Development and Demonstration of Medium- and Heavy-Duty PHEV Work Trucks

Principal Investigator: John Petras

Organization: Odyne Systems, LLC

Date: June 12, 2019

Project ID: elt094

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Project Overview

Timeline:

- Start Date: January 19, 2017
- Completion Date: January 31, 2021
- Percent Complete: 50%

Barriers

- Fuel efficiency of Medium/Heavy-duty work trucks
- Integration of Driving and Jobsite electrification of Medium/Heavy-duty work trucks
- Over 50% of Work Truck fuel use occurs during stationary operation – not addressed by traditional Hybrid solutions

Budget

- Total project funding: $6,955,281
  - DOE Share: $2,149,644
  - FFRDC Share: $ 782,549
  - Contractor Share: $4,023,088

- FY18 DOE Funding: $ 852,902
- FY19 DOE Funding: $ 945,218
  - *Includes FFRDC*

Project Partners

- Odyne Systems – Project Lead
- Freightliner Trucks
- Allison Transmission
- Ricardo Engineering
- Duke Energy
- Los Angeles Department of Power & Light
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- South Coast Air Quality Management

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

Relevance / Objectives

- Overall Objectives
  - To develop and demonstrate an advanced Plug-in Hybrid Electric (PHEV) Medium-Heavy Duty Work Truck
    - With greater than 50% reduction in fuel consumption when compared to a conventional diesel vehicle baseline
- 3 Phases of project
  - Period 1 (Completed FY18): System Design and Analysis
  - Period 2 (FY19, FY20): Prototype Build, Refinement and Verification
  - Period 3 (FY20, FY21): 10 Vehicle Customer Deployment and Demonstration
    - 5 Vehicles to be deployed in the South Coast Air Quality Management District
- 3 Focus areas
  - Optimization of Powertrain and Full Vehicle Energy Use
  - Battery System Sourcing and Development
  - Chassis, Vehicle, and System Development and Integration

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Relevance / Objectives

- Objectives this period
  - Finalize solution set
    - Controls: PHEV Driving algorithms and optimization
    - Components: Select Battery, power electronics, and drivetrain componentry
    - Integration: Vehicle, chassis and system detailed design
    - Integration: Build of project test chassis: Odyne/Freightliner M2 Chassis
  - Test solution
    - System integration and functionality on project test vehicle;
    - Driving algorithms on Oak Ridge Hardware-in-the-Loop (HIL) Dynamometer
    - Driving and full chassis integration at NREL ReFUEL Dynamometer test facility
- Relevance
  - Work trucks are unique in the proportion of fuel used during stationary activity and the diversity vehicle design and jobsite equipment utilized to fulfill their missions
  - This project will develop and demonstrate a modular PHEV Work truck solution which meets the needs of the work truck user while demonstrating a 50% reduction in full-day fuel use

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Milestones

Milestone	Date	Status 4/12/19
Budget Period 1		
Prototype Design Freeze (Go-No Go)	October, 2018	Complete
Budget Period 2		
Prototype Vehicle Functional Validation	May, 2018	On Track
Hardware in the Loop (HIL) Powertrain Verification	June, 2019	On Track
Prototype Vehicle Performance Validation (Go-No-Go)	August, 2019	On Track
Evaluation Fleet Build and Delivery	December, 2019	On Track
Budget Period 2		
Deployment Report	**April, 2020** **July, 2020** **October, 2020** **January, 2021**	On Track
Fleet Data Collection, Analysis, and Summary	**November, 2020**	On Track

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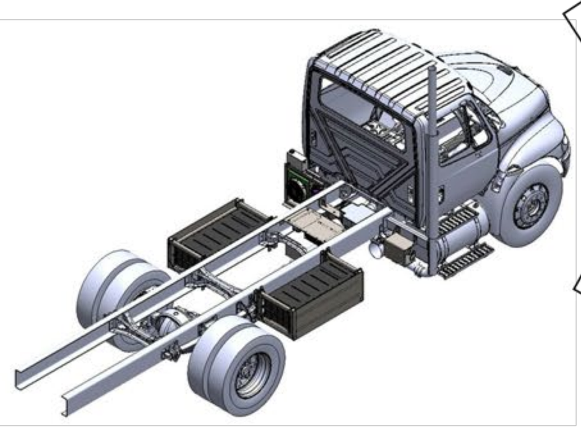
Approach:
PHEV System for multiple vocations



Hydraulic

Pneumatic

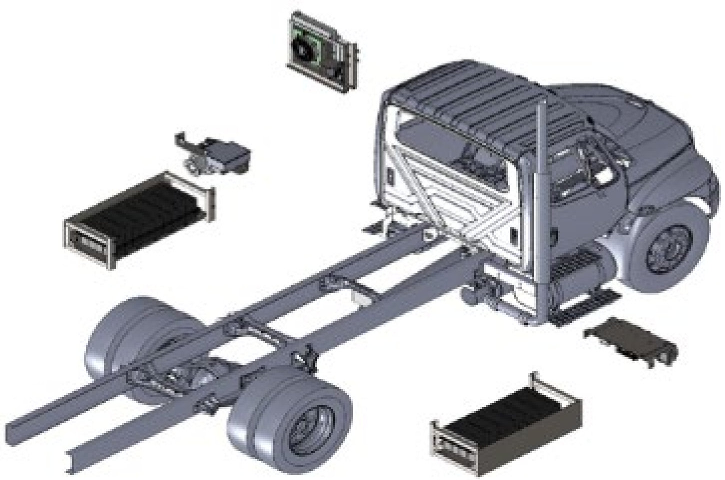
Electric

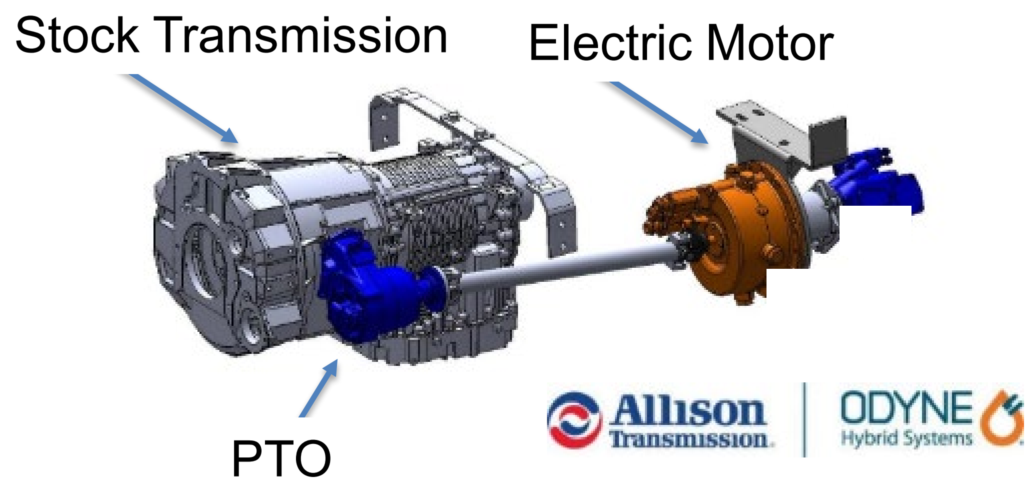
Work Trucks WORK

MANY OTHER UNTAPPED APPLICATIONS

Approach: Base System

Plug-in hybrid propulsion
+ work site idle reduction





Flexible

Modular Design applied to OEM Chassis
Multiple OEM and Application platforms
- Same base hybrid system

