Development of a Pent-Roof MD Spark-Ignited Natural Gas Engine in an Optimized Hybrid Vehicle System:

SOUTHWEST RESEARCH INSTITUTE®

Mid Project Review, Jan 31, 2023

Chris Chadwell

SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Agenda

- Executive Summary
- Team
- Task Updates
  - Engine Development
  - Hybrid System Development
  - Vehicle Integration
- Remaining Milestones

SwRI Project Team

Project Manager

Scott Sjovall, SwRI Program Manager

Email – scott.sjovall@swri.org / Phone (210) 522-5065

Technical Leads

- Design and Integration Lead

  Dustin Kramer, Principal Engineer

  Email - dustin.kramer@swri.org / Phone - (210) 522-3843

- Engine Development Lead

  Robert Mitchell, SwRI Research Engineer

  Email - robert.mitchel@swri.org / Phone - (210) 522-4651

- Hybrid System Development Lead

  Kevin Jones, SwRI Lead Engineer

  Email – kevin.jones@swri.org / Phone - (210) 522-6070

SwRI Contracts

Maricela Miranda	Contract Specialist Maricela.miranda@swri.org Phone (210) 522-5611

SwRI Project Oversight

Terry Alger	Executive Director Sustainable Energy and Mobility
Chris Hennessy	Director, Design and Development Powertrain Engineering
Chris Chadwell	Director, Automotive Propulsion Systems, Sustainable Energy and Mobility
Michael Kocsis	Manager, Engine Certification and Emissions Development

Executive Summary

Mission

Improve NG Engine and Vehicle Emissions and Efficiency – The objective is to reach an efficiency level similar to that of conventionally fueled vehicles and reduce emissions to near-zero levels with improvements to the natural gas engine as part of a hybrid powertrain, capable of being commercially saleable into a medium- or heavy-duty vehicle

Key program deliverables

- Medium Duty Natural Gas Hybrid Demonstration Vehicle
- 25% reduction in GHG compared to diesel baseline
- 0.02 g/bhp-hr NO_X

Engine Development

Single Cylinder Engine Research

To determine if the requirements of the project could be met, a single-cylinder research engine based on the Isuzu 4HK diesel platform was configured with a bespoke high-tumble, pent-roof cylinder head and converted to run on natural gas.

Key features included on SCE to support test program

- High Tumble Pent Roof Cylinder Head
- Variable valve timing
- Fumigated injection and port injection
- Cooled EGR

Displacement (cc)	1300
Bore (mm)	115
Stroke (mm)	125
Compression Ratio	12.2:1
MAT (°C)	40
Oil temp (°C)	100
Coolant temp (°C)	100
Boost	Electric SC
Exhaust BP	Manual, match to Intake
Valve Timing Control	Intake & Exhaust VVT
Ignition System	High-energy, single strike

SCE Test Results

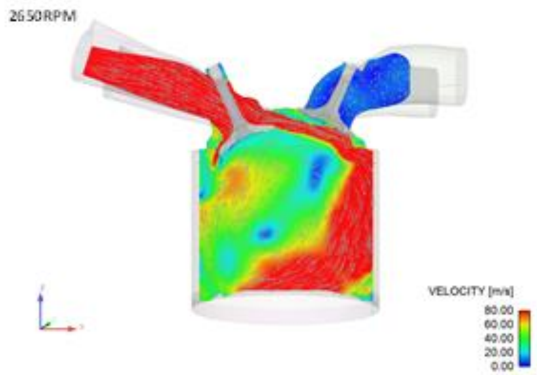
The results indicated that the Gen 2 combustion system would meet the vehicle demonstration requirements

The Gen 2 combustion system reduced the tumble levels with increased valve sizes relative to the Gen 1 system

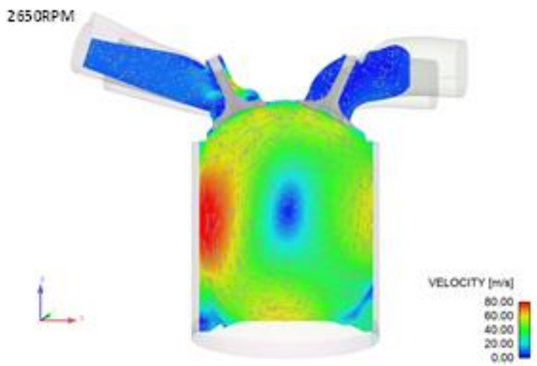
These improvements included:

- Reduction in pumping work of up to 0.1 bar PMEP
- Lower lumped efficiency losses
- Up to 10% higher EGR tolerance

Analysis results were also used to refine modeling efforts for the multi cylinder engine program



VELOCITY CONTOUR AT MAXIMUM VALVE LIFT



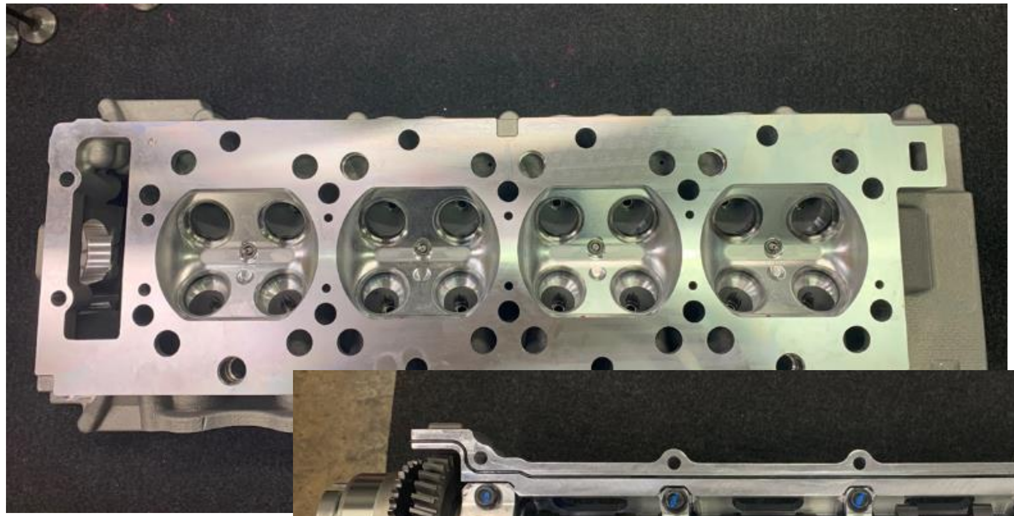
VELOCITY CONTOUR AT INTAKE VALVE CLOSING

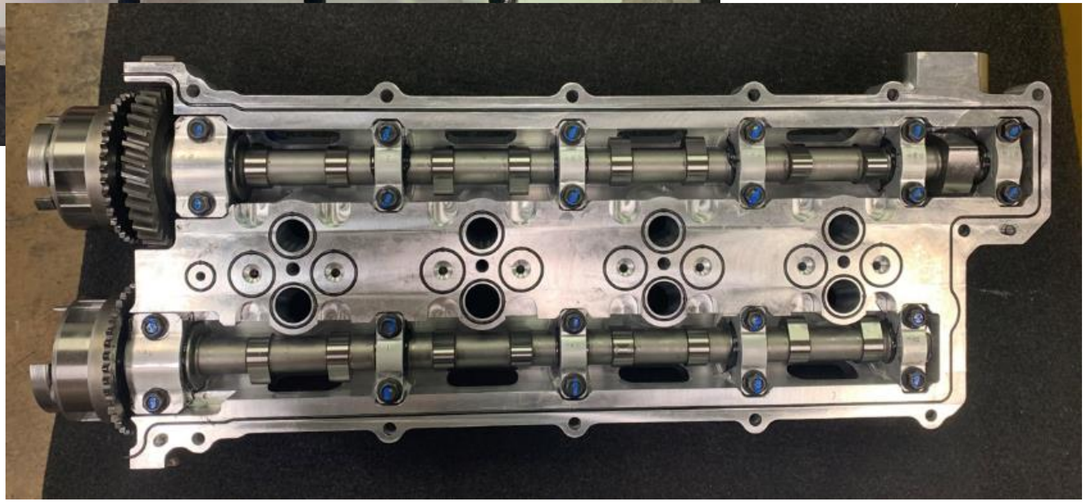
VELOCITY CONTOUR AT SPARK TIMING

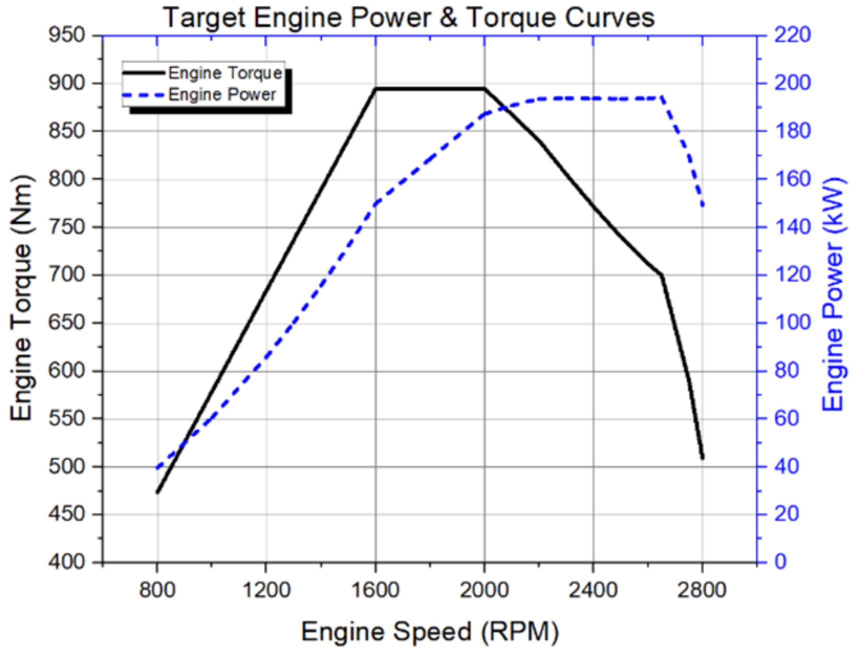
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

MCE Build & Test

- MCE build based on an Isuzu 4HK1 short block assembly
- Component updates based on SCE effort
  - 12:1 compression ratio pistons with custom designed connecting rods
  - New high tumble pent roof, four valve cylinder head
  - Dual cam carrier assembly
  - New intake and exhaust manifolds
  - Woodward ECU (OH6), EGR and fuel system
- Initial performance validation results
  - Target engine torque curve achieved (260/660)
  - Peak thermal efficiency (BTE) of 40% achieved

