MEDIUM-DUTY URBAN RANGE EXTENDED CONNECTED POWERTRAIN

P.I. – Alex Freitag, VP of Engineering, Powertrain Solutions-Commercial Vehicles

Presenter – Matt Thorington, Principal Engineer, Powertrain Solutions, Commercial Vehicle Electrification

Robert Bosch LLC

2019 DOE VTO Annual Merit Review

June 12th, 2019

Project ID #**ELT190 (GI190)**

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

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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 = 73%

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 2018
  - $ 1,767,850
- Funding for FY 2019
  - $413,050 (BP3)

Partners

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

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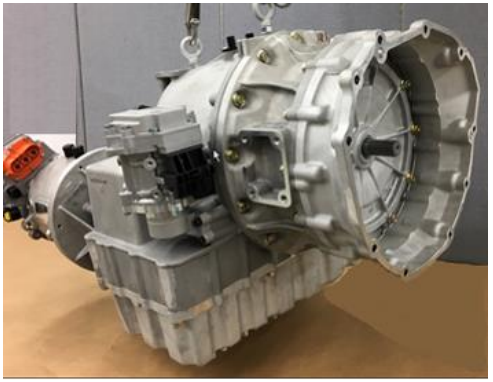
ELT190: MURECP Class4 Delivery PHEV
Relevance/Project Objectives

- 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 May ’18-April ‘19:
  - Receive two functional samples of the hybrid powersplit transmission
  - Conduct steady-state and transient testing of the hybrid system on a powertrain dyno
  - Install tested powertrain into the target chassis
  - Complete vehicle build and perform Go/No-Go #2 Milestone



- Evaluation against Project Barriers
  - **Performance:** current measurements + simulation modeling predicts ~18.5 MPG (~52% fuel consumption reduction) on CSHVC* in charge sustaining mode
    - >15 million gallons of diesel fuel saved per year class 4, >50 million gallons per year class 3-5
  - **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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ELT190: MURECP Class4 Delivery PHEV
Milestones BP2 (FY2018/ 2019)

Milestone	Type	Description	Date	Result
Validated supervisory controller with hybrid configuration	Technical	Supervisory controller validation in GT-SUITE is completed and produces preliminary fuel economy results	10/31/2018 ☑	Rule Based Eng. Optimal Completed- Jan. 2017 Rule Based Sys. Optimal Completed- Aug. 2017 Mode Switch Controller- May 2018 Equivalent Consumption Minimization Strategy- Oct. 2018
Completed 3D CAD model of the final design solution	Technical	Virtual packaging study completed in the vehicle space and installation locations for all new components defined	6/30/2018 ☑	On-going: Morgan Olson has received all component CAD models and begun virtual placement. Initial priority upon thermal system, second upon HV components.
Finalized driveline design	Technical	The hybrid drive system design, integration, and optimization will include an optimum final drive ratio(s)	4/30/2018 ☑	Completed. With large tires (~480mm RR) a 4.78:1 FDR is defined. For smaller/normal tires (~400mm RR) a 3.91:1 FDR is defined.
GEM "certification" via powertrain test procedure	Technical	Powertrain mapping procedure completed with input maps used to generate a GEM vehicle certification CO2 /fuel consumption values	6/15/2019 ☐	Delayed
Rolling chassis operational under its own power	Go/No Go	Class 4 PHEV delivery truck is assembled and basic drive functionality is demonstrated	6/15/2019 ☐	Delayed

