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

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Overview

Timeline

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

Budget Period	Start Date	End Date
1	10/1/2014	10/31/2015
2	11/1/2015	10/31/2016
3	11/1/2016	10/31/2017

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.

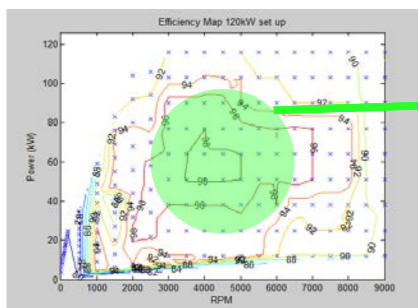
Reliable, efficient, affordable and low weight transmission

- 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.

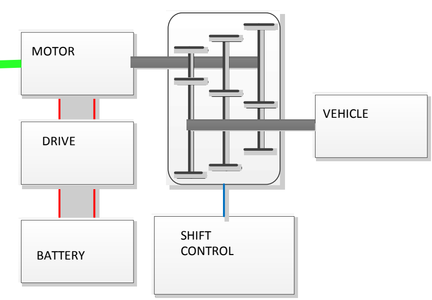
Approach/Strategy

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.



Narrow operating range of motor to the high efficiency region with multi speed transmission



Strategy

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

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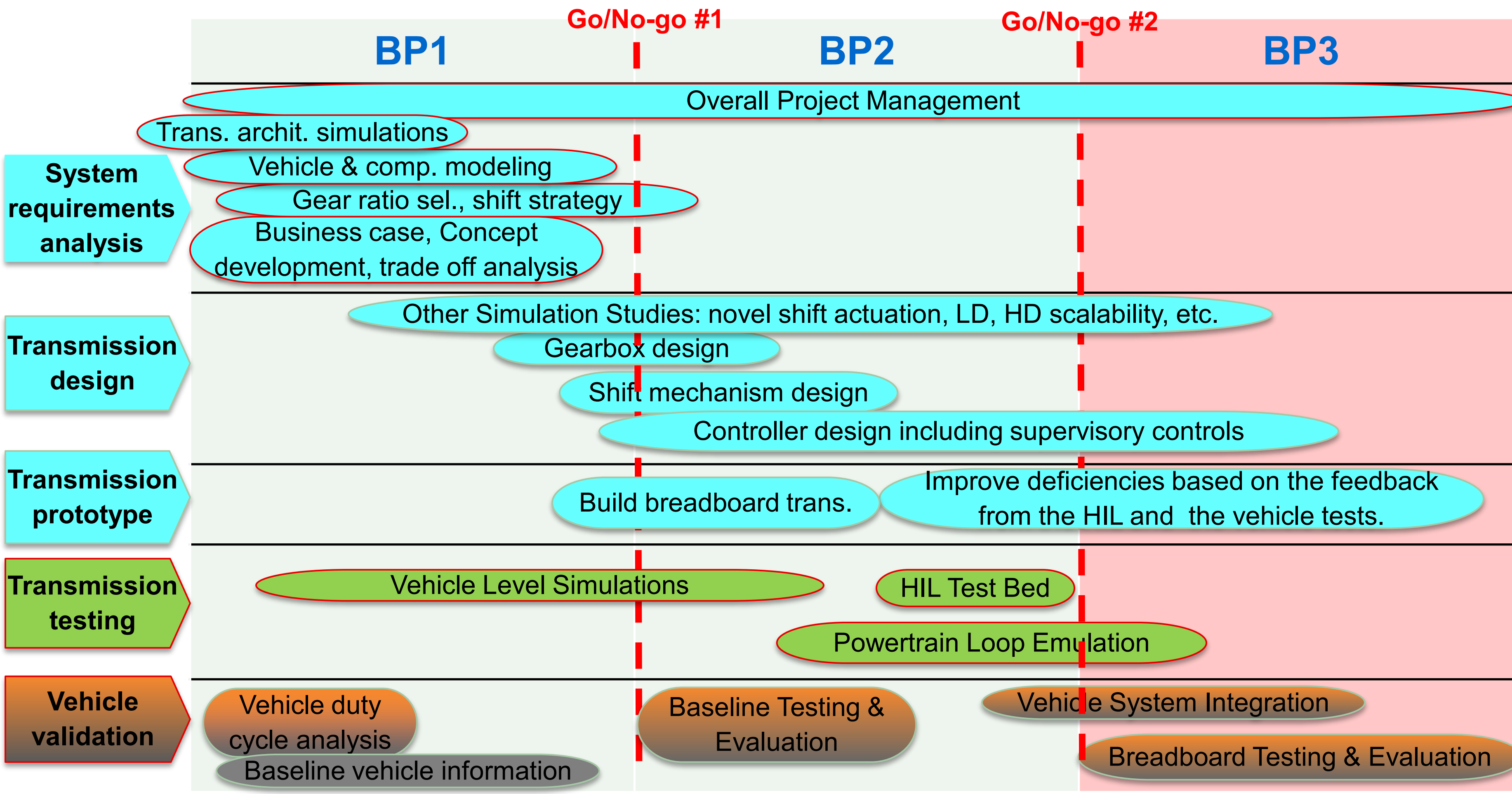
Approach/Strategy – Plan

