corporation
• Subcontractors
  • Smith Electric
  • Oak Ridge National Laboratory
  • National Renewable Energy Laboratory
Relevance for addressing barriers

Public acceptance and Performance of EVs

• Increasing the market penetration of MD-EVs, investigating the business case.
• Improving the utility of electric trucks across a variety of vehicle operational scenarios such high top speed, strong acceleration, improved range and hill climbing.

Reliable, efficient, affordable and low weight transmission

• Creating and validating a baseline 10 ton medium duty electric truck model.
• Benchmarking the baseline vehicle performance. Generating transmission concepts and selecting the best concept.
• Developing cost sensitive, high efficiency transmission by optimizing the number of gears, the gear ratios and the shift strategy.
• Implementing lightweighting concepts of housing, composite gears when available.
Approach/Strategy

Approach: Multi Speed Transmission helps

- Close the performance gap with ICDVs by operating the motor at its peak efficiency region.
- Provide higher gradeability and faster acceleration with a low gear.
- Increase top speed and range with a high gear.
- By selecting efficient, lightweight, reliable, automated, or automatic transmission concept with novel shifting, clutching and controls systems.

Strategy

- Customer requirements analysis, system analysis, concept development, prototype build and testing with DFSS methodology.

(continues on the next page)
Approach/Strategy – Plan

Go/No-go #1: Preliminary Transmission Design Complete. Concept selected, breadboard transmission selected, performance modeled.

Go/No-go #2: Transmission performance requirements met.
## Milestones, BP1

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone and Go/No-Go Decisions</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 2014</td>
<td><strong>Milestone:</strong> Vehicle performance requirements based on operational data and analysis defined.</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2015</td>
<td><strong>Milestone:</strong> Business Case Development Complete. Market segments, potential volume projections, scalability for penetration identified.</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2015</td>
<td><strong>Milestone:</strong> Baseline Vehicle Model Development Complete. Component and vehicle models integrated and validated for baseline level.</td>
<td>On track</td>
</tr>
<tr>
<td>August 2015</td>
<td><strong>Milestone:</strong> Breadboard Transmission Platform Selection Complete</td>
<td>On track</td>
</tr>
</tbody>
</table>
Technical Progress – MD-EV Drive Cycles

Task: Analysis of drive cycles and energy consumption rates of baseline MD-EV

- Custom and standard cycles will be used to model the efficiency gain with transmission
- Overall distribution of MD-EV energy consumption indicates a trend line around 25 mpge
- Average energy consumption of MD-EVs is 1.4-1.5 kWh/mile
Technical Progress – EV transmission volume estimates by 2023

Task: Potential transmission volume projections for market segments

- EV transmission sales are expected to be 36K units by 2023.
  - Aggressive scenario: 80K EVs, 40% Transmission adoption rate, 58K units
  - Conservative scenario: 40K EVs, 20% Transmission adoption rate, 14K units
- The EV transmission project helps achieve the aggressive scenario.
Technical Progress – Baseline Model Validation

Task: Baseline MD-EV model validation at ORNL

- Vehicle model was created based on 10t Smith Newton Electric Truck.

- Model was validated against experimental data:
  - Acceleration tests
  - HTUF4 and Orange County Bus cycles

- Established single speed baseline vehicle performance:
  - UDDS Truck cycle: 1242Wh/mile
  - CILCC cycle: 899Wh/mile
  - Max speed = 54.5mph
  - 0-30mph = 18.7sec
  - 30-50mph = 69.1sec
Technical Progress – Gearbox optimization

Task: Parametric gearbox configuration study with number of gears, axle ratios, gear ratios, and shifting efficiency

- Parametric study with 2-speed automated manual gearbox completed:
  - Acceleration from 0 to 50 mph improves 28%
  - Efficiency improves 12% and 7.5% in UDDS and CILCC respectively
  - Top speed improves 7.5%

- Parametric studies with 3 and 4 speed and automatic gearboxes are in progress.
Technical Progress – Voice of Customer

Task: Identification of end customer requirements for the selection of multispeed transmission by following the DFSS methodology