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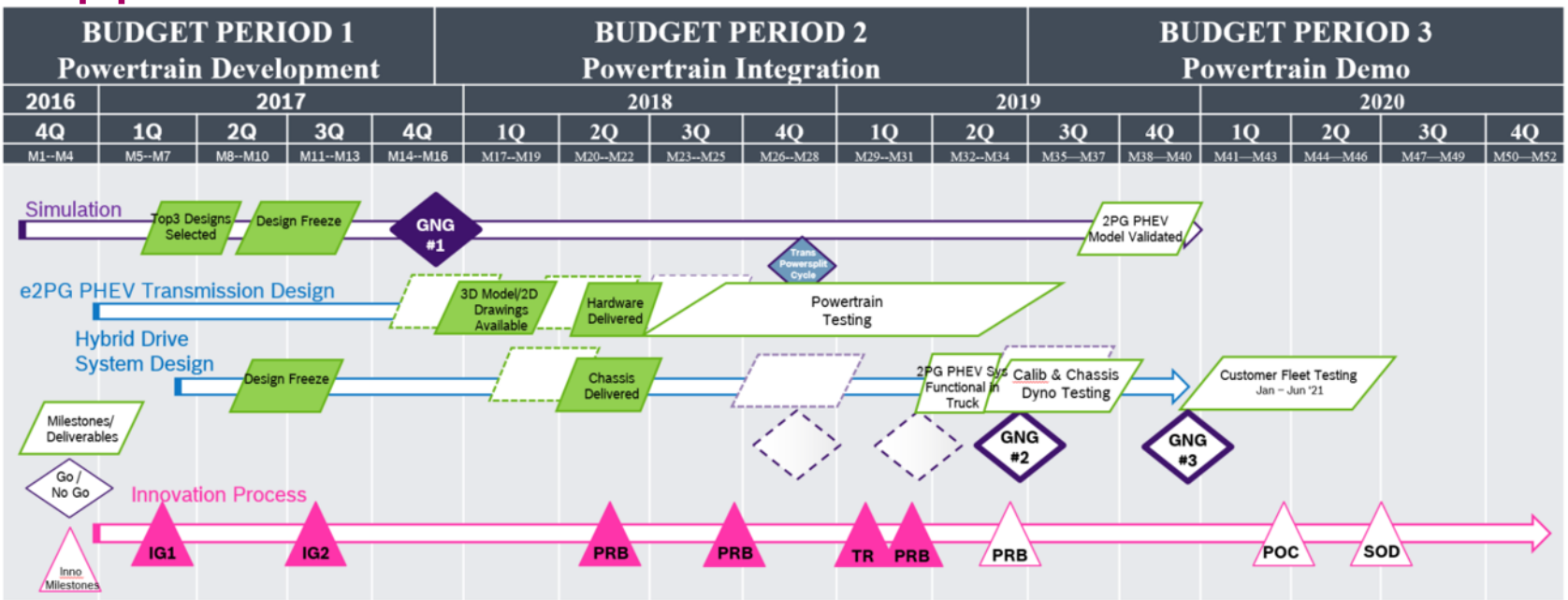
Milestones BP3 (FY2019/ 2020)

Milestone	Type	Description	Date
Steering committee ride-and- drive approval granted	Technical	After powertrain and vehicle calibration work is completed, steering committee will provide ride-and-drive sign-off	12/30/2019 ☐
Completed chassis dynamometer fuel consumption testing	Go/No-Go #3	Chassis Dyno testing at NREL completed to validate achievement of a 50% fuel consumption reduction	12/30/2019 ☐
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	12/30/2019 ☐
In-use fuel consumption determined	Technical	Quantify the fuel consumption reduction during a fleet demonstration of for a real-world driving cycle	6/30/2020 ☐

ELT190: MURECP Class4 Delivery PHEV
Approach- Overview



- BP2 GNG #2 milestone delayed ~6 months due to:
  - HW Delivery delays, mainly transmission samples (SN001 and SN002) and baseline chassis
  - Additional powertrain dyno testing requirements with vehicle powertrain
  - Transmission HW mechanical failures and design recursions
  - Chassis wire harness design, documentation, and build

Road release process critical for customer fleet testing after GNG #3. Product Safety Manager supporting ISO26262 Functional Safety Evaluation

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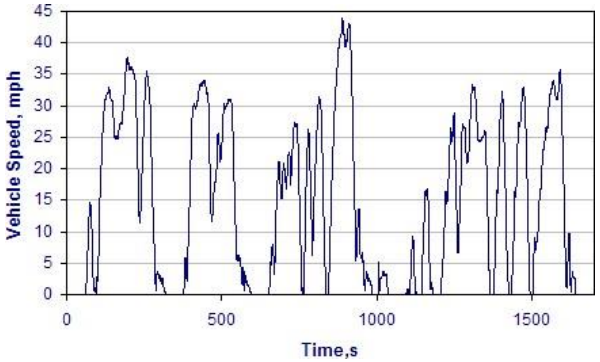
ELT190: MURECP Class4 Delivery PHEV
Technical Accomplishments and Progress

Powertrain Dyno Testing

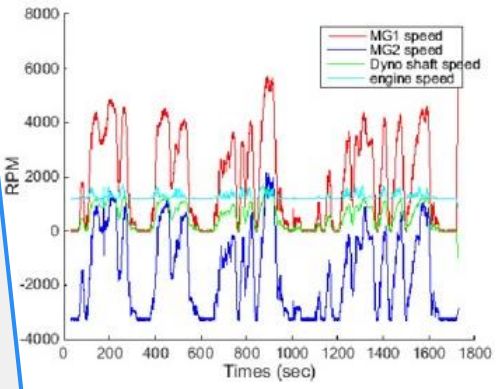
- ❑ CSHVC- City Suburban Heavy Vehicle Cycle