Eaton | ORNL
NREL | Smith



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

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

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Milestones, BP1

Date	Milestone and Go/No-Go Decisions	Status
Dec. 2014	Milestone: Vehicle performance requirements based on operational data and analysis defined.	Complete
March 2015	Milestone: Business Case Development Complete. Market segments, potential volume projections, scalability for penetration identified.	Complete
June 2015	Milestone: Baseline Vehicle Model Development Complete. Component and vehicle models integrated and validated for baseline level.	On track
August 2015	Milestone: Breadboard Transmission Platform Selection Complete	On track
Sept. 2015	Go/No-Go Decision Preliminary Transmission Design Complete. Concept selected, breadboard transmission selected, performance modeled.	On track

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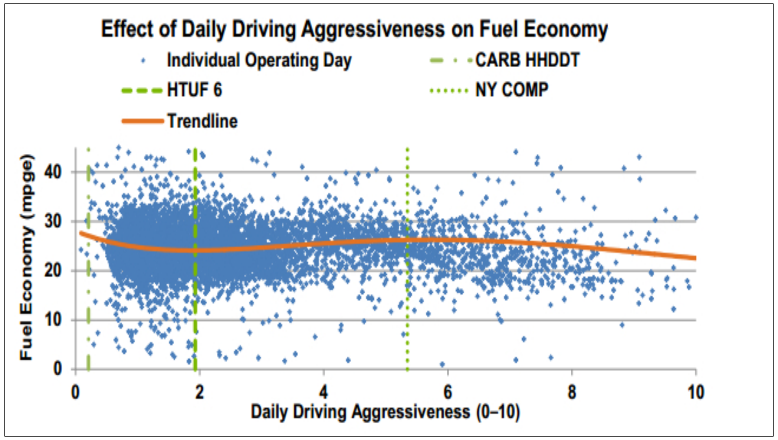
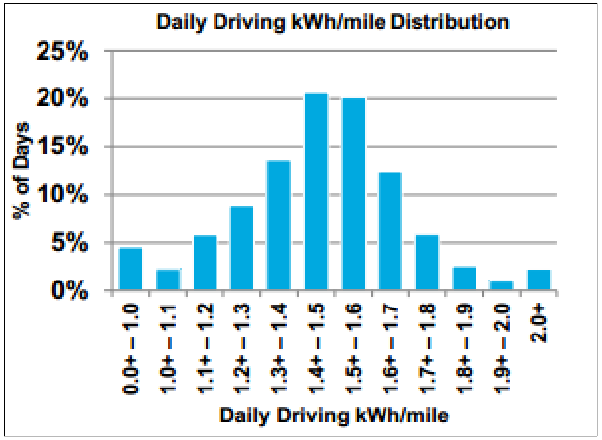
Technical Progress – MD-EV Drive Cycles