Minimally Intrusive

Hybrid Power through existing PTO port
No Changes to Base Powertrain
Allison Approved – Retains Powertrain Warranty

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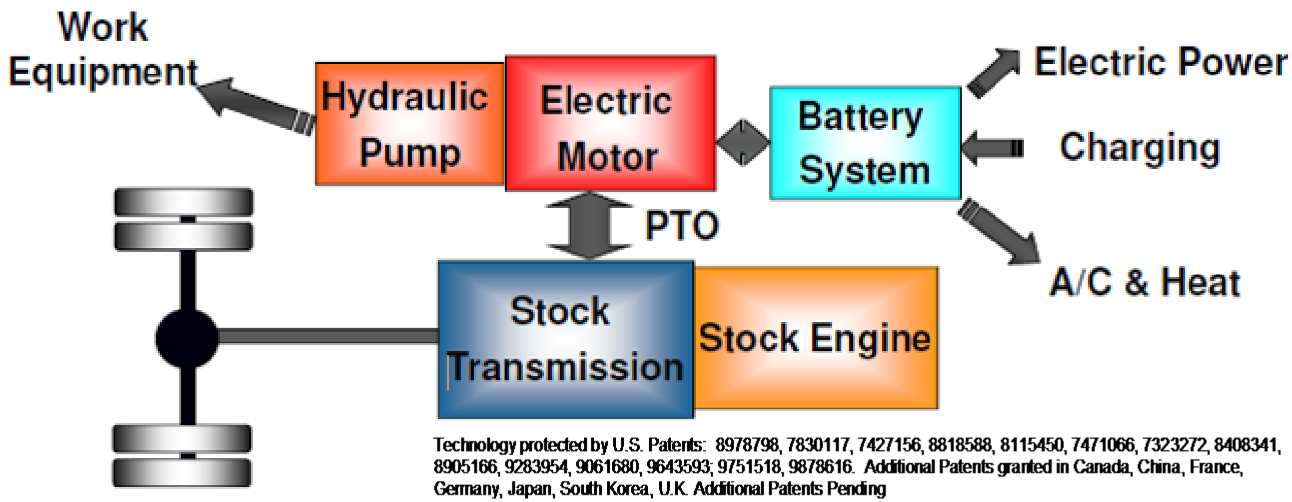
Approach: Base System



Technology protected by U.S. Patents: 8978798, 7830117, 7427156, 8818588, 8115450, 7471066, 7323272, 8408341, 8905166, 9283954, 9061680, 9643593; 9751518, 9878616. Additional Patents granted in Canada, China, France, Germany, Japan, South Korea, U.K. Additional Patents Pending

Bolts onto transmission, very robust and flexible design

- Hybrid propulsion through Power Take-off (PTO) connection with transmission
  - Launch assist and regenerative braking: more power, better driving efficiency
- Jobsite functions supported by Battery/Electric Motor:
  - Powers up to 60 kW of Hydraulic/ Pneumatic equipment
  - Provides up to 15kW of 120/240 VAC exportable power, 4 kW of 12VDC, Electric A/C
  - Field recharge via Diesel Engine if required – No interruption in jobsite function

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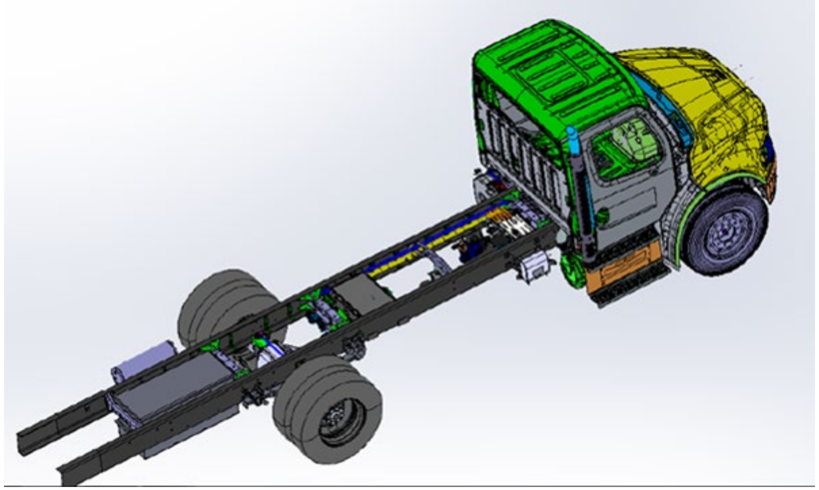
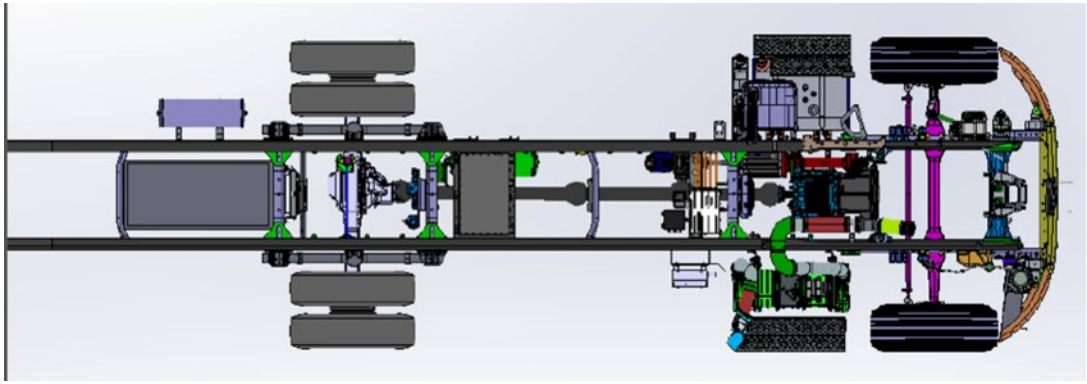
Technical Accomplishments
Design

- Subsystem and component selection has been completed
- Design integration into Freightliner M2 Chassis has been completed
- Final Subsystem Specifications:
  - 11/22kWh RESS
  - 250 Nm Peak, 150 Nm Continuous Motor Torque
  - 71 kW Peak, 50 kW Continuous Motor Power
  - 15 kW Exportable Power (120V/240V)
  - 4 kW DC/DC 12V support
  - 6 kW J1772 Level 2 Charging
  - Independent WEG Cooling System
  - Integrated Engine-off HVAC