<table>
<thead>
<tr>
<th>MD-EV Performance criteria</th>
<th>MD-EV Business criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria name</td>
<td>Relative importance (sums up to 1)</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.36</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.18</td>
</tr>
<tr>
<td>Gradeability</td>
<td>0.16</td>
</tr>
<tr>
<td>Range (efficiency)</td>
<td>0.12</td>
</tr>
<tr>
<td>Launch on a hill</td>
<td>0.09</td>
</tr>
<tr>
<td>Top speed</td>
<td>0.06</td>
</tr>
<tr>
<td>Comfort (NVH etc.)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

- Customer wants and needs were identified and ranked by Smith, ORNL, NREL and Eaton in Performance and Business categories
- The high ranking criteria will get more attention when selecting the transmission
- LD-EV VoC and CWN with VIA is in progress in collaboration with DOE-VT projects
Responses to Last Year Reviewers’ Comments

• This project started on October 1, 2014.
Collaborations

**PRIME**
- Program management
- Requirement definition
- Vehicle system simulations
- Gear ratios and shift strategy
- Transmission architecture
- Controller integration
- Design and prototype
- Component testing
- Vehicle integration
- Commercialization

**EATON**

**Bulent Chavdar**

**SMITH**
- Requirement definition
- Baseline vehicle
- Performance limits of baseline
- Vehicle integration
- Product deployment plan
- Commercialization support

**Relationship: Industry**
Subcontractor within VT Program

**Paul Chambon**

**OAK RIDGE National Laboratory**
- Vehicle level simulations
- Component testing
- HIL testing
- General support

**Relationship: Federal Laboratory**
Subcontractor outside VT Program

**NREL**

**Kevin Walkowicz**
- Requirement definition
- Duty cycle harvesting
- Battery downsizing
- Vehicle integration
- Performance testing and demonstration

**Relationship: Federal Laboratory**
Subcontractor outside VT Program
Remaining Challenges and Barriers

• The EV OEM limits the continuous power of motor to reduce the heat generation. A multi speed transmission will enable running the motor cooler. If the thermal model of motor/inverter is included in the simulations, then additional performance improvements by a transmission can be predicted.

• The transmission control unit needs to communicate with the motor controller. The communication protocols for the breadboard transmission and the real transmission will be different.

• Advanced technologies related to lightweighting, supervisory controls and advanced shifting technologies are considered for the real product but may not be available at the time of breadboarding.
Proposed Future Work

• BP1 – 2015 – Technology Development
  • Completing parametric gearbox optimization study with numbers of gears, ratio spreads, final axle ratios, and shift efficiency to improve the MD-EV performance
  • Understanding the performance needs of LD-EVs and HD-EVs
  • Transmission concept generation and concept selection by trade off analysis
  • Breadboard transmission selection and the reengineering plan to represent the selected concept.

• BP2 – 2016 – Technology Development and Prototype Demonstration

• BP3 – 2017 – Technology Integration, Testing, and Demonstration
## Summary

- Project is on schedule. All required project milestones have been met to date.
- Baseline vehicle model development was completed.
  - Baseline vehicle model was created and correlated at ORNL and Eaton.
  - Model was validated with on-route data of 10t Smith although not a perfect match.
- Transmission concept development is in progress
  - VoCs and CWNs of MD-EV were identified and ranked. Discussions on the functional requirements of transmission continue.
  - Optimization studies with 2-speed automated gearbox completed. 2, 3 and 4-speed optimization studies with automated and automatic gearboxes continue.

