MEDIUM-DUTY URBAN RANGE EXTENDED CONNECTED POWERTRAIN

P.I. – Matt Thorington, Principal Engineer, Powertrain Solutions, Commercial Vehicle Electrification

Robert Bosch LLC

2020 DOE VTO Annual Merit Review

June 3rd, 2020

Project ID #**ELT190**
(GI190)

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ELT190: MURECP Class4 Delivery PHEV

Overview

Timeline

- Project start date = 8/19/2016
- Project end date = 6/30/2020
- Percent complete = 95%

Barriers

- **Performance** – 50% Fuel Consumption Reduction for class 4 delivery truck
  - Baseline = 8.5 MPG, Target >17 MPG
  - Full performance capabilities meeting or exceeding baseline vehicle
- **Cost** - < 3 year payback period
- **EV Range** - > 35 miles all electric range

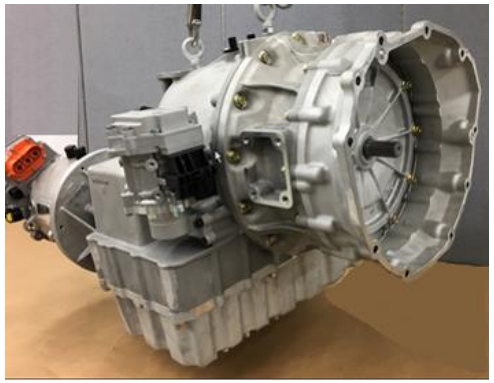
Budget

- Total project funding
  - DOE share = $4,731,884
  - Contractor share = $1,984,907
- Funding received in FY 2019 (BP3)
  - $123,045
- Funding for FY 2020 (BP3)
  - $150,000 (reduced amount from descope)

Partners

- Bosch – Project Lead
- Morgan Olson
- Voss Automotive, Inc.
- University of Michigan
- NREL
- Ricardo (vendor)

ELT190: MURECP Class4 Delivery PHEV
Relevance/ Project Objectives



- Demonstrate 50% fuel consumption reduction on CSHVC* utilizing a PHEV powertrain with a dual-planetary gear transmission via deep integration of electric components based on high-volume light duty vehicles
- Targets for April ’19- June ‘20:
  - Calibrate vehicle control unit, engine control unit, and transmissions control units
  - Conduct transient cycle testing on the chassis dyno and complete Go/No-Go #3 Milestone
  - Conduct additional vehicle testing on a private test track, including 3rd party performance and FE evaluation
  - Conduct vehicle demonstration
- Evaluation against Project Barriers
  - **Performance:** current chassis dyno measurements show a fuel economy range of ~21 MPGe to 14 MPGe (~43 to 58% fuel consumption reduction) on CSHVC* in charge sustaining mode (equiv. FE converted based on 1kWh = 244g Diesel)
    - >15 million gallons of diesel fuel saved per year class 4, >50 million gallons per year class 3-5 (based on ~50% avg.)
  - **Cost:** target ROI <3 years (Simple Pay-back)
    - ~3.5 years ROI with 2018 costs, HEV battery size (20 kW-hr), and 39k miles/year
    - ~2.5 years ROI with 2022 costs as PHEV w/ 60 mile EV range and 39k miles/year
  - **EV Range:** ~56 miles of all-electric range achievable with existing battery packs on the CSHVC* based on 2x 24 kW-hr packs in parallel (and 90% useable energy)

*CSHVC=City Suburban Heavy Vehicle Cycle

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Milestones BP3

Milestone	Type	Description	Date
Completed chassis dynamometer fuel consumption testing	Go/No-Go #3	Chassis Dyno testing at BOSCH completed to validate achievement of a 50% fuel consumption reduction	3/30/2020 ☑
Emissions Evaluation on Powertrain Dyno	Technical	Utilizing a production aftertreatment system from a LD Pickup truck (matched to the downsized 3.0l ICE), engine out and ATS out emissions will be measured and evaluated.	6/30/2020 ☐
Completed limited real-world driving cycle fuel consumption testing	Technical	In-use testing of fuel consumption and emissions conducted to validate achievement of a 50% fuel consumption reduction for a given drive cycle	REMOVED ☒
In-use fuel consumption determined	Technical	Quantify the fuel consumption reduction during a fleet demonstration of for a real-world driving cycle	REMOVED ☒

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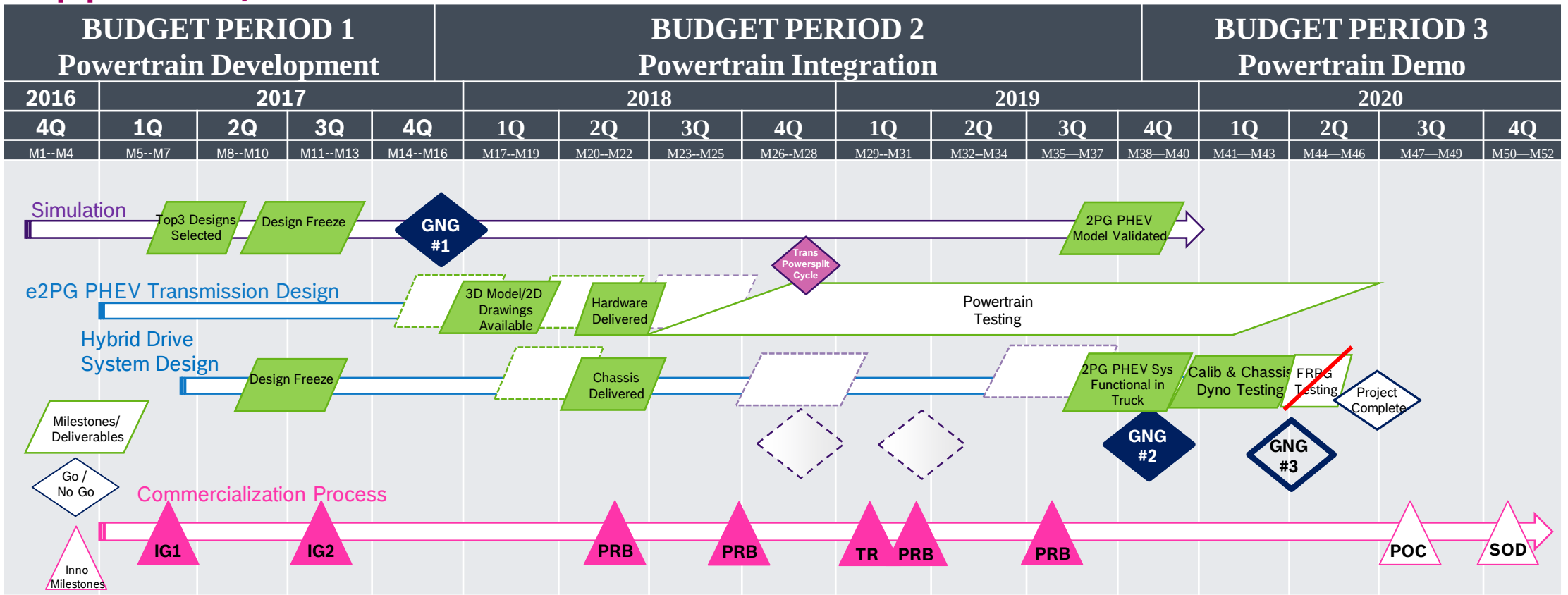
Approach/ Milestones