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

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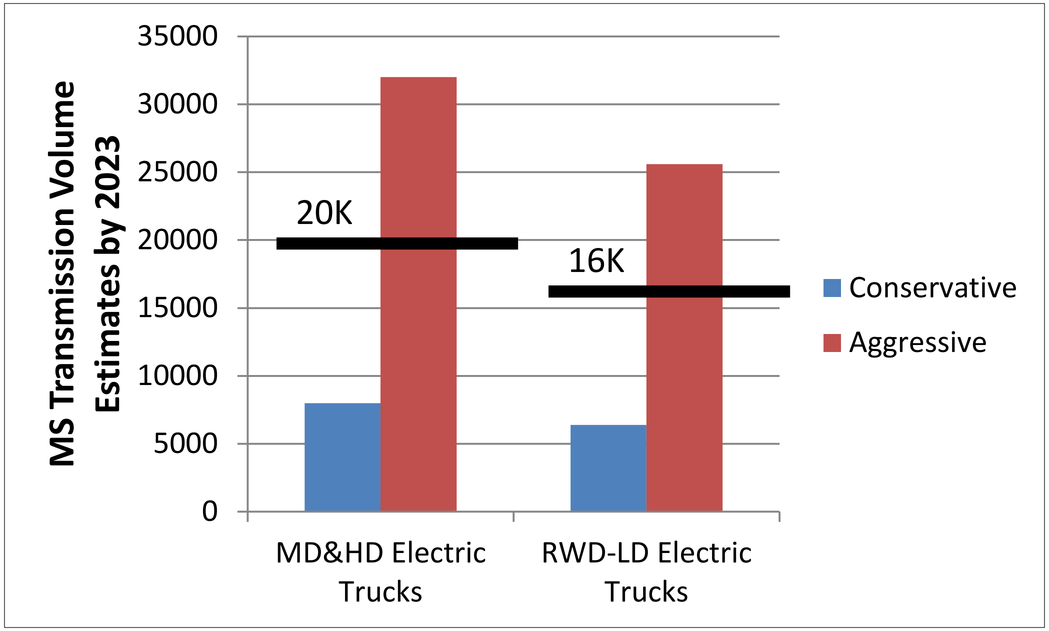
Technical Progress – EV transmission volume estimates by 2023

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.

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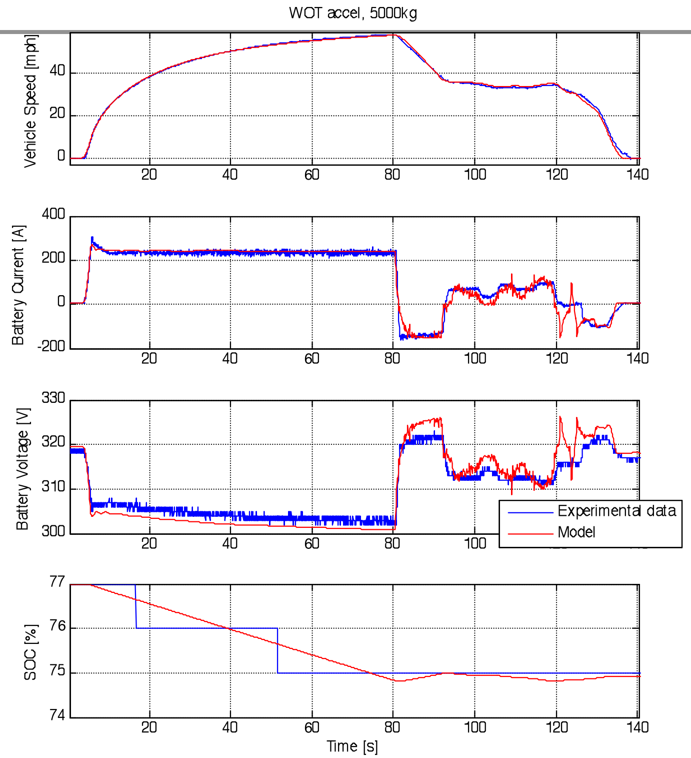
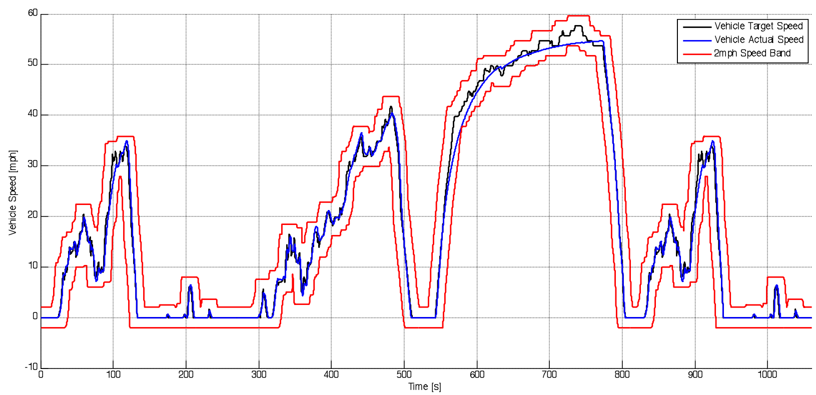
Technical Progress – Baseline Model Validation