Isometric View - Freightliner M2 Model with Hybrid Components



Plan View - Freightliner M2 Model with Hybrid Components

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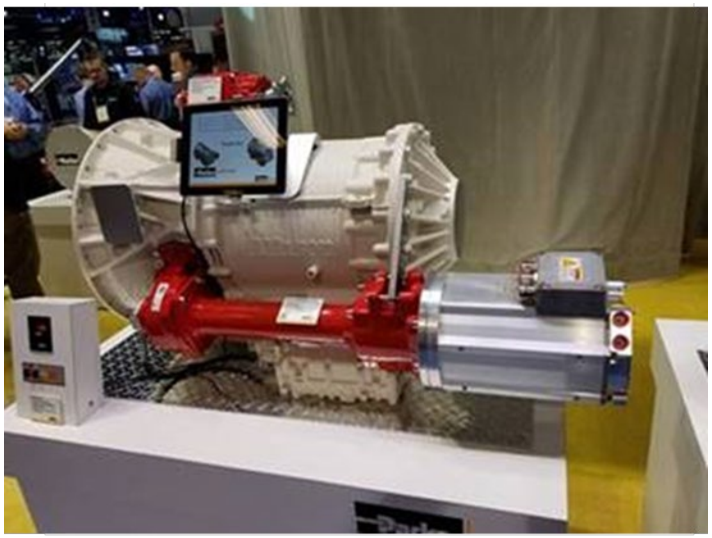
Technical Accomplishments
Powertrain Selection

- Parker motor and Chelsea extended PTO
  - More compact overall design
  - Family of motor envelopes is easier to accommodate
    - 200mm Base Diameter vs. 300mm for current
    - Multiple power options vary by length
  - Significantly easier installation
    - Fewer parts
    - Straight driveline, No parallelism concerns
    - No angular measurements at installation, service

Current Configuration

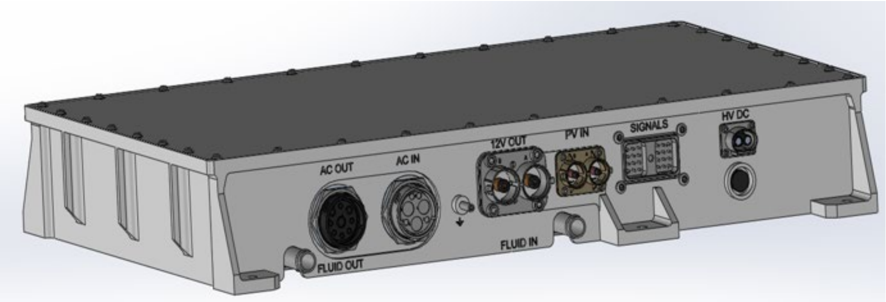


Project Direction

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

Technical Accomplishments
Power Electronics Integration

- Integrated Charger, DC/DC, Export Power unit
  - Integrated design
  - Improved performance
    - Charging 6 kW vs 3 kW
    - Export Power 15 kW vs 12 kW
    - 12V DC equivalent at 4 kW
  - Improved packaging
    - 45% less net volume – more when considering brackets and wiring clearances
  - Ancillary savings
    - 3 fewer Low Voltage, CAN, and HVIL nodes
    - 3 fewer high voltage lines
    - 6 fewer Cooling loop connections
    - 3 fewer brackets,



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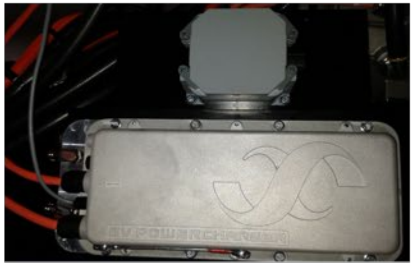

3 kW OB Charger and Drive-away Module

4 kW DC-DC

(2) 6 kW Exportable Power

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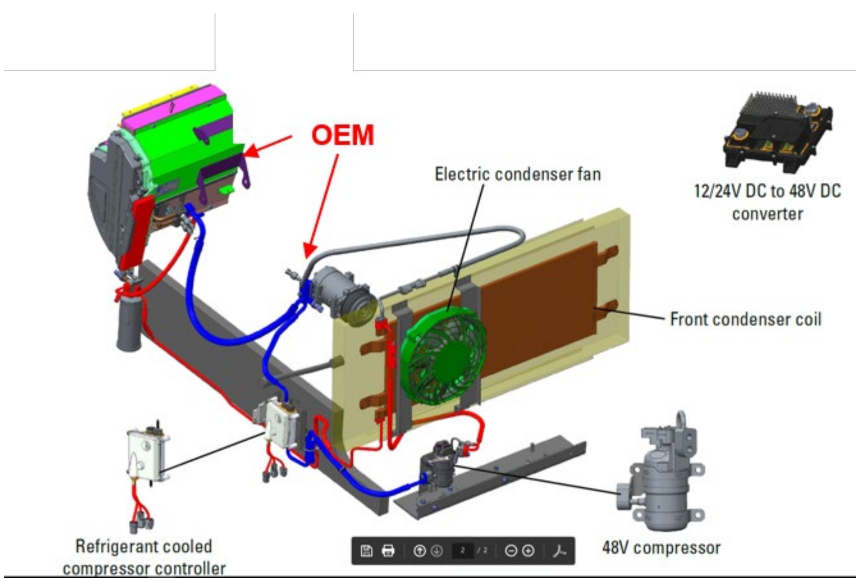
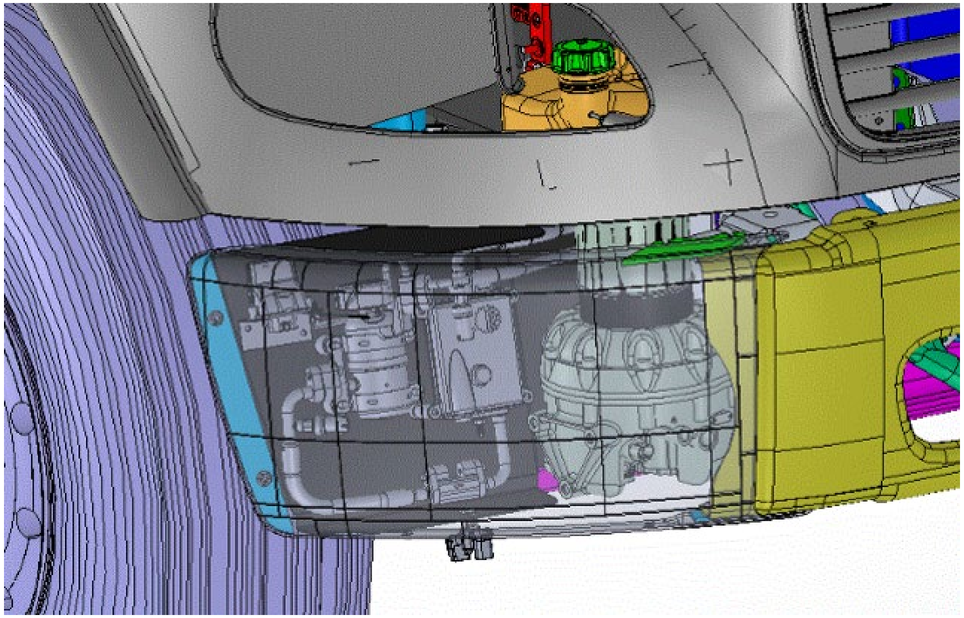
Technical Accomplishments
Air Conditioning integration