Due to delays and additional spending at BOSCH in BP2, along with the current business situation from COVID-19, BP3 has been rescoped to stop after chassis dyno testing (GNG#3 milestone).

*FRPG = Flat Rock Proving Ground (BOSCH Private Test Track)

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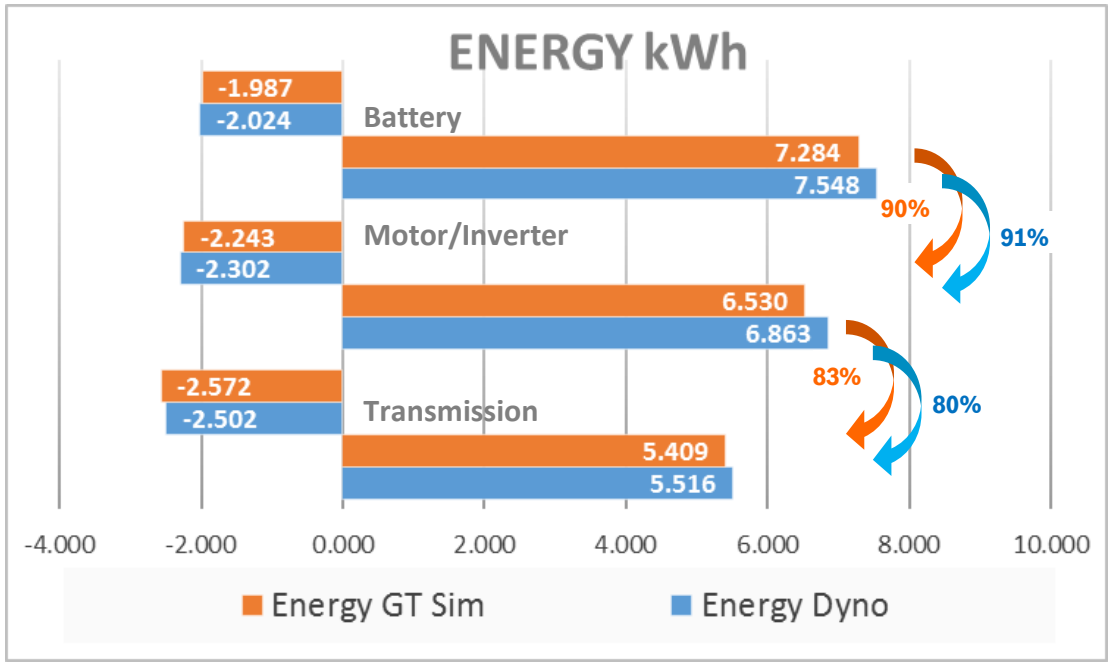
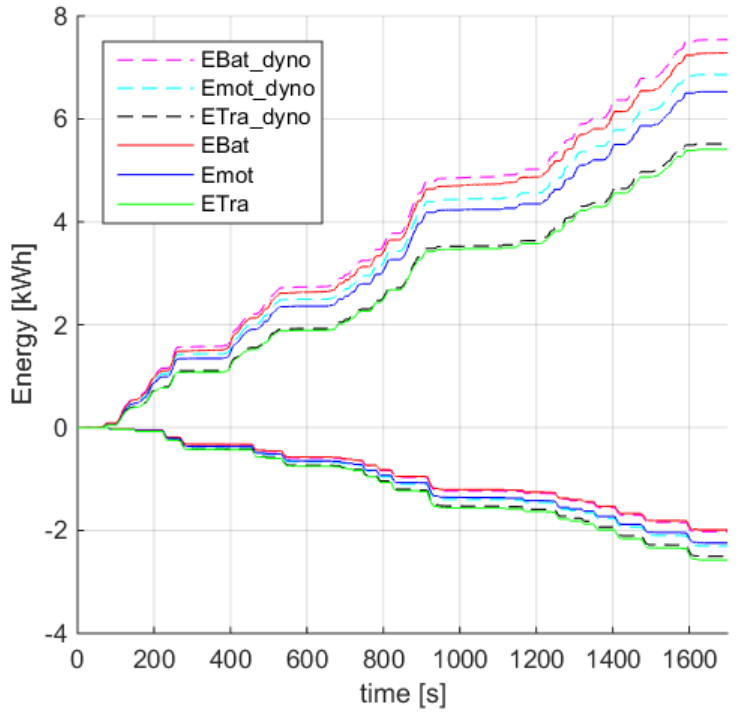
Technical Accomplishments and Progress

- Simulation model verification





Mutual verification of simulation and measurement, with excellent correlation and validation of GT Suite 1D Vehicle/ Powertrain simulation models