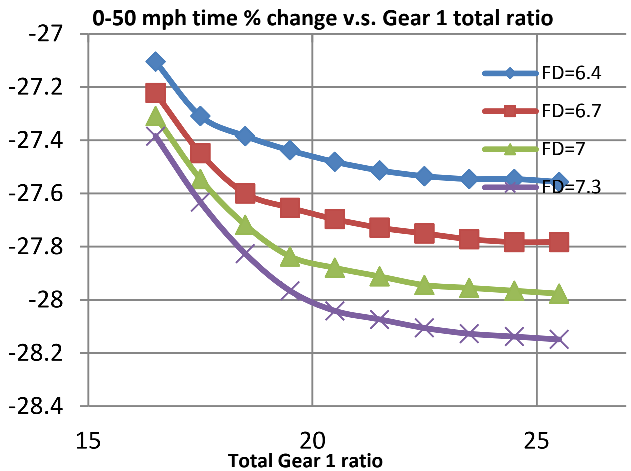
Task: Baseline MD-EV model validation at ORNL

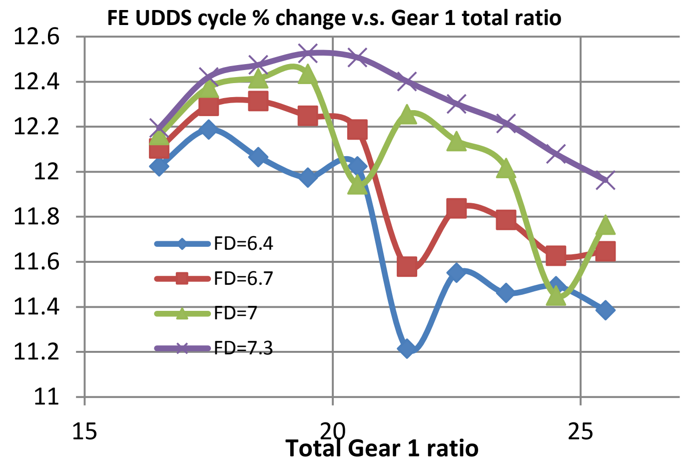
- Vehicle model was created based on 10t Smith Newton Electric Truck.
- Model was validated against experimental data:
    - Acceleration tests
    - HTUF4 and Orange County Bus cycles
- Established single speed baseline vehicle peformance:
    - UDDS Truck cycle: 1242Wh/mile
    - CILCC cycle: 899Wh/mile
    - 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.