- A/C – Integrated System technology
  - Integrated into Chassis system A/C
  - Modified for Odyne controls and Off-Idle energy
  - Eliminates Odyne Specialty components
    - Secondary Cab Evaporator/blower
    - HV Compressor/controller & condenser from Cooling Assy
    - 1 HV Connection, multiple sub harnesses
    - Special HV Compressor Oil
  - Significant Assembly, Service, Customer Satisfaction improvements



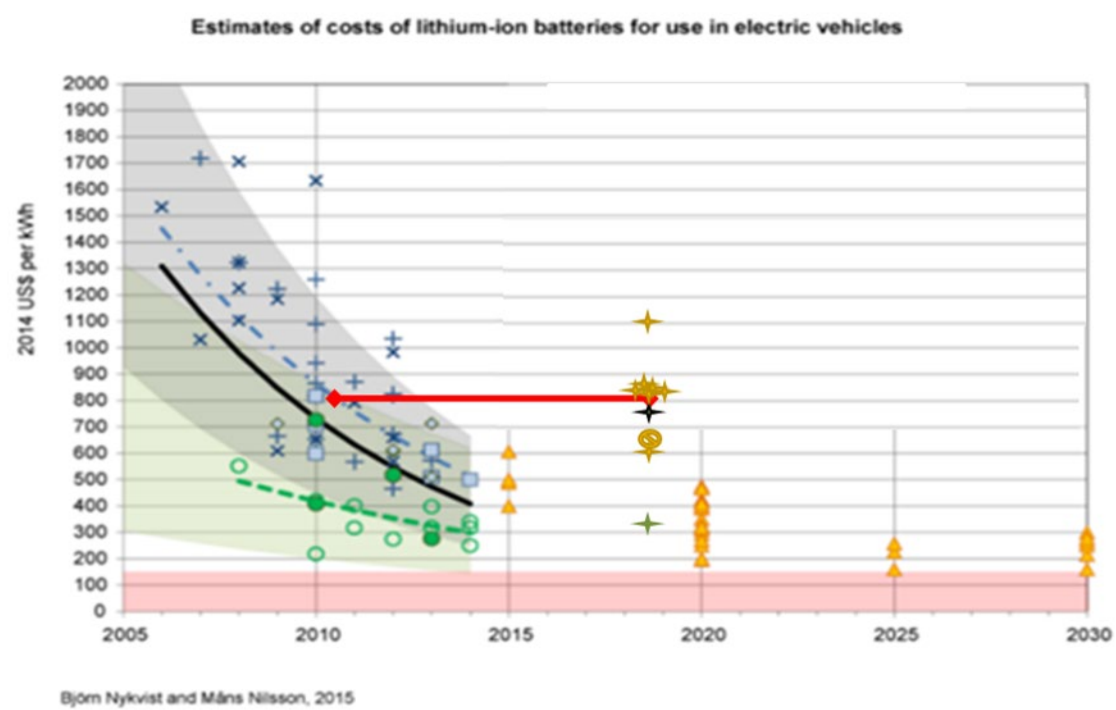


Technical Accomplishments
Battery System Selection

- Requirements and targets created around 350V, 10-16kWh base system
- Supplier Search was conducted by Odyne, AVL, Ricardo Strategic Consulting
  - Standard Packs
  - Configurable Solutions
- Over 50 OEM, Tier 1 and Mid-Level Pack Producers were contacted formally (RFQ) and informally

Observations

- Most Large OEM's and Tier I's were not interested due to low volume
- Many mid-range producers are now orienting towards the higher energy market (Bus, Port, EV)
  - Available modules produce >25kWh packs when configured to 350V
  - Difficult to package in a modular system
  - Some quoted, others no-quoted
- Typical Quoted cost is $800 - $850 / kWh



Technical Accomplishments
Battery System Selection

- Two battery systems were selected and are currently undergoing evaluation

- Torqeedo 11.6 kWh (In Production)
  - Chemistry: NMC
  - Nominal Voltage: 355V
  - Continuous Power: 55 kW
  - Size LxWxH (mm): 1460 X 305 X 330
  - $/kWh: $776

- Octillion 14.9 kWh (Developed for Odyne)
  - Chemistry: NMC
  - Nominal Voltage: 345V
  - Continuous Power: 32 kW
  - Size LxWxH (mm): 1101 X 527 X 301
  - $/kWh: $757

- Continuous Power target is >= 30 kW

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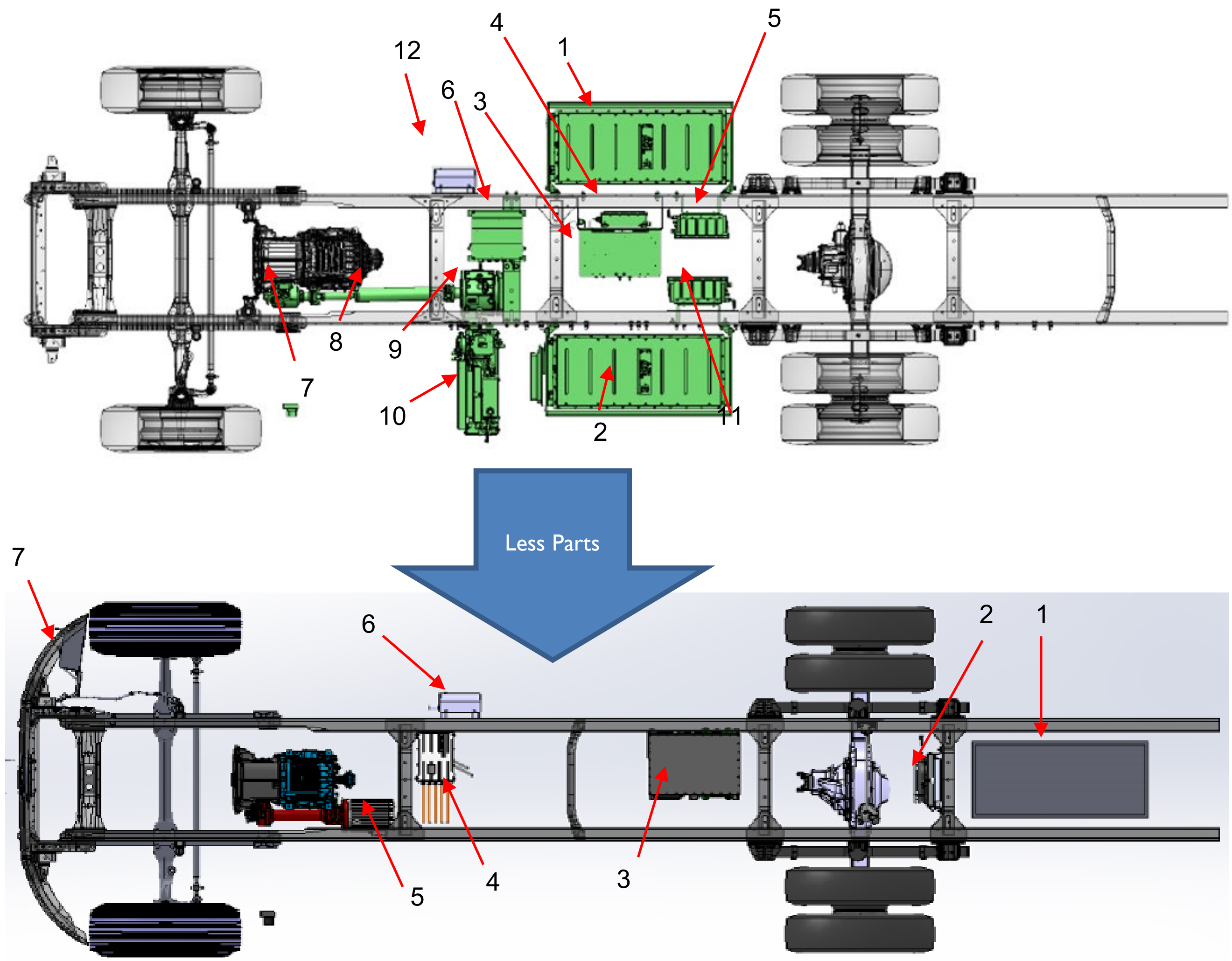
Technical Accomplishments Simplified Design