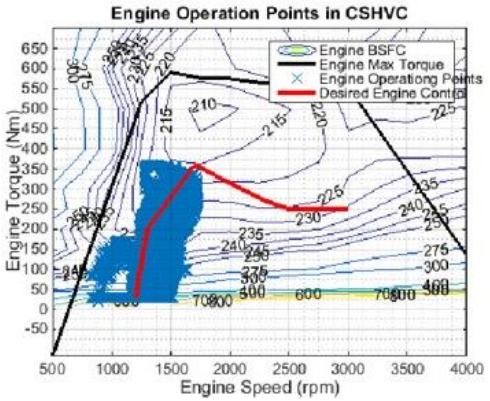


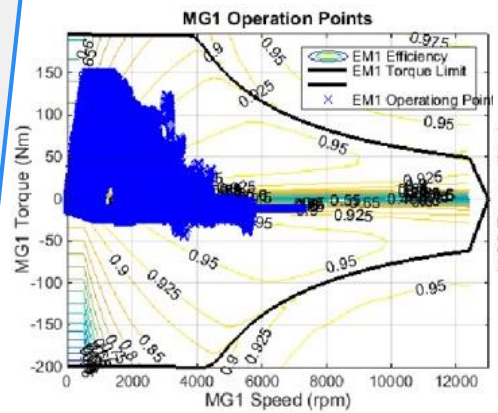
- ❑ Chassis dyno test for HD vehicles
- ❑ Chosen for Class 4 delivery vehicles
- ❑ Total distance: 10.75 km (6.68 mi)
- ❑ Maximum speed: 70.5 km/h (43.8 mph)
- ❑ Average speed: 22.8 km/h (14.2 mph)
- ❑ Fuel Consumption: **1.8 kg** (SOC adj)

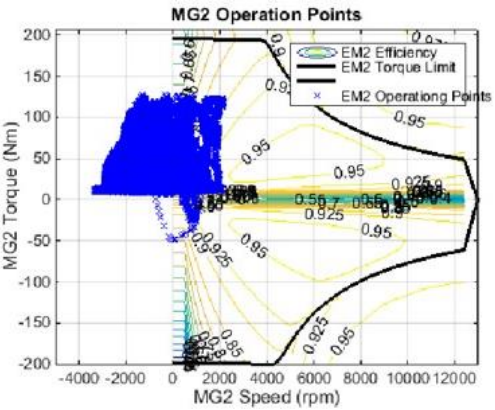
  ~12 MPG (not full potential, see boundary conditions slide 8)

Power Split CSHVC cycle at Powertrain Dyno









Dynamic cycle testing in fixed-mode (Powersplit) completed on powertrain dyno in Nov. 2018, verifying SW and controls development efforts.

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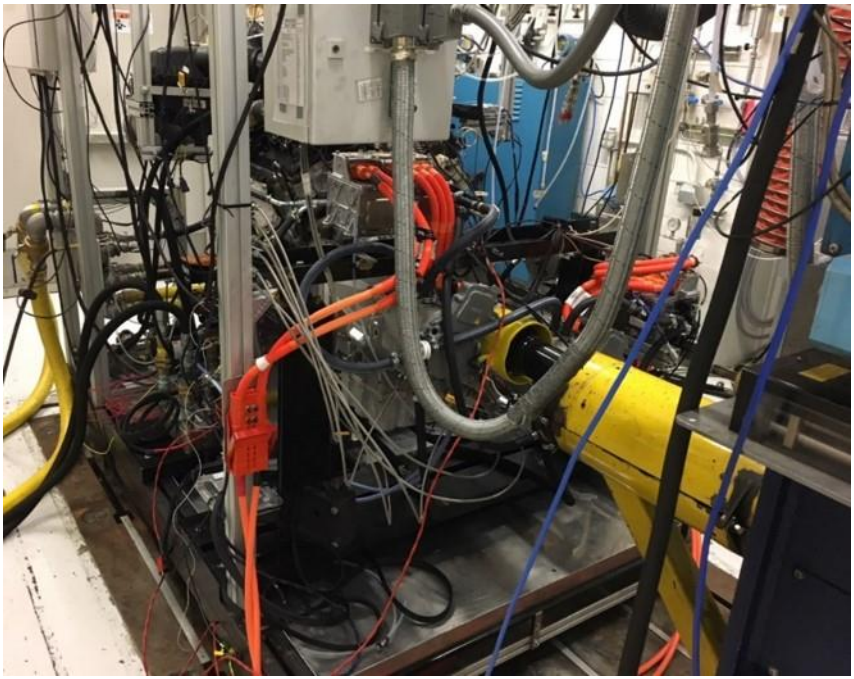
Technical Accomplishments and Progress