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Technical Progress – Voice of Customer

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

MD-EV Performance criteria

Criteria name	Relative importance (sums up to 1)
Reliability	0.36
Acceleration	0.18
Gradeability	0.16
Range (efficiency)	0.12
Launch on a hill	0.09
Top speed	0.06
Comfort (NVH etc.)	0.03

MD-EV Business criteria

Criteria name	Relative importance (sums up to 1)
Capital costs	0.34
Price of transmission	0.21
Non recurring eng. costs	0.15
Application commonality	0.13
Enable motor downsizing	0.09
Ease of maintenance	0.05
Weight	0.03

- 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

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Responses to Last Year Reviewers' Comments

- This project started on October 1, 2014.

Collaborations

PRIME

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Bulent Chavdar

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

SMITH

Terry Pageler

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

Relationship: Industry
Subcontractor within VT Program

Oak Ridge National Laboratory
Managed by UT-Battelle for the Department of Energy

Paul Chambon

- Vehicle level simulations
- Component testing
- HIL testing
- General support

Relationship: Federal Laboratory
Subcontractor outside VT Program

NREL
National Renewable Energy Laboratory

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

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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.

Characteristic	Units	FOA-Model Baseline 10t GVW with SS Gearbox, 95 kW	Proposed Targets with Transmission and 95 kW	Model Smith Newton 10t GVW, SS gearbox, 80 kW	Coastdown Test Smith Newton 10t GVW, SS gearbox, 80 kW	Model Status with 2-speed AMT and 80 kW
Top speed	mph	50	65+	54.5	49.6	59
Energy efficiency/range	mpge	37 on UDDS 50 on CILCC	40+ on UDDS 54+ on CILCC	30.3 on UDDS 41.8 on CILCC		33.9 on UDDS 44.7 on CILCC
Acceleration (0-30 mph)	s	20	15	18.7	20.4	18
Acceleration (30-50 mph)	s	70	30	69.1	70.8	43

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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 baseline10 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

Date	Milestone and Go/No-Go Decisions	Status
Jan. 2016	Milestone: Breadboard Transmission Gearbox Design Complete.	
March 2016	Milestone: Prototype Transmission Build Complete.	
June 2016	Milestone: Transmission and Controller Shakedown Testing Complete.	
Sept. 2016	Milestone: Integrated Powertrain HIL Testing Complete	
Sept. 2016	Go/No-Go Decision Transmission Performance Requirements Met	

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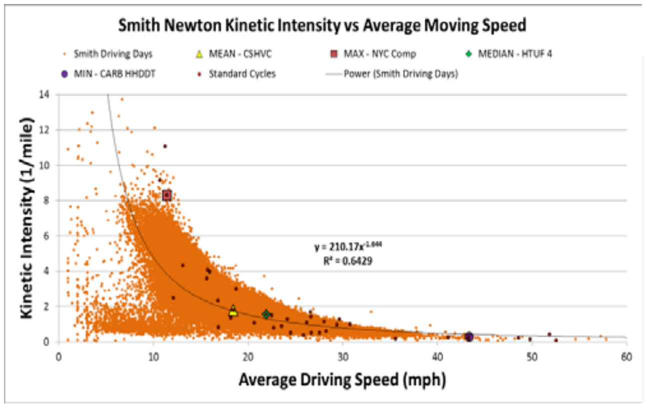
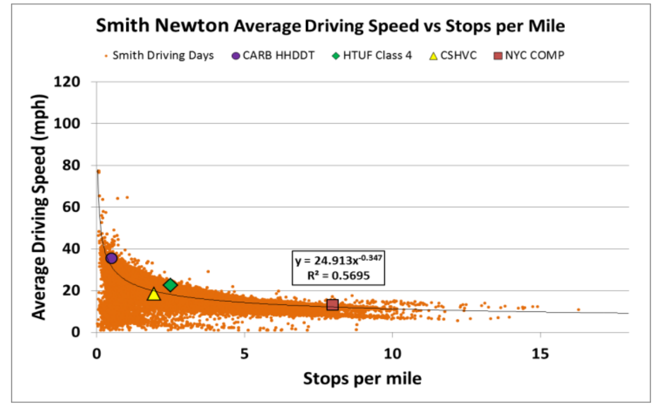
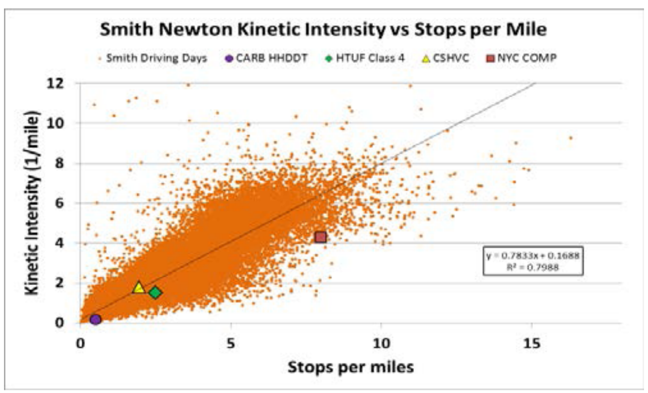
Technical Progress – MD-EV Drive Cycle Data