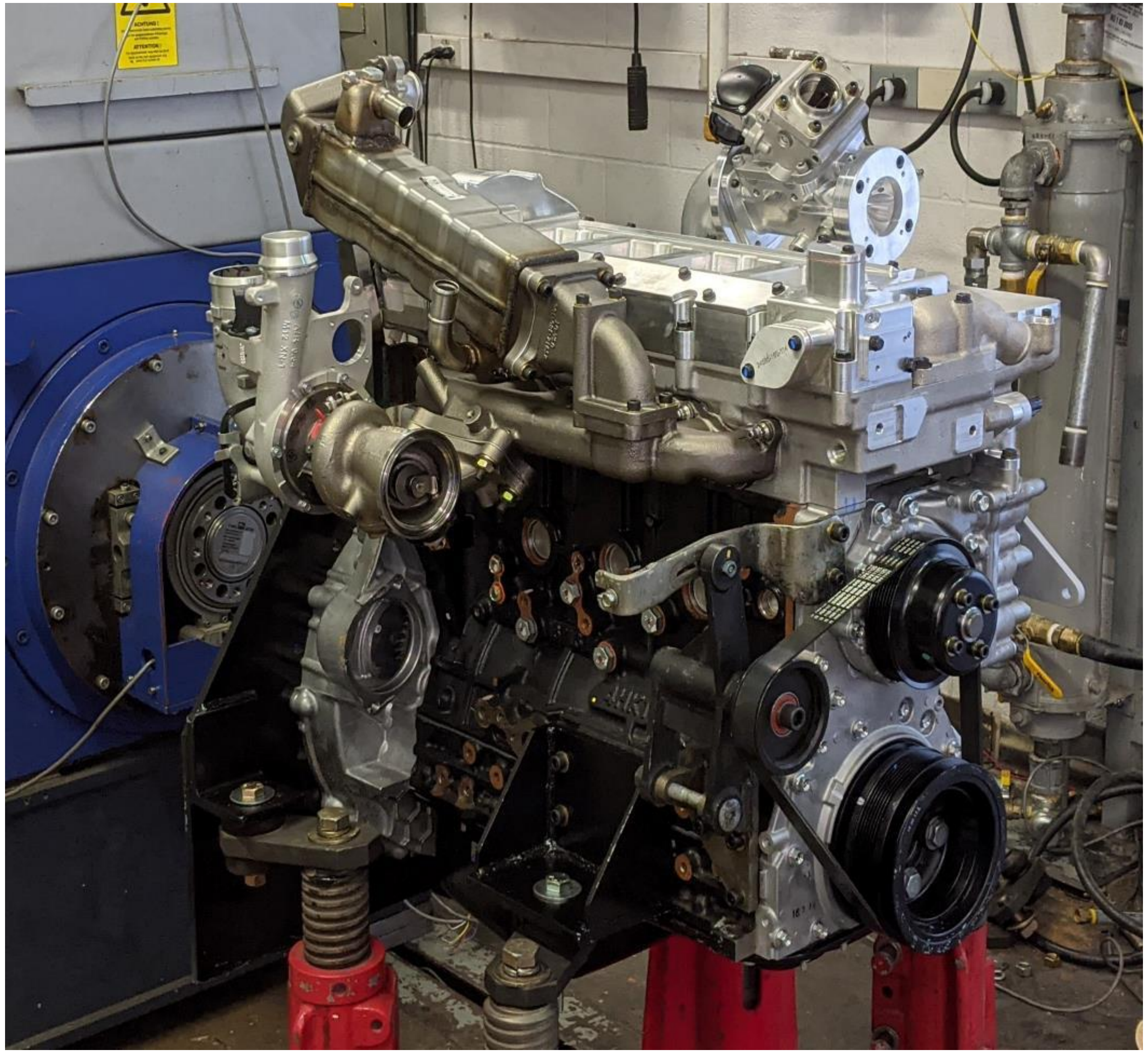


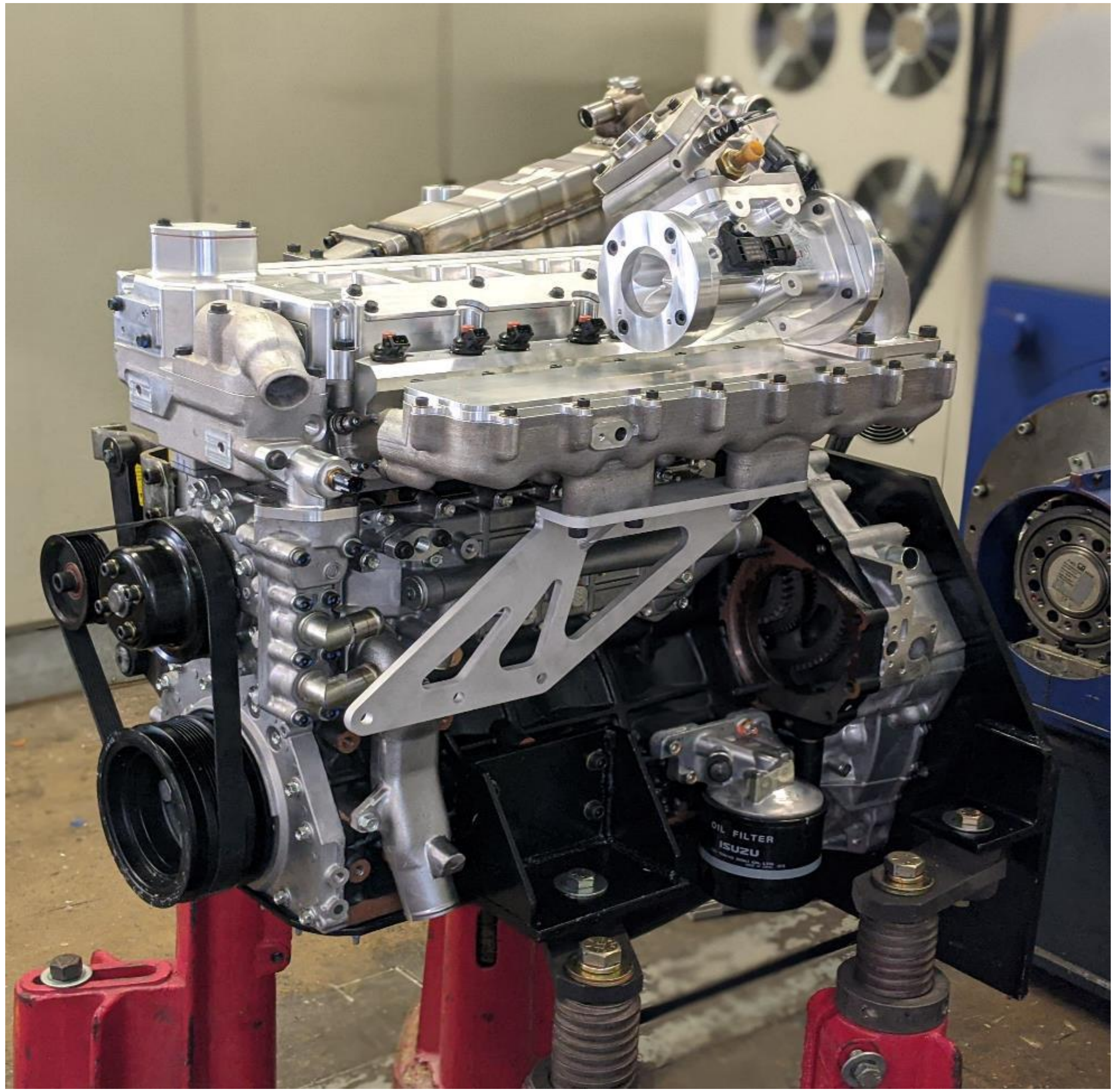




SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

MCE - Fully Assembled Engine

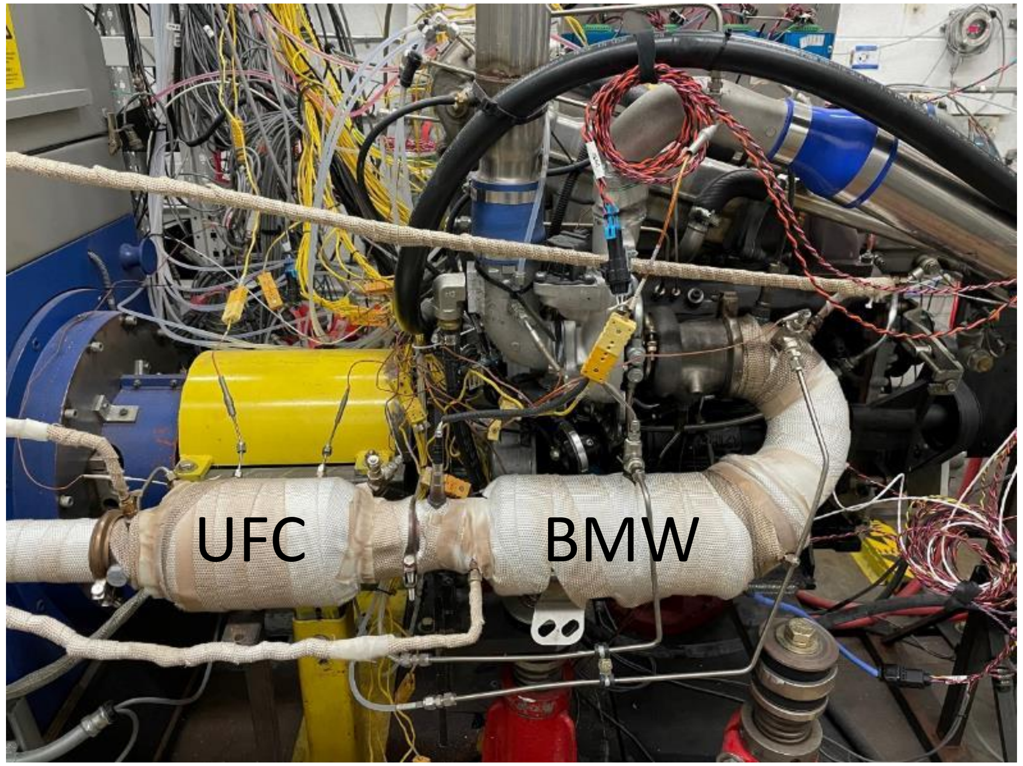




SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

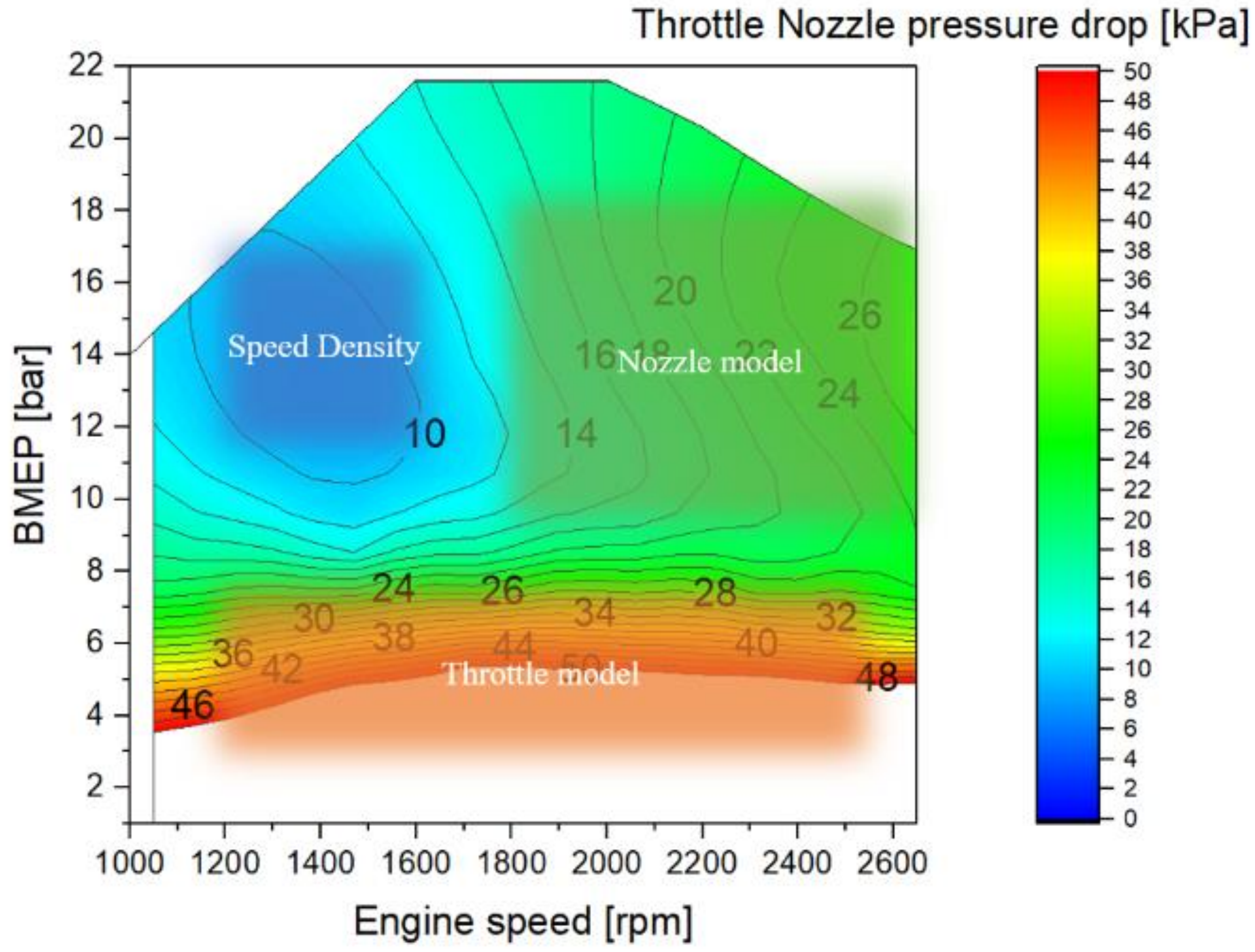
Catalyst System

- A BMW X7 xDrive 40i production catalyst was utilized
  - Time and cost constraints precluded a custom catalyst for this demonstrator
  - The BMW unit included close coupled (CCC) and an under-floor catalyst (UFC) blocks
- An additional custom UFC was utilized downstream of the BMW catalyst to obtain capacity needed for this application
- Relatively inexpensive gasoline catalyst system



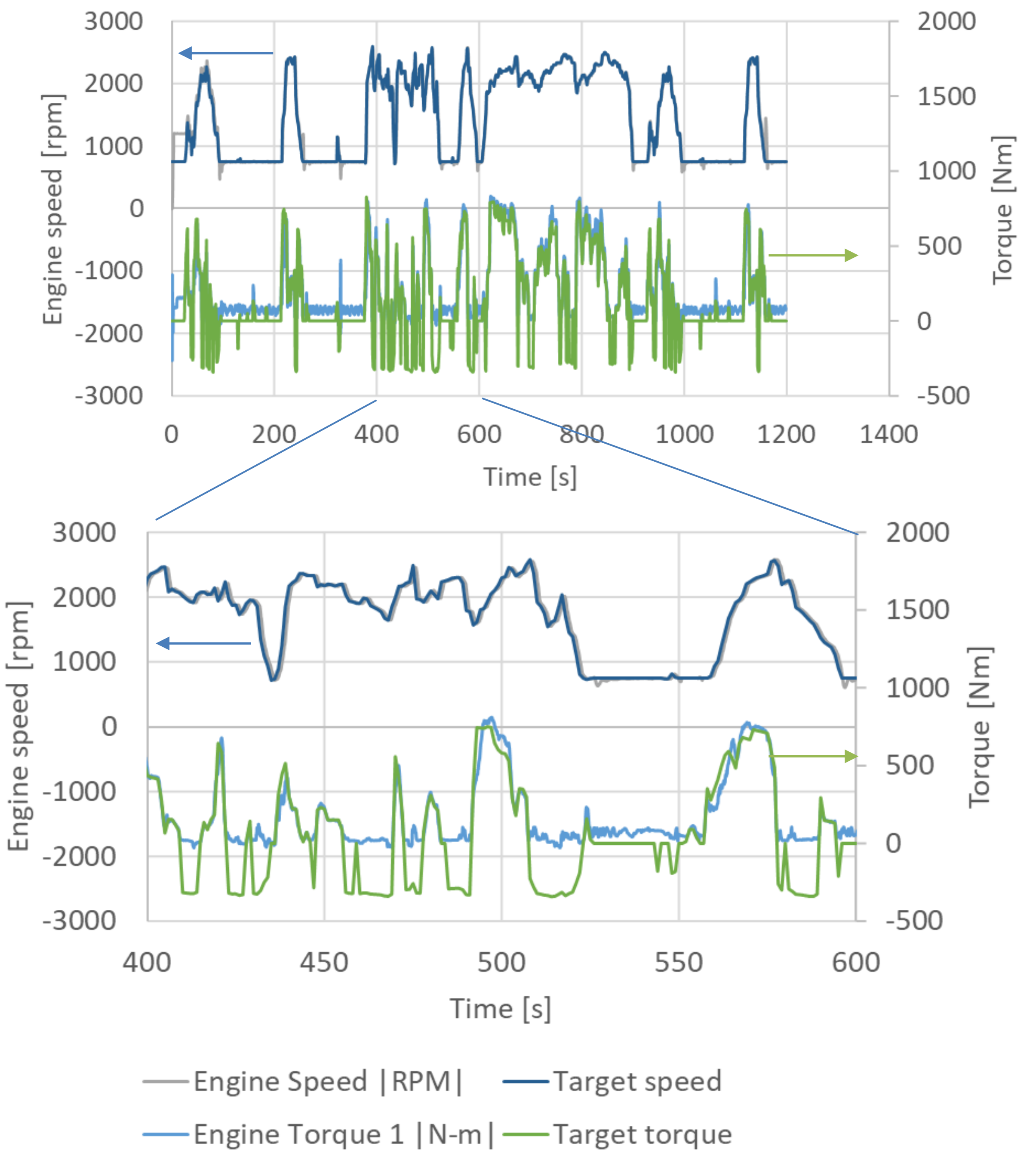
Steady State Calibration for Emissions

- The Woodward EGR module is designed to meet the 0.02 g/bhp-h NO_x emissions targets by measuring the airflow in the same location as the fuel is injected so there is no lag in fueling
  - This mitigates deviations from stoichiometric during transients
- The pressure drop across either the throttle or nozzle is used to calculate air flow
- At high torque low speeds where the pressure drop across the nozzle is too low for accurate estimation, the model reverts to a speed density calculation
- The nozzle size was selected to minimize the use of the speed density model but also minimize the overall pumping losses