### Table:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>FOA-Model Baseline 10t GVW with SS Gearbox, 95 kW</th>
<th>Proposed Targets with Transmission and 95 kW</th>
<th>Model Smith Newton 10t GVW, SS gearbox, 80 kW</th>
<th>Coastdown Test Smith Newton 10t GVW, SS gearbox, 80 kW</th>
<th>Model Status with 2-speed AMT and 80 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top speed</td>
<td>mph</td>
<td>50</td>
<td>65+</td>
<td>54.5</td>
<td>49.6</td>
<td>59</td>
</tr>
<tr>
<td>Energy efficiency/range</td>
<td>mpg</td>
<td>37 on UDDS 50 on CILCC</td>
<td>40+ on UDDS 54+ on CILCC</td>
<td>30.3 on UDDS 41.8 on CILCC</td>
<td>33.9 on UDDS 44.7 on CILCC</td>
<td></td>
</tr>
<tr>
<td>Acceleration (0-30 mph)</td>
<td>s</td>
<td>20</td>
<td>15</td>
<td>18.7</td>
<td>20.4</td>
<td>18</td>
</tr>
<tr>
<td>Acceleration (30-50 mph)</td>
<td>s</td>
<td>70</td>
<td>30</td>
<td>69.1</td>
<td>70.8</td>
<td>43</td>
</tr>
</tbody>
</table>
2015 DOE Vehicle Technologies Office Annual Merit

Technical Backup Slides

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Scope/Approach/Strategy

• Developing a new transmission with a new controller and shift strategy to match the bidirectional performance characteristics of a motor/generator of a baseline 10 ton MD-PEDV.
• Identifying the needs of LD and HD markets as well.
• Advancing TRL from 2 to 5, including:
  • Concept generation and selection
  • Design and construction of a breadboard transmission
  • Testing and evaluation of breadboard in the lab and on a vehicle
• Completing the project in 3 years:
  • BP1: Technology Development
  • BP2: Technology Development and Prototype Demonstration
  • BP3: Technology Integration, Testing, and Demonstration
## Milestones, BP2

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone and Go/No-Go Decisions</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 2016</td>
<td><strong>Milestone:</strong> Breadboard Transmission Gearbox Design Complete.</td>
<td></td>
</tr>
<tr>
<td>March 2016</td>
<td><strong>Milestone:</strong> Prototype Transmission Build Complete.</td>
<td></td>
</tr>
<tr>
<td>June 2016</td>
<td><strong>Milestone:</strong> Transmission and Controller Shakedown Testing Complete</td>
<td></td>
</tr>
<tr>
<td>Sept. 2016</td>
<td><strong>Milestone:</strong> Integrated Powertrain HIL Testing Complete</td>
<td></td>
</tr>
<tr>
<td>Sept. 2016</td>
<td><strong>Go/No-Go Decision</strong> Transmission Performance Requirements Met</td>
<td></td>
</tr>
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</table>
Technical Progress – MD-EV Drive Cycle Data

Task: MD-EV drive cycle analysis and the standard cycles by Smith and NREL

- NREL has collected thousands of Smith Newton drive cycles data in other DOE projects
- Standard drive cycles such as CARB, HTUF4, NYC-Comp can represent the real data

<table>
<thead>
<tr>
<th>Project</th>
<th>Standard Chassis Test Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>UPS MN Step Van</td>
<td>CARB HHDDT</td>
</tr>
<tr>
<td>UPS AZ Step Van</td>
<td>CILCC</td>
</tr>
<tr>
<td>Fed Ex CA Step Van</td>
<td>HTUF 4</td>
</tr>
<tr>
<td>Fed Ex Straight Truck</td>
<td>CARB HHDDT</td>
</tr>
<tr>
<td>Smith Gen 1</td>
<td>CARB HHDDT</td>
</tr>
<tr>
<td>Smith Gen 2</td>
<td>CARB HHDDT</td>
</tr>
<tr>
<td>Smith Step Vans</td>
<td>CARB HHDDT</td>
</tr>
<tr>
<td>Smith Cab Bodies</td>
<td>CARB HHDDT</td>
</tr>
</tbody>
</table>
MD&HD electric and hybrid vehicle sales will reach 160K by 2023.

The EV market will be shared 50/50 by full electric and hybrid.

LD-EV volumes will be similar to MD&HD-EV volumes combined.
Task: Baseline MD-EV model development at ORNL

- Vehicle model was created on Autonomie software based on:
  - Smith Newton Truck 10t GVW (250A, 80kW)
  - Single speed transmission
- Component parameters were decided by
  - Smith specifications and experimental data
  - A representative motor efficiency map