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







Project	Standard Chassis Test Cycles			
	Low	**Mean**	**Median**	**High**
UPS MN Step Van	CARB HHDDT	HTUF 4	HTUF 4	NYC Composite
UPS AZ Step Van	CILCC	WVU CITY	WVU CITY	CBD
Fed Ex CA Step Van	HTUF 4	OC Bus	OC Bus	New York City Cycle
Fed Ex Straight Truck	CARB HHDDT	HTUF 6	HTUF 6	NYC Composite
Smith Gen 1	CARB HHDDT	CSHVC	HTUF 4	NYC Composite
Smith Gen 2	CARB HHDDT	CSHVC	HTUF 4	NYC Composite
Smith Step Vans	CARB HHDDT	CILCC	HTUF 4	NYC Composite
Smith Cab Bodies	CARB HHDDT	CSHVC	HTUF 4	NYC Composite

- 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

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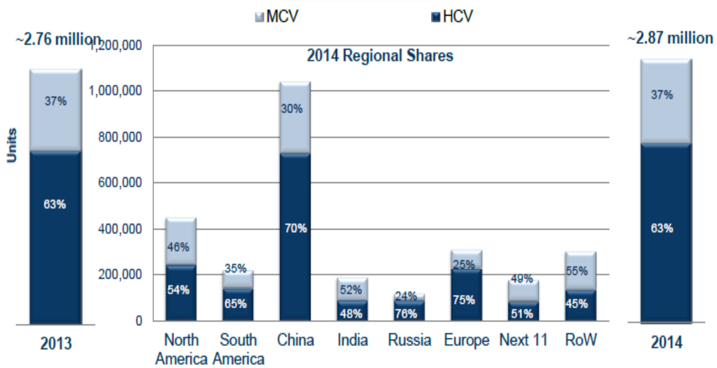
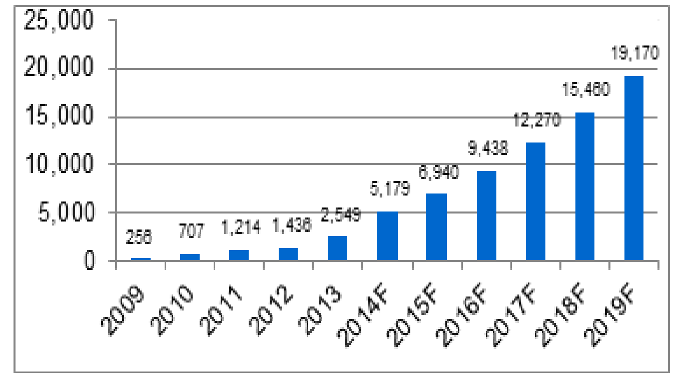
Technical Progress – EV Market Forecast