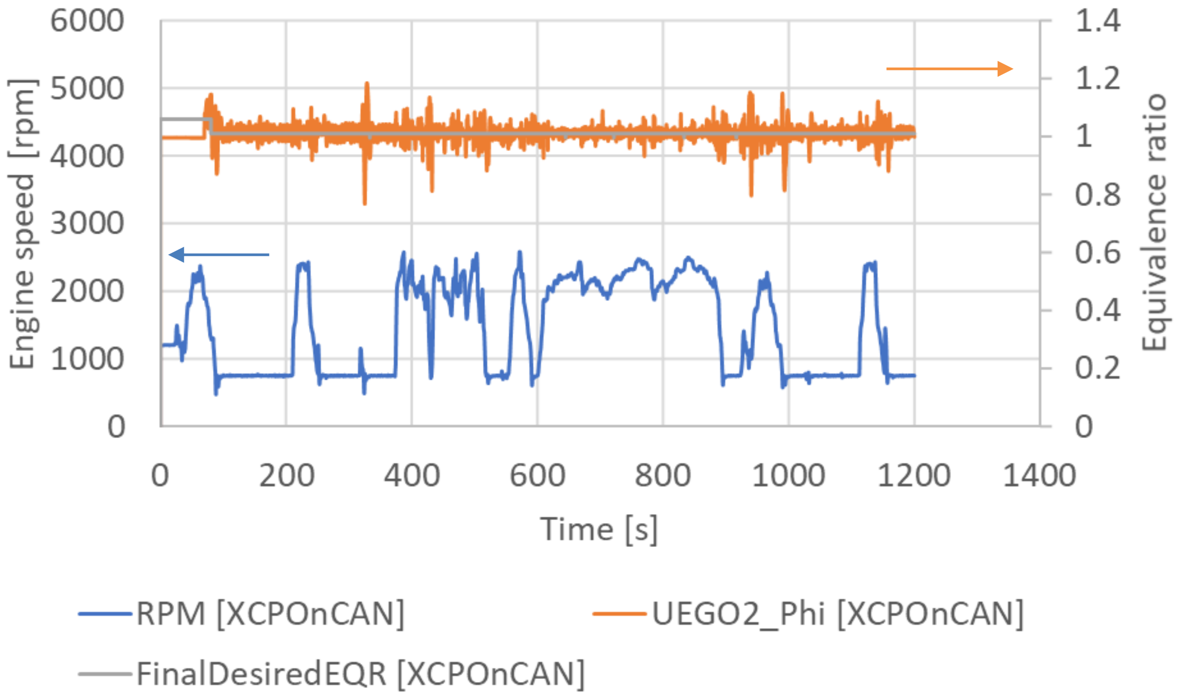
Transient Cycle Performance

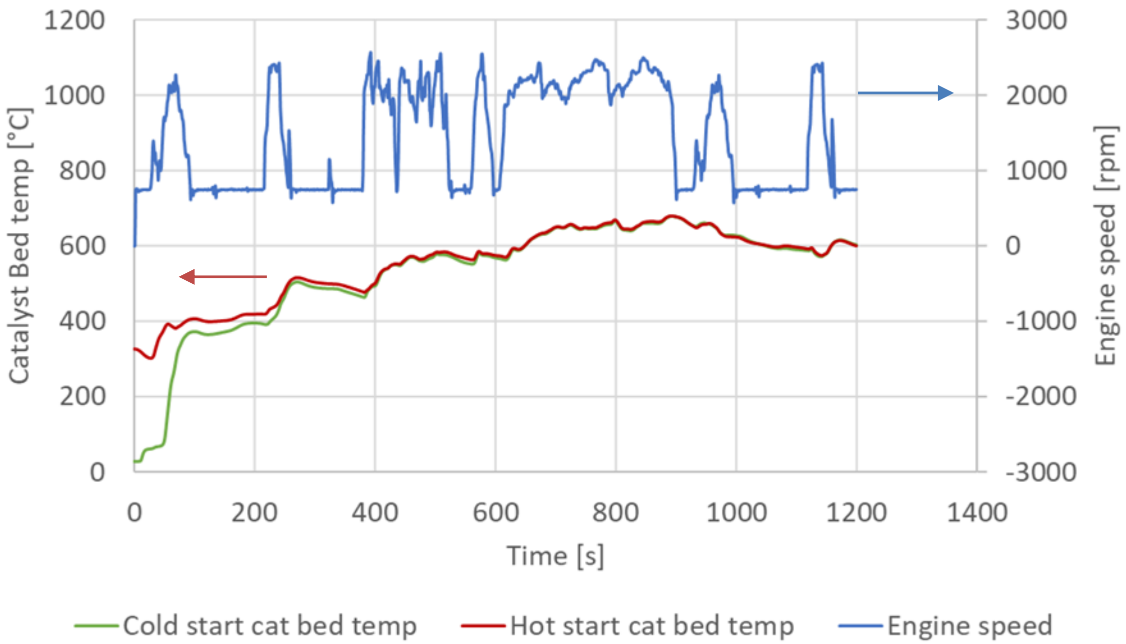
- The engine was tested over the Diesel HD FTP cycle
  - The engine was able to follow the cycle
- The target torque at idle is 0 Nm
  - The actual engine idles at a 20 Nm offset to represent auxiliaries
  - The engine was calibrated without fuel shut-off
    - Additional calibration effort would enable this and provide more fuel savings



Transient Control Strategies

- The ECU was calibrated to use cold start strategies including:
  - High idle at 1200 rpm
  - Phi offset of 0.005 rich
  - Spark retard
- Equivalence ratio control during cycle was held tight by the EGR module
  - Fuel is injected at the same location as the air flow is measured

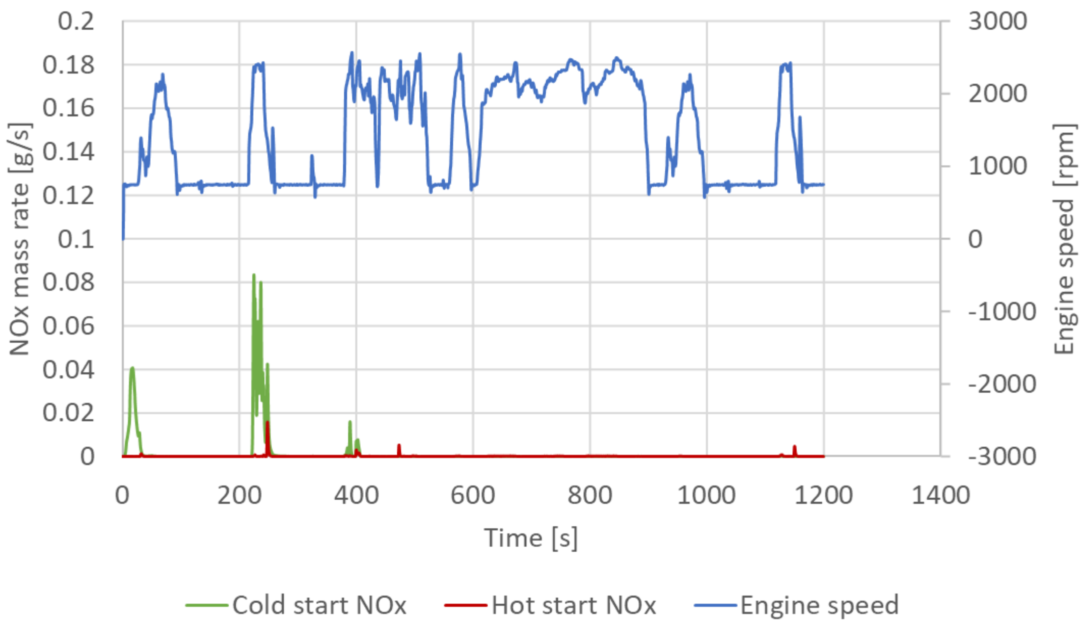


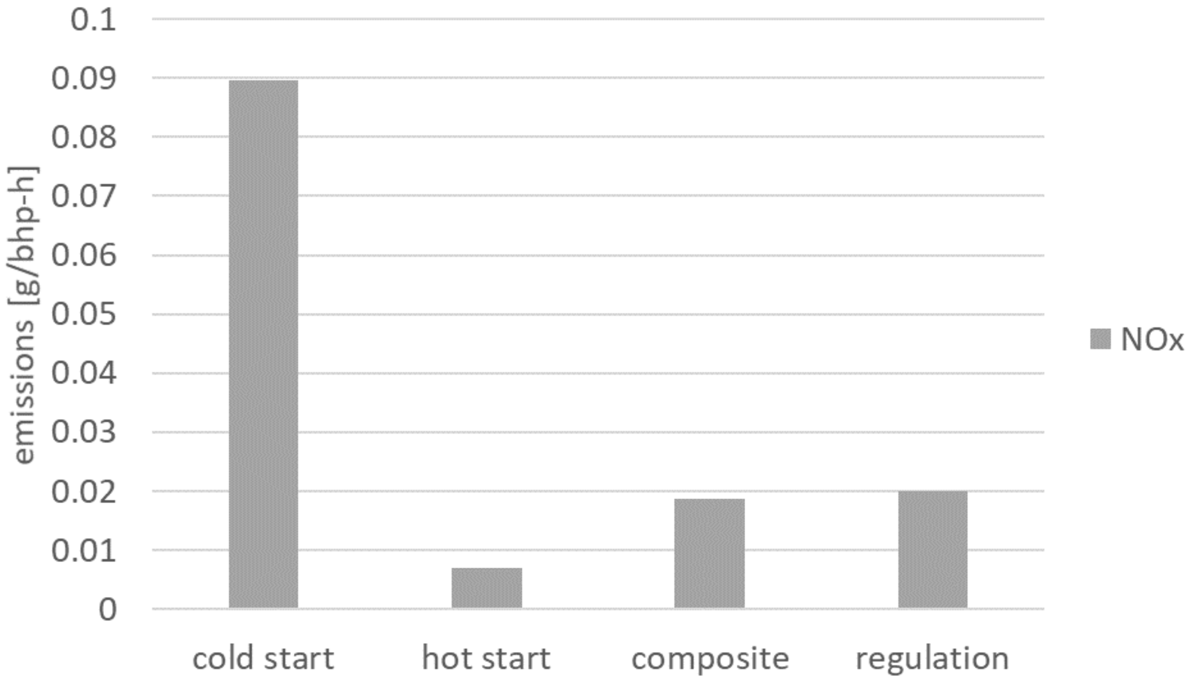


Transient Cycle Emissions Performance

- NO_x was able to meet 0.02 g/bhp-h
- CO_2 meets targets out to 2027 including CH_4 trading
  - 34g of CO_2 for each gram of CH_4 above the limit
- All pollutant emissions meet the current regulations
- Ammonia and PM were not measured but are expected to meet regulations

Emissions standards in g/bhp-h	NO_x	CO	NMHC	CO_2	CH_4
Composite tailpipe emissions	0.018	1.133	0.022	517	0.1
US 2015 Standard	0.02	15.5	0.14	600 (545 in 2021, 535 in 2027)	0.1