Powertrain Dyno Testing

- Due to the maturity of the SW and calibration, the following limitations were in place, limiting the fuel consumption reduction potential (12 MPG vs target >18 MPG)
  - Powertrain operated in power-split mode only (No mode switching)
  - No start/stop functionality included, ICE on during vehicle stand-still and charging the battery
  - Regeneration power limited
  - ICE max speed/ torque limited



Calibration and testing activities to continue with SN002 on Powertrain Dyno in 2019 to demonstrate full fuel consumption reduction benefit with mode-switching (D: 6/15/2019)

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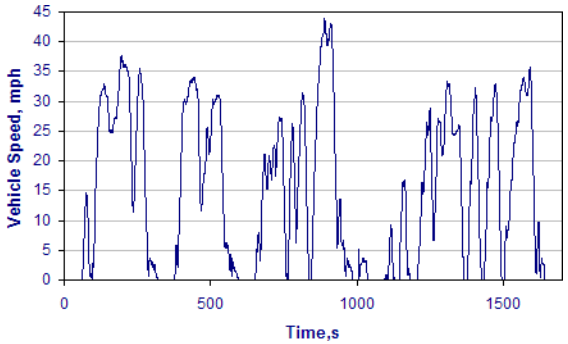
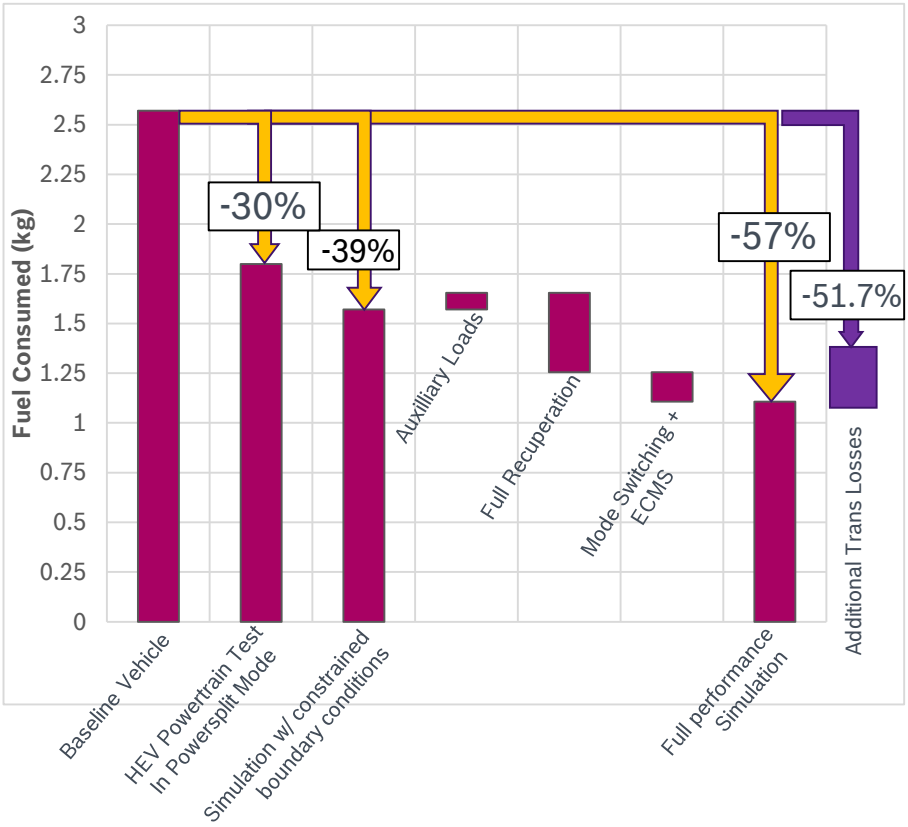
Technical Accomplishments and Progress