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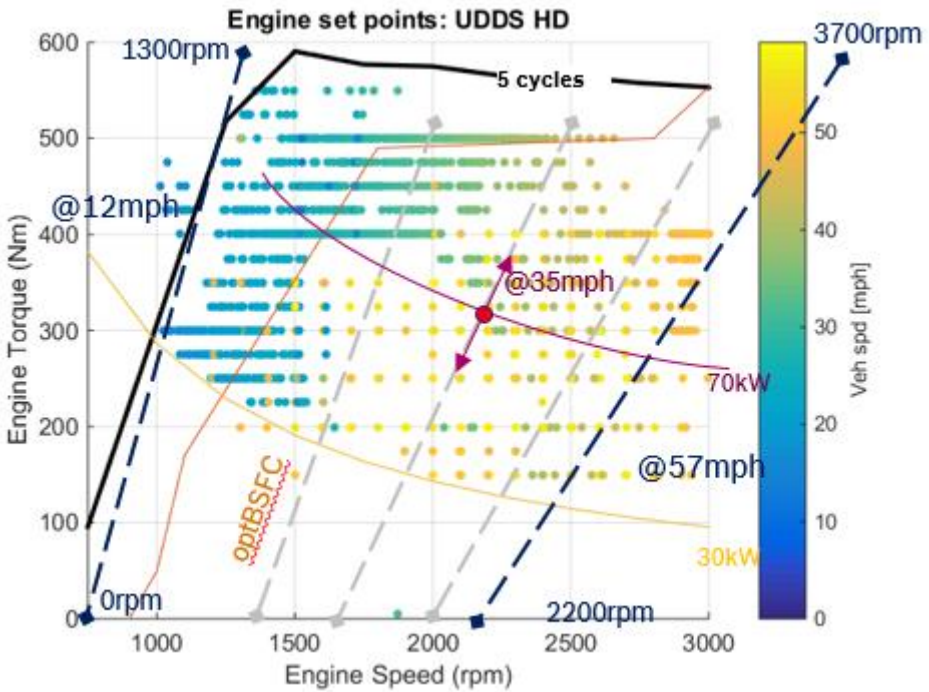
Technical Accomplishments and Progress

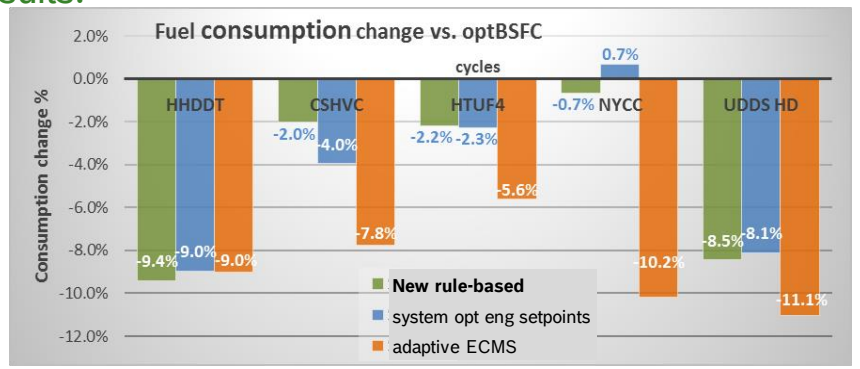
- Derivation of a rule-based power setpoint strategy with additional dependency upon vehicle speed



Power strategy:

SOC	Min power	Power offset
Mid, high	26.8 kW	20.5 kW
Low	74.5 kW	34.5 kW

Results:



New rule-based strategy nears improvement change potential of adaptive ECMS (online optimal strategy) without the SW development efforts required.

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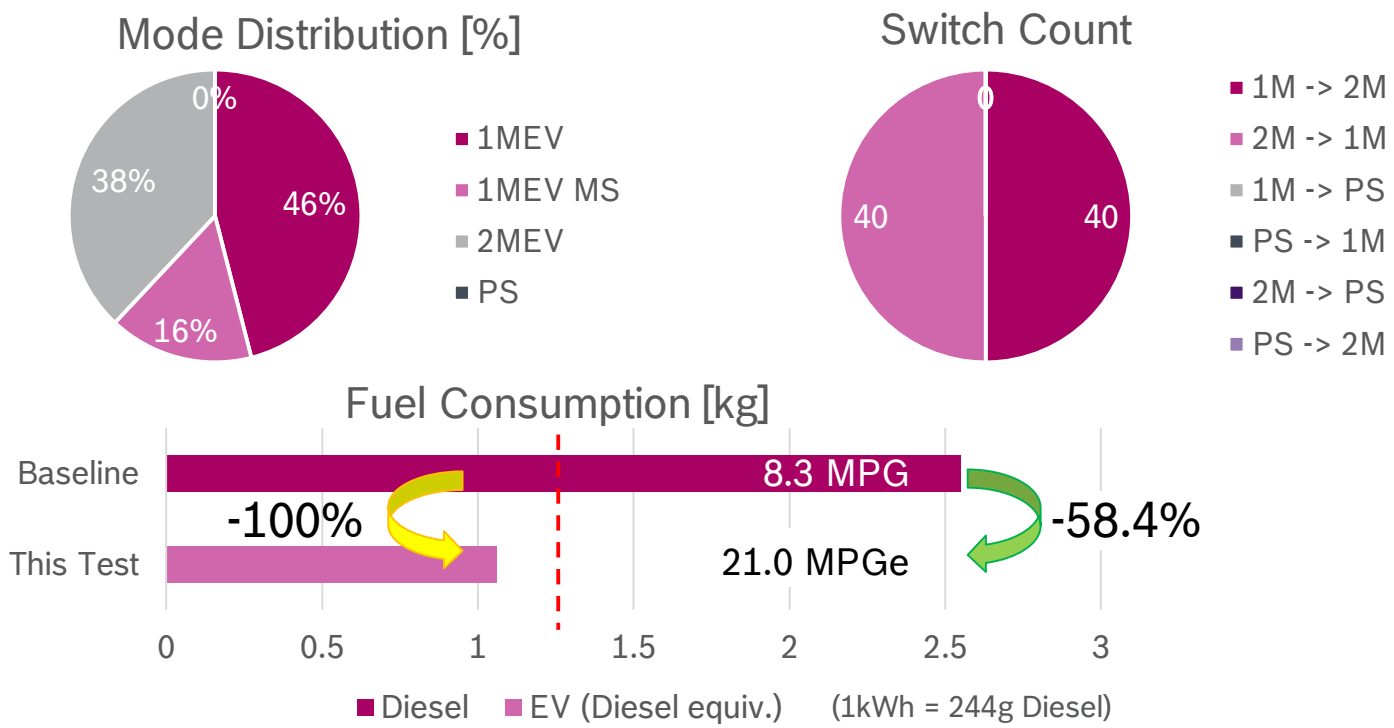
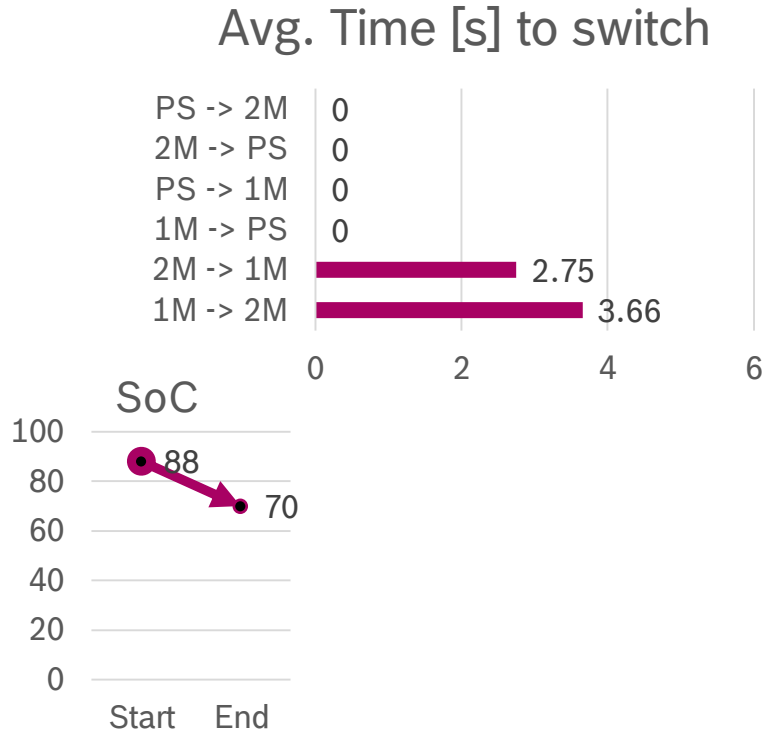
Technical Accomplishments and Progress