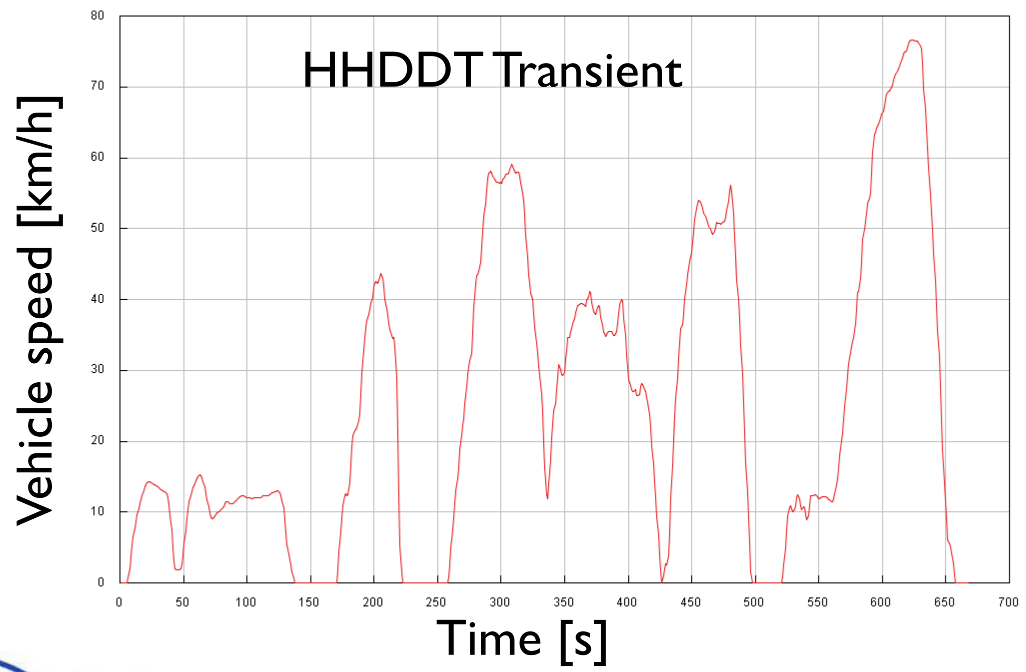


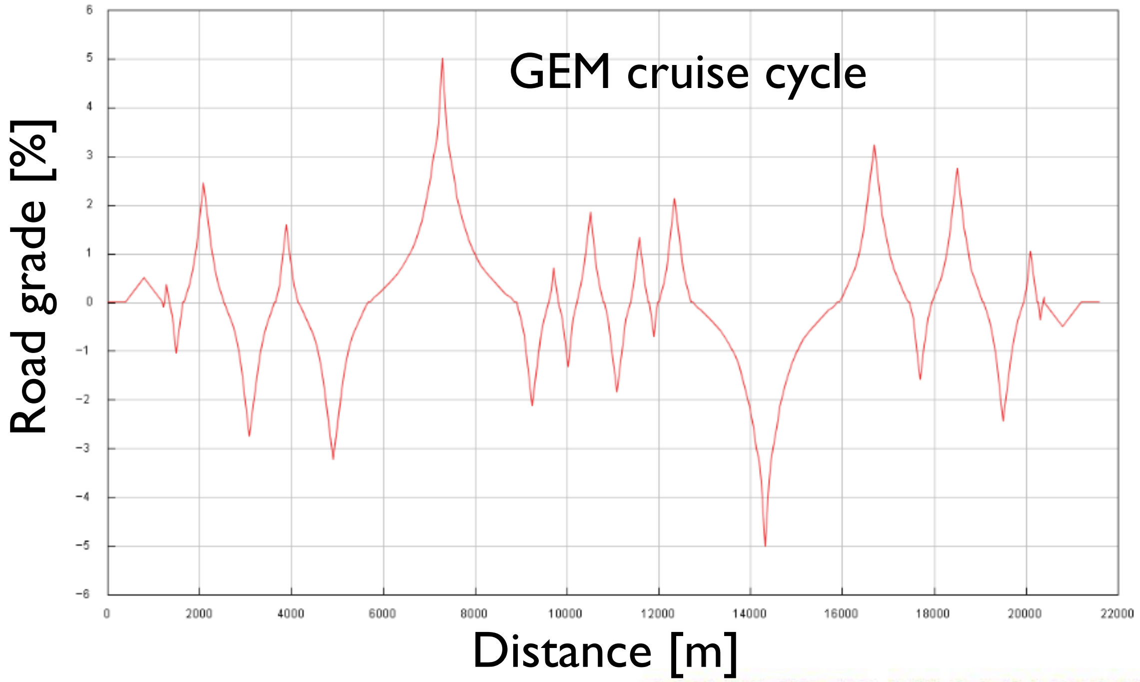


GEM Transient Cycles

- GEM uses three drive cycles
  - ARB transient
  - GEM cruise cycle at 55 mph and 65 mph with varying road grade
  - These three cycles add to a 100% weight that is the non-idle cycle weighting
  - There are 8 configurations of drive axle and rolling resistance
  - Start stop reduces drive idle emissions by 90%
- Vocational has three subcategories
  - Regional is weighted for more cruise driving
  - Urban is weighted for transient driving

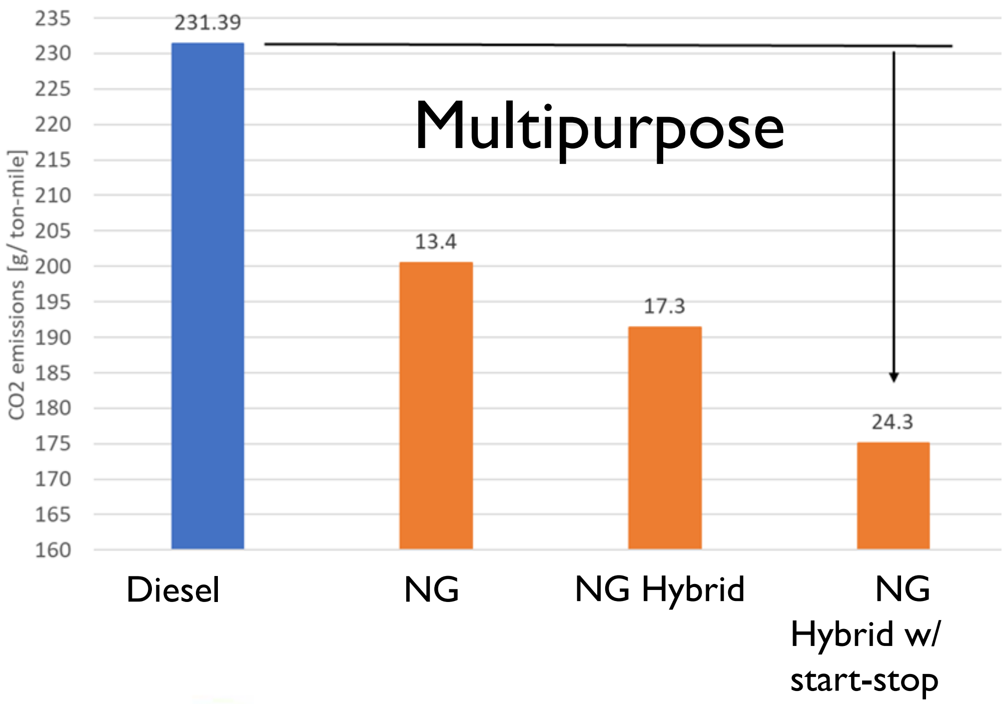
Regulatory Subcategory	MHD		
Duty Cycle	Regional	Multi-Purpose	Urban
Total weight (kg)	11408		
Aerodynamic Drag Area - CdA (m^2)	5.40		
Payload (tons)	5.60		
Electrical Accessory Power (W)	900		
Mechanical Accessory Power (W)	1600		
ARB Transient Drive Cycle Weighting	0.20	0.54	0.92
GEM 55 mph Drive Cycle Weighting	0.24	0.29	0.08
GEM 65 mph Drive Cycle Weighting	0.56	0.17	0.00
Parked Idle Cycle Weighting	0.25	0.25	0.25
Drive Idle Cycle Weighting	0.00	0.17	0.15
Non-Idle Cycle Weighting	0.75	0.58	0.60

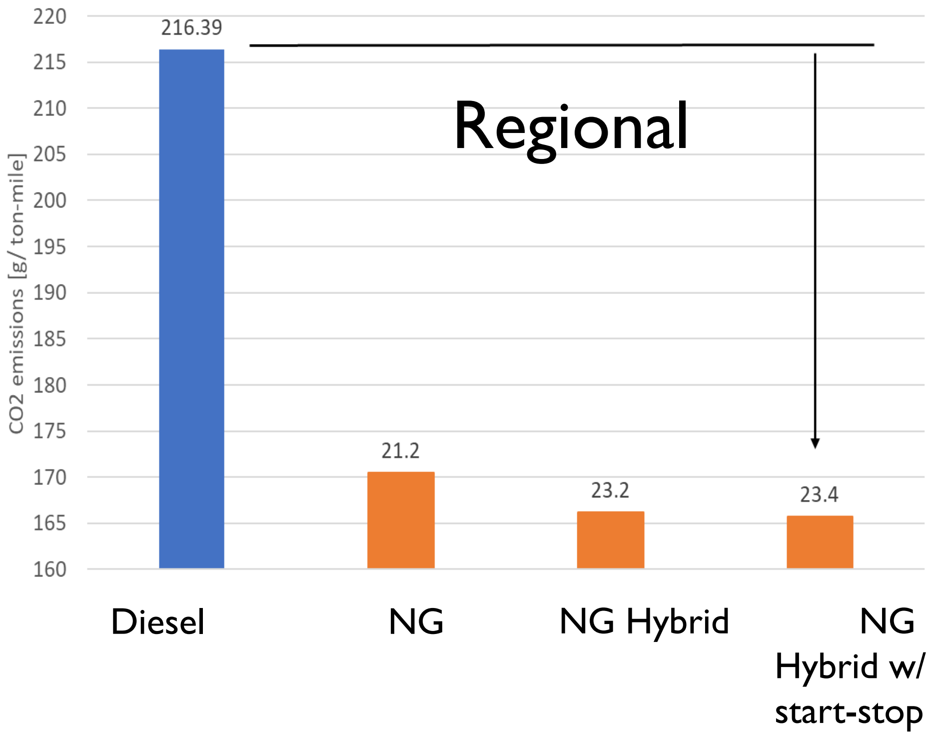


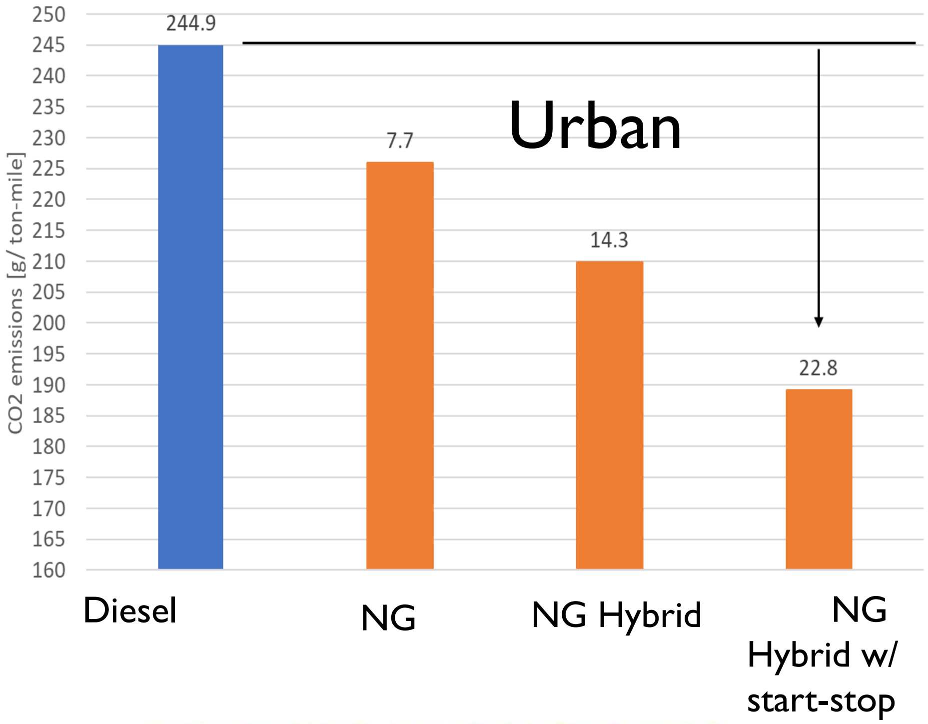


GHG Reduction Prediction

- Used GEM inputs for the baseline, provided by Isuzu
- Used a combination of GEM and GT-Drive for the hybrid versions
- With just the preliminary level of hybrid controls the NG hybrid is close to achieving the 25% GHG emissions reduction target
  - The hybrid was only used to show an improvement on the transient cycle and idle cycle
    - Hybrid controls used a charge sustain mode only
  - Hybrid showed 15% improvement over HHDDT transient cycle



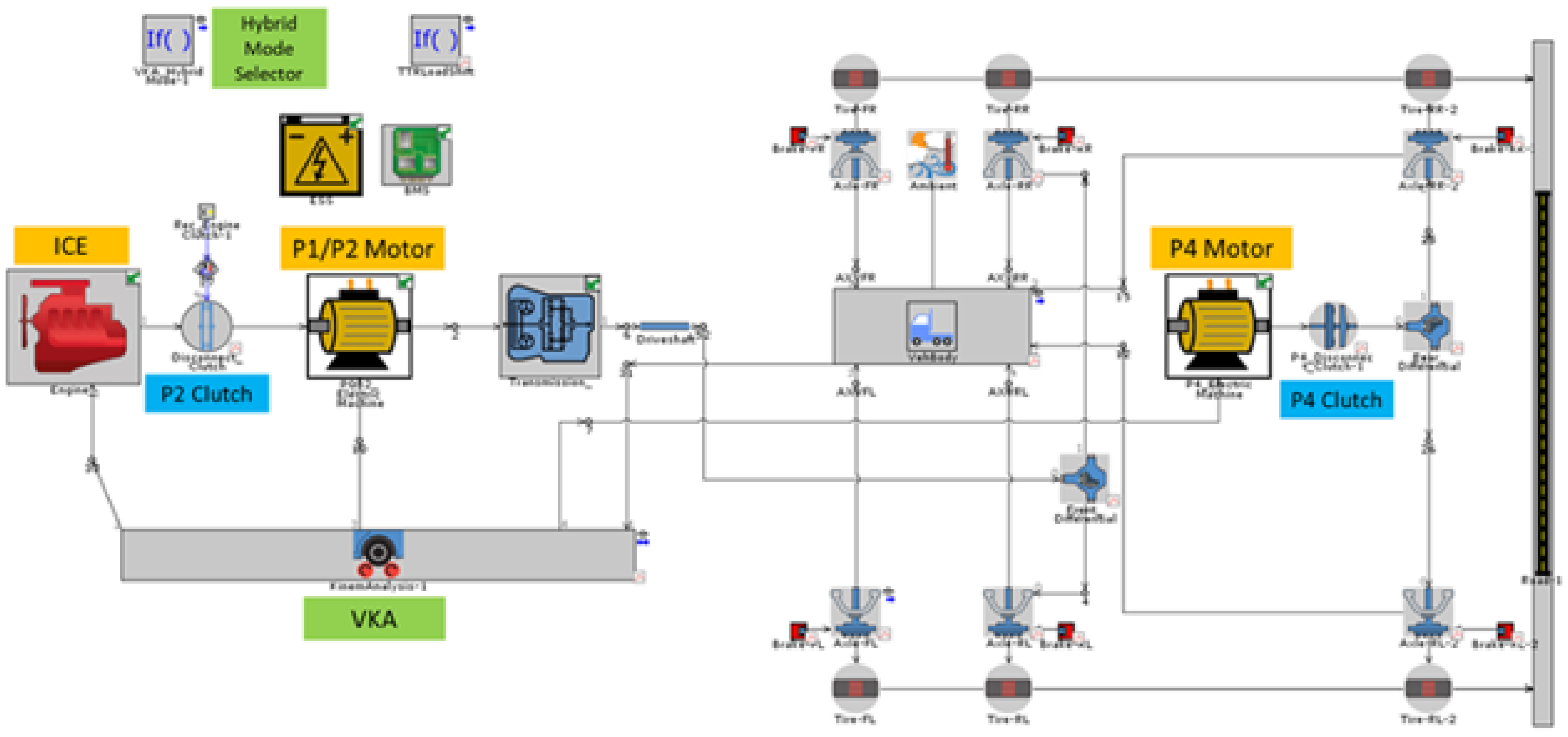




Hybrid System Development

Drive Cycle Performance Modeling

- The Isuzu 4H-Fseries-VF76 Class 6 medium-duty truck was modeled in GT-DRIVE
- The same hybrid vehicle model captures P2 and P4 hybrid architectures using clutch arrangements to select either configuration