Simulation Model Validation

- CSHVC- City Suburban Heavy Vehicle Cycle



- Predicted fuel consumption: 1.1 kg **~19 MPG** in charge-sustaining mode
  - **-57%** fuel consumption reduction
- Due to additional losses within the prototype transmission, updated fuel consumption reduction prediction **~51.7%**



Simulation model validation revealed a 9% higher fuel consumption than predicted

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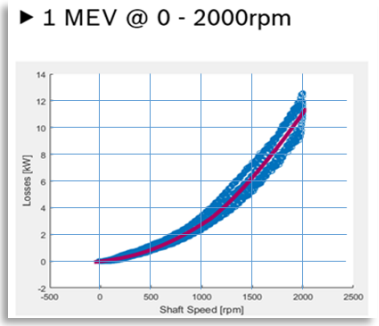
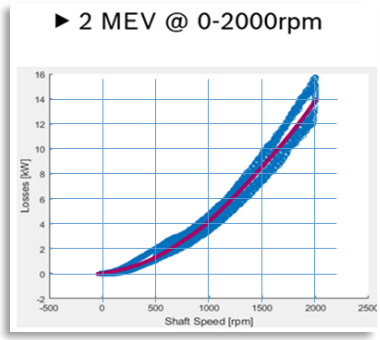
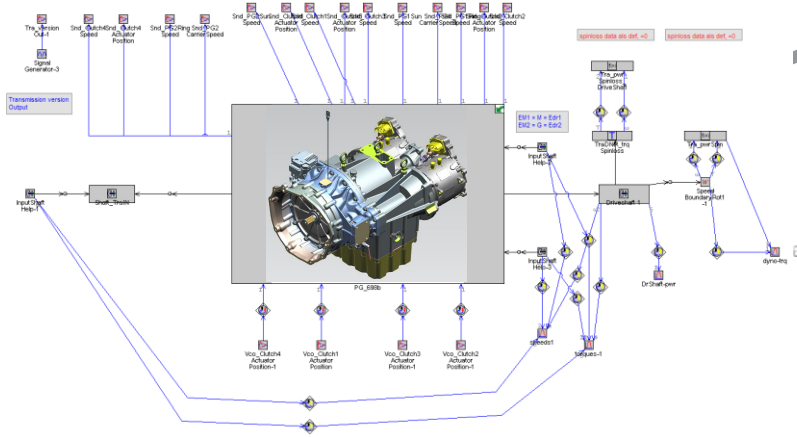
Technical Accomplishments and Progress

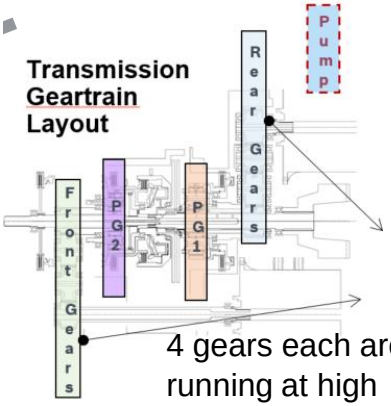
Transmission Loss Investigation

Dyno Measurements









4 gears each are running at high speeds! (high churning losses)

- Using a GT stand-alone transmission model we identified additional speed dependent loss parameters for external gears and mechanical oil pump by comparing vs dyno measurements

The initial transmission loss modeling omitted speed dependent spin losses present even without torque transfer. Mechanical oil pump losses were also higher than expected. Future improvements could include a variable displacement oil pump, reduced system pressure and flows, and geartrain speed reductions.

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Technical Accomplishments and Progress

Transmission Loss Investigation

	AMR Results in 2018		updated transmission losses		updated transmission losses & ECMS		
Drive Cycle	**AMR PHEV Fuel Cons. [g]**	**AMR Fuel Cons. Savings [%]**	**PHEV Fuel Consumption [g]**	**Fuel Saving [%]**	**PHEV Fuel Consumption [g]**	**Fuel Saving [%]**	**Diff. to AMR Saving**
CSHVC	1113	56.7%	1307	49.2%	1240	51.7%	-5.0%
NYCC	463	59.5%	518	54.7%	471	58.8%	-0.7%
HHDDT	5925	25.8%	7217	9.6%	7225	9.5%	-16.3%
HTUF4	2090	59.0%	2425	52.5%	2341	54.1%	-4.9%
UDDS-HD	1135	41.2%	1371	29.0%	1362	29.5%	-11.7%
NREL_Cluster_1	262	69.0%	283	66.4%	265	68.6%	-0.4%
NREL_Cluster_2	702	55.5%	795	49.6%	737	53.3%	-2.2%
NREL_Cluster_3	1081	39.5%	1306	26.9%	1302	27.1%	-12.4%
NREL_Composite	2022	51.5%	2445	41.4%	2312	44.6%	-6.9%
Average		**≈ 51%**		**≈ 42%**		**≈ 44%**	**> - 7%**

Strategy: Start at 25% SOC. Aim to end at 25% SOC. Fuel consumption results correct for any deviation in final SOC vs. target SOC.