- Chassis Dyno Testing: CSHVC in EV Mode only (High SOC)





On this CSHVC chassis dyno test, the PowerSplit PHEV system consumed 4.3 kW-hr of electrical energy, operating 46% of the time in single motor EV mode and 38% of the time in dual motor EV mode. This resulted in a 100% reduction in raw fuel consumed and 58% in diesel equivalent energy consumption (21 MPGe).

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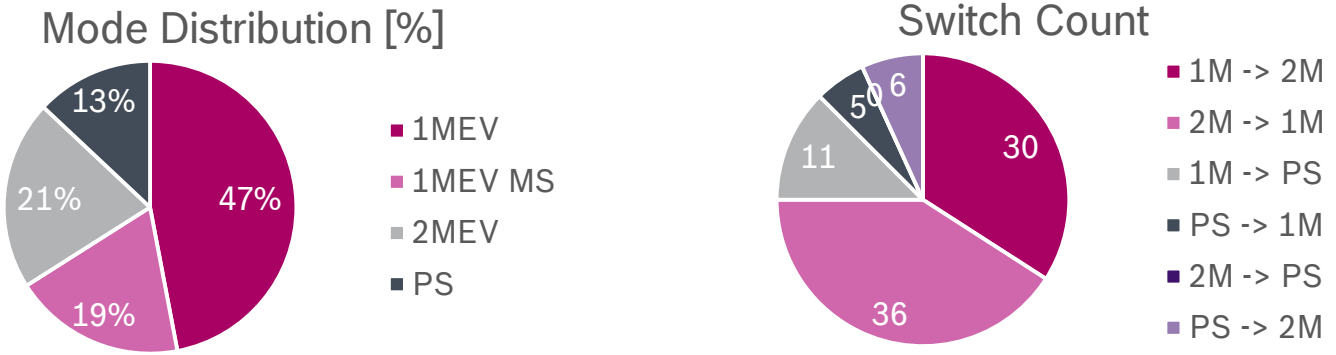
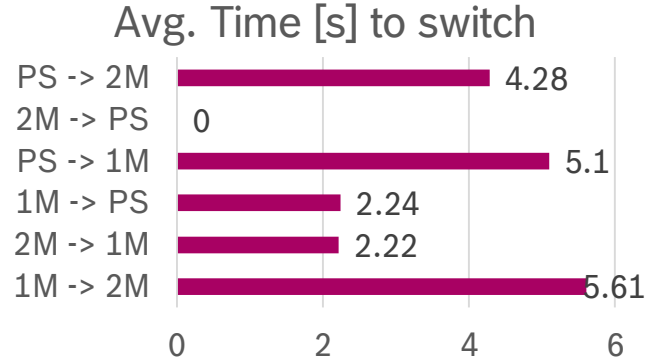
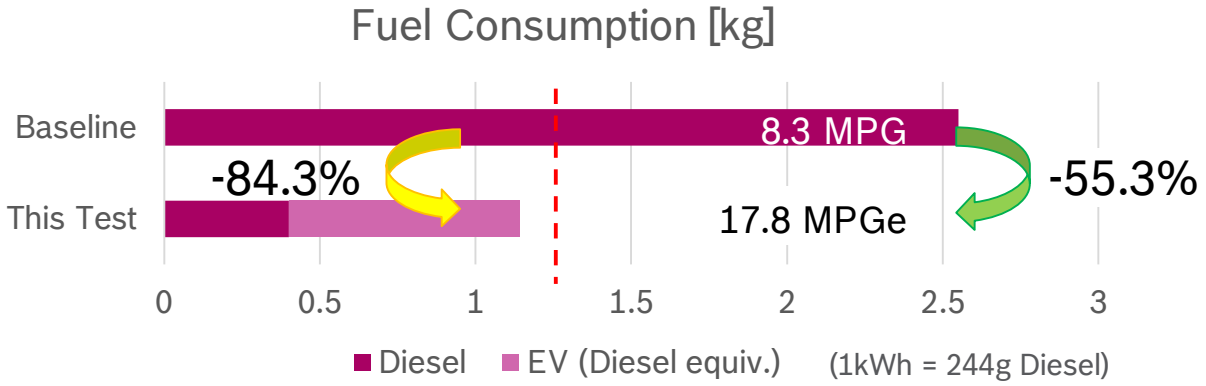
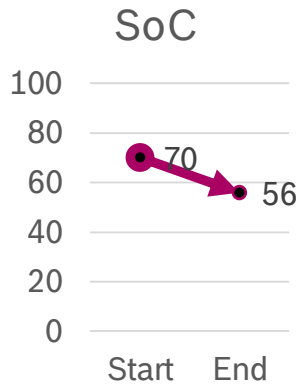
Technical Accomplishments and Progress

- Chassis Dyno Testing: CSHVC in HEV Mode (High to Med SOC)









Note: the longer switch times are due to low trans line pressure, caused by a failed oil temp sensor.