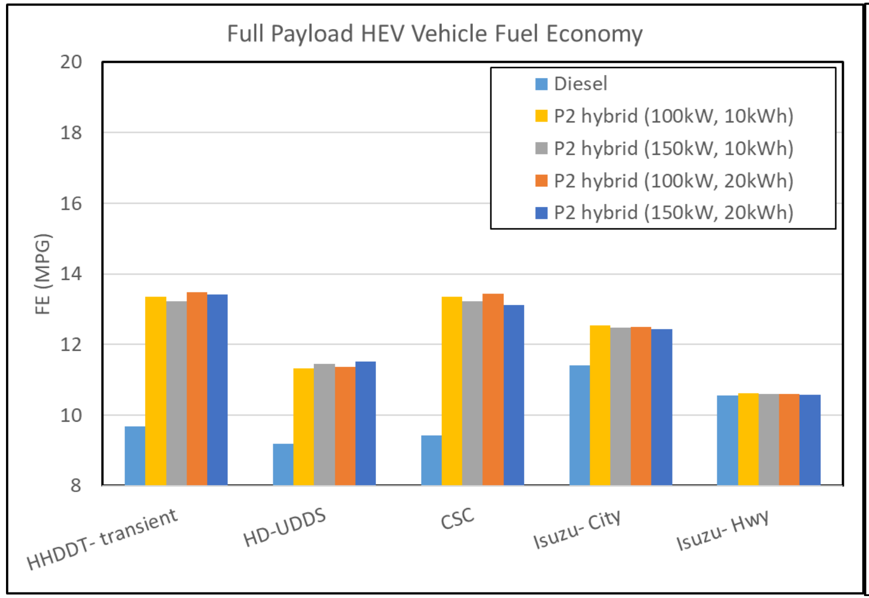


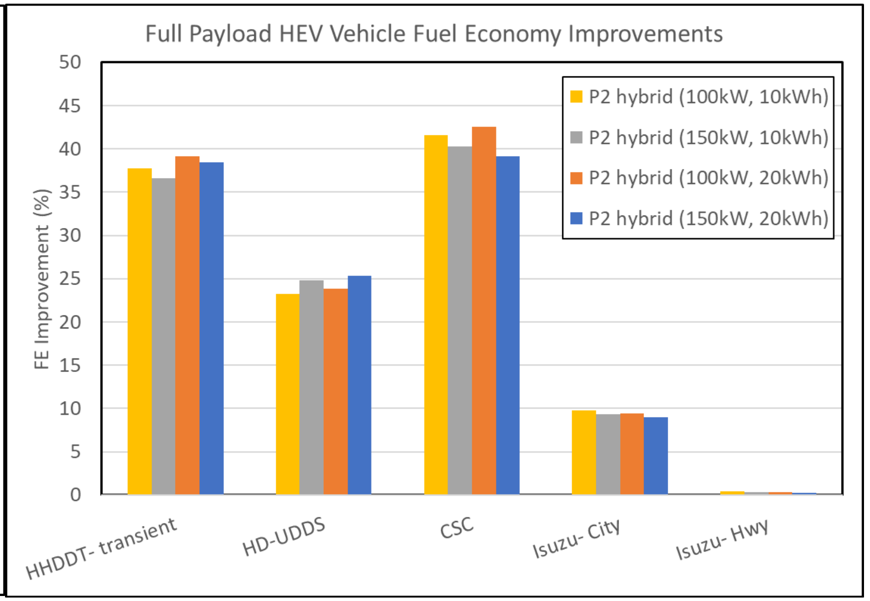
GT-DRIVE VEHICLE AND POWERTRAIN VKA MODEL

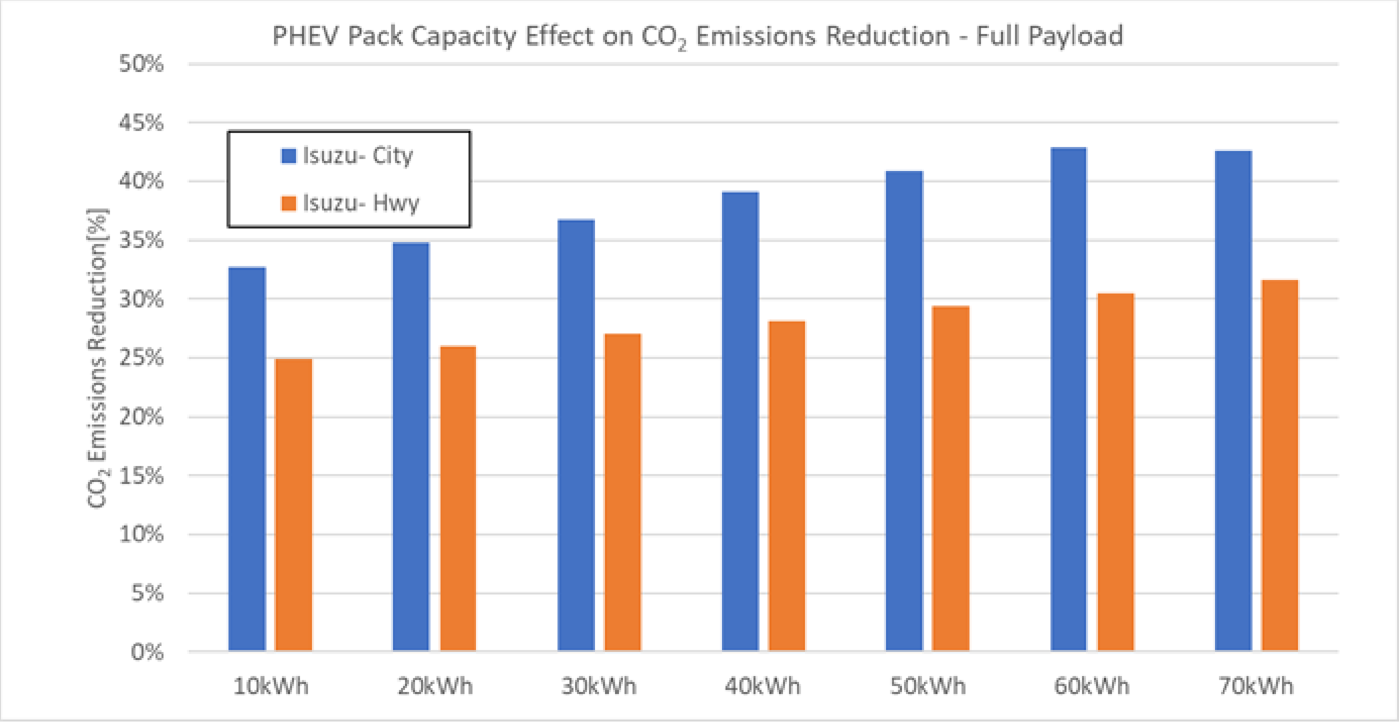
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Drive Cycle Performance PHEV Results

- Best PHEV architecture:
  - P2
  - 100 kW e-motor
  - 40kWh battery
- PHEV Fuel economy improvements
  - Standard cycles: 24% to 48%
  - Isuzu-City cycle: 10%
  - Isuzu-Highway cycle: less than 1%

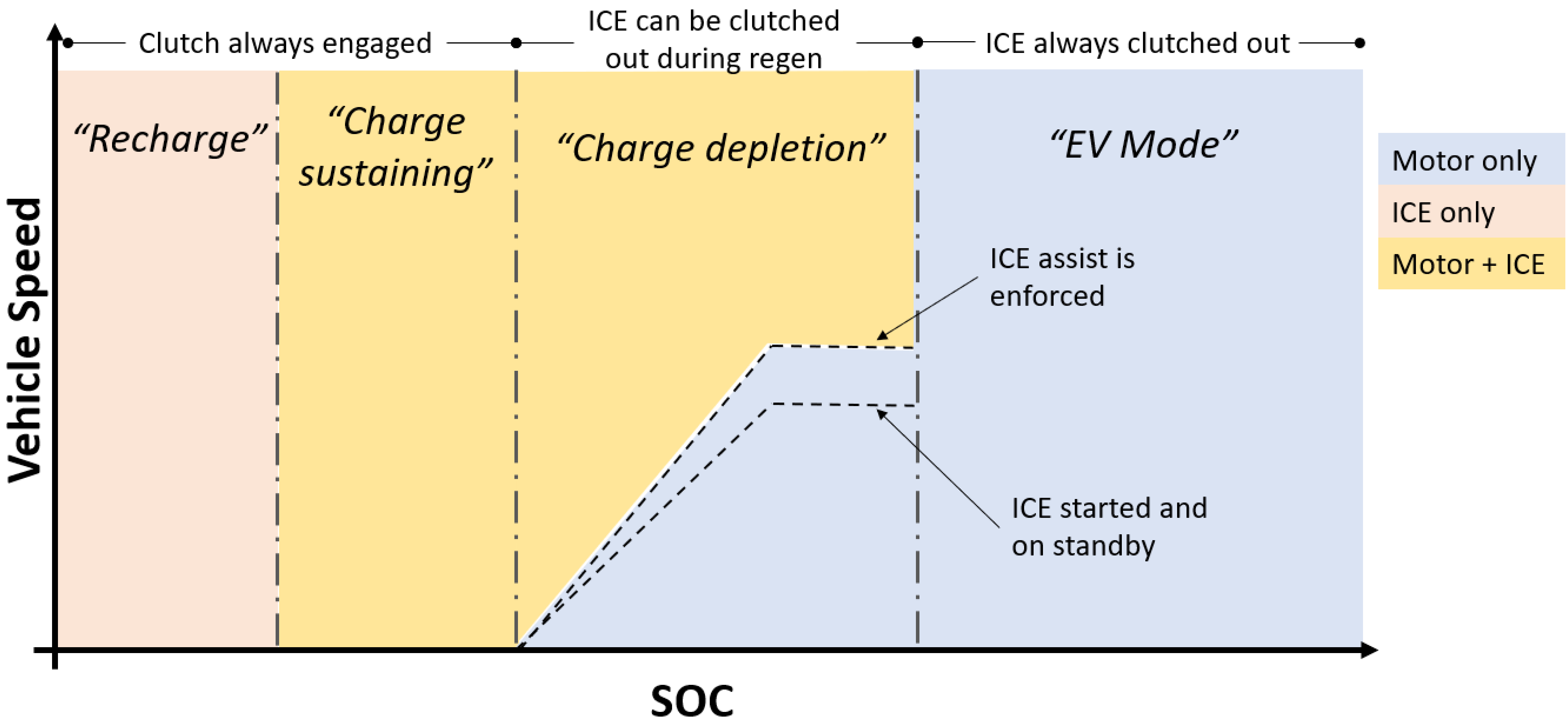






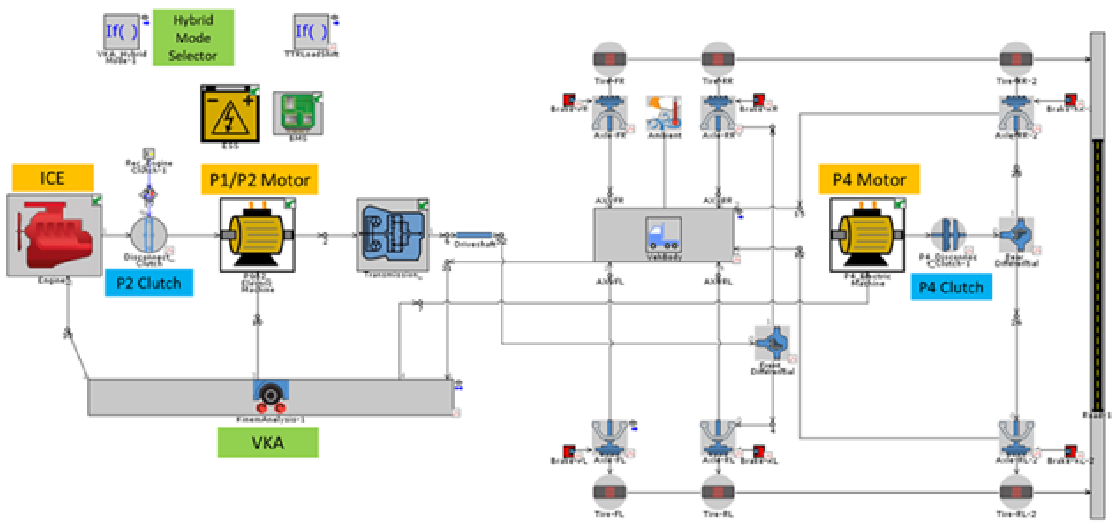
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Operating Modes