Current

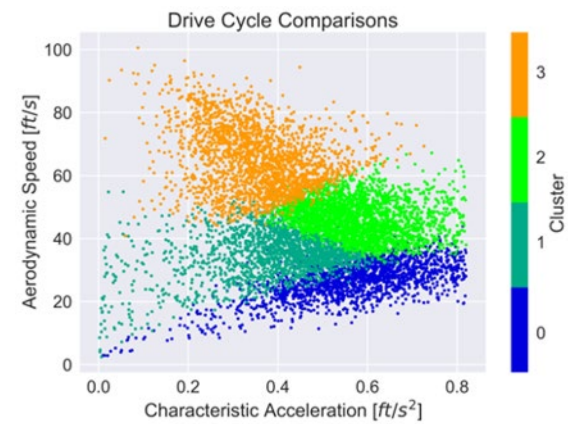
New

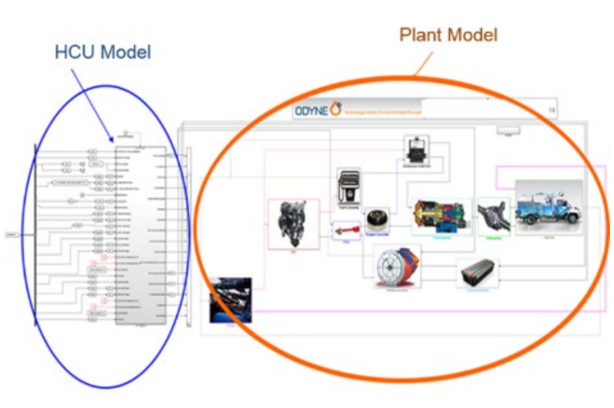


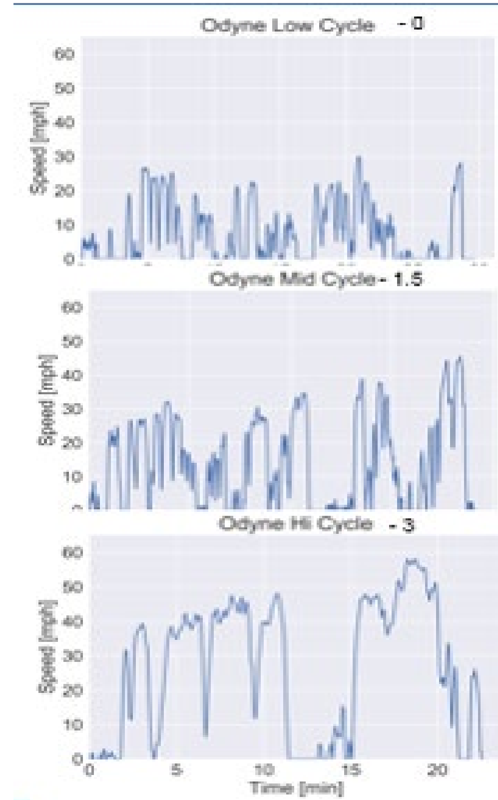
Lower Cost, Quick Installat ⇒ Expanded New & Retrofit Market

Technical Accomplishments
Powertrain Control – Prior Work

- NREL Duty Cycle Analysis
  - From 119 vehicle/15000 days Telematics data
- NREL Duty Cycle Development
  - 3 specific work truck duty cycles identified for modeling and dynamometer testing
- NREL Baseline Dynamometer Testing
- Odyne/Oak Ridge PHEV Model Development and correlation to dynamometer data







Odyne M2 ISB Correlation Results		UDDS			$HHDDT_{trans}$			NREL Low			NREL Med			NREL High		
Metric	Units	Dyno	Model	% Corr	Dyno	Model	% Corr	Dyno	Model	% Corr	Dyno	Model	% Corr	Dyno	Model	% Corr
Avg. Speed	MPH	18.55	18.59	100%	15.16	14.94	101%	7.55	7.45	101%	13.76	13.61	101%	25.98	25.94	100%
Fuel Use - Conventional	Gal	0.92	0.99	91%	0.49	0.50	98%	0.91	0.92	99%	1.52	1.60	95%	1.35	1.47	91%
Fuel Use - Hybrid Mild	Gal	0.89	0.93	95%	0.46	0.47	98%	0.83	0.80	103%	1.53	1.45	105%	1.35	1.43	94%