*ECMS- Equivalent Consumption Minimization Strategy

Even with higher than anticipated transmission losses, a >50% fuel consumption reduction benefit (in charge sustaining mode) is still possible on the CSHVC!

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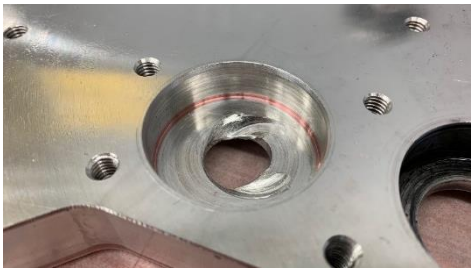
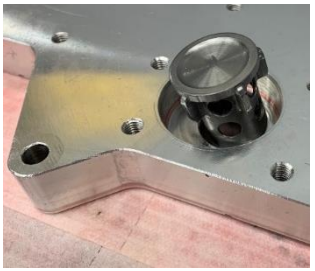
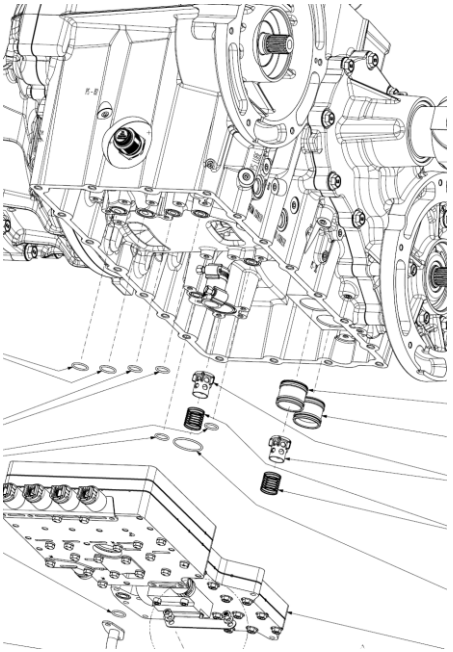
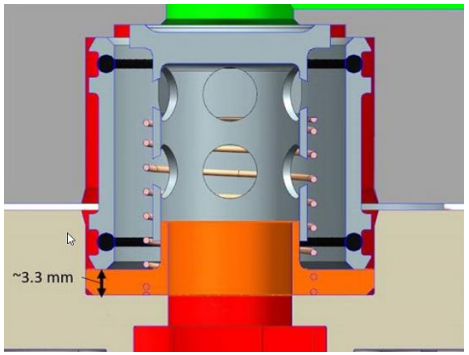
Technical Accomplishments and Progress

Transmission Mechanical Failure Analysis- Valve Body

- Failure Mode: Loss of hydraulic system pressure (SN002 only)

- Implemented fix: Steel washer w/ check valve guidance



SN002 transmission experience valve body wear after minimal run-time (<5 hr). Wear caused by a steel check valve which tilted during operation, gauging out the aluminum seat stop. Fix (orange piece) verified.

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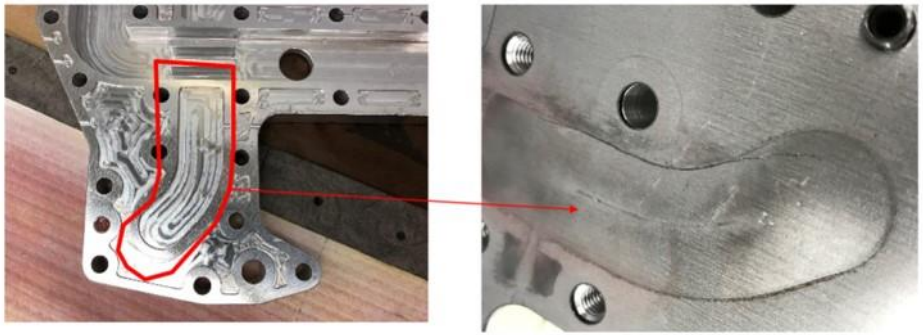
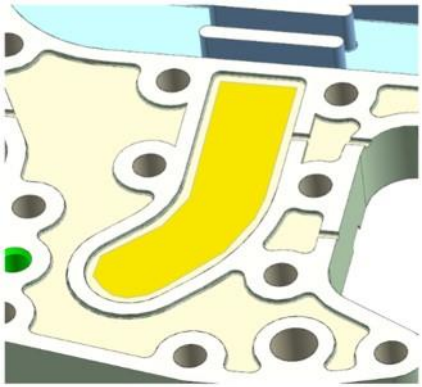
Technical Accomplishments and Progress