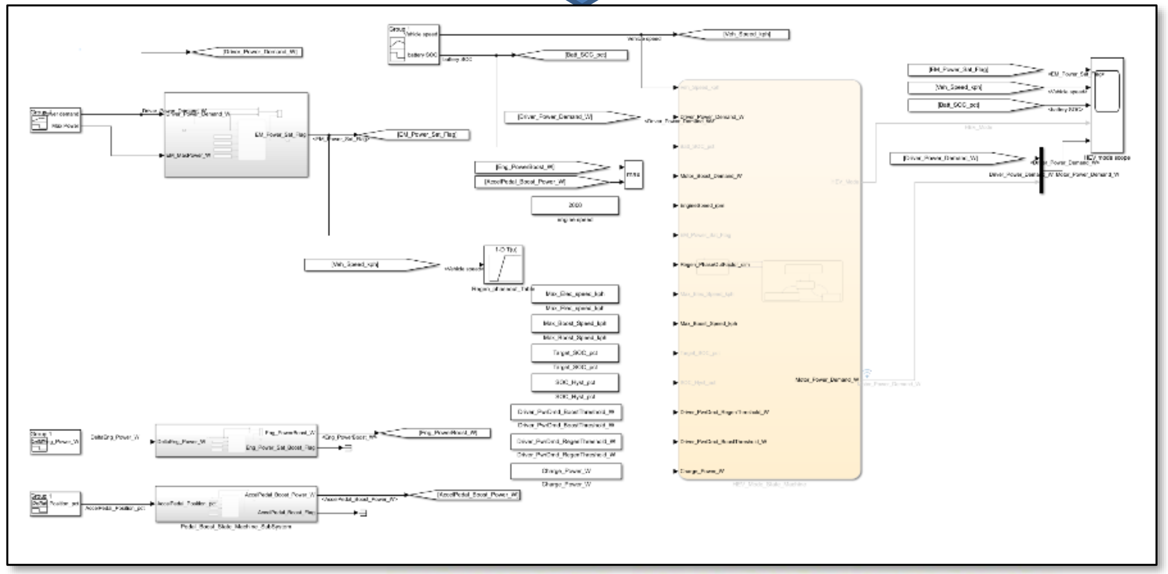


Hybrid Control Development

- Control strategies converted from GT-Drive to Simulink and refined
- Co-simulation of Simulink strategies with GT plant model
- Benefits:
  - More detailed control strategies in Simulink
  - Allows auto-coding of Simulink strategies straight to vehicle controller
  - Faster implementation and iteration when testing in vehicle



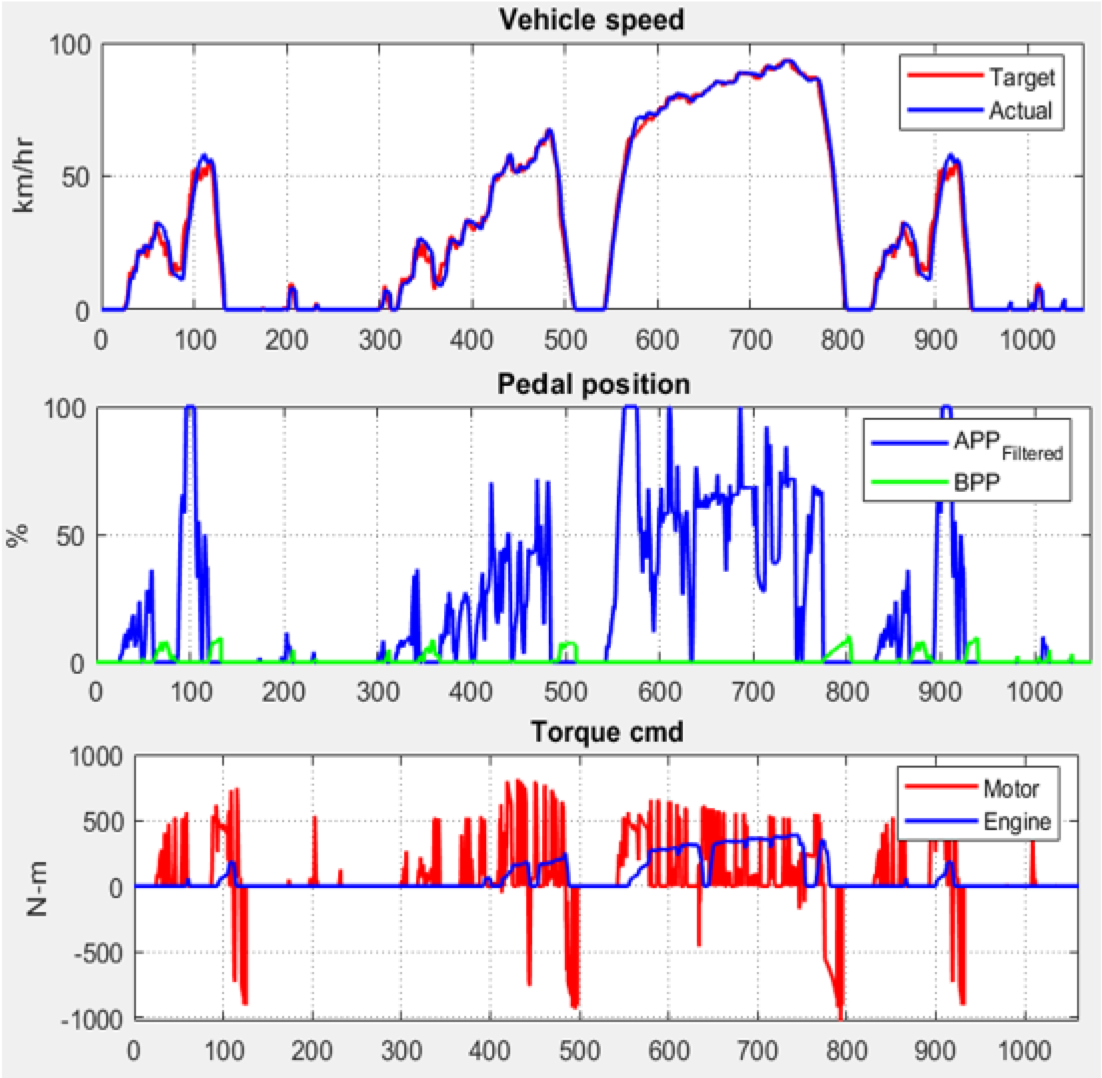
GT-DRIVE VEHICLE AND POWERTRAIN VKA MODEL



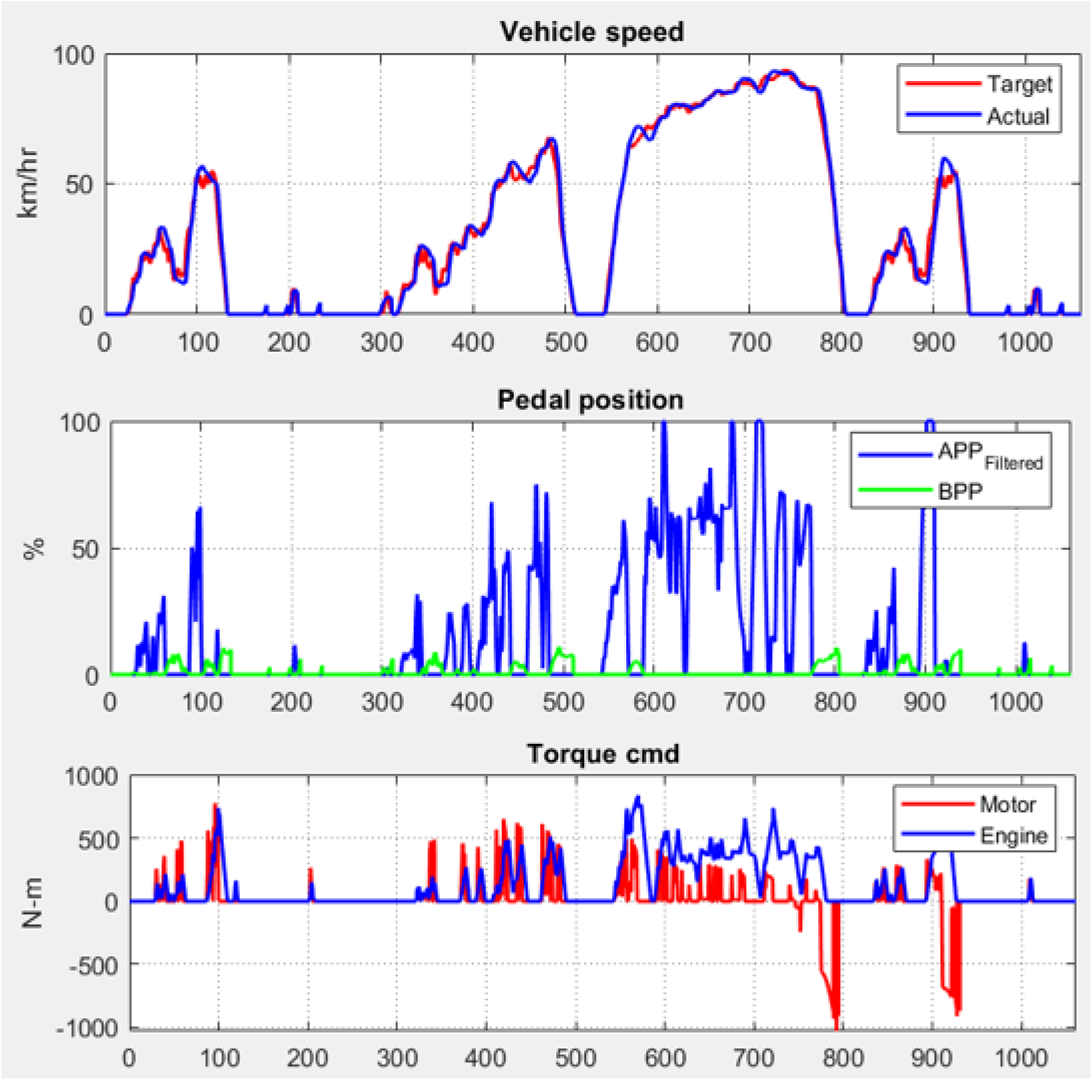
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

SIL Co-sim Verification & Calibration

Starting at 50% SOC



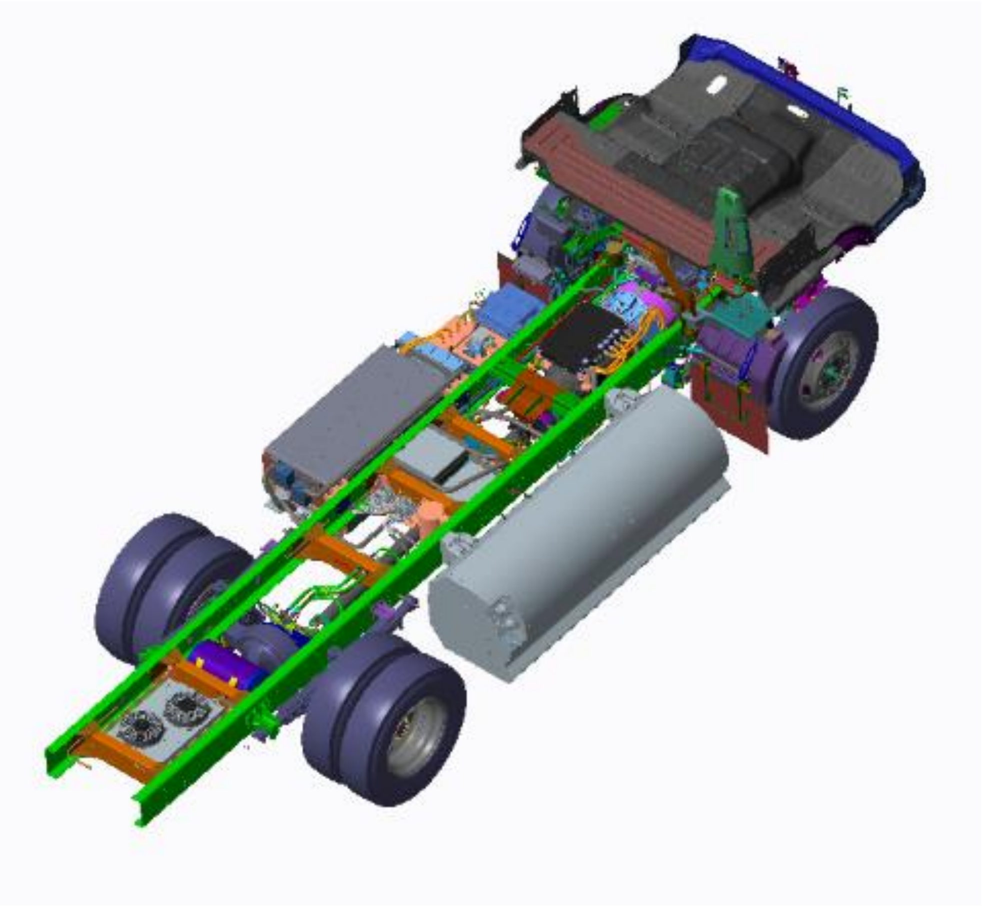
Starting at 25% SOC

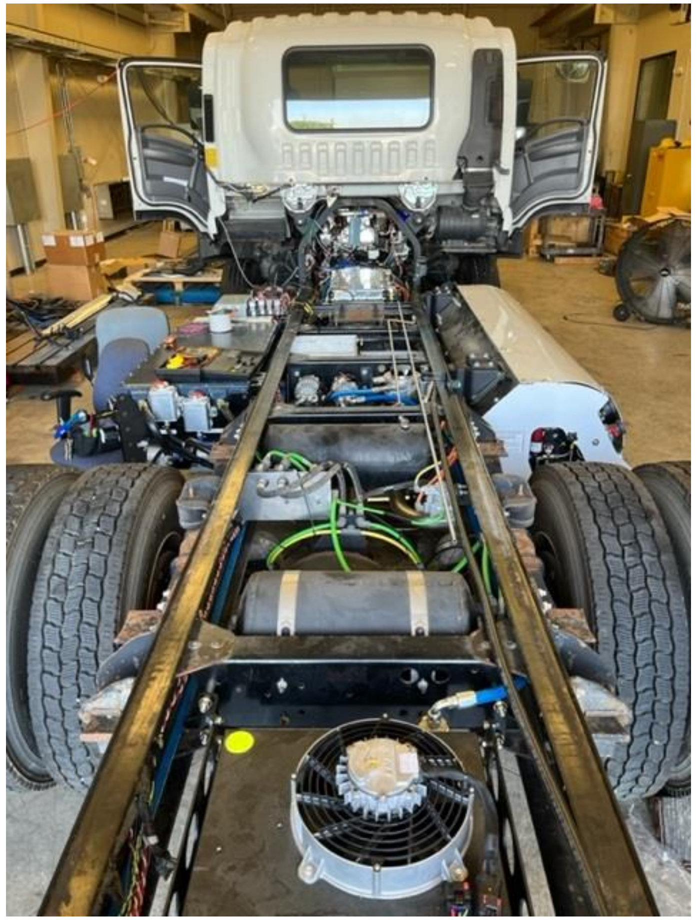


Vehicle Integration

SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Task 5.2 – Vehicle Integration