On this CSHVC chassis dyno test, the PowerSplit PHEV system operated 47% of the time in single motor EV mode, 21% of the time in dual motor EV mode, and 13% in Powersplit mode. This resulted in a 84% reduction in raw fuel consumed and 55% in diesel equivalent energy consumption (18 MPGe).

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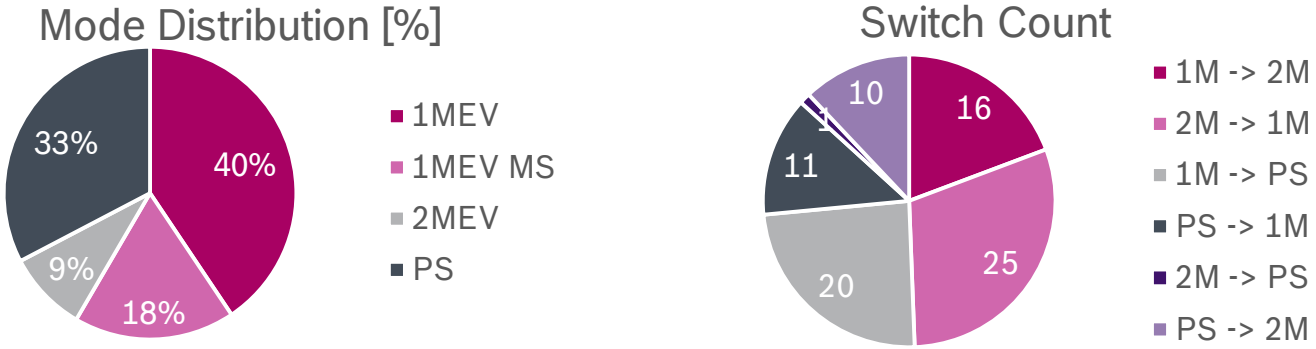
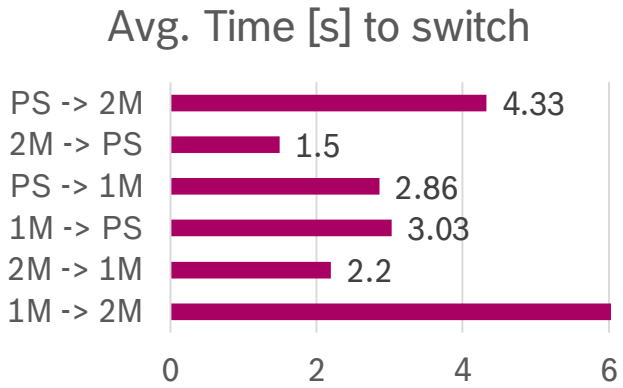
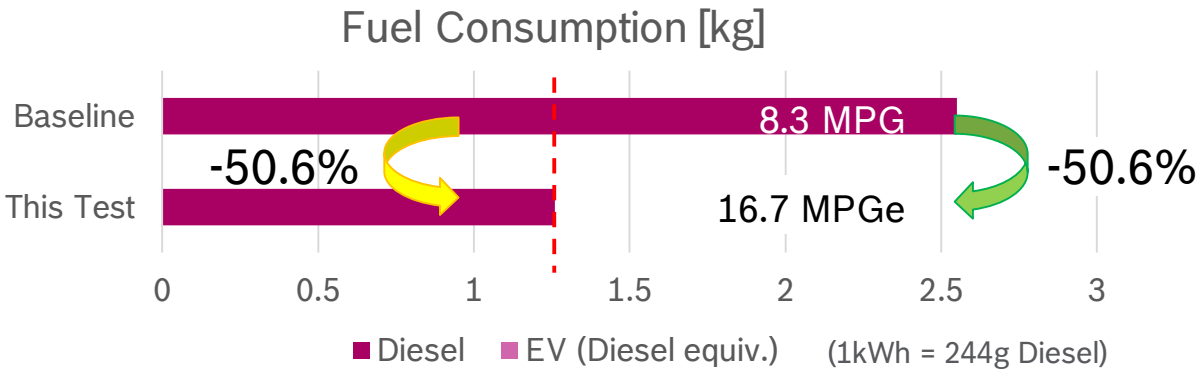
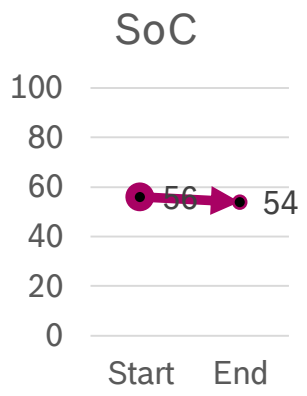
Technical Accomplishments and Progress

- Chassis Dyno Testing: CSHVC in HEV Mode (Med SOC)









Note: the longer switch times are due to low trans line pressure, caused by a failed oil temp sensor.

On this CSHVC chassis dyno test, the PowerSplit PHEV system operated 40% of the time in single motor EV mode, 9% of the time in dual motor EV mode, and 33% in Powersplit mode. This resulted in a 51% reduction in raw fuel consumed and 51% in diesel equivalent energy consumption (16 MPGe).