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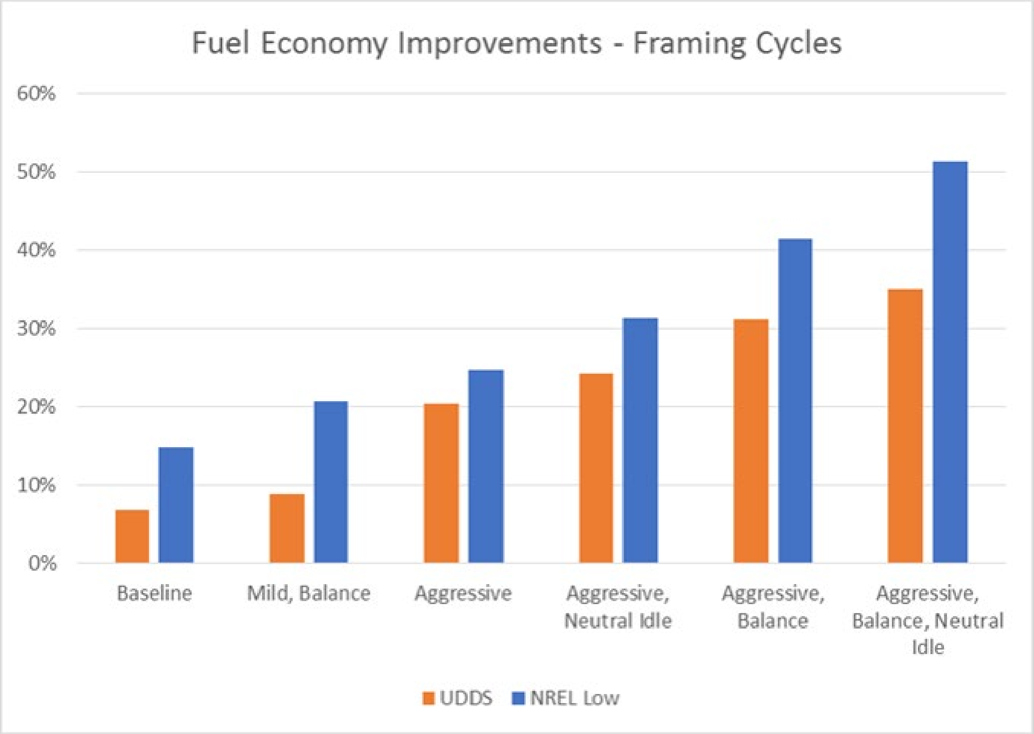
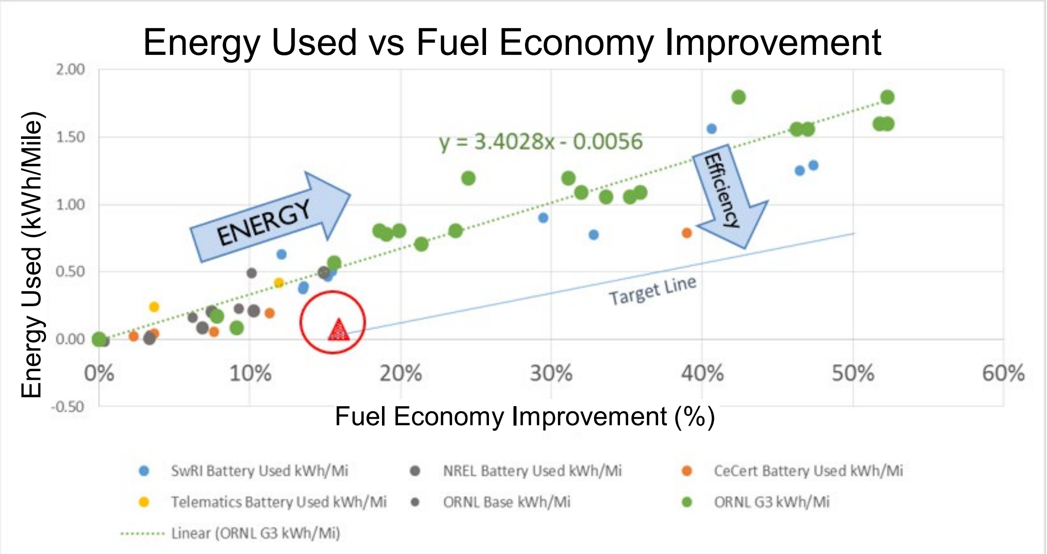
Technical Accomplishments
Powertrain Optimization

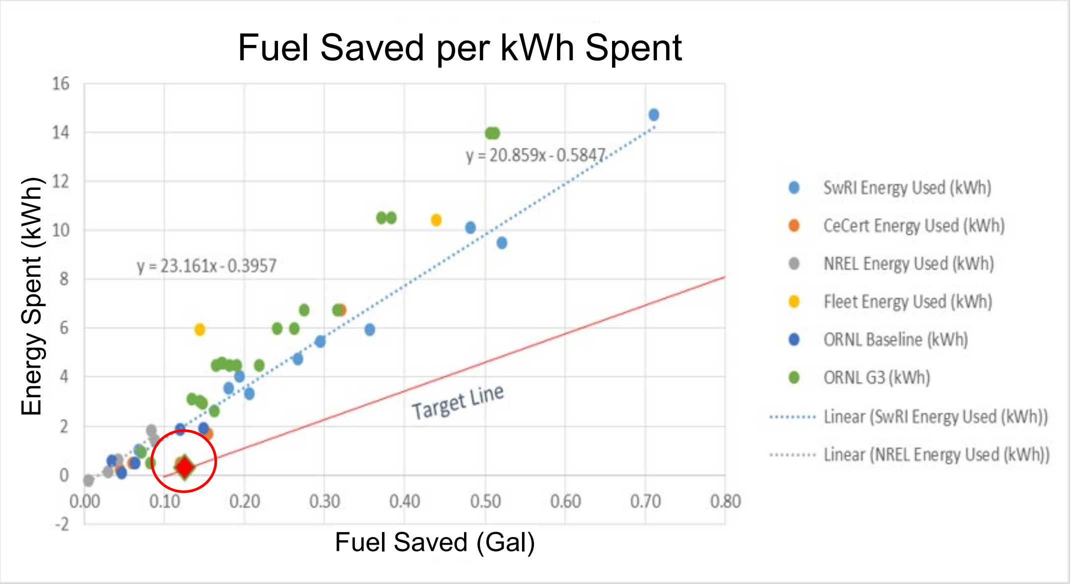
- Oak Ridge Simulation model was utilized to evaluate multiple iterations of refined Driving Strategies
- Primary features resulting in improved fuel economy included:
  - Increasing speed (MPH) range of Torque Assist
  - Increasing Peak Torque Available
  - Balance mode, reduce engine load by the amount hybrid motor is providing
  - Idle Neutral
- Results
  - Simulation of the combination of features above resulted in fuel economy improvements of 34-51% over baseline diesel



Technical Accomplishments
Powertrain Optimization - Continued

- Current System forms a bit of a trend
  - % improvement /kWh used
  - Gal saved / kWh used
- Indicates we can throw electrical energy at reducing fuel use
- Continuing optimization focuses on reducing energy spent per unit of improvement
  - Initial Results are promising (Red circle)
- Next Steps – Start adding energy and see if we can stay on the target line





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Technical Accomplishments
Full Year Model

- NREL developed Full Year Duty Cycles based on telematics data from 119 vehicle/15,000 day work truck fleet
- The duty cycle defines key parameters for both driving and stationary work on a daily basis
  - Driving
    - Miles
    - Average Speed
    - Kinetic Intensity
  - Working
    - Time
    - Average power
    - % demand time
  - Idle time
  - Key off time
- From these duty cycles, full year fuel use models can be developed for conventional and hybrid systems