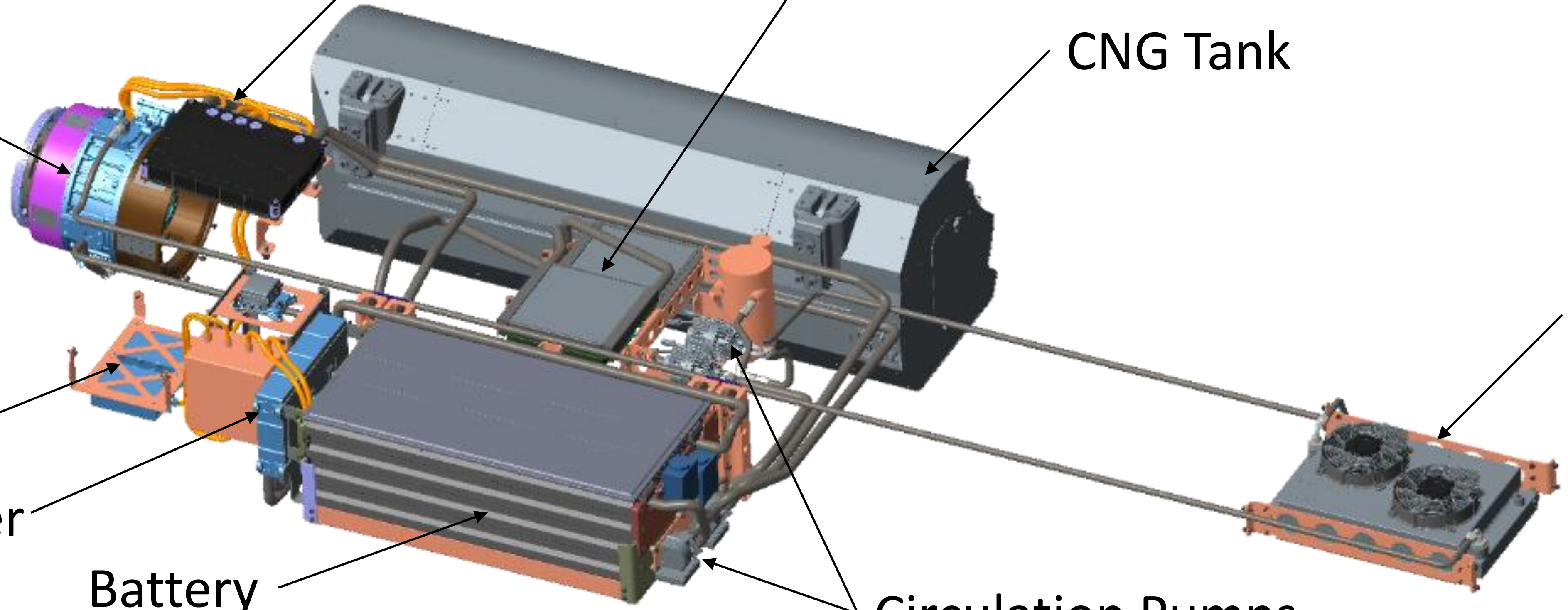


Status:

- Hybrid hardware integration complete
- NG Engine and fuel system integration complete
- Wiring complete

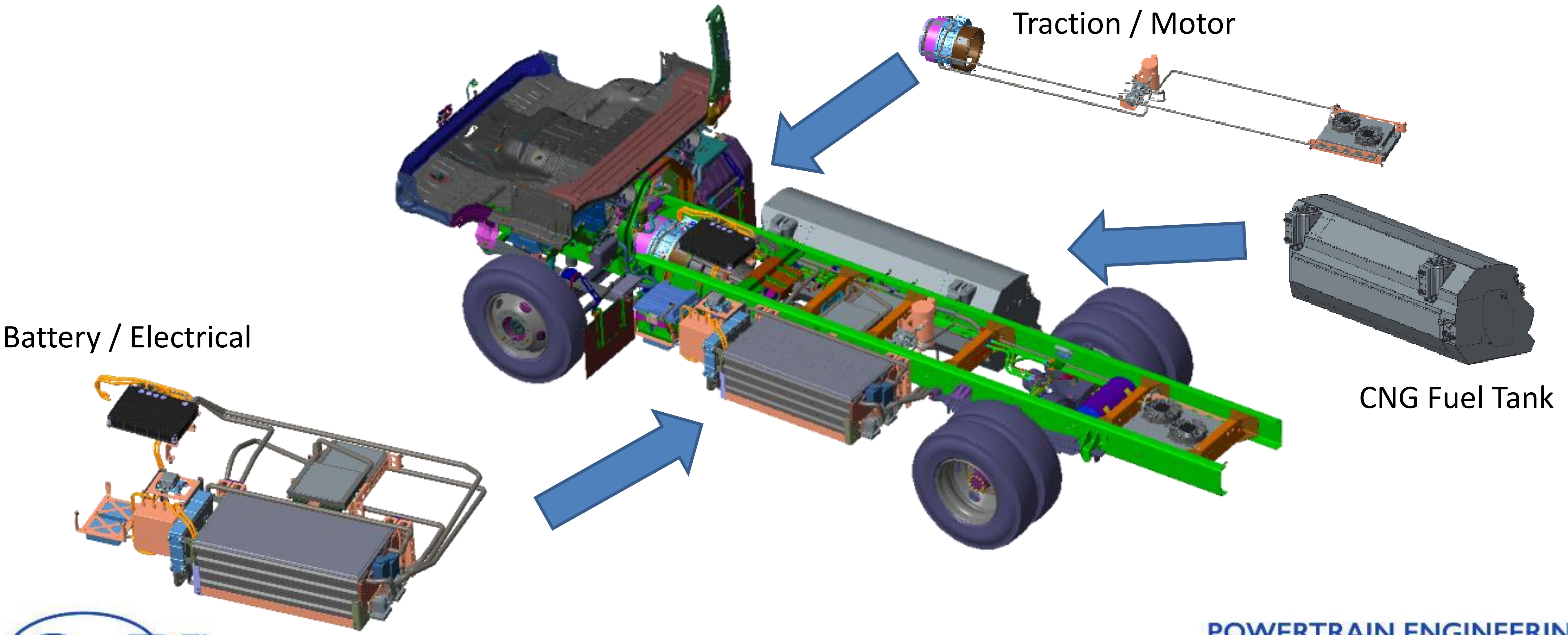
CNG / Hybrid Vehicle Integration

- Isolated hybrid system shown below (PN: 25912-900-000)
  - PN: 25912-950-100: Traction Motor Assembly
  - PN: 25912-950-200: Battery / Electrical
  - PN: 25912-950-300: CNG Fuel Tank



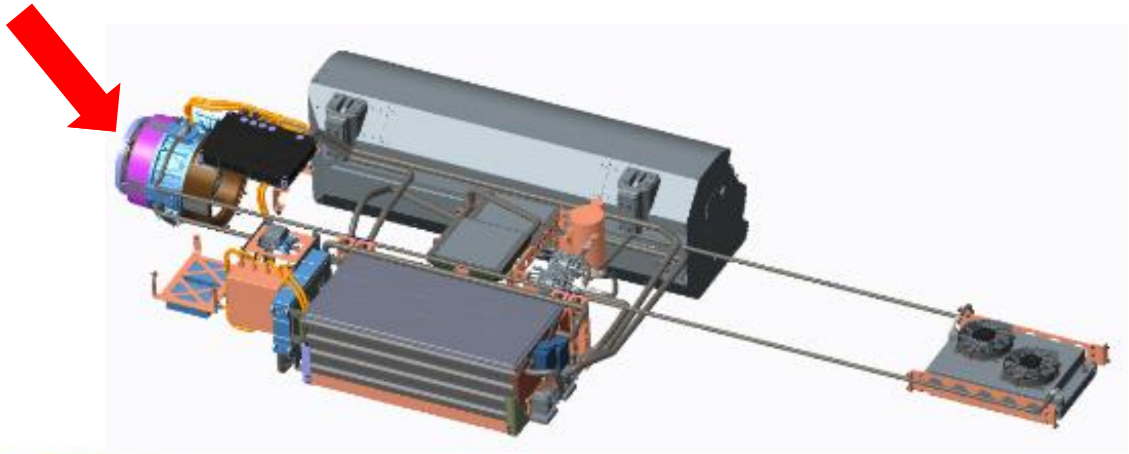
Vehicle and Hybrid System Overview

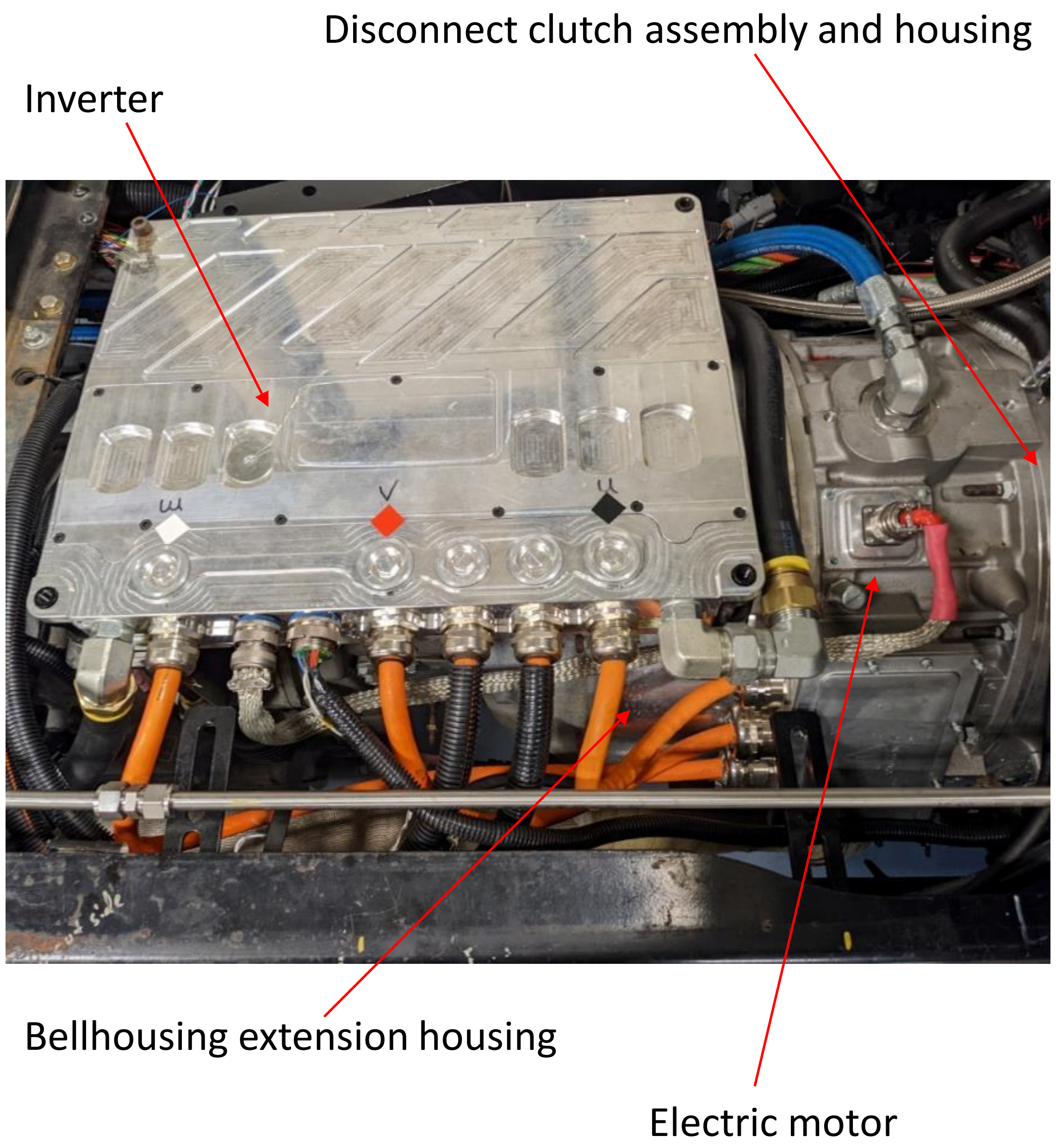
- The traction motor, battery / electrical and CNG systems have been integrated into the Isuzu F series vehicle chassis