MD and HD Commercial Vehicle Sales

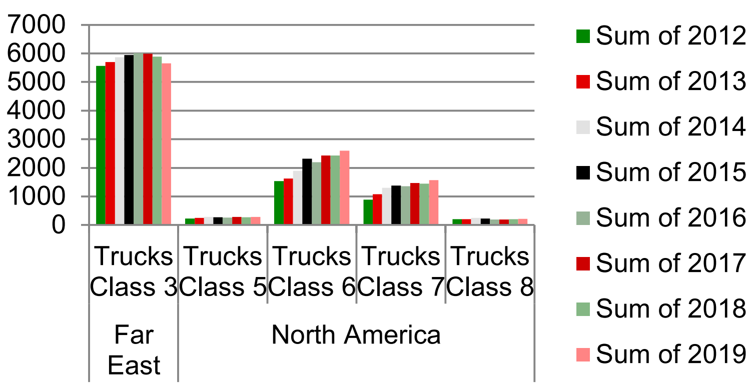


Source: Frost & Sullivan

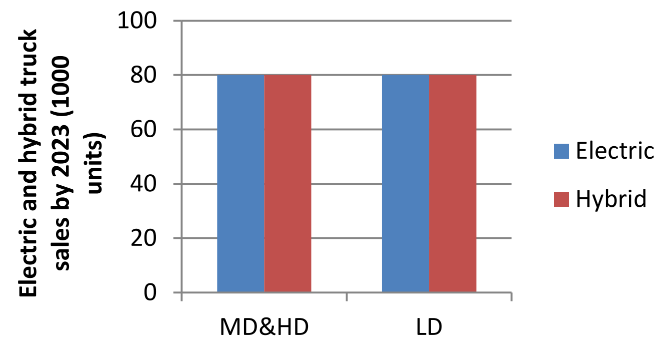
Electric Bus Forecast for China



Active Hybrid Truck Programs



EV and HEV Truck Forecast for 2023



- 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.

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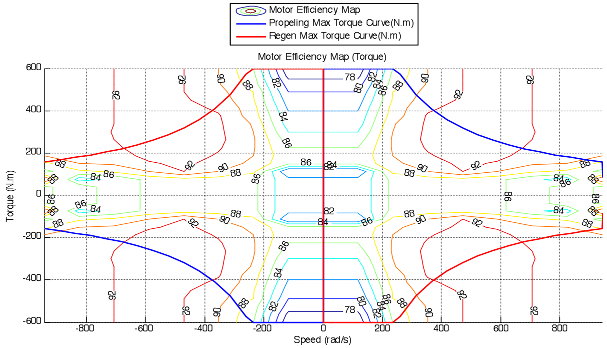
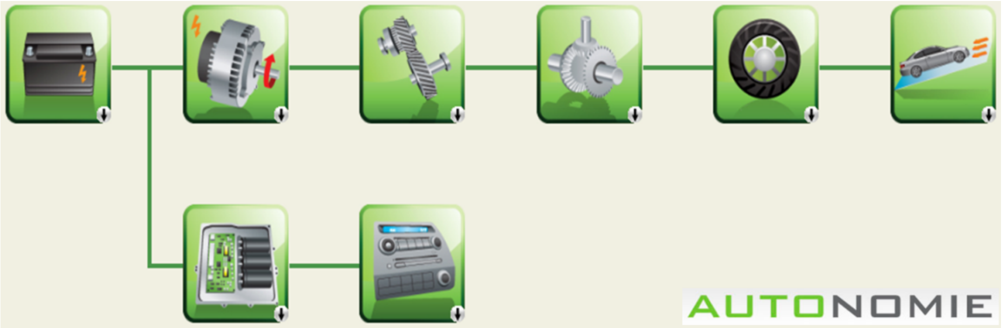
Technical Progress – Baseline Model Creation

Task: Baseline MD-EV model development at ORNL

- Vehicle model was created on Autonomie software of 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





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