Day	Driving	Fcharge	Idle	Key off	Plug-in	Working	Miles	KI	Driving Avg Speed	Demand Ratio
1-Jul-15	1.219722	0	0.385833	9.451944	0	0	18.16093	2.859436	9.641423	0
1-Jun-15	2.079167	0.126389	0.715833	0.073333	0	3.041389	39.58122	2.306074	12.02024	0.071577
1-Oct-14	0.098333	0	0.090278	0.0225	0	0	0.600959	0.49801	4.389788	0
1-Oct-15	0.8925	0.308611	0.353333	0.003333	1.349722	4.113333	15.00689	1.50997	10.61946	0.227115
1-Sep-15	1.039167	0	0.264722	4.099444	9.6275	0.741667	18.81908	2.242045	11.41663	0.017364
2-Apr-15	0.096944	0	0.101944	0.021944	0	2.680278	0.269688	28.52969	1.753885	0.062597
2-Jul-15	1.814444	0	1.588611	5.768056	0	0.808056	32.91486	2.666087	11.56391	0.1966
2-Jun-15	1.6675	0.177778	0.560556	1.377222	0	0	32.39362	2.334997	12.12426	0
2-Oct-14	0.109722	0.282222	0.074444	0.676944	0	1.015833	0.79156	5.708962	4.484784	0.070632
2-Oct-15	0.299444	0	0.196944	0.845556	6.379722	0	2.616966	10.46526	5.647033	0
2-Sep-15	0.652778	0	0.224444	5.292222	9.453611	3.183194	12.87734	1.979575	12.66252	0.067921
3-Jun-15	1.078889	0.550556	0.522778	0.124167	8.921944	2.257222	15.13736	4.032454	8.822911	0.196499
3-Sep-15	1.089444	0	0.569167	5.298056	9.191111	6.211389	25.77296	1.619039	14.83246	0.090976
4-Aug-15	0.851389	0	0.224722	1.361389	0	0	20.97293	1.598924	15.57251	0
4-Jun-15	1.340556	0	0.3625	6.551389	0	0	20.634	3.112269	9.705974	0
4-Sep-15	0.576111	0	0.143333	5.366389	10.33167	6.116389	13.02637	1.398708	14.49384	0.074444
5-Jun-15	1.128056	0	0.413611	0.190833	0	0.552222	16.72149	3.556249	9.562844	0.137639
5-Nov-15	0.209167	0	0.1175	0.156667	0	0.148611	2.099793	4.744647	7.895579	0
5-Oct-15	0.357222	0	0.113611	0.185278	0	0	5.88678	0.499883	10.37125	0
6-Aug-15	0.496944	0	0.159167	0.013333	0	0	7.053764	4.731945	9.149929	0
6-Feb-15	0.259722	0	0.116111	0.025278	0	0.011111	0.987386	23.39041	2.422141	0
6-Jan-15	0.100556	0	1.118611	0.053056	0	0	0.461523	21.47164	2.841751	0
6-Jun-15	0.605278	0	0.308333	0.005833	0	1.596944	10.7021	3.11421	10.95731	0.231562
6-Nov-15	0.311944	0	0.109444	0.474722	0	0	5.899539	2.538865	12.03424	0
6-Oct-14	0.251111	0	0.250833	0.773333	0	1.147778	1.05731	22.2244	2.697275	0.033623
6-Oct-15	0.624722	0	0.096667	0.409444	0	0	11.46428	2.542561	11.6743	0
7-Apr-15	0.018056	0	0.084444	0.012778	0	3.298889	0.067433	27.39132	2.322521	0.008851

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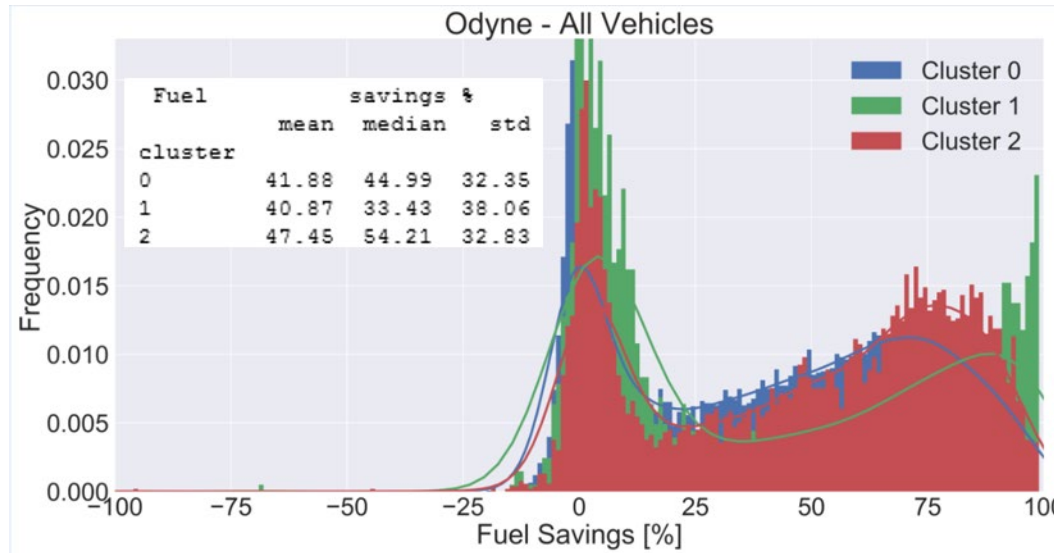
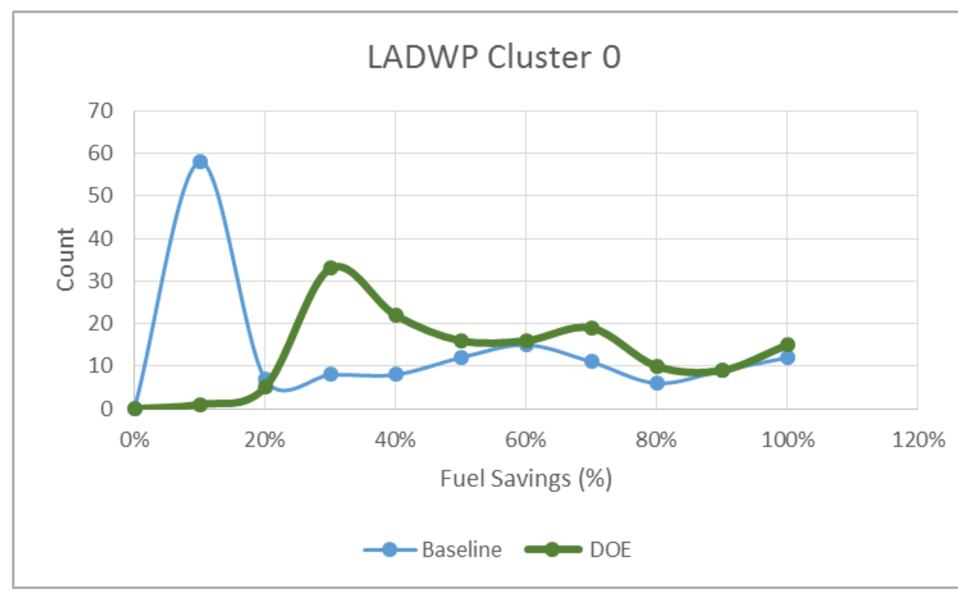
Technical Accomplishments
Full Year Model

- Utilize NREL Duty Cycles and Full Year Model to analyze full year fuel savings
  - Initial model average: 40-47% savings