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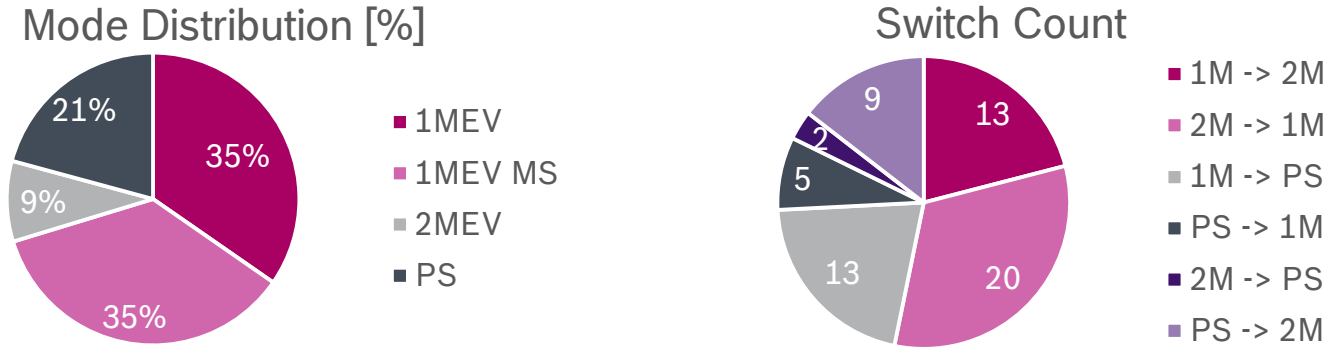
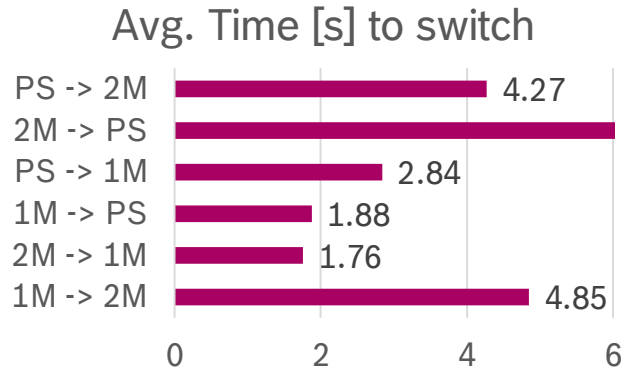
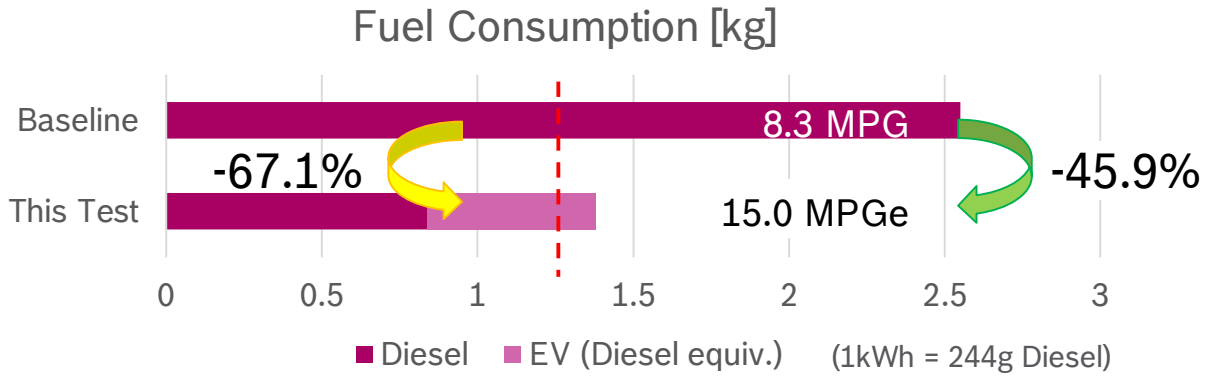
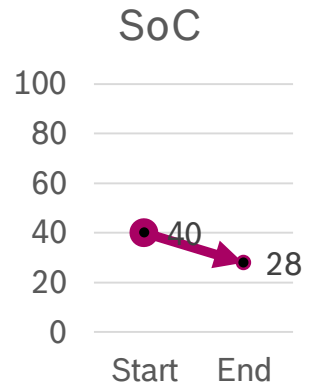
Technical Accomplishments and Progress

- Chassis Dyno Testing: CSHVC in HEV Mode (Med - Low SOC)









Note: the longer switch times are due to low trans line pressure, caused by a failed oil temp sensor.

On this CSHVC chassis dyno test, the PowerSplit PHEV system operated 35% of the time in single motor EV mode, 9% of the time in dual motor EV mode, and 21% in Powersplit mode. This resulted in a 67% reduction in raw fuel consumed and 46% in diesel equivalent energy consumption (15 MPGe).

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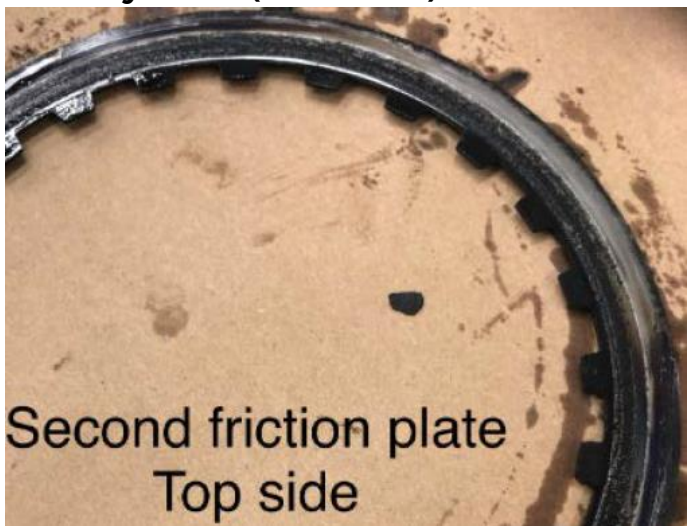
Technical Accomplishments and Progress

- Transmission failure from powertrain dyno, after measuring high speed cycles (HHDDT)



- Transmission SN002, Clutch 1 (Carrier – Carrier rotating clutch) Wear
  - Clutch slip event with electric motor max speed occurred on powertrain dyno during 2nd run of the HHDDT cycle. Subsequent investigation of transmission filter showed clutch like material debris.
  - Transmission returned to Ricardo for tear-down analysis. Premature wear of 1st friction plate was confirmed.
  - Data analysis and expert reviews indicates failure likely caused by engine speed/ torque oscillations