Transmission Mechanical Failure Analysis- Separator Plate

- Failure Mode: Cracked separator plate, due to yielding under system pressure without proper support on the valve body-middle part side



- Implemented fix: Aluminum support plate to fill void in valve body- middle part



During inspection of SN001 transmission a cracked separator plate was discovered. Fix is shown in yellow above and has been implemented on both SN001 and SN002 transmissions.

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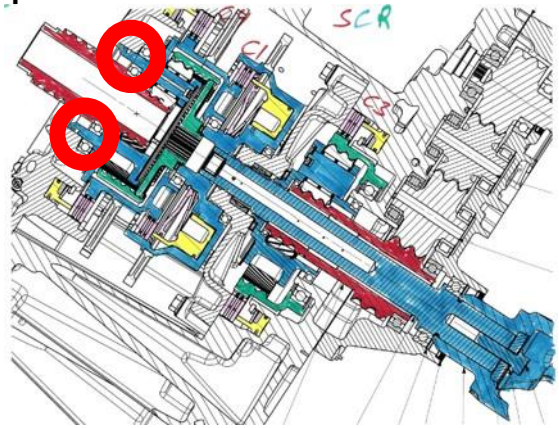
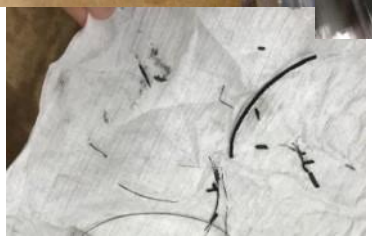
Technical Accomplishments and Progress

Transmission Mechanical Failure Analysis- Seized carrier gear

- Failure Mode: Loss of hydraulic pressure caused by clogged inlet filter
- Root Cause: Seized carrier gear due to galling of aluminum housing pieces onto the steel carrier





- Implemented fix: increase of tolerance gap between carrier and housing with new seal

After the rebuild of SN002, a loss of hydraulic pressure was experienced again, this time accompanied by high friction losses and the inability to free spin electric motor 2. Fix not yet tested.

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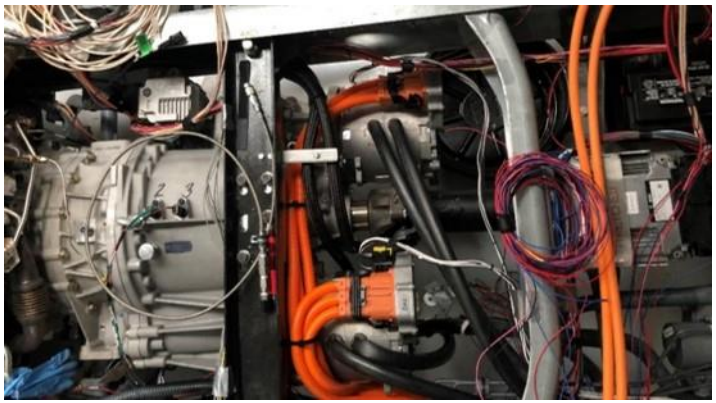
Technical Accomplishments and Progress

Vehicle Build and Testing

Open Items (prior to cab re-installation)- As of April 2019:

1) Wire harness functionality verification and CAN communication checks amongst controllers (VCU, ECU, TDG1, Inverters)
2) Complete wire harness routing (protective looms, mounting clips, etc.)