- Apply:
  - 5 Minute Idle Shut-down
  - Neutral at Idle
  - Fuel economy improvement
    - 20 % @ .6 kwh/mile
  - Higher load (Faster) field recharge
  - Driver activity selection:
    - If drive only day: increase drive power utilized
- Results:
  - Significant reduction in low savings days
  - Average savings 41%>>55%





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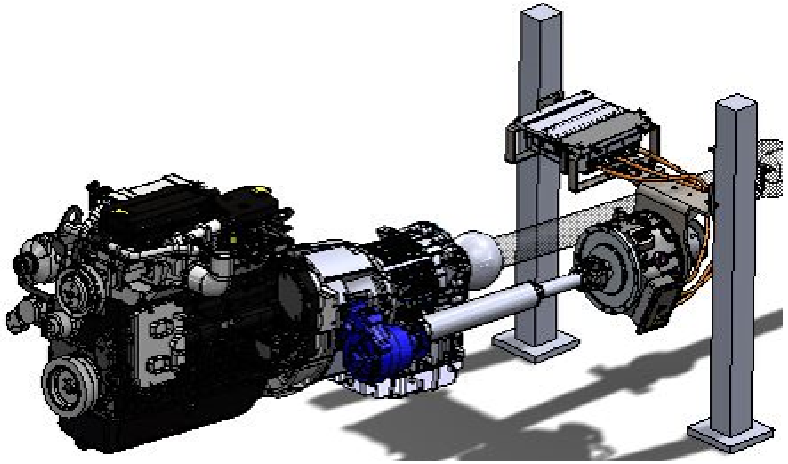
Technical Accomplishments
Moving towards testing (April Status)

- Hardware-in-Loop Parts are in final procurement for delivery to Oak Ridge
- Next Steps
  - Set-up at Oak Ridge HIL
  - Baseline tests to correlate to Dyno data and Model
  - Evaluation of Powertrain Optimization Strategies



- Test Chassis has been received and Hybrid build is 80% Complete
- Next Steps
  - Complete build
  - Start-up and De-bug
  - Odyne Functional Testing
  - NREL Full-Cycle Fuel and Emissions Testing

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Responses to Previous Year Reviewer Comments

ODYNE

Comments	Response
There could have been better collaboration with the actual users, such as fleet owners/operators. There was too much reliance on NREL,	- The presentation focused on the technical work performed to further understand and define the widely varied duty cycle of the Work truck market with regards to optimization of modular hybrid and electrification systems. - With regards to customer wants and needs, Odyne has spent the past 10 years working with over 70 fleets, mangers, and users to develop both technical requirements and user preferences for this class of work truck. - Subsystem minimum requirements based on ongoing understanding of work truck capacities and duty cycles were established and utilized during component selection
Focusing on an upfitting design rather than a more integrated approach will allow for rapid deployment of the technology into the fleet with a high level of confidence, but it precludes the opportunity to optimize the design.	- Agree, however the variety of work truck applications and specifications drives volumes so low for each that no one is willing to optimize for a single variant. - OEM's produce more generic vocational chassis and allow FSM's to add equipment and customize for their customers - There are hundreds of FSM's and equipment providers providing final vehicle solutions - Larger customers usually have many types of work trucks, often with different chassis, equipment, and power needs based on the mission - Odyne is focusing on providing a modular solution which can best hybridize and electrify this wide range of needs
The goal of a 50% reduction in fuel consumption when compared to a conventional diesel vehicle baseline is really so ill-defined that it is subjective. The reviewer commented that there is no specification for a baseline with respect to fuel consumption when the baseline transmission and diesel engine have not been defined.	- Because the work truck duty cycle is so varied and contains both driving and stationary work segments, the evaluation of fuel reduction will be based off a full year duty cycle model generated by NREL from 15,000 days of work truck telematics data - The model will include both the daily variation of driving and stationary work along Combined with driving and stationary fuel usage measured on the test vehicle at the NREL ReFuel dynamometer - Because the Odyne system is modular, both conventional and Hybrid can be tested on the same vehicle - The test vehicle is a 2018 Freightliner M2, Cummins ISB 6.7L, 250 H.P., Allison 3500 transmission.

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

Collaborators /Team

Organization	Function
National Renewable Energy Laboratory	• Telematics Duty Cycle Analysis • Fuel & Emissions Dynamometer Testing • Full Year Fuel Use Modeling
Oak Ridge National Laboratory	• Powertrain Simulation, Energy use optimization • Hardware-in-Loop (HIL) Powertrain Testing
Freightliner Trucks	• Chassis System Integration assistance, Vehicle models • Investigating commercialization codes for Odyne System • Truck Supplier for Prototype truck, Demo Fleet
Allison Transmission	• Powertrain and transmission optimization support • Transmission Control System integration
Ricardo Strategic Sourcing	• Battery System Sourcing
Los Angeles Department of Power & Light	• Provide 5 vehicles each for demo fleet • Participate in demo evaluation and feedback
South Coast Air Quality Management District	• Project cost share

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Remaining Challenges and Barriers

- Refine driving improvements on System Simulation and HIL development
  - Continue to strive to maximize fuel saved per kWh expended
- Evaluate remaining battery options and select final solution
  - Confirm capabilities meet specifications on test vehicle
  - Packaging trade-offs
  - Consider commercial details – this is a long term decision
- Develop simple strategy to address full-year duty cycle and how to best balance a modular system between stationary and driving activities, considering system cost

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

Proposed Future Research

- Period 2: Prototype Build, Refinement and Verification:
  - Install fully functional Hybrid/Diesel powertrain on Oak Ridge HIL
    - Correlate to model
    - Verify up to 40% improvement in driving fuel efficiency
    - Refine Driving algorithms and improve where needed
  - Complete prototype build and verify functionality of prototype test unit
    - Functional performance of driving, stationary, controls and subsystems
    - Dynamometer testing of Drive and Stationary fuel savings
  - Incorporate full day optimization
    - Strategies developed and incorporated into vehicle and code
    - Simulated effectiveness of full day strategies using new Dynamometer results
  - Build and Deploy Demonstration and Evaluation Fleet (10 Vehicles)
    - Work with Customer to specify and order vehicles
    - Work with OEM and FSM to design, build and deliver vehicles

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Summary

- Odyne and it’s project partners are working towards greater acceptance, improved fuel savings, and increased ROI of the Plug-in Hybrid/Jobsite Electrification system for Medium- Heavy-Duty Work Truck through:
  - Increased Driving Fuel Economy
  - Algorithms and/or inputs to manage the drive / work energy balance
  - Improved Full Year Fuel Savings
  - Reduced system cost, system simplification
- Initial advancements have been made in the areas of:
  - Development of driving, stationary duty cycles and full-year model for the work truck
  - Development and utilization of system model for driving optimization
  - Development of the system components and vehicle integration
- Next Period Deliverables:
  - Finalize driving optimization development and test on HIL
  - Completed Work Truck build and test
  - Analytical Demonstration of 50% reduction in Work Truck fuel use
  - Design and build of 10 vehicle demonstration fleet

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Thank You

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