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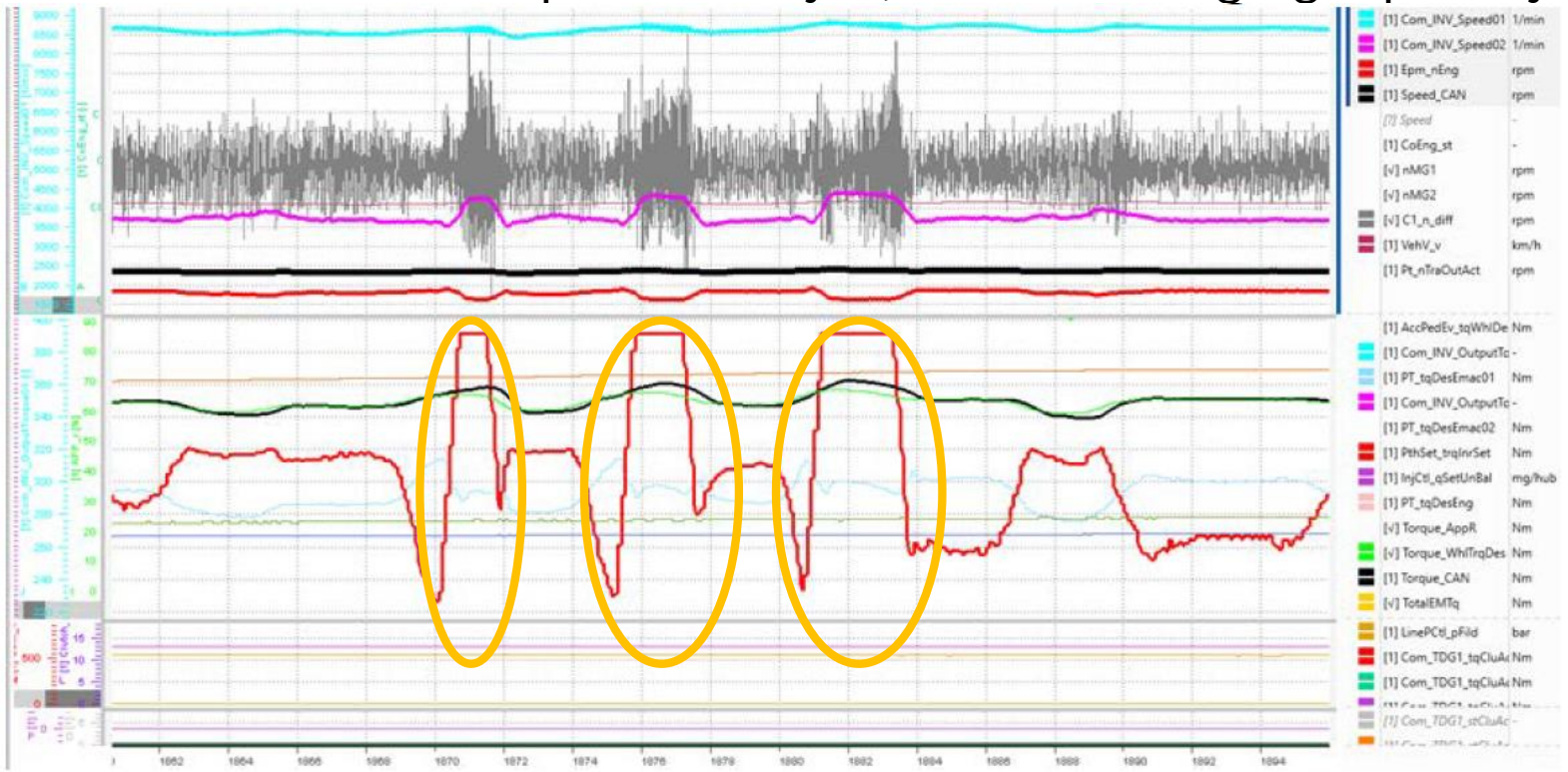
Technical Accomplishments and Progress

- Transmission failure from powertrain dyno, after measuring high speed cycles (HHDDT)



Electric Motor1 Speed

Clutch1 speed differential/ slip monitor

Electric Motor2 Speed

ICE Inner Torque

Dyno Torque/ Trans Output Torque

- SW design flaw causing the ICE torque to vary from min to max in <<1 sec, multiple times during operation at high vehicle speeds, assuming to have caused the premature C1 failure

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Collaboration with Other Institutions

Organization	Role	Responsibilities
Robert Bosch LLC	Project Lead	Technical project management, downsized engine calibration Vehicle calibration, monitoring strategy support DPF regen and SCR dosing strategy calibration Engine ECU SW modifications for PHEV Design, manufacturing, and interface support of electric motors and inverters Powertrain and controls simulation and calibration, electronic horizon calibration Battery management system, powertrain architecture optimization, controls R&D
University of Michigan	Partner	Powertrain architecture optimization, controls R&D
Morgan Olson	Partner	Vehicle integration, vehicle fleet testing, consulting
VOSS Automotive	Partner	Thermal management system design, build, integration
NREL	Partner	Vehicle fuel economy validation, drive-cycle definition, cost-benefit ratio analysis, chassis dynamometer testing, field evaluation
Ricardo	Vendor	Transmission design, manufacturing, and interface support
Freightliner Custom Chassis Corp.	Support	Base chassis information support, including CAD models and wiring diagrams

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Collaboration with Other Institutions

Organization	Role	Responsibilities
ZF	Support/ Vendor	Powertrain testing support (conventional PT w/ 8 sp. Auto trans), Torsional Damper Design and Supply
FCA	Support	Engine interface support, wire harness diagrams
Modine	Vendor	LT Radiator/Cooling System Package Design and Supply AC/Coolant Chiller Supplier
Dare Auto, Inc. (Formerly FZB)	Vendor	Electro-Hydraulic Power Steering System Design and Supply
Brusa/ Metric Mind	Vendor	HV/24V DC/DC Converter Supplier
Currentways	Vendor	On-Board Charger Module Supplier
Sanden	Vendor	HV A/C Compressor Supplier
Sensata	Vendor	AC Temperature and Pressure Sensor Supplier Resettable Crash Sensor Supplier
Kostal	Vendor	Electronic Shifter Module and Technical Support

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Remaining Challenges and Future Research

Key Challenges

- Commercialization plan implementation supported by Tier1 manufacturing partner, OEM, and Fleet Customer(s)
- Road release of a PHEV Powersplit hybrid vehicle w/ prototype transmission, VCU, and TCU software
- Prototype transmission reliability and durability

Future Research

BP3 (June ’19 – June ’20)

- Chassis dyno testing w/ fixed transmission temperature sensor
- Criteria emissions evaluation on powertrain dyno

Not planned within current project

- Private test track testing
- Fleet demonstration on public roads

Any proposed future work is subject to change based on funding levels.”