Traction Motor Integration

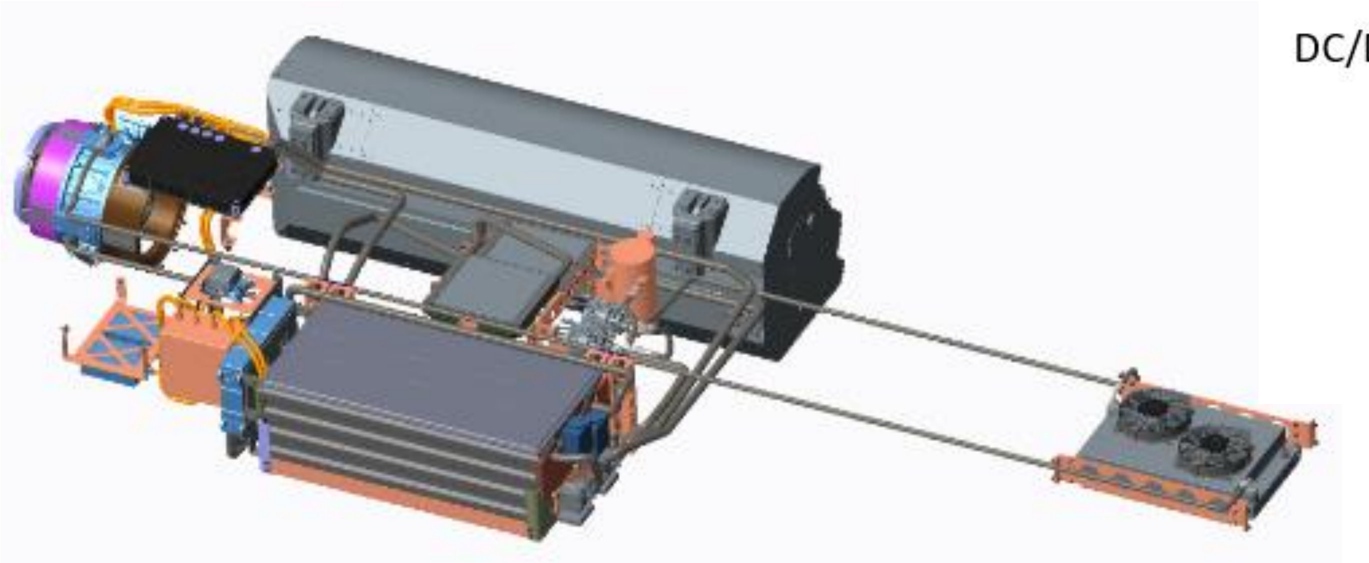
- Primary components:
  - Disconnect clutch assembly
    - South Bend 1947-OFE manual transmission clutch and Schaeffler CAN controlled electrohydraulic actuator
    - Custom flywheel housing extension
  - Borg Warner HVH410-075-DOM traction motor
  - Custom bellhousing extension and flex-plate adapter

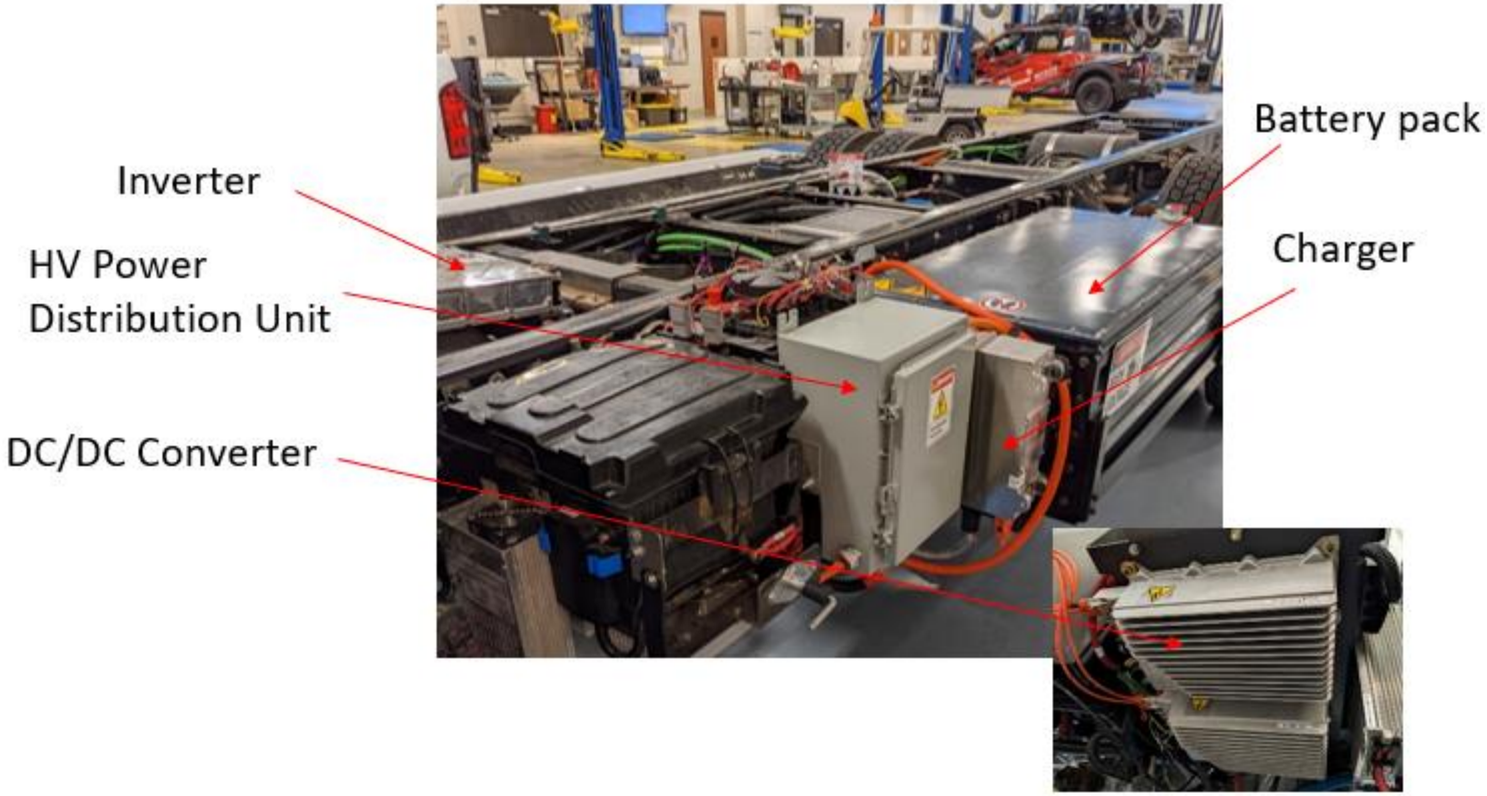




Battery / Electrical Integration

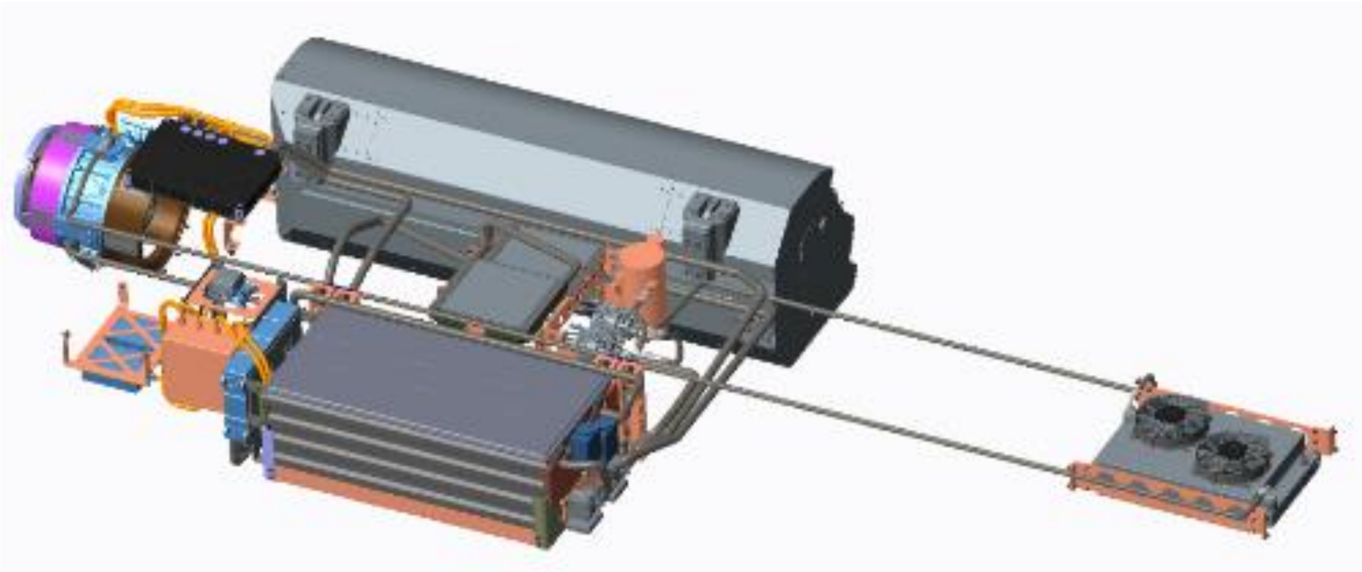
- Primary components:
  1. Leclanche INT-39HV Battery Pack
  2. Cascadia PM250DZ Inverter
  3. Sevcon Gen 5 HV DC-DC Converter
  4. EDN EVO11KL Charger
  5. HV Power Distribution unit

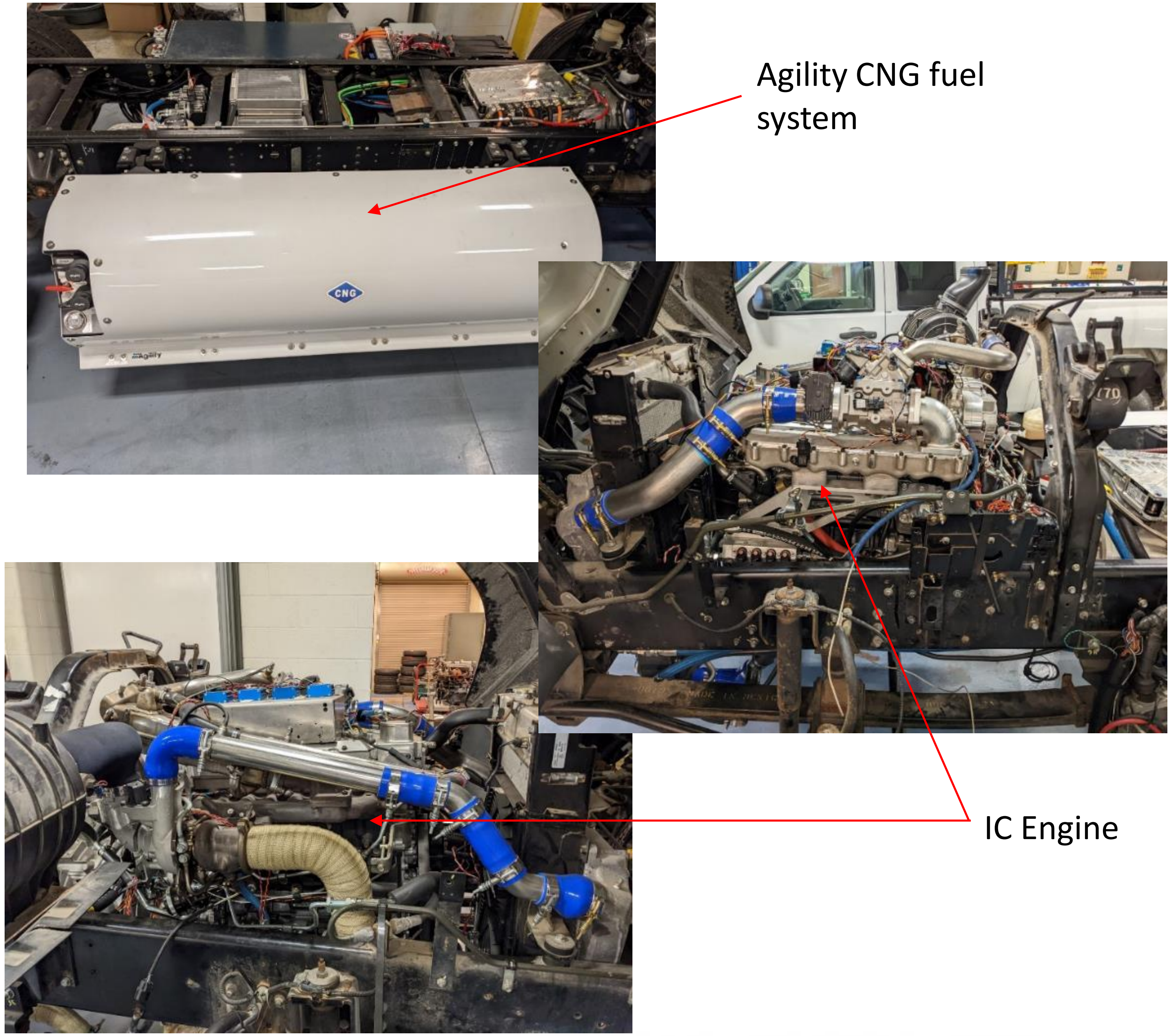




CNG Fuel System and Engine

- Primary components:
  - Agility CNG fuel system
  - CNG Fueled Engine





Next Steps

Powertrain evaluation, vehicle demonstration and reporting tasks

- Vehicle performance testing
  - Hybrid control and powertrain system calibration and testing on the SwRI heavy-duty chassis dyno
- Drive cycle and On-road testing
  - The truck will be operated on the SwRI chassis dyno and test track to validate drive cycle emissions performance and on-road drivability
- Final project reporting and vehicle demonstration