Vehicle build completion targeted for 4/30/2019. Chassis dyno testing utilizing fixed mode all-electric operation planned by 6/15/2019 (Go/ No-Go #2 Milestone)

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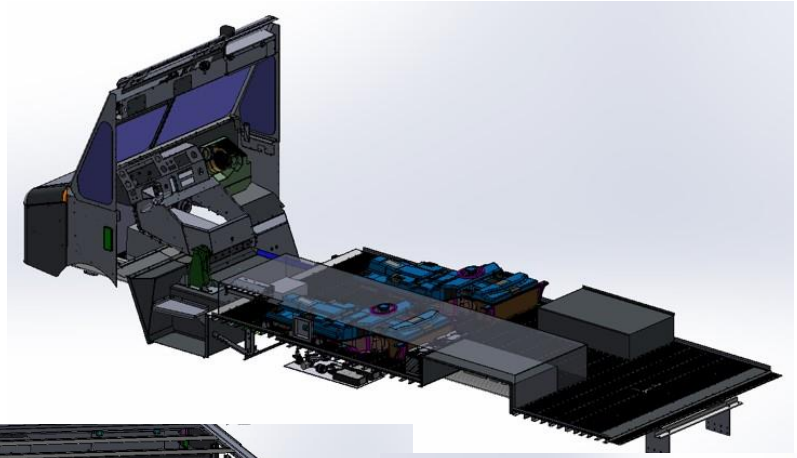
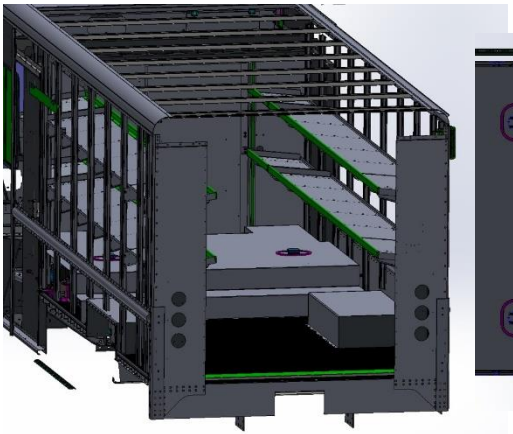
Technical Accomplishments and Progress

Vehicle Build and Testing

1) Install HVPDU in cargo area
2) Install battery packs in cargo area
3) Install multi-pack coordinator and on board charger in cargo area
4) Mount and connect VOSS fluids box and DEF tank
5) Connect and test communication of HV cables and HVIL
6) Conduct spin test (rear axle)





Vehicle build completion targeted for 4/30/2019. Chassis dyno testing utilizing fixed mode all-electric operation planned by 6/15/2019 (Go/ No-Go #2 Milestone)

ELT190: MURECP Class4 Delivery PHEV
Responses to Reviewers' Comments (Top 3)

Reviewer Comments- 2018	Response	Further Action?
6 month customer fleet testing too short	Although the plug-in hybrid electric truck will only be in the end customer hands for 6 months, BOSCH and partners will be operating the vehicle for the 6 months prior, conducting calibration and validation testing. The fuel economy and electrical energy consumption will be closely monitored during this phase also.	None.
Too many collaborators/ ineffective collaboration	The list of collaborators is extensive, however, it includes a lot of component suppliers who have supported the project along the way and deserve to be recognized. Key partners are denoted as such.	None.
Many assumptions that are yet to be proven	Agreed, during the 2018 AMR review the team still had a lot of assumptions to verify, as we had only just received HW to test. Powertrain testing has been underway since 8/2018 with many assumptions proven and/or updated.	None.

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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

ELT190: MURECP Class4 Delivery PHEV
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)
- Calibration and testing of mode switch SW and Controls
- Road release of a PHEV Powersplit hybrid vehicle

Future Research

BP2 (April ’19 – June ’19)

- Mode switch calibration and testing
- Chassis Build & Basic Drive Functionality
- Commercialization Plan

BP3 (June ’19 – June ’20)

- Vehicle calibration
- Chassis Dyno Test
- 6 Month Customer Fleet Testing

ELT190: MURECP Class4 Delivery PHEV

Summary

Simulation and powertrain dyno testing activities to-date indicate that our PHEV architecture w/ a dual planetary gear transmission will meet 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	51.7% (GT result, w/ testing validation)
PHEV w/ Dual-Planetary Gear Trans. and 3 Clutches (EV only)	100% (52.1 MPGe**) 1.38 miles/kW-hr

*CSHVC = City Suburban Heavy Vehicle Cycle
Model Basis: GT-Suite w/ ECMS based controls
DP = Dynamic Programming (Matlab)

**6.68 miles on CSHVC
37.656 kW-h/gallon diesel fuel

Medium-Duty Urban Range Extended Connected Powertrain

THANK YOU! QUESTIONS?

P.I. – Alex Freitag, VP of Engineering, Powertrain Solutions- Commercial Vehicles

Presenter – Matt Thorington, Principal Engineer, Powertrain Solutions, Commercial Vehicle Electrification

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ELT190: MURECP Class4 Delivery PHEV
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;