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Summary

Chassis dyno testing activities to-date indicate that our PHEV architecture w/ a dual planetary gear transmission has met the project objective of >50% fuel consumption reduction on the City Suburban Heavy Vehicle Cycle (CSHVC*), even in charge sustaining mode

Features	Fuel Consumption % Improvement
Baseline Vehicle	-- (8.9 MPG)
Downsized Engine	22% (DP result)
Parallel HEV w/ downsized engine	39% (DP result)
HEV w/ Dual-Planetary Gear Transmission and 3 Clutches	46-55% (Chassis dyno, 15-18 MPGe)
PHEV w/ Dual-Planetary Gear Trans. and 3 Clutches (EV only)	100% (Chassis dyno, 21 MPGe**) 1.54 miles/kW-hr

*CSHVC = City Suburban Heavy Vehicle Cycle
DP = Dynamic Programming (Matlab)

**6.68 miles on CSHVC
244 g diesel fuel/ kW-hr

MEDIUM-DUTY URBAN RANGE EXTENDED CONNECTED POWERTRAIN

THANK YOU! QUESTIONS?

P.I. – Matt Thorington, Principal Engineer, Powertrain Solutions, Commercial Vehicle Electrification

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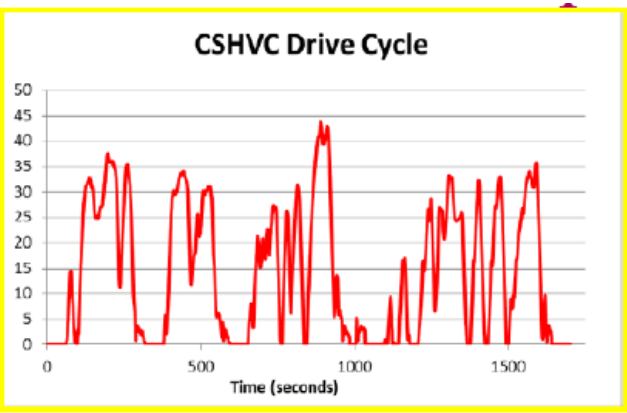
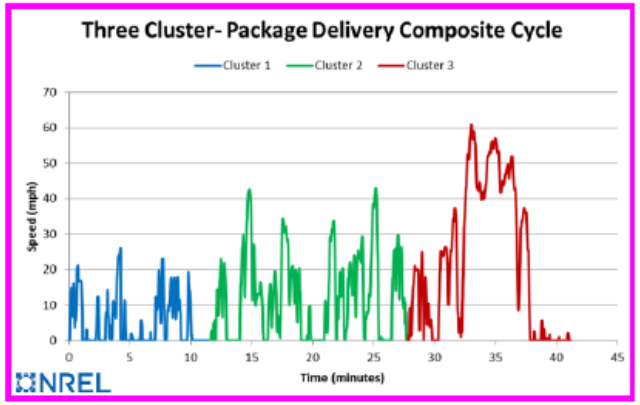
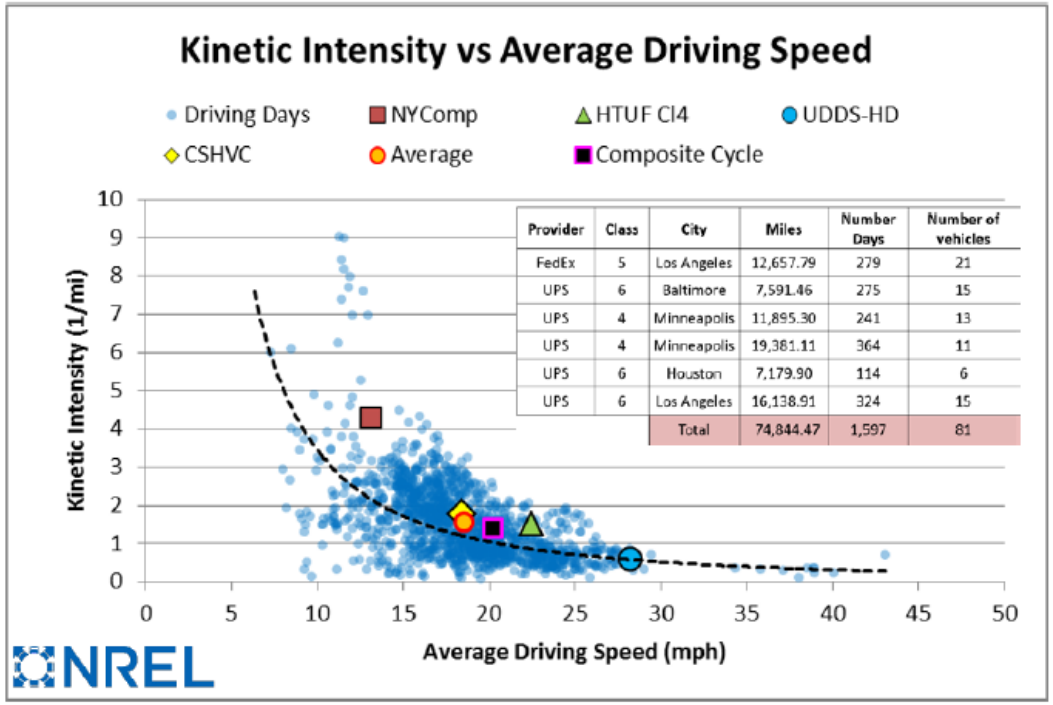
ELT190: MURECP Class4 Delivery PHEV
Technical Backup







Provider	Class	City	Miles	Number Days	Number of vehicles
FedEx	5	Los Angeles	12,657.79	279	21
UPS	6	Baltimore	7,591.46	275	15
UPS	4	Minneapolis	11,895.30	241	13
UPS	4	Minneapolis	19,381.11	364	11
UPS	6	Houston	7,179.90	114	6
UPS	6	Los Angeles	16,138.91	324	15
		Total	74,844.47	1,597	81

Baseline vehicle data from NREL Fleet DNA database. Target drive cycle defined in collaboration with NREL and Morgan Olson

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Technical Backup

System Attributes	Specification
Maximum ICE Input Speed/Torque	4000 RPM/ 600 Nm
Maximum Electric Motor Input Speed/Torque/ Power (Peak)	10000 RPM/ 200 Nm/ 80 kW (each)
Number of Planetary Gearsets	2
Number of clutches/ brakes	1/ 3
Maximum vehicle speed	80 mph
Transmission output maximum torque	1550 Nm
Battery Energy Capacity	48 kW-hr

Protected under provisional patent application for an invention entitled
“MULTI-MODE POWER SPLIT HYBRID TRANSMISSION WITH TWO PLANETARY GEAR MECHANISMS”
U.S. Serial No. 62/564,576, filed September 28, 2017;